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(54) **Title:** SECOND HARMONIC GENERATION (SHG) OPTICAL INSPECTION SYSTEM DESIGNS

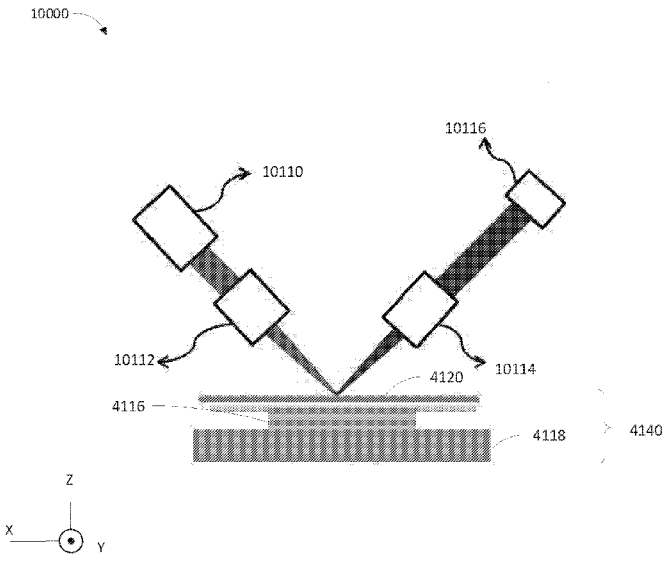


FIG. 23

(57) **Abstract:** Second Harmonic Generation (SHG) can be used to interrogate a surface of a sample such as a layered semiconductor structure. The SHG based sample interrogation systems may simultaneously collect different polarization components of the SHG signal at a time to provide different types of information. SHG imaging systems can provide SHG images or maps of the distribution of SHG signals over a larger area of a sample. Some such SHG imaging systems employ multiple beams and multiple detectors to capture SHG signals over an area of the sample. Some SHG imaging systems employ imaging optics to image the sample onto a detector array to form SHG images.

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SECOND HARMONIC GENERATION (SHG) OPTICAL INSPECTION SYSTEM DESIGNS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit under 35 U.S.C. §119(e) of U.S. Provisional Application No. 62/671,616, filed on May 15, 2018, titled "SECOND HARMONIC GENERATION (SHG) IMAGING BASED OPTICAL INSPECTION SYSTEM DESIGN" and U.S. Provisional Application No. 62/671,611, filed on May 15, 2018, titled "SYSTEM DESIGN FOR HYBRID-POLARIZATION OPTICAL SECOND HARMONIC GENERATION", both of which are incorporated herein by reference in their entirety.

FIELD

[0002] The subject filing relates to systems for Second Harmonic Generation (SHG) based wafer inspection, semiconductor metrology, materials characterization, surface characterization and/or interface analysis.

BACKGROUND

[0003] In nonlinear optics, light beam input(s) are output as the sum, difference or harmonic frequencies of the input(s). Second Harmonic Generation (SHG) is a non-linear effect in which light is emitted from a material at an angle with twice the frequency of an incident source light beam. The process may be considered as the combining of two photons of energy E to produce a single photon of energy 2E (i.e., the production of light of twice the frequency (2ω) or half the wavelength) of the incident radiation.

[0004] A survey of scientific investigations in which the SHG technique has been employed is provided by, "Optical Second-Harmonic Generation from Semiconductor Surfaces" by T. F. Heinz et al., Published in Advances in Laser Science III, edited by A. C. Tam, J. L. Cole and W. C. Stwalley (American Institute of Physics, New York, 1988) p. 452. As reviewed, the SHG process does not occur within the bulk of materials exhibiting a center of symmetry (i.e., in inversion or centrosymmetric materials). For these materials, the SHG process is appreciable only at surfaces and/or interfaces where the inversion symmetry of the bulk material is broken. As such, the SHG process offers a unique sensitivity to surface and interface properties.

[0005] So-understood, the SHG effect is described in U.S. Patent No. 5,294,289 to Heinz et al. Each of U.S. Patent Nos. 5,557,409 to Downer, et al., 6,795,175;

6,781,686; 6,788,405; 6,819,844; 6,882,414 and 7,304,305 to Hunt, 6,856,159 to Tolk, et al. and 7,158,284 to Alles, et al. also describe other approaches or "tools" that may be employed. Yet, the teachings of these patents appear not to have overcome some of the main obstacles to the adoption of SHG as an established technique for use in semiconductor manufacturing and metrology.

Summary

[0006] Part I

[0007] An SHG metrology tool is described in which electrons in a layered semiconductor substrate are excited, variously, by each of a pump light source and a probe light source having different power characteristics for the purpose of Sum Frequency Generation (SFG) (e.g.,typically SHG). For such an approach, a metrology characterization tool is provided with an "additional" integrated light source (e.g., a UV flash lamp or laser) operating as a "pump" to induce a potential difference across heterointerface(s) in layered semiconductor device templates, together with a short or ultra-short pulsed laser (e.g., a femto-second solid state laser) operating as a "probe" light source. Utility is derived from using the two different sources for different purposes in concert or in conjunction with each other (via various time-offset and/or variable pump energy methods as further described) as distinguished from a single laser SHG or a dual or multiple laser SFG system.

[0008] In one method, the pump is employed as a pre-exciting or pre-excitation light source to allow for total characterization time of some materials to be reduced. In many such implementations, the time-dependent electric field is not primarily produced by the probe/probing laser. In one variation of this method, the pump is used to UV flash an entire wafer and then use the probe laser to raster or otherwise scan the entire wafer or some portion thereof spending minimum probe time per point (e.g., scanning as fast as hardware can move the laser). Options in this regard include row-by-row scanning with a step along the (scan) column by wafer shift. Another approach may employ wafer rotating and scanning along the radii.

[0009] In another variation, the pump allows a quick charge up of the material interface at a sample site, followed by observation of the decay of that charged interface with the probe in connection with fast-blocking and/or optical delay methods further described in in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section II entitled, "CHARGE DECAY MEASUREMENT SYSTEMS AND METHODS".

Regardless, in various embodiments, the intent of pump use for pre-excitation is to inject charge carriers into, e.g., the dielectric in a quantity sufficient to impact the interfaces.

[0010] In another method, the pump laser is employed as a post-exciting or post-excitation light source to affect an SHG signal already being produced by the probe laser at a sample site. Yet another method employs a compare/contrast of the SHG signal generated by the probe pre- and post-pump laser energy application. By probing the sample and measuring the SHG response prior to pumping, then applying radiation from the pump light source and after that, re-probing, the difference in the SHG response pre- and post-pump can be used to determine additional material properties, such as trap density in the material dielectric.

[0011] In various methods discussed herein, a timing differential (i.e., in terms of pre- and/or post-excitation by the pump source in relation to probe laser use) is employed to deliver interrogation curves evincing further information about the material interface.

[0012] In various methods, the pump and probe sources are used simultaneously, with the combination used to provide an SHG signal for determining threshold injection carrier energy. Specifically, while probing with the probe laser, a tunable pump laser is ramped-up in frequency. At a particular frequency,, the SHG signal exhibits an inflection point (or a region of discontinuity). A value corresponding to the pump laser frequency at the inflection point (or the region of discontinuity) can be related to threshold injection carrier energy.

[0013] Various embodiments of the subject pump and probe system offers certain hardware-based advantage possibilities as well. In an example where the pump is a flash lamp, highly relevant cost savings can be achieved relative to 2-laser systems. Whether provided as a flash lamp or a second laser, the combination of a pump and probe as contemplated herein can also reduce the risk of optical damage to the substrate to be interrogated because illumination that is too powerful will degrade the dielectrics and even substrate if a threshold average power is exceeded. The threshold average power that causes optical damage to the substrate can be determined by experimental calibration study.

[0014] To understand the latter possibility in connection with the subject hardware some background is provided. Namely, both pump and probe energies, alone, are capable of producing an SHG signal with such hardware. While the pump and probe

sources do not need to operate in conjunction to produce SHG signal, relevant material properties are derived in the subject methods primarily from the SHG intensity produced by the probe, as the pump will generally not have the peak power to drive buried interfacial SHG appropriately. Time-dependent SHG intensity curves will change based on the distribution of charge carriers across an interface, for example, between the dielectric and substrate. The time it takes for injection of carriers across an interface, for example, between the dielectric and a semiconductor substrate, is dependent upon the average power targeted on the sample. In some implementations, the probe alone can enable injection of carriers across an interface between the dielectric and substrate. In such implementations due to the inability to decouple average power from peak power, the time taken to reach the target average power that allows for injection of carriers across an interface between the dielectric and substrate without exceeding the optical damage threshold of a material may be greater than implementations using a combination of pump and probe. By using a high average power but low peak power optical source as a pump to inject carriers across an interface between the dielectric and substrate prior to probing, the time savings of increased average power can be had without the potential damage complications a high peak power at said average power may induce.

[0015] Accordingly, as compared to the pump, the subject probe is typically a higher peak power source with low average power. Stated otherwise, the probe laser is typically relatively very weak. In one aspect, this allows for minimal disturbance to the native electric field present at the substrate interface to yield an initial time-independent signal.

[0016] With higher average power but low peak power, the pump induces an electric field (E) by causing charge carriers to jump up in energy level at the material interface or across the interface. By using a relatively high average power source as the pump and quickly "charging up" the interface by giving all the available electrons the energy at least sufficient to jump into the dielectric, a situation is created where the high peak power (providing high SHG conversion rates) but low average power (due to short pulse duration and limited number of such pulses) probe laser can quickly interrogate the surface to provide time-independent SHG signal data.

[0017] Accordingly, in various embodiments described herein a reduction in the time required for a/the probe laser to move electrons to higher energy levels or across interfaces can be achieved which can allow for faster evaluations of a steady-state

SHG signal and/or charge carrier time dynamics measurements. This approach also allows for separating the effects of the SHG probe from its own influence on the electric field at substrate interfaces. It also allows time-dependence in the SHG process to be sped up or ignored as well as allowing for faster acquisition of time-independent SHG data over at least part of an acquired signal from the probe beam. Likewise, another aspect allows for faster and/or more accurate determination of threshold energy for carrier injection into an interface (e.g., interface between a semiconductor and a dielectric), as well as fast(er) throughput in a line tool environment. Whatever the context, the available time reduction offered can advantageously facilitate high throughput testing in any sort of in-line metrology tool in the semiconductor industry. By way of example, to generate time dependence curves using pre-existing application of the SHG technique on a device including a 25 nm buried oxide layer under a 10 nm Silicon on Insulator (10 nm device layer / 25 nm BOX SOI) takes 6 to 12+ seconds per point. Using pre-excitation as described herein, time dependence can be generated in under 1 second, pending material and pump/probe power. This advance would enable a 10x+ surface area covered on a wafer given available time/wafer on the line, or enable equivalent confidence in 10% of the time. And while these sort of numbers will vary based on material, layer thickness and specific pump/probe power and wavelength, they should be illuminating.

[0018] Invention embodiments hereof include each of the methodology associated with the approaches described above, hardware to carry out the methodology, productions systems incorporating the hardware and products (including products-by-process) thereof.

[0019] Part II

[0020] To date, there has been limited adoption of SHG-based metrology tools. It is believed that this fact stems from an inability of existing systems to make distinctions between detected interfacial properties. In other words, while existing SHG techniques offer means of determining location and presence of interfacial electrically active anomalies, their methods rely on relative measurements and are not practically able to parse between electrically active anomaly types (e.g., gettered contaminants such as copper vs. bond voids) and/or to quantify detected contaminants.

[0021] However, the subject systems and methods variously enable capturing the quantitative information for making the determinations required for such activity. In

these systems and methods, after charging a wafer sample with optical electro-magnetic radiation (at a specific site with a pulsed laser or with a flash lamp or other electro-magnetic energy source or light source or other means) a plurality of measurements are made to monitor transient electric field decay associated with heterointerfaces controlling the decay period.

[0022] Using decay curve data generated and characterized with multiple points, spectroscopic parameters of an anomaly or problem at a sample site can be determined such that differentiation and/or quantification of defect type or contaminant(s) is possible. In all, the decay dependent data is collected and used to provide systems by which charge carrier lifetimes, trap energies and/or trapped charge densities may be determined in order that defects and contaminants can be discerned or parsed from one another, for species differentiation if a contaminant is detected and/or for contaminant quantification if detected.

[0023] Such activity is determined on a site-by-site basis with the selected methodology typically repeated to scan an entire wafer or other material sample or region thereof. As for the computer processing required to enable such determination, it may occur in "real time" (i.e., during the scanning without any substantial delay in outputting results) or via post-processing. However, in various embodiments, control software can run without lag in order to provide the precise system timing to obtain the subject data per methodology as described below.

[0024] Optionally, sample material charge-up is monitored in connection with SHG signal production. In which case, the information gained via this signal may be employed in material analysis and making determinations.

[0025] In any case, system embodiments may include an ultra-short pulse laser with a fast shutter operating in the range of 10^{2} seconds to picosecond (10^{-12} seconds) range. Such systems may be used to monitor SHG signal generation at a sample site from surface and buried interfaces of thin film materials after the introduction of a plurality of short blocking intervals. These intervals may be timed so as to monitor the field decay of interest.

[0026] The subject systems may also include an optical line delay. The delay line may be a fiber-based device, especially if coupled with dispersion compensation and polarization control optics. Alternatively, the delay line may be mirror-based and resemble the examples in USPNs 6,147,799 to MacDonald, 6,356,377 to Bishop, et al. or 6,751,374 to Wu, et al. In any case, the delay is used in the system in order to

permit laser interrogation of the material in the picosecond (10^{-12} second) to femtosecond (10^{-15} second) and, possibly, attosecond (10^{-18} second) ranges. Such interrogation may be useful in detecting multiple charge decay-dependent data points along a single decay curve.

[0027] The subject methods include one that involves measuring an SHG signal for decay data points acquired after successive charge-up events. The conditions for obtaining a SHG signal may be different at each charge-up event. Additionally, the time interval between successive charge-up events may be different. In this method, the multiple data points (at least two but typically three or more) can be correlated and expressed as a single composite decay curve. Another method employs minimally disruptive (i.e., the radiation used to produce the SHG signal does not significantly recharge the material) SHG signal interrogation events after a single charging event.

[0028] Yet another method for determining transient charge decay involves measuring discharge current from the sample material (more accurately, its structures that were charged by optical radiation). The time dependence (kinetics) of this signal may then be treated in the same way as if SHG sensing had been employed. Further, as above, such sensing may be done in the span of one decay interval and/or over a plurality of them following charge to a given level. In any case, electrode-specific hardware for such use is detailed below.

[0029] Regarding charge or charging level, this may be taken to a point of apparent saturation when charge dynamics are observed in standard linear time or against a log time scale. Per above, the subject methodologies optionally observe, record and analyze charging kinetic as this may yield important information.

[0030] For successive charge/interrogation events, if an initial charge state of a sample is measured and the saturation level is not far from the initial charge state, the system may omit further or subsequent characterization. In this context, what may be regarded as "not far" may mean about 1% to about 10% of charge increase versus the initial charge state to be determined by learning when the subject tool is used for a given time of sampling.

[0031] Stated otherwise, so-called "saturation" is a relative term. Using a linear time scale, material will appear saturated very quickly. But if an SHG signal intensity associated with charging is observed in log scale from 10-100 seconds, it can be observed that the later part of saturation occurs with a different time constant and is relatively more gradual or time-consuming. Thus, while examples of the methodology

provided herein discuss charging to saturation, the delay and other timing may be regarded as occurring with respect to apparent saturation. Rather than waiting the full amount of time for 100% saturation, as this may be unnecessarily time consuming to reach, instead, the instrument may delay until the time it takes to get to apparent saturation or the time in which can extract important parameters, regardless of how long it takes for full saturation.

[0032] Further, it is to be understood that when monitoring the amount or degree of charge-up toward saturation (e.g., in connection with SHG monitoring), the subject methods and systems may operate with charge and/or re-charging levels at less than saturation (as discussed above) while still yielding meaningful decay curve information. Without such measurement, however, when approximate saturation is a known parameter (e.g., by experience with the subject tool with a given material) charge to saturation is employed as the target level.

[0033] Introducing a DC bias across the sample being tested can also assist in analysis of the material. Employing a DC bias actively changes the initial charge distribution at the interfaces before photo-induced voltage has any effect. To do so, the sample being tested may be mounted atop a conductive chuck which can be used as a ground for DC biasing across the sample using sample top surface probes. Other means of introducing induced voltage biases are possible as well without the use of surface probes as further described in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section IV entitled, "FIELD-BIASED SHG METROLOGY".

[0034] Also, the subject systems may use a secondary light source in addition to the primary laser involved in blocking-type analysis for charge decay determination. Such a set of sources may be employed as a radiation pump/probe combination as further described in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section I entitled, "PUMP AND PROBE TYPE SHG METROLOGY".

[0035] All said, invention embodiments hereof include each of the methodology associated with the approaches described herein, alone or in combination with elements components or features from the referenced co-pending patent applications, hardware to carry out the methodology, productions systems incorporating the hardware and products (including products-by-process) thereof.

[0036] Part III

[0037] Various field-biased (e.g., magnetic-field biases, DC bias and/or voltage bias induced by an AC field alone, with a capacitive coupling and/or a changing magnetic field) SHG-based systems and their methods of use are described. These are treated in turn. They may be used independently and/or in a combined system. Various embodiments described herein include each of the methodology associated with the approaches described above, hardware to carry out the methodology, productions systems incorporating the hardware and products (including products-by-process) thereof.

[0038] Magnetic Field Bias

[0039] A static or changing magnetic field applied to the sample will cause the second order optical susceptibility tensor of a material to change. Thus, a magnetic field could be used to increase SHG signal from the sample, to an optimum value. Moreover, a changing magnetic field can be used to induce bias as further discussed below.

[0040] Induced Voltage Bias for Eliminating DC Contact Probes

[0041] Systems and methods are described for characterizing the SHG response of a layered semiconductor material that is subjected to a discrete electric field across its interfaces without use of contact bias probes in a system that can synchronize the pulses of a probing laser and/or the gating of a detector with a predetermined amplitude of voltage of an AC, variable or pulsed bias applied to the sample to produce a corresponding or coordinated induced voltage field at the surface to be interrogated.

[0042] The subject hardware comprises an SHG apparatus (e.g., further described in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section II titled, "CHARGE DECAY MEASUREMENT SYSTEMS AND METHODS") together with a means of inducing (e.g., a component configured to induce) a voltage at or along the “device” surface of a sample without contact. Such means or component may be either via backside contact with probes or a conductive chuck, involving capacitively coupled probes connected to a power source also in communication with backside contact probes or such a chuck, or by applying a changing magnetic field to the sample, with the purpose of inducing an external voltage field across its multilayer interfaces.

[0043] A transient electric field produced by a variable waveform (optionally AC) power supply (via any of the approaches above) induces an electric field across the interfaces of the multilayer semiconductor material. The relationship between the voltage and the material interface electrical field may be modeled by a transfer function or otherwise, including by accounting for various (capacitive or otherwise) external influences. The output of this function, given a particular amplitude and frequency of AC (or other) current, may be employed as a timing cue to trigger the laser shutter and/or photon counter simultaneously for SHG characterization of the testing point for constant near-instantaneous values of the electric field amplitude at the interfaces. As such, the system is able to simulate a constant (DC) voltage applied topside (i.e., at the device layer of the substrate) via contact electrical probes.

[0044] With direct application of AC to the backside of the sample, the system begins with the chuck at a 'neutral' or ground state, and bulk and device layers at an equilibrium potential. Then, an alternating bias is applied to the chuck, which is in galvanic contact with the bulk, or substrate layer of the multilayered semiconductor material. Since the device layer is separated from the bulk by the buried oxide layer, and not directly connected with a conductor, an electric potential field, or voltage will be created (i.e., induced) between the device and bulk layers.

[0045] Alternatively, capacitively coupled probe(s) that reside near (within about 1 to about 2 mm) but without touching the top side of the sample may be employed. A preferred approach in this regard may be a plate sized to cover (but not touch) the entire wafer, hovering with a small hole for the incident laser to pass through on its way to the sample and for the SHG beam to pass through on its way out of the sample.

[0046] In some implementations, a non-contacting electrode can be implemented using MEMS technology. For example, in an implementation, a Si wafer can be oxidized on both sides. A spiral or a grid-like electrode can then be placed by deposition on one or more locations of the wafer. The oxide material can be removed from the back-side of the wafer at those locations. An electro-magnetic field applied to the electrode can inductively bias the wafer in such implementations through near-field inductive coupling. The magnetic field produced by an external electric current can be used to generate an electric current across the wafer by inducing a current in the deposited electrode. Other methods of implementing non-contacting probes can also be used.

[0047] In any case, SHG methodology is used to interrogate the sample, for example, as further described in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section I titled, "PUMP AND PROBE TYPE SHG METROLOGY". The same holds true with respect to the other embodiments discussed below.

[0048] Regardless, in the subject embodiments, since it is desirable to monitor SHG as a function of the voltage across the interfaces, the SHG signal will be synchronized with the power supply. This synchronization can be accomplished by controlling the laser(s) used for SHG signal production and SHG signal processing software, the laser(s) alone, or only the SHG signal processing software, in time with voltage changes. The voltage of the chuck can also be controlled.

[0049] An advantage of this synchronization is that voltage biased SHG measurements can be obtained that would be similar to DC biased SHG measurements, without using contact voltage bias probes on the front surface of the wafer. Instead of applying a DC bias, the system would use an AC bias synchronized with SHG measurement and/or generation to collect SHG data at discrete points on the voltage cycle. The AC bias could be applied using near-field inductive coupling, or via capacitive coupling of the sample. SHG data collected with these biasing techniques would yield the same material properties information as DC biased SHG.

[0050] To reduce or minimize noise and obtain statistically relevant indicator(s) of SHG intensity as a function of voltage across the interfaces, multiple photon counting windows may be desirable as further described below.

[0051] Induced Voltage Bias for Characterizing Interfacial Leakage

[0052] Systems and methods are described for characterizing interfacial leakage current and/or carrier injection energies between layers of layered (e.g., semiconductor) materials using SHG and a voltage change (such as an alternating, variable and/or pulsed voltage or current signal or a device that changes magnetic field in a manner to induce voltage change in a device layer of a sample) applied to the layered semiconductor material as per above.

[0053] By measuring the SHG response from optical pulses generated by a pulsed laser directed at a layered semiconductor/dielectrics structure while or shortly after an alternating, variable or pulsed voltage is applied to the layered semiconductor material, interfacial leakage current and/or carrier injection energies between layers can be characterized. In some embodiments, the time evolution of the SHG signal

from interfaces as a function of the time constant of decay of the induced voltage can be measured. This yields information about charge carrier mobility across the interfaces.

[0054] Induced Voltage Bias for Characterizing Threshold Carrier Injection Energy

[0055] Systems and methods are described for SHG measurement applied in connection with a varied electrical field at a sample device layer in lieu of using tunable wavelength laser excitation to determine energy thresholds for photo-induced charge carrier injection into the dielectric in a layered semiconductor material. More specifically, to measure the threshold energy necessary for photo-induced charge carrier injection into the dielectric one can expose the material to a substantially monochromatic incident photon beam for SHG production and then incrementally change voltage across an interface of the exposed layered semiconductor material, measuring SHG signal count at each incremental voltage change until the SHG response has significant inflection or discontinuity or sudden change in slope from prior measurements. This change in slope could be a maximum or minimum (e.g., local maximum or minimum) or cusp, or step function, etc. The net charge change transfer due to all these processes can be described as the integral of the contributions of the 3rd harmonic injection current, "forward" leakage current to the dielectric due to the strong electric field, and "backward" discharge leakage current. Put in equation form:

$Q(t) = \int (I_{3} + I_{E} - I_{L})dt$ Kinetic features of this curve shape (bending moment and saturation moments of time) will then provide information for determining threshold carrier injection energy.

[0056] All said, invention embodiments hereof include each of the methodology associated with the approaches described herein, alone or in combination with elements components or features from the referenced co-pending patent applications, hardware to carry out the methodology, productions systems incorporating the hardware and products (including products-by-process) thereof.

[0057] The systems, methods and devices disclosed herein each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein. A variety of example systems and methods are provided below.

[0058] EFFICIENT COLLECTION OF MULTILPLE POLARIZATIONS

Example 1: A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

at least one optical source configured to direct a light beam onto said sample so as to produce second harmonic generation;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprises first and second detectors;

at least one polarization beamsplitter disposed in an optical path between said sample and said optical detection system so as to receive second harmonic generated light from said sample, said at least one polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to said first and second detectors, respectively; and

processing electronics configured to receive signals from said first and second detectors based on said received first and second polarization components.

Example 2: The system of Example 1, wherein said first and second polarization components comprise orthogonal polarizations states.

Example 3: The system of Examples 1 or 2, wherein said first and second polarization components comprise linearly polarized light oriented in different polarization directions.

Example 4: The system of any of the examples above, wherein said first and second polarization components are s and p polarizations, respectively.

Example 5: The system of any of the examples above, wherein said at least one polarization beamplitter comprises a polarization beamsplitter cube.

Example 6: The system of any of the examples above, further comprising at least one polarizer disposed in an optical path between said light source and said sample such that polarized light is directed to said sample.

Example 7: The system of Example 6, wherein said at least one polarizer disposed in said optical path between said light source and said sample comprises a linear polarizer.

Example 8: The system of any of the examples above, further comprising at least one focusing lens disposed between the light source and the sample to focus light from the light source onto the sample.

Example 9: The system of any of the examples above, further comprising at least one collimating lens disposed between the sample the polarization beamsplitter to collimate second harmonic generated light from the sample.

Example 10: The system of any of the examples above, wherein said sample holder comprise a translation stage.

[0059] SHG IMAGING

Example 1: A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

at least one optical source configured to direct a light beam onto said sample to produce second harmonic generation;

at least one beamsplitter disposed in an optical path between said light source and said sample, said at least one beamsplitter configured to separate said light from said light source into a plurality of beams that are incident at a plurality of locations on said sample at a one time such that said plurality of beams produce a plurality of second harmonic generation signals;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprising a plurality of detectors, respective ones of said plurality of beams from said beam splitter configured to produce respective SHG signals that are directed to respective ones of said plurality of detectors; and

processing electronics configured to receive signals from said plurality of detectors.

Example 2: The system of Example 1, wherein said at least one beamsplitter comprises a diffractive beamsplitter configured to receive one beam and split said beam into a plurality of beams.

Example 3: The system of any of the examples above, wherein said at least one beamsplitter comprises an acousto-optic modulator configured to receive one beam and split said beam into a plurality of beams.

Example 4: The system of any of the examples above, wherein said at least one beamsplitter is configured to separate an input beam into at least three output beams that are directed onto the sample.

Example 5: The system of any of the examples above, wherein said at least one beamsplitter is configured to separate an input beam into at least five output beams that are directed onto the sample.

Example 6: The system of any of the examples above, wherein said at least one beamsplitter is configured to separate an input beam into at least ten output beams that are directed onto the sample.

Example 7: The system of any of the examples above, wherein said plurality of detectors comprise three detectors.

Example 8: The system of any of the claims above, wherein said plurality of detectors comprise five detectors.

Example 9: The system of any of the examples above, wherein said plurality of detectors comprise ten detectors.

Example 10: The system of any of the examples above, further comprising at least one dichroic reflector in an optical path between the beamsplitter and the sample to receive said SHG signals from the sample and direct said SHG signals to respective ones of said plurality of detectors.

Example 11: The system of any of the examples above, wherein said sample holder comprises a translation stage.

Example 12: The system of any of the examples above, further comprising a beam scanning system configured to scan said plurality of beams.

Example 13: The system of any of the examples above, further comprising at least one polarization beamsplitter disposed so as to receive second harmonic generated light from said sample, said at least one polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detectors, respectively.

Example 14: The system of any of the examples above, further comprising a plurality of polarization beamsplitters disposed so as to receive second harmonic generated light from said sample, said polarization beamsplitters configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detectors, respectively.

Example 15: The system of Examples 13 or 14, wherein said first and second polarization components are s and p polarizations, respectively.

Example 16: A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

at least one optical source configured to direct a light beam onto said sample to produce second harmonic generation;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprising at least one detector array;

projection optics configured to project second harmonic generation light from said sample onto said at least one detector array; and

processing electronics configured to receive signals from said at least one detector array.

Example 17: The system of Example 16, wherein said at least one detector array comprises a 2-D array.

Example 18: The system of any of the examples above, wherein said at least one detector array comprises a CCD array.

Example 19: The system of any of the examples above, wherein said at least one detector array comprises a time dependent integration device.

Example 20: The system of any of the examples above, wherein said projection optics is configured to image the sample onto said detector array.

Example 21: The system of any of the examples above, wherein said projection optics comprises at least one imaging lens, said at least one detector array being disposed at a conjugate image plane of said sample.

Example 22: The system of any of the examples above, further comprising at least one focusing lens configured to focus light from said light source onto said sample.

Example 23: The system of any of the examples above, further comprising at least one translation stage configured to translate said sample with respect to said light source and said detector array.

Example 24: The system of Example 23, wherein said at least one translation stage comprises an x-y translation stage.

Example 25: The system of any of the examples above, further comprising at least one polarization beamsplitter disposed so as to receive second harmonic generated

light from said sample, said at least one polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detector arrays, respectively.

Example 26: The system of any of the examples above, further comprising at least one polarization beamsplitters disposed so as to receive second harmonic generated light from said sample, said polarization beamsplitters configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detectors, respectively.

Example 27: The system of Examples 25 or 26, wherein said first and second polarization components are s and p polarizations, respectively.

Example 28: A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

at least one optical source configured to direct a light beam onto said sample to produce second harmonic generation;

at least one beamsplitter disposed in an optical path between said light source and said sample, said beamsplitter configured to separate said light from said light source into a plurality of beams that are incident at a plurality of locations on said sample at a one time such that said plurality of beams produce a plurality of second harmonic generation signals;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprising at least one detector array, respective ones of said plurality of beams from said at least one beam splitter configured to produce respective SHG signals that are directed to respective regions of said of at least one detector array; and

processing electronics configured to receive signals from said detector array.

Example 29: The system of Example 1, wherein said at least one beamsplitter comprises a diffractive beamsplitter configured to receive one beam and split said beam into a plurality of beams.

Example 30: The system of any of the examples above, wherein said at least one beamsplitter comprises an acousto-optic modulator configured to receive one beam and split said beam into a plurality of beams.

Example 31: The system of any of the examples above, wherein said at least one beamsplitter is configured to separate an input beam into at least three output beams that are directed onto the sample.

Example 32: The system of any of the examples above, wherein said at least one beamsplitter is configured to separate an input beam into at least five output beams that are directed onto the sample.

Example 33: The system of any of the examples above, wherein said at least one beamsplitter is configured to separate an input beam into at least ten output beams that are directed onto the sample.

Example 34: The system of any of the examples above, wherein said at least one detector array comprises a plurality of pixels.

Example 35: The system of any of the examples above, wherein said regions of said at least one detector array comprises one or more pixels.

Example 36: The system of any of the examples above, wherein said at least one detector array comprises a CCD detector array.

Example 37: The system of any of the examples above, further comprising at least one dichroic reflector in an optical path between the beamsplitter and the sample to receive said SHG signals from the sample and direct said SHG signals to respective regions of said at least one detector array.

Example 38: The system of any of the examples above, wherein said sample holder comprises at least one translation stage.

Example 39: The system of any of the examples above, further comprising a beam scanning system configured to scan said plurality of beams.

Example 40: The system of any of the examples above, further comprising at least one polarization beamsplitter disposed so as to receive second harmonic generated light from said sample, said at least one polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detector arrays, respectively.

Example 41: The system of any of the examples above, further comprising a plurality of polarization beamsplitters disposed so as to receive second harmonic generated light from said sample, said polarization beamsplitters configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detectors, respectively.

Example 42: The system of Examples 40 or 41, wherein said first and second polarization components are s and p polarizations, respectively.

BRIEF DESCRIPTION OF THE DRAWINGS

[0060] The figures diagrammatically illustrate aspects of various embodiments of different inventive variations.

[0061] Fig. 1A is a diagram of an SHG metrology system embodiment hereof; Fig. 1B is a perspective view of a chuck for use in such an SHG system. Fig. 1C is a diagram of another SHG metrology system embodiment hereof;

[0062] Figs. 2A/2B and 3A/3B are diagrams illustrating example pump/probe system uses for producing characteristic SHG signals.

[0063] Fig. 4 is a diagram illustrating probe/pump system use to determine threshold injection carrier energy.

[0064] Fig. 5 is a flowchart detailing methods to produce signals as presented in the diagrams.

[0065] Figs. 6A-6C are diagrams of systems embodiments;

[0066] Fig. 7 is a chart of system function; Figs. 8A and 8B are charts representative of the manner of delivering such function; Fig. 9 represents system function in a graphical output.

[0067] Figs. 10 and 11 plot SHG interrogation-related method embodiments; Figs. 12A-12E plot time dynamics associated with the system in Fig. 6C that may be employed in the methods of Figs. 10 and 11.

[0068] Fig. 13 plots a current-based interrogation method for observing transient electric field decay; Figs. 14A and 14B illustrate hardware configurations that may be employed in the method of Fig. 13.

[0069] Figs. 15A and 15B are schematic diagrams of SHG system components as may be used herein.

[0070] Figs. 16A is a perspective view of a first chuck configuration hereof; Fig. 16B is a side-sectional view of the chuck configuration in Fig. 16A.

[0071] Figs. 17A and 17B are partial cutaway, perspective views of a second chuck configuration hereof; Fig. 17C is cutaway top view of the chuck in Fig. 17A/17B.

[0072] Figs. 18A and 18B relate to AC voltage applied to and exhibited in a sample for DC bias probe elimination.

[0073] Figs. 19A and 19B relate to AC voltage applied to and exhibited in a sample for testing leakage current.

[0074] Fig. 20 illustrates a schematic diagram of an example SHG system that may be employed to control the polarization of light directed onto the sample as well as the polarization of the SHG light collected from the sample.

[0075] Fig. 21 illustrates a schematic diagram of an example SHG system comprising a polarization beamsplitter such that first and second polarizations (e.g., s- and p-polarization components) of the SHG signal can be separately collected at the same time.

[0076] Figs. 22A and 22B illustrates schematic diagrams of example SHG imaging systems comprising a beamsplitter configured to split a laser beam into a plurality of beams that produce a plurality of respective SHG signals that can be directed to a plurality of respective detectors.

[0077] Fig. 23 illustrates a schematic diagram of an example SHG system comprising a detector array and optics configured to project light from a plurality of SHG signals from a plurality of locations on the sample onto the detector array.

DETAILED DESCRIPTION

[0078] Part I

[0079] Fig. 1 is a diagram of a system 100 as may employed in connection with the subject methodology. Other suitable system variations are presented in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section II entitled, "CHARGE DECAY MEASUREMENT SYSTEMS AND METHODS" for example, as to intermediate optics, the inclusion of optical delay line(s) and optional electrode features.

[0080] As shown, system 100 includes a primary or probe laser 10 for directing an interrogation beam 12 of electro-magnetic radiation at a sample wafer 20, which is held by a vacuum chuck 30. As illustrated in Fig. 1B, the chuck 30 includes or is set on x- and y- stages and optionally also a rotational stage for positioning a sample site 22 across the wafer relative to where the laser(s) are aimed. The x-y stage enables scanning multiple wafer surface sites or locations 22 without movement of other hardware. A rotational stage optionally enables assessing crystal structure effects on SHG such as strain, and associated defects or areas of concern on materials being characterized. Further optional features, aspects and/or uses of chuck 30 are presented

in portions of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section IV entitled, "FIELD-BIASED SHG METROLOGY". The sample site 22 can include one or more layers. The sample site 22 can comprise a composite substrate including at least two layers. The sample site 22 can include an interface between two dissimilar materials (e.g., between two different semiconductor materials, between two differently doped semiconductor materials, between a semiconductor and an oxide, between a semiconductor and a dielectric material, between a semiconductor and a metal or an oxide and a metal).

[0081] When system 100 is in use, a beam 14 of reflected radiation directed at a detector 40 will include an SHG signal. The detector may be any of a photomultiplier tube, a CCD camera, a avalanche detector, a photodiode detector, a streak camera and a silicon detector. System 100 may also include one or more shutter-type devices 50. The type of shutter hardware used will depend on the timeframe over which the laser radiation is to be blocked, dumped or otherwise directed away from the sample site. An electro-optic blocking device such as a Pockel's Cell or Kerr Cell can be used to obtain very short blocking periods (i.e., with actuation times on the order of 10^{-9} to 10^{-12} seconds).

[0082] For longer blocking time intervals (e.g., from about 10^{-5} seconds and upwards) mechanical shutters or flywheel chopper type devices may be employed. However, electro-optic blocking devices will allow a wider range of materials to be tested in accordance with the methods below. A photon counting system 44 capable of discretely gating very small time intervals, typically, on the order of picoseconds to microseconds can be employed to resolve the time-dependent signal counts. For faster-yet time frames optical delay line(s) may be incorporated as noted above.

[0083] System 100 can include an additional electromagnetic radiation source 60 also referred to as a pump source. In various implementations, the radiation source 60 can be a laser illustrated as emitting a directed beam 62 or a UV flash lamp emitting a diverging or optically collimated pulse 64. In the case of a laser source, its beam 62 may be collinear with beam 12 (e.g., as directed by additional mirrors or prisms, etc.) Source 60 output wavelengths of light may be anywhere from about 80 nm and about 1000 nm. Using shorter wavelengths in this range (e.g. less than about 450 nm), is possible to drive charge excitation using fewer photons and/or with lower peak intensities than at longer wavelengths.

[0084] For a flash lamp, energy per flash or power level during flash may be substrate material dependent. A flashlamp producing a total energy of 1 J to 10 kJ per flash would be appropriate for fully depleted silicon-on-insulator (FD-SOI). However a pulsed or constant UV source would be viable as well. The important factor in the pump characteristics and use is that charge carriers are injected into the dielectric of the material to be interrogated. Manufacturers of suitable flash lamps include Hellma USA, Inc. and Hamamatsu Photonics K.K.

[0085] When a laser is employed as source 60, it may be any of a nanosecond, picosecond or femtosecond or faster pulse laser source. It may even be a continuous solid-state laser. In various embodiments, the pump source is tunable in wavelength. Commercially available options regarding lasers which are tunable include Spectra Physics' Velocity and Vortex Tunable Lasers. Additional tunable solid state solutions are available from LOTIS Ltd.'s LT-22xx series of solid state lasers.

[0086] Whether provided as a laser or a flash lamp, pump source 60 can be selected for relatively high average power. This could be from about 10 mW to about 10 W, but more typically from about 100 mW to about 4 W, depending on material to be interrogated (as, again, the consideration is ensuring that charge carrier mobility is induced in a way such that charge carriers are injected into the interface of the material (e.g., the dielectric interface), which can be material specific. The average power of the pump source 60 is selected to be below the optical damage threshold of the material. For example, pump source 60 can be selected to have an average optical power between 1 – 2 W when the interrogating material comprises silicon so as to not exceed the optical damage threshold for silicon.

[0087] Probe laser 10 may be any of a nanosecond, picosecond or femtosecond or faster pulse laser source. Two options that are currently commercially available lasers having the peak power, wavelength and reliability needed are doped fiber and Ti:Sapphire units. Coherent's VITESSE and Spectra Physics' MAI TAI lasers are examples of suitable Ti:Sapphire devices. Femtolasers Gmbh and others manufacture also manufacture other relevant Ti:Sapphire devices. Suitable doped fiber lasers are produced by IMRA, OneFive, and Toptica Photonics. Pico- and/or nano-second lasers from many manufacturers, such as Hamamatsu, may be options as well depending on the substrate material and pump type. Laser 10 may operate in a wavelength range between about 100 nm to about 2000 nm with a peak power between about 10 kW and 1 GW, but delivering power at an average below about 150 mW.

[0088] Various other optional so-called "intermediate" optical components may be employed in system 100. For example, the system may include a dichroic reflective or refractive filter 70 for selectively passing the SHG signal coaxial with reflected radiation directly from laser 10 and/or source 60. Alternatively, a prism may be employed to differentiate the weaker SHG signal from the many-orders-of-magnitude-stronger reflected primary beam. However, as the prism approach has proved to be very sensitive to misalignment, a dichroic system as referenced above may be preferred. Other options include the use of diffraction grating or a Pellicle beam splitter. An optical bundle 80 for focusing and collimating/columniation optics may be provided. Alternatively, a filter wheel 90, polarizer(s) 92 and/or zoom len(s) 94 units or assemblies may be employed in the system. Also, an angular (or arc-type) rotational adjustment (with corresponding adjustment for the detector) and in-line optical components may be desirable.

[0089] In the implementation illustrated in Fig. 1C, the beam 12 from the laser 10 can be split by a beam splitter 74 between two optical paths. The beam splitter 74 can split the beam 12 unequally between the two optical paths. For example, 70% of the energy of the beam 12 can be directed along a first optical path (e.g., as beam 16) and 30% of the energy of the beam 12 can be directed along a second optical path (e.g., as beam 18). As another example, 60% of the energy of the beam 12 can be directed along the first optical path and 40% of the energy of the beam 12 can be directed along the second optical path. As yet another example, 80% of the energy of the beam 12 can be directed along the first optical path and 20% of the energy of the beam 12 can be directed along the second optical path. The split may thus be unequal (e.g., 70-30%, 80-20%, 60-40% or any range therebetween, such as between 60-90% in one path and between 40-10% in another path as well as outside these ranges), sending a majority of the power in the pump beam, and a minority in the probe beam. For example, the split may be 60-70% and 40-30%, for the pump and probe, respectivley, 70-80% versus 30-20% for the pump and probe, respectively, 80-90% versus 20-10%, for the pump and probe respectively, or 90-99.999% versus 10-0.001%, for the pump and probe respectively,. In different embodiments, the probe beam could be between 0.001% to 49.99% while the pump beam could be between 50.001% and 99.999%, for example. The sum of the two beams may be 100% or approximate thereto. The split may be determined by the particular material system being characterized in some cases. In the example shown in Fig. 1C, 5% of the beam

energy of the beam 12 is directed along the first optical path and 95% of the energy of the beam 12 is directed along the second optical path.

[0090] The beam splitter 74 can comprise a dielectric mirror, a splitter cube, a metal coated mirror, a pellicle mirror or a waveguide splitter. In implementations, where the beam 12 includes optical pulses, the beam splitter 74 can include an optical component having negligible dispersion that splits the beam 12 between two optical paths such that optical pulses are not broadened. As illustrated in Fig. 1C, each of the beams can be redirected or aimed using various mirror elements 2072.

[0091] The output from the detector 40 and/or the photon counting system 44 can be input to an electronic device 48. The electronic device 48 can be a computing device, a computer, a tablet, a microcontroller or a FPGA. The electronic device 48 includes a processor, processing electronics, control electronics, processing/control electronics, or electronics that may be configured to execute one or more software modules. In addition to executing an operating system, the processor may be configured to execute one or more software applications, including a web browser, a telephone application, an email program, or any other software application. The electronic device 48 can implement the methods discussed herein by executing instructions included in a machine-readable non-transitory storage medium, such as a RAM, ROM, EEPROM, etc. The electronic device 48 can include a display device and/or a graphic user interface to interact with a user. The electronic device 48 can communicate with one or more devices over a network interface. The network interface can include transmitters, receivers and/or transceivers that can communicate such as, for example, wired Ethernet, Bluetooth ®, or wireless connections.

[0092] Regarding other options, since an SHG signal is weak compared to the reflected beam that produces it, it is desirable to improve the signal-to-noise ratio of SHG counts. As photon counting gate times for the photon counting system 44 decrease for the blocking and/or delay processes described herein, improvement becomes even more important. One method of reducing noise that may be employed is to actively cool the photon counter. This can be done using cryogenic fluids such as liquid nitrogen or helium or solid state cooling through use of a Peltier device. Others areas of improvement may include use of a Marx Bank Circuit (MBC) as relevant to shutter speed. Moreover, system 100 may be incorporated in-line within a production line environment. Production line elements preceding or following system 100 may

include any of epitaxial growth system, lithography and/or deposition (CVD, PVD, sputtering, etc.) systems.

[0093] Turning now to Figs. 2A/2B and 3A/3B, these are schematic diagrams illustrating example types of SHG curves that may be produced with the subject pump/probe system in their methods of use. In Fig. 2A and 2B, the timescale to obtain such signals in on the order of milliseconds (10^{-3} s). Thus, these are "fast" processes. As further discussed below, they may offer several orders of magnitude of time-wise improvement relative to existing approaches. For example, a flash lamp capable of exposing the entire surface of a test material to UV radiation prior to SHG probing drastically reduces the overall scan time since sustained measurements at each point may not be required.

[0094] Specifically, in Fig. 2A an SHG signal 200 is measured with an initial intensity 202. This signal is produced by the probe source radiation applied at a surface location. Upon adding pump source radiation (to that of the probe which stays on) after a given temporal offset (O_1), the signal intensity drops along a time-dependent curve 204 to a lower level 206. Conversely, in Fig. 2B SHG signal 200' at a lower level 212 produced by probe radiation alone increases along a time-dependent curve 214 to a higher plateau 216 upon applying pump radiation after a time offset (O_2). Signals 200 and 200' also include a time-independent component or portion at the beginning and end of the curves.

[0095] Both observations in Figs. 2A and 2B may be made with the subject system depending on substrate material and different laser powers (e.g., in this case, that of the pump). In various embodiments charge separation comprise electrons and holes separating from each other after excitation from a photon. Electrons injected into the SiO_2 conduction band from the silicon valence band by the photons from the laser are trapped primarily on the top surface of the oxide. The holes congregate mostly in the silicon valence band close to the Si/SiO_2 interface. This separation of charge carriers due to excitation from the incident radiation or from internal photoemission contributes to the electric field(s) present inside the subject system, which in turn changes the SHG measured. Various factors, such as the presence of gaseous Oxygen at the testing site, as well as the composition and structure of the sample in question, will determine whether the observation is made as in Figure 2A or 2B.

[0096] Indeed, a combination of signals 200 and 200′ has been observed in some instances. In those instances, the signal intensity first dropped from a peak, bottomed

out, and then rose to an asymptote again. Generally, the SHG intensity curves are determined by the non-linear susceptibility tensor, which is in turn affected by molecular orientation, atomic organization, electronic structure and external fields. Charge carriers moving across the interface will change the charge state in the structure and the electric field in the sub-interfacial layer where the SHG signal generation occurs. Depending on the type (positive or negative) of charge carriers crossing the interface, and the initial state of the field across the interface, different time-dependent curves will be observed. The intensity of the detected SHG signal can depend on various factors including spot size, average laser power, and peak laser power. In various implementations, the system 100 can be configured to detect SHG signal having an intensity in a range between about 400 counts/second and about 7 million counts/second. The pump/probe system described herein can reduce the time required for the charge carriers moving across the interface to reach a saturation level. In various embodiments, the time required for the charge carriers moving across the interface to reach a saturation level can between 1 millisecond and 1000 seconds in the pump/probe system described herein. Since it may be advantageous to obtain the time evolution of the SHG signal when the charge carrier density in the region including interface is below saturation as well as when the charge carrier density in the region including interface reaches saturation level, the system can be configured to obtain SHG signal measurements within about 1 microsecond after turning on/turning off the pump radiation. For example, the system can be configured to obtain SHG signal measurements within 10 seconds after turning on/turning off the pump radiation (or probe radiation), within about 6 seconds after turning on/turning off the pump radiation, within about 1 second after turning on/turning off the pump radiation, within about 100 milliseconds after turning on/turning off the pump radiation or within about 1 millisecond after turning on/turning off the pump radiation, within 1 microsecond after turning on/turning off the pump radiation, within 1 nanosecond after turning on/turning off the pump radiation or in any range formed by any of these values (for example, for time periods greater than a nanosecond, greater than a microsecond, greater than a millisecond, etc.) as well as outside any of those ranges. These values and ranges apply for obtaining data obtained from a single point, but with proper imaging optics, could be increased to substantial areas of the wafer, up to and including the entire wafer at once. As indicated by the parenthetical above, these values and ranges also apply to the probe

radiation. Reducing the charging time and the time required to obtain the SHG signal can allow for faster testing of interfaces and thus increase through-put of testing and/or manufacturing production lines.

[0097] By way of comparison, Figs. 3A and 3B schematically illustrate SHG signal curves 300 and 300′ for corresponding materials in which only one radiation source is used (in this case a high average power and high peak power laser) to interrogate the substrate as in existing SHG techniques. The time scale for generating signals 300 and 300 in Figs. 3A and 3B is on the order of tens-to hundreds (10^2 s) seconds.

[0098] Over such time, these signals (like the signals in Figs. 2A and 2B) include lower and upper plateaus 306, 316 that can be characterized after initial 302 and/or time-dependent signals. Thus, while similar (or identical) analysis may be performed with the signals 200/200′ and 300/300′, the main difference is that with the subject systems (i.e., using a lower peak power femto-second probe laser in conjunction with a higher average power pump for material pre-excitation) allows for vastly improved time-wise efficiency in obtaining the requisite signal information. Moreover, the subject approach provides a way to more easily determining time-independent SHG measurements without the use of a filter-wheel or some other method.

[0099] In any case, Fig. 4 illustrates a method for determining threshold injection carrier energy. In this case, the pump comprises a tunable wavelength laser. This allows ramp-up of the output frequency (and hence energy by E=hν) of the photons over time from the pump incident on the sample. The observed SHG activity action is illustrated as signal 400. With the pump laser so-applied or engaged, an initial SHG signal level 402 generated by application of a probe laser is observed to the point the signal suddenly changes (i.e., producing an inflection, discontinuity, maximum, minimum, step function, cusp, or sudden change in slope of sorts at 404). The frequency at this point is taken to correspond to the threshold energy. In various implementations, the threshold energy is the energy required to transport electrons from the valence band of one semiconductor material to the conduction band of another semiconductor material across an interface between two materials such as two semiconductor materials or a semiconductor material and a dielectric material (e.g., Si and SiO_2, Si and Si_3N_4, Si and Ta_2O_5, Si and $BaTiO_3$, Si and $BaZrO_3$, Si and ZrO_2, Si and HfO_2, Si and La_2O_3, Si an Al_2O_3, Si and Y_2O_3, Si and $ZrSiO_4$). The system 100 can be configured to measure threshold energy in the range between about 1.0 eV and about 6.0 eV. The systems and methods described herein can be configured to

determine threshold energy for a variety of interfaces such as for example, between two different semiconductors, between a semiconductor and a metal, between a semiconductor and a dielectric, etc.

[00100] Fig. 5 is a flowchart 500 illustrating an implementation of a method for characterizing semiconductor devices with SHG. Various process flowpaths are indicated. Any such methods may begin at 502 with positioning a sample at a desired location (e.g., typically by locating chuck 30 after a wafer 20 has been secured thereto). Progressive positioning (i.e., re-positioning) may occur after any given SHG detection event 520 as further described for scanning multiple surface positions or even every surface position in a region of the sample or even every surface position of the sample. Alternatively, such action may occur after a given determination at 540 is made concerning a detected SHG signal (either "return" option indicated by dotted line). Further details regarding alternative determinations may be appreciated in reference to the other portions of this application referenced above. In any case, following sample positioning or re-positioning, a given flowpath is selected (or another flowpath may be run at the same surface position after in sequence to generate different data).

[00101] Following a one process flowpath (solid lines, in part), at 504 probe source radiation is applied to the sample surface at a given location. Next, at 506 pump source radiation is applied. In this example, the pump radiation is applied in a varying manner that (optionally) increases photon energy linearly by decreasing the radiation wavelength. The resulting SHG is detected at 520. At 542 signal analysis (per the example in Fig. 4) allows for carrier injection threshold energy to be determined. In various implementations, the energy of the pump radiation can correspond to the threshold energy of the semiconductor interface. Accordingly, the energy of the pump radiation can be between about 1.0 eV and about 6.0 eV. For example, to determine the threshold energy across a Si and SiO_2 interface, the threshold energy of the pump radiation can vary between about 4.1 eV and about 5.7 eV. Variation in the energy of the pump radiation can be accomplished by varying the frequency (or wavelength) of the radiation. For example, to interrogate a sample with an expected value of the threshold energy around 3.2 eV, the wavelength of the pump radiation can be varied between about 443 nm and about 365 nm. In various implementations, the energy of the pump radiation can be below the threshold energy of the semiconductor interface since the photons from the pump radiation can generate

electrons with twice energy (e.g., when a single electron absorbs two photons). In such implementations, the charging time is increased which may provide observation with increases resolution and intensity. Increasing the charging time can also increase the time required to test a sample site which can reduce throughput.

[00102] Following another flowpath (dashed lines, in part), at 508 pump radiation is applied to the substrate. Such application may be directed only at the surface (e.g., by a laser) to be immediately interrogated or the entire surface of the wafer (e.g., using a flash lamp). Next, at 510 the section of the sample to be interrogated is exposed to probe source radiation. The resulting SHG is detected at 520. The pump-probe-detect aspects of the method may then repeat potentially after sample repositioning at 502. As indicated, however, action box 508 may be skipped and pumping again may be avoided or omitted from a sequential scanning process, as in the example above where the whole substrate was initially exposed to pump radiation. In any case, at 544 any of a variety of SHG-based signal analysis may be conducted to make a determination other than for threshold energy as in block 542 as discussed elsewhere in this patent application.

[00103] Following another process flow path (dash-and-dot/centerline lines, in part) probe interrogation is performed at 504 and 510 before and after pump radiation is applied at 508 with SHG signal data collection at 520 directly after probe radiation application at 504 and 510. Again, this method may be done recursively to sample a plurality of sites such as every section of a substrate or a region thereof, returning to flowchart element 502 for repositioning and the probe-detect-pump-probe-detect method or sub-method repeated.

[00104] Notably, any of the SHG signal analysis methods or sub-methods (generically embraced in box 540 and 542) can be performed in real-time, as in instantaneous or near-instantaneous output. In doing so, any of the spectrographic properties determined by the data gathered can be computed by a software package either by integrated software on the machine or remotely. Alternatively, SHG signal analysis may be handled in post-processing after some or all of the SHG data has been detected or collected.

[00105] The systems and methods described herein can be used to characterize a sample (e.g., a semiconductor wafer or a portion thereof). For example, the systems and methods described herein can be used to detect defects or contaminants in the sample as discussed above. The systems and methods described herein can be

configured to characterize the sample during fabrication or production of the semiconductor wafer. Thus, the systems and methods can be used along a semiconductor fabrication line in a semiconductor fabrication facility. The systems and methods described herein can be integrated with the semiconductor fabrication/production line. The systems and methods described herein can be integrated into a semiconductor fab line with automated wafer handling capabilities. For example, the system can be equipped with an attached Equipment Front End Module (EFEM), which accepts wafer cassettes such as a Front Opening Unified Pod (FOUP). Each of these cassettes can be delivered to the machine by human operators or by automated cassette-handling robots which move cassettes from process to process along fabrication/production line.

[00106] In various embodiments, the system can be configured such that once the cassettes are mounted on the EFEM, the FOUP is opened, and a robotic arm selects individual wafers from the FOUP and moves them through an automatically actuated door included in the system, into a light-tight process box, and onto a bias-capable vacuum chuck. The chuck may be designed to fit complementary with the robotic arm so that it may lay the sample on top. At some point in this process, the wafer can be held over a scanner for identification of its unique laser mark.

[00107] Accordingly, a system configured to be integrated in a semiconductor fabrication/assembly line can have automated wafer handling capability from the FOUP or other type of cassette; integration with an EFEM as discussed above, a chuck designed in a way to be compatible with robotic handling, automated light-tight doors which open and close to allow movement of the robotic wand/arm and software signaling to EFEM for wafer loading/unloading and wafer identification.

[00108] Part II

[00109] Fig. 6A is a diagram of a first system 2100 as may employed in connection with the subject methodology. Alternative systems 2100′ and 2100″ are shown in Figs. 6B and 6C. Each system includes a primary laser 2010 for directing a primary beam 2012 of electro-magnetic radiation at a sample wafer 2020, which sample is held by a vacuum chuck 2030. The chuck 2030 includes or is set on x- and y- stages and optionally also a rotational stage for positioning a sample site 2022 across the wafer relative to where the laser(s) are aimed. A beam 2014 of reflected radiation directed at a detector 2040 will include an SHG signal. The detector may be any of a photomultiplier tube, a CCD camera, a avalanche detector, a photodiode detector, a

streak camera and a silicon detector. The sample site 2022 can include one or more layers. The sample site 2022 can comprise a composite substrate including at least two layers. The sample site 2022 can include an interface between two dissimilar materials (e.g., between two different semiconductor materials, between two differently doped semiconductor materials, between a semiconductor and an oxide, between a semiconductor and a dielectric material, between a semiconductor and a metal, between an oxide and a metal, between a metal and a metal or between a metal and a dielectric).

[00110] Also common to each of the embodiments is the inclusion of one or more shutter-type devices 2050. These are employed as described in connection with the methodology below. The type of shutter hardware used will depend on the timeframe over which the laser radiation is to be blocked, dumped or otherwise directed away from the sample site.

[00111] An electro-optic blocking device such as a Pockel's Cell or Kerr Cell is used to obtain very short blocking periods (i.e., with switching times on the order of 10^{-9} to 10^{-12} seconds). For longer blocking time intervals (e.g., from about 10^{-5} seconds and upwards) mechanical shutters or flywheel chopper type devices may be employed.

[00112] However, electro-optic blocking devices will allow a wider range of materials to be tested in accordance with the methods below. A photon counting system 2044 capable of discretely gating very small time intervals, typically, on the order of picoseconds to microseconds can be included to resolve the time-dependent signal counts.

[00113] Hardware is contemplated for pushing the methods into faster-yet time frames. Namely, as shown in Fig. 6C, the system(s) may include delay line hardware 2060. Beam splitting and switching (or shuttering on/off) between a plurality of set-time delay lines for a corresponding number of time-delayed interrogation events is possible. However, a variable delay line may be preferred as offering a single solution for multiple transient charge decay interrogation events on a time frame ranging from immediately (although delay of only 10^{-12} seconds may be required for many methodologies) to tens of nanoseconds after pump pulse. The desired delay time may even go into the microsecond regime if using a slower, kilohertz repetition laser. And while such hardware is uniquely suited for carrying out the subject methodology (both of which methodology and such hardware is believed heretofore unknown), it might be put to other uses as well.

[00114] In the implementation illustrated in Fig. 6C, the beam 2012 from the laser 2010 can be split by a beam splitter 2070 between two optical paths. The beam splitter 2070 can split the beam 2012 unequally between the two optical paths. For example, 70% of the energy of the beam 2012 can be directed along a first optical path (e.g., as beam 2016) and 30% of the energy of the beam 12 can be directed along a second optical path (e.g., as beam 2018). As another example, 60% of the energy of the beam 2012 can be directed along the first optical path and 40% of the energy of the beam 2012 can be directed along the second optical path. As yet another example, 80% of the energy of the beam 2012 can be directed along the first optical path and 20% of the energy of the beam 2012 can be directed along the second optical path. The beam splitter 2070 can comprise a dielectric mirror, a splitter cube, a metal coated mirror, a pellicle mirror or a waveguide splitter. In implementations, where the beam 2012 includes optical pulses, the beam splitter 2070 can include an optical component having negligible dispersion that splits the beam 2012 between two optical paths such that optical pulses are not broadened. As indicated by the double-arrow in Fig. 6C, the path of an "interrogation" beam 2016 taken off a beam splitter 2070 from primary beam 2012 can be lengthened or shortened to change its arrival timing relative to a "pump" beam 2018 wherein each of the beams are shown directed or aimed by various mirror elements 2072. Another approach (mentioned above) employs fiber optics in the optical delay component and/or other optical pathways (e.g., as presented in U.S. Patent No. 6,819,844 incorporated herein by reference in its entirety for such description).

[00115] The output from the detector 2040 and/or the photon counting system 2044 can be input to an electronic device 2048 (see, e.g., Figures 6A and 6B). The electronic device 2048 can be a computing device, a computer, a tablet, a microcontroller or a FPGA. The electronic device 2048 includes a processor, processing electronics, control electronics, processing/control electronics, or electronics that may be configured to execute one or more software modules. In addition to executing an operating system, the processor may be configured to execute one or more software applications, including a web browser, a telephone application, an email program, or any other software application. The electronic device 2048 can implement the methods discussed herein by executing instructions included in a machine-readable non-transitory storage medium, such as a RAM, ROM, EEPROM, etc. The electronic device 2048 can include a display device and/or

a graphic user interface to interact with a user. The electronic device 2048 can communicate with one or more devices over a network interface. The network interface can include transmitters, receivers and/or transceivers that can communicate over wired or wireless connections.

[00116] Another potential aspect of system 2100″ concerns the manner in which the initial beam splitter works. Namely, the split may be unequal (e.g., 70-30%, 80-20%, 60-40% or any range therebetween, such as between 60-90% in one path and between 40-10% in another path as well as outside these ranges), sending a majority of the power in the pump beam, and a minority in the probe beam. For example, the split may be 60-70% and 40-30%, for the pump and probe, respectively, 70-80% versus 30-20% for the pump and probe, respectively, 80-90% versus 20-10%, for the pump and probe respectively, or 90-99.999% versus 10-0.001%, for the pump and probe respectively,. In different embodiments, the probe beam could be between 0.001% to 49.99% while the pump beam could be between 50.001% and 99.999%, for example. The sum of the two beams may be 100% or approximate thereto. The split may be determined by the particular material system being characterized in some cases. The value (at least in part) of doing so may be to help facilitate methods such as shown in Figs. 10 and 11 in which the power involved in SHG interrogation subsequent to material charging is desirably reduced or minimized as discussed below. Still another aspect is that the pump and probe beams are brought in at different angles. Such an approach facilitates measuring pump and probe SHG responses separately. In such cases, two detectors may be advantageously employed with one for each reflected beam path.

[00117] Various other optional optics distinguish the embodiments shown. For example, embodiments 2100 and 2100′ are shown including a dichroic reflective or refractive filter 2080 for selectively passing the SHG signal coaxial with reflected radiation directly from the laser 2010. Alternatively, a prism may be employed to differentiate the weaker SHG signal from the many-orders-of-magnitude-stronger reflected primary beam. However, as the prism approach has proved to be very sensitive to misalignment, a dichroic system as referenced above may be preferred. Other options include the use of diffraction grating or a Pellicle beam splitter. As shown in system 2100, an optical bundle 2082 of focusing and collimating/collimation optics may be provided. As shown in system 2100′, a filter wheel 2084, zoom lens 2086 and/or polarizers 2088 may be employed in the

system(s). Also, an angular (or arc-type) rotational adjustment (with corresponding adjustment for the detector 2040 and in-line optical components) as shown in system 2100′ may be desirable. An additional radiation source 2090 (be it a laser illustrated emitting a directed beam 2092 or a UV flash lamp emitting a diverging or optically collimated or a focused pulse 2094) may also be incorporated in the system(s) to provide such features as referenced above in connection with the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section I entitled "PUMP AND PROBE TYPE SHG METROLOGY," and/or initial charging/saturation in the methods below.

[00118] In these systems, laser 10 may operate in a wavelength range between about 700 nm to about 2000 nm with a peak power between about 10 kW and 1 GW, but delivering power at an average below about 100 mW. In various embodiments, average powers between 10 mW and 10W should be sufficient. Additional light source 2090 (be it a another laser or a flash lamp) may operate in a wavelength range between about 80 nm and about 800 nm delivering an average power between about 10 mW and 10 W. Values outside these ranges, however, are possible.

[00119] Regarding other system options, since an SHG signal is weak compared to the reflected beam that produces it, it may be desirable to improve the signal-to-noise ratio of SHG counts. As photon counting gate times decrease for the blocking and/or delay processes described herein, improvement becomes even more useful. One method of reducing noise that may be employed is to actively cool the detector. The cooling can decreases the number of false-positive photon detections that are generated randomly because of thermal noise. This can be done using cryogenic fluids such as liquid nitrogen or helium or solid state cooling through use of a Peltier device. Others areas of improvement may include use of a Marx Bank Circuit (MBC) as relevant to shutter speed.

[00120] These improvements may be applied to any of the systems in Figs. 6A-6C. Likewise, any or all of the above features described above in connection with systems 2100 and 2100′ may be incorporated in system 2100″. Indeed a, mix-and-match of features or components is contemplated between all of the systems.

[00121] With such systems running the subject methodology, various determinations can be made not heretofore possible using laser-blocking and/or delay related techniques. Fig. 7 illustrates a process map or decision tree 2200 representing such possibilities. Namely, a so-called problem 2210 that is detected can be parsed between

a defect 2210 (extended defects such as bond voids or dislocations, Crystal Originated Particle (COP) or the like) and a contaminant 2220 (such as copper inclusion or other metals in point defect or clustered forms). In terms of a defect, the defect type 2222 and/or a defect quantification 2224 determination (e.g., in terms of density or degree) can also be made. In terms of a contaminant, the contaminant species or type 2232 and/or a contaminant quantification 2234 determination can be made. Such parsing between defect and contaminant and identification of species may be performed in connection with determining charge carrier lifetimes, trap energies, trap capture cross-section and/or trap densities then comparing these to values in look-up tables or databases. Essentially these tables or databases include listings of properties of the material as characterized by the subject methods, and then matching-up the stated properties with entries in a table or database that correspond to particular defects or contaminants.

[00122] Trap capture cross-section and trap density may be observed in connection with, optionally, detected charging kinetics. As for determining charge carrier lifetimes and trap energies, the following equation based on work by I. Lundstrom, provides guidance:

$$\tau = \tau_0 \exp\left\{\frac{4}{3\hbar}\sqrt{2m_{ox}}\left[\phi_t^{3/2} - (\phi_t - E_{ox}d_t)^{3/2}\right]/E_{ox}\right\}$$

where τ is the tunneling time constant for the tunneling mechanism of the trap discharge, ϕ_r denotes the trap energy, E_{ox} denotes the strength of the electric filed at the interface and the remaining equation variables and context are described at I. Lundstrom, JAP, v.43,n.12,p.5045,1972 which subject matter is incorporated by reference in its entirety.

[00123] In any case, the decay curve data obtained by the subject sample interrogation can be used to determine the parameters of trap energy and charge carrier lifetime by use of physical models and related mathematics. Representative sets of curves 2300, 2300′ such as those pictured in Figs. 8A and 8B may be calculated (where Fig. 8B highlights or expands a section of the data from Fig. 8A) from the equation above.

[00124] These curves demonstrate the relationship between time constant (vertical axis) and dielectric thicknesses (horizontal axis) for different trap or barrier energies. The vertical axis includes the ultrafast time scales of down to nanoseconds (1E-9s)). The horizontal axes are tunneling distances (or dielectric thickness, both terms being

generally equivalent in this example). The different curves are lines of constant barrier energy. For example, in Fig. 8B, an electron caught in a trap with an energy depth of the listed barrier energy of 0.7 eV would exhibit a detrapping time constant of about 1E-5 seconds if the dielectric thickness was 40 Angstroms.

[00125] Further modeling with Poisson/Transport solvers can be used to determine trap density in MOS-like structures and more exotic devices using charge carrier lifetimes and known trap energies. Specifically, the photo-injected current due to femto-second optical pulses induces bursts of charge carriers which reach the dielectric conduction band. The average value of this current can be related to carrier concentration and their lifetimes in the regions. The E-field across the interface is the proxy by which SHG measures these phenomena.

[00126] In the plot of Fig. 8A, it can be observed (see dashed lines) that 20 Angstrom of oxide has 1 msec discharge time constant for a trap having an energy of about 3 eV To relate the plots to an example of use in the subject system, suppose a 20 Angstrom oxide is interrogated after blocking laser excitation. As shown in Fig. 8B (see highlighted box) the result will be observable current from 1 μsec to about 1 msec and then all the current dies out.

[00127] The decay curves discussed in this application can be a product of multiple processes (e.g., charge relaxation, charge recombination, etc.) from traps having different energies and different relaxation/recombination time constants. Nevertheless, in various embodiments, the decay curves can be generally expressed by an exponential function $f(t) = Aexp(-\lambda t) + B$, where A is the decay amplitude, B denotes the baseline offset constant and λ denotes a decay constant. This general exponential function can be used to approximately characterize the "extent of decay" from experimentally obtained decay data curve. In various embodiments, it is possible to use the half-life $t_{1/2}$, average lifetime τ, and decay constant λ, to characterize the extent of decay for a decay curve (obtained experimentally or by simulation). For example, the parameters A, B, and λ can be obtained from the decay data points that are obtained experimentally as discussed below. An average lifetime τ can then be calculated from the parameters A, B, and λ using theory of radioactive decay as a way of setting benchmarks for what is qualitatively called partial, or full-decay. For example, in some embodiments, τ can be given by the equation $(t_{1/2})/(\ln(2))$.

[00128] In various implementations, the charge state can be considered to have fully decayed after a time span of three average lifetimes τ, which corresponds to ~95% decay from full saturation. Partial decay can be expressed in terms of signal after a certain number of average lifetimes τ have elapsed.

[00129] In operations, the systems determine parameters (e.g., carrier lifetimes, trap energies, trapping cross-section, charge carrier density, trap charge density, carrier injection threshold energy, charge carrier lifetime, charge accumulation time, etc.) based at least in part on the subject methodology on a point-by-point basis on a portion (e.g., die size portion)of the wafer or an entire wafer. An entire wafer (depending on the material, surface area, and density of scan desired) can often be scanned in less than about 10 minutes, with these parameters determined for each point scanned. In various embodiments, a location of the wafer can be scanned in a time interval between about 100 milliseconds and about 3 seconds. For example, a location of the wafer can be scanned in about 950 milliseconds.

[00130] A matrix of data containing the spatial distributions of the parameters determined can be plotted as individual color-coded heat maps or contour maps for each parameter, as a means for quantitative inspection, feedback and presentation. Fig. 9 illustrates one such map 2400. It depicts how a defect 2402 may be portrayed. But it is possible to show any of the further refined subject matters in Fig. 7. Once quantitative data has been obtained, providing such output is merely a matter of changing the code in the plotting program/script.

[00131] Such information and/or other information treated below may be shown on a computer monitor or dedicated system display and/or it may be recorded for later reference or use for analysis on digital media. In addition, each wafer spatial distribution can be cross-correlated by referencing with ellipsometry data to correct for layer thickness variability and cross-calibrated with independent contamination characterization data obtained, for example, by Total Reflection X-ray Fluorescence (TXRF), Time of Flight Secondary Ion Mass Spectroscopy (TOF-SIMS) and the like. These initial or corrected spatial distributions can then be compared to those from wafers known to be within specification, to determine if the samples in question have any defects or problematic features which warrant further testing. In general, however, it is desirable to use low-cost SHG and other methods hereof calibrated with, by or against slow and expensive direct methods like TXRF, etc.

[00132] Human decisions may be employed (e.g., in inspecting a generated heat map 2400) initially in determining the standard for what is an acceptable or unsatisfactory wafer, until the tool is properly calibrated to be able to flag wafers autonomously. For a well-characterized process in a fab, human decisions would then only need to be made to determine the root cause of any systemic problem with yields, based on the characteristics of flagged wafers.

[00133] However implemented, Fig. 10 provides a plot 2500 illustrating a first method embodiment hereof that may be used in making such determinations. This method, like the others discussed and illustrated below relies on characterizing SHG response with multiple shutter blocking events in which interrogation laser is gated for periods of time.

[00134] In this first example, a section of a sample to be interrogated is charged (typically by a laser) to saturation. In this example, a single source is used to generate as pump beam and probe beam, although separate pump and probe sources can be used in other embodiments. During which time, the SHG signal may be monitored. The saturation level may be known by virtue of material characterization and/or observing asymptotic behavior of the SHG signal intensity associate with charging (I_{ch}). Upon (or after) reaching saturation, the electromagnetic radiation from the laser (pump beam) is blocked from the sample section. The laser (probe beam) is so-gated for a selected period of time (t_{bl1}). After gating ceases, an SHG intensity measurement (I_{dch1}) is made with the laser (probe beam) exposing the surface, thus observing the decay of charge at a first discharge point. After charging the material section (with the pump beam) to saturation again over a period of time (t_{ch}), a second blocking event occurs for a time (t_{bl2}) different than the first in order to identify another point along what will become a composite decay curve. Upon unblocking the laser (probe beam), SHG signal intensity (I_{dchs2}) is measured again. This reduced signal indicates charge decay over the second gating event or blocking interval. Once-again charged to saturation by the laser (pump beam), a third differently-timed blocking event (t_{bl3}) follows and subsequent SHG interrogation and signal intensity measurement (I_{dch3}) is made for a third measurement of charge decay in relation to SHG intensity.

[00135] Although in the above example, the sample is charged to a saturation level, in other examples, the sample can be charged to a charge level below saturation. Although in the above example, the three blocking times t_{bl1}, t_{bl2} and t_{bl3} are different, in other examples, the three blocking times t_{bl1}, t_{bl2} and t_{bl3} can be the same. In various

examples, the sample can be charged to a charging level initially and the SHG intensity measurement (I_{dch1}), (I_{dch2}) and (I_{dch3}) can be obtained at different time intervals after the initial charging event.

[00136] As referred to above, these three points (corresponding to I_{dch1}, I_{dch2} and I_{dch3}) can be used to construct a composite charge decay curve. It is referred to herein as a "composite" curve in the sense that its components come from a plurality of related events. And while still further repetition (with the possibility of different gating times employed to generate more decay curve data points or the use of same-relation timing to confirm certainty and/or remove error from measurements for selected points) may be employed so that four or more block-then-detect cycles are employed, it should be observed that as few as two such cycles may be employed. Whereas one decay-related data point will not offer meaningful decay curve characterization, a pair defining a line from which a curve may be modeled or extrapolated from to offer some utility, whereas three or more points for exponential decay fitting will yield an approximation with better accuracy. Stated otherwise, any simple (e.g.,not stretched by dispersive transport physics) decay kinetics has a general formula: Measurable(t)=M_0*exp(-t/tau) so to find two unknown parameter M_0 and tau at least 2 points are needed assuming this simple kinetics. In dispersive (i.e., non-linear) kinetics it is desirable to measure as many point as possible to extract (n-1)-order correction parameters if n-points are measured and then apply a model appropriate for that order of approximation. Also, that set of measurements is to be measured for different electric fields (E) to be real practical and precise with the tau to assign it for a certain type of defects.

[00137] The method above can provide parameter vs. time (such as interfacial leakage current or occupied trap density v. time) kinetic curve by obtaining measurements at a few time points. A time constant (τ) can be extracted from the parameter vs. time kinetic curve. The time constant can be attributed to a time constant characteristic for a certain type of defect.

[00138] In any case, the decay-dependent data obtained may be preceded (as in the example) by SHG data acquisition while saturating the material with the interrogation (or probe) laser. However, charging will not necessarily go to saturation (e.g., as noted above). Nor will the measurement necessary be made prior to the blocking of a/the charging laser. Further, the charging will not necessarily be performed with the interrogation/probe laser (e.g., see optional pump/probe methodology cited above).

[00139] Regardless, after the subject testing at one sample site, the sample material is typically moved or indexed to locate another section for the same (or similar) testing. In this manner, a plurality of sections or even every section of the sample material may be interrogated and quantified in scanning the entire wafer as discussed above.

[00140] Fig. 11 and plot 2600 illustrate an alternative (or complimentary approach) to acquiring charge decay related data by scanning is shown in plot 2600. In this method, after charging to saturation a/the first time, continuous (or at least semi-continuous) discharge over multiple blocking time intervals (t_{bl1}, t_{bl2}, t_{bl3}) is investigated by laser pulses from an interrogation or a probe laser measuring different SHG intensities (I_{dch1}, I_{dch2}, I_{dch3}). The intensity and/or frequency of the laser pulses from the interrogation/probe laser are selected such that the average power of the interrogation/probe laser is reduced to avoid recharging the material between blocking intervals while still obtaining a reasonable SHG signal. To do so, as little as one to three laser pulses may be applied. So-reduced (in number and/or power), the material excitation resulting from the interrogation or probe laser pulses may be ignored or taken into account by calibration and or modeling considerations.

[00141] In various embodiments, a separate pump source can be used for charging. However, in some embodiments, the probe beam can be used to charge the sample.

[00142] In any case, the delay between pulses may be identical or tuned to account for the expected transient charge decay profile or for other practical reason. Likewise, while the delay is described in terms of "gating" or "blocking" above, it is to be appreciated that the delay may be produced using one or more optical delay lines as discussed above in connection with Fig. 6C. Still further, the same may hold true for the blocking/gating discussed in association with Fig. 10.

[00143] Further, as above, the method in Fig. 11 may be practiced with various modifications to the number of blocking or delay times or events. Also, SHG signal may or may not be measured during charge to saturation. Anyway, the method in Fig. 11 may be practiced (as illustrated) such that the final gating period takes the SHG signal to null. Confirmation of this may be obtained by repeating the method at the same site in a mode where charging intensity (I_{ch}) is measured or by only observing the SHG signal in (re)charging to saturation.

[00144] Figs 12A-12E are instructive regarding the manner in which the subject hardware is used to obtain the decay-related data points. Fig. 12A provides a chart 2700 illustrating a series of laser pulses 2702 in which intermediate or alternating

pulses are blocked by shutter hardware (e.g., as described above) in a so-called "pulse picking" approach. Over a given time interval, it is possible to let individual pulses through (indicated by solid line) and block others (as indicated by dashed line).

[00145] Fig. 12B provides a chart 2710 illustrating the manner in which resolution of a blocking technique for SHG investigation can be limited by the repetition (rep) rate of the probe laser. Specifically, when presented with a decay curve like decay curve 2712 it is possible to resolve the time delay profile with blocking of every other pulse using a pulsed laser illustrated to operate at the same time scale as in Fig. 12A. However, a shorter curve 2714 cannot be resolved or observed under such circumstances. As such, use optical delay stage(s) can offer additional utility.

[00146] Accordingly, chart 2720 in Fig. 12C illustrates (graphically and with text) how blocking and introducing a delay with respect to a reference time associated with charging the sample can offer overlapping areas of usefulness, in terms of the decay time of the curve relative to the rep rate of the laser. It also shows how there are short time ranges when only delay stages would allow interrogation of the decay curve, and longer time ranges when only blocking the pumping and/or the probing beam would be practical.

[00147] Figs. 12D and 12E further illustrate the utility of the combined block/delay apparatus. Chart 2730 illustrates exemplary SHG signals produced by individual laser pulses 2702. With a delay stage alone, only the range (X) between each such pulse may be interrogated by varying optical delay. In contrast, additional utility over a range (Y) may be achieved with a system combining a delay stage and blocking or shutter means such as a chopper, shutter, or modulator. As illustrated by chart 2740, such a system is able to measure decay curves (and their associated time constants) in the range from one to several pulse times.

[00148] Fig. 13 provides a plot 2800 illustrating a third method embodiment hereof. This embodiment resembles that in Fig. 11, except that discharge current (J_{dch1}, J_{dch2}, J_{dch3}) is measured at time intervals (e.g., $t_i=t_0$, $2t_0$, $3t_0$, $7t_0$, $10t_0$, $20t_0$, $30t_0$, $70t_0$ -- basically according to a log time scale vs. linear time -- where t_0 is a scale parameter of about 10^{-6} sec or 10^{-3} sec when measurement is started) after charging the material with a laser (optionally monitoring or capturing its SHG intensity (I_{ch}) signal) or other electro-magnetic radiation source and then blocking or otherwise stopping the laser radiation application to the sample, thereby allowing discharge. This approach gives an estimation of the mobile carrier lifetime in the substrate by the moment after the e-

h-plasma in the substrate is decayed and when the discharge current starts to be seen, thus offering an important physical parameter of the wafer. And after carrier lifetime is determined, the discharge of current can be interpreted in its time dependence (i.e., its kinetics regarding charge decay) in the same manner as if it were obtained by SHG sensing of discharged charge.

[00149] Various embodiments can be used to measure time constant (e.g., for decay) having a range of values. For example, the time constants can range between 0.1 femtosecond and 1 femtosecond, 1 femtosecond and 10 femtoseconds, 10 femtoseconds and 100 femtoseconds, 100 femtoseconds and 1 picosecond, between 1 picosecond and 10 picoseconds, between 10 picoseconds and 100 picoseconds, between 100 picoseconds and 1 nanosecond, between 1 nanosecond and 10 nanoseconds, between 10 nanosecond and 100 nanoseconds, between 100 nanoseconds and 1 microsecond, between 1 nanoseconds and 100 microseconds, between 100 microseconds and 1 millisecond, between 1 microsecond and 100 milliseconds, between 100 microsecond and 1 second, between 1 second and 10 seconds, or between 10 second and 100 seconds or larger or smaller. Likewise, time delays (Δ) for example between the probe and pump (or pump and probe) can be, for example, between 0.1 femtosecond and 1 femtosecond, 1 femtosecond and 10 femtoseconds, 10 femtoseconds and 100 femtoseconds, 100 femtoseconds and 1 picosecond, between 1 picosecond and 10 picoseconds, between 10 picoseconds and 100 picoseconds, between 100 picoseconds and 1 nanosecond, between 1 nanosecond and 10 nanoseconds, between 10 nanosecond and 100 nanoseconds, between 100 nanoseconds and 1 microsecond, between 1 nanoseconds and 100 microseconds, between 100 microseconds and 1 millisecond, between 1 microsecond and 100 milliseconds, between 100 microsecond and 1 second, between 1 second and 10 seconds, between 10 second and 100 seconds. Values outside these ranges are also possible.

[00150] Various physical approaches can be taken in providing a system suitable for carrying out the method in Fig. 13 -- which method, notably, may be modified like those described above. Two such approaches are illustrated in Figs. 14A and 14B.

[00151] Systems 2900 and 2900′ use gate electrodes 2910 and 2920, respectively, made of a conductive material that is transparent in the visible light range. Such an electrode may touch a wafer 2020 to be inspected, but need not as they may only be separated by a minimal distance. In various implementations, the electric field in the

dielectric can be estimated by extracting the electrode-dielectric-substrate structure parameters using AC measurement of the Capacitance-Voltage curve (CV-curve). CV-curve measurement can be done by using a standard CV-measurement setup available on the market, connected to a material sample in the subject tool (e.g., the applied voltage is to provide the electric field in the dielectric between about 0.1 MV/cm and about 5 MV/cm). The wafer may be held upon a conductive chuck 2030 providing electrical substrate contact. Another alternative construction for a gate electrode would be an ultra-thin Au film or Al film on a glass of 10-30A thickness which can reduce the sensitivity due to absorption of some photons by the thin semi-transparent metal layer.

[00152] However, electrodes 2910 and 2920 present no appreciable absorption issues (although some refraction-based considerations may arise that can be calibrated out or may be otherwise accounted for in the system). These electrodes may comprise a transparent conductor gate layer 2930 made of a material such as ZnO, SnO or the like connected with an electrical contact 2932. An anti-reflective top coat 2934 may be included in the construction. Gate layer 2930 may be set upon a transparent carrier made 2936 of dielectric (SiO_2) with a thickness (D_{gc}) as shown. In various embodiments, the transparent carrier comprises an insulator that is used as a gate for a noncontact electrode that may employ for example capacitive coupling to perform electrical measurements, similar to those described in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section IV entitled, "FIELD-BIASED SHG METROLOGY". As the wafer is charged from the incoming laser radiation, the electric field across one or more of its interfaces will change, and the layers of the wafer should capacitavely couple with the plates in the electrode similar to a plate capacitor. The charging of the electrode will involve movement of charge carriers that will be measured as current.

[00153] D_{gc} would be calibrated by measuring CV curve on the semiconductor substrate with a non-invasive approach and used in electric field (E) calculation when applied voltage is known. A negligible gap distance between the gate and sample can be an air gap. Alternatively the electrode can be directly in contact with the sample rather than being separated by an air gap or dielectric. Accordingly normal CV or IV measurements may be performed in various embodiments.

[00154] Or given a close refractive index match between water and SiO_2, filling the gap with deionized water may be helpful in reducing boundary-layer reflection without any ill effect (or at least one that cannot be addressed). Deionized (or clean-room grade) water can maintain cleanliness around the electrically sensitive and chemically pure substrate wafers. Deionized water is actually less conductive than regular water.

[00155] In Fig. 14B, a related construction is shown with the difference being the architecture of the carrier or gate-holder 2938. Here, it is configured as a ring, optimally formed by etched away in the center and leaving material around the electrode perimeter as produced using MEMS techniques. But in any case, because of the large unoccupied zone through with the laser and SHG radiation must pass, it may be especially desirable to fill the same with DI water as described above.

[00156] Regardless, in the overall electrode 2910, 2920 constructions each embodiment would typically be stationary with respect to the radiation exciting the material in use. Prior to and after use, the electrode structure(s) may be stowed by a robotic arm or carriage assembly (not shown).

[00157] As describe above, in various embodiments the electrode directly contacts the wafer to perform electrical measurements such as measuring current flow. However, non-contact methods of measuring current, such as for example using electrodes that are capacatively coupled with the sample, can also be used.

[00158] The systems and methods described herein can be used to characterize a sample (e.g., a semiconductor wafer or a portion thereof). For example, the systems and methods described herein can be used to detect defects or contaminants in the sample as discussed above. The systems and methods described herein can be configured to characterize the sample during fabrication or production of the semiconductor wafer. Thus, the systems and methods can be used along a semiconductor fabrication line in a semiconductor fabrication facility. The systems and methods described herein can be integrated with the semiconductor fabrication/production line. The systems and methods described herein can be integrated into a semiconductor fab line with automated wafer handling capabilities. For example, the system can be equipped with an attached Equipment Front End Module (EFEM), which accepts wafer cassettes such as a Front Opening Unified Pod (FOUP). Each of these cassettes can be delivered to the machine by human operators

or by automated cassette-handling robots which move cassettes from process to process along fabrication/production line.

[00159] In various embodiments, the system can be configured such that once the cassettes are mounted on the EFEM, the FOUP is opened, and a robotic arm selects individual wafers from the FOUP and moves them through an automatically actuated door included in the system, into a light-tight process box, and onto a bias-capable vacuum chuck. The chuck may be designed to fit complementary with the robotic arm so that it may lay the sample on top. At some point in this process, the wafer can be held over a scanner for identification of its unique laser mark.

[00160] Accordingly, a system configured to be integrated in a semiconductor fabrication/assembly line can have automated wafer handling capability from the FOUP or other type of cassette; integration with an EFEM as discussed above, a chuck designed in a way to be compatible with robotic handling, automated light-tight doors which open and close to allow movement of the robotic wand/arm and software signaling to EFEM for wafer loading/unloading and wafer identification.

[00161] Part III

[00162] Figs. 15A and 15B show suitable hardware for use in the subject systems and methods as further described in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section I entitled "PUMP AND PROBE TYPE SHG METROLOGY". Other system and method options are presented in the portion of U.S. Provisional Application No. 61/980,860, filed on April 17, 2014, titled "WAFER METROLOGY TECHNOLOGIES," referred to as Section II entitled "CHARGE DECAY MEASUREMENT SYSTEMS AND METHODS," for example, as to intermediate optics, the inclusion of optical delay line(s) and optional electrode features.

[00163] As shown, system 3000 includes a primary or probe laser 3010 for directing an interrogation beam 3012 of electro-magnetic radiation at a sample wafer 3020, which is held by a vacuum chuck 3030. As illustrated in Fig. 15B, the chuck 3030 includes or is set on x- and y- stages and optionally also a rotational stage for positioning a sample site 3022 across the wafer relative to where the laser(s) are aimed. The x-y stage enables scanning multiple wafer surface sites or locations 3022 without movement of other hardware. A rotational stage optionally enables assessing crystal structure effects on SHG. Further optional features, aspects and/or uses of chuck 3030

are presented elsewhere in this application entitled. The sample site 3022 can include one or more layers. The sample site 3022 can comprise a composite substrate including at least two layers. The sample site 3022 can include an interface between two dissimilar materials (e.g., between two different semiconductor materials, between two differently doped semiconductor materials, between a semiconductor and an oxide, between a semiconductor and a dielectric material, between a semiconductor and a metal or an oxide and a metal).

[00164] When system 3000 is in use, a beam 3014 of reflected radiation directed at a detector 3040 will include an SHG signal. The detector 3040 may be any of a photomultiplier tube, a CCD camera, an avalanche detector, a photodiode detector, a streak camera and a silicon detector. System 3000 may also include one or more shutter-type devices 3050. The type of shutter hardware used will depend on the timeframe over which the laser radiation is to be blocked, dumped or otherwise directed away from the sample site 3022. An electro-optic blocking device such as a Pockel's Cell or Kerr Cell can be used to obtain very short blocking periods (i.e., with actuation times on the order of 10^{-9} to 10^{-12} seconds).

[00165] For longer blocking time intervals (e.g., from about 10^{-5} seconds and upwards) mechanical shutters or flywheel chopper type devices may be employed. However, electro-optic blocking devices will allow a wider range of materials to be tested in accordance with the methods below. A photon counting system 3044 capable of discretely gating very small time intervals, typically, on the order of picoseconds to microseconds can be employed to resolve the time-dependent signal counts. For faster-yet time frames optical delay line(s) may be incorporated as noted above.

[00166] System 3000 can include an additional electromagnetic radiation source 3060 also referred to as a pump source. In various implementations, the radiation source 3060 can be a laser illustrated as emitting a directed beam 3062 or a UV flash lamp emitting a diverging or optically collimated pulse 3064. In the case of a laser source, its beam 3062 may be collinear with beam 3012 (e.g., as directed by additional mirrors or prisms, etc.) Source 3060 output wavelengths of light may be anywhere from about 80 nm and about 1000 nm. Using shorter wavelengths in this range (e.g. less than about 450 nm), is possible to drive charge excitation using fewer photons and/or with lower peak intensities than at longer wavelengths.

[00167] For a flash lamp, energy per flash or power level during flash may be substrate material dependent. A flashlamp producing a total energy of 1 J to 10 kJ per flash

would be appropriate for fully depleted silicon-on-insulator (FD-SOI). However a pulsed or constant UV source would be viable as well. The important factor in the pump characteristics and use is that charge carriers are injected into the dielectric of the material to be interrogated. Manufacturers of suitable flash lamps include Hellma USA, Inc. and Hamamatsu Photonics K.K.

[00168] When a laser is employed as source 3060, it may be any of a nanosecond, picosecond or femtosecond or faster pulse laser source. It may even be a continuous solid-state laser. In various embodiments, the pump source is tunable in wavelength. Commercially available options regarding lasers which are tunable include Spectra Physics' Velocity and Vortex Tunable Lasers. Additional tunable solid state solutions are available from LOTIS Ltd.'s LT-22xx series of solid state lasers.

[00169] Whether provided as a laser or a flash lamp, pump source 3060 can be selected for relatively high average power. This could be from about 10 mW to about 10 W, but more typically from about 100 mW to about 4 W, depending on material to be interrogated (as, again, the consideration is ensuring that charge carrier mobility is induced in a way such that charge carriers are injected into the interface of the material (e.g., the dielectric interface), which can be material specific. The average power of the pump source 3060 is selected to be below the optical damage threshold of the material. For example, pump source 3060 can be selected to have an average optical power between 1 – 2 W when the interrogating material comprises silicon so as to not exceed the optical damage threshold for silicon.

[00170] Probe laser 3010 may be any of a nanosecond, picosecond or femtosecond or faster pulse laser source. Two options are currently commercially available regarding lasers have the peak power, wavelength and reliability needed are doped fiber and Ti:Sapphire units. Coherent's VITESSE and Spectra Physics' MAI TAI lasers are examples of suitable Ti:Sapphire devices. Femtolasers Gmbh and others manufacture also manufacture other relevant Ti:Sapphire devices. Suitable doped fiber lasers are produced by IMRA, OneFive, and Toptica Photonics. Pico- and/or nano-second lasers from many manufacturers, such as Hamamatsu, may be options as well depending on the substrate material and pump type. Laser 3010 may operate in a wavelength range between about 100 nm to about 2000 nm with a peak power between about 10 kW and 1 GW, but delivering power at an average below about 150 mW.

[00171] Various other optional so-called "intermediate" optical components may be employed in system 3000. For example, the system 3000 may include a dichroic

reflective or refractive filter 3070 for selectively passing the SHG signal coaxial with reflected radiation directly from laser 3010 and/or source 3060. Alternatively, a prism may be employed to differentiate the weaker SHG signal from the many-orders-of-magnitude-stronger reflected primary beam. However, as the prism approach has proved to be very sensitive to misalignment, a dichroic system as referenced above may be preferred. Other options include the use of diffraction grating or a Pellicle beam splitter. An optical bundle 3080 for focusing and collimating/columniation optics may be provided. Alternatively, a filter wheel 3090, polarizer(s) 3092 and/or zoom len(s) 3094 units or assemblies may be employed in the system. Also, an angular (or arc-type) rotational adjustment (with corresponding adjustment for the detector) and in-line optical components may be desirable.

[00172] The output from the detector 3040 and/or the photon counting system 3044 can be input to an electronic device 3048. The electronic device 3048 can be a computing device, a computer, a tablet, a microcontroller or a FPGA. The electronic device 3048 includes a processor, processing electronics, control electronics, processing/control electronics, or electronics that may be configured to execute one or more software modules. In addition to executing an operating system, the processor may be configured to execute one or more software applications, including a web browser, a telephone application, an email program, or any other software application. The electronic device 3048 can implement the methods discussed herein by executing instructions included in a machine-readable non-transitory storage medium, such as a RAM, ROM, EEPROM, etc. The electronic device 3048 can include a display device and/or a graphic user interface to interact with a user. The electronic device 3048 can communicate with one or more devices over a network interface. The network interface can include transmitters, receivers and/or transceivers that can communicate such as, for example, wired Ethernet, Bluetooth ®, or wireless connections.

[00173] Regarding other options, since an SHG signal is weak compared to the reflected beam that produces it, it is desirable to improve the signal-to-noise ratio of SHG counts. As photon counting gate times for the photon counting system 3044 decrease for the blocking and/or delay processes described herein, improvement becomes even more important. One method of reducing noise that may be employed is to actively cool the photon counter. This can be done using cryogenic fluids such as liquid nitrogen or helium or solid state cooling through use of a Peltier device. Others areas of improvement may include use of a Marx Bank Circuit (MBC) as relevant to

shutter speed. Moreover, system 3000 may be incorporated in-line within a production line environment. Production line elements preceding or following system 100 may include any of epitaxial growth system, lithography and/or deposition (CVD, PVD, sputtering, etc.) systems.

[00174] In any case, Figs. 16A and 16B provide views of a first set of purpose-specific chuck hardware that may be employed in the subject SHG system. The chuck 3030 holds a wafer 3020 by vacuum thereto or other means. The chuck 3030 is conductive and connected to a power supply. Optionally, a capacitive coupling probe 3100 is also connected to the power supply 3120. The power supply may be computer controlled, or at least its output is coordinated by computer for timing reasons as summarized above. The probe 3100 may likewise be controlled and/or monitored. It will be controlled in the sense that it will be part of a capacitive circuit attached to the power supply 3120. It may be monitored along with the chuck 3030 by a voltmeter to ensure that voltage is being induced as intended.

[00175] The probe 3100 includes a hole 3102 or port (e.g., 0.2 mm in diameter) in its ring 3104 to allow the optical beams 3012, 3014 (interrogation beam(s) and reflected SHG beam) to pass unblocked, and is fixed relative to the optics so that it moves or stays with the optical elements to remain centered on the (re)positioned sample site 3022 as the device surface is scanned. The coupling (indicated as having a positive "+" charge) is positioned close to the sample device surface (e.g., within about 1 mm to about 2 mm) but does not touch. It is supported by a cantilever arm or otherwise. The probe 3100 may be provided as a ring 3104 as shown in Figure 16B, or it may comprise a larger disc or plate.

[00176] With the example shown in cross section in Fig. 16B, a wafer 3020 or device surface (comprising silicon) is separated from a silicon bulk layer by SiO_2 insulator. Thus, as explained above, the need for inductive bias to the device surface because it is otherwise (at least substantially) electrically insulated or isolated from the underlying silicon in contact with the conductive chuck 3030.

[00177] Figs. 17A-17C detail an electromagnetic chuck 3030 that includes electrical coil(s) 3130 connected to a power supply 3120. In use, the wafer 3020 sits and is secured on top of the chuck 3030. When an alternating current (AC) is applied to the coil(s) 3130, this generates an alternating magnetic field through the wafer 3020. The magnetic field induces an electric potential across the wafer 3020 including its device surface. This electric field then enables the various modes of SHG interrogation noted

above, some of which are detailed below. Alternatively, DC current may be applied to the coils 3130 which are oriented parallel to the chuck 3030, creating a constant magnetic field across the chuck for other effects as described above.

[00178] Fig. 18A shows an example AC voltage (V) profile (sinusoidal wave) applied to the substrate bulk layer over time. Fig. 18B shows a hypothetical response for induced voltage between the device and bulk layers (V_i) of the substrate on which the device is fabricated. In various embodiments, the substrate can comprise the silicon wafer or a portion of a semiconductor material. Fig. 19A shows an example AC voltage (V_o) profile (square wave) applied to the substrate bulk layer over time. Fig. 19B shows a hypothetical response for induced voltage between the device and bulk layers (V_i). Notably, the voltage input in either of Fig. 18A or 19A may differ from that shown, and could potentially be applied in steps, ramps, sine waves, or other forms.

[00179] More specifically regarding Figs. 18A and 18B, as alluded to above, in order to minimize noise and obtain statistically relevant indicator(s) of SHG intensity as a function of voltage across the interfaces, multiple photon counting windows may be desirable. For such purposes, example points A1 and A2 are timed so that the voltage between the bulk and device layers, voltage A, is the same for both points. This is true for example points B1 and B2 at voltage B, and example points C1 and C2 at voltage C. Using voltage A as an example, SHG is recorded, and counts at points A1 can be summed with counts at point A2 and further at A3, A4, A_n... in an arbitrarily long series depending on the desired measurement time. The total number of counts measured in this period is then divided by the time over which this "gate" spans as a way of finding the average number of counts per second, so that SHG intensity can be plotted as a function of bulk-device voltage A. The same method can be used to obtain measurements for voltage B at points B1 and B2 as well as at B3, B4, B_n... in an arbitrarily long series depending on the desired measurement time. The total number of counts measured in this period is then divided by the time over which this "gate" spans as a way of finding the average number of counts per second, so that SHG intensity can be plotted as a function of bulk-device voltage B. Likewise, this method can be used to obtain measurements for voltage C at points C1 and C2 as well as at C3, C4, C_n... in an arbitrarily long series depending on the desired measurement time. The total number of counts measured in this period is then divided by the time over which this "gate" spans as a way of finding the average number of counts per

second, so that SHG intensity can be plotted as a function of bulk-device voltage C. Further details regarding the utility of SHG intensity as a function of bias voltage can be found in the DC biasing literature, an example of which is, "Charge Trapping in Irradiated SOI Wafers Measured by Second Harmonic Generation," IEEE Transactions on Nuclear Science, Vol. 51, No. 6. Dec. 2004 and "Optical probing of a silicon integrated circuit using electric-field-induced second-harmonic generation," Applied Physics Letters 88, 114107, (2006), each of which publication is incorporated herein by reference in its entirety.

[00180] More specifically regarding Figs. 19A and 19B, these figures illustrate an example for interrogating a Silicon-On-Insulator (SOI) device. In this example, a conductive chuck begins at a 'neutral' ground state, and bulk and device layers being at an equilibrium potential. At moment 'A', voltage applied to the chuck is changed rapidly, applying that voltage to the sample's conductive bulk layer. Since the sample's device layer is separated from the bulk by a thin buried oxide layer and not directly connected with a conductor, an electric potential field, or voltage will be induced between the device and bulk layers. Between times 'A' and 'B', the voltage applied to the chuck is not changed. Since the dielectric between the bulk and device layers is not perfect, the induced potential will drive a leakage current between the layers, causing the potential between the bulk and device layers to return to its natural state. This spike and decay in electric field is then monitored via SHG to provide insight to the leakage current. At time 'B' the voltage applied to the chuck is returned to ground, causing the voltage across the interface to reverse.

[00181] The systems and methods described herein can be used to characterize a sample (e.g., a semiconductor wafer or a portion thereof). For example, the systems and methods described herein can be used to detect defects or contaminants in the sample as discussed above. The systems and methods described herein can be configured to characterize the sample during fabrication or production of the semiconductor wafer. Thus, the systems and methods can be used along a semiconductor fabrication line in a semiconductor fabrication facility. The systems and methods described herein can be integrated with the semiconductor fabrication/production line. The systems and methods described herein can be integrated into a semiconductor fab line with automated wafer handling capabilities. For example, the system can be equipped with an attached Equipment Front End Module (EFEM), which accepts wafer cassettes such as a Front Opening Unified Pod

(FOUP). Each of these cassettes can be delivered to the machine by human operators or by automated cassette-handling robots which move cassettes from process to process along fabrication/production line.

[00182] In various embodiments, the system can be configured such that once the cassettes are mounted on the EFEM, the FOUP is opened, and a robotic arm selects individual wafers from the FOUP and moves them through an automatically actuated door included in the system, into a light-tight process box, and onto a bias-capable vacuum chuck. The chuck may be designed to fit complementary with the robotic arm so that it may lay the sample on top. At some point in this process, the wafer can be held over a scanner for identification of its unique laser mark.

[00183] Accordingly, a system configured to be integrated in a semiconductor fabrication/assembly line can have automated wafer handling capability from the FOUP or other type of cassette; integration with an EFEM as discussed above, a chuck designed in a way to be compatible with robotic handling, automated light-tight doors which open and close to allow movement of the robotic wand/arm and software signaling to EFEM for wafer loading/unloading and wafer identification.

[00184] EFFICIENT COLLECTION OF MULTIPLE POLARIZATIONS

[00185] Different polarization components of the second harmonic generation signal can provide information related to different material properties. For silicon-based materials or crystals with identical symmetry as silicon, for example, the p-polarized second harmonic generation signal may be sensitive to electric properties. In contrast, the s-polarized second harmonic generation signal may provide strain or crystal related information. Accordingly, systems that can control which polarization or polarization component is collected, may be useful in isolating in on and collecting data relating to particular properties of the sample. Various implementations of systems for collecting different polarization components of the second harmonic generated signal are therefore described herein.

[00186] FIG. 20 depicts such a system that is capable of collecting second harmonic generation signal of a particular polarization. In particular, FIG. 20 illustrates a schematic diagram of example components that may be employed for interrogating a sample such as a wafer. As shown, a system 4000 for interrogating a wafer 4120 can include a light source 4110, polarization optics (e.g. polarizer) 4112, focusing optics (e.g., focusing lens) 4114, a rotational stage 4116, a translational stage 4118,

collecting optics (e.g., collimating optics) 4124, polarization optics (e.g., polarization filtering optics or polarizer) 4122, a spectral filter 4126, and a detector 4130. In the illustrated configuration the light source 4110, polarization optics (e.g. polarizer) 4112, and focusing optics (e.g., focusing lens) 4114, are in a first optical path for directing light to the sample (e.g., wafer) and the collecting optics (e.g., collimating optics) 4124, polarization optics (e.g., polarization filtering optics or polarizer) 4122, spectral filter 4126, and detector 4130 are in a second optical path for light reflected from the sample.

[00187] When system 4000 is in use, input light 4132 may be emitted from a light source 4110. The light source 4110 may include a laser source or other source of electromagnetic radiation. For example, the light source 4110 may be a laser such as a pulsed laser such as a nanosecond, picosecond, femtosecond, or continuous laser. In various implementations the laser comprises a solid-state laser. In other examples, the light source 4110 can be a lamp emitting a diverging or optically collimated light. The light source 4110 may emit light 4130 having any number of wavelengths. For example, the light source 4110 may emit light 4130 having wavelengths that include from 80 nm to 1000 nm of spectrum.

[00188] The system 4000 may direct polarized light onto the sample. In some implementations, the light source 4110 may output polarized light such as linearly polarized light. In some implementations, the system 4000 may polarize the input light 4132 with polarization optics 4112. The polarization optics 4112 may, for example, include a polarizer(s) to alter the polarization state of the input light 4132. In some implementations, the polarization optics 4112 can include any suitable type of polarizer(s) for altering the polarization state of the input light 4132. For example, the polarizing optics may include an absorptive polarizer that can linearly polarize the input light 4132. In some implementations, the polarization optics 4112 may comprise polarization control optics configured to vary the polarization state, for example, to alter the orientation of linearly polarized light (e.g., from vertically polarized to horizontally polarized). In some implementations, for example, the polarization optics 4112 provides linearly polarized light having a particular angle, θ_1, for light incident on the sample. The polarization optics 4112 may alter the polarization state, for example, the orientation of the linearly polarization, θ_1, of the input light 4132 relative to the wafer 4120, a region of the wafer 4120, or a pattern on the wafer 4120. For example, polarization optics 4112 may generate s-polarized light

with respect to a pattern on the wafer 4120. In various implementations, one or more hardware processors may be able to control the polarization optics 4112 in order to change the polarization state of the input light 4132.

[00189] The system 4000 may focus the input light 4132 with the focusing optics 4114. The focusing optics 4114 can include any suitable focusing optics for focusing the input light 4132 towards a region 4136 of the wafer 4120. For example, focusing optics 4114 can include one or more lenses that can focus the input light 4132 towards the region 4136 of the wafer 4120.

[00190] The system can also include collecting optics that collects light reflected from the sample. The collecting optics may include, for example, one or more lenses or mirrors disposed to received light the SHG light from the sample.

[00191] In some implementations, the collecting optics 4124 comprises collimating optics to collect the SHG light from the sample. The collimating optics 4124 can include any suitable collimating optics for collimating output light 4134 received from the wafer 4120. For example, collimating optics 4124 can include one or more collimators, such as one or more collimating lens. Such a collimating lens or lenses may, for example, have a focal length, f, and be disposed at a position that is a distance away from the sample corresponding to the focal length, f. Other configurations are possible.

[00192] As discussed above, since information about different material properties may be contained in different polarization components of the second harmonic generated signal, the system 4000 may be configured to select different polarizations of the SHG signal for detection. The system 4000 may, for example, direct light with certain polarization properties, for example, having a particular polarization state, to the detector 4130 using the polarization optics 4122. The polarization optics 4122 may, for example, comprise a polarization filter or polarizer(s) configured to select and pass a particular polarization state of the output light 4134. The polarization optics 4122 can include any suitable type of polarizer(s). For example, the polarizing optics 4122 may include an absorptive polarizer that can selectively transmit linearly polarize light of a particular orientation. Control electronics that may include, for example, one or more hardware processors, may be able to control the polarization optics 4122 in order to change the polarization state selected from the output light 4134. For example, the polarizer 4122 may be configured to rotate to select linearly polarized light having an particular polarization angle, θ_2, In some implementations,

the control electronics may be configured to alter the angle of linear polarized light selected, e.g., selectively transmitted, for example, by rotating the polarizer 4122. The control electronics may control the polarization optics 4122, for example, to selectively permit s-polarized SHG light from the sample to reach the detector in comparison to p-polarized SHG when in a first state and to selectively permit p-polarized SHG light from the sample to reach the detector in comparison to s-polarized SHG when in a second state. For example, the control electronic may control the polarization optics 4122, for example, to transmit s-polarized SHG light from the sample such s-polarized SHG light from the sample is incident on the detector and transmit no more than negligible amounts of p-polarized SHG such that no more than negligible amounts of p-polarized SHG light from the sample are incident on the detector when in the first state. Similarly, the control electronic may control the polarization optics 4122, for example, to transmit p-polarized SHG light from the sample such p-polarized SHG light from the sample is incident on the detector and to transmit no more than negligible amounts of s-polarized SHG such that no more than negligible amounts of s-polarized SHG light from the sample are incident on the detector when in the second state.

[00193] The system 4000 may include other optional optical elements. For example, the system 4000 can include a spectral filter 4126 to select certain wavelengths of light. For example, the filter 4126 may be a band pass filter, high pass filter, or low pass filter. The filter 4126 may, for example, selectively transmit light having a particular wavelength or range of wavelengths.

[00194] As discussed above, the system 4000 may include a detector 4130. The detector may be any of a photomultiplier tube, an avalanche detector, a photodiode detector, a streak camera and a silicon detector. The detector 4130 may detect output light 4134 that may include an SHG signal.

[00195] The wafer 4120 may be held in place using a sample stage 4140, which may comprise chuck in some implementations. The sample stage or chuck 4140 may, in some designs, comprise a translation stage 4118 and/or a rotational stage 4120 that can position the wafer 4120 to move in the plane of the wafer. For example, the rotational stage 4120 may be able to rotate the wafer 4120 about an axis 4128 relative to a wafer region 4136. The translation stage may be able to change the x and y position of the wafer 4120. The rotational stage 4120 and the translation stage 4118

may be controlled by control electronics that may include, for example, one or more hardware processors.

[00196] As discussed above, this system may detect SHG signal having the first polarization, for example, s-polarization to obtain a first type of information regarding the sample and may detect SHG signal having the second polarization, for example, p-polarization to obtain a second type of information regarding the sample. The polarization controller may, for example, to be set to collect the first polarization component initially and then collect the second polarization component subsequently or vice versa. Other implementations described herein are configured to direct light from a plurality of polarizations components, for example, a first polarization (e.g., s-polarized light) and a second polarization (e.g., p-polarized light) to first and second detectors, respectively, at the same time.

[00197] FIG. 21 shows, for example, a system such as depicted in FIG. 20 that includes a polarization beamsplitter 5122 instead of the polarization optics 4122 as well as first and second detectors 5130A, 5130B disposed to receive light from the polarization beamplitter, instead of a single detector 4130. The polarization beamsplitter is configured to receive light and split the light into first and second polarization components. In the system shown in FIG. 21, the beamsplitter is disposed to receive second harmonic generation light from the sample and split the light into first and second (e.g., orthogonal) polarization components (such as, e.g., s- and p- polarized light). The polarization beamsplitter directs the first and second polarization components along first and second respective paths to said first and second detectors, respectively. As a result, data regarding the first and second polarization components of the second harmonic generation signal can be collected at the same time.

[00198] In some implementations, the sample can be scanned or the beam 4132 from the light source 4110 directed onto the sample can be scanned to obtain an SHG signal for different portions of the sample possibly to create SHG images of the sample or portions thereof. Images can be formed from second harmonic generation light from the sample using other approaches as discussed below. Advantageously, in the system shown in FIG. 21, the first and second polarizations of the SHG signal can be separately collected and measured at the same time. For example, orthogonal polarizations such as p and s polarization components can be collected simultaneously from one scan of the sample. Throughput can thereby be increased, e.g., doubled,

when signals with both polarization states are simultaneously collected to assess the material. As discussed above, for silicon-based materials or crystals with identical symmetry as silicon, the p-polarized SHG signal component can provide information relating to the electrical properties such as interfacial electric properties while the s-polarized SHG signal component can provide strain or crystal related information. Using the systems disclosure herein such information can be collected simultaneously thereby providing a more comprehensive material property assessment with the two polarization components with increased throughput and/or processing speed. Signal normalization may also be provided with multiple polarization components.

[00199] The polarization beamsplitter may comprise a polarization beamsplitter cube, a plate or other optical element with a surface having a polarization selective reflective coating thereon. Other types of polarizers may also be employed. The other components in the system can be the same as those shown in FIG. 20. Likewise, various features and modes of operation discussed above with respect to FIG. 20 or elsewhere through this disclosure can apply to the system shown FIG. 21. A wide range of variations, however, may also be possible. For example, instead of having first and second detectors 5130A, 5130B to receive the first and second polarization components, a detector array (e.g., a CCD detector array) may receive the first and second polarization components. For example, the detector array may comprise a plurality of pixels. Different regions of the detector array, for example, first and second regions of the detector array, may receive the first and second polarization components, respectively. One region of the detector array may comprise one or more pixels of the detector array. Still other variations are possible.

[00200] SHG IMAGING

[00201] As discussed above, second harmonic generation can provide sensitive non-destructive detection of critical interfacial electric properties. Various point-based measurement/sampling approaches, however, have reduced throughput for large area coverage and spatial profiling of large areas with high resolution. Accordingly, various implementations disclosed herein provide designs for SHG imaging-based inspection systems. These imaging systems can provide SHG images or maps of the distribution of SHG signals over a larger area of a sample, yet can also provide high resolution. These imaging systems may extend existing application capabilities of second harmonic generation with high resolution and coverage for defects/issues with random distribution over a larger area with increased throughput. In some cases, such

SHG imaging systems may employ one or more beamsplitter to produce multiple beams and multiple detectors to capture multiple SHG signals over an area of the sample to form SHG images. Scanning techniques may also be used. In some cases, SHG imaging systems may employ imaging optics to image the sample or an area of the sample and/or project the SHG signals associated with an area of a sample onto a detector array to form SHG images. Examples of such systems are discussed below.

[00202] FIG. 22A, for example, depicts an SHG imaging system 8000 configured to split or separate a laser beam 7126 into a plurality of beams 7122A, 7122B, 7122C. In some implementations, this plurality of beams 7122A, 7122B, 7122C can be scanned across an area of the sample 4120 to provide SHG images of the sample or portions thereof.

[00203] As with other SHG systems discussed herein, the system 8000 shown in FIG. 22 includes a light source (e.g., a laser light source) 7108 configured to output light 7126 that can be directed to the sample 4120 that is supported on a sample stage 4140 to produce second harmonic generation from a sample 4120. As with other systems described herein, the sample stage 4140 may include a translation stage such as an x-y translation stage 4118 and/or a rotation stage 4116.

[00204] The system 8000 shown in FIG. 22A additionally includes a beamsplitter 7110 configured to receive in one beam and split or separate the beam into a plurality of beams. Such a beamsplitter 7110 may also be referred to as a multispot beam generator or an array beam generator. The plurality of beams may be a linear array of beams or a two-dimensional (2D) array of beams. The beamsplitter 7110 may comprise a diffractive beamsplitter such as a grating or diffractive optical element configured to diffract light from a beam into a plurality of beams. In some implementations, the beamsplitter 7110 may comprise an acousto-optic modulator. The acousto-optic modulator may, for example, be configured to diffract light from an input beam so as to produce a plurality of output beams. In the system 8000 shown in the FIG. 22A, the beamsplitter 7110 receives the beam 7126 output from the laser light source 7110 and produces the plurality of beams 7122A, 7122B, 7122C therefrom. Although three beams are shown, more or less beams may be produced by the beamsplitter 7110. The number of beams 7122A, 7122B, 7122C (and corresponding spots or locations on the sample that may be illuminated by the beams as well as the number of resultant SHG signals) may be, for example, greater than 3, 5, 10, 15, 20, 25, 30 or any range between any of these values. More or less beams

7122A, 7122B, 7122C, illuminated spots or locations on the sample 4120, and/or SHG signals are also possible.

[00205] The system 8000 additionally includes a scanner 7112 configured to receive the plurality of beams 7122A, 7122B, 7122C produced by the beamsplitter 7110. The scanner 7112 may comprise, for example, one or more mirrors or reflective surfaces that tips, tilts, rotates, and/or varies its orientation to re-direct light received into different directions. Other types of scanners or beam scanners may be employed. In various implementations, the scanner 7112 may be configured to scan the beams 7122A, 7122B, 7122C across one or more areas of the sample 4120.

[00206] The system 8000 further includes an objective 7116 disposed between the beamsplitter 7110 and the sample such that the objective 7116 receives the plurality beams 7122A, 7122B, 7122C that thereafter proceed onto the sample 4120 as beams 7120A, 7120B, 7120C illustrated in FIG. 22A. In some implementations, the objective 7116 focuses the plurality of beams 7120A, 7120B, 7120C on the sample 4120. In the system shown in FIG. 22A, the scanner 7112 is in an optical path between the beamsplitter 7110 and the objective 7116 such that the plurality of beams 7122A, 7122B, 7122C incident on the objective are being scanned. Likewise, the plurality of beams 7120A, 7120B, 7120C incident on the sample 4120 are scanned across at least a portion of the sample after being acted on (e.g., being focused) by the objective 7116. In some implementations such as shown in FIG. 22A, the objective 7116 may also direct the plurality of beams 7120A, 7120B, 7120C onto the sample along a path that is more normal to the sample 4120.

[00207] The plurality of beams 7120A, 7120B, 7120C incident on the sample 4120 produce a plurality of respective SHG signals. These separate SHG signals may be directed back to the objective 7116. In some implementations such as shown in FIG. 22A, the plurality of SHG signals may be directed along a path to the objective 7116 that is substantially normal to the sample 4120.

[00208] The system 8000 shown in FIG. 22A further includes a dichroic mirror or reflector 7114. This dichroic mirror 7114 may be disposed to receive the separate SHG signals produced by the plurality of beams 7122A, 7122B, 7122C (and 7120A, 7120B, 7120C), respectively. The dichroic mirror 7114 may be disposed between the beamplitter 7110 and the scanner 7112 such that the SHG signals received from the objective 7116 and the scanner are incident on the dichroic mirror. The dichroic mirror 7114 may be configured to reflect light having wavelengths of the SHG

signals. The plurality of SHG signals will therefore be reflected by the dichroic mirror 7114.

[00209] The dichroic mirror 7114 may also be configured so as to transmit the plurality of beams 7122A, 7122B, 7122C from the light source 7108 and beamsplitter 7110. For example, the dichroic mirror 7114 may be configured to transmit wavelengths of light (e.g., the fundamental frequency) corresponding to the light the plurality of beams 7122A, 7122B, 7122C. As a consequence, insertion of the dichroic mirror 7114 in an optical path between the laser light source 7108 and the sample 4120 may enable the plurality of beams 7122A, 7122B, 7122C from the laser light source and beamsplitter 7110 to be transmitted therethrough to be incident on the sample 4120. However, the plurality of respective SHG signals produced by the plurality of beams 7122A, 7122B, 7122C (and 7120A, 7120B, 7120C) may have suitable wavelength to be reflected from the dichroic mirror 7114.

[00210] The system 8000 shown in FIG. 22A further includes a plurality of detectors 8130A, 8130B, 8130C (e.g., photomultiplier tubes or PMTs) disposed to receive the plurality of SHG signals. In particular, in the system 8000 shown, the dichroic mirror 7114 is configured to reflect the plurality of SHG signals to a plurality of detectors 8130A, 8130B, 8130C along optical paths 8128A, 8128B, 8128C. Although these optical paths 8128A, 8128B, 8128C are schematically illustrated as curved in FIG. 22A, these paths may be different, e.g., straight and closer together. The paths 8128A, 8128B, 8128C may also be varied with optical elements such as mirrors or may comprise other optical components such as optical fiber or fiber devices or integrated optical or waveguide devices. As discussed above, the dichroic mirror 7114 may be configured to reflect wavelengths of light of the SHG signals such that the SHG signals are reflected from the dichroic mirror. Further, the plurality of detectors 8130A, 8130B, 8130C may be disposed in optical paths with respect to the dichroic mirror 7114 to receive the respective SHG signals.

[00211] Although three optical detectors 8130A, 8130B, 8130C are shown in the system 8000 shown in the FIG. 22A, more or less optical detectors may be used. The number of optical detectors 8130A, 8130B, 8130C (and corresponding number of SHG signals) may be, for example, greater than 3, 5, 10, 15, 20, 25, 30 or any range between any of these values. More or less optical detectors 8130A, 8130B, 8130C and/or SHG signals are also possible. As discussed below, in some implementations,

a detector array (or more than one detector array) may be used as the detectors 8130A, 8130B, 8130C.

[00212] Such a system 8000 may advantageously provide SHG data for a plurality of points or locations using the plurality of detectors 8130A, 8130B, 8130C, thereby increasing throughput. Additionally, the plurality of locations may be scanned to obtain SHG signals over a portion of the sample. For example, the plurality of beams 7122A, 7122B, 7122C may extend in a first direction, e.g., the x (or y) direction. These beams 7122A, 7122B, 7122C may be scanned in a second (possibly orthogonal) direction, e.g., y (or x) direction, to sample SHG signal levels over an area of the sample 4120. In addition or alternatively, the sample 4120 may be moved with respect to the light source 7108 and objective 7116 so as to provide further scanning of the regions of interrogation across the sample. In some implementations, for example, the scanner 7112 scans the plurality of beams 7122A, 7122B, 7122C in one direction dimension, e.g., x, and the sample stage 7140 scans the sample in another direction or dimension, e.g., y, or vice versa. In this manner, SHG images or maps of the distribution of SHG signal over an area on the sample 4120 can be obtained. Having the plurality of detectors 8130A, 8130B, 8130C may advantageously increase the efficiency or speed of data collection.

[00213] Accordingly, in various implementations, with systems such as illustrated in FIG. 22A, light from the laser light source (as well as the SHG signal) is split into multiple beams. The multiple beams can be scanned over separate regions in parallel. SHG signals produced by different beams of incident light may be detected by different channels (e.g., photomultiplier tube or PMT channels). A final image can be produced from the combination of data from the array or plurality of PMT detectors. Fast scan speeds can thus be achieved by using multi-beam scanning setup with signals collected from multiple channels simultaneously.

[00214] Accordingly, in various implementations, fast scanning of either the laser beam or wafer (or both) can be used to form two-dimensional imaging of the SHG signal over an areas or areas of the sample. Point-to-point mapping of the SHG signal from different locations (e.g., x, y locations) can be generated, which can provide a spatial distribution of physical parameters (such as, for example, charge density, strain, interface states) related to the SHG signal.

[00215] A wide range of variations are possible, for example, instead of one light source, one beamsplitter, one scanner, one dichroic mirror and one objective, more

than one of any of these components may be included in the system 8000. Additionally, the components may be located differently. For example, as shown in FIG. 23B, the dichroic mirror 7114 may be disposed between the objective 7116 and the scanner 7112 such that the SHG signals received from the objective are incident on the dichroic mirror. Additionally, optical fiber or integrated optical components (e.g., waveguide-based components) may be used in the SHG interrogation system 8000. Also, one or more detector arrays (e.g., CCD arrays) may be used in place of the plurality of detectors 8130A, 8130B, 8130C. For example, different regions of the detector array may collect different SHG signals produced by respective beams 7122A, 7122B, 7122C incident on the sample 4120. In some implementations, the SHG signal for a particular one of the incident beams 7122A, 7122B, 7122C may be obtained by integration across the respective region on the detector array. Additionally, any of the components, features, and/or methods or techniques disclosed elsewhere herein may be employed. For example, one or more polarization beamsplitters may be used to simultaneously collect light of first and second polarization states such as s- and p- polarization components. See for example FIG. 21 and the associated discussion.

[00216] FIG. 23 shows another system 10000 for producing SHG images of an area of a sample 4120. This SHG imaging system 10000 employs imaging optics 10114 to image the sample 4120 or an area of the sample and/or project the SHG signals associated with an area of a sample onto a detector array 10116 to form SHG images.

[00217] As with other SHG systems discussed herein, the system 10000 shown in FIG. 23 includes a light source (e.g., a laser light source) 10110 configured to output light that can be directed to the sample 4120 that is supported on a sample stage 4140 to produce second harmonic generation from the sample 4120. As with other systems described herein, the sample stage 4140 may include a translation stage such as an x-y translation stage 4118 and/or a rotation stage 4116.

[00218] The system 8000 shown in FIG. 23 additionally includes optional focusing optics 10112 to focus light from the light source 10110 onto a location on the sample 4120. The focusing optics may comprise, for example, one or more lenses or mirrors in some implementations.

[00219] The system 8000 shown in FIG. 23 also includes projection optics 10112 configured to collect light, for example, second harmonic generated light from the

sample 4120. The projection optics 10112 may comprise, for example, one or more lenses or mirrors in some implementations.

[00220] The system 8000 shown in FIG. 23 includes a detector array 10116 disposed to receive second harmonic generation light from the sample 4120. The detector array or pixelated detector 10116 comprises a plurality of detectors or pixels. Electrical signals produced by the pixels of the detector array can be processed to form an image or map of intensity levels of the optical signal received by the pixels. The detector array 10116 may comprise, for example, a charge coupled detector (CCD) array, in some implementations, although other types of detector arrays may possibly be used. The detector array 10116 may also comprise a time dependent integration based device in certain implementations. Integrating signal over time may provide for increased signal measurements.

[00221] In some implementations, the projection optics 10112 comprises imaging optics such as one or more optical element with optical power. The imaging optics 10112 may comprise, for example, such as one or more lenses, one or more mirror or combinations thereof. In some implementations, for example, the detector array 10116 is located at a conjugate plane (e.g., image plane) of the sample (which may be at a corresponding object plane). Accordingly, in some implementations, the sample 4120 (or at least an image formed by SHG light emanating from different locations on the sample) is imaged onto the detector array 10116. The SHG light is produced by the illumination of the sample with the laser light and may extend over a region of the sample or spot on the sample illuminated by the incident laser beam.

[00222] Accordingly, in various implementations, SHG signals from different locations on the sample 4120 are mapped onto different locations on the detector array 10116. The SHG signals at the different locations may be produced by light from the laser source 10110 incident on different locations of the sample 4120. Accordingly, the detector array 10116 can measure the SHG signal at different locations on the sample 4120 and produce an image or map of the distribution of SHG signals on the sample.

[00223] In some implementations, the sample is translated with respect to the laser light source and projection optics to provide imaging over a wider area of the sample. Similarly, the laser and projection optics (and detector) could be translated with respect to the sample to provide imaging over a wider area of the sample. Additionally, time integration may be used to increase the signal levels measured.

[00224] Accordingly, in various implementations, the laser beam may remain still and the sample (e.g., wafer) is translated while an SHG signal is projected onto the pixelated detector. Time dependent integration may be employed in some implementations to increase the signal level measured. Different pixel elements from the detector can record the local SHG signal from the spatial location on the wafer surface conjugated to the corresponding pixel on the detector array.

[00225] A wide range of variations are possible, for example, instead of one light source 10110, one detector array 10116, one set of focusing optics 10112, or one set of projection optics 10114, more than one of any of these components may be included in the system 8000. Additionally, any of the components, features, and/or methods or techniques disclosed elsewhere herein may be employed. For example, one or more polarization beamsplitters may be used to simultaneously collect light of first and second polarization states such as s- and p- polarization components. See for example FIG. 21 and the associated discussion.

[00226] VARIATIONS

[00227] Example invention embodiments, together with details regarding a selection of features have been set forth above. As for other details, these may be appreciated in connection with the above-referenced patents and publications as well as is generally known or appreciated by those with skill in the art. The same may hold true with respect to method-based aspects of the invention in terms of additional acts as commonly or logically employed. Regarding such methods, including methods of manufacture and use, these may be carried out in any order of the events which is logically possible, as well as any recited order of events. Furthermore, where a range of values is provided, it is understood that every intervening value, between the upper and lower limit of that range and any other stated or intervening value in the stated range is encompassed within the invention. Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein.

[00228] As used herein, a phrase referring to "at least one of" a list of items refers to any combination of those items, including single members. As an example, "at least one of: a, b, or c" is intended to cover: a, b, c, a-b, a-c, b-c, and a-b-c.

[00229] Though the invention embodiments have been described in reference to several examples, optionally incorporating various features, they are not to be limited

to that which is described or indicated as contemplated with respect to each such variation. Changes may be made to any such invention embodiment described and equivalents (whether recited herein or not included for the sake of some brevity) may be substituted without departing from the true spirit and scope hereof. Certain features that are described in this specification in the context of separate implementations also can be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation also can be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[00230] The various illustrative processes described may be implemented or performed with a general purpose processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. The processor can be part of a computer system that also has a user interface port that communicates with a user interface, and which receives commands entered by a user, has at least one memory (e.g., hard drive or other comparable storage, and random access memory) that stores electronic information including a program that operates under control of the processor and with communication via the user interface port, and a video output that produces its output via any kind of video output format, e.g., VGA, DVI, HDMI, DisplayPort, or any other form.

[00231] A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. These devices may also be used to select values for devices as described herein.

[00232] The steps of a method or algorithm described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software

module executed by a processor, or in a combination of the two. A software module may reside in Random Access Memory (RAM), flash memory, Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An example storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an ASIC. The ASIC may reside in a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a user terminal.

[00233] In one or more example embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on, transmitted over or resulting analysis/calculation data output as one or more instructions, code or other information on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. The memory storage can also be rotating magnetic hard disk drives, optical disk drives, or flash memory based storage drives or other such solid state, magnetic, or optical storage devices.

[00234] Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and Blu-ray disc where disks usually reproduce data

magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

[00235] Operations as described herein can be carried out on or over a website. The website can be operated on a server computer, or operated locally, e.g., by being downloaded to the client computer, or operated via a server farm. The website can be accessed over a mobile phone or a PDA, or on any other client. The website can use HTML code in any form, e.g., MHTML, or XML, and via any form such as cascading style sheets ("CSS") or other.

[00236] Also, the inventors hereof intend that only those claims which use the words "means for" are to be interpreted under 35 USC 112, sixth paragraph. Moreover, no limitations from the specification are intended to be read into any claims, unless those limitations are expressly included in the claims. The computers described herein may be any kind of computer, either general purpose, or some specific purpose computer such as a workstation. The programs may be written in C, or Java, Brew or any other programming language. The programs may be resident on a storage medium, e.g., magnetic or optical, e.g. the computer hard drive, a removable disk or media such as a memory stick or SD media, or other removable medium. The programs may also be run over a network, for example, with a server or other machine sending signals to the local machine, which allows the local machine to carry out the operations described herein.

[00237] It is also noted that all features, elements, components, functions, acts and steps described with respect to any embodiment provided herein are intended to be freely combinable and substitutable with those from any other embodiment. If a certain feature, element, component, function, or step is described with respect to only one embodiment, then it should be understood that that feature, element, component, function, or step can be used with every other embodiment described herein unless explicitly stated otherwise. This paragraph therefore serves as antecedent basis and written support for the introduction of claims, at any time, that combine features, elements, components, functions, and acts or steps from different embodiments, or that substitute features, elements, components, functions, and acts or steps from one embodiment with those of another, even if the following description does not explicitly state, in a particular instance, that such combinations or substitutions are possible. It is explicitly acknowledged that express recitation of every possible combination and substitution is overly burdensome, especially given that the

permissibility of each and every such combination and substitution will be readily recognized by those of ordinary skill in the art.

[00238] In some instances entities are described herein as being coupled to other entities. It should be understood that the terms "interfit", “coupled” or “connected” (or any of these forms) may be used interchangeably herein and are generic to the direct coupling of two entities (without any non-negligible, e.g., parasitic, intervening entities) and the indirect coupling of two entities (with one or more non-negligible intervening entities). Where entities are shown as being directly coupled together, or described as coupled together without description of any intervening entity, it should be understood that those entities can be indirectly coupled together as well unless the context clearly dictates otherwise.

[00239] Reference to a singular item includes the possibility that there are a plurality of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "an," "said," and "the" include plural referents unless specifically stated otherwise. In other words, use of the articles allow for "at least one" of the subject item in the description above as well as the claims below.

[00240] It is further noted that the claims may be drafted to exclude any optional element (e.g., elements designated as such by description herein a "typical," that "can" or "may" be used, etc.). Accordingly, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or other use of a "negative" claim limitation language. Without the use of such exclusive terminology, the term "comprising" in the claims shall allow for the inclusion of any additional element -- irrespective of whether a given number of elements are enumerated in the claim, or the addition of a feature could be regarded as transforming the nature of an element set forth in the claims. Yet, it is contemplated that any such "comprising" term in the claims may be amended to exclusive-type "consisting" language. Also, except as specifically defined herein, all technical and scientific terms used herein are to be given as broad a commonly understood meaning to those skilled in the art as possible while maintaining claim validity.

[00241] While the embodiments are susceptible to various modifications and alternative forms, specific examples thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that these embodiments are not to be limited to the particular form disclosed, but to the contrary, these

embodiments are to cover all modifications, equivalents, and alternatives falling within the spirit of the disclosure. Furthermore, any features, functions, acts, steps, or elements of the embodiments may be recited in or added to the claims, as well as negative limitations (as referenced above, or otherwise) that define the inventive scope of the claims by features, functions, steps, or elements that are not within that scope. Thus, the breadth of the inventive variations or invention embodiments are not to be limited to the examples provided, but only by the scope of the following claim language. That being said, we claim:

What is Claimed:

1. A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

an optical source configured to direct a light beam onto said sample so as to produce second harmonic generation;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprises first and second detectors;

a polarization beamsplitter disposed in an optical path between said sample and said optical detection system so as to receive second harmonic generated light from said sample, said polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to said first and second detectors, respectively; and

processing electronics configured to receive signals from said first and second detectors based on said received first and second polarization components.

2. The system of Claim 1, wherein said first and second polarization components comprise orthogonal polarizations states.

3. The system of Claims 1 or 2, wherein said first and second polarization components comprise linearly polarized light oriented in different polarization directions.

4. The system of any of the claims above, wherein said first and second polarization components are s and p polarizations, respectively.

5. The system of any of the claims above, wherein said polarization beamplitter comprises a polarization beamsplitter cube.

6. The system of any of the claims above, further comprising a polarizer disposed in an optical path between said light source and said sample such that polarized light is directed to said sample.

7. The system of Claim 6, wherein said polarizer disposed in said optical path between said light source and said sample comprises a linear polarizer.

8. The system of any of the claims above, further comprising a focusing lens disposed between the light source and the sample to focus light from the light source onto the sample.

9. The system of any of the claims above, further comprising a collimating lens disposed between the sample the polarization beamsplitter to collimate second harmonic generated light from the sample.

10. The system of any of the claims above, wherein said sample holder comprise a translation stage.

11. A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

an optical source configured to direct a light beam onto said sample to produce second harmonic generation;

a beamsplitter disposed in an optical path between said light source and said sample, said beamsplitter configured to separate said light from said light source into a plurality of beams that are incident at a plurality of locations on said sample at a one time such that said plurality of beams produce a plurality of second harmonic generation signals;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprising a plurality of detectors, respective ones of said plurality of beams from said beam splitter configured to produce respective SHG signals that are directed to respective ones of said plurality of detectors; and

processing electronics configured to receive signals from said plurality of detectors.

12. The system of Claim 11, wherein said beamsplitter comprises a diffractive beamsplitter configured to receive one beam and split said beam into a plurality of beams.

13. The system of any of the claims above, wherein said beamsplitter comprises an acousto-optic modulator configured to receive one beam and split said beam into a plurality of beams.

14. The system of any of the claims above, wherein said beamsplitter is configured to separate an input beam into at least three output beams that are directed onto the sample.

15. The system of any of the claims above, wherein said beamsplitter is configured to separate an input beam into at least five output beams that are directed onto the sample.

16. The system of any of the claims above, wherein said beamsplitter is configured to separate an input beam into at least ten output beams that are directed onto the sample.

17. The system of any of the claims above, wherein said plurality of detectors comprises three detectors.

18. The system of any of the claims above, wherein said plurality of detectors comprises five detectors.

19. The system of any of the claims above, wherein said plurality of detectors comprises ten detectors.

20. The system of any of the claims above, further comprising a dichroic reflector in an optical path between the beamsplitter and the sample to receive said SHG signals from the sample and direct said SHG signals to respective ones of said plurality of detectors.

21. The system of any of the claims above, wherein said sample holder comprises a translation stage.

22. The system of any of the claims above, further comprising a beam scanning system configured to scan said plurality of beams.

23. The system of any of the claims above, further comprising at least one polarization beamsplitter disposed so as to receive second harmonic generated light from said sample, said at least one polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detectors, respectively.

24. The system of any of the claims above, further comprising a plurality of polarization beamsplitters disposed so as to receive second harmonic generated light from said sample, said polarization beamsplitters configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detectors, respectively.

25. The system of Claims 23 or 24, wherein said first and second polarization components are s and p polarizations, respectively.

26. A system for characterizing a sample using second harmonic generation, the system comprising:

a sample holder configured to support a sample;

an optical source configured to direct a light beam onto said sample to produce second harmonic generation;

an optical detection system configured to receive second harmonic generated light from said sample, said optical detection system comprising at least one detector array;

projection optics configured to project second harmonic generation light from said sample onto said detector array; and

processing electronics configured to receive signals from said detector array.

27. The system of Claim 23, wherein said detector array comprises a 2-D array.

28. The system of any of the claims above, wherein said detector array comprises a CCD array.

29. The system of any of the claims above, wherein said detector array comprises a time dependent integration device.

30. The system of any of the claims above, wherein said projection optics is configured to image the sample onto said detector array.

31. The system of any of the claims above, wherein said projection optics comprises an imaging lens, said detector array being disposed at a conjugate image plane of said sample.

32. The system of any of the claims above, further comprising a focusing lens configured to focus light from said light source onto said sample.

33. The system of any of the claims above, further comprising a translation stage configured to translate said sample with respect to said light source and said detector array.

34. The system of Claim 33, wherein said translation stage comprises an x-y translation stage.

35. The system of any of the claims above, further comprising at least one polarization beamsplitter disposed so as to receive second harmonic generated light from said sample, said polarization beamsplitter configured to separate light into first and second polarization components and to direct said first and second polarization components to first and second detector arrays, respectively.

36. The system of Claim 35, wherein said first and second polarization components are s and p polarizations, respectively.

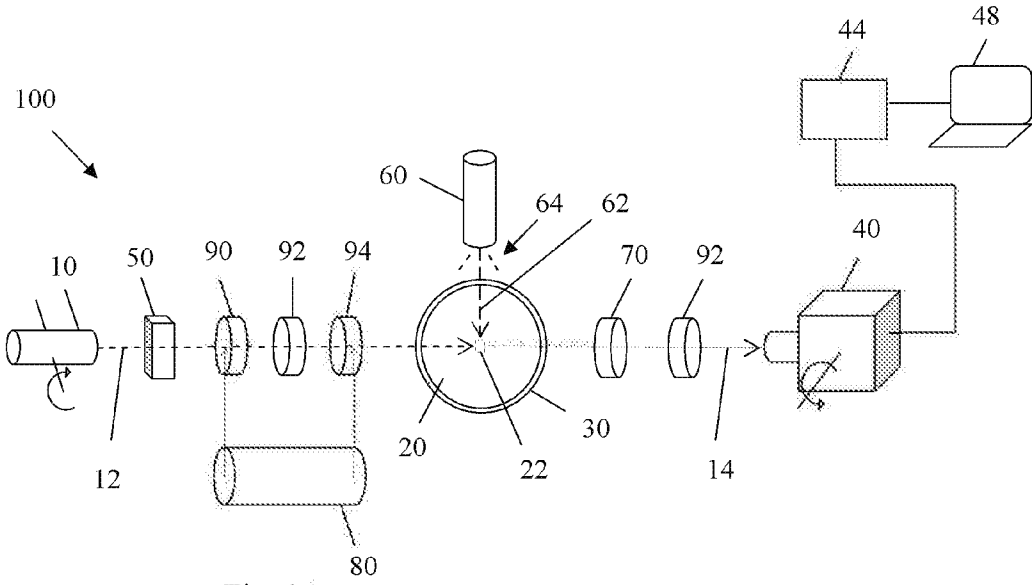


Fig. 1A

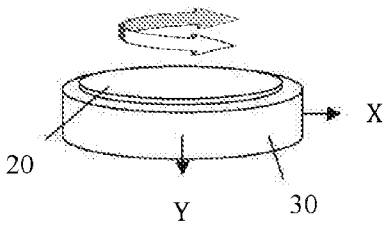


Fig. 1B

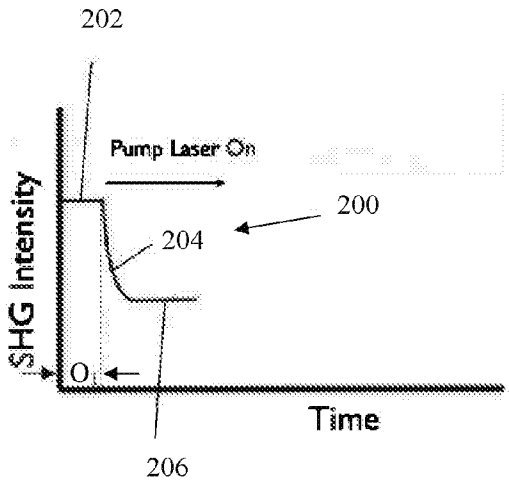


Fig. 2A

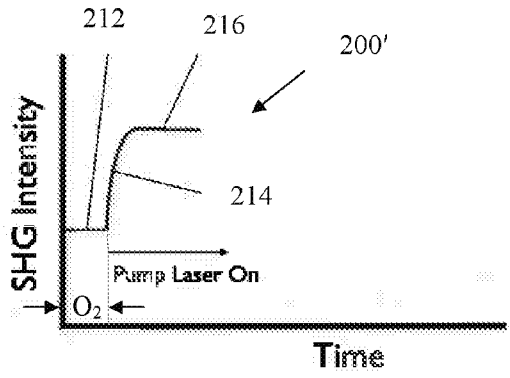


Fig. 2B

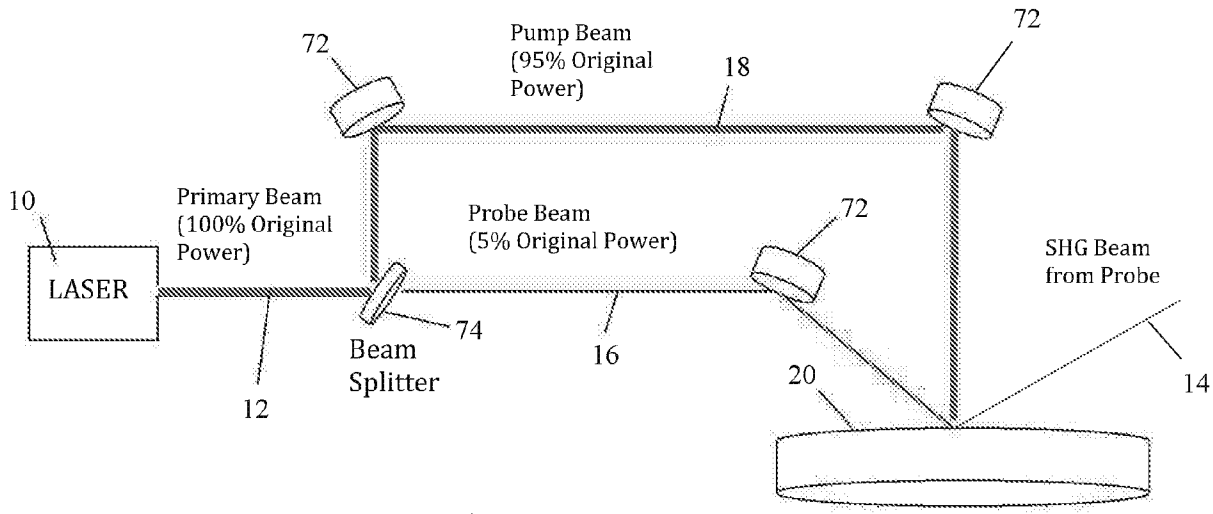

72
Pump Beam
(95% Original
Power)
18
72
10
Primary Beam
(100% Original
Power)
Probe Beam
(5% Original Power)
72
SHG Beam
from Probe
LASER
74
Beam
Splitter
16
20
14
12
Sample

Fig. 1C

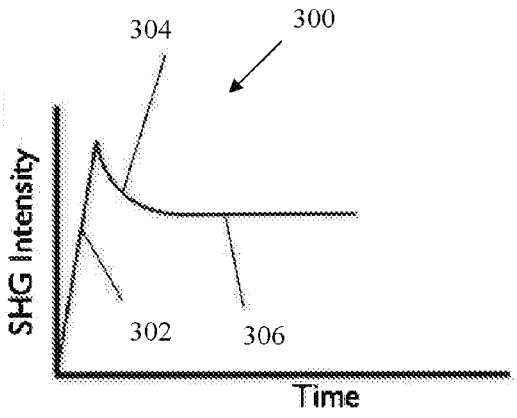


Fig. 3A

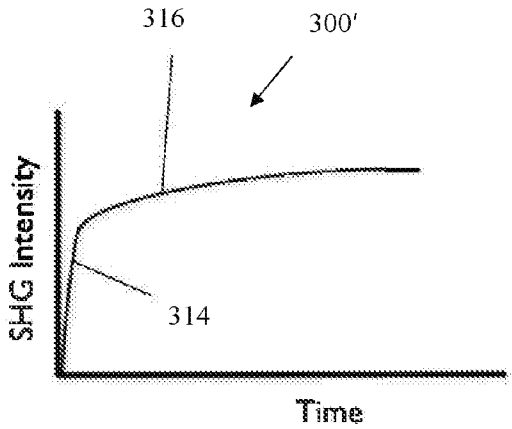


Fig. 3B

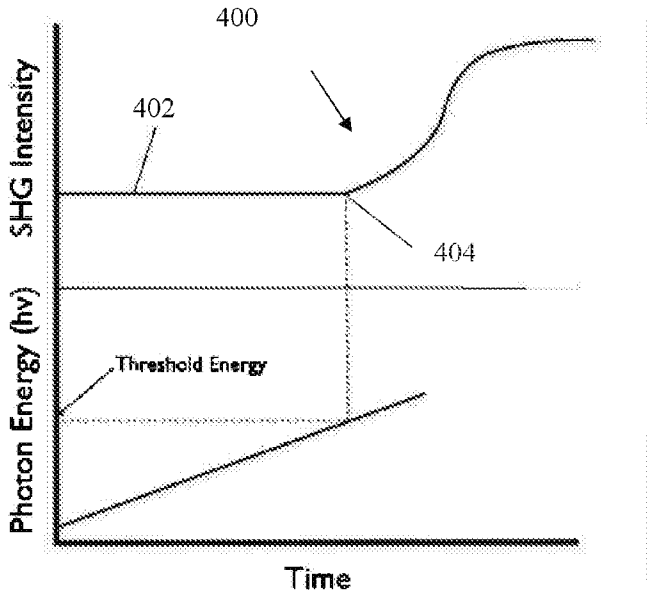


Fig. 4

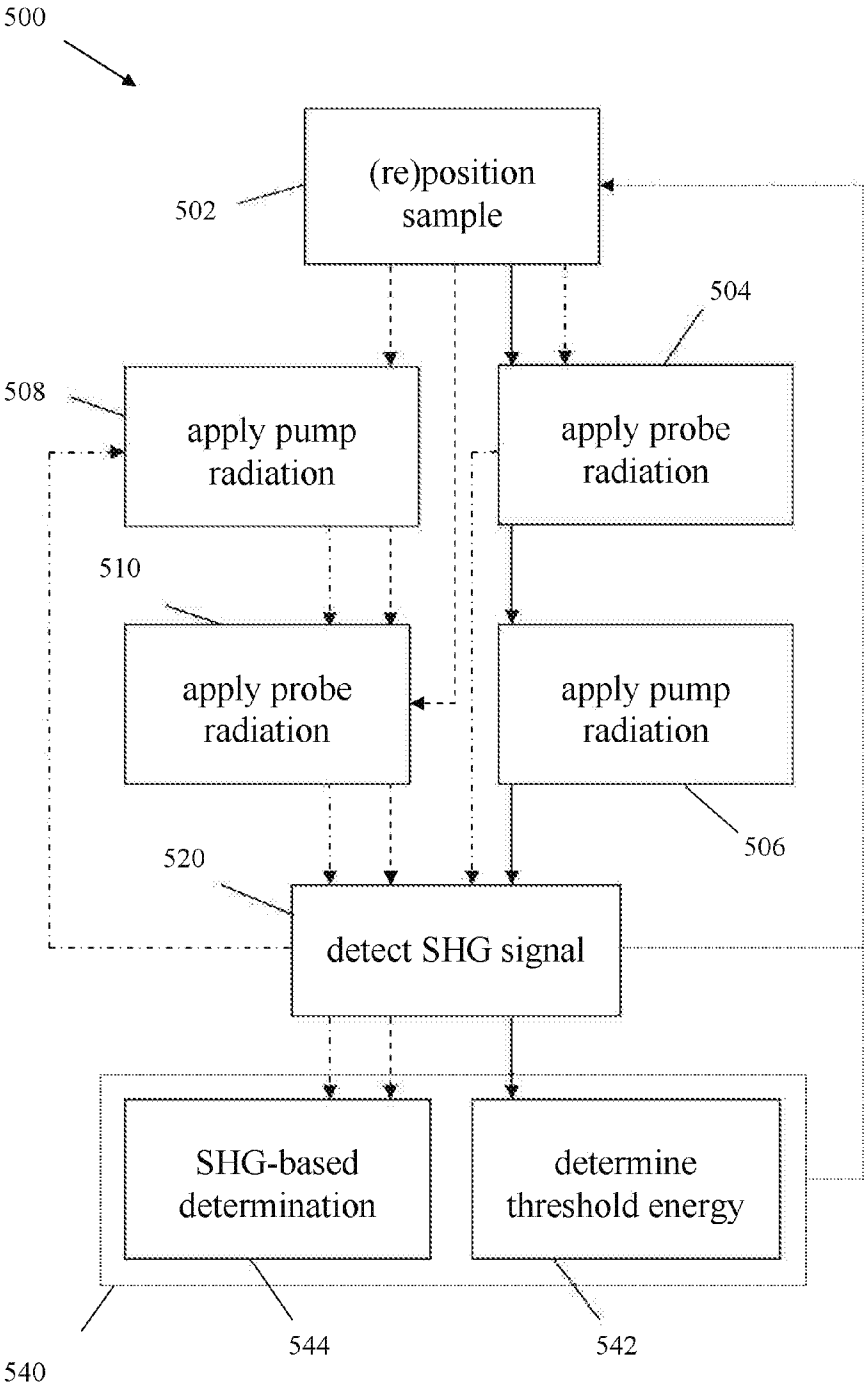

500
(re)position sample
502
504
508
apply pump radiation
apply probe radiation
510
apply probe radiation
apply pump radiation
506
520
detect SHG signal
SHG-based determination
determine threshold energy
544
542
540

Fig. 5

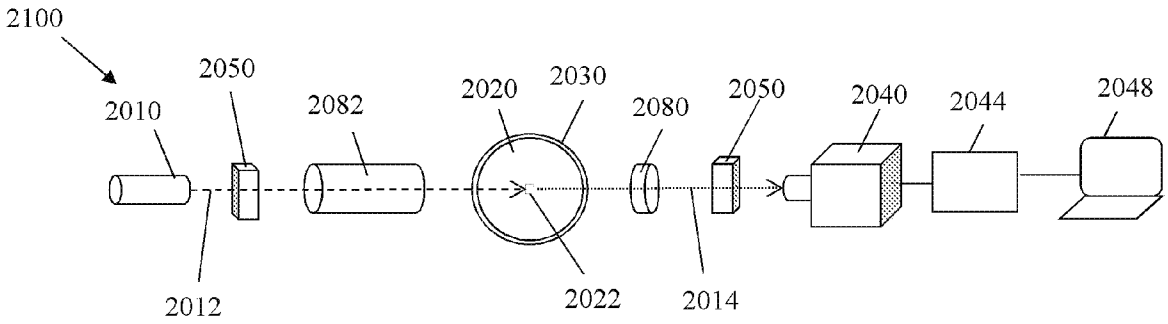

2100
2010
2050
2082
2020
2030
2080
2050
2040
2044
2048
2012
2022
2014

Fig. 6A

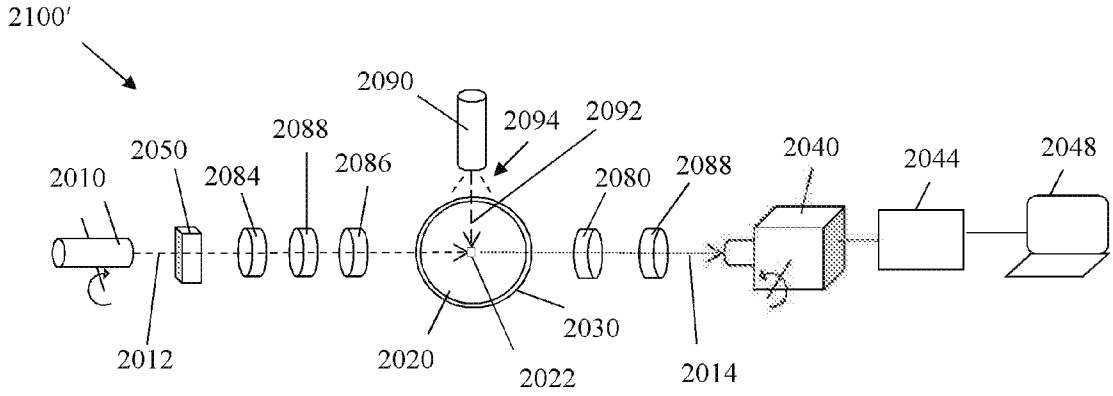

2100'
2090
2094
2092
2088
2050
2010
2084
2086
2080
2088
2040
2044
2048
2012
2020
2022
2030
2014

Fig. 6B

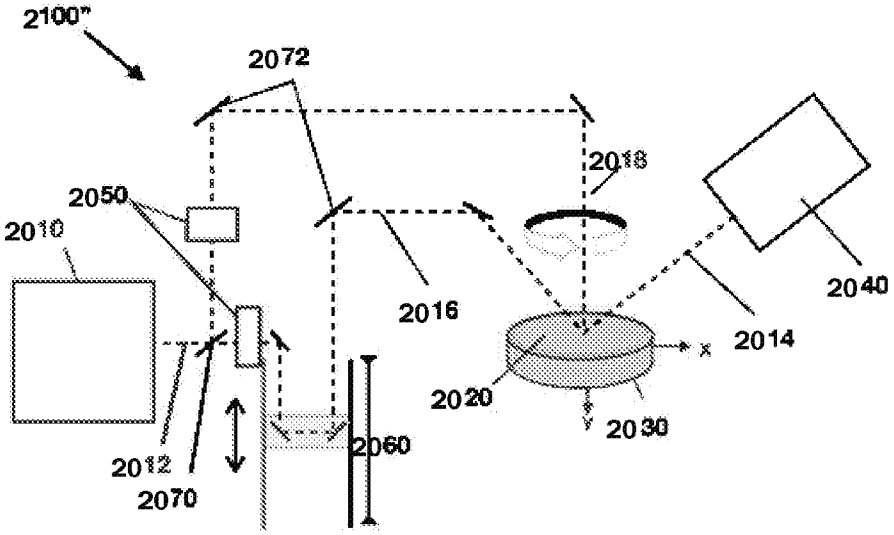

2100"
2072
2018
2050
2010
2016
2040
2014
2020
2030
2060
2012
2070

Fig. 6C

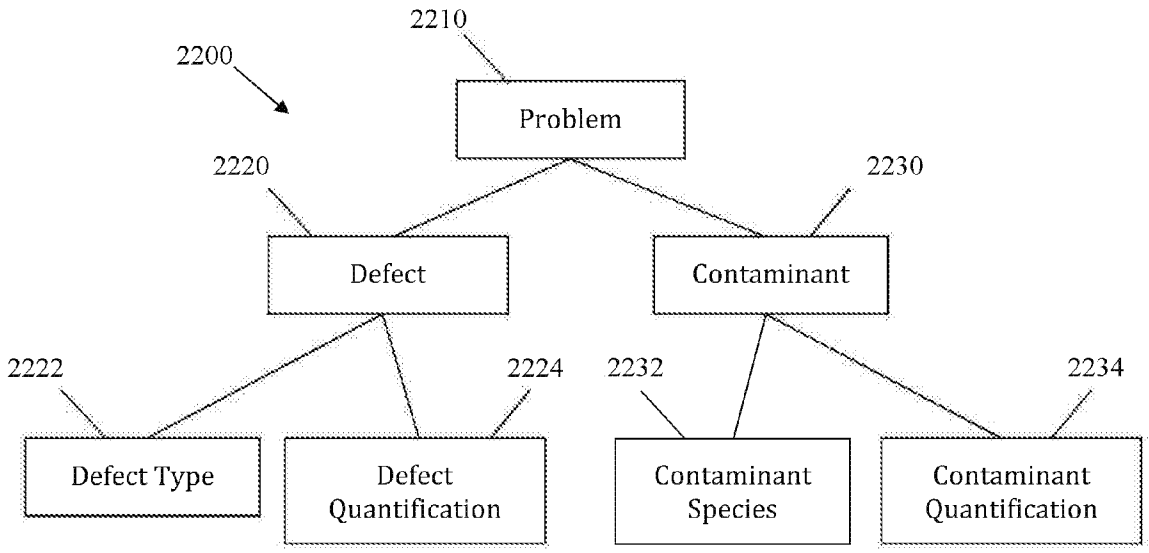

2210
2200
Problem
2220
2230
Defect
Contaminant
2222
2224
2232
2234
Defect Type
Defect Quantification
Contaminant Species
Contaminant Quantification

Fig. 7

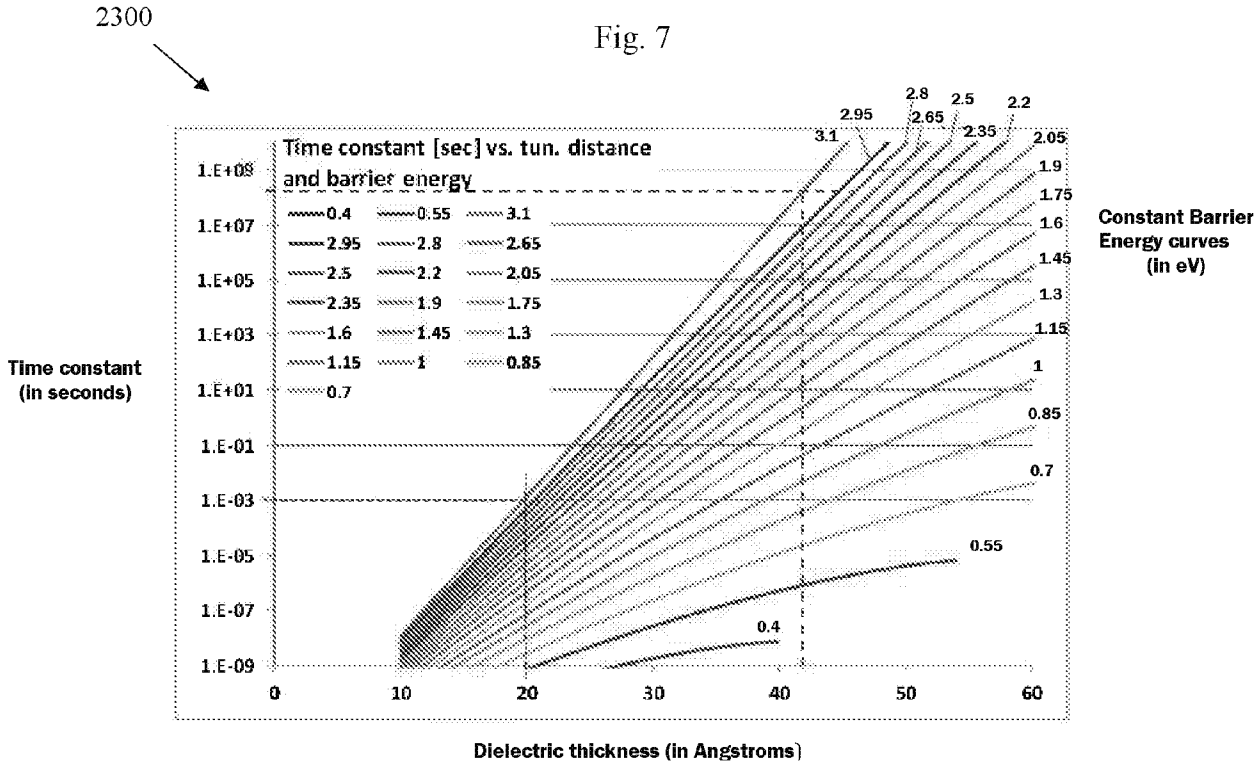

2300
Time constant [sec] vs. tun. distance and barrier energy
0.4 0.55 3.1
2.95 2.8 2.65
2.5 2.2 2.05
2.35 1.9 1.75
1.6 1.45 1.3
1.15 1 0.85
0.7
1.E+09
1.E+07
1.E+05
1.E+03
1.E+01
1.E-01
1.E-03
1.E-05
1.E-07
1.E-09
0
10
20
30
40
50
60
Time constant (in seconds)
Dielectric thickness (in Angstroms)
Constant Barrier Energy curves (in eV)

Fig. 8A

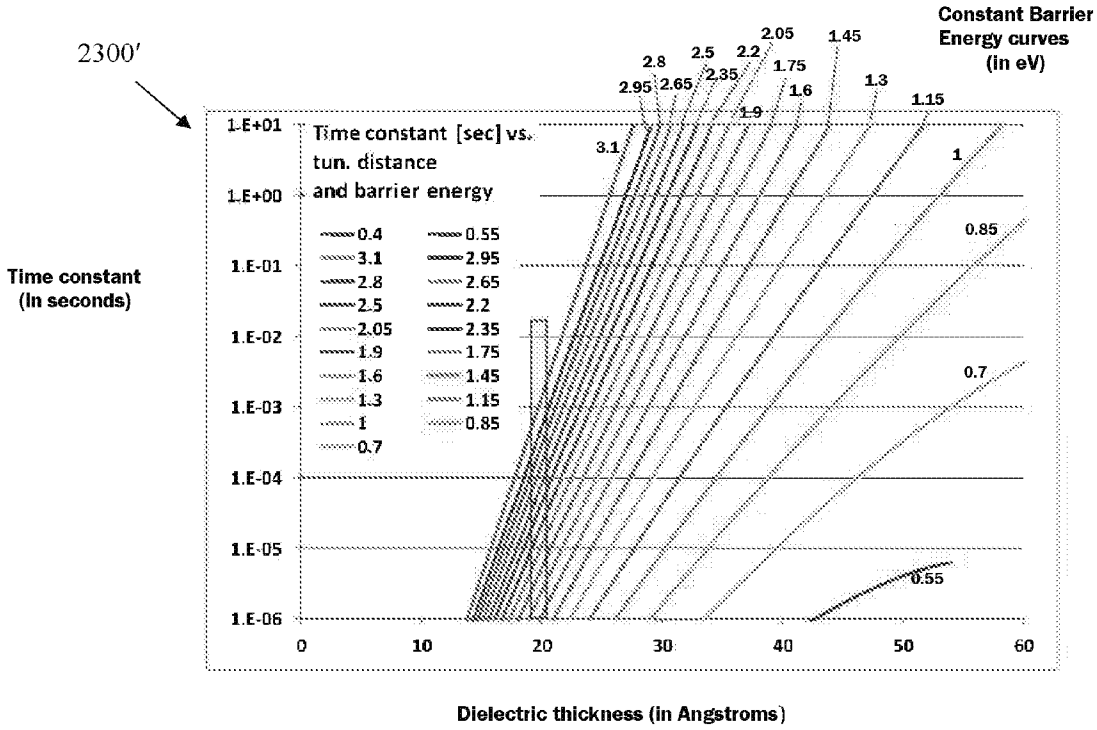

2300'
Constant Barrier Energy curves (in eV)
Time constant [sec] vs. tun. distance and barrier energy
Time constant (In seconds)
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
0.4
3.1
2.8
2.5
2.05
1.9
1.6
1.3
1
0.7
0.55
2.95
2.65
2.2
2.35
1.75
1.45
1.15
0.85
0
10
20
30
40
50
60
Dielectric thickness (in Angstroms)

Fig. 8B

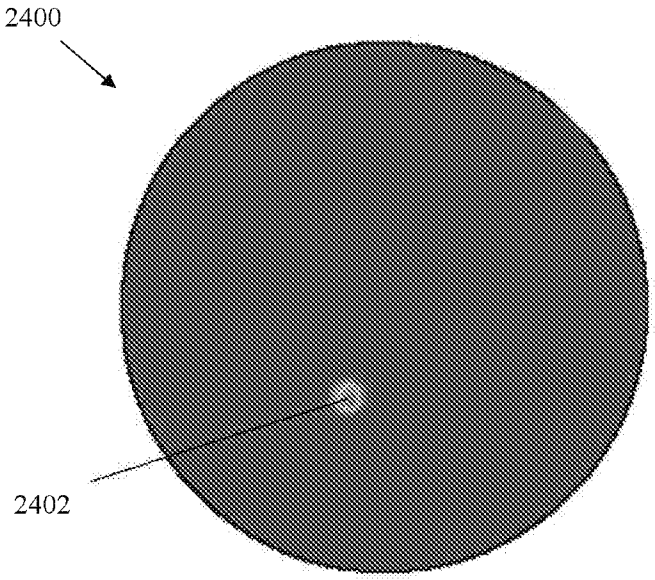

2400
2402

Fig. 9

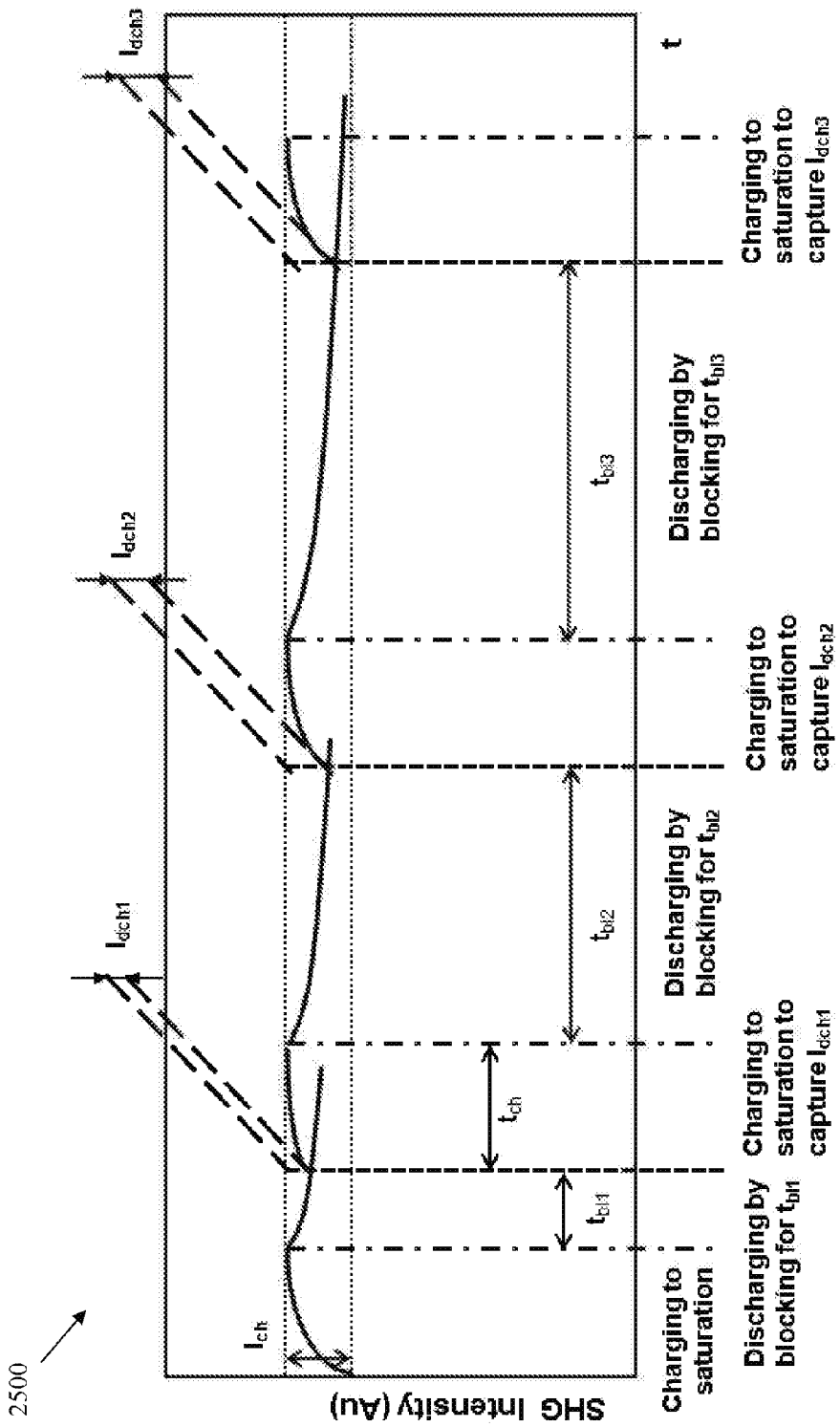

2500
SHG Intensity (Au)
t
I_{ch}
I_{dch1}
I_{dch2}
I_{dch3}
t_{ch}
t_{bl1}
t_{bl2}
t_{bl3}
Charging to saturation
Discharging by blocking for t_{bl1}
Charging to saturation to capture I_{dch1}
Discharging by blocking for t_{bl2}
Charging to saturation to capture I_{dch2}
Discharging by blocking for t_{bl3}
Charging to saturation to capture I_{dch3}

Fig. 10

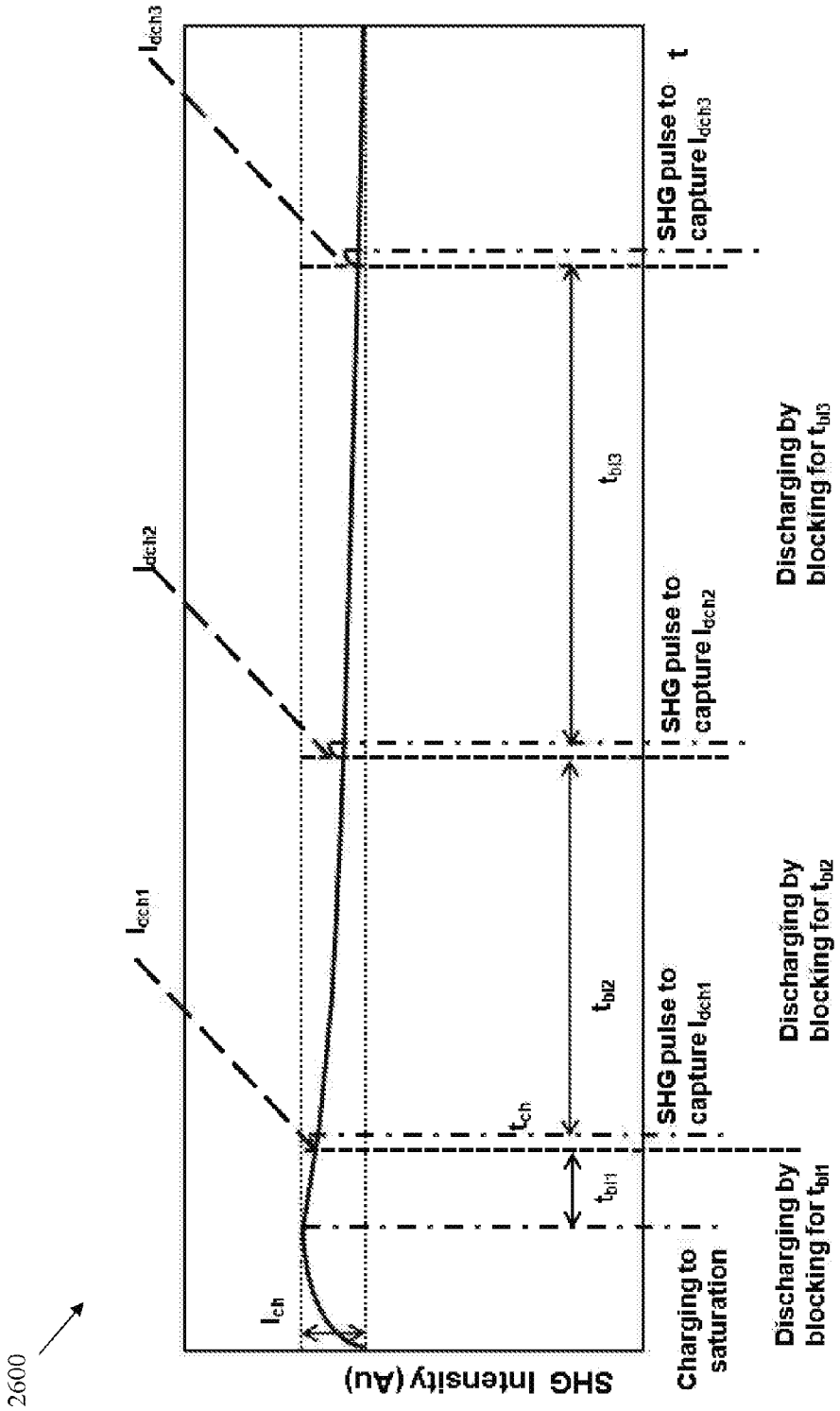

2600
SHG Intensity (Au)
t
I_{dch3}
I_{dch2}
I_{dch1}
I_{ch}
t_{ch}
t_{bl1}
t_{bl2}
t_{bl3}
Charging to saturation
Discharging by blocking for t_{bl1}
SHG pulse to capture I_{dch1}
Discharging by blocking for t_{bl2}
SHG pulse to capture I_{dch2}
Discharging by blocking for t_{bl3}
SHG pulse to capture I_{dch3}

Fig. 11

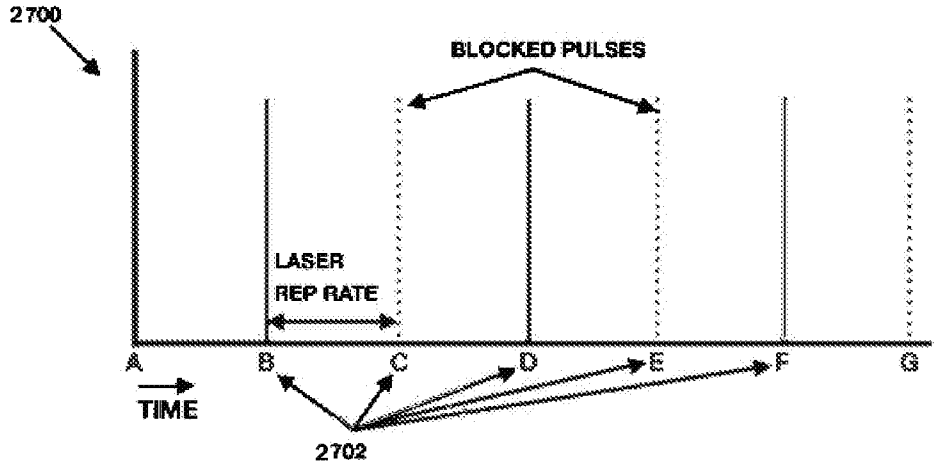


Fig. 12A

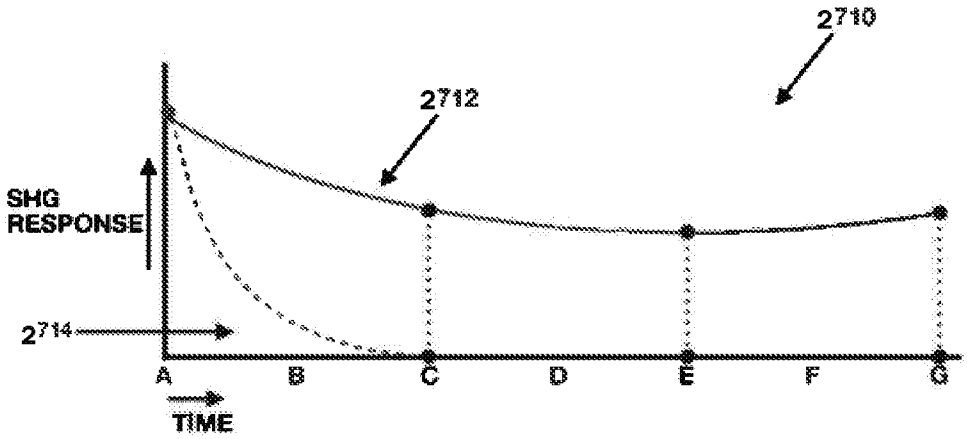


Fig. 12B

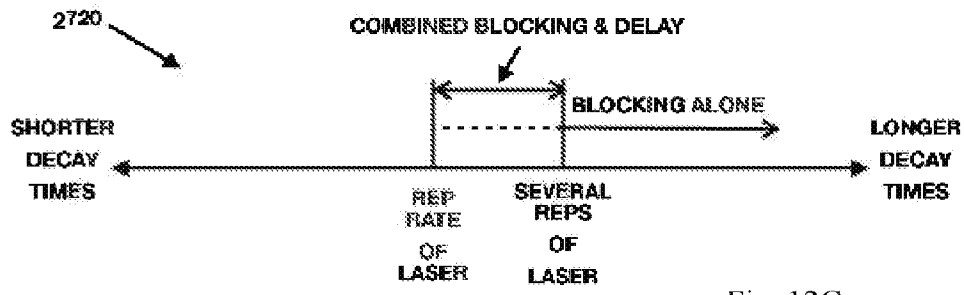


Fig. 12C

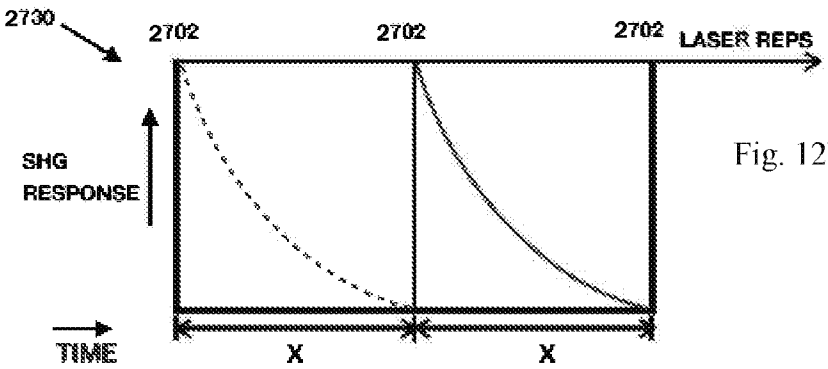


Fig. 12D

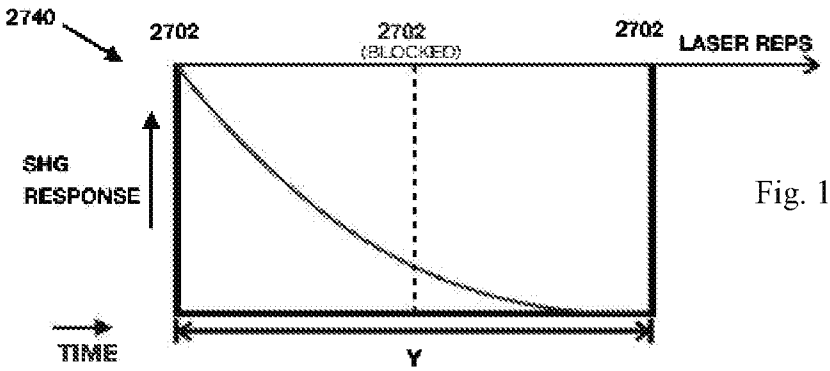


Fig. 12E

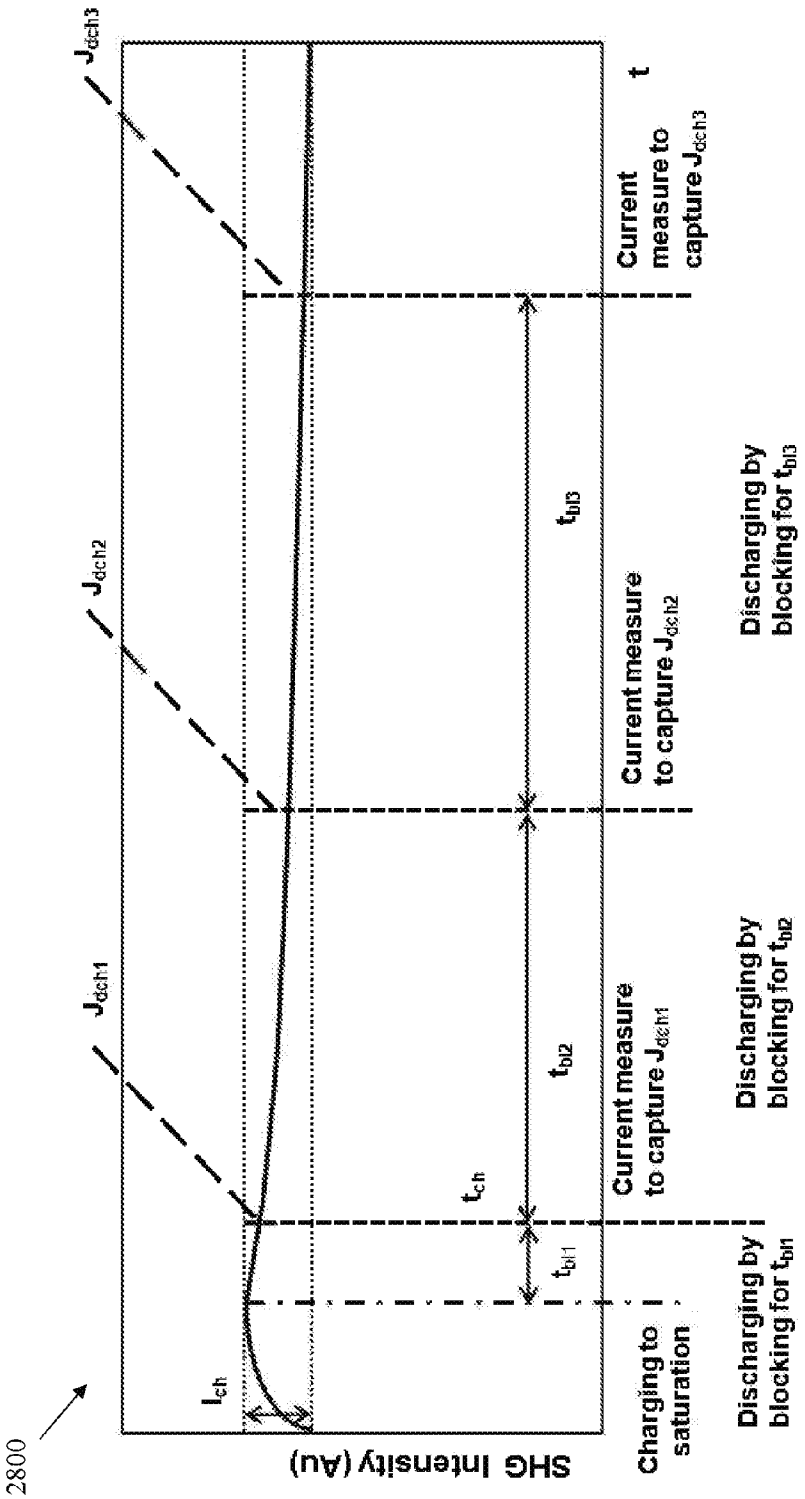

2800
SHG Intensity (Au)
t
J_{dch1}
J_{dch2}
J_{dch3}
I_{ch}
t_{ch}
t_{bl1}
t_{bl2}
t_{bl3}
Charging to saturation
Current measure to capture J_{dch1}
Discharging by blocking for t_{bl1}
Current measure to capture J_{dch2}
Discharging by blocking for t_{bl2}
Current measure to capture J_{dch3}
Discharging by blocking for t_{bl3}

Fig. 13

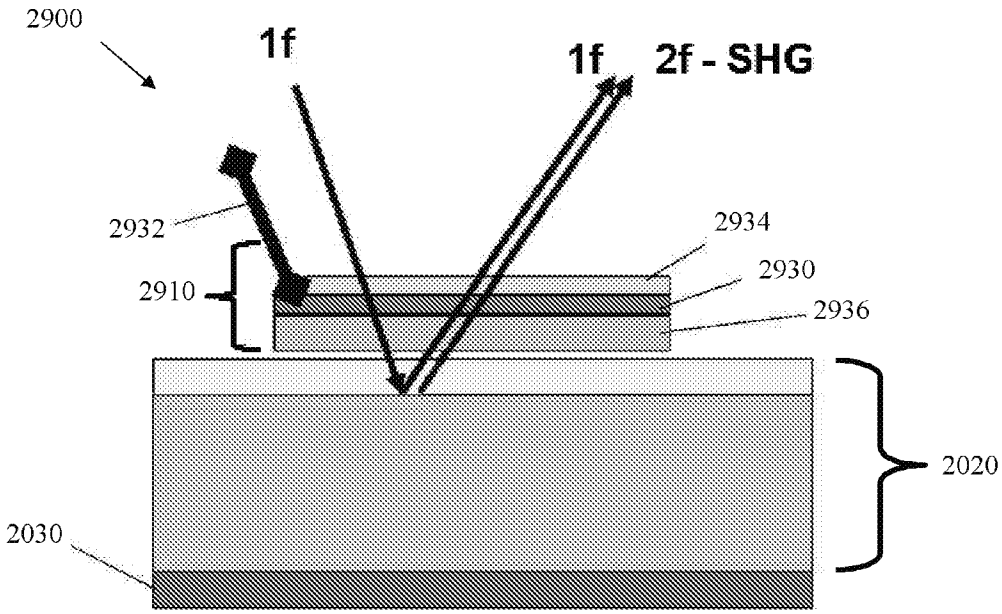


Fig. 14A

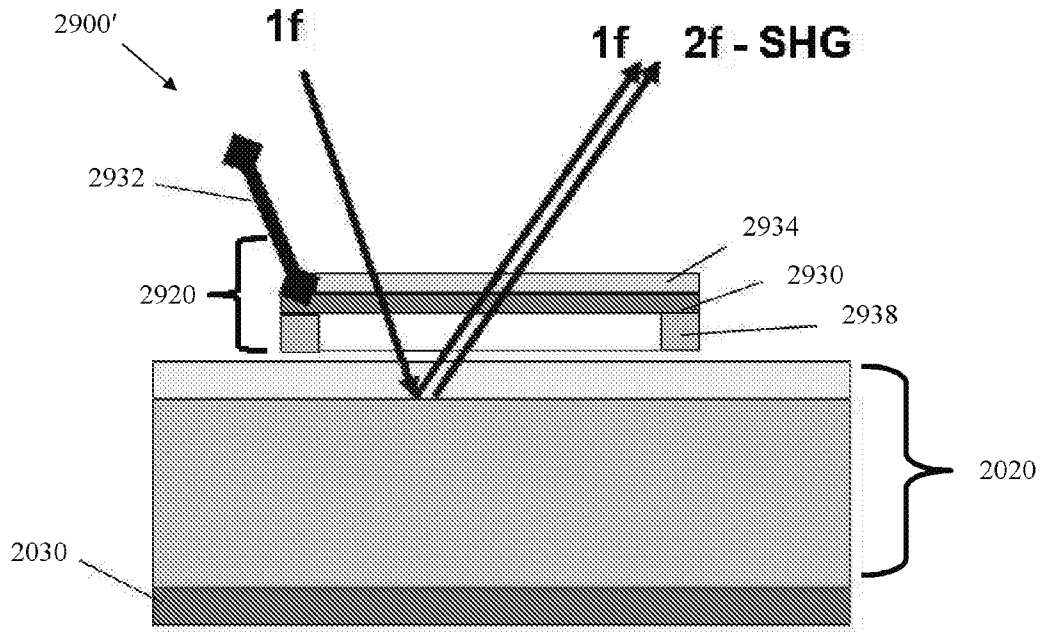


Fig. 14B

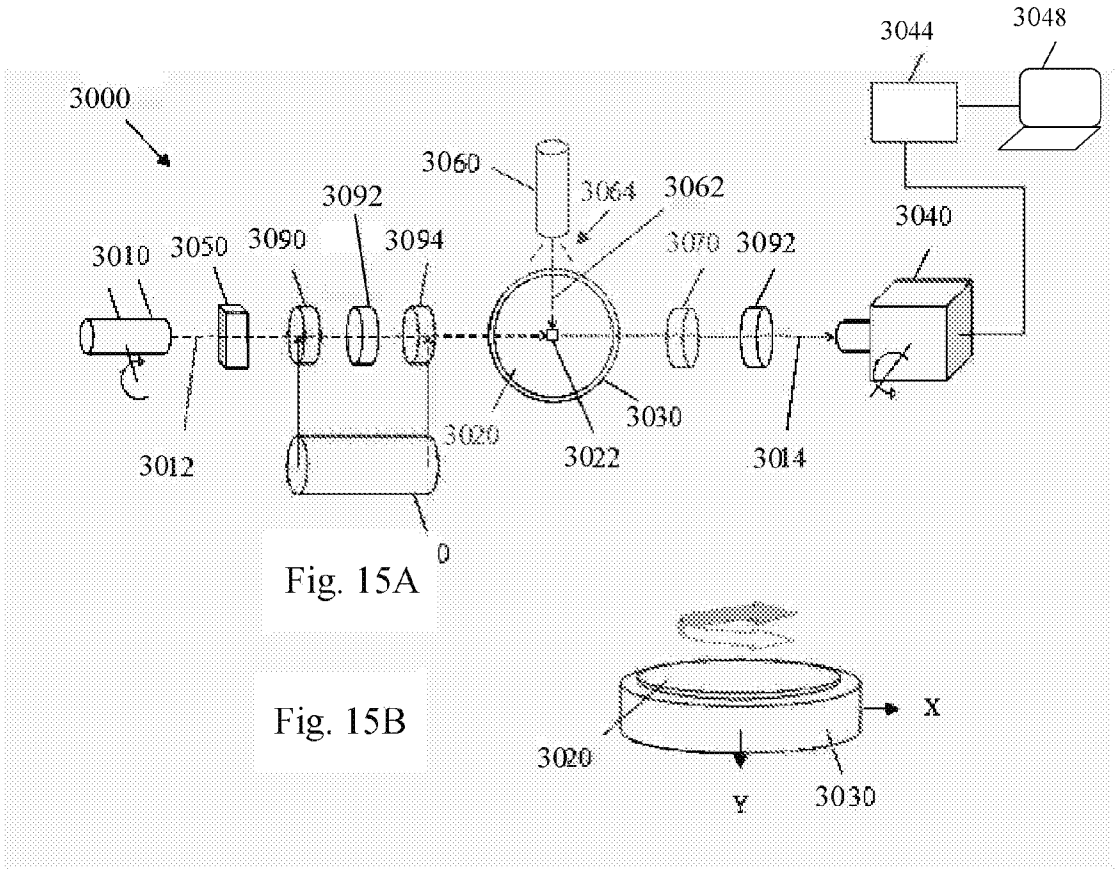


Fig. 15A

Fig. 15B

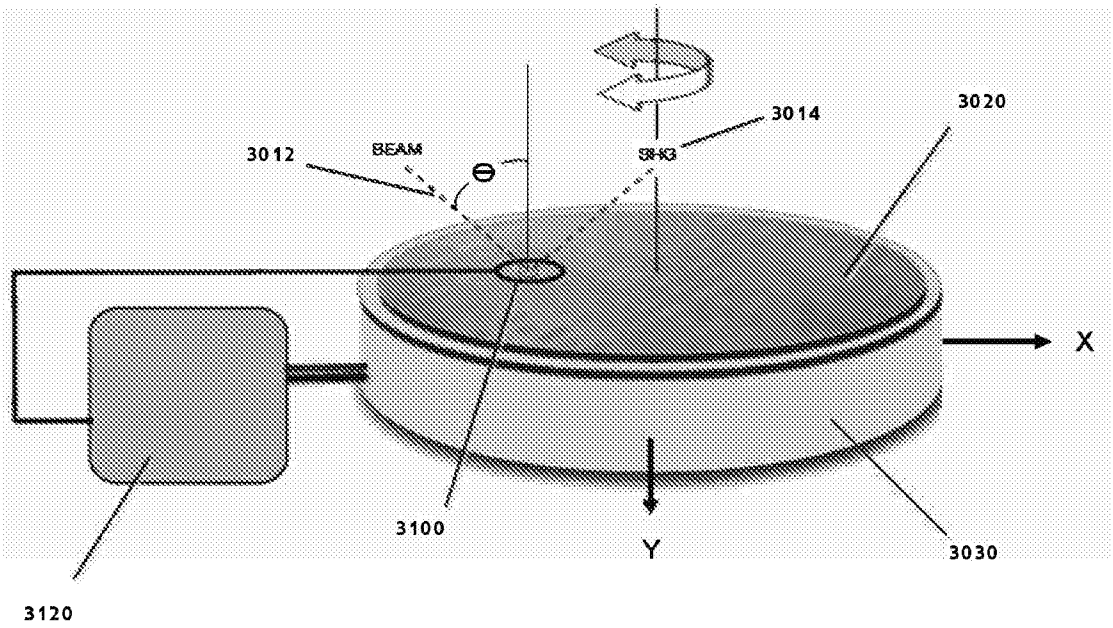


Fig. 16A

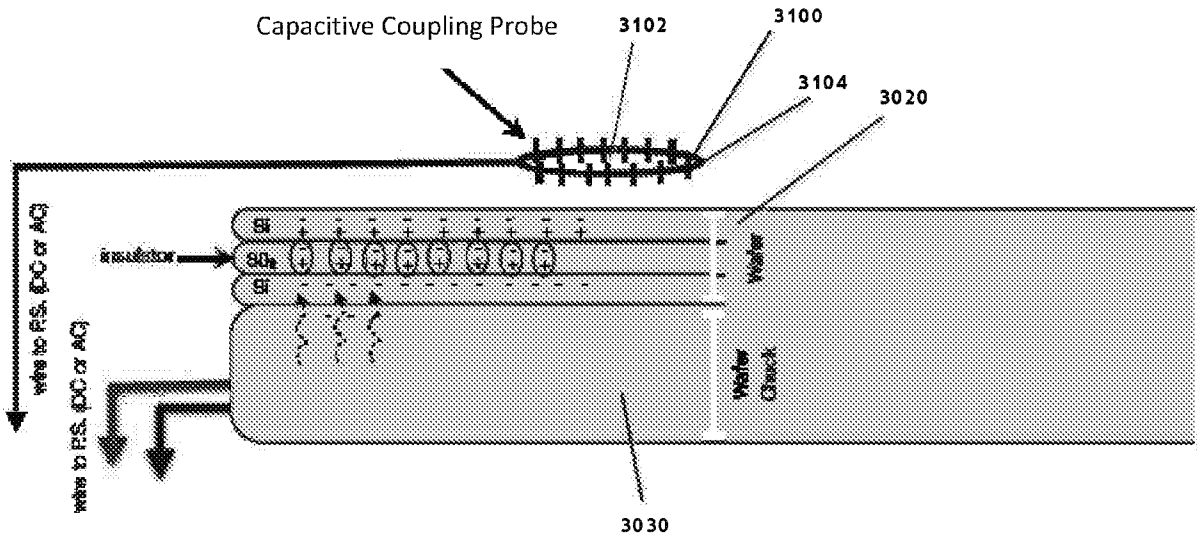


Fig. 16B

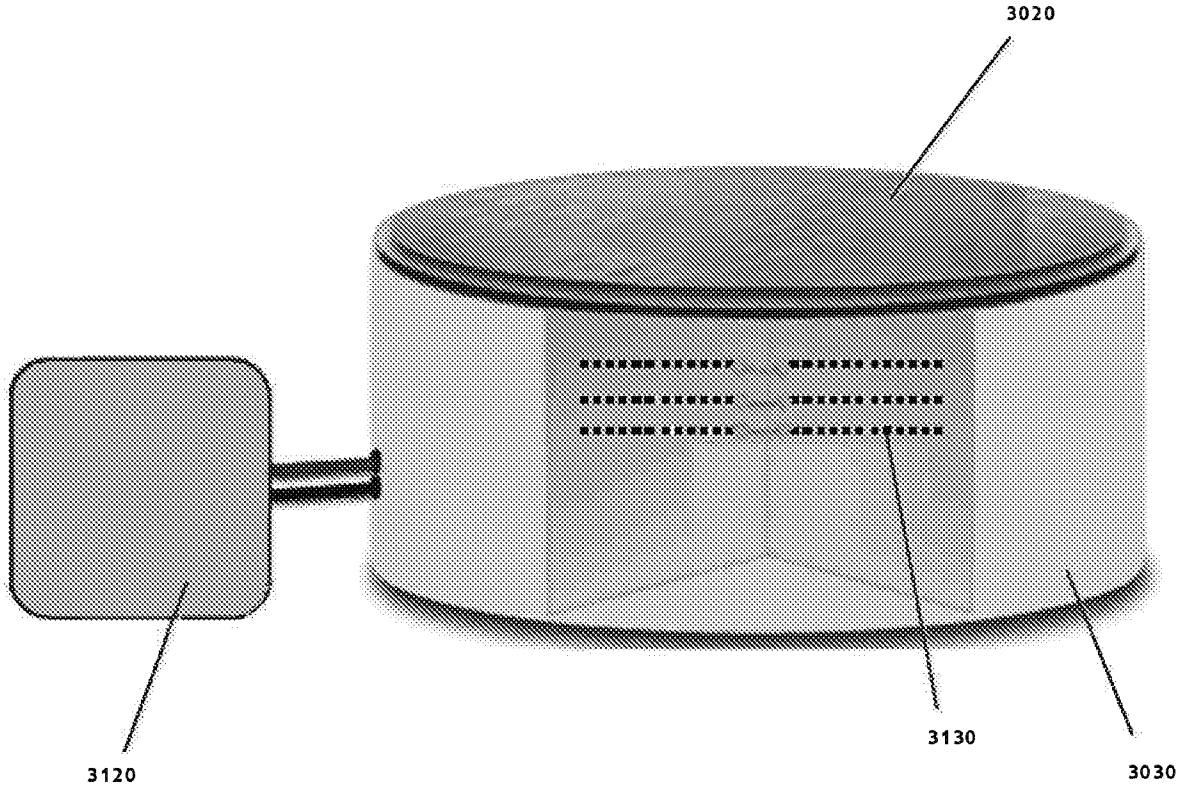


Fig. 17A

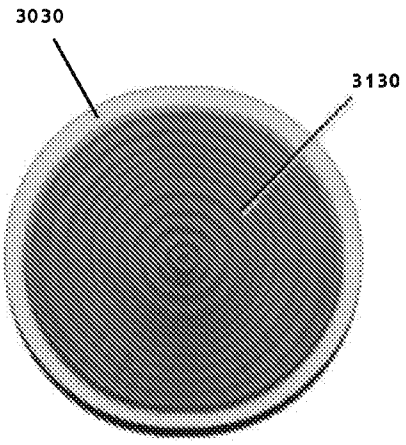


Fig. 17B

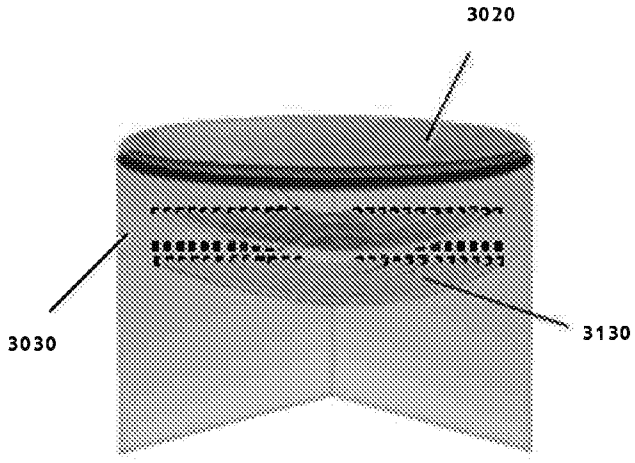


Fig. 17C

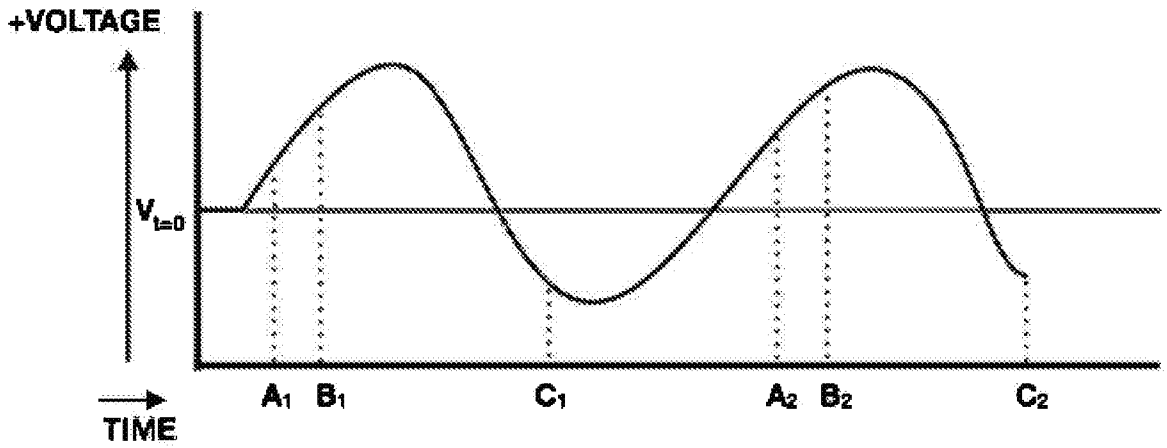


Fig. 18A

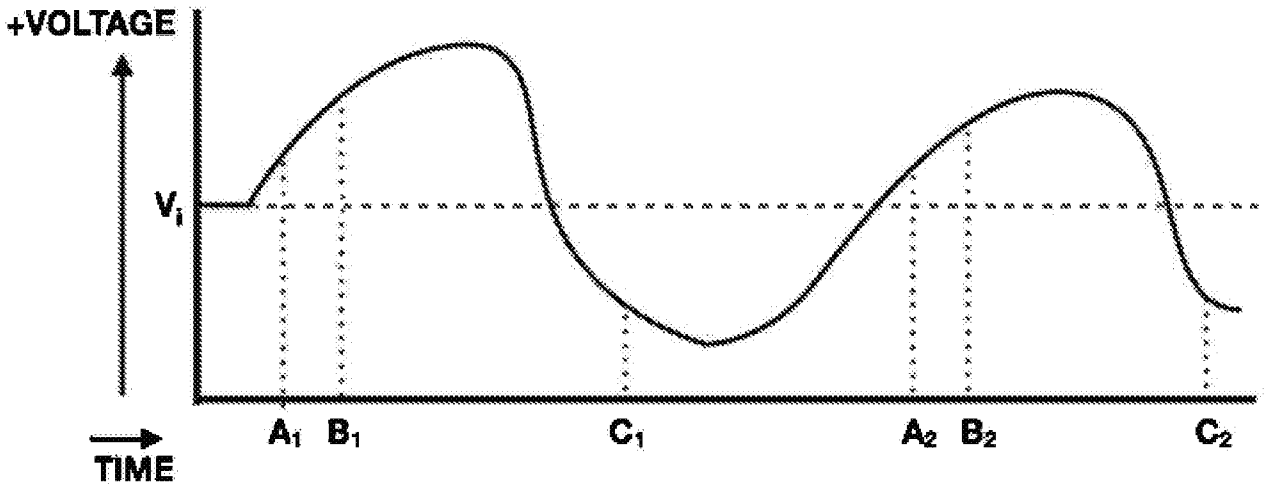


Fig. 18B

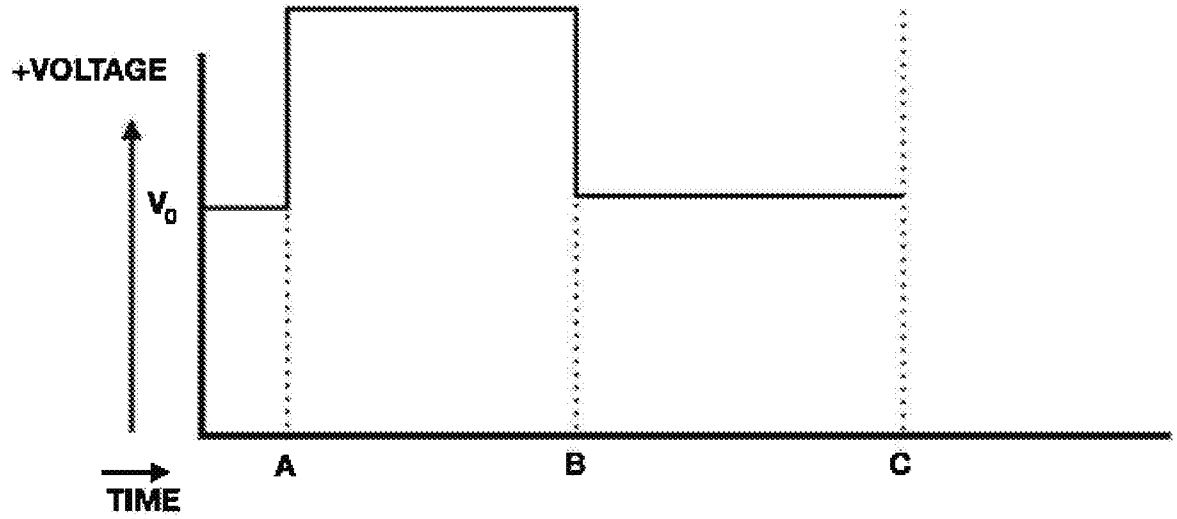


Fig. 19A

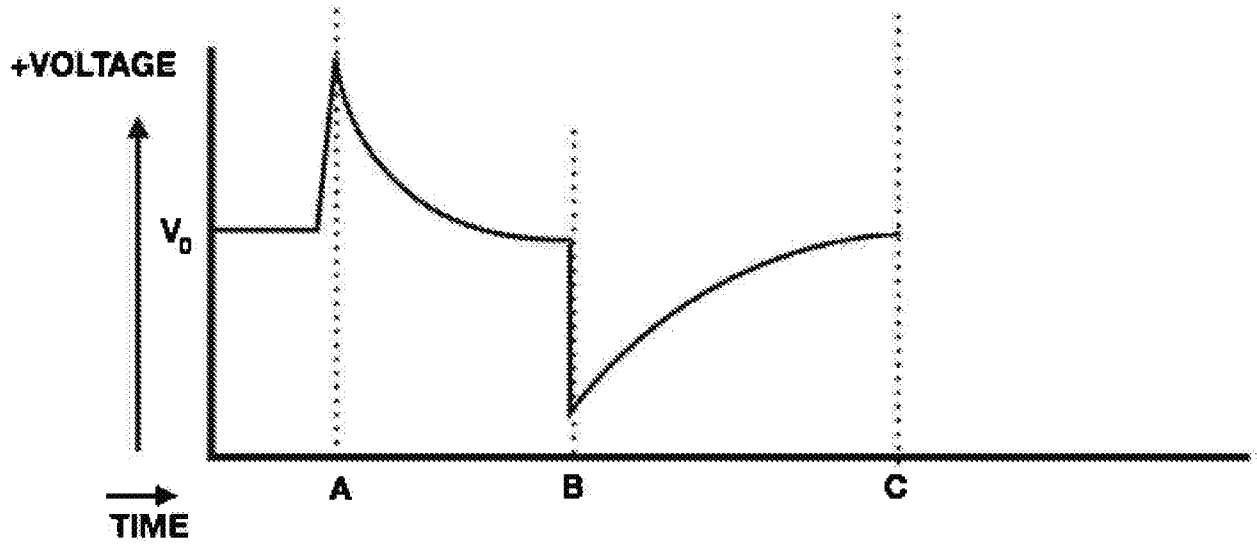


Fig. 19B

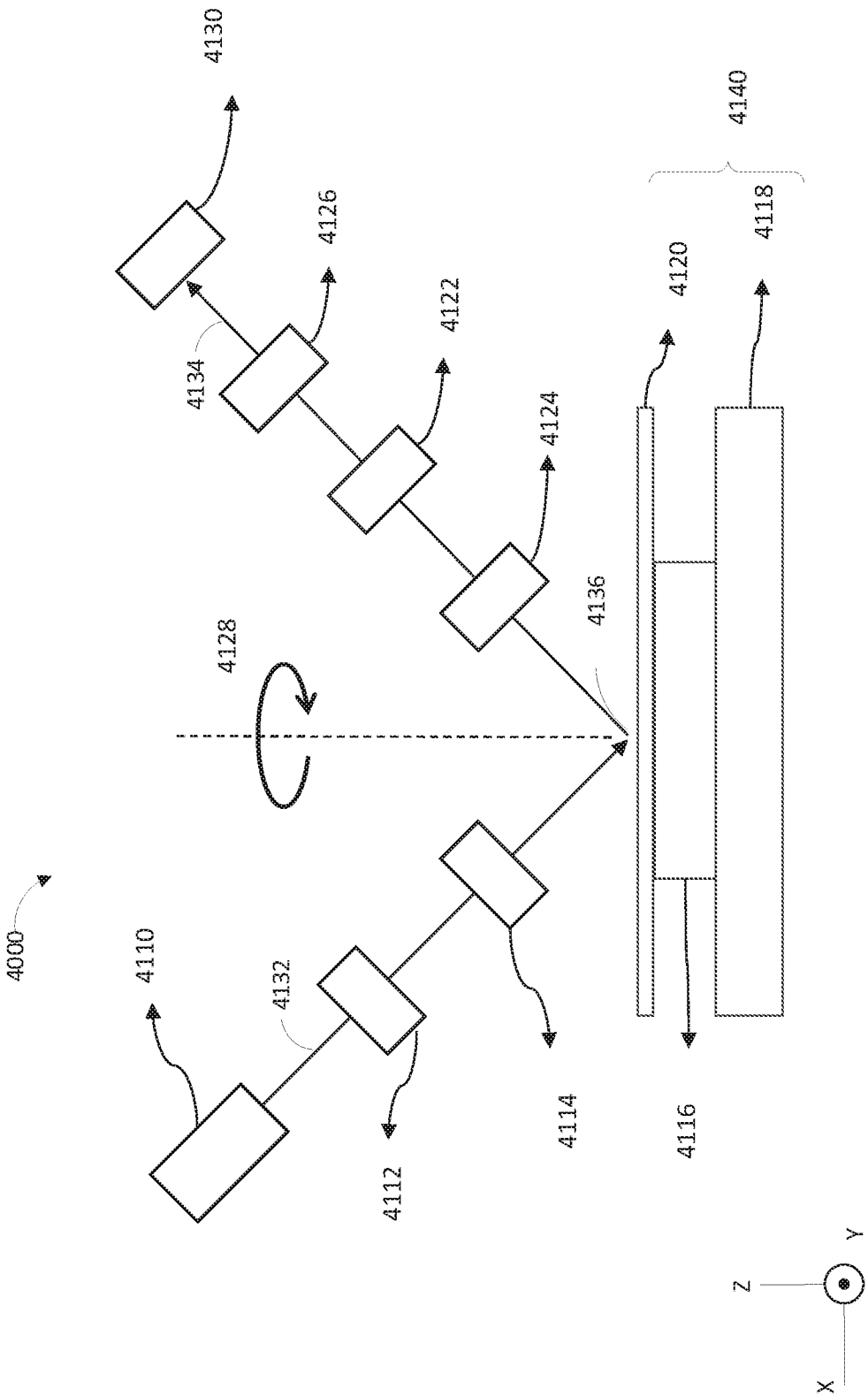

4000
4110
4132
4112
4114
4116
4128
4136
4124
4122
4126
4134
4130
4120
4118
4140
Z
Y
X

FIG. 20

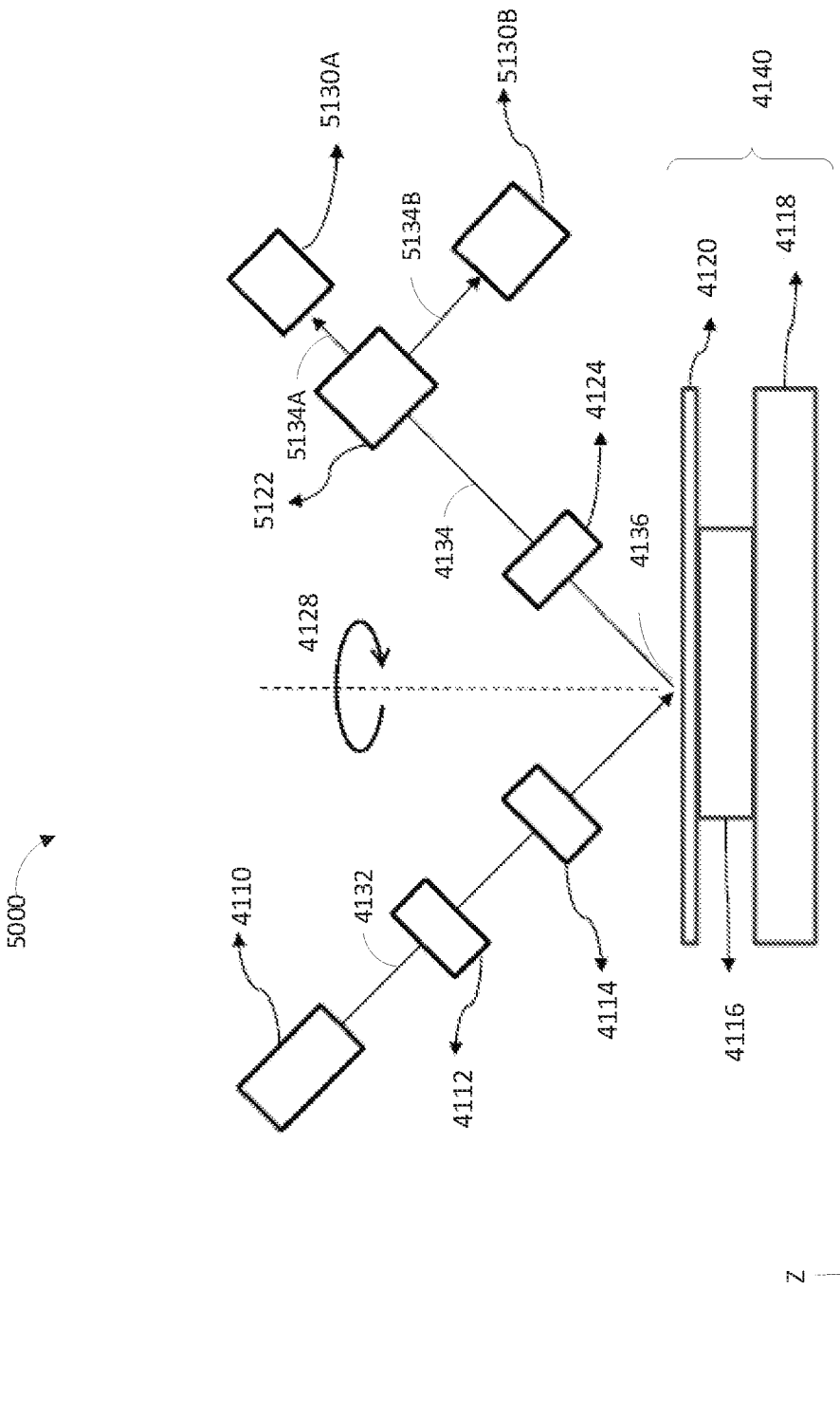

5000
4110
4132
4112
4114
4116
4128
4134
4136
4124
4120
4118
4140
5130A
5130B
5134A
5134B
5122
Z
Y
X

FIG. 21

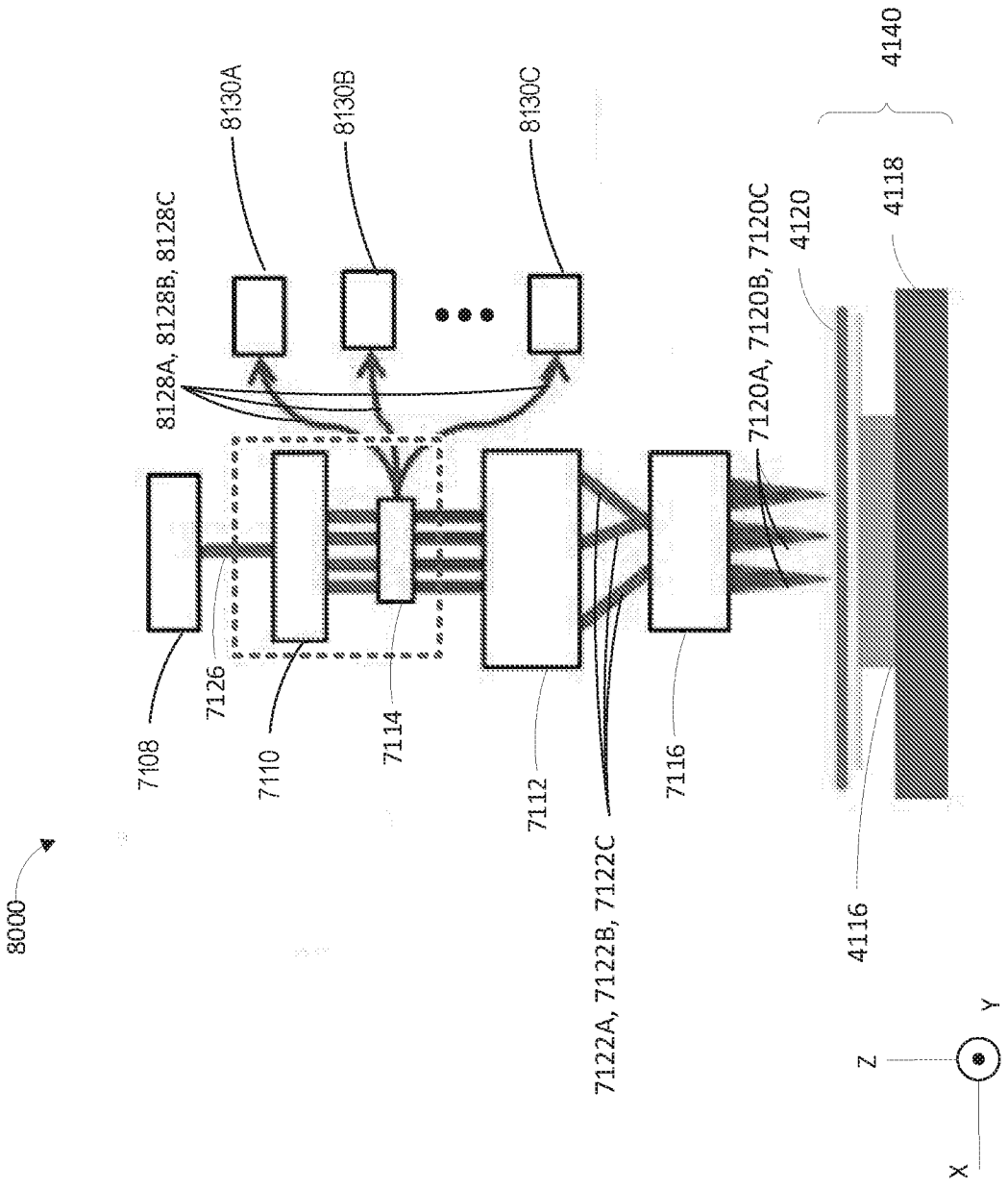

8000
7108
7126
7110
7114
7112
7122A, 7122B, 7122C
7116
8128A, 8128B, 8128C
8130A
8130B
8130C
7120A, 7120B, 7120C
4120
4118
4140
4116
Z
Y
X

FIG. 22A

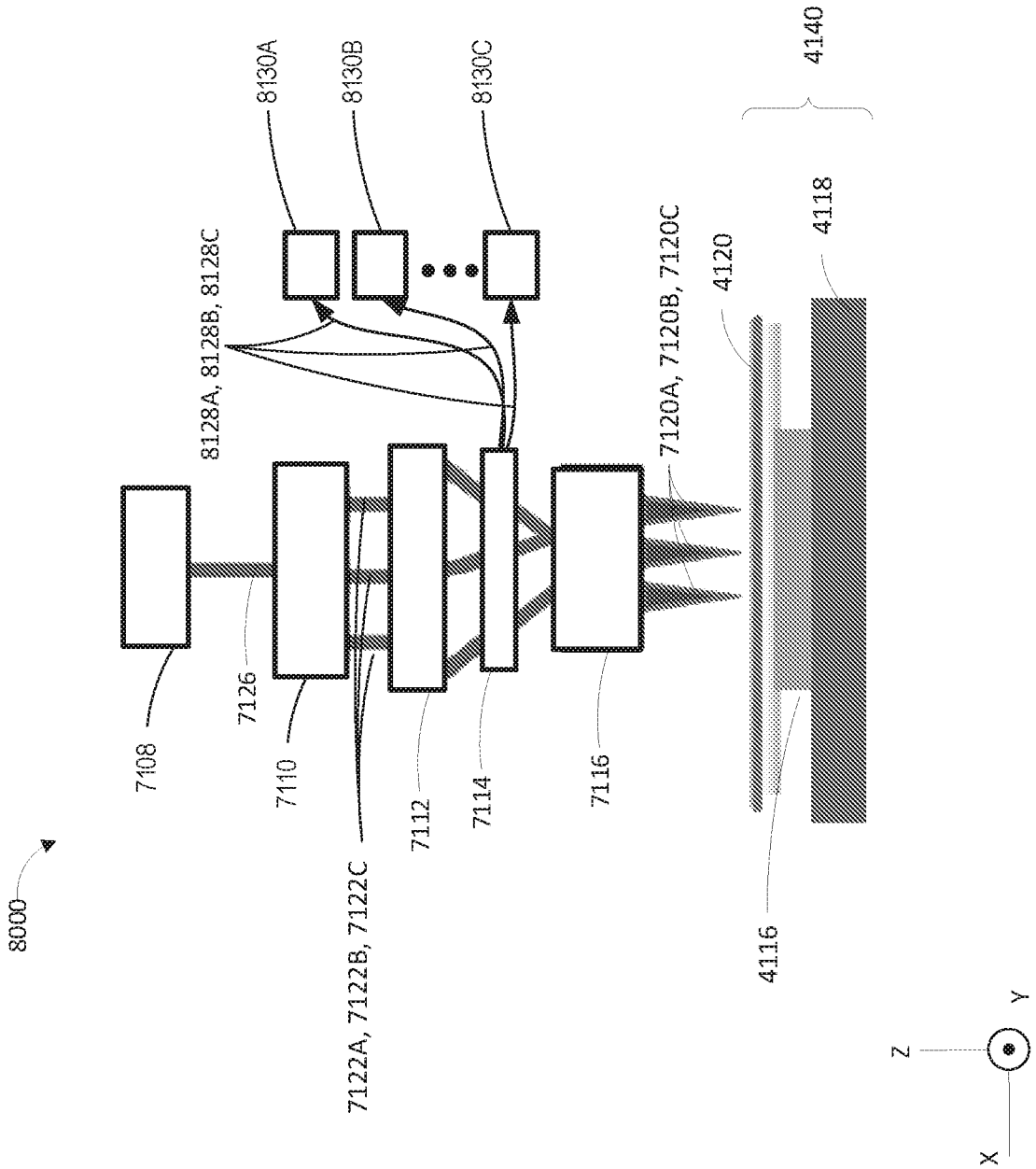

8000
7108
7126
7110
7122A, 7122B, 7122C
7112
7114
7116
8128A, 8128B, 8128C
8130A
8130B
8130C
7120A, 7120B, 7120C
4120
4116
4118
4140
Z
Y
X

FIG. 22B

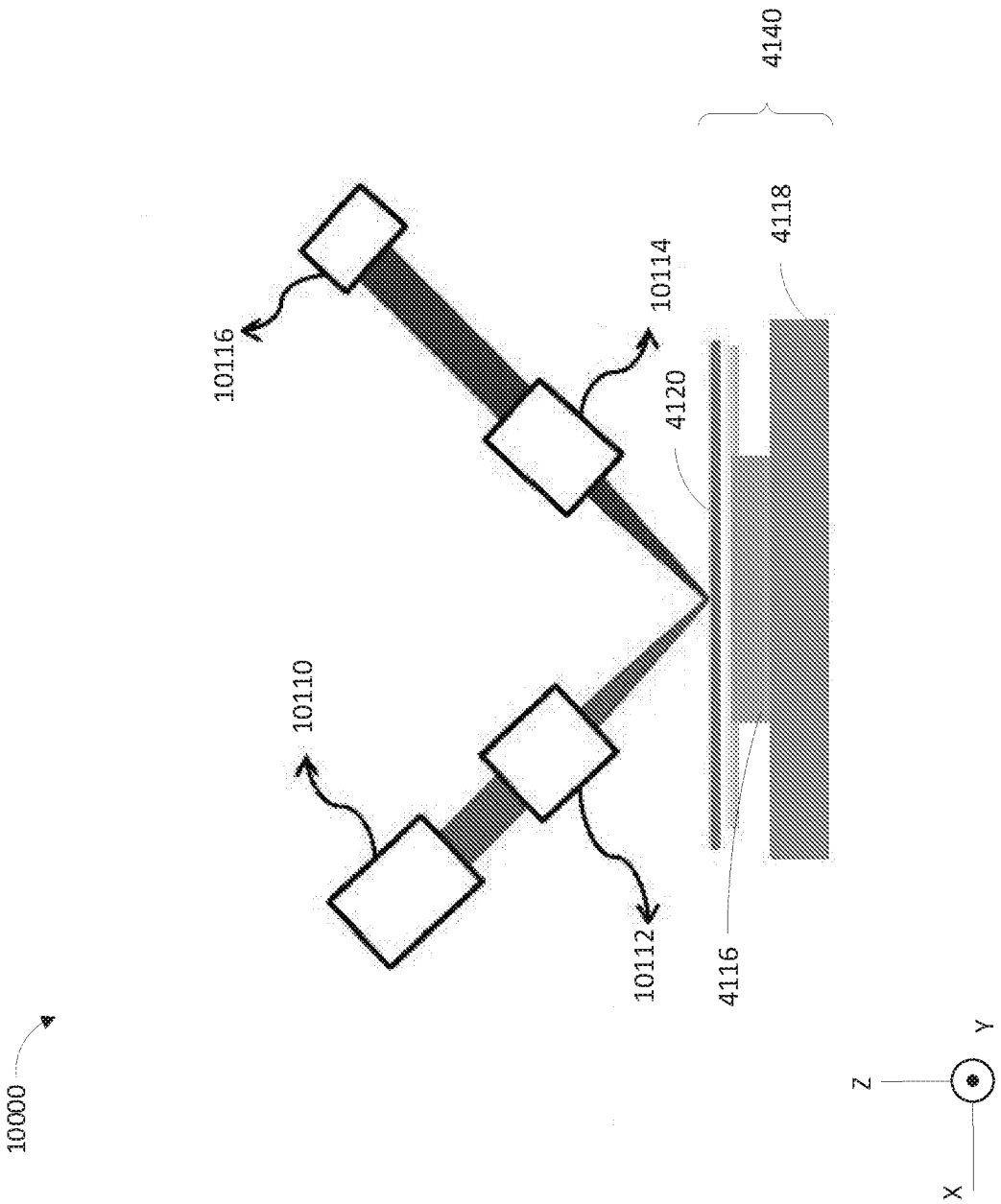


FIG. 23

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/032282

A. CLASSIFICATION OF SUBJECT MATTER

G01N 21/88(2006.01)i, G01N 21/95(2006.01)i, G01N 21/01(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N 21/88; G01N 21/86; G01N 29/24; G01N 29/44; G02F 1/35; G02F 1/355; G02F 1/37; G11B 7/00; H01S 3/133; G01N 21/95; G01N 21/01

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: second harmonic generation, sample, optical source, polarization beamsplitter, detector

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2002-0109110 A1 (SOME et al.) 15 August 2002 See paragraphs [0028]-[0039], claims 1, 10, and figures 1-3.	11-12,26-27
Y		1-3
Y	EP 0378061 A2 (INTERNATIONAL BUSINESS MACHINES CORPORATION) 18 July 1990 See column 3, line 54 - column 4, line 17 and figure 1.	1-3
A	US 2009-0303574 A1 (GUNTER et al.) 10 December 2009 See paragraphs [0072]-[0077] and figure 4.	1-3,11-12,26-27
A	US 2017-0205377 A1 (VANDERBILT UNIVERSITY) 20 July 2017 See paragraph [0073] and figure 1.	1-3,11-12,26-27
A	US 2010-0188957 A1 (KNITTEL et al.) 29 July 2010 See paragraph [0043] and figure 1.	1-3,11-12,26-27

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 September 2019 (24.09.2019)	**25 September 2019 (25.09.2019)**

Name and mailing address of the ISA/KR
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/032282

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 7, 34, and 36
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 7, 34, and 36 are regarded to be unclear because they refer to a multiple dependent claim which does not comply with PCT Rule 6.4(a).

3. ☒ Claims Nos.: 4-6, 8-10, 13-25, 28-33, and 35
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2019/032282

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