



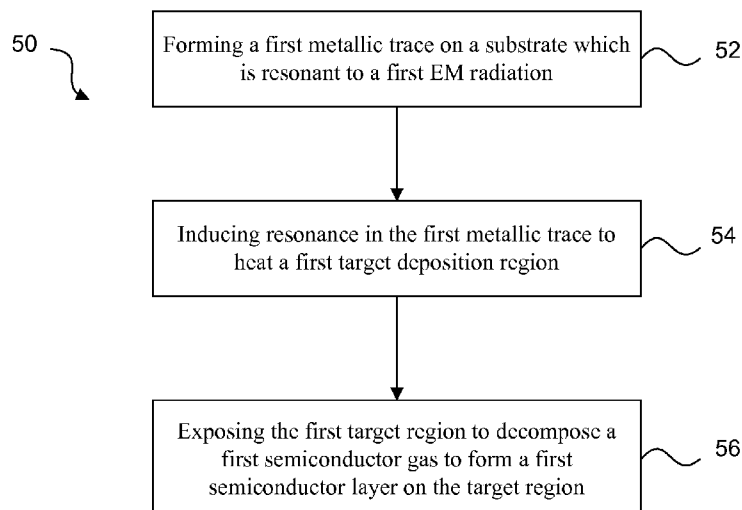
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(54) **Title:** METHOD AND SYSTEM FOR MANUFACTURE OF A ELECTRONIC DEVICES BASED ON LOCALIZED DEPOSITION OF PRECURSOR GASES



(57) **Abstract:** A method of fabricating an integrated circuit includes forming (52) a metallic trace over a substrate. Resonance in the metallic trace can be induced (54), resulting in a resonating metallic trace and a localized heated target deposition region. A semiconductor material can be deposited on the target deposition region via gas decomposition (56) of a semiconductor precursor gas.

FIG. 3a

METHOD AND SYSTEM FOR MANUFACTURE OF ELECTRONIC DEVICES BASED ON LOCALIZED DEPOSITION OF PRECURSOR GASES

GOVERNMENT INTEREST

This invention was made with government support under Award #N66001-08-1-2042 awarded by the U.S. Department of Defense/ Defense Advanced Research Projects Agency.

5 The Government has certain rights in the invention.

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 61/488,573, filed May 20, 2011 and which is incorporated herein by reference in its entirety.

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BACKGROUND

Various lithographic patterning and manufacturing processes exist for structuring material on a fine scale. Such processes are often referred to as microlithography or nanolithography. Some example lithography processes include electron beam lithography, nanoimprint lithography, interference lithography, X-ray lithography, extreme ultraviolet lithography, magnetolithography, surface charge lithography, and scanning probe lithography.

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Another common example of nanolithography is photolithography. Photolithography is often applied to semiconductor manufacturing of microchips and fabrication of micro-electrical-mechanical system (MEMS) devices. In photolithographic processes parts of a thin film or the bulk of a substrate can be selectively removed. More specifically, photolithography uses light to transfer a pattern from a photo mask to a light-sensitive chemical "photoresist" (or "resist") on the substrate. Chemical treatments can be used to engrave a pattern into material underneath the resist or to deposit a new material in the pattern upon the material underneath the resist.

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Nanomanufacture involving photolithography typically involves several steps performed in a sequence. For example, a surface may be cleaned and prepared using application of various chemicals, heat, promoters, and so forth. A layer of a material can be applied to the surface. The layer can be covered with the resist, such as by spin coating. The resist-coated surface is then prebaked to remove excess photoresist solvent. The resist is then exposed to a pattern of light. Exposed portions of the resist can undergo a chemical

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change that allows some of the resist to be removed by a special solution. The resulting structure is then "hard-baked" to solidify the remaining resist. Next a chemical agent can be used to remove or etch material from a layer exposed by the removed portions of the resist. After etching, the resist is no longer needed and is removed from the substrate by applying a resist stripper or through oxidization.

Photolithography and other lithographic techniques thus involve many steps of adding, removing, and treating materials to form desired patterns and structures.

SUMMARY

A method of fabricating an integrated circuit includes depositing a metallic trace over a substrate; inducing resonance in the metallic trace, resulting in a resonating metallic trace; and depositing a material on the resonating metallic trace. Resonance can be at least partially a function of the trace configuration. As such, deposition can be preferentially directed toward resonating portions of the metallic trace.

A method of fabricating an integrated circuit can include depositing a first metallic trace having a first dimension over a substrate. A second metallic trace having a second dimension different from the first dimension can be deposited on the substrate. A first radiation energy can be emitted towards the first and second metallic traces to cause one of the first and the second metallic traces to resonate as a first resonating trace. A first semiconductor material can be deposited in a first semiconductor material layer over the first resonating trace. A second radiation energy can be emitted towards the first and second metallic traces to cause a different one of the first and the second metallic traces to resonate as a second resonating trace. A second semiconductor material can then be deposited in the first semiconductor material layer over the second resonating trace.

An integrated circuit assembly can include a substrate and a plurality of metallic traces patterned over the substrate. At least two of the plurality of metallic traces comprise a different dimension with respect to one another and the at least two of the plurality of metallic traces resonate at different frequencies of radiation. A first radiation source can be configured to emit radiation toward the plurality of metallic traces at a first frequency; while a second radiation source can be configured to emit radiation toward the plurality of metallic traces at a second frequency. The assembly can also include a plurality of semiconductor materials, wherein at least one of the plurality of semiconductor materials is configured to be deposited over at least one of the plurality of metallic traces when the first radiation source

emits the radiation at the first frequency and a different one of the plurality of semiconductor materials is configured to be deposited over a different one of the plurality of metallic traces when the second radiation source emits the radiation at the second frequency.

Additional variations and aspects of the invention can be appreciated from the
5 following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1a-1b illustrate a photograph and block diagrams on integrated circuit assemblies in accordance with example of the present technology;

10 FIGs. 2a-2q are perspective views of an integrated circuit assembly with metallic traces caused to resonate by impinging electromagnetic radiation in accordance with examples of the present technology;

FIGs. 3a-3b are flow diagrams of methods for fabricating integrated circuits in accordance with examples of the present technology;

15 FIGs. 4a-4c are respectively perspective, bottom and SEM (Scanning Electron Microscope) views of a probe and tip region of the probe in accordance with an example of the present technology.

FIGs. 5 is an atomic force microscope image of silicon dots deposited on silicon by functionalized AFM tip using SiCl_4 on silicon in accordance with an example of the present
20 technology.

FIG. 6 is a Paschen curve calculated for Argon at different pressures as a function of electrode gap in the device in accordance with an example of the present technology.

FIG. 7 is a side view of gas ionization near the functionalized tip and deposition of heavy ions under the apex in accordance with an example of the present technology.

25 FIG. 8 is a schematic diagram of “coupling” of a probe and an insulating substrate to direct Ar^+ ions toward the sample to etch and correct deposits in accordance with an example of the present technology.

FIG. 9a is a top partial cutaway view of a functionalized probe with dual piezoelectric actuators and piezoresistive deflection sensors in accordance with an example of the present
30 technology.

FIGs. 9b-9d are side views of a functionalized probe illustrating movement of a support beam with respect to a substrate when actuators are moved in and out of sync with respect to one another in accordance with examples of the present technology.

FIG. 10 is a schematic diagram of a sigma-delta tracking loop to sense and control a functionalized probe's tip in accordance with an example of the present technology.

FIG. 11 is a micrograph of helium microplasma operating at atmospheric pressure in an array in accordance with an example of the present technology.

5 FIG. 12 is a flow diagram of a method of nanofabrication in accordance with an example of the present technology.

FIG. 13 is a schematic diagram of a deposition chamber for use with a probe in accordance with an example of the present technology.

10 FIG. 14 is a block diagram side cutaway view of a fabrication system including different micro-chambers enclosing groups of parallel local probes to deposit different materials in parallel in accordance with an example of the present technology.

FIGs. 15a-15b are respectively simplified cross-section and top views of the nanotips in accordance with an example of the present technology.

15 FIGs. 16a-16e illustrate a simplified process flow of manufacturing a nanotorch device in accordance with an example of the present technology.

FIGs. 17a-17d are SEM images at various magnifications of a microfabricated nanotorch on a suspended cantilever beam approximately 500 μm long in accordance with an example of the present technology.

20 FIG. 18 is a flow diagram of a method of manufacturing a nanofabrication device in accordance with an example of the present technology.

FIG. 19 is a perspective cross-sectional view of a probe with piezoelectric/thermal actuators and piezoresistor sensors in accordance with an example of the present technology.

25 FIG. 20 is an electronics block diagram illustrating a system for sensing and actuating a probe in accordance with an example of the present technology.

DETAILED DESCRIPTION

Reference will now be made to the exemplary embodiments illustrated, and specific language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the technology is thereby intended. Additional features and advantages of the technology will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of example, features of the technology.

In describing and claiming the present invention, the following terminology will be used in accordance with the definitions set forth below.

Electromagnetic radiation, as referred to herein, may consist of radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.

5 As a non-limiting example, the electromagnetic radiation used to induce resonance can include microwaves.

As used herein, "electrically coupled" refers to a relationship between structures that allows electrical current to flow at least partially between them. This definition is intended to include aspects where the structures are in physical contact and those aspects where the
10 structures are not in physical contact. Typically, two materials which are electrically coupled can have an electrical potential or actual current between the two materials. For example, two plates physically connected together by a resistor are in physical contact, and thus allow electrical current to flow between them. Conversely, two plates separated by a dielectric material are not in physical contact, but, when connected to an alternating current source,
15 allow electrical current to flow between them by capacitive means. Moreover, depending on the insulative nature of the dielectric material, electrons may be allowed to bore through, or jump across the dielectric material when enough energy is applied.

As used herein, "adjacent" refers to near or close sufficient to achieve a desired effect. Although direct physical contact is most common and preferred in the structures or volumes
20 of the present invention, adjacent can broadly allow for spaced apart features.

As used herein, the term "substantially" refers to the complete or nearly complete extent or degree of an action, characteristic, property, state, structure, item, or result. The exact allowable degree of deviation from absolute completeness may in some cases depend on the specific context. However, generally speaking the nearness of completion will be so
25 as to have the same overall result as if absolute and total completion were obtained. The use of "substantially" is equally applicable when used in a negative connotation to refer to the complete or near complete lack of an action, characteristic, property, state, structure, item, or result. For example, a composition that is "substantially free of" particles would either completely lack particles, or so nearly completely lack particles that the effect would be the
30 same as if it completely lacked particles. In other words, a composition that is "substantially free of" an ingredient or element may still actually contain such item as long as there is no measurable effect on the property of interest thereof.

As used herein, the term “about” is used to provide flexibility to a numerical range endpoint by providing that a given value may be “a little above” or “a little below” the endpoint with a degree of flexibility as would be generally recognized by those skilled in the art. Further, the term about explicitly includes the exact endpoint, unless specifically stated
5 otherwise.

As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a de
10 facto equivalent of any other member of the same list solely based on their presentation in a common group without indications to the contrary.

Concentrations, amounts, and other numerical data may be expressed or presented herein in a range format. It is to be understood that such a range format is used merely for convenience and brevity and thus should be interpreted flexibly to include not only the
15 numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. As an illustration, a numerical range of “about 1 to about 5” should be interpreted to include not only the explicitly recited values of about 1 to about 5, but also include individual values and sub-ranges within the indicated
20 range. Thus, included in this numerical range are individual values such as 2, 3, and 4 and sub-ranges such as from 1-3, from 2-4, and from 3-5, etc., as well as 1, 2, 3, 4, and 5, individually. This same principle applies to ranges reciting only one numerical value as a minimum or a maximum. Furthermore, such an interpretation can apply regardless of the breadth of the range or the characteristics being described.

Reference will now be made to the exemplary embodiments illustrated, and specific
25 language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the technology is thereby intended. Additional features and advantages of the technology will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of
30 example, features of the technology.

With the general examples set forth in the Summary above, it is noted in the present disclosure that when describing the system, or the related devices or methods, individual or separate descriptions are considered applicable to one other, whether or not explicitly

discussed in the context of a particular example or embodiment. For example, in discussing a nanofabrication device per se, other device, system, and/or method embodiments are also included in such discussions, and vice versa.

Furthermore, various modifications and combinations can be derived from the present disclosure and illustrations, and as such, the following figures should not be considered limiting.

As set forth above, photolithography and other lithographic techniques typically involve many steps of adding, removing, and treating materials to form desired patterns and structures. The present technology enables a simplification of nanofabrication systems and methods. As opposed to steps of adding, removing, and treating materials for creating nanostructures and heterogeneous layers of materials, the present technology enables substantially simultaneous deposition of heterogeneous materials in a same layer by inducing resonance in metallic traces.

With reference to FIG. 1a, a photograph of an electronic circuit board 10 is shown with a detail block diagram view of an integrated circuit assembly 12. The integrated circuit assembly is a hot spot for heterogeneous deposition of materials. The hot spot comprises transistors each having a source (S), gate (G), and drain (D). FIG. 1a illustrates the gates extending outward, away from one another. However, the dotted lines of the gate assemblies shown in FIG. 1b indicate that the gate assemblies can instead be directed into or out of the page such that the gate assemblies are substantially parallel to one another. The transistors can be formed and electrically coupled to one or more circuits in the circuit board according to known methodologies. In one aspect, the transistors can be formed using a nano-tip fabrication device, which will be described in further detail below.

Referring to FIG. 1b, in one example, a hot spot includes a plurality of transistors, or a pair of transistors. The pair of transistors can be oriented opposite one another such that a path between the drain and source for each transistor of the transistor pair is parallel but the drains and sources are located on opposite ends of the paths. Thus, a source can be adjacent a drain in another transistor of the transistor pair and vice versa.

The source and drain can form a bowtie antenna geometry with the gate connected at a center of the bowtie geometry. A distance or length of one half of the bowtie antenna geometry can be approximately one half of the wavelength of radiation used to induce resonance in the bowtie antenna. The bowtie antenna configuration can be seen as a pair of metallic trace features having proximate ends with tapered tips. The tapered tips allow for

focusing of energy to create a localized hot spot within the gap between the pair of trace features within the bowtie configuration. In one aspect, the metallic traces can be defined by dimension. A deposited metal layer may include multiple traces which are connected or which are separated by a space. When the traces are connected and form a single piece of metal with different dimensions, radiation of a specific frequency can cause a portion of the piece of metal (i.e., one of the traces) to resonate while another portion does not resonate depending on the dimensions at that location. As a result, deposition locations can be designed to occur at predetermined locations across the substrate.

The frequency selectivity is achieved by the active length of bow-tie antenna structures. The dimension of the bow-tie is directly related to its ability to interact with electromagnetic waves with a specific wavelength. The orientation of the bow-tie antenna determines its ability to interact with a given polarization of the electromagnetic wave. To separate different devices on the circuit from each other so that excitation of one device, or a group of devices, does not affect the adjacent device, or group of devices, quarter wavelength isolators can be used. Other microwave engineering techniques can also be used to emphasize or de-emphasize excitation of certain devices. This invention can be extended to a class of household microwave utensils that enable heating a portion of the food while enabling the rest of the food to be not affected by the microwave energy.

This approach allows the use of the metallic traces on an integrated circuit to concentrate electromagnetic radiation energy generated using different sources such as microwave, laser, light emitting diode, halogen lamps, or other sources, into a nearby region (i.e., the hot-spot) and deposit a desirable semiconducting material for a particular device. A wide variety of electronic devices can be formed using this approach, although field effect transistors (FET) such as MOSFET, DMOS FET, JFET, OFET, and the like, light emitting diodes (LEDs), or any other feature which utilizes a semiconducting material.

For example, for FET devices, the gate, insulating layer, and metallization strips can all be deposited using conventional photolithography and deposition techniques. However, the channel materials can be deposited by providing resonance structures which locally heat deposition target areas where materials can be decomposed and deposited as discussed herein. In this manner, multiple different materials can be deposited in a single plane in an additive manner by selectively orienting the corresponding resonance structures for each material in a common resonance pattern. As such, a first set of resonance structures can be

configured to respond to a first radiation while a second set of resonance structure can be configured to resonate in response to a second radiation.

More specifically, metallic traces with different dimensions resonate with radiation sources having different frequencies. Metallic traces with orientations parallel or perpendicular to a propagation direction of the radiation will also resonate or fail to resonate depending on the trace orientation relative to the propagation direction. The resonance of a specific device or group of devices is enabled by a specific relationship between the size of the device (that has a bow-tie receiving structure) and the wavelength of the excitation microwave. Quarter wavelength section and other microwave techniques are used to “isolate” devices or group of devices that are nearby to be excited by the devices that resonate with a particular microwave that has a corresponding specific wavelength and polarization.

The particular frequency at which a metallic trace produces a hot-spot is related to its dimension. In its most simple form, an electromagnetic radiation with frequency f produces a wave with wavelength of $\lambda = v/f$ where v is the wave velocity. A metallic trace with appropriate regions with length L proportional to $\lambda_n/2$ will resonate with a wave frequency of $f_n = v/\lambda_n$ where “n” is an integer index used here to refer to different values of frequencies.

When metal structures are exposed to electromagnetic radiation, modes of collective charge carrier motion, called plasmons, can be excited and a charge carrier separation is built up. The attraction between the separated charges produces a restoring force that mainly depends on the dynamic polarizability of the metal in the intraband region, like plasma frequency and relaxation rate. This gives rise to collective electronic oscillations at the surface of the metal, known as surface plasmons. The surface plasmons can propagate along a distance of several tens of micrometers on the surface of a film and the plasmon resonance condition is achieved for one specific wave vector and one specific excitation wavelength. The strength of the oscillation is influenced from radiative (scattering) and nonradiative (absorption) damping.

Coupled metallic systems produce red shifts and plasmon hybridization. The lowest energy resonance usually generates a strong local field in the vicinity of the coupling area. The use of cavities or other effective configurations can produce a large field enhancement. While bowtie antennas have are primarily described herein as the form of the metallic traces, other configurations can be used as well, such as adjacent metal traces, dimers, sets of metal nanoparticles, and coupled nanorods. Any suitable configuration or shape can be used as long

as the resonant structure produces a localized resonance response which triggers decomposition of the corresponding precursor gases.

The strong local field with the large field enhancement caused by the electromagnetic radiation can decompose gases used in semiconductor manufacture in the vicinity of the coupling area when an appropriate precursor gas is selected which is decomposable by the resonant field. The decomposition of material can be controlled according to the frequency of radiation used because the decomposition occurs where the resonance occurs (e.g. decomposition occurs where temperatures are highest). This generally occurs where energy within the resonant structure is directed or localized. In the bow-tie antenna structures, the gap or constriction is the location of highest temperature where materials will tend to deposit. Resolution for deposition is limited by fabrication size limits of the bowtie antennas or other structures and by the ability to cause the strong local field with large field enhancement at smaller and larger sizes of structures.

Referring to FIGs. 2a-2c, bow-tie transistor pairs 16, 18 are oriented perpendicular to one another on a substrate 14. A radiation source or radiation emitter 20 can direct radiation toward a substrate on which the metallic traces are formed. FIGs. 2b-2c illustrate the principle that bow-tie pairs of same or similar dimensions which are oriented perpendicular to one another will result in resonance 24, 25 of different pairs based on an orientation 22, 23 of incident radiation.

Resonance of a bow-tie pair in the presence of an appropriate gas 26, 27 will cause a deposition of the material in the gas in the general location of the resonance and not elsewhere away from the resonance. Therefore, use of the resonance effect of the bow-tie pairs can result in deposition of materials in discrete areas on a circuit board without subsequent patterning and/or etching processes to remove material from areas other than the desired discrete areas.

Because resonance is affected based on orientation of the traces relative to the electromagnetic radiation as well as dimensions of the traces relative to a wavelength of the electromagnetic radiation, it is possible to have many different structures with different dimensions on a same substrate. Use of appropriate radiations with different frequencies can produce hot-spots and deposit different active materials at different locations near associated metallic traces. This technology can enable integration of many different types of devices requiring many different types of active layers such as Ge, Si, $\text{Si}_{1-x}\text{Ge}_x$, GaN, AlN, SiC, and graphene on the same layer. The materials of the active layers Ge, Si, $\text{Si}_{1-x}\text{Ge}_x$, GaN, AlN,

SiC, graphene, carbon nanotubes, most oxides and metals are example materials depositable from corresponding precursor gases. The deposition of one or more of the materials over one or more contiguous or discreet areas of a substrate or other layer onto the metallic traces can be performed substantially simultaneously or can be performed sequentially without
5 performing etching or other conventional subtractive steps.

Semiconductors and other nanodevices manufactured using this technology can benefit from reduced processing steps, which reduces a time and monetary cost of fabrication.

Referring to FIG. 2d, a larger integrated circuit assembly 30 is illustrated in
10 accordance with an example of the present technology. The integrated circuit assembly can include a substrate 32. A plurality of metallic traces 34 can be patterned over the substrate. While in this example the traces are patterned directly onto the substrate, one or more intervening layers may be present between the substrate and the traces. Semiconductor manufacture conventionally involves formation of one or more material layers on a silicon
15 substrate or a similar material. Deposition of additional layers is typically over metallic or dielectric layers. Conventional lithography and other nanofabrication technologies are generally unusable over other less conventional materials. However, the present technology makes available a wide variety of previously unused materials as semiconductor substrates. Some non-limiting examples include plastics, ceramics, metals, composites, polymers, wood,
20 textiles, and so forth. Virtually any material upon which the metallic traces can be patterned may act as a suitable substrate for deposition of materials. The localized resonance and consequent heating can limit average substrate temperatures to less than 100 °C while target deposition regions on the surface can rise to over 1000 °C and in some cases over 1200 °C. Thus, a unique variety of substrates and deposited materials can be selected.

25 In one example, at least two of the metallic traces may have a different dimension with respect to one another and can resonate at different frequencies of radiation from one another. A first radiation source can be configured to emit radiation toward the metallic traces at a first frequency. A second radiation source can be configured to emit radiation toward the metallic traces at a second frequency.

30 The system can include a plurality of semiconductor materials (identified as “Gas” or M_1 - M_6 in FIGs. 2e-2q). At least one of the semiconductor materials can be configured to be deposited over at least one of the metallic traces when the first radiation source emits the radiation at the first frequency. A different at least one of the plurality of semiconductor

materials can be configured to be deposited over a different one of the metallic traces when the second radiation source emits the radiation at the second frequency. FIGs. 2e-2q show the use of all of the semiconductor materials for every frequency, electromagnetic radiation orientation, and metallic trace size and orientation. However, fewer than all of the

5 semiconductor materials can also be used for a particular frequency, electromagnetic radiation orientation, etc., and combinations thereof. In some examples, a single semiconductor material may be used for a particular individual frequency, electromagnetic radiation orientation, etc.

This approach can be used with a variety of metal-organic gases for depositing many

10 important semiconductors including GaN (from gallium triethyl and triethyl amine), SiC (from trimethylsilane and methane), and diamond (from acetylene), metals such as nickel (from nickelocene), and gold (from gold monochloride), oxides including SiO₂ (from trimethyl silane and oxygen), Al₂O₃ (from aluminum isopropoxide and oxygen), hafnium oxide, zinc-oxide, aluminum nitride, and other materials from appropriate precursors.

15 In another example, the integrated circuit assembly can include a substrate and metallic traces patterned over the substrate, where at least two of the metallic traces resonate in response to different orientations of radiation with respect to orientations of the metallic traces. A first radiation source can be configured to emit radiation toward the metallic traces at a first orientation and a second radiation source can be configured to emit radiation toward

20 the metallic traces at a second orientation. Although this example and the previous example describe first and second radiation sources, the first and second radiation sources may optionally comprise a single radiation source capable of emitting multiple different radiations, where the different radiations differ in at least one of wavelength and orientation. A difference in orientation of the radiation can be a result in a difference of direction of

25 propagation of the radiation.

As with the example above, a system can include a plurality of semiconductor materials. At least one of the semiconductor materials can be configured to be deposited over at least one of the plurality of metallic traces when the first radiation source emits the radiation at the first orientation and a different at least one of the plurality of semiconductor

30 materials can be configured to be deposited over a different at least one of the plurality of metallic traces when the second radiation source emits the radiation at the second orientation.

The metallic traces on the substrate of FIG. 2d are formed in different sizes and orientations, the orientations being preferably perpendicular to one another. The bow-tie

pairs can optionally be arranged such that two parallel and similar-structured bow-tie pairs are adjacent to one another, resulting in sets of four bow-tie antennas for any particular region on the substrate. The bow-tie pairs can also be arranged to include more than four bow-tie antennas in the set.

5 A specific arrangement of the bow-tie pairs on the substrate may vary between applications. FIG. 2d illustrates an example arrangement of bow-ties with six different sizes for depositing six different materials based upon the frequency and orientation of the incident radiation. The particular arrangement illustrated is selected to demonstrate the versatility of use with regards to deposition based on resonance, and also to show an example arrangement
10 more or less maximizing usage of the substrate surface. The arrangement is intended to be a non-limiting example, and indeed a variety of other arrangements are possible and contemplated. The arrangement of the bow-tie pairs can be based upon a desired shape or arrangement of the one or more materials and/or layers to be deposited. We note that in this invention most of the metallic (or conductive traces) and other parts of the circuits are
15 deposited and patterned using conventional photo-lithography techniques, while the microwave approach described herein is used to deposit mostly active materials in devices in the circuit. The metallic traces composing the circuit, are fashioned intelligently to intercept and become excited at specific microwave frequencies and polarizations to deposit heterogeneous materials only in the desired device or group of devices.

20 FIG. 2e illustrates simultaneous impingement of the electromagnetic radiation at six different frequencies f_1 - f_6 and in two different orientations $E_{\perp}$ and $E_{\parallel}$, such that up to twelve different bow-tie pair configurations can be used to deposit six materials M_1 - M_6 over the substrate. In this example, because all six frequencies at both orientations are directed toward the integrated circuit assembly, causing all of the traces to resonate, the gas materials will
25 decompose over the appropriate metallic trace to form or begin forming a desired layer.

FIG. 2f illustrates an example where radiation $E_{\perp}$ at frequency f_1 is directed toward the metallic traces in the presence of multiple gases. Despite the presence of multiple gases and the many different bow-tie pairs, the orientation and dimensions, such as length, width, and/or height, of the bow-tie pairs limit where decomposition will occur to the two areas
30 illustrated in the figure. FIG. 2g illustrates an example with a same radiation $E_{\perp}$ is directed toward the metallic traces but at a different frequency f_2 . As shown in this figure, a different two areas of bow tie pairs are caused to resonate than occurred with the radiation of FIG. 3c.

Similarly, FIGs. 2h-2q illustrate resonance in differing groups of bow tie pairs based on the size or dimensions, and orientation, of the bow ties in the pairs.

Referring to FIG. 3a, a flow diagram of a method 50 is illustrated for fabricating an electronic device such as an integrated circuit. The method includes forming 52 a first
5 metallic trace on a substrate. The first metallic trace being configured to resonate in response to a first electromagnetic radiation and to focus energy toward a first target deposition region. The method further includes inducing 54 resonance in the first metallic trace by directing the first electromagnetic radiation toward the first metallic trace to cause the first metallic trace to resonate sufficient to heat the first target deposition region to a first decomposition
10 temperature of a first semiconductor precursor gas. The method also includes exposing 56 the heated first target deposition region to the first semiconductor precursor gas so as to form a first semiconductor material layer over the first target deposition region.

Decomposition of precursor gases over the metallic traces can continue for a predetermined period of time to accumulate a desired layer thickness. In one aspect, different
15 areas of the integrated circuit may be fabricated to differing degrees. For example, a base or lowermost layer deposited on the metal traces and substantially adjacent to the substrate may be formed from a variety of materials, and different materials, or same materials in different areas, may be deposited to differing depths to suit particular applications. Also, there is a physical limit to the depth to which material may be deposited on a particular metallic trace
20 before forming a new trace on top of the deposited material to continue deposition. In many applications, however, the layers are deposited for a predetermined period of time defined by a period of time during which the metallic traces are exposed to the electromagnetic energy or radiation.

FIG. 3b illustrates flow diagram of another method 70 in accordance with an example
25 of the present technology. The method is a method of fabricating an integrated circuit where multiple semiconductor materials can be deposited throughout the device selectively (i.e. on a common plane) in subsequent steps without the requirement of intermediate masking or etching steps. This method can be a continuation of the method described in FIG. 3a which is repeated with a second set of trace features which are responsive to either a different
30 frequency or polarization of radiation. Specifically, the method can include forming 72 a second metallic trace on the substrate. The second metallic trace can be configured to resonate in response to a second electromagnetic radiation and to focus energy toward a second target deposition region. The target deposition regions are the regions where the

semiconductor material is desired (i.e. for a particular active feature, channel, etc). The method also includes inducing 74 resonance in the second metallic trace by directing the second electromagnetic radiation toward the second metallic trace to cause the second metallic trace to resonate sufficient to heat the second target deposition region to a second decomposition temperature of a second semiconductor precursor gas. This particular method also includes exposing 76 the heated second target deposition region to the second semiconductor precursor gas so as to form a second semiconductor material layer over the second target deposition region.

The method enables deposition and patterning of metallic layers before deposition of active layers. In current integrated circuits, the active layer is deposited first and the metallic contacts and layers are deposited afterward. The present technology inverts the conventional fabrication approach of semiconductor first sequence and includes deposition of at least one patterned metallization layer first. Additionally, the present technology enables integration of many different active layers on top of one another, provided that each heterogeneous active layer is preceded by one patterned metallization layer that provides the resonant metallic traces and structures needed in producing the hot-spots described herein. The present technology further enables simultaneous or sequential deposition and/or integration of devices with different active materials in a same or common layer (e.g. coplanar heterogeneous semiconductor materials), without intervening etching or other material removal steps.

Systems and methods for heterogeneous integration of devices with different active materials can be performed using many conventional deposition systems and methods. Alternatively, the systems and methods for heterogeneous integration of devices with different active materials can be performed using the nanotip device and associated methodology described below. Specifically, the nanotip device can be used to clean a substrate before manufacture is begun, to deposit the metallic traces, or to introduce the precursor gases to be decomposed by the resonating metallic traces.

In one example, local probes with integrated channels can be used to deliver gases near the probe tip with electrodes to produce large stationary and alternating electric fields to deposit and etch quantum dots on electronic materials including insulators, semiconductors and metals. The microfabrication and use of an atomic force microscopy (AFM)-tip-like device, or nanotorch, for use in microfabrication is described. This microfabrication device is capable of generating a very localized microplasma at a tip thereof. A submicron region near

the tip provides a manufacturing environment where controlled direct-write nanofabrication can be performed. The microfabrication device can be fabricated using both surface and bulk micromachining techniques. More specific fabrication methods are described herein. After fabrication, the microfabrication device has been used successfully in semiconductor

5 microfabrication. In specific examples, the microfabrication device has been used successfully in an O₂ environment at atmospheric conditions with an AC (alternating current) voltage of approximately 1000V. Microfabrication in O₂ environments and at atmospheric conditions reflects an improvement over many previous devices which use environments filled with a gas other O₂ and maintained at a pressure other than atmospheric pressure.

10 Microfabrication using the microfabrication device and processes described below can result in less complex and less costly microfabrication. The device described herein can be a fabrication device capable of fabricating structures on a small scale. For example, the device is capable of microfabrication and nanofabrication, as well as fabrication at other scales. Reference to a specific scale of fabrication, such as microfabrication, is therefore included for
15 exemplary purposes but is not limited thereto.

While much of the following discussion describes an AFM tip or a type of AFM-tip-like device (also referred to herein as a “nanotorch”), the microfabrication device used in connection with the heterogeneous material deposition systems and methods described above is not limited to AFM tip applications. In one aspect, a tip, such as a probe tip, can be
20 functionalized by adding structure to or around the tip in order to enable the micro or nanofabrication described below. Accordingly, the nanotorch or microfabrication device can also be referred to as a “functionalized tip” device, or a device which includes a functionalized tip. The microfabrication device can generate a localized microplasma around a tip thereof to provide an energetic nano-manufacturing environment that can produce
25 reactive gas species for etching and deposition. The entire microfabrication device structure can be suspended on a cantilever. The cantilever can be formed of any suitable material (e.g. silicon nitride).

Reference will now be made to FIGs. 4a-4c. Referring first to FIG. 4a, a
nanofabrication device 100 is shown which includes a conducting nanotip 110 and a gas
30 microchannel 115 adjacent to the nanotip. The microchannel can be configured to deliver a gas to the nanotip. The nanofabrication device can include an electrode 120 in electronic communication with a power supply and the nanotip, the electrode being configured to deliver an electric charge from the power supply to the nanotip. The nanofabrication can

include a substrate 125 upon which the conducting nanotip, the gas microchannel, and the electrode are arranged. In one aspect, the electrode can be the substrate or may be a metallic layer positioned over a non-conducting substrate. In the example shown in FIG. 4a, the device includes two electrode leads, a tip and a microchannel. One of the two electrode leads
5 120 is buried within the microchannel leading to the tip apex. The second electrode lead 122 runs on top of plasma ignited by DC (direct current) and AC (alternating current) signals. The device tip can be formed to focus deposition and decomposition conditions to a localized decomposition area. The specific shape, size and material of the device tip can affect the resolution of the localized deposition area. For example, the device tip can include an
10 oxidation sharpened polysilicon tip coated with a thin layer of refractory Cr metal. The tip is protruding out of an interior of a microchannel through a small orifice which is formed at an end of the microchannel. A diameter of the orifice can vary depending on application, but in some examples is less than approximately 10 μm , or less than approximately 5 μm , or less than approximately 3 μm .

Referring to FIG. 4b, a bottom view of the nanotip 110 of the device 100 of FIG. 4a is shown. The nanofabrication device can include a metallic shield 130 substantially circumscribing the nanotip and defining the orifice. The metallic shield can be a ring electrode. The nanotip can include a conducting apex 135. FIG. 4c is a Scanning Electron Microscope (SEM) image of a side view of the tip shown in FIG. 4b. An annular
20 microchannel exit can allow for relatively uniform distribution of gases about the nanotip. Although the annular microchannel 115 for gas delivery is shown, other microchannel configurations can be suitable. For example, a microchannel can have a single exit opening which is located adjacent to the nanotip 110 such as to a side of the nanotip.

The functionalized probe 100 shown in the schematic of FIG. 4a can be fabricated
25 using standard silicon micro-machining techniques. The probe can be coated with harsh-environment and tribological SiC (silicon carbide) and diamond-like films, by bulk SiC and/or diamond tips or coatings, or by other suitable ceramic or corrosion resistant coatings. The tips can deposit, image, and etch materials to form nano-scale objects with precise dimensions. For example, the tips can be used to deposit, image, or etch materials with width
30 and diameter down to about 10 nm, length down to about 10 nm - 100 μm , and thickness down to about 10 nm – 1 μm). The basic approach can be used with many gases and metal-organic precursors to deposit insulators, semiconductors, and a variety of metals, among other materials. Non-limiting examples of materials which can be deposited include silicon, silicon

dioxide, silicon-germanium, silicon nitride, silicon carbide, silicon oxynitride, copper, aluminum, molybdenum, tantalum, titanium, nickel, tungsten, and the like. Corresponding precursors can be chosen as needed, but non-limiting examples of precursors include silane, dichlorosilane, oxygen, ammonia, nitrogen, metal chlorides, metal carbonyls, and the like.

5 Dopants and other alloys can be optionally introduced into the deposited material via diffusion from the substrate and/or included within the source precursor gas. For example, phosphorus can be decomposed from phosphine gas and oxygen. Deposited materials can be polycrystalline, monocrystalline, or amorphous and can be epitaxial. Although the typical morphology can vary, structures can be produced such as quantum dots, nanofibers,
10 nanowires, films, pads, and the like.

For the purpose of illustrating the principles of this nanodeposition device, silane and argon gases (SiH_4/Ar) can be used to deposit silicon quantum dots. Misplaced deposited material can be subsequently removed. For example, etching can be accomplished using 20-50 eV Ar ions generated near the probe tip. These ions can be used directly in an “ion
15 milling” mode and can also be used to excite surface-adsorbed SF_6 molecules on the sample to perform reactive ion etching to correct line widths and pattern lines for device formation. This can further augment resolution of the deposition patterns which can be achieved.

Nanotips 110 with micro-channels 115 and integrated electrodes 120, 122 can be fabricated to deliver and/or excite gas molecules directly under the tip apex as schematically
20 shown in FIG. 4a. A tip with microchannels and electrodes is referred to herein as a “functionalized” tip or probe. The electrodes on the tip enable more precise deposition and etching of materials as well as enable deposition/etching over insulating (oxide or nitride) substrates. For example, these functionalized probes can be characterized and used with a thermo-microscope AFM setup to deposit/etch silicon nanowires on silicon dioxide.

25 Moreover, deposition and fabrication of probes with integrated piezoelectric and thermal actuators can be provided as will be described in further detail below.

Piezoelectric actuation can be used for y-z-deflections and piezoresistive sensing for tip-sample interactions and for sensing and actuating movement of a direction of the nanotip with respect to the sample. The piezoresistive sensing can operate at ranges of approximately
30 0.5 to 1.5 nm stand off sensing, or more specifically at approximately 1 nm stand off sensing. These actuators and sensors can be integrated with the probe to enable multi-axis probe control of a multi-tip array with on-board hybrid electronics. For example, a 30-tip array with integrated actuators, sensors and on-board electronics can provide for deposition of large

areas and/or multiple deposition materials. The piezoresistor position sensors produce current changes on the order of a few microamperes and can be shielded from relatively large signals applied to the piezoelectric actuators (approximately 10-15 volts and a low current of less than a few tens of microamperes current) and deposition/etching electrodes

5 (approximately 20-100 volts and a few tens of microamperes current). A multi-tip array can include an array of microchannels, where at least one microchannel is associated with each tip in the multi-tip array. In one aspect, an individual tip can have multiple microchannels associated therewith to deliver at least two different gases to the individual tip. The ability to individually deflect tips in y-z directions can allow for minute adjustments to deposition
10 locations. In connection with moving the substrate a wide variety of deposition patterns can be achieved. The inherent resolution limitation provided by movement of a substrate support mechanism can be augmented and increased by finer deflection control of individual cantilevered and supported tips.

Local probes can be used to deposit and modify conducting samples or to deposit
15 nano-ink and perform nano-lithography. In one example, light emission spectra were recorded from a scanning tunneling tip in the presence of argon. This experiment demonstrates that currents passing through very narrow gaps can be used to ionize gases. In another experiment shown in the image of FIG. 5, germanium was deposited over silicon using germane gas to demonstrate the use of a probe to ionize gases and to deposit the
20 resulting ions in the form of a patch over a conducting sample.

As described above, two or more electrodes on the probe or microfabrication device can be used to perform deposition and etching tasks. These electrodes on the tip eliminate the need for a conducting substrate. As such, patterned deposition can be provided on a wide variety of substrates including, but not limited to, metals, polymers, ceramics, carbon fiber
25 composites, and a variety of other materials. This approach can be used with a variety of metal-organic gases for depositing many important semiconductors including GaN (from gallium triethyl and triethyl amine), SiC (from trimethylsilane and methane), and diamond (from acetylene), metals such as nickel (from nickelocene), and gold (from gold monochloride), oxides including SiO₂ (from trimethyl silane and oxygen), Al₂O₃ (from
30 aluminum isopropoxide and oxygen), hafnium oxide, zinc-oxide, aluminum nitride, and other materials from appropriate precursors can be deposited.

The electrodes of the functionalized AFM tip with a ~1 μm gap produce a highly non-uniform electric field near the pointed and sharp (~10 nm curvature) apex. Extensive research

using pointed electrodes ($\sim 1\text{-}25\ \mu\text{m}$ curvature) but much larger gaps of $50\text{-}100\ \mu\text{m}$ has shown that different regimes of discharge and gas excitation exist. The DC breakdown of gases is illustrated by a Paschen curve in FIG. 6 that shifts to lower fields at high excitation frequencies (optimum at around $3\text{-}50\ \text{MHz}$ depending on the tip geometry), or when the voltage is pulsed, or when an appropriate optical illumination (usually UV) is used, or by radio-active ionization. The breakdown of gas results in the generation of positive and negative charges in the gas that are commonly referred to as “plasma”. The initial breakdown regime that occurs at low current densities but high fields is called “self-sustained Townsend discharge” and is followed by a second regime called “glow discharge” where the current is high but the gap voltage drops due to high gas conductivity. In this regime a “feedback” involving electrons, ions, and photons from the breakdown in the gas occurs that sustains the current flow in the gap. This regime is followed by “corona discharge,” then by “spark discharge,” and finally by “arc discharge.” In the arc discharge, the gap voltage is rather low and the current is relatively high, leading to rapid evaporation of the electrode material in some cases. The spark breakdown is nearly the opposite where the voltage is high and the current is low. Glow discharges are relatively “cold” breakdowns, whereas coronas are relatively “hot” breakdowns. In a pulsed mode, a new mode of breakdown is enabled called a “streamer” regime which is a much faster process and is based on the notion that a thin plasma channel can travel by ionizing the gas in front of a charged head of the plasma channel by the strong field of the head.

Both steady-state and transient plasmas can be used to deposit and etch materials near the tip. Transient plasmas can achieve smaller deposition/etch spots, but may occur randomly. To reduce randomness, the AFM tip and associated electrodes can be designed with reduced symmetry to favor transient plasma formation in a well-defined region. FIG. 7 schematically shows how ionization near the tip in combination with gas flow and tip geometry can be used to deposit/etch with high spatial resolution. For example, gases 410 are delivered adjacent to a negatively charged nanotip 405. The charge of the nanotip causes the gases to excite and decompose into positively 425 and negatively 430 charged components. The positively charged components form a solid product 420 on a substrate 415 and the negatively charged components are repelled by the charge of the tip.

Due to a small gap size of a few micrometers, the present device works in the “near-field” or the “circuit” limit even when the electrodes are excited with millimeter waves of $100\text{-}300\ \text{GHz}$ frequencies. Thus, the classical models of plasma do not appear to apply. As

soon as the gas molecules are ionized, the molecules are separated and traverse the gap region as described above. The impedance of the AFM electrodes is capacitive before the gas breakdown and inductive afterwards. By adjusting the impedance matching circuit during the gas breakdown, an efficient scheme can be devised to transfer maximum energy to dissociate gas molecules near the electrodes. The impedance matching can be accomplished using a manual technique by monitoring the reflected wave amplitude and minimizing the reflected wave to maximize energy transfer. The impedance matching can also be accomplished automatically using a variable capacitor device controlled by a microcontroller. A combination of gas pressure, flow rates, and ionization parameters can be used to deposit and etch within the desired spatial resolutions. For example, very high quality dots can be deposited using a slow deposition rate and careful control of ionic species near the dot during deposition. High flow rates use a larger electronic current, which leads to high deposition rates, while lower flow rates are desirable for low deposition rates. Environmental parameters, such as humidity, and contaminants, such hydrocarbons, CO₂, and the like may affect growth more substantially at low deposition rates. As a result, carrier gases can be used to control the growth environment.

To increase reproducible and high-quality deposition and etching of nanoparticles, the starting surface can be cleaned. Moisture and hydrocarbons are common contamination layers on electronic materials in laboratory environments. A sample can be cleaned immediately before an AFM-assisted nanofabrication step by using standard degreasing and decontamination procedures followed by heating the sample to approximately 300° C in high-purity argon flow for about 30 minutes to remove most of the contaminants. The functionalized probe can be used in an etching mode to locally etch or clean the sample before a deposition step. These steps are compatible with CMOS (complementary metal-oxide-semiconductor) and silicon-based integrated circuits and do not adversely affect electronic properties of any existing devices on the sample.

In a specific example, controlled deposition of silicon quantum dots can be performed using silane and argon (SiH₄+ Ar). Silane can be dissociated near the AFM apex by the strong field generated between the tip electrodes and the electrons injected by the tunneling current. Extensive literature has been devoted to species generated in SiH₄ discharge. SiH₄ has a heat of formation of 34.3 J/mol and a Si-H bond distance of 0.15 nm. SiH₃ and SiH₂ radicals are important precursors for silicon deposition. The SiH₃-H, SiH₂-H, SiH-H, and Si-H bond energies are respectively 3.9 eV, 3.0 eV, 3.4 eV, and 3.0 eV. Rate constants for

formation of these radicals have also been extensively studied. Most existing models of silicon deposition from SiH_4 (with hydrogen or argon carrier gases) are based on processes that occur in large reactors with high and uniform substrate temperatures (such as 700-1000° C, for example) and large ion kinetic energies. In contrast, the entire reactor for the present technology is located underneath the tip and many parameters are highly non-uniform. In the narrow gap between the AFM electrodes the primary processes involving electron impact reactions dominate, whereas neutral-neutral and positive ion-neutral reactions are seemingly less important.

Mass spectrometry and/or ion mobility spectroscopy can be performed to analyze reaction products generated by the functionalized AFM probe as a function of pressure, excitation voltage and carrier gas ratio. To ensure compatibility with existing CMOS or other electronics on the sample, external sources of energy that are used in addition to the electrical excitation of the electrodes are typically limited to include energy sources such as photo-excitation, illumination with an external (low power ~ mW) microwave, and moderate heating of the substrate, which heating is generally limited at a high end to around 400° C. A UV (ultraviolet) fiber optic illumination source, moderate substrate heating, and illumination using an external low-power microwave source, in addition to the excitation voltage applied to the electrodes, can be used together, for example. The conical AFM tip can be used as a concentrator antenna to focus energy to the apex region to deposit very high quality silicon quantum dots in a very controlled manner. Post deposition rapid thermal annealing can also be used to further improve quantum dot properties.

In another example, argon ions (Ar^+) can be generated near the functionalized AFM tip in a similar fashion to SiH_4 radicals discussed above. The Ar^+ ions can be used to physically remove deposited silicon to correct the quantum dot dimensions. Other gases such as He (helium), Xe (xenon), and nitrogen can also be used for plasma generation. This “ion milling” mode of material removal is non-reactive and can be used to remove semiconductor materials, as well as oxide and metal materials. To direct an appreciable component of the kinetic energy of the Ar^+ ions toward the insulating substrate, an evanescent field profile near the tip will preferably have a large component perpendicular to the insulating substrate. This condition can be achieved by carefully maximizing the capacitive coupling of the probe electrodes through the insulating substrate as shown in the finite element model of FIG. 8. FIG. 8 illustrates capacitive coupling C_{at} with the Argon between the Electrodes and the Tip, capacitive coupling C_a with the Argon between the tip and the SiO_2 substrate, capacitive

coupling C_e between the electrodes and the substrate, and capacitive coupling C_s between the electrodes and tip within the substrate. The Ar^+ can also be used to activate surface-adsorbed SF_6 molecules to reactively etch materials to achieve higher etch rates if desired.

Referring now to FIG. 9a, a functionalized AFM probe 600 with integrated electrodes 605, sensors and actuators is schematically shown. The cantilevered arm length is shortened merely for convenience in illustration. A fabrication process of the probe can be carried out using conventional lithography techniques and, in one example, consists of three different processes of beam formation using bulk micromachining, electrode formation, and channel 602 formation. The fabrication process will be described in further detail below.

Piezoresistive position sensors 610, 615 and piezoelectric actuators 620 can be used for y-z directed actuations as shown in FIGs. 9b-9d. For example, FIG. 9b illustrates use of the sensors and actuators substantially simultaneously in a common direction on both sides of the tip 625 to move the device up and down uniformly with respect to a substrate 630 or sample. FIGs. 9c-9d illustrate use of the sensors and actuators substantially simultaneously on both sides of the tip in substantially opposite directions to tilt or turn the device one direction or another with respect to the substrate.

Referring now to FIG. 10, a 4-channel ASIC (application-specific integrated circuit) 710 can provide sensor/actuation/control electronics for the microfabrication device. The ASIC can similarly provide a convenient interface to a computer which can host a process or control system. In the example of the 30-tip system described above, the system can be built using a single PCB (printed circuit board) with eight of the ASICs. The ASIC can be formed using a conventional 1.5- μm mixed-signal CMOS process with lightly doped drain (LDD) transistors for high-voltage operation using n-well and p-base layers as drain junctions and second poly layer as the gate.

To address control of tip deflection using the electronics, a mixed-signal approach can be provided using a binary (digital) output driver using pulse-density modulation (PDM). PDM can be readily implemented in mixed-signal CMOS technology in the form of a sigma-delta tracking loop, as illustrated in FIG.10. The comparator 715 can be clocked at about 100 times a resonance frequency, such as at 5 MHz for example, and the result of the comparison can be used to actuate the high-voltage binary driver 720 in the desired direction to maintain the set point 730. The high Q (resonator quality factor) of the cantilever beam (~ 100) can act as a two-pole filter that destabilizes the sigma-delta tracking loop. As in a linear analog approach, however, the loop can be stabilized by inserting a zero in the frequency response

(i.e., a differential predictor 725) prior to the comparator, as illustrated in FIG. 10. The error signal generated at any given x-y location is proportional to the height variations at that location and can be used to construct the topography image of the sample. Onboard electronics can be provided to generate voltage pulses for deposition/etching of quantum dots. These pulses can be synchronized with the sense/control/imaging electronics using a computer.

Controlled deposition and etching of silicon quantum dots over SiO₂ can be performed to produce 50 +/- 5 nm and 80 +/- 8 nm diameters dots (1/min) with nominal thickness of ~10 nm located at 50 nm from a land mark using the AFM-compatible probes with integrated electrodes and micro-channels. The tip stand-off distance can be sensed with a resolution of 20 nm of the surface and tip height (7 μm) deterioration less than 10% with tip radius (10 nm) deterioration less than 20% after 100 operations. Controlled deposition, etching and imaging of silicon quantum dots over SiO₂ using 5-probe arrays has been demonstrated to produce twenty five dots (5/min/tip) with diameters ranging from 60 +/- 2 nm to 100 +/- 3 nm with 10 nm increments and with thicknesses ranging from 10 +/- 0.3 nm to 30 +/- 0.9 nm with 5 nm increments. These dots can be located within 25 nm distance from a reference landmark. The tip stand-off distances can be sensed with 10 nm resolution while tip height (7 μm) deterioration can be less than 5% and tip radius (10 nm) deterioration can be less than 10% after 1000 operations.

The underlying mechanics of the deposition techniques will now be described. The probe structure includes a conical tip with a conducting apex that is co-axially located with an electrode ring at the bottom of the tip's insulating outer region. A channel etched between the inner cone and the outer insulator introduces and delivers gases to the region between the probe apex and a sample. A static and or alternating potential between the apex and the tip electrode ring causes dissociation, and in some cases ionization, of the gas molecules near the tip, leading to deposition of solid material over the substrate under the probe apex.

Gas mean free path in 1 atmosphere pressure at room temperature is around 0.1 μm and in examples where the probe channel cross-section is around a few μm², the flow rates may be low and the gas in the channel may be pressure driven. The ionization products near the tip will be removed by a slight vacuum that will also help to drive the gas molecules through the narrow channels.

In the gas-phase deposition technique, the probe can be used as a nano plasma torch, or nanotorch, by using an etching gas instead of a metal-organic gas. Some non-exhaustive

examples of etching gases include oxygen, fluorine, chlorine, and the like, as well as gases which are oxygenated, fluorinated, chlorinated, etc. Two or more channels around the tip can be used to flow two or more types of different gases near the tip for deposition and subsequent etching. In this case, the ionizing source will be the cold cathode tip or ionized gases can be introduced to the channel and guided by the electrode fields. In liquid-phase deposition, the tip can be used as an electrochemical probe where the tip polarity is reversed to etch and reversed again to deposit. Etching liquid can be introduced using one of the channels while the other channel carries the deposition liquid. In colloid-phase deposition, the tip polarity can be reversed to remove the nanoparticles by attracting the particles to the tip.

The tip can be used as a nano-plasma torch, an electron source, or electrostatic tweezers depending on how the tip is operated. In each of these examples the probe can be used to etch the deposited materials or nano-particles.

Microplasmas are miniaturized glow discharges that operate at high pressures (> 1 atm) and small dimensional scales (< 100 microns). Microplasmas are typically formed between two metal electrodes, a cathode with a pin-hole ($d < 100$ microns) and an arbitrarily shaped anode. As a result of the high electric fields created by the cathode cavity, microplasmas contain large concentrations of high-energy electrons (tunneling through the cold cathode tip, etc.) which allow rapid disassociation of gases. Other electron sources for gas ionization, such as implanted radioactive materials and the like, such as those used in smoke detectors, can also be used. Microplasmas are well-suited to non-lithographic applications in materials processing. Since microplasmas can be operated over small dimensions, an approach to etching (or deposition) would be to use a stencil mask which transfers the pattern directly. Microplasmas in flexible copper-polyimide structures have been used to pattern silicon using CF_4/Ar chemistry. Further scaling down of the plasma source can enable direct patterning of nanoscale structures on substrates.

In FIG. 11, a photo of a microplasma array is shown made-up of 20×20 $100 \mu m$ diameter holes. The gas flows through channels with a diameter of $20 \mu m$. As smaller scales are approached, these plasmas allow micro- and nanostructured materials to be created directly on substrates. Thus, microplasma operation can be combined with AFM technology to directly grow or deposit nanostructures on various substrates. Towards this end, a microplasma source can be designed and fabricated that operates on a significantly smaller scale, such as less than 100 nm in dimension. A single microplasma source can be used to

etch and/or deposit nanostructures on substrates. The microplasma source can be scaled down to less than 100 nm to allow direct synthesis of metal or semiconductor nanostructures. The properties of the microplasma source can be a function of several operating parameters, including but not limited to: plasma power, gas flow rate, pressure, and gap between the plasma and substrate. Single structures with dimensions less than 10 nm using a single microplasma source can be obtained, depending on the parameters chosen.

Microplasma arrays can be fabricated by microfabrication techniques that allow the device geometry to be modified easily. Ordered nanostructure arrays can be grown on substrates in parallel. In addition, the gas flows in the microplasma device can be independently controlled to allow the growth conditions in individual plasmas to be varied.

Referring to FIG. 12, a flow diagram of a method 900 of nanofabrication is illustrated. The method can include positioning 910 a conducting nanotip in a desired location proximal to a substrate. The desired location can be the location where etching, deposition, or imaging is desired. The location proximal to the substrate can be sufficient to enable the capacitive coupling described above, which may vary depending on operating conditions and materials. The method can further include delivering 920 a precursor gas to the nanotip through a gas microchannel adjacent to the nanotip and decomposing 930 the precursor gas to form a solid product by exposing the precursor gas to an electric field using the nanotip such that the solid product deposits on the substrate.

As has been described, the substrate can be an insulating substrate. The step of positioning 910 can therefore include positioning the conducting nanotip in the desired location proximal to the insulating substrate. The step of decomposing can include decomposing the gas over the insulating substrate.

In a variation or alternative to the method 900, or as a corollary to the method, the nanotip can be positioned in a location proximal to the solid product. A same or different precursor gas can be delivered to the nanotip through the gas microchannel. The precursor gas can be decomposed into argon ions by exposing the same or different precursor gas to an electric field using the nanotip, and the solid product on the insulating substrate can be etched using the argon ions. Ions other than argon ions may also be used in the etching process.

In one aspect, reversing a polarity of the electric field will switch the device or method between causing the solid product to be deposited on the substrate and etching the solid product on the substrate.

Where the device includes an array of nanotips and gas-delivering microchannels, the method 900 can include positioning the array of nanotips, delivering the precursor gas to the array of nanotips through the array of gas microchannels adjacent to the array of nanotips, and decomposing the precursor gas using the array of nanotips (or rather the electric field generated by or near the array of nanotips).

The method 900 can include multiple common or different precursor gases substantially simultaneously either to different nanotips each being associated with a respective microchannel or to a common nanotip being associated with a plurality of microchannels which exit to deliver precursor gases to a common nanotip.

The method 900 can include sensing and actuating movement of a direction of the nanotip in a plurality of directions using a piezoresistive position sensor and a piezoelectric actuator, which can be integrally formed with the nanofabrication device.

Also, the method 900 can include decomposing comprised of transient plasma discharge decomposition as has been described above in relation to FIG. 11.

A more specific example of gas phase deposition will now be described. To calculate the electric field, current and the speed of deposition, a cylinder underneath the probe that approximately encloses the reaction region can be selected. At one atmosphere (0.1 MPa) and at 50°C, the volume enclosed by a cylinder of 100 Å height and 100 Å diameter, will contain approximately 18 atoms. Using a moderate voltage of approximately 5 volts applied across the 100 Å gap, an electric field is produced of approximately 5×10^6 V/cm. (The breakdown field of air under these conditions is marginally higher than 6×10^6 V/cm). Pre-breakdown tunneling current flow may be approximately 0.3 nA. An electrostatic attraction exists between the tip and the substrate which may cause clamping, but this clamping can be prevented using commonly employed feedback mechanisms known in AFM technologies. The electric field generated will draw nearby gas molecules into the tip-ring electrode gap region due to a dipolar interaction. Once the gas molecule is situated in the high-field region near the tip, the tunneling electronic current is modified and assisted through the electronic transitions in the localized gas molecule. This apex-molecule-electrode double junction provides a mechanism to “pump” electrons into the gas molecule that, in addition to decomposing the molecule, may ionize the gas molecule under proper conditions. The power dissipated in the gap is approximately $5 \times 0.1 \times 10^{-9} = 500$ pW. This power will increase the temperature of the gap (mainly the electrons in the gap) to in excess of a few thousand Kelvin locally in 1 ns. The temperature thus becomes sufficient to decompose the precursor gas.

Using the appropriate tip-substrate field polarity, the metallic ion can be directly deposited on various substrates.

Assuming that roughly 10 atoms are present at any given moment under the tip in the reaction region, and assuming that decomposition of the atoms takes approximately 1
5 nanosecond, the deposition rate would be 10 atoms per nanosecond or 10^{10} atoms per second. A strip of 100 Å width and 1 μm length with 100 Å thickness contains $\approx 10^9$ atoms (assuming 5 Å lattice constant) and would thus be deposited in approximately 0.1 second.

Metal substrates, such as Mo(CO)_6 and W(CO)_6 start to decompose at about 150° C. Mo (molybdenum) and W (tungsten) have been deposited by thermal decomposition of the
10 Mo or W vapor to produce the metal (Mo or W) and carbon monoxide (CO). If the deposition temperature is low around 250°C, the films become highly contaminated with CO. However, at temperatures of about 500°C the process produces very pure deposits. The temperature is equivalent to a kinetic energy 0.04 eV. If nanoprobe tips are used with a top voltage of 5V (5×10^6 V/cm gradient), there is more than sufficient energy to decompose the
15 compounds completely.

The metal atoms are attracted to the substrate by van der Waals forces (dipolar interactions) or by Coulombic forces if the atoms are ionized. Because generating a positive charge on the metal is typically easier than generating a negative charge, the probe tip will generally be positively charged to “extract” electrons from electrically (dipolar) trapped gas
20 molecules near the tip. The carrier gas (e.g., argon) and the metal atom are both charged and attracted to the negative substrate, decomposing more metal carbonyl molecules on the way toward the substrate.

The vapor pressures of metal carbonyls may be low at room temperature but are still much higher than those of the other compounds studied for CVD (chemical vapor
25 deposition). Mo(CO)_6 boils at 153°C, at which temperature the Mo(CO)_6 decomposes slowly. Deposition can be run at 100° C with a vapor pressure of several hundred mm for the compound. W(CO)_6 boils at 175°C and will have a slightly lower vapor pressure than Mo(CO)_6 at any given temperature. However, both Mo(CO)_6 and W(CO)_6 compounds are volatile enough to achieve rapid deposition of the metal under the conditions generated under
30 the probe’s apex.

A similar principle can be applied to generate metal oxides, except that oxygen may be used to prevent partial reduction of the oxide or the formation of silicon carbide. SiO_2 can be made from tetramethoxy silane (bp = 122°C), trimethyl silane (bp = 6.7 °C) or dimethyl

silane (bp=-20 °C). Similarly, Al₂O₃ can be made using aluminum isopropoxide (bp=140.5 °C at 8 mm pressure) in the presence of oxygen. This is safer than using trimethyl aluminum (bp=20°C), which is pyrophoric and can react spontaneously with O₂. The advantage of using the metal alcoholates is that the metal alcoholates are completely stable in the presence of oxygen at room temperature. However, the organic fragments generated under the probe tip can react rapidly to H₂O and CO₂, leaving SiO₂ or Al₂O₃ as the remaining non-volatile product. The probe energy can be adjusted so that the effective temperature of the fragments will be approximately 1000 K, or high enough that all organic material is oxidized (by injecting tunneling ions) while maintaining stability of the oxides.

Many semiconductors can be deposited. Some specific examples include GaN (gallium nitride), Si (silicon), SiC (silicon carbide), and Graphene. However, many other semiconductor materials can also be deposited. GaN can be generated from gallium triethyl and an amino (such as ammonia) precursor. If this forms a stable complex that deposits on all surfaces, triethyl amine can be used. Alternatively, gallium chloride (bp = 201.3 °C) can be used as a precursor and which is easier to manage. Silicon and SiC can be deposited using silane and trimethylsilane. Graphene can be deposited using methane. Nickel quantum dots can be deposited first as catalysts. Other catalysts can also be used, depending on the corresponding precursor. The current generated near the apex is billions of times larger than the number of molecules under the probe tip. At 1-10 eV energy and in the presence of ~1 nA tunneling electronic current, molecules can be heated up to a few thousand Kelvin. The molecules can be effectively fragmented with individual atoms and ions. The ions are attracted to the substrate, neutralized and quenched to give the final deposited layer. The effective temperature can be adjusted so that the semiconductor fragments are stable and can be deposited stably. Outside the active area, any residual fragments are diluted sufficiently rapidly that there is little or no contamination.

Non-limiting examples of other semiconductor materials can include group IV materials, compounds and alloys comprised of materials from groups II and VI, compounds and alloys comprised of materials from groups III and V, and combinations thereof. More specifically, exemplary group IV materials can include silicon, carbon (e.g. diamond), germanium, and combinations thereof. Various exemplary combinations of group IV materials can include silicon carbide (SiC) and silicon germanium (SiGe). In one specific aspect, the semiconductor material can be or include silicon. Exemplary silicon materials can include amorphous silicon (a-Si), microcrystalline silicon, multicrystalline silicon, and

monocrystalline silicon, as well as other crystal types. In another aspect, the semiconductor material can include at least one of silicon, carbon, germanium, aluminum nitride, gallium nitride, indium gallium arsenide, aluminum gallium arsenide, and combinations thereof.

Exemplary combinations of group II-VI materials can include cadmium selenide
 5 (CdSe), cadmium sulfide (CdS), cadmium telluride (CdTe), zinc oxide (ZnO), zinc selenide (ZnSe), zinc sulfide (ZnS), zinc telluride (ZnTe), cadmium zinc telluride (CdZnTe, CZT), mercury cadmium telluride (HgCdTe), mercury zinc telluride (HgZnTe), mercury zinc selenide (HgZnSe), and combinations thereof.

Exemplary combinations of group III-V materials can include aluminum antimonide
 10 (AlSb), aluminum arsenide (AlAs), aluminum nitride (AlN), aluminum phosphide (AlP), boron nitride (BN), boron phosphide (BP), boron arsenide (BAs), gallium antimonide (GaSb), gallium arsenide (GaAs), gallium nitride (GaN), gallium phosphide (GaP), indium antimonide (InSb), indium arsenide (InAs), indium nitride (InN), indium phosphide (InP), aluminum gallium arsenide (AlGaAs, Al_xGa_{1-x}As), indium gallium arsenide (InGaAs,
 15 In_xGa_{1-x}As), indium gallium phosphide (InGaP), aluminum indium arsenide (AlInAs), aluminum indium antimonide (AlInSb), gallium arsenide nitride (GaAsN), gallium arsenide phosphide (GaAsP), aluminum gallium nitride (AlGaN), aluminum gallium phosphide (AlGaP), indium gallium nitride (InGaN), indium arsenide antimonide (InAsSb), indium gallium antimonide (InGaSb), aluminum gallium indium phosphide (AlGaInP), aluminum
 20 gallium arsenide phosphide (AlGaAsP), indium gallium arsenide phosphide (InGaAsP), aluminum indium arsenide phosphide (AlInAsP), aluminum gallium arsenide nitride (AlGaAsN), indium gallium arsenide nitride (InGaAsN), indium aluminum arsenide nitride (InAlAsN), gallium arsenide antimonide nitride (GaAsSbN), gallium indium nitride arsenide antimonide (GaInNAsSb), gallium indium arsenide antimonide phosphide (GaInAsSbP), and
 25 combinations thereof.

A high vacuum chamber 1000, as depicted in FIG. 13, can be used to examine the conditions for depositing materials from precursor gases using field and electron-assisted decomposition and ionization of gas molecules. In FIG. 13, a carrier gas inlet enables the carrier gas to enter the vacuum chamber. One or more same or different gases 1015 can be
 30 used separately or in combination with the gas from the carrier gas inlet, and may be heated using heaters 1020 before entering the vacuum chamber. The influx of the gas(es) can provide a sublimation stage in which sufficient temperatures and pressures cause a substance to endothermically transition from a solid phase to a gas phase without an intermediate liquid

phase. An x-y stage 1025 with a heater can be provided for a deposition stage of the process over which the nanotip can operate to deposit, etch, or image a sample. Gases can exit through the outlet, which may be a vacuum-type outlet.

FIG. 14 is a block diagram side view of a fabrication system 1100 including different micro-chambers 1115 enclosing groups of parallel local probes 1110 to deposit different materials 1120 in parallel on a substrate 1125 or other layer 1130 in accordance with an example of the present technology.

Because some precursors may be unstable in air or flammable, neutral carrier gases and a moderately low vacuum can be used to remove reactive gas species and reduce exposure to ambient oxygen. This can be easily accomplished using a “global” vacuum chamber 1200 schematically shown in FIG. 15 where scanning probes 1210 are enclosed in micro-chambers 1215 with gas supply lines 1220. Arrows indicate the flow of gas into and out of the micro-chambers. Micro-pumps and valves are all fabricated on silicon using MEMS (microelectromechanical systems) technology. Parallel local probes deposit patches of semiconductors, metals, and insulators over the substrate 1225. The probes with two-axis control combined with linear motion of the substrate underneath the probes (using a linear motor) have sufficient degrees of freedom to deposit quantum dots, tubes, wires, and the like.

The semiconductor materials of the present disclosure can be made using a variety of manufacturing processes. In some cases the manufacturing procedures can affect the efficiency of the device, and may be taken into account in achieving a desired result. Exemplary manufacturing processes can include Czochralski (Cz) processes, magnetic Czochralski (mCz) processes, Float Zone (FZ) processes, epitaxial growth or deposition processes, and the like. It is contemplated that the semiconductor materials used in the present invention can be a combination of monocrystalline material with epitaxially grown layers formed thereon.

The probes with integrated microfluidic channels are capable of forming extremely localized (~5-10 nm spot size) plasma-deposition and etching of electronic materials. FIGs. 16a-b show side cross-sectional and top views of a nanotorch probe 1300. The device includes an oxidation sharpened polysilicon tip 1310 coated with a thin layer of refractory metal 1315, SiC or diamond and the tip is protruding out of the interior of a microchannel 1320 through a small (~3 μ m) orifice 1325. A strong refractory metal is desirable to (a) prevent erosion of the tip during etching, and (b) plasma cleaning of any deposited material in a deposition mode. The entire structure can be suspended on a silicon nitride cantilever 1330.

The substrate 1335 and cantilever can be mounted on a conventional high-resolution AFM micromanipulator stage with <5 nm positioning resolution. Probes with integrated sense and actuation can be fabricated. The back of the cantilever tip is also coated with a thin reflective metal layer 1340 used to optically determine the vertical tip displacement. To generate nano-plasma, reactive gases (such as SF₆, CHF₃, etc. for etching for example) are introduced into the microchannel inlet 1345. This flow exits the microchannel at the orifice. When a potential difference of a few dozen volts is established between the conductive microchannel walls and the tip, the very high electric field and tunneling electron current (cold cathode emission) present at the sharp tip creates a highly confined plasma region where reactive species responsible for the etching and deposition are generated. These reactive species are transported upwards by the incoming flow toward a sample. In this device, controlled localized etching and deposition is accomplished through: (a) an active gas delivery system that ensures a continuous transfer of new reactive species exiting the tip area and (b) highly localized electric fields near the tip.

A fabrication process can be used in fabricating co-axial tips similar to the tip shown in the SEM image of FIG. 4c. LPCVD (low-pressure chemical vapor deposition) oxide and photoresist can be used as sacrificial layers, oxidation sharpening can be used to form sharp tips, and a thick-photoresist process can be used to pattern co-axial metallic layers above the tip region. The probe shown in FIGs. 16a-b has only one channel. Two or more channel probes along with multiple electrodes connected to apex (highly doped silicon region), tip ring electrode, and top electrodes can also be fabricated.

A nanofabrication device can be fabricated as shown in FIGs. 16a-16e. A 2 μm layer of low-stress silicon nitride (Si₃N₄) 1315 is deposited on a silicon (Si) substrate 1310 to provide structural support for the cantilever tip beam. An opening 1320 is etched for a backside access hole. An oxide layer 1325 can form in the access hole and may have a thickness of approximately 0.4 μm. A 6 μm layer of doped LPCVD polysilicon 1330 is deposited over the silicon nitride. The polysilicon can be patterned to form the tip apex and leave a polysilicon layer with a thickness of approximately 1 μm on top of the silicon nitride. Polysilicon piezoresistors 1335 and interconnect lines 1340 to the tip can be defined. The tip can be sharpened by oxidation and a Cr layer 1345 is sputtered and patterned to metalize and harden the tip. A 1 μm of PSG (phosphosilicate glass) sacrificial layer 1350 can be patterned to form the microchannel. A 2 μm wall layer 1355 of low stress Si₃N₄ is deposited to serve as the wall for the channel and piezoresistor passivation. Contact holes 1360a, 1360b are

opened for the piezoresistors and the tip. A lead layer 1365 of Cr/Au is sputtered and patterned to form the electrode leads. Next holes are opened on the Si_3N_4 down to the silicon. A 10 μm layer 1370 of polyimide is spin coated over the structure, which keeps the entire structure frozen while the backside is etched. Backside openings 1375a, 1375b for the gas access hole and beam regions are defined. The wafer backside is etched in a DRIE (deep reactive-ion etch) etchant and half diced. The structure or wafer is exposed to an extended O_2 plasma that releases the entire structure, including from the polyimide spin coat layer. The microchannel is released by sacrificially etching the PSG in HF (hydrofluoric acid). FIGs. 17a-17d show SEM photographs of the device. The cantilever beam 1410 is shown extending from a substrate 1415 in FIGs. 17a-17b. Piezoresistors 1420a, 1420b, a ring electrode 1425 and a tip 1430 are shown in FIG. 17c. The ring electrode 1435, apex 1440, and micro-channel 1445 are visible in FIG. 17d. The device manufactured according to this process was successfully tested in an O_2 environment at atmospheric conditions and with an AC voltage of 1000 V.

Referring to FIG. 18, a flow diagram of a method 1500 of manufacturing or fabricating a nanofabrication device is shown in accordance with an example of the present technology. The method is similar in many regards to the fabrication process described above, and includes depositing 1510 a base material for use as nanotip on a substrate. A sacrificial layer is deposited 1520 over the base material. A microchannel layer is then deposited 1530 over the sacrificial layer. The sacrificial layer can be dissolved 1540, leaving a microchannel between the microchannel layer and the base material. The base material can be oxidized 1550 to sharpen the base material to form the nanotip. As may be appreciated, the steps of the method are not necessarily in the order presented in the figure, and there may be some degree of interchangeability in the order in which the steps are performed in this method or any other methods or processes described herein.

The method 1500 can further include patterning co-axial metallic layers on the microchannel layer around the nanotip to form a ring electrode around the nanotip.

In one aspect, the nanofabrication device being fabricated can be used to fabricate other nanofabrication devices. Thus, for example, the steps of depositing can be performed using a nanofabrication device comprising a conducting nanotip and a gas microchannel adjacent to the nanotip, the gas microchannel being configured to deliver a gas to the nanotip. In another example, the substrate can be cleaned prior to depositing the base material using the nanofabrication device.

SiC and Diamond-like films can be used to improve the reliability and longevity of the AFM cantilever tips by incorporating these films into the high-wear regions of the structures. Diamond deposition is similar to SiC deposition which will be briefly discussed here. SiC is a desirable choice as a tribological coating, due to chemical inertness, high hardness, and mechanical durability. SiC is also desirable because of an inherent compatibility with Si substrates. One example implementation can utilize single crystal 3C-SiC films applied to Si-based tips while another example implementation can use amorphous hydrogenated SiC films on silicon and silicon nitride based structures. Single crystal 3C-SiC films can be grown directly on Si when using a growth process that involves conversion of the Si surface to 3C-SiC by a process called carbonization. Carbonization is typically performed by exposing a heated Si surface to a gaseous mixture at atmospheric pressure consisting of a hydrocarbon gas that is highly diluted in hydrogen. The substrate temperatures are typically in excess of 1000°C. The carbonization-based 3C-SiC films exhibit the properties required of a high quality tribological coating on Si-based AFM tips. An interface between the 3C-SiC layer and the underlying film will generally be continuous and absent of interfacial voids.

Using conducting substrates, the silicon probe apex can be heated by passing a tunneling current that will carbonize the tip in the presence of methane. Carbonization is temperature and material dependent, so non-Si regions will not be coated as well as Si regions that are below the threshold temperature for carbonization. As a consequence, carbonization, and SiC growth, will occur in the region in which the coating is desired. This process can be repeated to maintain the tip after a few runs. Another method involves the use of amorphous hydrogenated SiC (a-SiC:H) films deposited by PECVD and offers several distinct advantages over carbonization, namely that the substrate temperatures are substantially lower (350°C) and the coatings can be applied directly to a very wide range of substrate materials, including metals, SiO₂ and Si₃N₄. PECVD processes can be self-applied using these probes. A PECVD process for a-SiC:H can use trimethylsilane as the precursor for use as a solid lubricant in MEMS. Trimethylsilane can be used along with appropriate voltage pulses (polarity and amplitude) to coat the tips with SiC. A molding technique can be used to fabricate SiC and Diamond tips.

Ion-implanted piezoresistive sensors can be integrated on the cantilever beam arm as described to sense the beam deflection caused by the sample pushing back on the tip. Shielding can be used to prevent the actuation voltage applied to the piezoelectric actuators

(tens of volts) from coupling to the μ volt changes detected across the piezoresistors to sense the tip position. Within 0.5-2 nm of the substrate, the vibration amplitude of the probe is modified due to loading effects by the substrate and vibration frequency and damping can be monitored using the piezoresistor or the piezoelectric signal to sense the substrate within 1-2 nm of the apex.

A piezoelectric actuator patch 1610 can be used as schematically shown in FIG. 19 to actuate the probe 1625 in the z-direction. The tip-sample interaction causes the beam to deflect changing the piezoresistors' value. To maintain a constant touching or interaction force, the change in piezoresistors' resistance is monitored and used to provide a feedback to the piezoelectric actuator. A PZT (piezoelectric transducer) ceramic and/or ZnO (zinc oxide) material can be suitable as piezoelectric materials, although other materials can also be used. The actuation of the probe tip parallel to the sample's surface can be achieved using thermal actuators 1615 integrated on a section of the probe arms 1620 as shown in the figure.

The piezoresistive sensing uses small voltages and currents to measure resistance of a wheatstone bridge. Piezoelectric actuation uses approximately 10-20 volts depending on d_{31} (piezo strain coefficient) of the material, and a poling state of the material that is used. PZT uses around 10 volts while ZnO uses a few tens of volts. The thermal actuation uses a few mA current at a few volts. Thus, these sense/actuate techniques are relatively low power and can be accomplished using mixed signal IC's. High-gain and up to a few MHz bandwidth amplifiers can be used to amplify micro-volt piezoresistor voltage changes to a few tens of volts necessary to actuate the piezoelectric actuators. The probes and associated sense/actuate/control electronics can be modular to enable large number of probes to operate simultaneously to comply with DARPA GNG metrics of a 30-tip array. Using extensive mixed-signal IC (integrated circuit) designs, a digital controller can be integrated with analog high gain amplifiers and high-voltage (10-20 volts) amplifiers. A block diagram of modular probe sense/control electronics is shown in FIG. 20.

A challenging aspect of this technology is to use the AFM tip to deposit a controlled amount of silicon from silane. The nature of field-ionization in the very narrow inter-electrode gap near the f-AFM tip makes the process somewhat random due to gas density fluctuations. To address this issue, mass spectroscopy, SEM, TEM and finite element modeling can be used to fine tune the deposition and etching parameters to deposit and etch/remove a precise amount of silicon. The arrangement of electrodes, the gap symmetry, the gap distance and the thickness of an insulator layer between the electrodes, the silane to

argon and hydrogen ratios, gas pressure and temperature and the excitation method(s) can be adjusted to improve the reproducibility of deposition/etching using the probe.

The functionalized probe tips can be configured to be compatible with existing AFM and can be directly used in the THERMO-MICROSCOPE and NANOSCOPE IV LPM systems. The relationship between the dot size, silane concentration, hydrogen concentration, chamber pressure, temperature, excitation energy and modality (stationary filed, pulsed field, RF, millimeter wave, UV photon energy and intensity, etc.), and the c-AFM tip radius and stand-off distance can be correlated. The electric excitation signal can be applied between the c-AFM tip and the conducting substrate. The UV light can be carried by a UV fiber optic and will illuminate the tip-sample gap. The microwave signal can also be applied externally illuminating the tip-sample region. This arrangement focuses the microwave energy inside the tip-sample gap and is an effective way of bringing in the microwave excitation to affect the gas ionization and does not have to deal with impedance matching in waveguiding the signal to the tip since the technique is a “free-space” technique.

EXAMPLES

While various examples have been provided above within the description of the technology, two additional examples are also provided below.

In one example, a conducting nanotip, such as an atomic force microscopy (AFM) tip or c-AFM tip, and a metallic substrate (nickel) to demonstrate deposition of silicon quantum dots with the ability to etch and correct their widths and lengths in less than 2 minutes. The two silicon quantum dots can be situated within 50 nm from a reference alignment object on the substrate. A suitable tip material (diamond-like carbon (DLC) and SiC coatings) can be selected to limit the wear in the conducting AFM tip after 100 such operations to less than 10% tip height and less than 20% radius variations. The thermo-microscope's laser probe sensing apparatus can be used to control tip height (from the sample) with better than 20 nm resolution.

In another example, the probes may deposit silicon dots at 1-10 atm Argon pressure with a few percent silane introduced directly nearly the AFM tip using a 100 μ m-diameter nozzle appropriately situated to not interfere with the AFM operation. The AFM-sample DC voltages of around 100 Volts with tip-sample stand-off distance of around 5 μ m can be used as the starting values. Voltage pulses (ns rise time and durations), as well as AC (6 MHz) signal, millimeter wave signals (100 GHz) externally directed on the AFM apex, and 400 nm UV light guided through UV fiber optic illuminating the AFM apex excitations can all be

examined to lower the energy needed for deposition, lower the pressure (to bring it down as close to 1 atmosphere as possible) and reduce the tip-sample distance to around 10-20 nm. The probe tip height variation of less than 10% and tip radius variations of less than 20% can be desirable for manufacturing consistency.

5 While the forgoing examples are illustrative of the principles of the present technology in one or more particular applications, it will be apparent to those of ordinary skill in the art that numerous modifications in form, usage and details of implementation can be made without the exercise of inventive faculty, and without departing from the principles and concepts of the technology. Accordingly, it is not intended that the technology be limited,
10 except as by the claims set forth below.

CLAIMS

What is claimed is:

1. A method of fabricating an electronic device, comprising:

forming a first metallic trace on a substrate, said first metallic trace being
5 configured to resonate in response to a first electromagnetic radiation and to focus
energy toward a first target deposition region;

inducing resonance in the first metallic trace by directing the first
electromagnetic radiation toward the first metallic trace to cause the first metallic
trace to resonate sufficient to heat the first target deposition region to a first
10 decomposition temperature of a first semiconductor precursor gas; and

exposing the heated first target deposition region to the first semiconductor
precursor gas so as to form a first semiconductor material layer over the first target
deposition region.

15 2. The method of claim 1, further comprising

forming a second metallic trace on the substrate, said second metallic trace
being configured to resonate in response to a second electromagnetic radiation and to
focus energy toward a second target deposition region;

inducing resonance in the second metallic trace by directing the second
20 electromagnetic radiation toward the second metallic trace to cause the second
metallic trace to resonate sufficient to heat the second target deposition region to a
second decomposition temperature of a second semiconductor precursor gas; and

exposing the heated second target deposition region to the second
semiconductor precursor gas so as to form a second semiconductor material layer over
25 the second target deposition region.

3. The method of claim 2, wherein the first semiconductor layer and the second
semiconductor layer are coplanar.

30 4. The method of claim 2, wherein the first metallic trace has a first dimension and
the second metallic trace has a second dimension different from the first dimension, the first
and second dimensions being determinative in whether the first or second metallic trace
resonates as a result of emitting the first or second electromagnetic radiation.

5. The method of claim 2, wherein the first metallic trace has a different orientation than the second metallic trace, and wherein orientations of the first and second metallic traces are determinative in whether the first or second metallic trace is caused to resonate as a result of emitting the first or second electromagnetic radiation.

6. The method of claim 5, wherein the first and second electromagnetic radiation comprise common frequencies and different polarizations.

7. The method of claim 1, further comprising patterning the first metallic trace prior to inducing resonance in the first metallic trace.

8. The method of claim 1, where the exposing is performed using a nanofabrication device, comprising:

a conducting nanotip; and
a gas microchannel adjacent to the nanotip and configured to deliver the first semiconductor precursor gas to the nanotip.

9. The method of claim 1, wherein the first metallic trace is shaped as a bow-tie.

10. The method of claim 1, wherein the first metallic trace includes a plurality of discrete resonant structures and the first target deposition region includes a corresponding plurality of deposition regions.

11. The method of claim 1, wherein the first decomposition temperature is at least 1100 °C.

12. The method of claim 1, wherein the first semiconductor layer is a channel.

13. The method of claim 1, wherein the electronic device is a field effect transistor or a light emitting diode.

14. An integrated circuit assembly, comprising:

a substrate;

a first metallic trace patterned over the substrate configured to resonate in response to a first incident electromagnetic radiation to form a first target deposition region;

5 an electromagnetic radiation source configured to emit the first electromagnetic radiation toward the first metallic trace; and

a first semiconductor precursor gas for decomposition and deposition over the first target deposition region in response to resonance of the first metallic trace when the electromagnetic radiation source emits the first electromagnetic radiation toward
10 the first metallic trace.

15 15. The integrated circuit assembly of claim 14, wherein the first metallic trace comprises a plurality of metallic traces patterned over the substrate so as to form a corresponding plurality of deposition regions.

16. The integrated circuit assembly of claim 14, further comprising:

a second metallic trace patterned over the substrate configured to resonate in response to a second incident electromagnetic radiation to form a second target deposition region.

20

17. The integrated circuit assembly of claim 16, wherein the first metallic trace and the second metallic trace are configured to resonate at a different frequency from one another.

25 18. The integrated circuit assembly of claim 16, wherein the first metallic trace and the second metallic trace are configured to resonate at a different frequency from one another.

19. The integrated circuit assembly of claim 16, wherein the first metallic trace and the second metallic trace are configured to resonate at a different polarization from one another based on respective orientation on the substrate.

30

20. The integrated circuit assembly of claim 16, wherein the substrate comprises plastic, ceramic, polymer, wood, textiles, composite thereof, or combination thereof.

21. The integrated circuit assembly of claim 16, wherein the first metallic trace comprises a plurality of bowtie antenna transistors with a gate of each of the plurality of bowtie antenna transistors oriented in a common direction and a drain and source of the plurality of bowtie antenna transistors oriented in opposite directions.

5

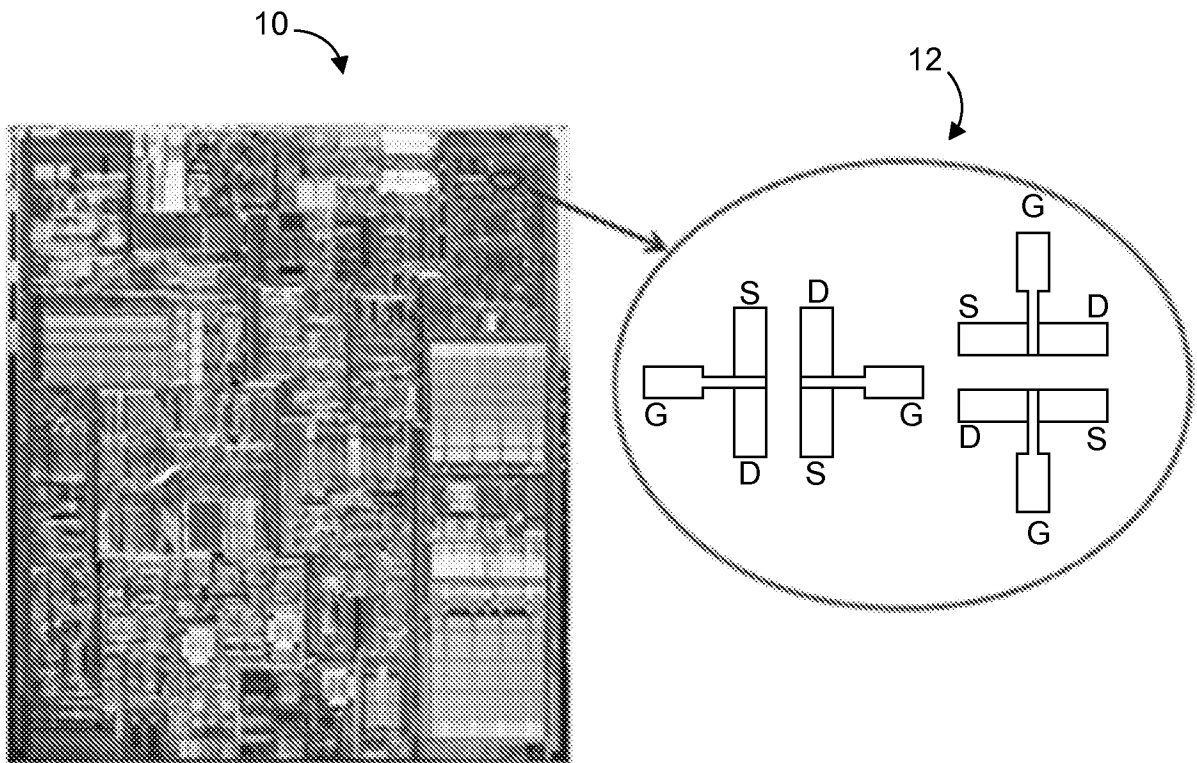


FIG. 1a

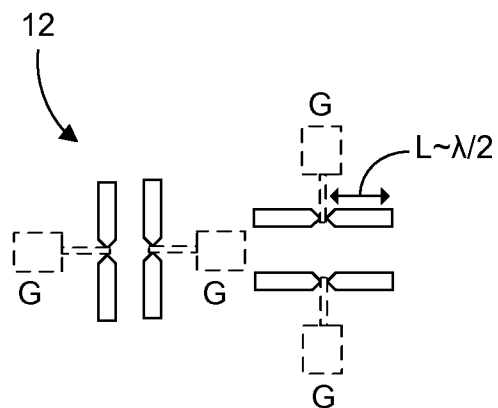


FIG. 1b

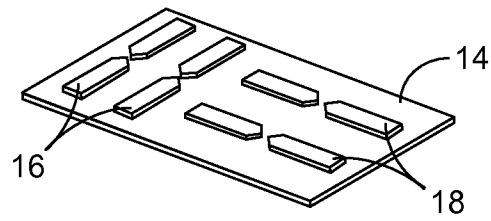


FIG. 2a

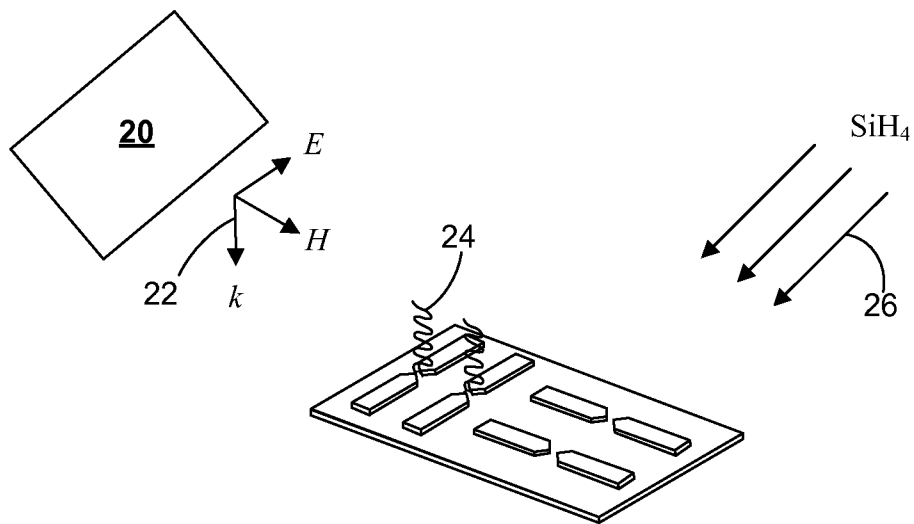


FIG. 2b

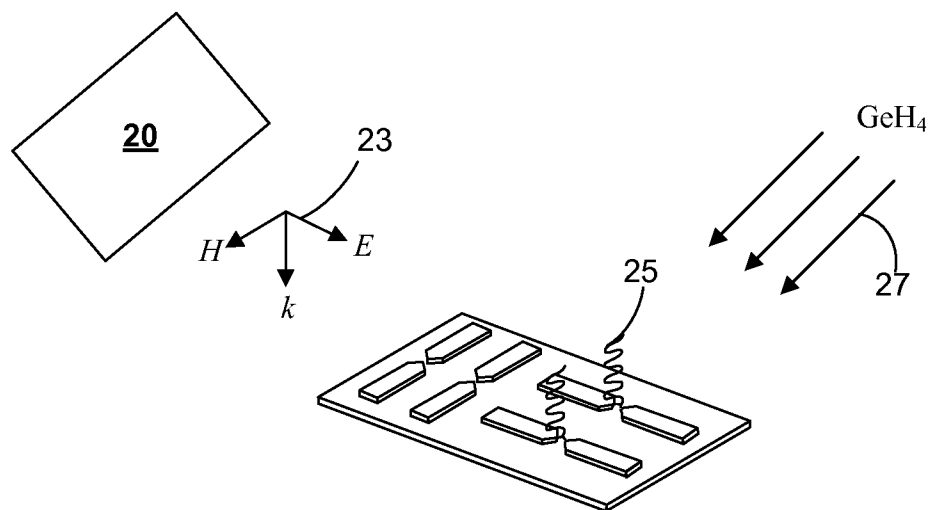


FIG. 2c

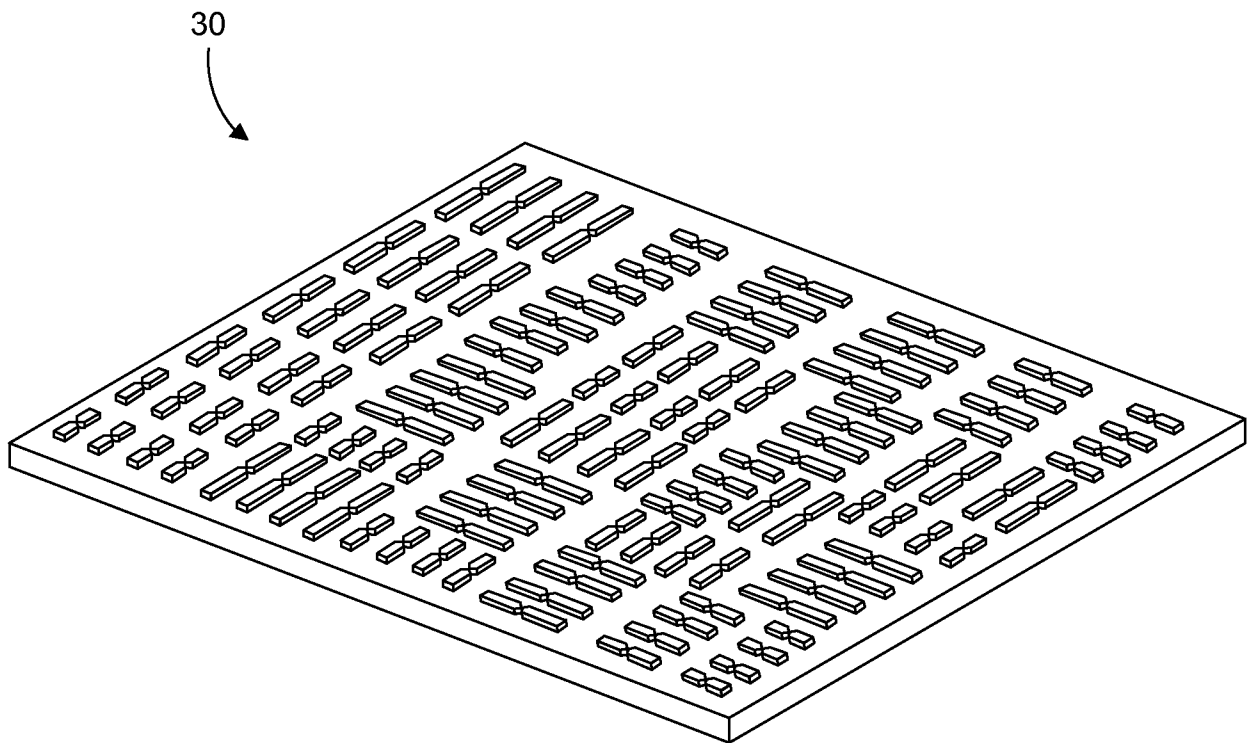


FIG. 2d

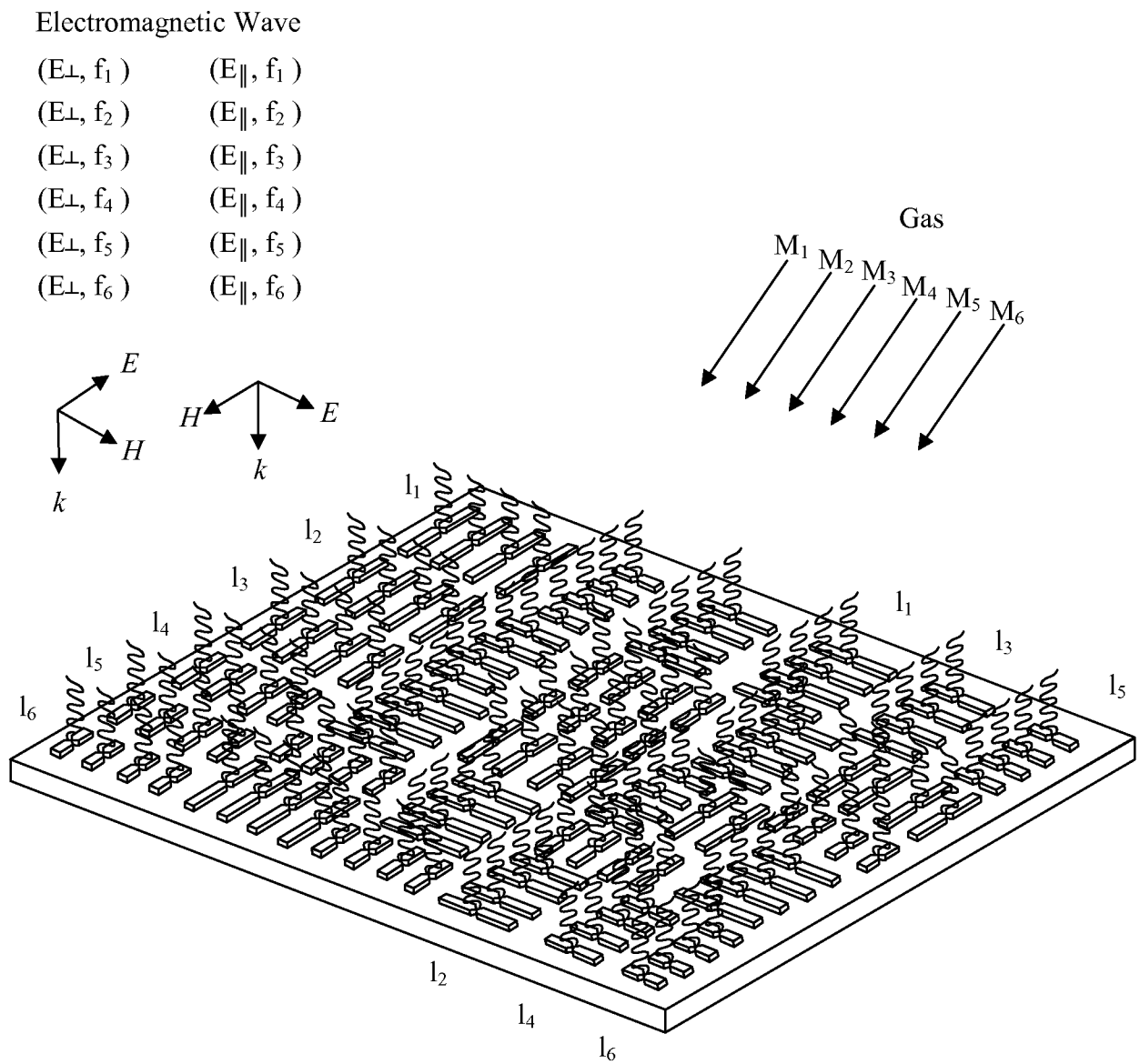


FIG. 2e

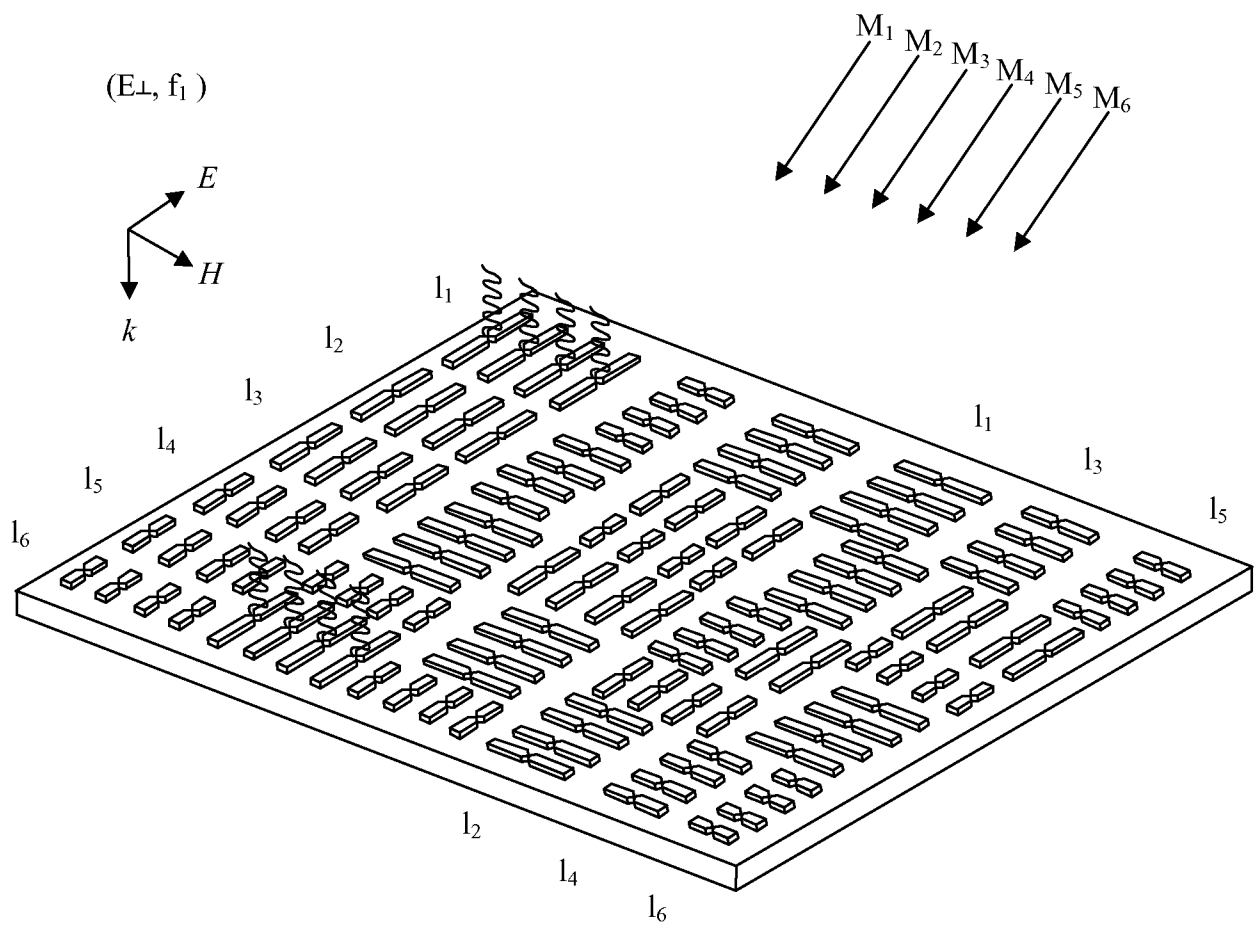


FIG. 2f

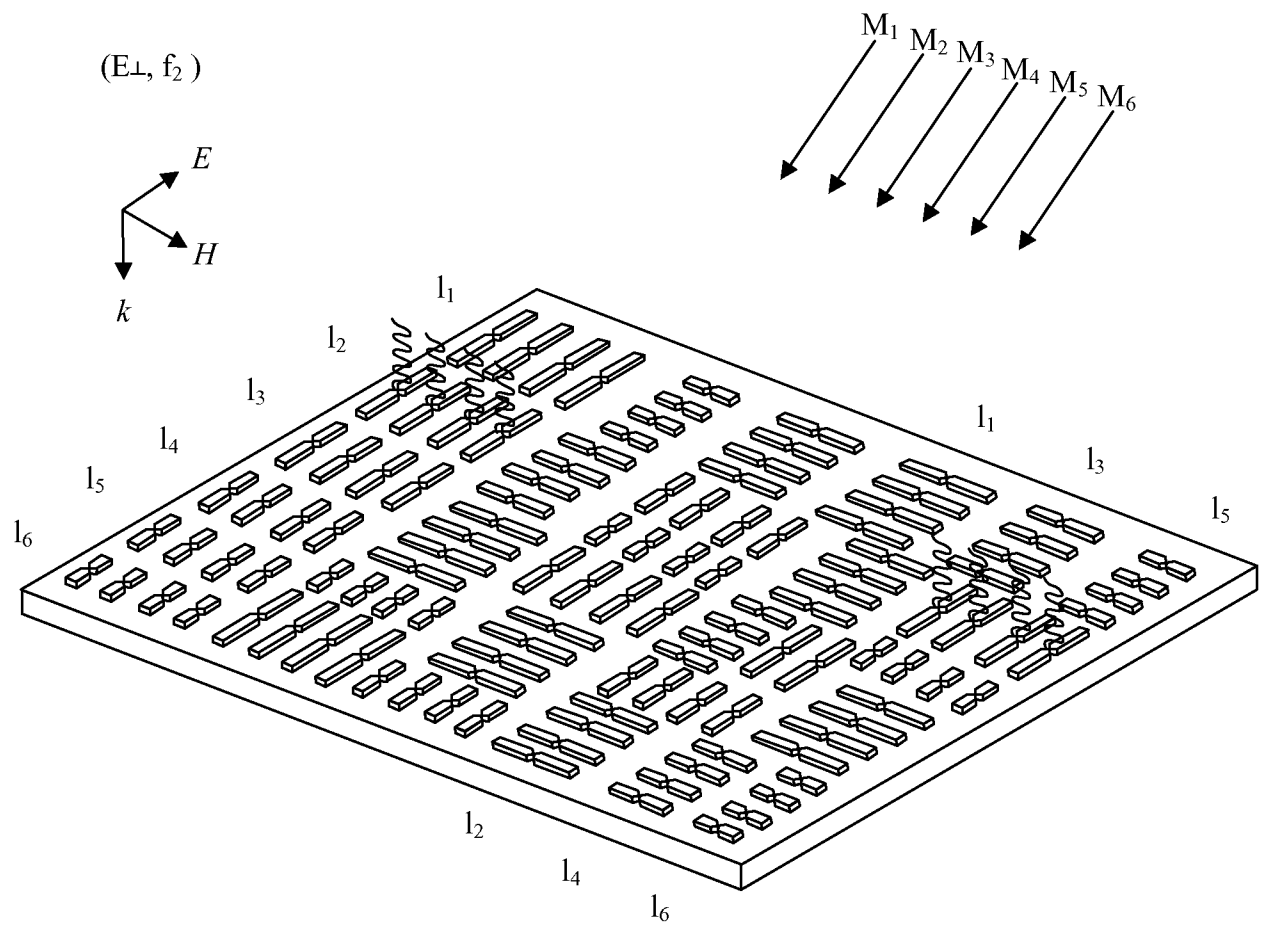


FIG. 2g

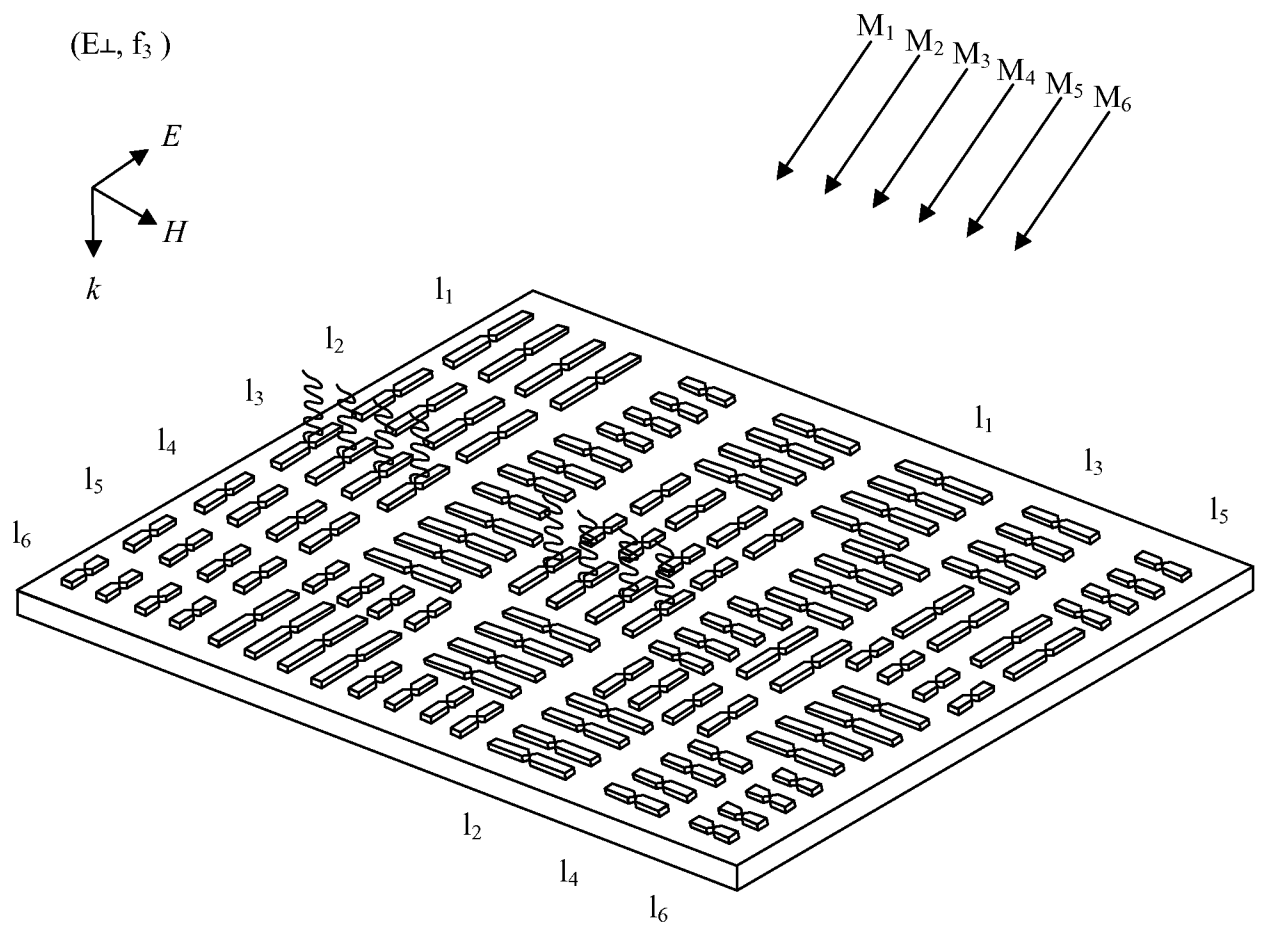


FIG. 2h

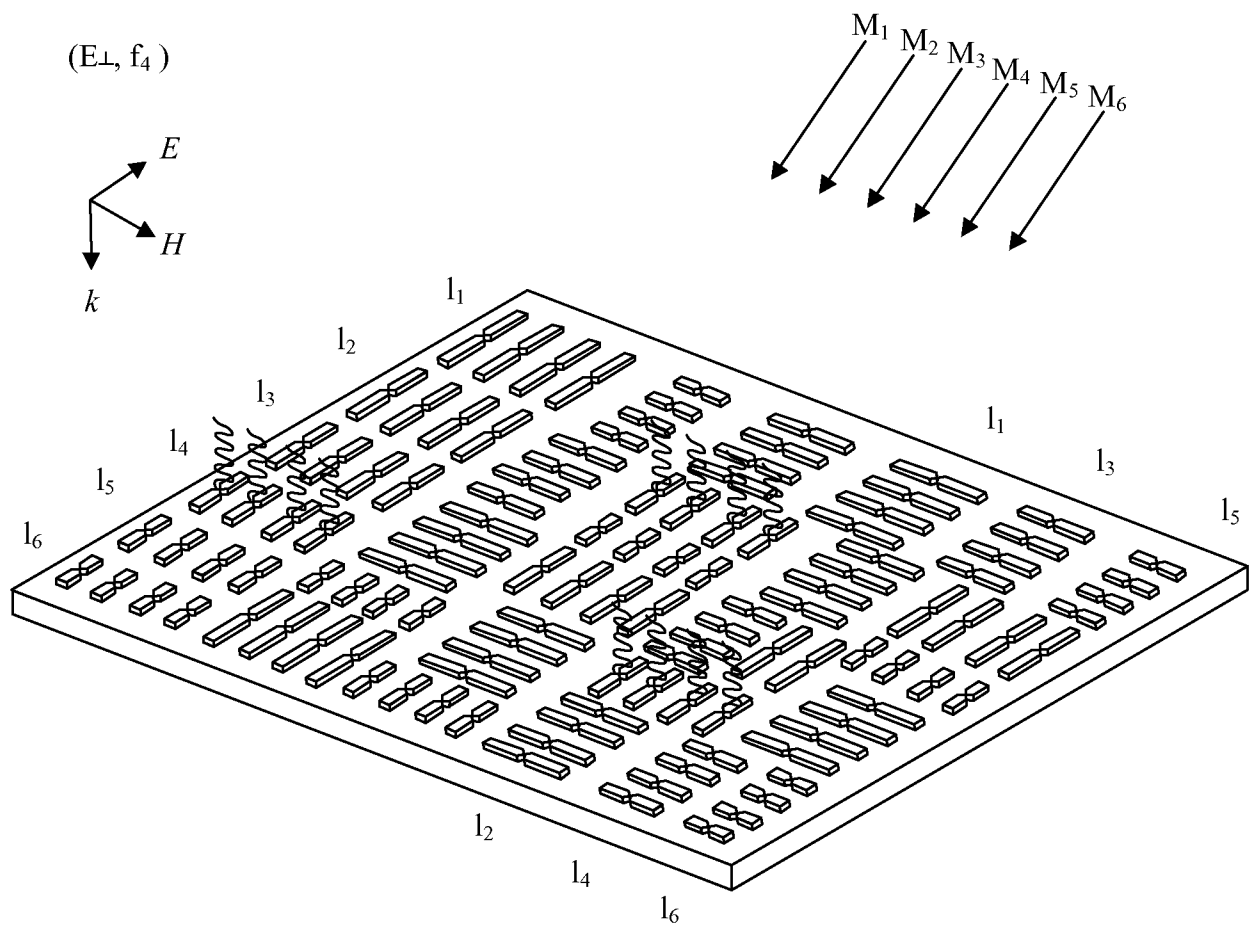


FIG. 2i

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

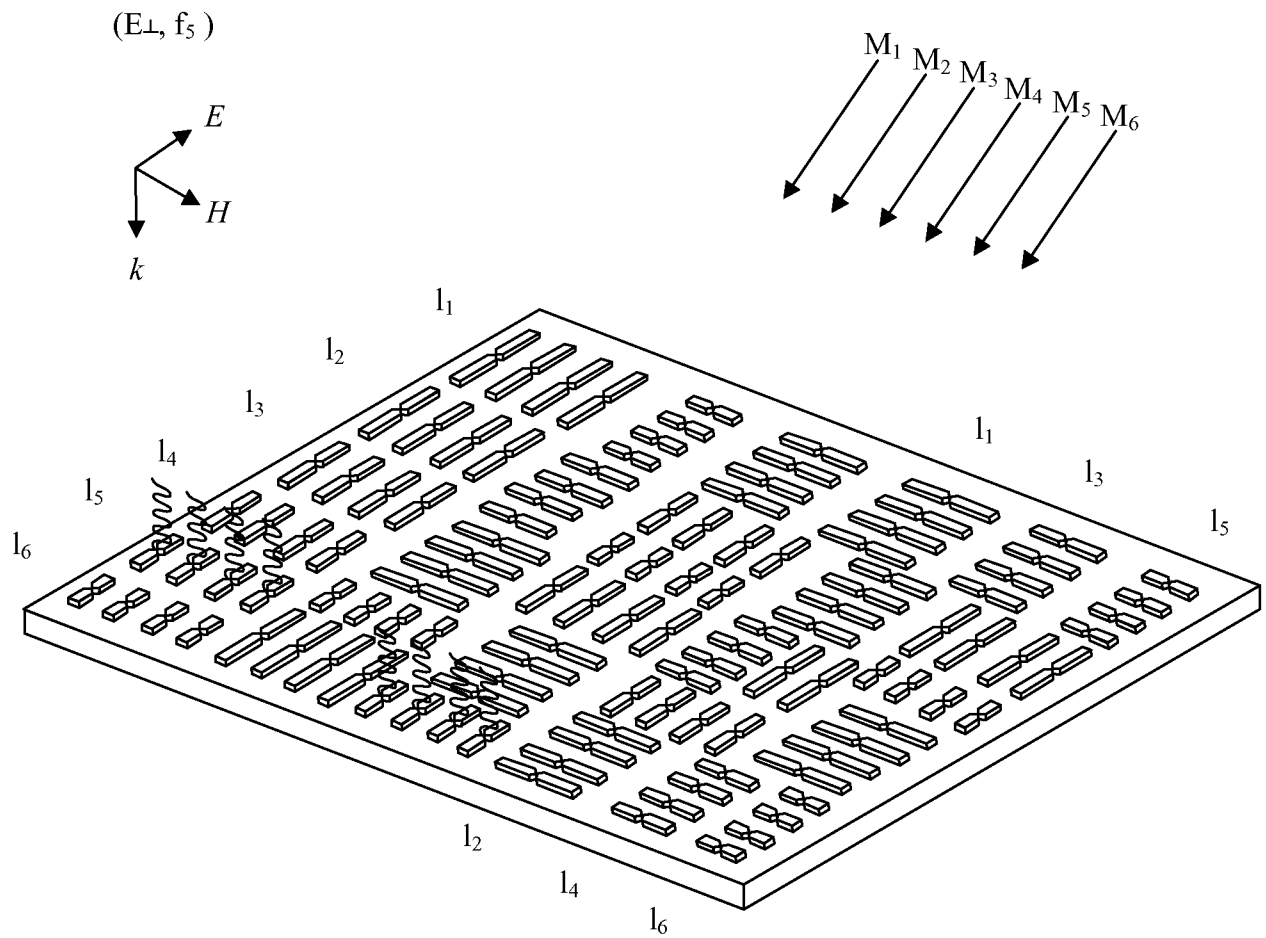


FIG. 2j

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

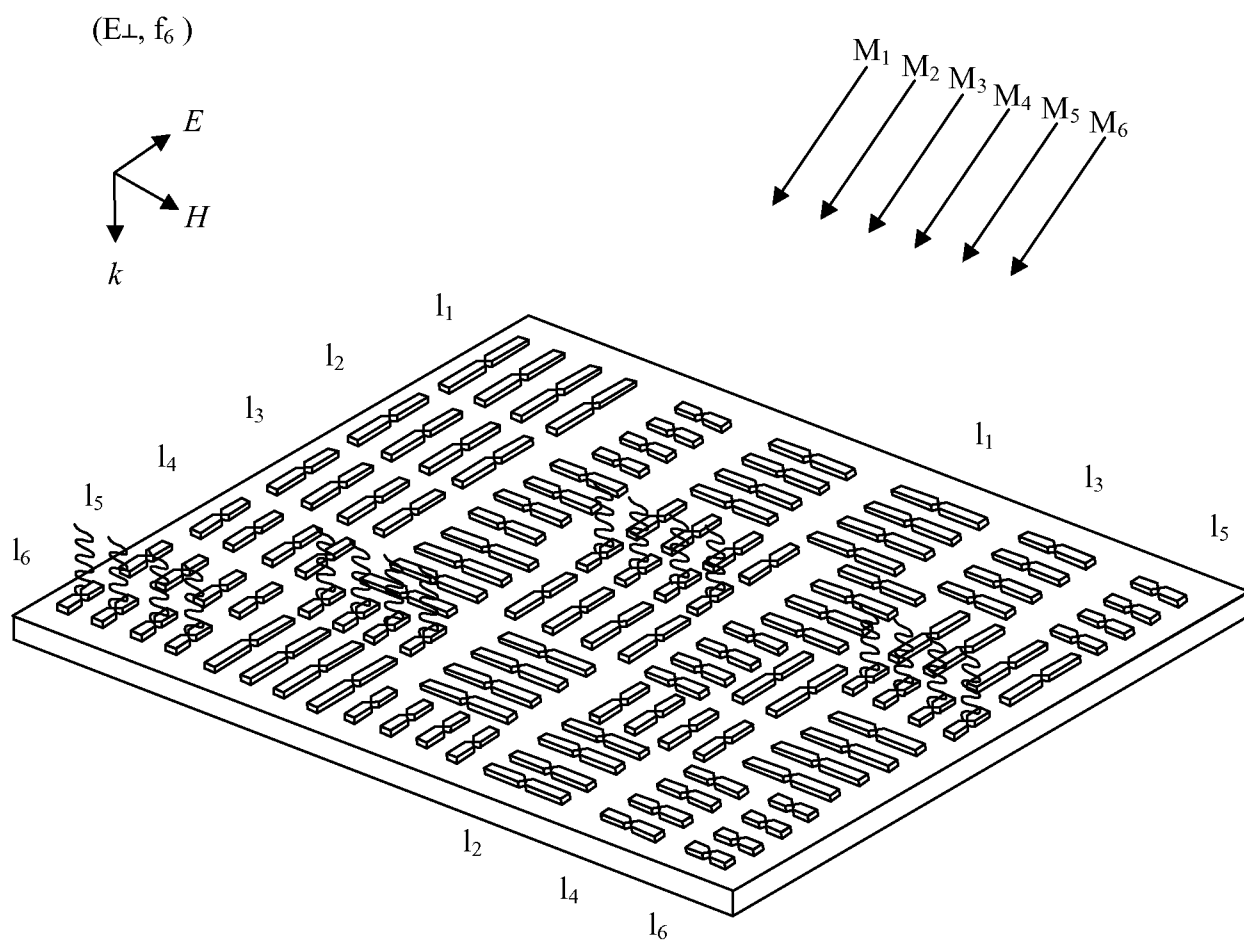


FIG. 2k

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

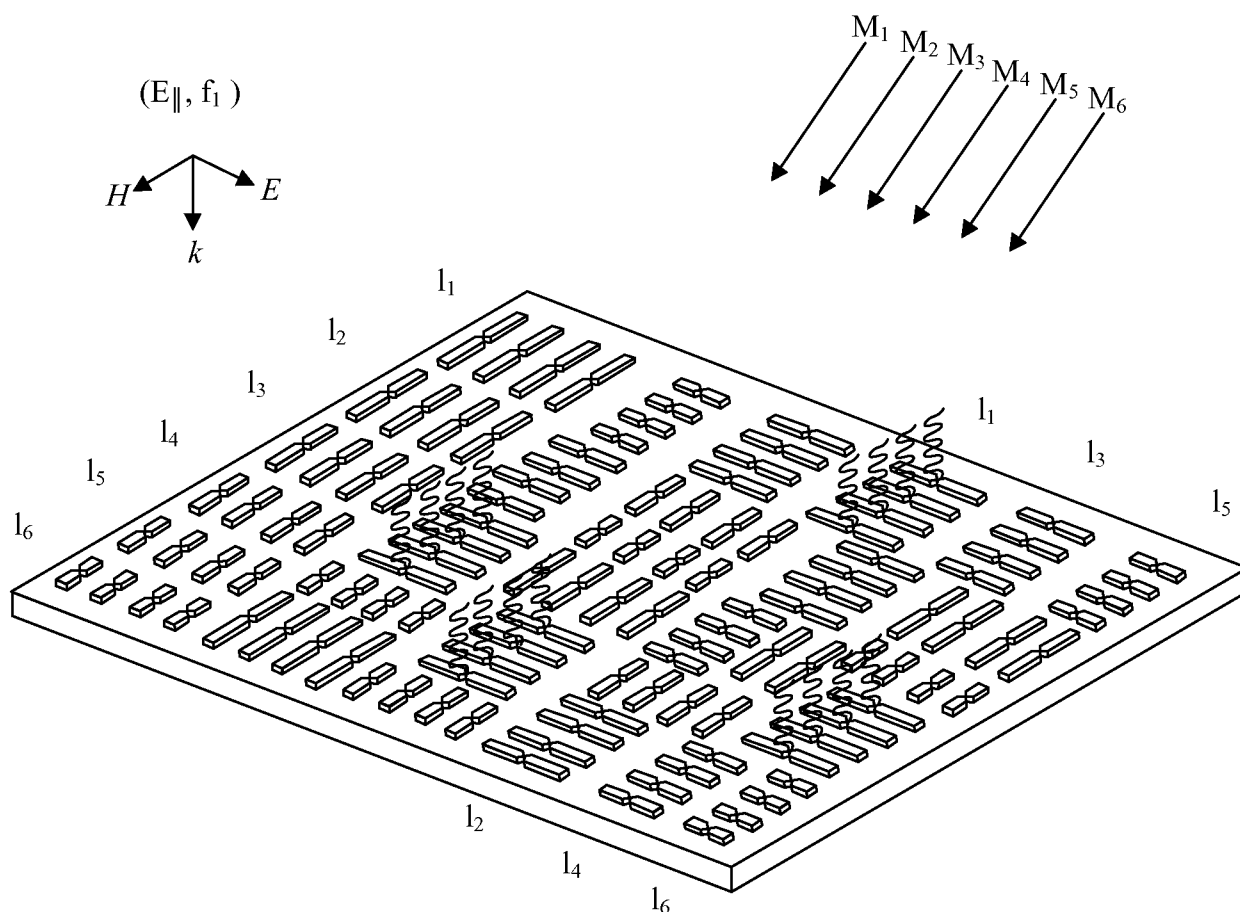


FIG. 2I

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

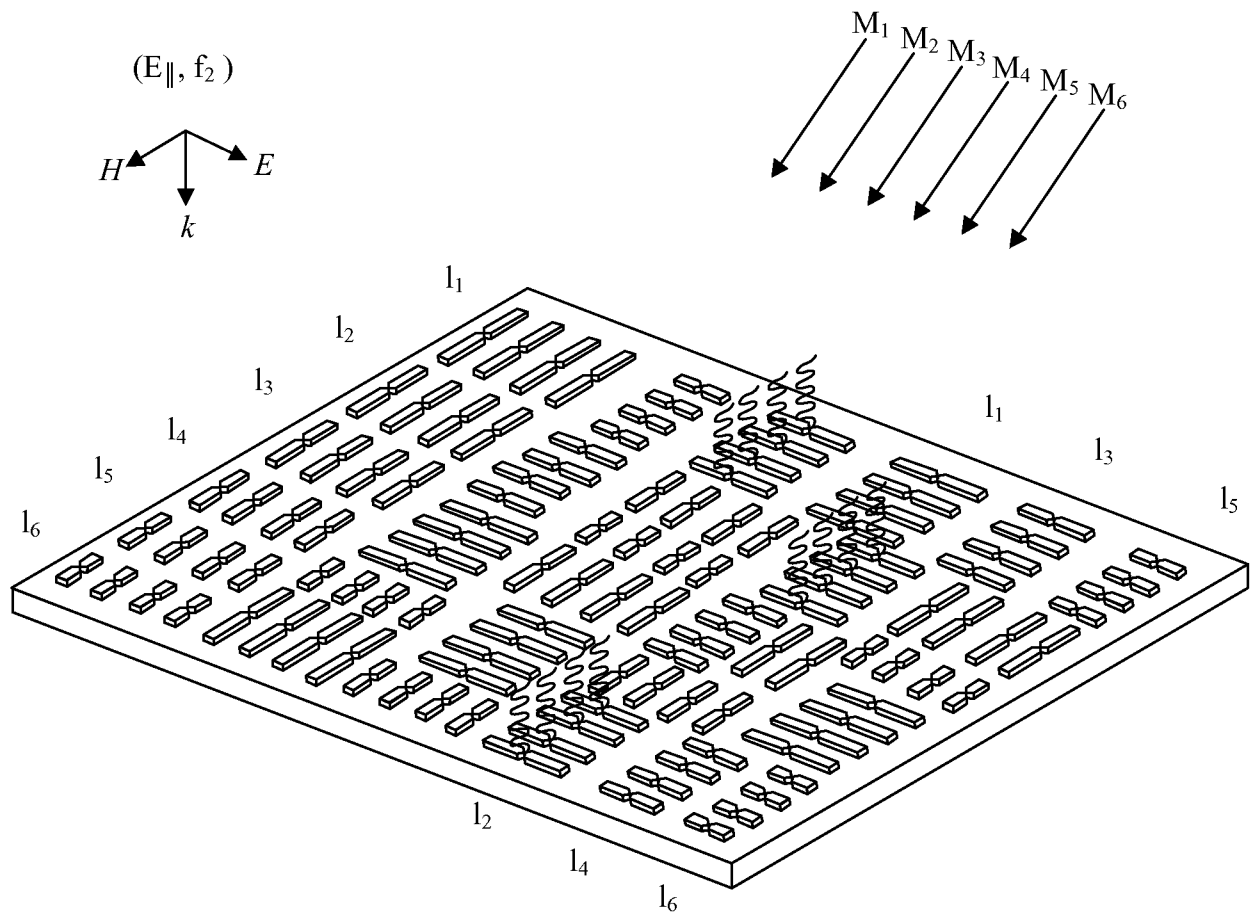


FIG. 2m

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

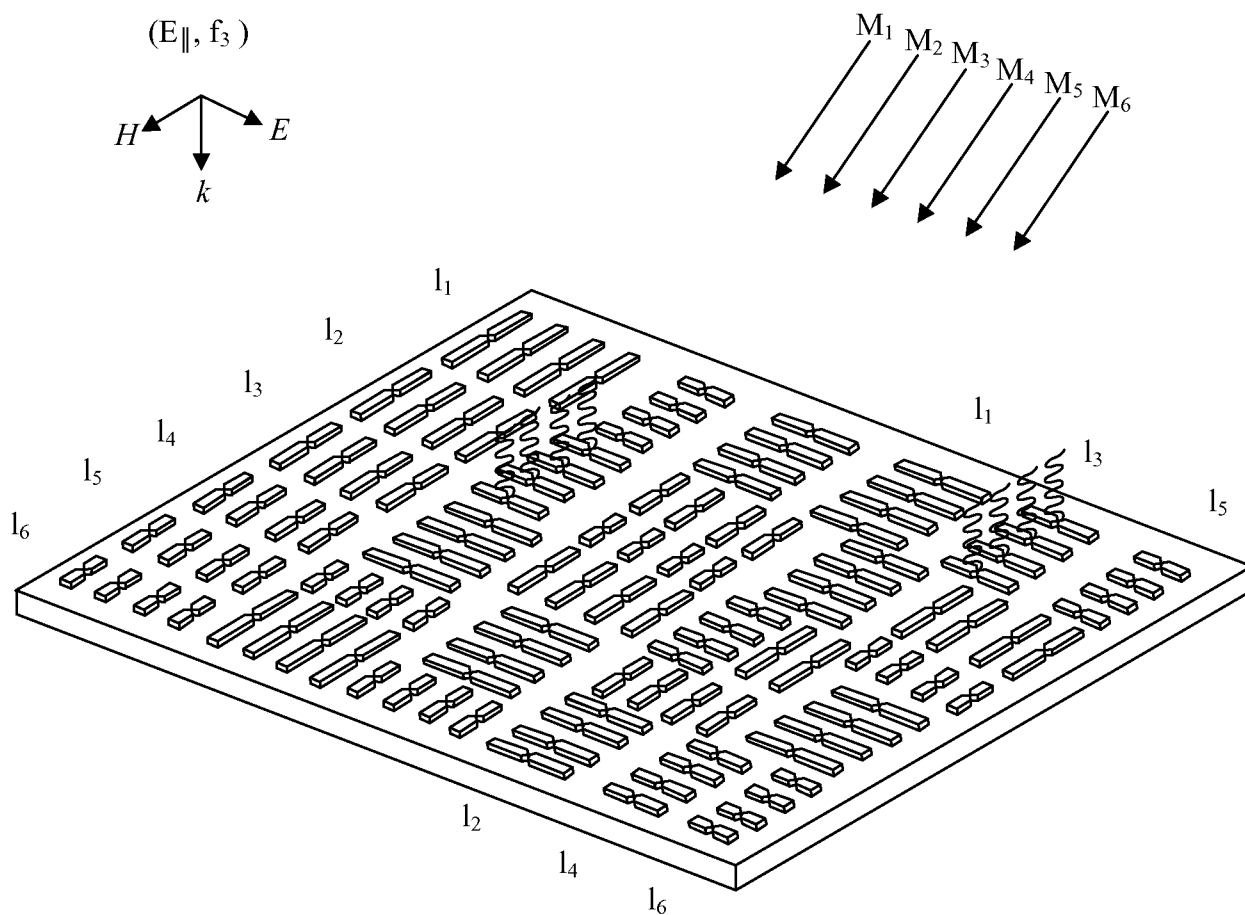


FIG. 2n

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

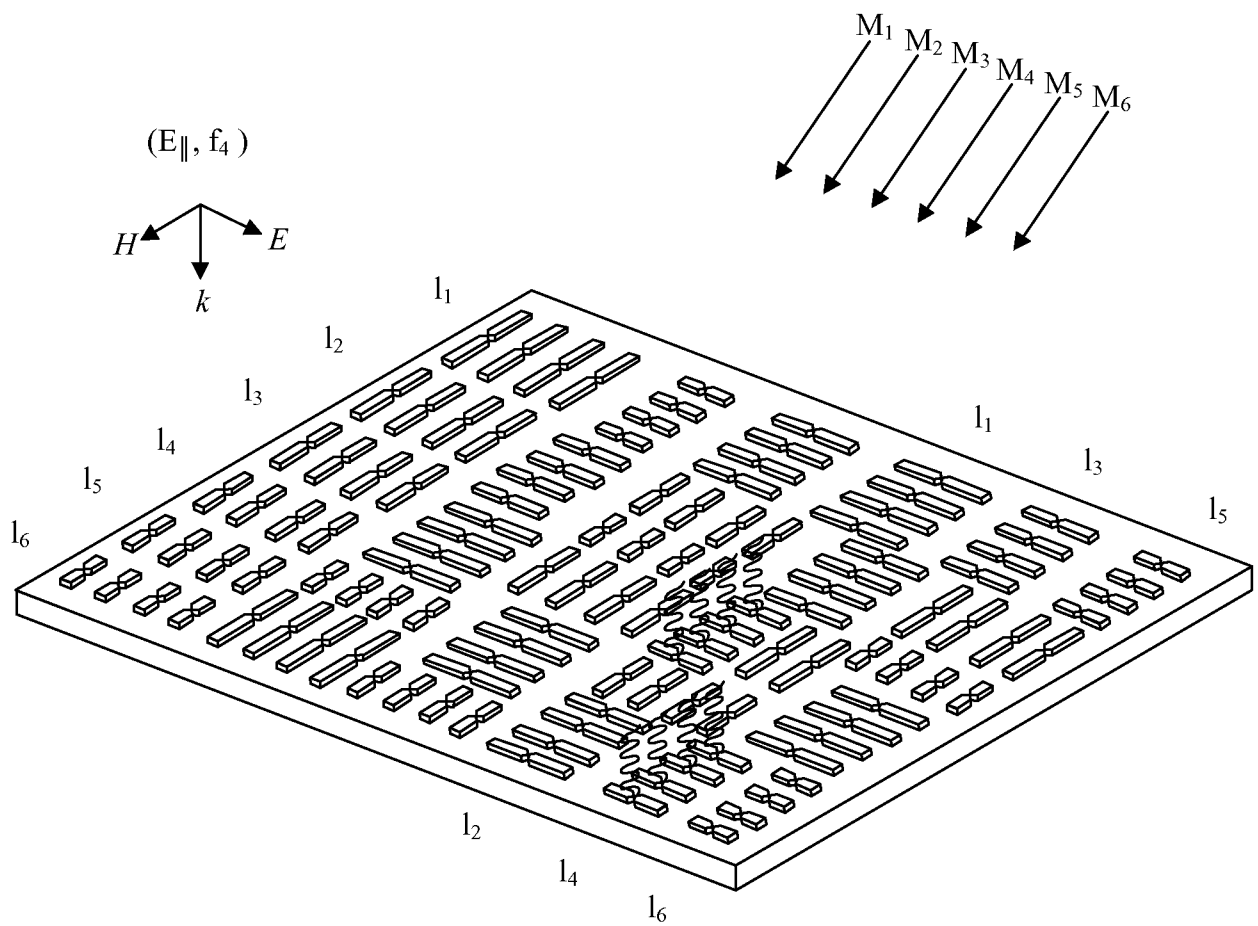


FIG. 2o

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

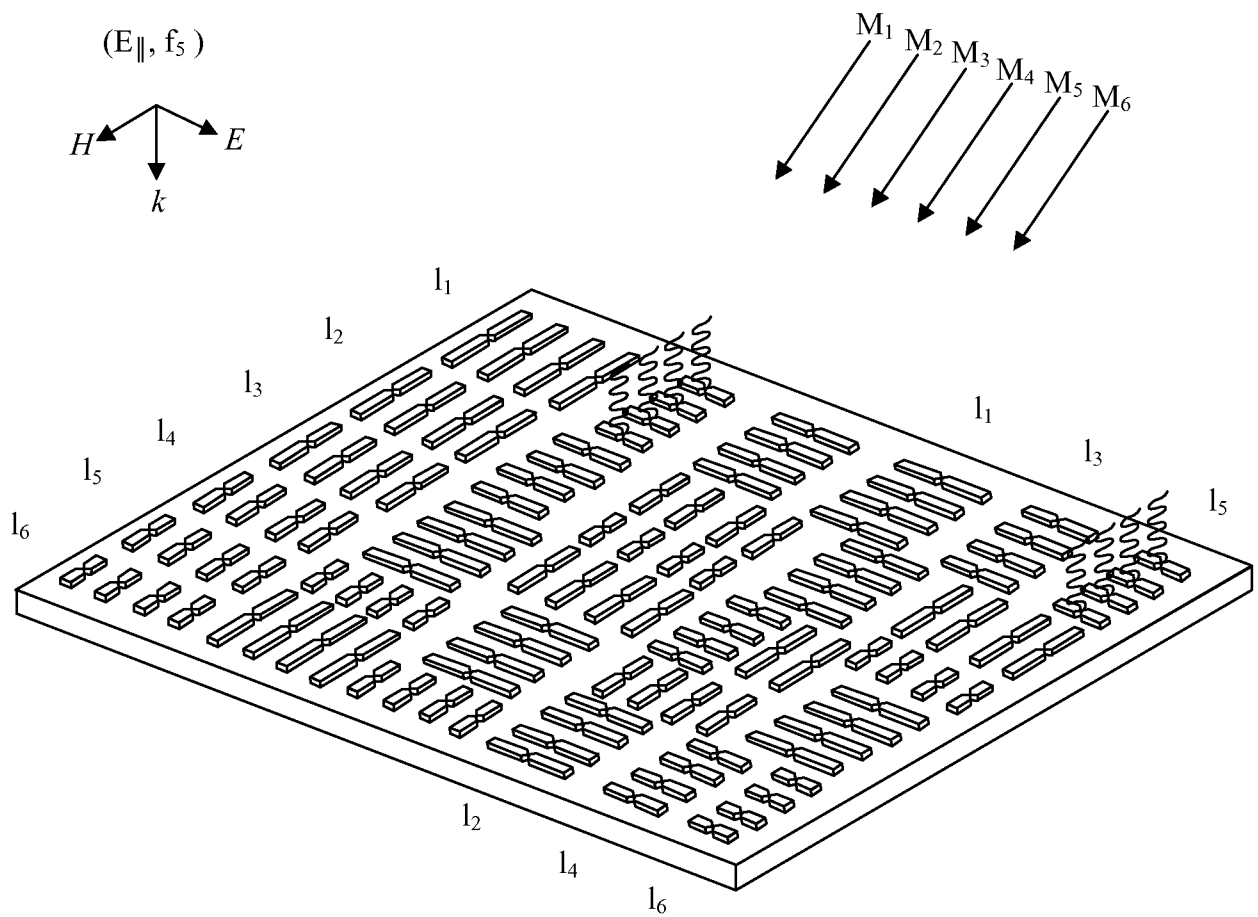


FIG. 2p

Inventor: Massood Tabib-Azar
346-U4750.PROV2.PCT

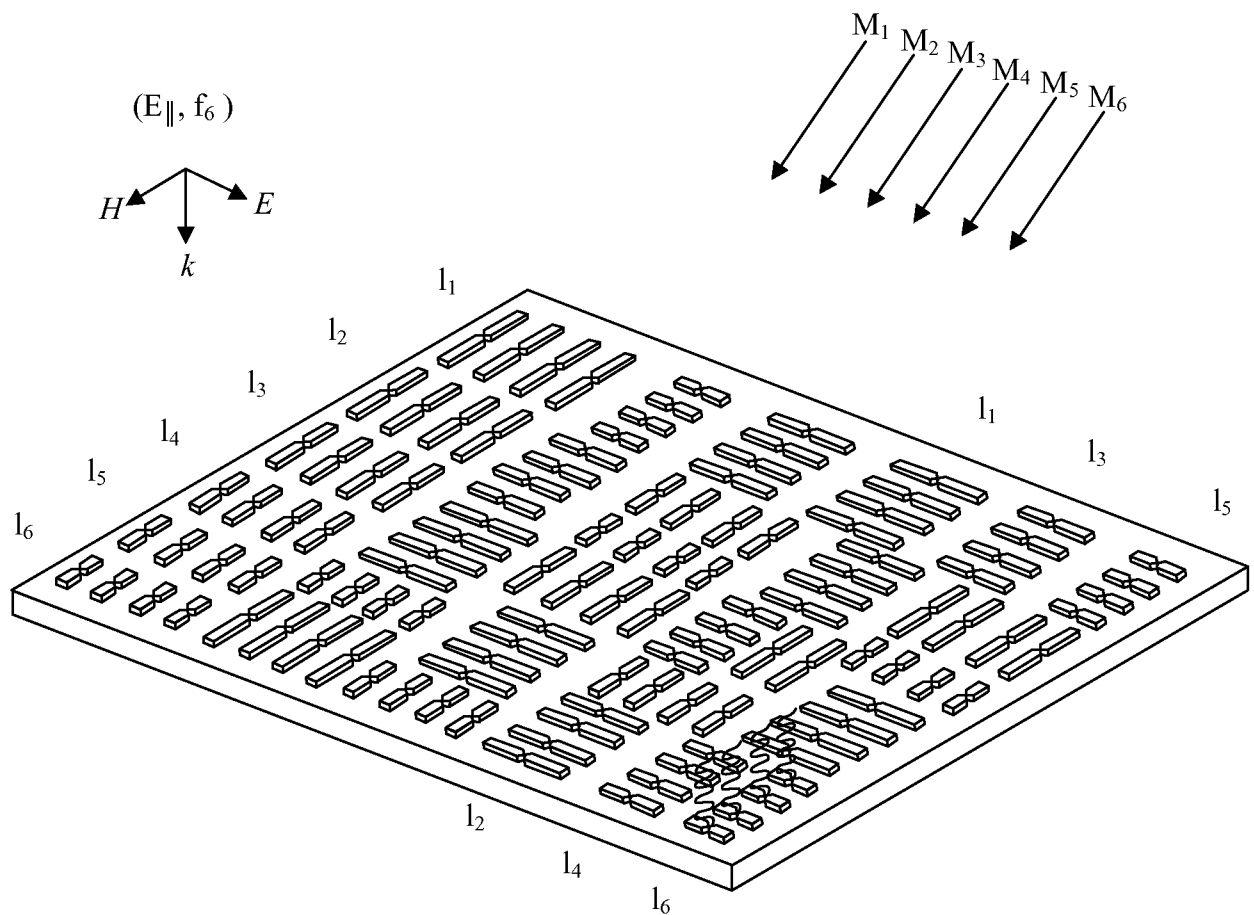


FIG. 2q

Inventor: Massood Tabib-Azar et al.
346-U4750.PROV2.PCT

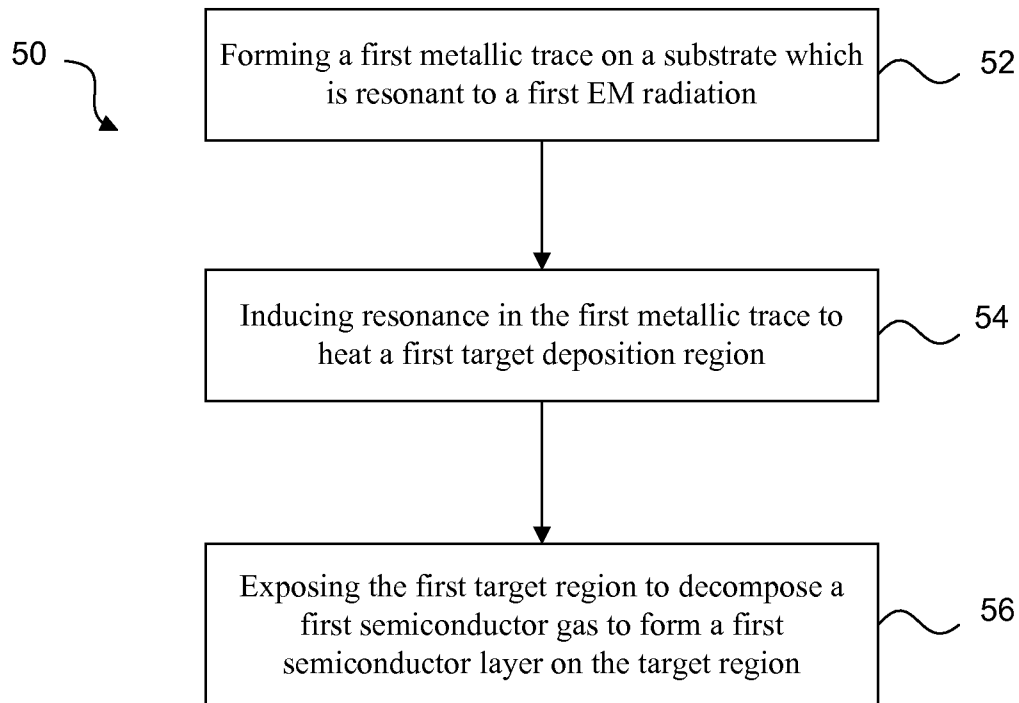


FIG. 3a

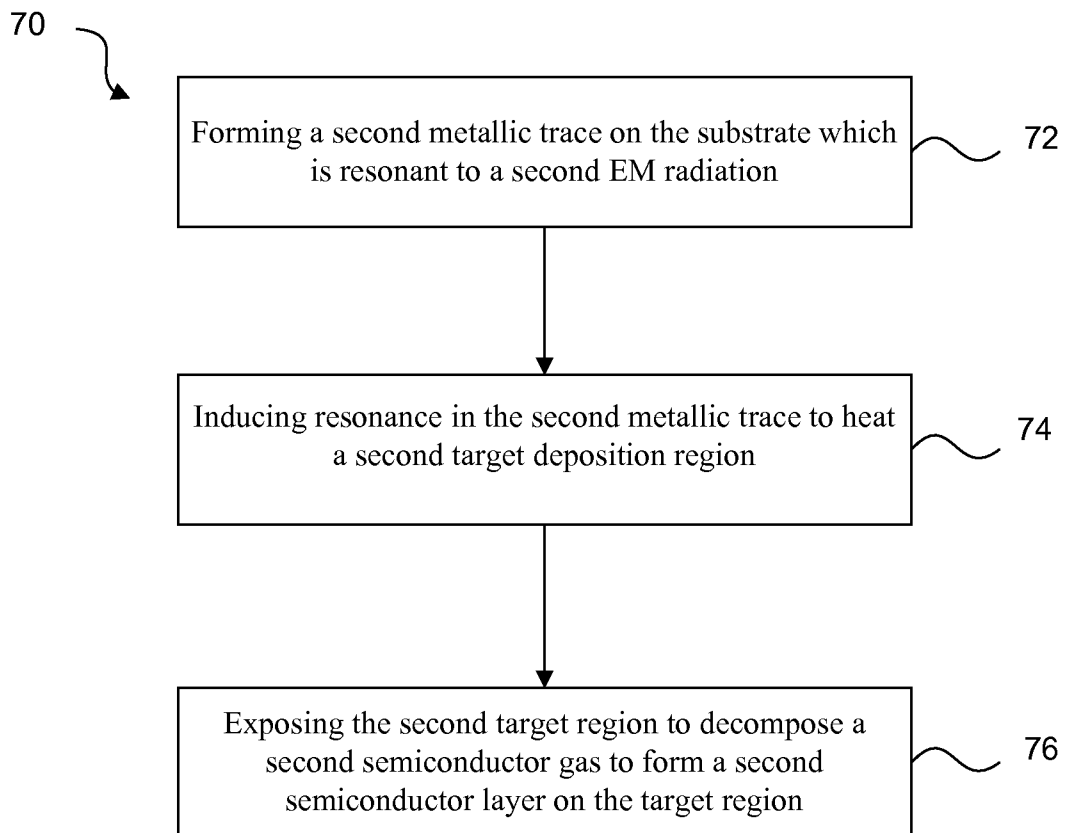


FIG. 3b

Inventor: Massood Tabib-Azar et al.
846-U4750.PROV2.PCT

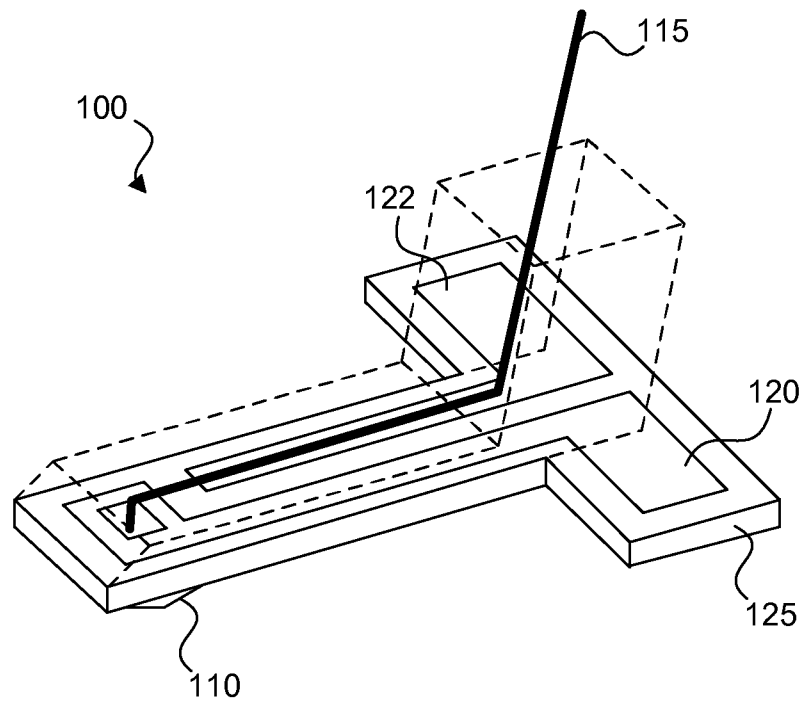


FIG. 4a

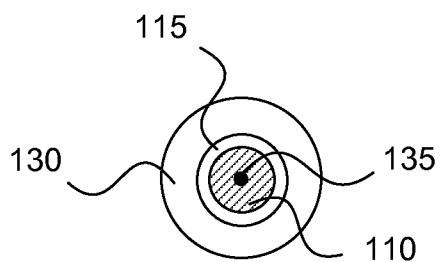


FIG. 4b

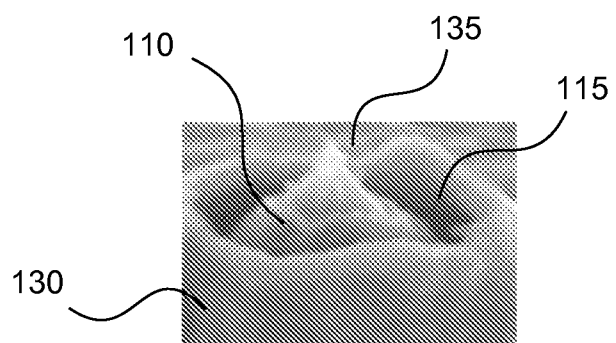


FIG. 4c

Inventor: Massood Tabib-Azar et al.

- - - - - }-U4750.PROV2.PCT

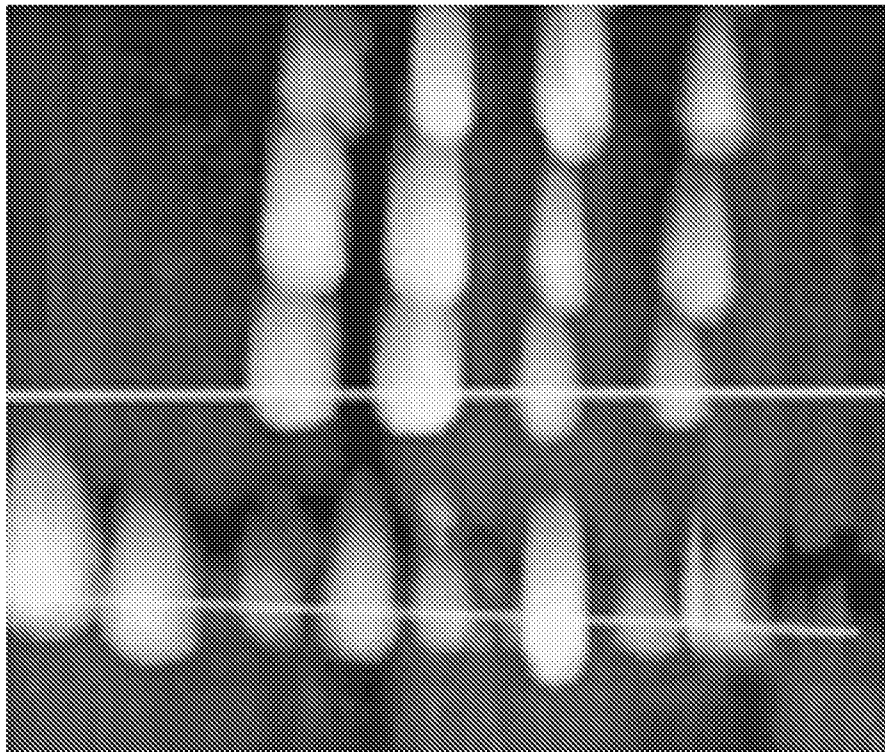


FIG. 5

Inventor: Massood Tabib-Azar et al.
3-U4750.PROV2.PCT

Breakdown Voltage (V)

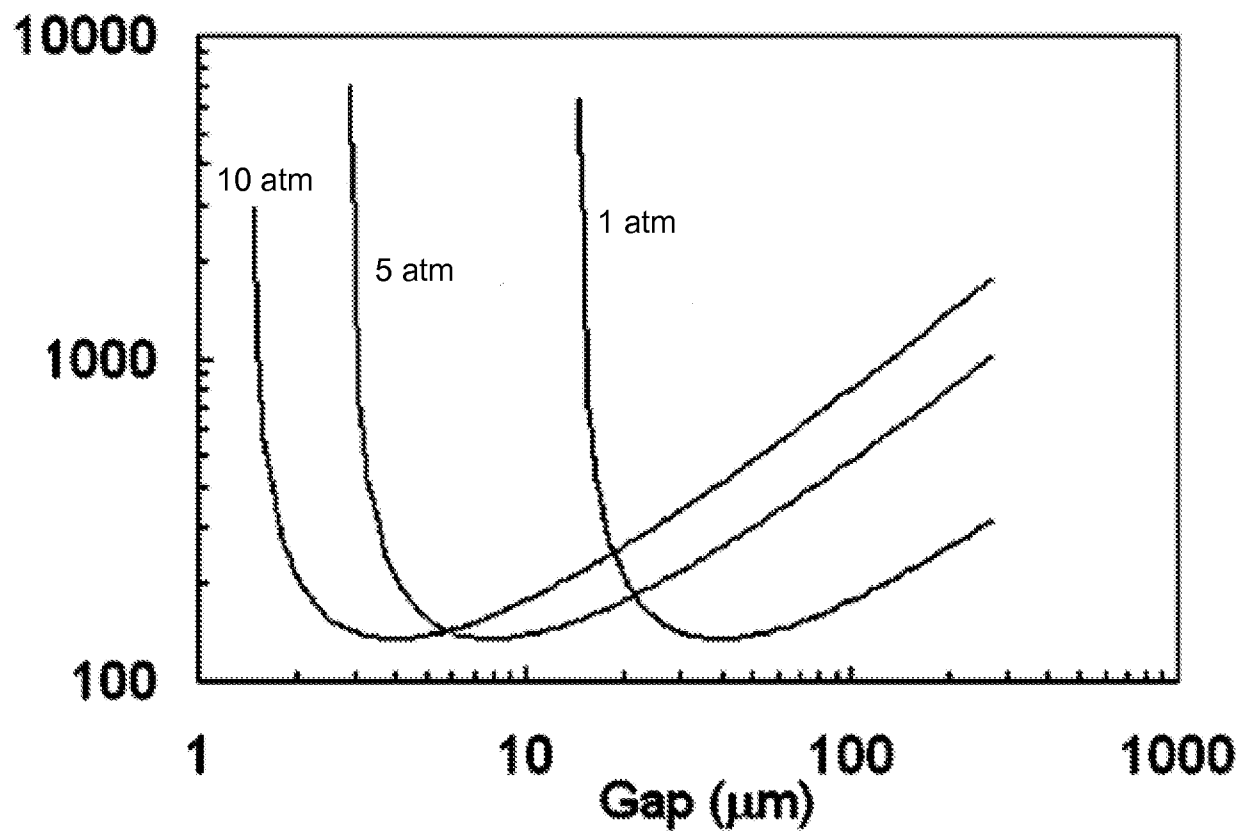


FIG. 6

Inventor: Massood Tabib-Azar et al.
846-U4750.PROV2.PCT

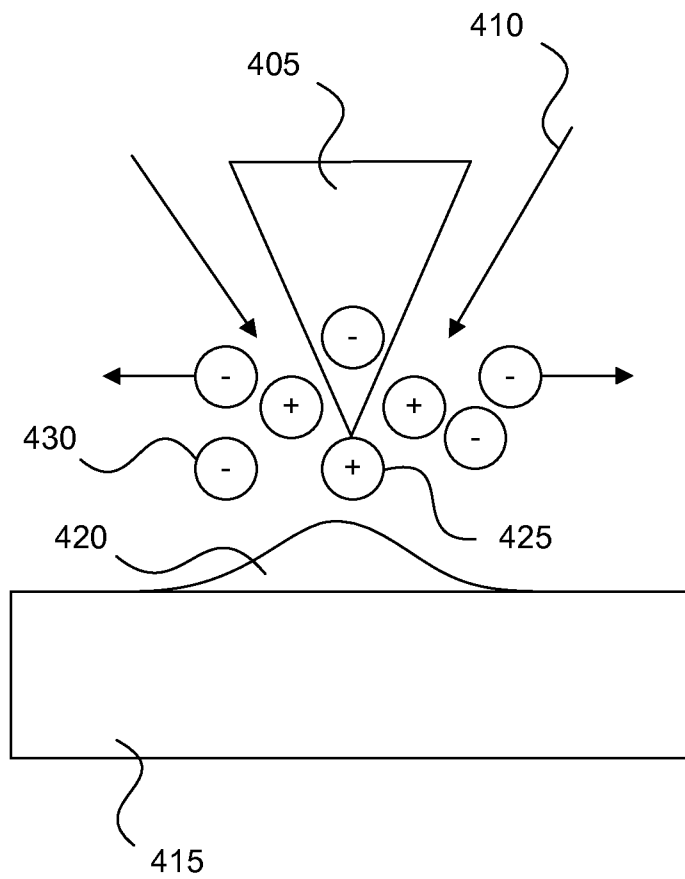


FIG. 7

Inventor: Massood Tabib-Azar et al.
346-U4750.PROV2.PCT

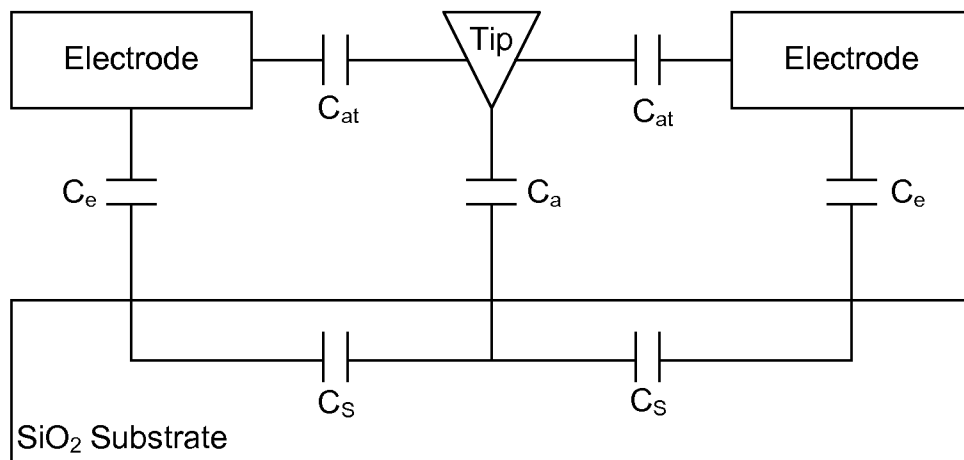


FIG. 8

Inventor: Massood Tabib-Azar et al.
46-U4750.PROV2.PCT

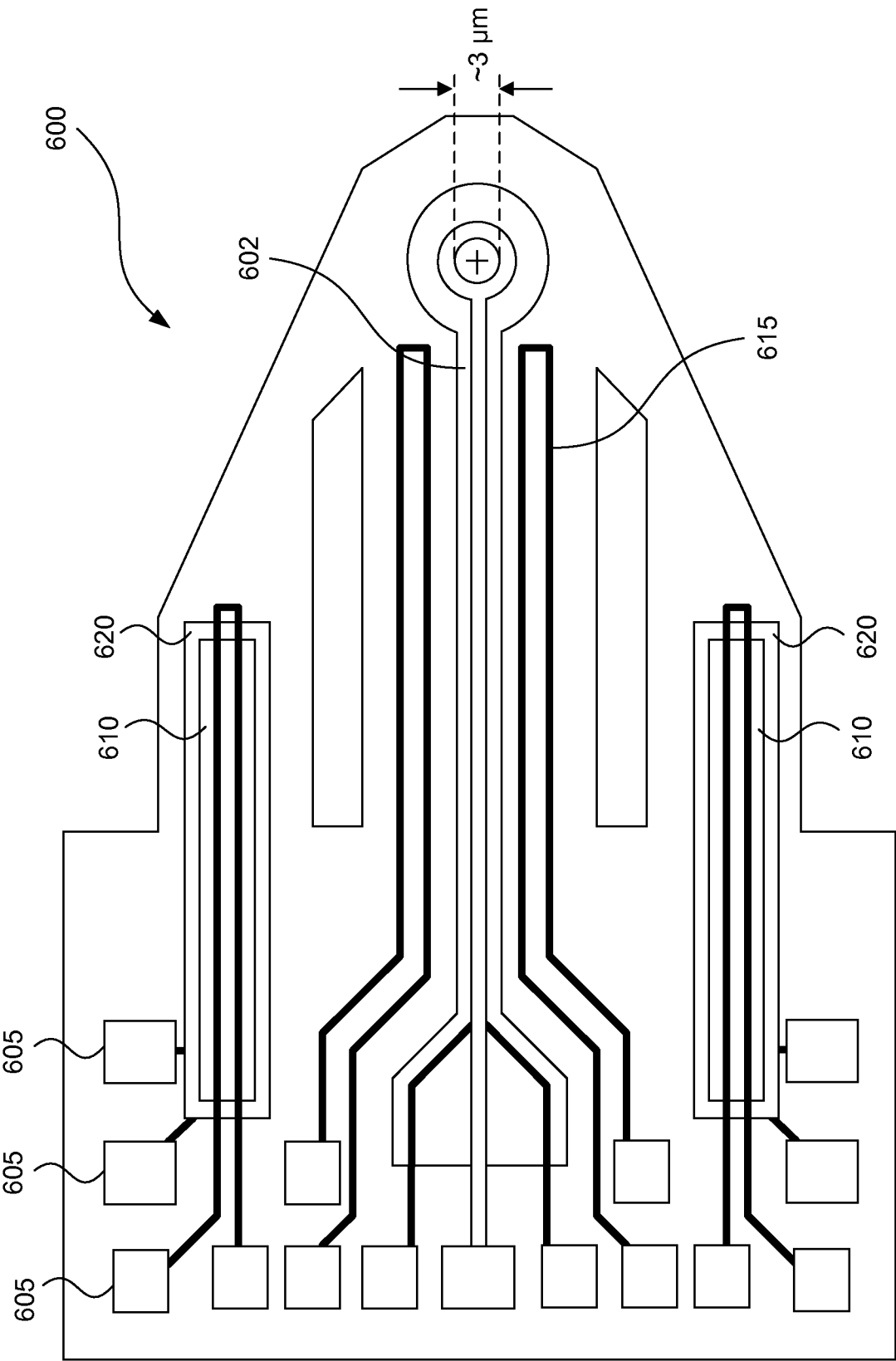


FIG. 9a

Inventor: Massood Tabib-Azar et al.
Docket No.: 00846-U4750.PROV2.PCT

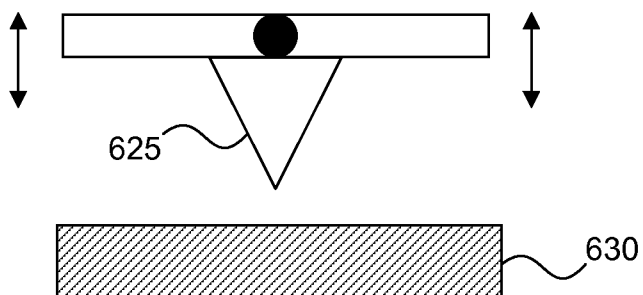


FIG. 9b

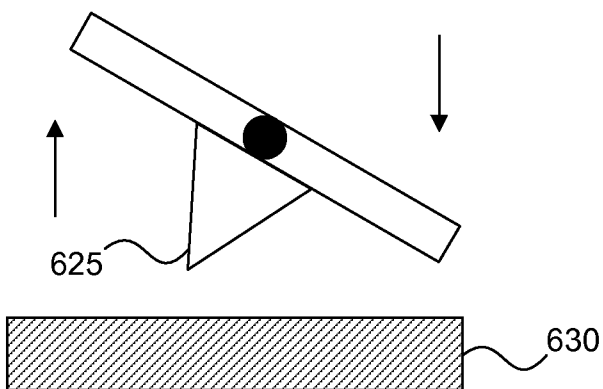


FIG. 9c

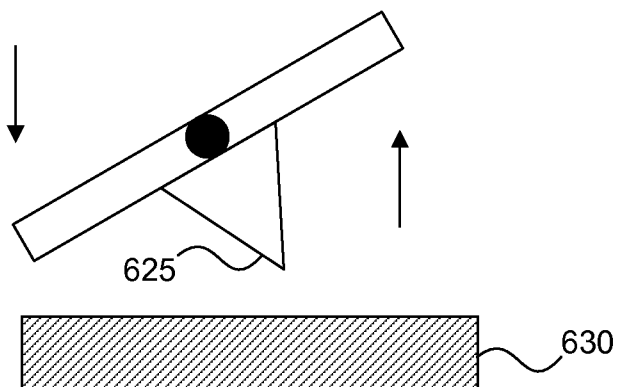


FIG. 9d

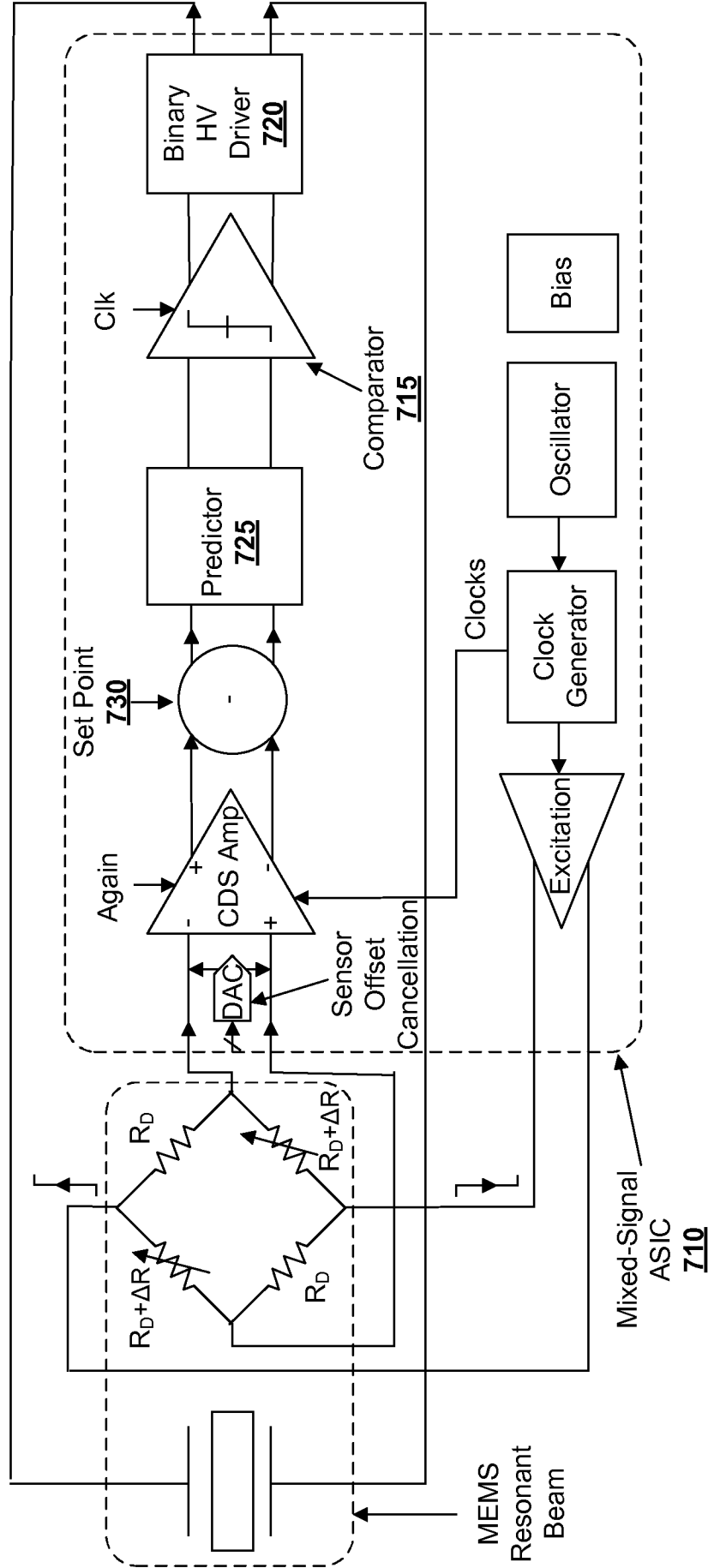


FIG. 10

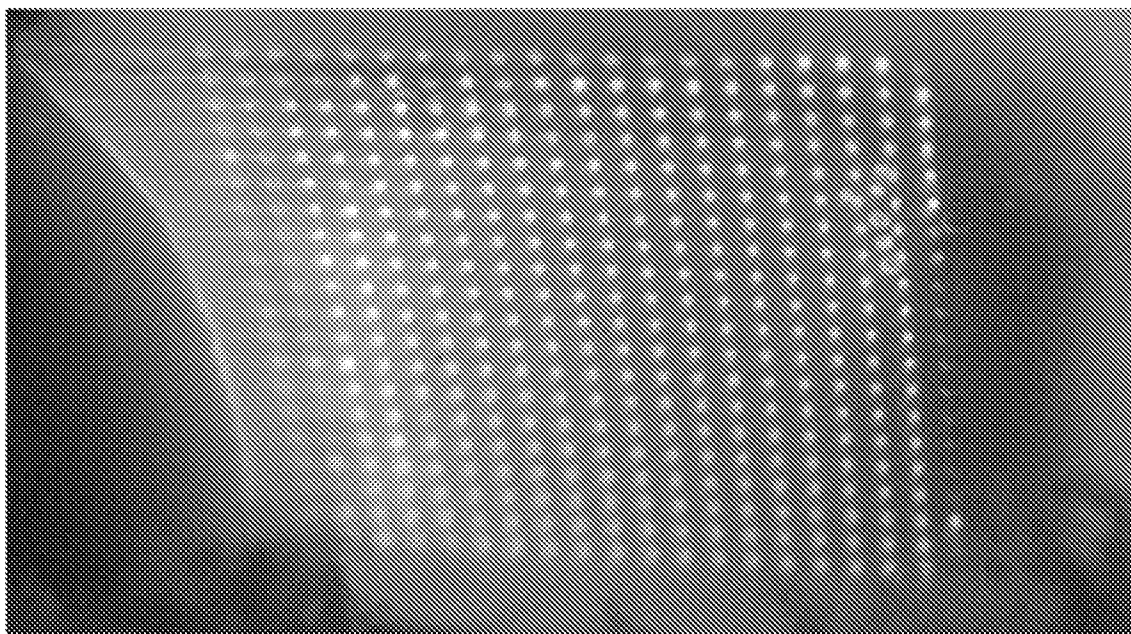
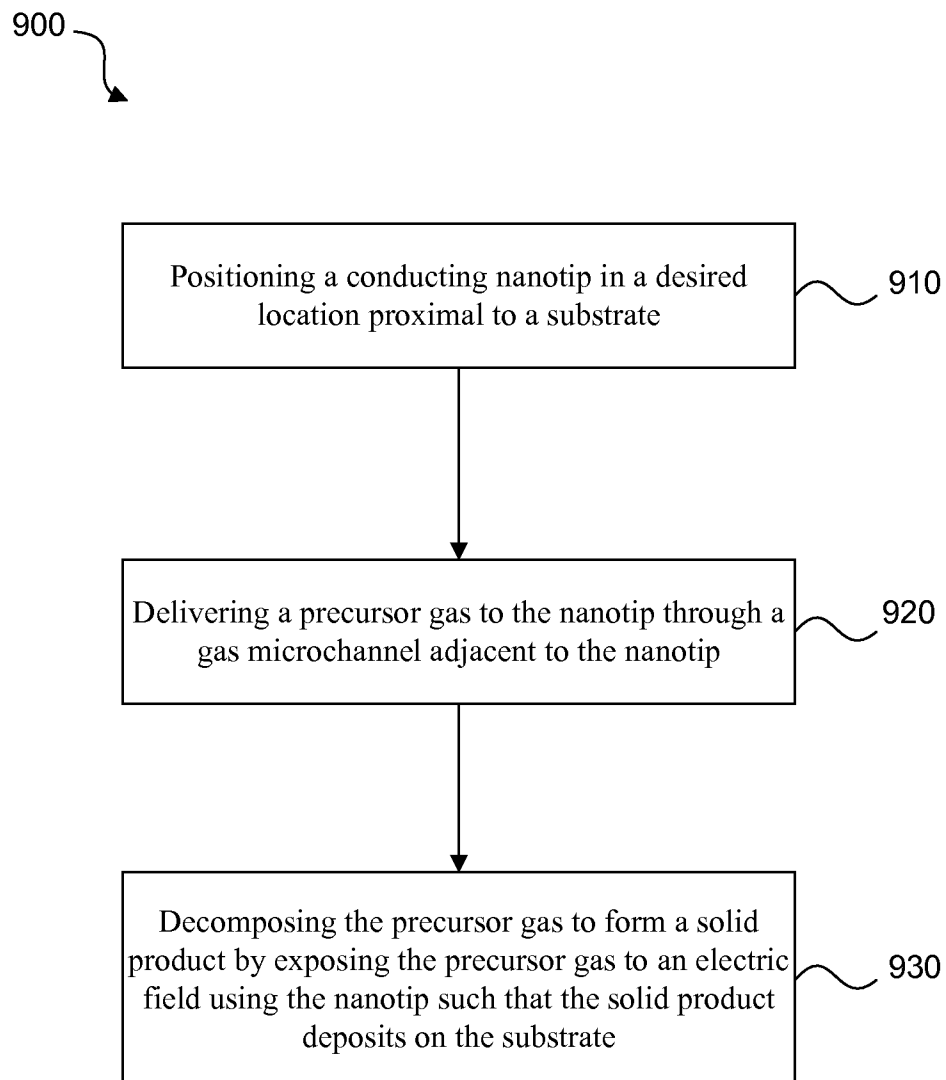


FIG. 11

**FIG. 12**

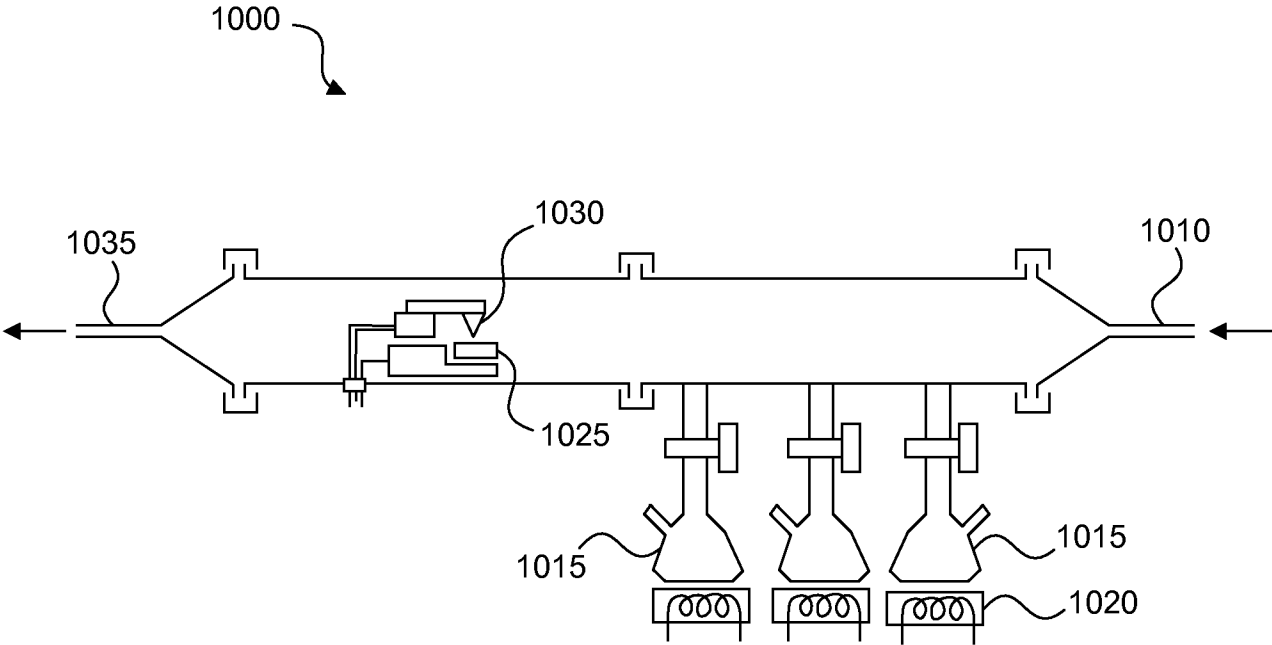


FIG. 13

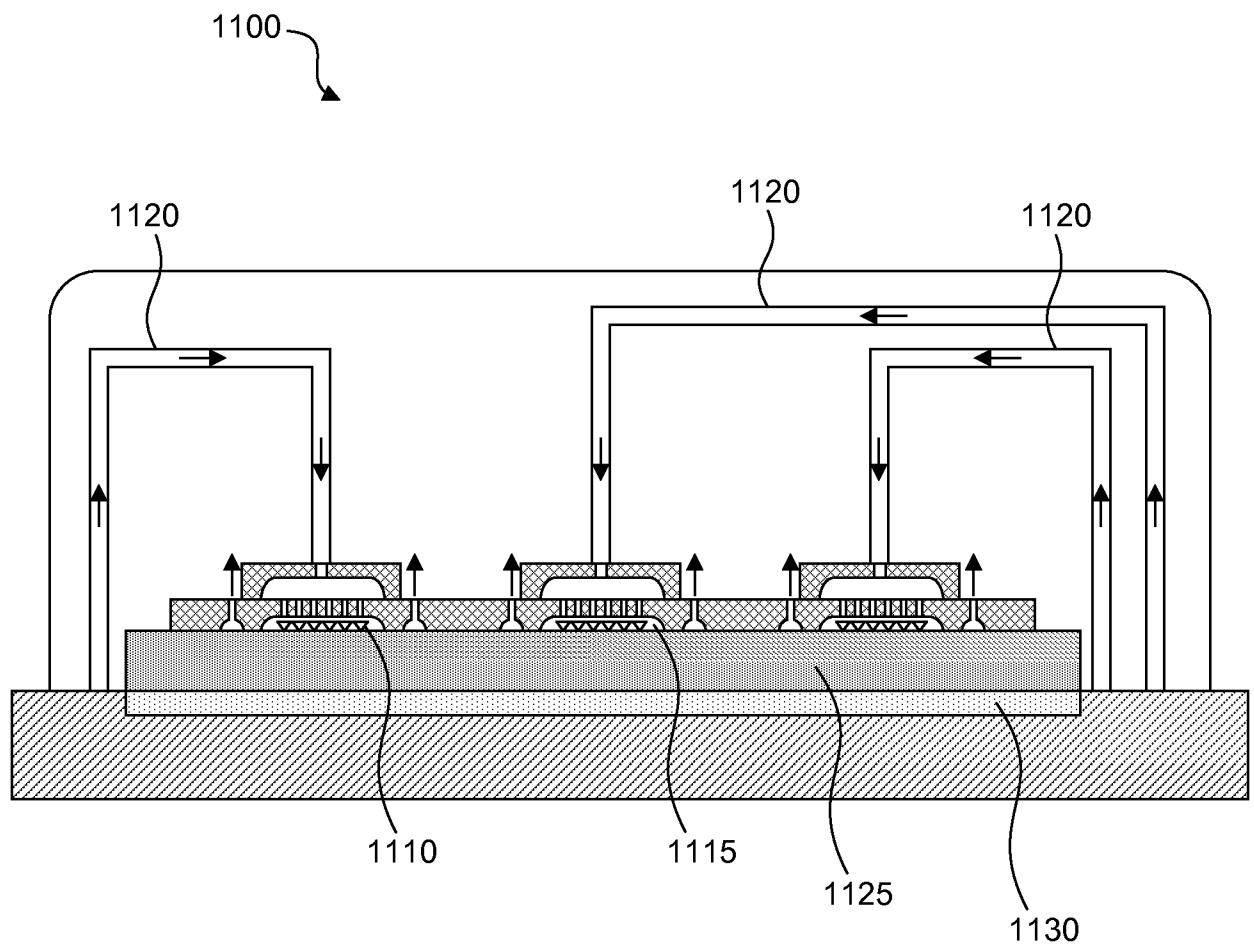


FIG. 14

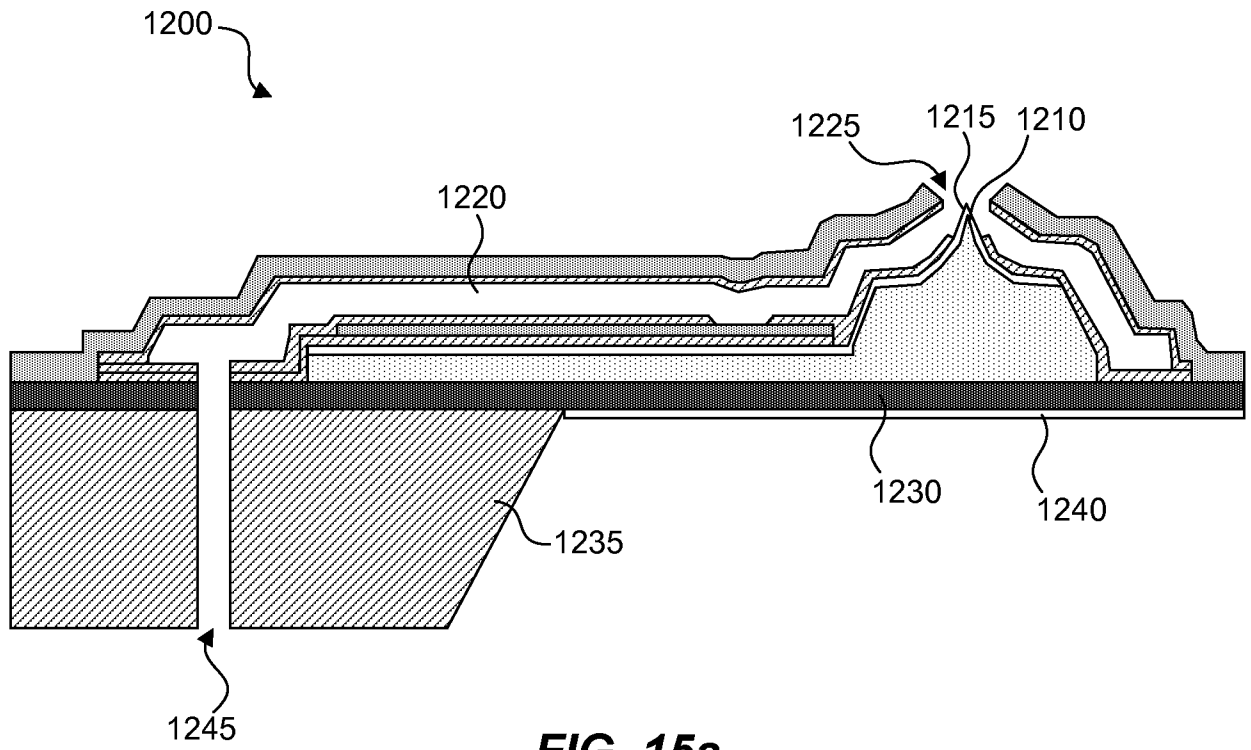


FIG. 15a

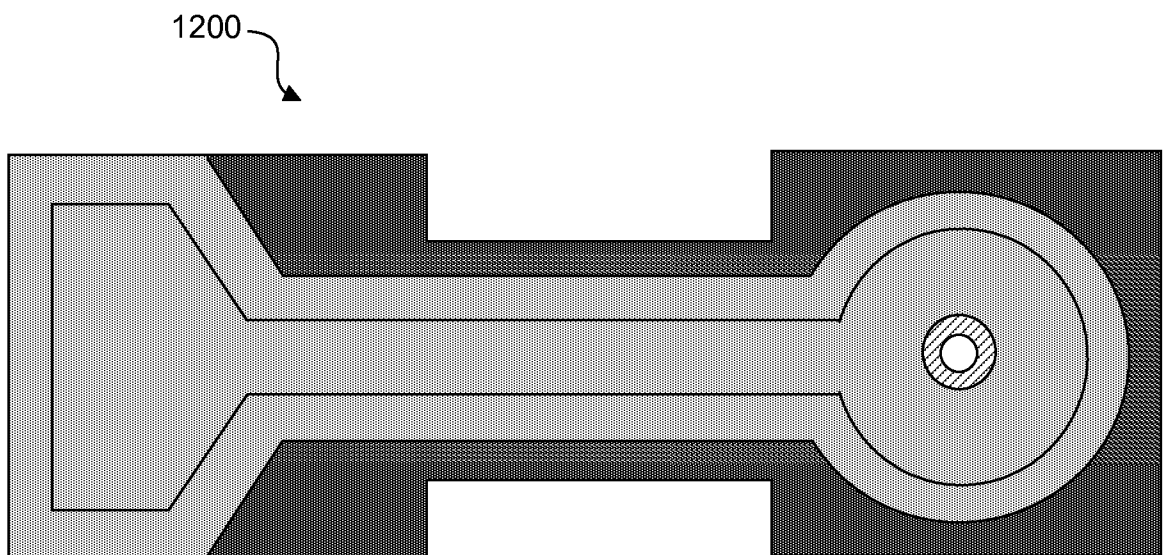


FIG. 15b

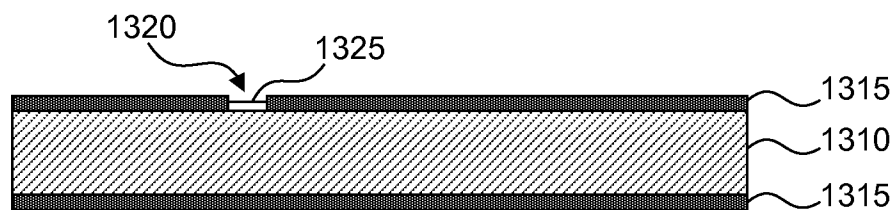


FIG. 16a

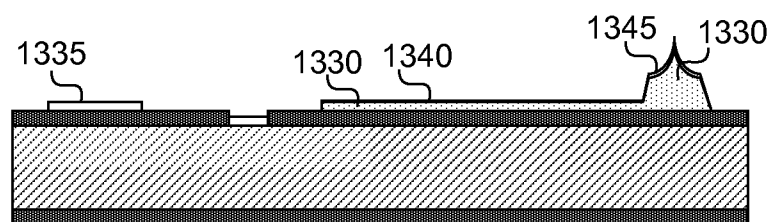


FIG. 16b

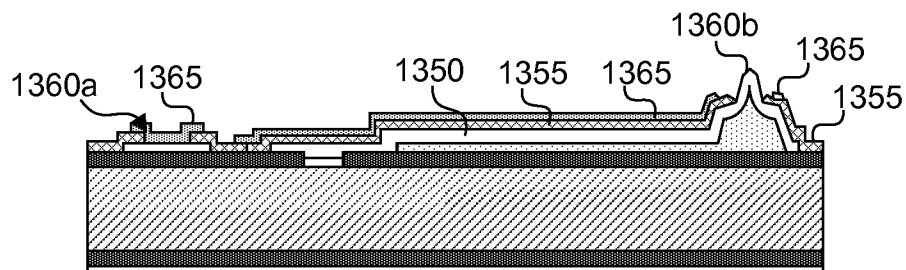


FIG. 16c

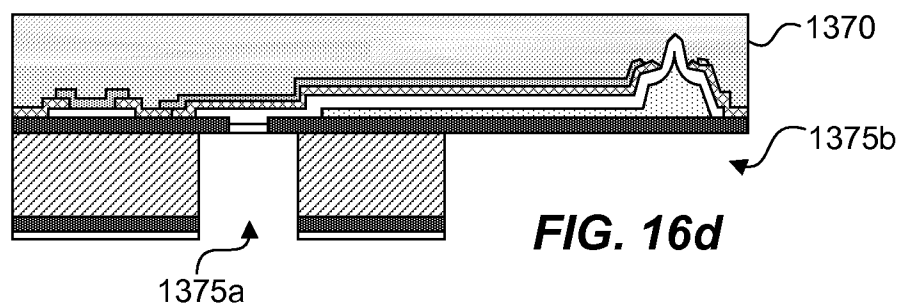


FIG. 16d

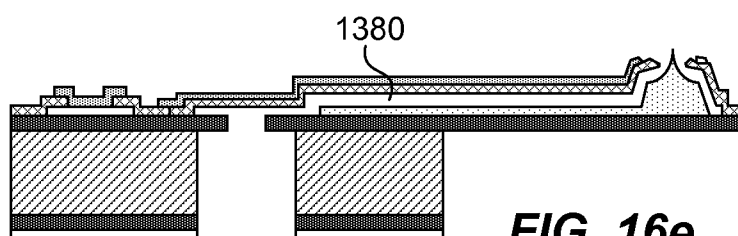


FIG. 16e

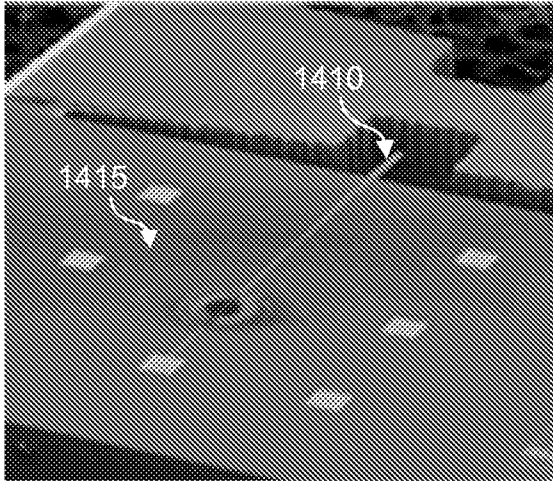


FIG. 17a

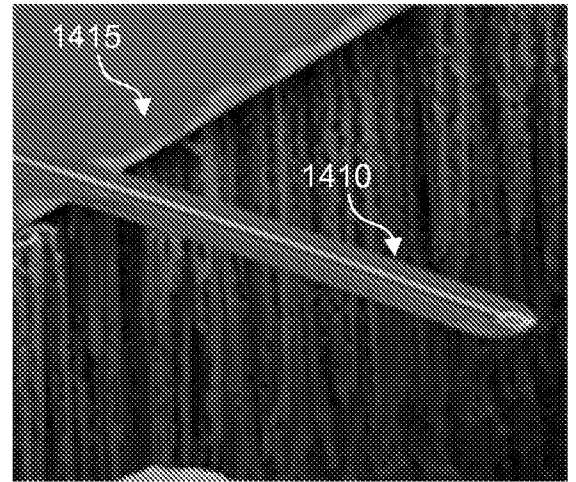


FIG. 17b

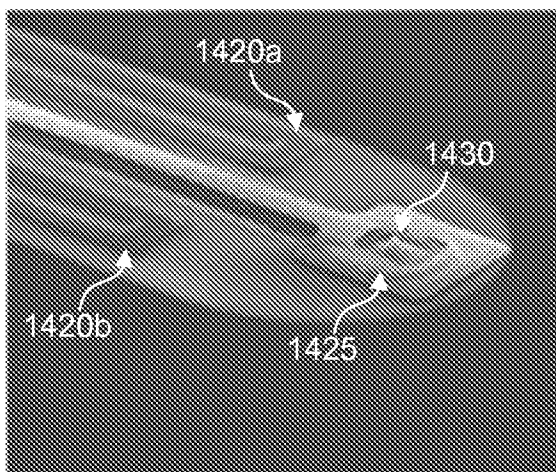


FIG. 17c

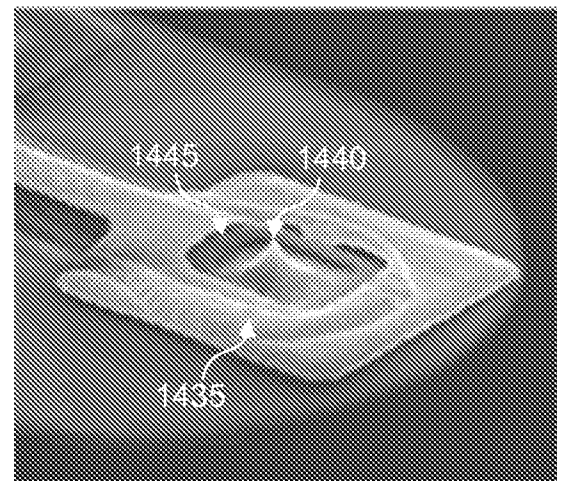
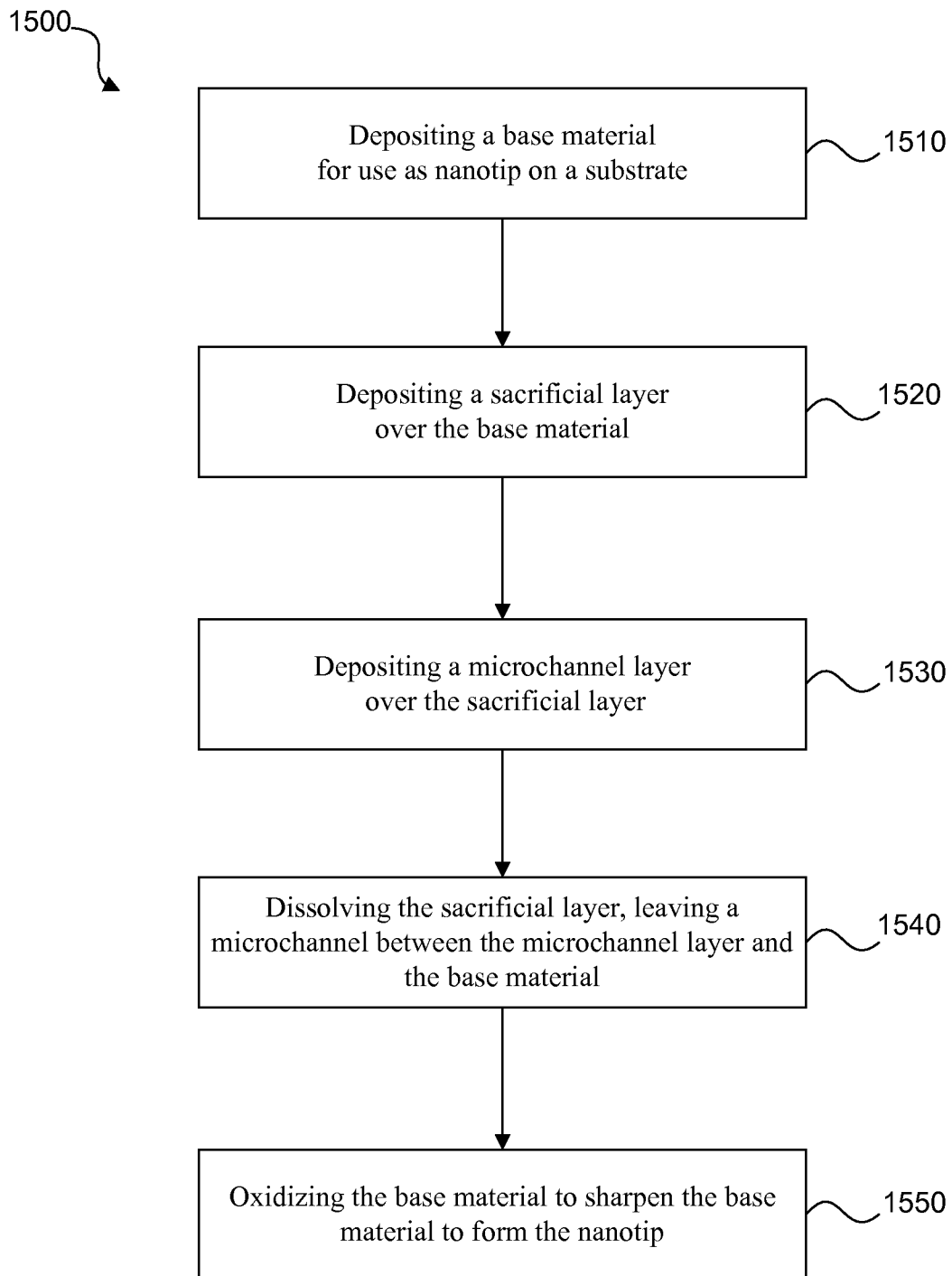


FIG. 17d

**FIG. 18**

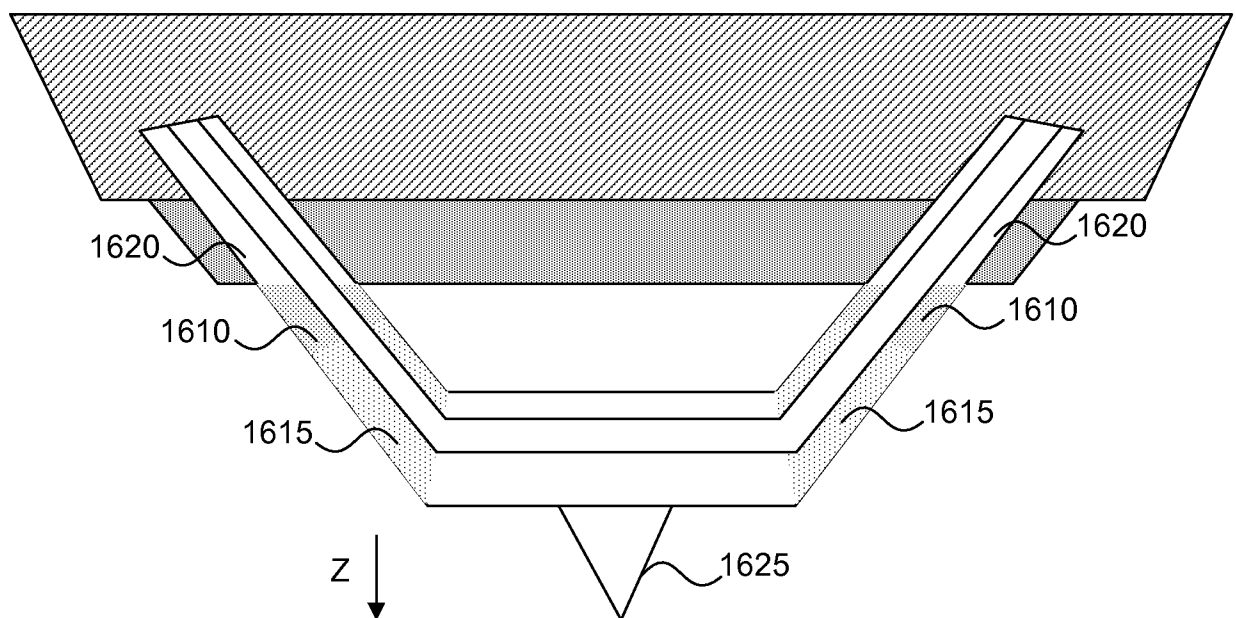
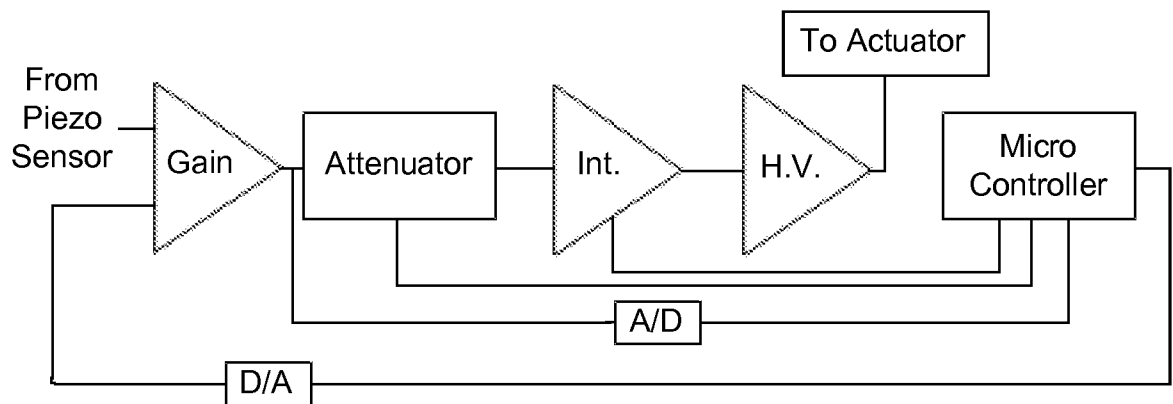


FIG. 19

**FIG. 20**