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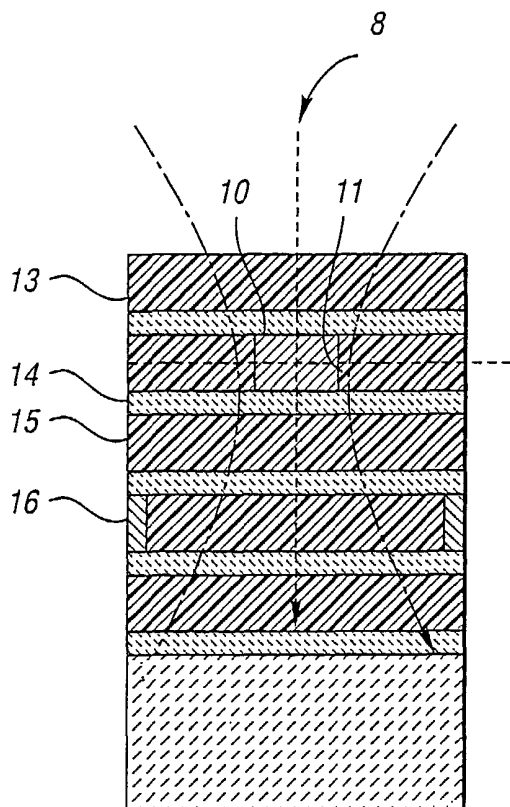
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(54) Title: METHODS AND SYSTEMS FOR PROCESSING A DEVICE, METHODS AND SYSTEMS FOR MODELING SAME
AND THE DEVICE



(57) Abstract: A method and system for locally processing a prede-
termined microstructure (10) formed on a substrate without causing
undesirable changes in electrical or physical characteristics of the sub-
strate (13) or other structures formed on the substrate. The method
includes providing information based on a model of laser pulse (13)
interactions with the predetermined microstructure (10), the substrate
(13) and other structures. At least one characteristic of at least one
pulse (13) is determined based on the information. A pulsed laser beam
(3) is generated including the at least one pulse (3). The method fur-
ther includes irradiating the at least one pulse (3) having the at least one
determined characteristic into a spot on the predetermined microstruc-
ture (10). The at least one determined characteristic and other char-
acteristics of the at least one pulse (3) are sufficient to locally process
the predetermined microstructure (10) without causing the undesirable
changes.

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METHODS AND SYSTEMS FOR PROCESSING A DEVICE,
METHODS AND SYSTEMS FOR MODELING SAME AND THE DEVICE

BACKGROUND OF THE INVENTION

1. Field of the Invention

5 The present invention relates to the field of laser processing methods and systems, and specifically, to laser processing methods and systems for processing microstructures formed on substrates. This invention is particularly applicable, but not limited to, laser repair of redundant semiconductor memory devices.

10 2. Background Art

 In the repair of memory integrated circuits such as DRAMs and laser programming of high-density logic devices, the use of new materials, such as aluminum, gold, and copper, coupled with the small geometry of these devices, make the problem of link removal difficult. The new materials are typically metals
15 or highly conductive composites having reflectivity that is well over 90% in the visible and near infrared wavelength regions. Aluminum, for example, reflects greater than 90% of the laser energy over the range from the UV through to the near infrared. Gold and copper reflects even more strongly in the near infrared, the wavelengths of choice used by most of the lasers repairing memories in production.

20 Further, economics and device performance have driven the size for the DRAMs and logic devices to very small physical dimensions. Not only are the devices small, but the interconnects and links thickness have also decreased dramatically in recent years.

 Thermal laser processing of links relies on the differential thermal
25 expansion between the oxide above the link and the link itself. This differential expansion results in a high pressure build-up of the molten link contained by the

oxide. The oxide over the link is necessary to contain the link in a molten state long enough to build-up sufficient pressure to crack the oxide and explosively expel the link material. If the pressure is too low, the link will not be removed cleanly. Alternative laser wavelengths and laser control strive to increase the laser “energy window” without damaging the substrate and material contiguous to the link.

Descriptions of an all-copper, dual-Damascene process technology can be found in “Benefits of Copper – Copper Technology is Here Today in Working Devices,” NOVELLUS DAMASEUS, December 20, 2001; and “Preventing Cross-Contamination Caused By Copper Diffusion and Other Sources,” P. Cacouvis, MICRO, July 1999.

Figures 2a and 2b illustrate prior art laser processing of multi-layer structure wherein a target structure is located in proximity to a substrate, with a q-switched pulse 20 from a conventional solid state laser 21 irradiating and overfilling a target structure 23. A laser spot size is typically significantly larger than the (target) link size which relaxes precision positioning requirements. A laser wavelength is typically selected based on substrate 27 (commonly Silicon) transmission so as to allow for higher peak laser power or other system and process variations. In certain cases, a layer 28,25 absorption coefficient is controlled (*e.g.*, as a transition or protective layer) and/or a wavelength selected wherein substrate damage is avoided.

Further information is available regarding link blowing methods and systems, including material processing, system design, and device design considerations, in the following representative U.S. patents and published U.S. applications: 4,399,345; 4,532,402; 4,826,785; 4,935,801; 5,059,764; 5,208,437; 5,265,114; 5,473,624; 6,057,180; 6,172,325; 6,191,486; 6,239,406; 2002-0003130; and 2002-0005396.

Other representative publications providing background on link processing of memory circuits or similar laser processing applications include: “Laser Adjustment of Linear Monolithic Circuits,” Litwin and Smart, ICAELO,

(1983); "Computer Simulation of Target Link Explosion In Laser Programmable Memory," Scarfone, Chlipala (1986); "Precision Laser Micromachining," Boogard, SPIE Vol. 611 (1986); "Laser Processing for Application Specific Integrated Circuits (asics)," SPIE Vol. 774, Smart (1987); "Xenon Laser Repairs Liquid
5 Crystal Displays," Waters, Laser and Optonics, (1988); "Laser Beam Processing and Wafer Scale Integration," Cohen (1988); "Optimization of Memory Redundancy Link Processing," Sun, Harris, Swenson, Hutchens, Vol. SPIE 2636, (1995); "Analysis of Laser Metal Cut Energy Process Window," Bernstein, Lee, Yang, Dahmas, IEEE Trans. On Semicond. Manufact., Vol 13, No. 2. (2000).

10 Also, the following co-pending U.S. applications and issued patents are assigned to the assignee of the present invention and are hereby incorporated by reference in their entirety:

1. U.S. Patent No. 5,300,756, entitled "Method and System for Severing Integrated-Circuit Connection Paths by a Phase Plate
15 Adjusted Laser beam";
2. U.S. Patent No. 6,144,118, entitled "High Speed Precision Positioning Apparatus";
3. U.S. Patent No. 6,181,728, entitled "Controlling Laser Polarization";
- 20 4. U.S. Patent No. 5,998,759, entitled "Laser Processing";
5. U.S. Patent No. 6,281,471, entitled "Energy Efficient, Laser-Based Method and System for Processing Target Material";
6. U.S. Patent No. 6,340,806, entitled "Energy-Efficient Method and System for Processing Target Material Using an Amplified,
25 Wavelength-Shifted Pulse Train";
7. U.S. Serial No. 09/572,925, entitled "Method and System For Precisely Positioning A Waist of A Material-Processing Laser Beam To Process Microstructures Within A Laser-Processing Site", filed 16 May 2000, and published as WO 0187534 A2, December, 2001;
- 30 8. U.S. Patent No. 6,300,590, entitled "Laser Processing"; and

9. U.S. Patent No. 6,339,604, entitled "Pulse Control in Laser Systems."

However, it is to be understood that this listing is not an admission that any of the above references are prior art under the Patent Statute.

- 5 The subject matter of the above referenced applications and patents is related to the present invention. References to the above patents and applications are cited by reference number in the following sections.

SUMMARY OF THE INVENTION

- 10 An object of the present invention is to provide improved methods and systems for processing a device, methods and systems for modeling same and the device.

- 15 In carrying out the above object and other objects of the present invention, a method is provided for laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate. The method includes the steps of: a) generating a pulsed laser beam having a predetermined wavelength and including at least one laser pulse having a predetermined characteristic comprising at least one of a temporal shape and spatial shape; b) relatively positioning the microstructure and a waist of the laser beam in
20 three-dimensional space based on at least a position measurement obtained at a reference location wherein the position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist; and c) irradiating the microstructure with the at least one laser pulse based on the predicted common location at a time wherein the beam waist and the microstructure substantially
25 coincide, wherein the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure and wherein an undesirable change to the inner layers of the stack and substrate is avoided.

Further in carrying out the above object and other objects of the present invention, a system is provided for laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate. The system includes means for generating a pulsed laser beam having a predetermined wavelength and includes at least one laser pulse having a predetermined characteristic comprising at least one of a temporal shape and spatial shape. The system also includes means for relatively positioning the microstructure and a waist of the laser beam in three-dimensional space based on at least a position measurement obtained at a reference location. The position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist. The system further includes means for irradiating the microstructure with the at least one laser pulse based on the predicted common location at a time. The beam waist and the microstructure substantially coincide, wherein the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure and wherein an undesirable change to the inner layers of the stack and substrate is avoided.

Still further in carrying out the above object and other objects of the present invention, a method is provided for laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack. The stack has inner dielectric layers which separate the microstructure from the substrate. The method includes generating a pulsed laser beam having a predetermined wavelength and includes at least one laser pulse. At least reflections of the laser beam by the layers of the stack substantially reduce pulse energy density at the substrate relative to at least one other wavelength. The microstructure is processed with the at least one laser pulse. Pulse energy density at the microstructure is sufficient to remove the microstructure while avoiding damage to the substrate and the inner layers of the stack.

Yet still further in carrying out the above object and other objects of the present invention, a system is provided for laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack. The

stack has inner dielectric layers which separate the microstructure from the substrate. The system includes means for generating a pulsed laser beam having a predetermined wavelength, and includes at least one laser pulse wherein at least reflections of the laser beam by the layers of the stack substantially reduce pulse
5 energy density at the substrate relative to at least one other wavelength beyond the absorption edge. The system also includes means for processing the microstructure with the at least one laser pulse wherein pulse energy density at the microstructure is sufficient to remove the microstructure while avoiding damage to the substrate and the inner layers of the stack.

10 Further in carrying out the above object and other objects of the present invention, a method for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate is provided. The method includes providing
15 information regarding material of the structures including the predetermined microstructure and the substrate. The method also includes determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information. The method further includes determining at least one characteristic of the at least one pulse based on the
20 optical propagation characteristics.

Still further in carrying out the above object and other objects of the present invention, a system for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of
25 other structures formed on the substrate is provided. The system includes means for providing information regarding material of the structures including the predetermined microstructure and the substrate. The system also includes means for determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information. The
30 system further includes means for determining at least one characteristic of the at least one pulse based on the optical propagation characteristics.

Yet still further in carrying out the above object and other objects of the present invention, a method for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate is provided. The method includes providing information regarding material and spacing of the structures including the predetermined microstructure and the substrate. The method also includes determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information. The method further includes determining at least one characteristic of the at least one pulse which avoids undesirable changes in electrical or physical characteristics of the substrate and the other structures based on the optical propagation characteristics.

Still further in carrying out the above object and other objects of the present invention, a system for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate is provided. The system includes means for providing information regarding material and spacing of the structures including the predetermined microstructure and the substrate. The system also includes means for determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information. The system further includes means for determining at least one characteristic of the at least one pulse which avoids undesirable changes in electrical or physical characteristics of the substrate and the other structures based on the optical propagation characteristics.

Yet still further in carrying out the above object and other objects of the present invention, a method is provided for laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate. The method includes generating a pulsed laser beam having a predetermined wavelength

and includes at least one laser pulse having a predetermined characteristic wherein:
a) the predetermined wavelength is below an absorption edge of the substrate, and
b) the at least one pulse has duration less than about 10 nanoseconds, and a repetition rate of 10 KHz or higher. The method also includes relatively positioning
5 the microstructure and a waist of the laser beam in three-dimensional space based on at least a position measurement obtained at a reference location. The position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist. The method further includes irradiating the microstructure with the at least one laser pulse based on the predicted common
10 location at a time wherein the beam waist and the microstructure substantially coincide and the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure, and an undesirable change to the inner layers of the stack and substrate is avoided.

Yet still further in carrying out the above object and other objects of
15 the present invention, a system is provided for laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate. The system includes means for generating a pulsed laser beam having a predetermined wavelength and includes at least one laser pulse having a predetermined
20 characteristic wherein: a) the predetermined wavelength is below an absorption edge of the substrate, and b) wherein the at least one pulse has duration less than about 10 nanoseconds, and a repetition rate of 10 KHz or higher. The system also includes means for relatively positioning the microstructure and a waist of the laser beam in three-dimensional space based on at least a position measurement obtained
25 at a reference location. The position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist. The system further includes means for irradiating the microstructure with the at least one laser pulse based on the predicted common location at a time wherein the beam waist and the microstructure substantially coincide, the microstructure is cleanly removed with
30 substantially maximum pulse energy density at the microstructure, and an undesirable change to the inner layers of the stack and substrate is avoided.

Further in carrying out the above object and other objects of the present invention, a multi-level, multi-material device is provided. The device includes a substrate, a microstructure, and a multi-layer stack having inner layers which separate the microstructure from the substrate. At least one of the inner
5 layers has a predetermined physical parameter based on interactions of a pulsed laser beam with the stack. The laser beam has a predetermined wavelength, wherein undesirable changes to the substrate and the inner layers of the stack are avoided during laser processing with the pulsed laser beam.

In carrying out the above object and other objects of the present
10 invention, a method for thermal-based laser processing a multi-material device including a substrate and at least one microstructure is provided. The processing occurs with multiple pulses in a single pass operation controlled with a positioning subsystem of a thermal processing system. The positioning subsystem induces relative motion between the device and laser beam waists. The processing removes
15 the at least one microstructure without damaging the substrate. The method includes generating a first pulse having a first predetermined characteristic, and irradiating the at least one microstructure with the first pulse wherein a first beam waist associated with the first pulse and the at least one microstructure substantially coincide. The step of irradiating at least initiating processing of the at least one
20 microstructure. The method also includes generating a second pulse having a second predetermined characteristic. The second pulse is delayed a predetermined time relative to the first pulse. The method further includes irradiating the at least one microstructure with the second pulse wherein a second beam waist associated with the second pulse and the at least one microstructure substantially coincide. The
25 step of irradiating the at least one microstructure with the second pulse further processing the at least one microstructure wherein the processing of the at least one microstructure with the first and second pulses occurs during relative motion of the at least one microstructure and the beam waists in a single pass whereby throughput of the thermal processing system is substantially improved.

30 Further in carrying out the above object and other objects of the present invention, a system for thermal-based laser processing a multi-material

device including a substrate and at least one microstructure is provided. The processing occurs with multiple pulses in a single pass operation controlled with a positioning subsystem which induces relative motion between the device and laser beam waists. The processing removes the at least one microstructure without
5 damaging the substrate. The system includes means for generating a first pulse having a first predetermined characteristic, and means for irradiating the at least one microstructure with the first pulse wherein a first beam waist associated with the first pulse and the at least one microstructure substantially coincide. The first pulse at least initiating processing of the at least one microstructure. The system also
10 includes means for generating a second pulse having a second predetermined characteristic. The second pulse is delayed a predetermined time relative to the first pulse. The system further includes means for irradiating the at least one microstructure with the second pulse wherein a second beam waist associated with the second pulse and the at least one microstructure substantially coincide. The
15 second pulse further processing the at least one microstructure wherein the processing of the at least one microstructure with the first and second pulses occurs during relative motion of the at least one microstructure and the beam waists in a single pass whereby throughput of the system is substantially improved.

Still further in carrying out the above object and other objects of the
20 present invention, a method for thermal-based laser processing a multi-material device including a substrate and a microstructure is provided. The method includes generating the at least one laser pulse having at least one predetermined characteristic based on a differential thermal property of materials of the device. The method also includes irradiating the microstructure with the at least one laser
25 pulse wherein a first portion of the at least one pulse increases a difference in temperature between the substrate and the microstructure, and a second portion of the at least one pulse further increases the difference in temperature between the substrate and the microstructure to process the multi-material device without damaging the substrate.

30 Yet still further in carrying out the above object and other objects of the present invention, a system for thermal-based laser processing a multi-material

device including a substrate and a microstructure is provided. The system includes means for generating the at least one laser pulse having at least one predetermined characteristic based on a differential thermal property of materials of the device. The system also includes means for irradiating the microstructure with the at least
5 one laser pulse wherein a first portion of the at least one pulse increases a difference in temperature between the substrate and the microstructure, and a second portion of the at least one pulse further increases the difference in temperature between the substrate and the microstructure to process the multi-material device without damaging the substrate.

10 In carrying out the above object and other objects of the present invention, a method for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined target having a first material to be laser processed is provided. The method includes measuring position of at least one alignment target formed at a predetermined
15 measurement location to obtain a measurement. The at least one alignment target is covered by at least one layer of a second material. The step of measuring includes selectively irradiating a portion of a region to be measured with a radiation cleaning beam to remove debris from the region to compensate for reflectivity variations and reduce multiplicative noise and associated signal variations at a
20 detector. The method also includes predicting relative location of the predetermined target and a waist of the laser beam based on the measurement to obtain a predicted relative location. The method further includes inducing relative motion between the predetermined target and the beam waist based on the predicted relative location. The method further includes generating the laser beam including at least one pulse,
25 and irradiating the at least one pulse into a spot on the predetermined target wherein the at least one pulse is sufficient to process the predetermined target.

Further in carrying out the above object and other objects of the present invention, a system for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined
30 target having a first material to be laser processed is provided. The system includes means for measuring position of at least one alignment target formed at a

predetermined measurement location to obtain a measurement. The at least one alignment target is covered by at least one layer of a second material. The means for measuring includes means for selectively irradiating a portion of a region to be measured with a radiation cleaning beam to remove debris from the region to
5 compensate for reflectivity variations and reduce multiplicative noise and associated signal variations at a detector. The system also includes means for predicting relative location of the predetermined target and a waist of the laser beam based on the measurement to obtain a predicted relative location. The system further includes means for inducing relative motion between the predetermined target and the beam
10 waist based on the predicted relative location. The system also includes means for generating the laser beam including at least one pulse, and means for irradiating the at least one pulse into a spot on the predetermined target wherein the at least one pulse is sufficient to process the predetermined target.

Still further in carrying out the above object and other objects of the
15 present invention, in a system for laser processing a target structure of a multi-layer, multi-material device, a method of controlling energy delivered to the target structure is provided. The method includes obtaining at least one measurement at each of at least two predetermined wavelengths. The method also includes determining thickness of at least one layer of the device based on the measurements.
20 The method further includes controlling energy delivered to the target structure based on the determined thickness to compensate for variations in energy required to process the target structure caused by interference effects of the at least one layer.

In a system for laser processing a target structure of a multi-layer, multi-material device, a control system for controlling energy delivered to the target
25 structure is provided. The control system includes means for obtaining at least one measurement at each of at least two predetermined wavelengths. The control system also includes means for determining thickness of at least one layer of the device based on the measurements. The control system further includes means for controlling energy delivered to the target structure based on the determined
30 thickness to compensate for variations in energy required to process the target structure caused by interference effects of the at least one layer.

Yet still further in carrying out the above object and other objects of the present invention, a method for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined target having a first material to be laser processed is provided. The method includes measuring position of at least one alignment target formed at a predetermined measurement location to obtain at least one measurement. The method also includes predicting relative location of the predetermined target and a laser beam based on the at least one measurement to obtain a predicted relative location. The method further includes generating a laser beam including at least one pulse, and inducing relative motion between the predetermined target and the laser beam based on the predicted relative location. The method further includes updating the predicted relative location during relative motion based on updated position information. The updated position information is obtained during the relative motion. The method still further includes irradiating the at least one pulse into a spot on the predetermined target to process the predetermined target based on the updated position information.

Still further in carrying out the above object and other objects of the present invention, a system for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined target having a first material to be laser processed is provided. The system includes means for measuring position of at least one alignment target formed at a predetermined measurement location to obtain at least one measurement. The system also includes means for predicting relative location of the predetermined target and a laser beam based on the at least one measurement to obtain a predicted relative location. The system also includes means for generating a laser beam including at least one pulse, and means for inducing relative motion between the predetermined target and the laser beam based on the predicted relative location. The system further includes means for updating the predicted relative location during relative motion based on updated position information. The updated position information is obtained during the relative motion. The system still further includes means for irradiating the at least one pulse into a spot on the predetermined target to process the predetermined target based on the updated position information.

The above object and other objects, features, and advantages of the present invention are readily apparent from the following detailed description of the best mode for carrying out the invention when taken in connection with the accompanying drawings.

5

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1a is a block diagram of a laser system which generates a laser pulse in response to a trigger signal obtained from a control system, the pulse having a temporal shape including a fast rise and fall time, and a duration selected for the material processing application of the present invention;

10

FIGURES 1b and 1c are views partially broken away illustrating a multi-layer, multi-material device wherein a laser pulse with pre-determined temporal and spatial characteristics irradiates the device; FIGURE 1b is a first side sectional view of a portion of the device, showing a target structure having a rectangular cross-section, wherein a high numerical aperture laser beam, having a non-unity aspect ratio, is incident on the target structure having a plurality of layers forming a stack; FIGURE 1c is a second side sectional view of a portion of the device, orthogonal to the first, showing a rectangular target structure, wherein a high numerical aperture laser beam, having a non-unity aspect ratio, is incident on the target structure;

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FIGURE 2a is a block diagram of a prior art laser system which shows a conventional q-switched or Gaussian pulse;

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FIGURE 2b is a view of a conventional multi-layer structure having a single oxide layer between the link and substrate, therefore being located in proximity to a substrate, with a conventional q-switched laser pulse irradiating and substantially overfilling the narrow dimension of the target structure;

FIGURE 3 is a graph of reflection as a function of wavelength of a multi-layer stack having 28 layers in 14 pairs, the stack representative of a device processed with a method and system of the present invention;

FIGURES 4a and 4b are top views and associated graphs which illustrate the effect of irradiating the target structure with laser beam profiles of varying dimension with respect to the target structure; FIGURES 4a and 4b show the result of truncating a representative non-uniform Gaussian shaped laser spatial profile, wherein the energy enclosed by the target structure is strongly affected, the energy at the target edge varies, and potential stray radiation effects result from energy not absorbed by the target structure;

FIGURE 4c is a side schematic view of a plurality of microstructures formed on a layer and which illustrate that for decreasing spacing (pitch) inter-reflections and stray energy result in irradiation of neighboring target structures;

FIGURES 5a and 5b are graphs which show the reduction in irradiance on the device as a function of depth resulting from precise position control of a high numerical aperture beam (at the top surface), wherein the position and depth of focus of the beam provides for processing of the target structure without creating undesirable changes to other materials; In particular, Figure 5a illustrates the increase in spot area with for various spherical and elliptical Gaussian irradiance distributions, for a representative multi-layer stack used in a copper memory process;

FIGURE 5b normalizes the defocus function relative to the energy density (fluence) at the target location;

FIGURES 6a and 6b are schematic views of a stack of layers formed on a wafer substrate and which illustrate exemplary results obtained with a ray trace simulation used to estimate the level of radiation impinging on the internal layers and adjacent links with a specified beam numerical aperture;

FIGURES 7a, 7b, 8 and 9 are views of images taken from detectors and which illustrate, on a continuous scale spanning 5 decades, simulated patterns of radiation at the surface, substrate, and with the stack removed respectively;

FIGURE 10 is a schematic diagram of a system for measuring
5 fiducials or other alignment targets;

FIGURE 11 is a graph of reflectivity versus outer layer thickness;

FIGURE 12 shows a pair of graphs of reflectivity versus thickness of the outer oxide layer for two different laser beam wavelengths;

FIGURE 13 is a schematic diagram of a system for automatically
10 controlling pulse energy based on a thickness measurement;

FIGURE 14a shows schematic and graphical representations of an effect of debris on signal fidelity during alignment measurements;

FIGURE 14b shows similar representations with improved signal fidelity after cleaning with a pulsed laser beam;

15 FIGURES 15a-15c show various arrangements for combining laser pulses or generating a sequence of closely spaced pulses using optical or electronic delay methods; Figure 15a illustrates use of multiple lasers with delayed triggering; Figure 15b illustrates a basic arrangement with a single laser and an optical delay path; and Figure 15c illustrates yet another modular optical delay line providing for
20 pointing stability and simplified alignment;

FIGURE 16 is a graph of temperature versus time which illustrates simulation results for metal link (top) and substrate (bottom) irradiance with a pair of delayed pulses wherein the substrate temperature decays rapidly exhibiting a differential thermal property of the materials; the two laser pulses each had a square
25 temporal shape;

FIGURE 17 is a series of schematic views of a metal link which illustrate a multiple pulse sequence wherein: (1) a first pulse irradiates the metal link; (2) debris is left after removing the link; (3) a second pulse with a spatial pulse shape is used wherein the central zone is attenuated, the second pulse having a lower peak energy density than the first pulse; and (4) 25 ns after the start of the first pulse the debris is removed;

FIGURE 18 is a block diagram of a system which generates and controllably selects pulses;

FIGURE 19 is a block diagram of a system of the present invention wherein a portion of a high repetition rate pulse train (*e.g.*, 1 μ Hz) is selected and a high speed beam deflector (*e.g.*, electro-optic or acousto-optic device) synchronized with microstructure positions is used to process a single microstructure with multiple pulses during relative motion; and

FIGURE 20 is a block diagram of another system of the present invention wherein a beam deflector is used to spatially split a single pulse so as to irradiate either one or two microstructures (or none) with a pair of pulses during relative motion.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

One aspect of the invention is removal of a microscopic target structure which is part of a multilayer, multimaterial device, wherein laser energy is incident on several materials having dissimilar optical and thermal properties. One application is memory repair. A new fabrication process (Damascene) includes a copper target structure, multiple dielectric layers in the form of a "stack," and functional circuitry disposed at the dielectric layers. The target structure and layers are typically formed on a silicon substrate. This is illustrated in Figures 1b and 1c and corresponds to a device processed with an embodiment of the present invention. This will be referred to as a "multilevel" process.

With the use of more complex structures at finer scale (*e.g.*, at or below a wavelength of visible light), considerations for reliable operation of laser processing system increase to meet the standards for high yield in the semiconductor industry.

5 Aspects of the invention include methods and subsystems for operation of the laser processing system. At the microscopic scale, the laser beam waist diverges rapidly due to the small spot size and depth of focus. The materials within the 3D beam location may include functional circuitry. In an automatic system, robust measurement of target locations is used in conjunction with database
10 information to position a laser beam in three dimensions at high speed. The interaction of a laser beam within the multilevel device influences yield. Modeling of thermal interaction is useful of understanding and predicting performance in the thermal processing regime. However, at the microscopic scale, a more detailed understanding of interaction based on physical optics is also beneficial.

15 In the following sections, detailed aspects of spatial and temporal pulse shaping, three-dimensional measurement and prediction, device modeling and process design are disclosed with emphasis on solving the problem of cleanly removing links on a multilevel device, wherein damage is avoided to inner layers and functional circuitry between a link and the substrate. However, various
20 methods, subsystems, and experimental results may also be applied for link processing of conventional single inner layer devices, and generally for processing microstructures surrounded by materials having dissimilar thermal or optical properties.

Processing Links on a Multilevel Device

25 A pulsed laser beam, the beam having pre-determined characteristics for processing of microscopic structures, is used to cleanly remove at least a portion of a target structure. An application of the method and system of the present invention is severing of highly reflective copper links which are part of a high speed semiconductor memory device. The method and system of the present invention is

particularly advantageous for processing of targets having a sub-micron dimension, including targets with a dimension below the wavelength of the laser beam. The target is separated from a semiconductor substrate by a multi-layer stack, which may have several dielectric layers. Furthermore, both the temporal and spatial
5 characteristics of the pulse may be selected or controlled based on the thermal and optical properties of the microscopic target, underlying layer materials, and the three-dimensional layout of the device structure, including the spacing of target structures and functional inner conductor layers.

Figures 1a-1c generally show an embodiment of the present invention
10 A laser pulse 3 irradiates a rectangular target structure or microstructure 10, side views of which are shown in Figures 1b and 1c, with a focused beam. In a preferred embodiment, an output from short pulse amplified laser system 1 is generated to produce the pulse 3 which has a rise time 4 fast enough to efficiently couple energy into a highly reflective target structure. The duration 5 is sufficient
15 to process the target structure wherein at least a portion of the structure is cleanly removed without leaving residue, slag, or other debris. The fall time 6 is preferably fast enough to avoid creating undesirable damage to the layers or substrate.

The temporal pulse shape is selected, in part, based on physical properties of the target microstructure 10, for instance, thickness, optical
20 absorption, thermal conductivity, or a combination thereof. In an advantageous embodiment of the invention, the processing will occur with a single pulse having a fast edge leading relative to a selected pulse duration of several nanoseconds. In an alternative embodiment, the laser output may be a series of narrow q-switched or rectangular pulses, with very fast rise time, for example 800 ps pulses
25 representative of the output of commercially available q-switch micro-lasers. The pulses may be delayed with respect to each other so as to provide a burst of pulses to irradiate the target structure. The laser output may be generated with a combination of a high bandwidth seed laser diode and fiber optic amplifier with Raman shifting, or with a waveguide amplifier system. Alternatively, a desirable
30 pulse characteristic may be provided with various modified q-switched systems or with the use of high speed electro-optic modulators. Other pulse shapes may be

selected for the material processing requirements. For instance, a sequence of closely spaced pulses having duration from a few picoseconds to several nanoseconds is taught in Reference 5.

5 In one embodiment, a high bandwidth MOPA configuration is used to amplify the laser output of a high speed semiconductor diode. Generation of various pulse shapes and duration with direct modulation of the diode is considered advantageous, provided any affect associated with variable amplitude drive waveforms does not affect overall performance. Further details of various aspects of pulse generation and amplification can be found in references 5 and 6 (*e.g.*, in
10 '471 — Reference 5 — Figures 5 and columns 14-16).

As indicated above, embodiments of the laser system may include fiber optic amplifiers which amplify the preferred square pulse shape generated by a seed laser. The seed laser may be a high speed semiconductor diode or the shaped output of a modified q-switched system. The amplified output may be matched in
15 wavelength to the input or Raman-shifted as taught in References 4 and 6 (*e.g.*, in Reference 6, Figures 12-13 and column 14, line 57 - column 19, line 3). Wavelength shifting of a short pulse q-switched laser output is generally taught in '759 Reference 4.

In an alternative arrangement the seed laser is a semiconductor diode
20 and the optical amplifier is a waveguide amplifier. Advantages of an embodiment with a waveguide amplifier when compared to a fiber system include avoidance of Raman shifting, lower pulse distortion at the speed of operation, and, with proper design, minimal thermal lensing. A precision anamorphic optic system is used to optimize coupling between the seed and amplifier. Basic description of waveguide
25 amplitude and lasers can be found in product literature provided by Maxios, Inc. and in the article "CW and passively Q-switched Cladding Pumped Planar Waveguide Lasers," Beach et. al. Yet another amplifier system including a 28 DB planar waveguide amplifier for use at 1.064 μm wavelengths was developed by University of Southampton and described in "A Diode Pumped, High Gain,
30 PlanarWaveguide, Nd:Y3Al5O12 Amplifier."

In an alternative arrangement, for generation of a fast rising pulse or other desirable shape, a plurality of q-switched micro-lasers can be used. The modules produce a q-switched waveform with pulse durations of about 1 nanosecond or less, for example 800 ps to 2 ns for commercially available units. An example of a commercially available laser is the AOT-YVO-1Q available from Advanced Optical Technology (AOTLasers.com). These recently developed short pulse, active q-switch lasers can be triggered with a TTL pulse at a variable repetition rate while maintaining specified sub-nanosecond timing jitter. In general, the pulse shape incident on the target microstructure will vary significantly at repetition rates approaching the maximum rate. Reference 9 teaches methods of maintaining a constant pulse shape despite variations in the temporal spacing of pulses incident on a target (*e.g.*, see the figures and associated specification). AOT offers a pulsewidth of 2 nanoseconds available at a repetition rate of 20 KHz. Frequency doubled versions are also available (532 nm). IMRA America reports 800 ps pulses with the PicoLite system, and high peak power was obtained with fiber amplification at repetition rates up to 10 KHz. Shorter pulsewidths, for instance about 1 ns or less, are available at slower repetition rates.

As known in the art and illustrated in Reference 5 (*e.g.*, Figures 1c, 2), the q-switched waveforms may approximate (at least to 1st order) a symmetric Gaussian shape, or a fast rising pulse with an exponential tail, depending on the stored energy. With reference to Figures 15a-15c, a series of devices, with appropriate delays introduced by a plurality of triggering signals, or delays of a trigger signal with a delay line, is used to generate a series of spaced apart pulses. The optical outputs are preferably combined with appropriate bulk optics (polarization sensitive), fiber optics, or waveguides to form a single output beam. The resultant addition of the q-switched waveforms produces a fast rise time characteristic and relatively short duration. An optical amplifier 122 may be used to increase the output power as needed.

Figure 15a shows a schematic of one basic embodiment with bulk optics, where a beam combiner 123 is used to deliver the output of two lasers 120,121 to an amplifier 122. A delay circuit 126, which may be programmable,

controls triggering. Polarization optics 127,128 are used to provide the proper input to the beam combiner. In one arrangement the pulses are spaced apart and appear as a high frequency burst 124. In a second arrangement triggering of the second pulse occurs at a slightly delayed (but controlled) position which produces a characteristic approximating a square pulse shape 125. In the latter arrangement the controlled delay is about 50% of the FWHM. Those skilled in the art will recognize that alternative arrangements may be used with multiple amplifiers, combiners, with bulk, fiber, or integrated optic arrangements.

Generation of multiple pulse waveforms may also include some form of active q-switching of two separate microlasers or detecting a first pulse from a passively q-switched laser and subsequently triggering an actively q-switched laser or MOPA relative to the first pulse.

Figure 15-b is a basic schematic showing the use of a single laser wherein the laser output is divided by beam splitter 142, whereby a portion of the beam propagates along a path 141, followed by combining with combiner 143, after polarization adjustment with rotator 146 which may be a half-wave plate. An optional optical amplifier 145 may then be used to produce higher output power.

In an arrangement using a single laser and an optical delay line, the optical system will preferably be stable and easy to align. Figure 15c shows an exemplary embodiment wherein the use of opposing corner cube retroreflectors 130 makes the setup insensitive to tilt of the folding elements. The angular alignment of the delayed beam paths 131,132 is very stable even in a high vibration environment. One of the corner cubes in each pair of retroreflectors 130 is initially adjusted in the X/Y translation and Z rotation to get the transverse position of the delayed beam path centered. Each of the $\lambda/2$ retarders 133 in the main beam path is adjusted so that vertical or horizontally polarized light will have its polarization rotated by 45 degrees. The $\lambda/2$ retarder 133 in the second delay loop is adjusted so that vertical or horizontal polarized light will have the polarization rotated by 90 degrees causing the delayed pulse in the second loop to circulate twice before exiting. The peak-to-peak spacing of the output waveform 135 (e.g., 4 combined

pulses) is controlled by the length of the delay loops. If non-equal amplitudes for the delayed pulses are desired, the $\lambda/2$ retarders 133 in the main beam can be set for a polarization of other than 45 degrees. Likewise, the pulse shape can be varied at the time a system is setup or possibly in operation by manually or automatically
5 controlling the spacing. Those skilled in the art of laser pulse generation and shaping will appreciate the advantages of the compact and modular arrangement for short pulse for typical delays ranging from a few nanoseconds to tens of nanoseconds. For instance, U.S. Patent No. 5,293,389 to Hitachi describes a polarization-based fiber delay line for generating laser pulses of decreasing
10 amplitude for generating longer pulses, for instance 100 ns or longer.

Another means of producing a shaped pulse is to use the modulator approach to chop the leading edge or tail of the pulse but with a two-stage or shaped modulation voltage pulse. For example: with a 10ns q-switched pulse, the modulator could have 100% transmission for the first 1-5ns followed by 25%
15 transmission for the remainder of the pulse. Early pioneering work by Koechner (U.S. Patent No. 3,747,019) and Smart (U.S. Patent No. 4,483,005) demonstrate exemplary amplitude and pulse shape control methods using electro-optic modulators.

The multiple pulses shown in Figures 15a-15c may or may not have
20 the same wavelength, and the temporal shape of a pulse may be varied depending upon specific requirements. For example, in certain embodiments an output may be a q-switched pulse of short duration and high peak power combined with a lower power square pulse shape.

Referring to Figures 1a and 1b, during system operation for memory
25 repair, position information, obtained with a precision measurement system, is used to relatively position the focused beam waist of the pulsed laser at a location in space 7,8,9 to substantially coincide with the target 10 three-dimensional coordinates (Xlink,Ylink,Zlink). A trigger pulse 2, generated at a time where the laser beam waist and target position substantially coincide, operates in conjunction with the

laser and associated control circuitry in laser subsystem 1 to produce an output pulse.

References 2 and 7 describe details of a method and system for precision positioning, including three-dimensional beam waist positioning. Reference 7 describes a preferred embodiment for producing an approximate diffraction limited spot size with a range of spot size adjustment (*e.g.*, Figures 7-9 of WO0187534 ('534) and the associated specification), and a preferred method and system for three-dimensional positioning of the beam waist. Three-dimensional (height) information is obtained, for instance with focus detection, and used to estimate a surface and generate a trajectory (*e.g.*, Figures 2-5 of '534 and the associated specification). The laser is pulsed at a location substantially corresponding to the three-dimensional position of the link (Xlink, Ylink, Zlink) (*e.g.*, Figures 10a-b of '534 and the associated specification).

In practice, the three-dimensional measurement and positioning are used to compensate for topographical variations over a wafer surface, or other position variations introduced in a system (mis-alignment). These variations are generally system or application dependent and may exceed several microns, which in turn exceeds the depth of focus of the focused laser beam. In some micro-machining applications the system positioning requirements may be relaxed if certain tolerances are maintained, or if external hardware manipulates the device position, as might be done with a micro-positioning sub-system. The device may comprise a miniature part (*e.g.*, single die) which is positioned by an external micro-positioning subsystem to a predetermined reference location. Similarly, if a miniature part has a pre-determined tolerance the positioning may be based on single measurement at a reference location or perhaps a single depth measurement combined with a lateral (X,Y) measurement. For processing of multilevel devices on wafers, (*e.g.*: 300 mm) at high speed it is expected that densely sampled three-dimensional information will improve performance, particularly as link dimensions shrink.

In applications requiring very high speed operation over a large surface (*e.g.*, 300 mm wafer), an alternative method is to combine information which may be predetermined (*e.g.*, the plane of a wafer chuck relative to a beam positioner plane of motion measured during a calibration process) with dimensional information obtained from each part to be processed. For example, in '534, Figures 1-2, a fraction of the tilt of region 28 may be associated with fixturing). For example, the steps may include (a) obtaining information identifying microstructures designated for removal, (b) measuring a first set of reference locations to obtain three-dimensional reference data, (c) generating a trajectory based on at least the three-dimensional reference data to obtain a prediction of beam waist and microstructure surface locations, (d) updating the prediction during relative motion based on updated position information, the updated position information obtained from a position sensor (*e.g.*, encoder) and/or from data acquired during the relative motion. The additional data may be measurement data acquired at additional alignment target or at other locations suitable for an optical measurement (*e.g.*, dynamic focus). Reference 2 describes a system wherein a precision wafer stage is used to position a wafer at high speed. A method of obtaining feedback information with resolution of a fraction of one nanometer is disclosed wherein interferometric encoders are used, and such a high precision method is preferred. In Reference 2 it was noted that other conventional laser interferometers may also be used. Figures 9-11 and columns 5-6 of Reference 2 describe aspects of the precision measurement subsystem associated with the precision positioning apparatus. Additionally, designated reference locations on the workpiece (*e.g.*, wafer) which may be an x,y alignment target or a region suited for a three-dimensional measurement may be used for various applications. It should also be noted that height accuracy of about .1 μm was reported in "In-situ height correction for laser scanning of semiconductor wafers," Nikoonhad et al., Optical Engineering, Vol. 34, No. 10, October 1995, wherein an optical position sensor obtained area averaged height data at high speeds. Similarly, a dynamic focus sensor (*e.g.*, astigmatic systems used for optical disk tracking and control) may be used to obtain height information provided the data rate is fast enough to support "on the fly" measurement.

Various combinations of the above technologies can be used depending upon the application requirements. A combination may be based on the number and typical distribution over a device of microstructures designated for removal. When a large number of repair sites are distributed across a device, the throughput may be maximized by providing updates “on the fly.”

In an application of the invention, the target structure 10 is provided as a part of a multi-material, multi-layer structure (*e.g.*, redundant memory device). The multi-layer stack having dielectric layers 14,15 provides spacing between the link and an underlying substrate 17. In one type of multi-layer memory device, alternating layers of Silicon Dioxide 15 and Silicon Nitride 14 may be disposed between a copper link target structure 10 and a Silicon substrate 17. The copper target structure is generally located in proximity to other similar structures to form a 1-D or 2-D array of fuses which are designated for removal. In addition to the copper link structure, underlying conductors 16 disposed as part of the functional device circuitry, may be in proximity to the link structure, and arranged in a series of patterns covered by relatively thin ($< .1 \mu\text{m}$ typical) Silicon Nitride 14 and thicker ($\sim 1 \mu\text{m}$ typical) Silicon Dioxide 15 materials.

The irradiance distribution at the link may substantially conform to a diffraction limited, circular Gaussian profile. In another useful embodiment, the beam has an approximate elliptical Gaussian irradiance profile, as might be produced with an anamorphic optical system, or with a non-circular laser output beam. In one embodiment, the incident beam has a non-uniform aspect ratio 12,11 as also illustrated in Figure 4b (*e.g.*, 3:1). Alternatively, rectangular or another chosen spatial profiles may be implemented in a lateral dimension. For example, Reference 1 discloses various advantageous methods and optical systems for “non-Gaussian” spatially shaping of laser beams for application to memory repair.

With the nearly diffraction limited elliptical Gaussian case, the preferable minimum beam waist dimension at location 11 approximates the narrow target 10 dimension of Figure 1b, which, in turn, produces high pulse energy

density at the link. Further, with this approach, a high fraction of the laser energy is coupled to the link and background irradiance is reduced.

A typical copper link used in a present memory has width and thickness of about $1\text{ }\mu\text{m}$ or less, for example, $.6\text{ }\mu\text{m}$, and length of about five
5 microns. Future memory requirements are expected to further reduce the scale of target dimensions. The minimum beam waist dimension W_{y0} at 11 will typically overfill the sub-micron link to some degree, whereas aspect ratio W_{x0}/W_{y0} 12,11 with W_{x0} a few microns along the link, can facilitate clean link removal. Additionally, rapidly decreasing energy density on the layers 14,15 and substrate
10 17 is achieved through defocus of the high numerical aperture beam portion 11.

The graphs of Figures 5a and 5b illustrate the estimated defocus for various aspect ratios, relative to a circular Gaussian and an elliptical beam at best focus. Figure 5a shows the very rapid falloff of a $1.6\text{ }\mu\text{m}$ circular Gaussian ($.002\text{ mm}$ numerical divisions = $2\text{ }\mu\text{m}$). Figure 5b shows a normalized result to scale the
15 energy density at best focus for the different spot shapes. These results indicate that with precision beam positioning in depth, wherein the power density is maximized at the target site, at relative reduction in energy density of more than one decade occurs at the substrate level for an exemplary multi-layer stack used in a copper based process for memory fabrication. Further, the rapid defocus relative to the
20 waist W_{y0} is beneficial for avoiding inner layer damage, provided the "tails" of the incident beam irradiate functional inner layer 16 (e.g., copper) at a low level.

In one embodiment for processing a multilevel device, copper link removal is initiated with application of the fast rise time pulse, having a nominal 10-90% rise time 4 in a preferred range of less than 1 nanosecond to about 2
25 nanoseconds. A pulse duration 5 in the range of about 2 nanoseconds to 10 nanoseconds is preferable to sever the link while limiting thermal diffusion. Pulse energies in the range of about 0.1 microjoules (μj) to $3\text{ }\mu\text{j}$ were effective, with a preferred typical range of about 0.1- $5\text{ }\mu\text{j}$ considered sufficient margin for spot shape and process variations. The preferred pulse duration may be selected based upon
30 the nominal link thickness specifications, or based on a model of the dissimilar

thermal and optical properties of adjacent materials. During the pulse duration, thermal shock of top layer 13 and thermal expansion of the target 10 result in explosion of the link through ruptured top oxide layers 13, which in turn reduces the stress at the lower corner of the link structure adjacent to the layer 14. The laser pulse is rapidly terminated, preferably within a few nanosecond fall time 6 after the explosion, at a time just after the thin link is cleanly severed, and prior to a time the lower corner of the link results in cracking of at least layer 14. Further details and results related to the interaction of a laser pulse with a metal link and overlying layers is disclosed in references 4 and 5. The '471 patent and the associated specification describe the interaction process (*e.g.*, Figures 1a, 1b, 11a, 11b, and in column 18).

Hence, a combination of the spatial characteristics (*e.g.*, beam waist shape and position) and the temporal (*e.g.*, rise time 4, flatness, and duration 5) pulse characteristics avoids undesirable cracking of lower layers 14,15, avoids significant pulse interaction with inner layer conductor 16, and limits substrate 17 heating. Hence, despite the high reflectivity of the copper link at visible and near infrared wavelengths, and the expectation in the prior art of incomplete removal and damage to surrounding structures and substrate, the target structure is processed without undesirable damage to other structures. It is also known that copper, in addition to having nearly maximum reflectance in the near IR, is also more reflective than other link materials (*e.g.*, aluminum, platinum). Nevertheless, due to the optical interaction of the near IR beam with the target and the optical and thermal properties of adjacent (overlying) layers, the preferred copper material can be processed.

Furthermore, near IR (Infrared) wavelengths also conveniently correspond to wavelengths where high bandwidth laser diodes are available, and to the spectral range where optical amplification of the pulsed laser beam can be efficiently produced with fiber and waveguide amplifiers. Those skilled in the art will recognize that amplified laser diode outputs, having a desired temporal pulse shape, may also be frequency multiplied to produce visible laser outputs when advantageous. The fast rise time of semiconductor diodes is particularly

advantageous for producing a fast rise time, square pulse characteristic. Future developments in visible diode and optical amplifier technology may support direct pulse amplification in the visible range.

5 In a preferred system for copper link blowing, the link width is a fraction of one micron and the link spacing (pitch) is a few microns with present process technology. The link width may typically correspond to a wavelength of visible light. Further, at the microscopic scale of operation, where the lateral and/or thickness dimensions of the materials of Figures 1b and 1c are on the order of the laser wavelength, the thickness and indices of refraction of the stack materials can
10 significantly affect the overall optical characteristics of the stack.

In one embodiment of the invention, a preferred reduced wavelength is selected in the visible or near infrared range wherein a non-absorptive optical property of the layers (*e.g.*, interference or reflection loss) is exploited. The device structure of Figures 1a and 1b can be damaged with substantial absorption within
15 the lower layers, such damage is prohibitive because of the presence of adjacent circuitry. This is in contrast to link processing with the prior art system of Figure 2b where inner layer damage is not generally detrimental to overall device performance.

U.S. Patent No. 6,300,690 (Reference 8) describes a system and
20 method for vaporizing a target structure on a substrate. The method includes providing a laser system configured to produce a laser output at the wavelength below an absorption edge of the substrate. Furthermore, Reference 4 discloses benefits of a wavelength less than 1.2 μm for processing links on memory devices wherein the substrate is Silicon, namely smaller spot size and shorter laser
25 pulsewidths. In accordance with the present invention, improved performance can be realized by exploiting the non-absorbing stack properties with wavelength selection. Furthermore, at least one of precision positioning of a high numerical aperture beam, spatial shaping of the spot, or temporal pulse shaping also will provide for reduced energy at the substrate. The result corresponds to a relatively
30 low value of energy expected to be deposited in the substrate, despite an incident

beam energy necessary to deposit unit energy in the target structure sufficient to vaporize the target structure.

The factors affecting the energy deposited in the substrate are, in effect, multiplicative. Likewise, at short visible wavelengths, copper is absorbing (e.g., about 50% at 500 nm, 70% in the near UV, compared to 2% at 1.064 μm) so less energy is required for clean removal, at least an order of magnitude. The preferred identified wavelength corresponding to a relatively low value of the energy expected to be deposited in the substrate is within a visible or near IR region of the spectrum. A model-based approach may be used to estimate the shortest wavelength with sufficient margin for a specified dielectric stack, spot position, tolerance, temporal and three-dimensional spatial pulse characteristics.

For processing on links on multilevel devices with Silicon substrates, the limiting wavelength corresponding to a relatively low value of the energy expected to be deposited in the substrate (e.g., below the image threshold) may be within the green or near UV region of spectrum, but the use may require tightly controlled system parameters, including possible control of the stack layer thickness or index of refraction.

With wavelength selection in accordance with the present invention, where the internal transmission and preferably reflection of the stack is at or near a maximum, stack layer damage is avoided. Furthermore, decreasing substrate irradiance, while simultaneously providing a reduced spot size for link removal (at or near diffraction limit), is preferred provided irradiation of functional internal layers is within acceptable limits. Spectral transmission curves for typical large bandgap dielectric materials generally show that the transmission decreases somewhat at UV wavelengths. For example, in HANDBOOK OF LASER SCIENCE AND TECHNOLOGY, the transmission range of Silicon Dioxide is specified as wavelengths greater than .15 μm . The absorption coefficient of both Silicon Nitride and Silicon Dioxide remains relatively low in the visible range ($> 400 \text{ nm}$) and gradually increases in the UV range.

Figure 3 is a graph which illustrates the estimated back reflection produced by a representative multi-layer stack of 14 Silicon Dioxide 15 and Silicon Nitride 14 pairs over a range of near IR wavelengths, where the thickness of the layers is about 1 μm and .07 microns, respectively. In accordance with the present invention, a large number of layers can be accommodated, and may range from about 4-28 dependent upon the process (*e.g.*, sometimes multiple layers may separate a functional conductor layer).

By way of example, it is shown that significant reflection occurs over relatively broad wavelength range. A single layer disposed as an internal layer 14 will typically reflect roughly 2% at each surface over the visible and near IR spectrum. It is well known in the art of link and semiconductor processing that Silicon absorption varies by orders of magnitude in the near IR spectral range. Further, studies of Silicon material processing have shown that the absorption is unstable and non-linear with increased laser power and substrate heating at wavelengths near the absorption edge, as taught in reference 4. However, as stated above, the shorter wavelengths are preferred to produce smaller spots (references 4-6, and 8) and higher energy concentration at the link position.

In accordance with the present invention, exploiting the layer reflection with wavelength can further enhance the system performance and supplement the benefits associated with temporal and spatial control of the pulse in a preferred short wavelength range. Such wavelength selection is regarded as particularly advantageous at wavelengths where the substrate absorption would otherwise greatly increase, and significant margin can be obtained when the number of layers 14,15 disposed between the link and substrate substantially exceeds the number of overlying layers 13. A preferred structure for processing will comprise a substantial number of layers, with large reflectance at a predetermined short wavelength, the wavelength being well matched for generation of the preferred fast square temporal pulse shape.

Standard laser wavelengths in the range of Figure 3 include 1.047 μm and 1.064 μm , the latter being a standard wavelength of semiconductor diodes.

Further, custom wavelengths include 1.08 μm , and other wavelengths generated with Raman shifting. Those skilled in the art will recognize that frequency multiplication of the near IR wavelengths can be used to generate short wavelengths, and with appropriate design multiple wavelengths may be provided in a single system. For instance a preferred temporal pulse shape, with a fast rise time, may be generated in the green portion of the visible spectrum by frequency doubling a near IR laser.

In an alternative embodiment, wavelength tuning is used to match the wavelength to the approximate peak reflectance of the stack. Such an arrangement may be particularly advantageous for adjustment of a laser wavelength at the edge of the reflectance range (*i.e.*, "cutoff" range) over a limited wavelength range, whereby sensitivity to tolerances in the material thickness and index of refraction are avoided. As noted above, further discussion of laser amplifier systems and application to other link structures can be found in references 4-6.

Generation of the pulsed laser beam may include the step of shifting the wavelength of the laser beam from a first wavelength to a predetermined wavelength. The predetermined wavelength may be based on material characteristics comprising at least one of: (1) coupling characteristics of the microstructure, (2) multi-layer interference, and (3) substrate reflectivity.

Experimental results have shown that at a wavelength of 1.047 μm , where the absorption of Silicon is orders of magnitude higher than at 1.2 μm , substrate damage is avoided with a short q-switched (standard) pulse and the stack characteristic of Figure 3. However, the results with a standard laser having a q-switched temporal pulse shape showed cracking of an oxide layer 14 below the link. The relatively slow rising q-switched pulse shape, which for a Gaussian approximation is a substantial fraction of the duration, was considered a limiting factor for link removal without cracking of the inner layer based on experimental results. However, based on the teachings of the prior art, severe damage to the Silicon substrate would be expected at the 1.047 μm wavelength because the absorption is orders of magnitude higher than at a wavelength corresponding to

maximum transmission. In accordance with the teachings of the present invention, the spatial pulse characteristics and the stack reflection are important factors to consider so as to avoid inner layer and substrate damage and short wavelengths of operation (which also provide for a smaller spot size and higher energy concentration at the link). Further, in accordance with the present invention, a predetermined square pulse shape generated at a laser wavelength of 1.047 μm would be expected to produce clean removal without undesirable changes to the stack and substrate.

Laser Processing and Process Design at the Sub-Micron Scale

Furthermore, in an exemplary advantageous embodiment for short wavelength processing of reflective microscopic structures, a specification for a multi-layer stack may be considered in process design. For example, a quarter-wave stack of alternating dielectrics or other suitable arrangement having a large difference in the index of refraction, and high transmission within each layer, is specified at a selected wavelength. It can be shown that very high reflectance is achievable, the quarter-wave stack being easily computed in closed form and modeled. Hence, the method and system of the present invention can be used effectively with other aspects of process design, and may be advantageous where the absorption of deeply buried layers and the substrate is relatively high, or where the width of a target structure is well below the laser wavelength.

The design of the device structure may have certain constraints related to the layout of the circuitry. As such, certain thickness and material for a certain layer may be defined, for instance an insulator in a plane of a conductor having the approximate thickness of the conductor, or related to the thickness of the conductor. It may be possible to select a material having a different index of refraction than the specified layer. A specified thickness may be based on the estimated reflection at an advantageous laser wavelength which may reduce or eliminate a requirement for special laser equipment operating at "exotic" wavelengths where the lasers are difficult to manufacture with high yield. The

reflection may be estimated using a model wherein the thickness is a variable, and an estimate made to maximize the reflection, subject to other device constraints.

Thickness of the layers can be tuned to a wavelength in as much as the wavelength (or angle) can be tuned to the layers. Index of refraction could be used to fine-tune over a limited range, but the range may not be significant for small changes in index. Even with all thicknesses fixed by the process, the addition of a variable thickness tuning layer or layers with predetermined thickness could be used to significantly affect reflectivity of the whole stack. For example, a layer not constrained by metallization requirements could be used as a precision spacer between an upper and a lower stack portion. This could be a very powerful tool for tuning the process with adjustment of perhaps only one layer.

Physical Optics and Laser Processing of Multi-Level Devices

Other controllable laser characteristics may be exploited, alternatively or in conjunction with wavelength selection, to provide further improvements in the processing energy window. Reference 3 describes an advantageous method and system for polarization control, including dynamic polarization selection and computer control so as to align the polarization with a link orientation (*e.g.*, details shown in Figure 4 and the associated description in the reference). The polarization can be selected on the basis of the target coupling characteristics, the film reflectance, or a combination thereof.

With a link dimension below the spot size, effects like diffraction, scattering, and edge reflection should be considered as physical phenomena which can have either advantageous or detrimental results depending upon the device geometry and beam characteristics. Likewise, at high energy density, non-linear absorption may affect results, with particular concern of semiconductor material damage.

An additional important consideration with fine pitch (spacing) of adjacent links and circuitry is collateral damage. Furthermore, functional circuitry

in a plane of the layers must not be damaged. With an increasing trend toward fine pitch and high density memory, the three-dimensional structure of the device should be considered and may affect a choice of beam spatial and temporal characteristics. By way of example, Figures 4a-4c illustrate effects of reflection and diffraction associated with sub-micron width link 10 resulting in truncated 43,44 Gaussian beams 11, where the spot size (as measured at the 13.5% point) is wider than the link by varying degrees. The sketches are representative of a diffraction limited beam waist at a near IR wavelengths. The central lobe is clipped by the link, which appears as a near field obscuration, resulting in transmitted beam portions which are truncated 43,44. Energy which is not incident on the link may propagate at wide angles into the layers 49 which may be advantageous from the standpoint of avoiding damage to the substrate 17 as shown in Figure 1. In any case, there will be some correlation of neighbor irradiance with spot size. Large spots with a relatively large depth of focus have reduced divergence and neighbor irradiance can be small, provided that the link spacing is large enough that the non-absorbed energy 43 of the incident beam impinging on an adjacent structure is weak, for instance corresponding to level 44. With a higher N.A. and smaller spot size, the reflected beam diameter at the link location 46 is increased. There will be a maximum value for some spot size 41,42. Then irradiance at a neighboring link 48 decreases as the reflected energy grows larger in area.

Simultaneously there is an angular variation in internal reflection. Hence, the stack layer thickness can also effect the irradiance of adjacent structures, including the internal structures 16 of Figure 1. Furthermore, polarization variations with angle are expected to produce variations. Figures 6a and 6b illustrate by way of example geometric ray tracing effects of internal reflections propagating over an extended area.

Similarly, as shown in Figure 4c, if a portion 45 of the laser beam incident on the edge of the link 46 is considered, the energy which is not coupled into the link structure may also be scattered and/or specularly reflected to the adjacent links 48. The inter-reflection 47 occurs as a consequence of at least the link 46 physical edge profiles which may be slightly curved or sloped.

An additional consideration is the three-dimensional spacing between an inner conductor layer 16 of Figure 1, the beam waist 11, and the adjacent links 48 of Figure 4c. A large numerical aperture beam waist 11, producing the smallest spot size at the link, while diverging and reflecting in a manner so as to avoid significant interaction with the inner layer 16 is preferred. Examination of Figures 4a-4c suggest a reduced spot size with controlled precision 3D waist positioning is expected to reduce collateral damage by maximizing energy coupled into the link. With high enclosed energy within the link and a low intensity transmitted profile 44, edge reflection is minimized. The spatial profile should also be selected subject to the constraint of only low level, negligible interaction between the beam angular distribution at 16.

It is preferred that the interaction mechanisms associated with a portion of the three-dimensional device structure be modeled for selection of at least a spatial pulse characteristic, such a characteristic may be the N.A. and position of the beam waist. Preferably, the model will include an estimate of the irradiance seen by each adjacent link structures 48, internal layer 16, and substrate 17. Whereas damage to adjacent link structures may be relatively apparent with conventional microscopy, assessment of inner layer 16 and substrate 17 damage may be considerably more difficult with the 3-D device structure.

With link widths below 1 μm , and pitch of a few microns, precise, sub-micron alignment is required to compensate for variations between wafers, and local variations within a wafer, and system tolerances (*e.g.*, 300 mm wafer with 25 μm of topographical variation, and 5 μm of manufacturing tolerances, for instance). In accordance with the present invention, a precision positioning method and system is used to relatively position the beam waist so as to provide high laser energy concentration at the link. Also, one important consideration for precision positioning is predicting accurate (Xlink,Ylink) location information. The prediction is subsequently used by a motion control and positioning system to generate a laser output via trigger 2 at the target coordinates, during relative motion of the target 10 and laser beam. A preferred embodiment includes a polarization insensitive scanning and detection system as described hereinbelow, wherein a

region containing an alignment target location is imaged to obtain reference data. The target location is often covered by a dielectric layer of Silicon Dioxide, Silicon Nitride, or other insulating material. Experiments have indicated that polarization insensitive detection is advantageous to avoid spurious measurements. The results
5 led to a hypothesis that that birefringence is introduced in the insulating layers by polishing or other process operations, which is manifested by polarization variations in the reflected beam. These variations reduce the signal-to-noise ratio and appear to induce position distortion. The digital output data from each target location is used by an 8-parameter least squares alignment algorithm to estimate and correct
10 position information affected by offset, angle, scale, orthogonality, and trapezoidal variations over the wafer containing the links to be processed.

Given the variations in the received beam at the target location, concerns arise that process variations may affect layer optical properties near the target structure. Furthermore, in practice, variations occur in the thickness and
15 reflectivity of the target and layers, either over a wafer to be processed or from batch-to-batch. Measurement of the thickness and reflectivity is useful for process monitoring, and can also be used to determine adjustments for the laser power and wavelength to increase the energy window. For instance, any variation in the reflectivity of the link can affect the energy required for processing. A preferred
20 method and system for adaptive energy control is also described hereinbelow.

As dimensions of links and other microscopic structures continue to rapidly shrink, those skilled in the art will appreciate the benefits of multi-parameter modeling. A model-based approach leads to selection and precision control of the spatial and temporal characteristics of the laser output, resulting in controlled
25 three-dimensional interaction of the laser with complex multi-layer, multi-material structures.

Polarization Insensitive Detection and X,Y Reference Measurements

Commercial laser systems of the assignee of the present invention use a beamsplitter to pick off a portion of the reflected light from the work surface (*e.g.*,

a multi-layer memory device) as the laser is relatively positioned 152 over the alignment targets (*e.g.*, fiducials). A block diagram of the subsystem is shown in Figure 10. The reflectance/transmission (R/T) split of the beamsplitter 150 depends on the laser that is being used. In cases where the laser has low total energy and as much transmission as needed is necessary, the split of 90% transmission and 10% reflectance is made. This gives 90% going to the work surface on the way in and the 10% reflected is dumped. But this only picks off 10% of the reflected light, 90% of the reflected light is transmitted back down the laser path. When possible, the split 70/30 is made. This gives less total energy to the work surface but gives higher reflected signal.

Regardless of the R/T split, the specification is the R/T for S polarization = R/T for P polarization (within 5%). This is accomplished with a special dichroic coating, which produced good results. Because any polarization state can be thought of as a vector sum of S and P, the beamsplitter works at the correct R/T ratio for any polarization.

This is important because switching polarization to any desired state is done in the preferred link processing system to improve link cutting efficiency. For example, co-pending U.S. application Serial No. 01/013,956, filed 13 December 2001, a continuing application of U.S. Patent No. 6,181,728 (Reference 3) and assigned to the assignee of the present invention reports results wherein a process window improvement occurs with polarization perpendicular to the link, particularly as the spot size is reduced. The preferred polarization controller disclosed in the '728 patent is used to switch states.

The method and system of the present invention are advantageous when there are oxide layers over the targets to be scanned and measured. The oxide layer may affect the polarization of the beam. This may happen because the oxide layer is stressed and creates birefringence. With the polarization insensitive arrangement this is not a problem, no matter how the polarization is changed one gets the same reflectance from the beamsplitter and the same signal level. If a more typical polarizing beamsplitter or simpler coating is used for the beamsplitter, the

changed polarization will result in a change in the reflected signal. If the stress in the oxide layer varies, especially where it is over the target microstructure (it may be stressed because it is going over a target edge) then the polarization may vary as the beam scans the target. Again, this is not a problem because of the coating. In the polarizing beamsplitter case the reflected signal 151 measured at the detector would vary because the polarization is varying at the same time that one is trying to gather edge data, skewing the results uncontrollably and unpredictably.

This polarization insensitive technique is regarded as the most robust method and is preferred for measuring targets covered by at least one oxide layer. However, other imaging and edge location methods may be used, but may require more complex measurement algorithms to accurately measure the targets in the presence of multiplicative image noise.

*Measurement with Anomalous Reflectivity Variations -
Cleaning with a Pulsed Laser Beam*

A typical alignment target 100 is depicted in the schematic drawings of Figures 14a and 14b. The target 100 is typically covered with one or more passivation layers, these may correspond to the layer 13 in Figures 1b and 1c, but are not so restricted. During experiments with link removal on a multi-level, the preferred polarization insensitive measurement method was used to obtain X,Y target locations. However, it was discovered that debris 1001 within the target area 100, possibly from residual solder flux from nearby solder deposits (solder balls), significantly affected the reflected signals obtained with a detector resulting in noisy profiles 101. The impact on the measurement was manifested as a large residual in the least squares fit algorithm used to estimate location. In this illustration, the target area is shown as a positive contrast (*e.g.*, higher measured intensity) region, but those skilled in the art will recognize that contrast reversal is acceptable provided that the contrast between the target 100 and the background is adequate for measurement.

A pulsed beam with lower peak power was used to remove the debris. An enhanced exemplary signal profile 102 (*e.g.*, associated with relatively uniform intensity and a mostly debris-free region) was obtained as a result of the cleaning operation, as shown in Figure 14b. Representative energies for cleaning were on the order of .01 μj , for instance, .005 μj . This is well below the damage threshold of the materials, and well below the typical energies used for removal of links 12.

In one embodiment, a single linear scan or a plurality of linear scans 104 across the target 100 are used to obtain reflected intensity data which is analyzed statistically to measure fidelity, for instance by determining the % intensity variation or standard deviation. In an exemplary embodiment, data is taken along the line(s) 104 at about every .001". However, the sample space may be finer or coarser depending upon the signal fidelity obtained. If the spacing is too fine, additional "texture noise" may be introduced. If too coarse, an edge contrast 107 will be reduced or errors introduced by undersampling. If the variation is excessive, a cleaning operation is initiated with a pulsed beam. Preferably, the laser power is controlled with an acousto-optic modulator (*i.e.*, "energy control" of Figure 13) which is a standard part of the laser processing equipment. The operation of the modulator for intensity control and pulse selection within a link blowing system is described in more detail in U.S. Patent No. 5,998,759 (*e.g.*, Reference 4, col. 7, and the associated drawings). Those skilled in the art will recognize that such modulators provide for intensity control over a wide dynamic range, *e.g.*, 100:1. A relatively simple user interface can provide for operator interaction to initiate operation, based on "pass/fail" or other criteria.

In another embodiment, the linear scan(s) may be done automatically and the cleaning operation performed at each measurement location.

In a preferred arrangement, only an adjustment of the energy will be needed, and other system parameters unaltered during the cleaning operation or as a result of cleaning. Those skilled in the art of measurement will be able to make various adjustments in the system parameters based on correlation of the results with other process parameters.

In a preferred arrangement, the cleaning operation will be applied only to scanned regions as needed. In one arrangement, the process is iterative with a measurement goal of obtaining suitable residuals in the least squares fit algorithm. If the residuals are above a designated value, scans of at least one region are obtained and cleaning occurs. In some cases, it may be desirable to adjust the positions of the scan lines (*e.g.*, if cleaning is difficult). A fidelity measurement (*e.g.*, contrast, standard deviation) may be used to guide the cleaning operation. Preferably, no more than one pass will be required.

It is to be understood that numerous arrangements could be used to practice the cleaning invention. For instance, an array camera could be used with different wavelength illumination to identify regions of non-uniform intensity. These regions could then be designated for cleaning. Those skilled in the art of optical measurement will be able to implement such arrangements, and such arrangements are within the scope of the present invention.

15 *Reflectivity Measurement and Power*
Adjustment – Case 1: Single Wavelength

The above discussion related to a preferred measurement method and system for locating and measuring X,Y reference locations. An additional option to further improve the process energy window is measurement and control concept to adjust the laser energy and power as required by the material to be processed. If the reflectivity is high, then the energy is to be increased to compensate for these reflection losses. If the reflection is low, then the energy and power is to be decreased since more energy is being coupled into the workpiece or target microstructure. There are a number of ways that one can adjust this power and energy. The simplest is to measure the reflectance from the surface and adjust the energy and power control for optimum energy coupling.

Light interference between metal and oxide layers can greatly affect the reflection and hence the absorption in the metal links (see Figures 11 and 12). Even though the process engineer tries to optimize the absorption in the link by

designing the best oxide thickness, the necessary thickness tolerance is difficult to control. Typically, the thickness of a layer may vary by 10% and there may be several layers of oxide between the top layer and the metal layer to be processed.

5 If the thickness and index refraction over the link could be determined, then the energy required to process the link could be calculated and adjusted accordingly. There are two methods of determining the optical constants of a film. These are ellipsometry and spectral analysis. Ellipsometry uses the change in polarization as a light beam either transmits or reflects from a surface. The amount of change in polarization determines the index of refraction of the material and thickness of the material that the light beam traverses. The spectrometric method measures the reflection from a surface at different wavelengths to determine the same optical constants. In commercial versions of the spectrometer, the reflected light is sensed at 256 different wavelengths and calculations made on thickness, index of refraction and extinction coefficient
10 (absorptivity) of the layers to very high accuracy.
15

Another method is to measure the reflectance at two different wavelengths and calculate the thickness of the oxide. If the index of refraction of the oxide used for the device could be measured, then the reflectance and hence the fraction of the laser radiation absorbed over the link can be calculated. Knowing
20 this absorption, the optimum laser energy to remove the link can be programmed into the laser system. This second method is more accurate for thin film trimming where the material to be trimmed is thin and some of the energy is transmitted through the film.

The implementation of the thickness measurement and energy control
25 is as shown in Figure 13. The laser 160 used to remove the link provides one of the laser wavelengths for the thickness measurement. The energy delivered to the part is controlled by an acousto-optical modulator (*i.e.*, "energy control") 161 as shown in Figure 13 and is reduced to a level to measure the reflectance without damaging the part. The other wavelength to measure the reflectivity can be provided by a red
30 laser diode (*i.e.*, 670 nm diode) 162 added into the optical path as shown.

Beamsplitters 166,167 (*e.g.*, dichroic mirrors) are generally used to transmit the two wavelengths to the device surface and to direct the reflected beams to the photodiode detectors 164,165. The reflectance can be monitored by the two photodiodes 164,165 as shown in Figure 13. From the reflectance intensity of the two
5 photodiodes (*i.e.*, the 670 nm diode and 1047 nm detectors) and knowing the index of refraction of the oxide layers, the thickness of the oxide is uniquely determined. Once the thickness and the index of refraction is known, then the absorption in the link material can be calculated and the optimum energy programmed into the acousto-optic energy control device by the computer.

10 For the highest accuracy, the size of the spot and the link dimensions can be used in the calculation. Referring to Figures 4a and 4b, one sees that there is some energy that will fall off the link and therefore the difference in the reflected light that does not fall on the link has to be calculated. Hence, two measurements have to be made to accommodate for the reflected energy that is not covered by the
15 link. These measurements can be made on each die if required and the energy per pulse can be varied as the thickness of the oxide varies across the wafer. Alternatively, the method could be selectively applied on a wafer-by-wafer basis for process monitoring, for instance. This technique will reduce the requirement to use a laser processing energy that is on the high side to account for the variations in
20 absorption in the link due to interference effects.

*Reflectivity Measurement and Power Adjustment –
Case 2: Tunable or Adjustable Wavelength*

The process energy window may be improved in certain cases by adjusting the wavelength over a range wherein the coupling of energy to the target
25 is improved, the stack reflectance is increased by way of the interference effect, or where the substrate reflectivity increases. Special solid state tunable lasers – Optical Parametric Oscillators (OPO), Raman, or other tunable lasers may be used provided that power and repetition rate requirements are met for a given application. For example, parametric oscillators may be used which are of fixed wavelengths, that
30 use 2 or 3 crystals at the same time. Under certain circumstances, tunable lasers are

operable. Published U.S. patent application 2001-0036206 describes a tunable laser diode having a 40 nm range developed for the telecommunications industry (*i.e.* 1.55 μm wavelength). Standard OPO lasers provide for high power and narrow pulses but generally a very slow rep rate, but may be suitable for certain applications. However, 10 KHz versions have been demonstrated and proposed for 20 KHz repetition rates. U.S. Patent Nos. 6,334,011 and 5,998,759 (Reference 4), and U.S. Patent No. 6,340,806 (Reference 6) disclose various combinations of shifters. As disclosed in the '759 patent, Fosterite lasers have a tunable region that essentially straddles the absorption edge region of silicon, and can permit operation both beyond and below the absorption edge of silicon. At the present state of the art, they do not appear to be as efficient as they may become in time. As materials and improvements are being continually developed in the laser field, it is within the invention to use such devices and obtain corresponding benefits for processing. For instance, the multilayer thickness and reflectivity measurements may be extended to select a wavelength range which will provide for an improved energy window.

Application to a Cu Link with a Single Layer Between the Substrate and the Link

It should be noted that the above teachings can also be selectively applied to conventional link structures (see Figure 2-B), for instance processing of high reflectivity copper links separated from the substrate by a single layer dielectric layer. Production trends are pushing away from polysilicon structures and toward metal structures of Al and Cu, which poses on-going challenges for link processing systems to avoid reliability problems and to increase yield. As discussed above, many Cu-based devices have a multi-layer stack wherein substrate and stack damage can be avoided with wavelength selection, spatial beam shaping, or temporal shaping in accordance with the above teachings. However, some manufacturers etch all the dielectrics under the copper link and build the fuse on a single layer dielectric, with no SiN layers between the link and substrate. With conventional laser processing, the likelihood of substrate damages increases due to the high power required for Cu processing.

In certain cases processing with multiple pulses (“double blast”) has been used to process metal fuses. However, there is generally a throughput problem for the double blast approach because two passes are required in present on-line memory processing systems. Simulated results and experiments indicate a second
5 blast may open the link completely even if 1st blast failed, despite extended time between first and second blasts. In specific cases improved yield was reported. According to the simulation results, double blast with 50% energy of a single blast energy was very interesting; it was observed that the Si substrate acts as a heat sink and cools down very fast. As shown in Figure 16, the results indicated only 10 to
10 20 ns are needed for the Si substrate 201 to stabilize to room temperature. The copper target 202 recovery was much slower indicating a significant differential thermal property. The second pulse will also clear debris at cut site resulting in an “open circuit”. It is estimated that about 60-70% of the energy used in a “single blast” is needed for each pulse of “double blast.” The pulse energy may be varied
15 with each pulse. In this example, the pulse delay was 50 ns, but it is clear that a much shorter delay may be possible.

In one embodiment, a delay line arrangement of Figure 15a may be used to avoid any delay in throughput. For example, with a preferred positioning system of the ‘118 patent (*i.e.*, Reference 2) assume about 150mm/sec for fine stage
20 speed movement. With 30 ns between two pulses, the change in beam position at the link location would be only 0.0045 μm which is negligible. In an optical delay line (Figures 15b and 15c, for instance), 9 meters of extended path in air for the beam will delay 30 ns for the second pulse. Alternatively, as shown in Figure 15a, a second laser could be used with a 30 ns or other controllable delay between the
25 trigger pulses, and the trigger delay may be generated with a programmable digital delay line. The temporal pulse shape may be a fast rising, square pulse (as was used in the simulation) generated with a seed laser diode, for instance.

Numerous options for generating the pulse combinations may be implemented based on the teachings herein. For example, at least one pulse may
30 have a duration of greater than a few picoseconds to several nanoseconds. The pulses may be amplified mode locked pulses. At least one pulse may generated with

a q-switched microlaser having a pulsewidth less than 5 nanoseconds. At least one pulse may propagate along a second optical path whereby the pulse delay is determined by a difference in optical path length as shown in Figures 15b,c. Multiple laser and/or amplifiers may be used as shown in Figure 15a.

5 As shown in Figure 18, the generated pulses 275 may have a repetition rate and a corresponding temporal spacing approximately equal to or shorter than a pre-determined delay (*e.g.*, 60 MHz mode locked system) and a modulator is used to select the at least second pulse irradiating the microstructure or groups of pulses 276. U.S. Patent 5,998,759 (*e.g.*, Reference 4, col. 7, and the
10 associated drawings) teaches the use of a modulator to allow pulses to irradiate a link on demand. At very high speed repetition rates an electro-optic modulator is preferred.

 Additional optics may be used to spatially shape at least one of the delayed pulses, prior to combining for instance. For instance, as shown in Figure
15 17, a first pulse 210 may be an elliptical or circular Gaussian spatial shape, or a top hat along the length of the link. The second pulse 212 may have a different aspect ratio, or may be a special form of a "cleaning pulse" wherein the central zone of the spot is attenuated with an apodizing filter or effectively removed with a central obscuration. In such a case, the energy will be concentrated at the link periphery
20 to remove debris 211 around the link location resulting from processing with the first pulse, thereby completing the processing 213. (For clarity, this "on-the-fly" link site cleaning step is to be distinguished from the "cleaning for measurement" method described above). Reference 1 provides at least one example of beam shaping for link blowing applications, wherein a uniform distribution rather than
25 Gaussian spot profile is disclosed.

 In certain cases, the relative motion between the microstructure and the laser beam may be significant between the pulses, *e.g.*, greater than 25% of the spot size. This may be the result of a slower repetition rate (with increased pulse energy), faster motion speed, a longer pre-determined delay, or decreased target
30 area. For example, an ultrashort or other short pulse laser system with amplified

pulses with output energy in the range of several microjoules-millijoules may have a 100 KHz - 10 MHz repetition rate whereas a system with 10-40 nanojoule output may have 50 MHz repetition rate. In the former case, a high speed, small angle beam deflector may be used to compensate for the motion and deflect a delayed
5 pulse to substantially irradiate the first microstructure at the slower repetition rate during relative motion 258.

In one embodiment generally illustrated in Figure 19, the deflector would be operatively coupled to the relative positioning system controller 251 in a closed loop arrangement. The deflector is preferably solid state and may be a single
10 axis acousto-optic device which has a very fast "retrace"/access time. Alternatively, a higher speed electro-optic deflector (*e.g.*, a gradient index reflector or possibly a digital light deflector) may be used. The time-bandwidth product (number of spots) can be traded for response time on an application basis. The deflector would preferably be used for intensity control and pulse gating/selection, as taught in
15 Reference 4 (col. 7, and associated drawings). Alternatively, an electro-optic modulator may be used with a separate acousto-optic deflector operated in a "chirp mode" 252 (*e.g.*, linear sweep as opposed to random access mode) and synchronized (triggered) 253 based on the positioning system coordinates 254. The positioning system coordinates are, in turn, related to the time at which the laser pulses are
20 gated by the modulator to irradiate the same single microstructure 256 at times t_1 , t_2 , t_3 corresponding to the selected pulses 259 during relative motion 258.

In yet another embodiment, a single laser pulse is used to blast up to two links at one time (*e.g.*, no, one or two links). Referring to Figure 20, two focused spots 306,307 are formed on two links by spatially splitting the single
25 collimated laser beam 310 into two diverging collimated beams 309. The use of acousto-optic devices for spatially splitting beams in material processing applications is known in the art. For example, patent abstract JP 53152662 shows one arrangement for drilling microscopic holes using a multi-frequency deflector having selectable frequencies $f_1 \dots f_n$.

A laser 300 is pulsed at a predetermined repetition rate. The laser beam goes through relay optics 302 that forms an intermediate image of the laser beam waist into the acoustic optic modulator (AOM) aperture. The AOM 303, which operates in the Bragg regime, preferably is used to controllably generate the two slightly diverging collimated first order diffraction laser beams and control the energy in each beam. The AOM is driven by two frequencies, f_1 and f_2 where $f_1 = f_{0+\Delta f}$ and $f_2 = f_{0-\Delta f}$ where Δf is a small percentage of the original RF signal frequency f_0 . The angle between the two beams is approximately equal to the Bragg angle for f_0 multiplied by $2(\Delta f/f_0)$. The AOM controls the energy in each of the laser beams by modulating the signal amplitudes of two frequency components, f_1 and f_2 , in the RF signal and making adjustments for beam cross-coupling.

After exiting the AOM, the beams go through the beam rotation control module 313 to rotate the beam 90 degrees on axis with links orientated in either the X or Y. In one embodiment, a prism is used for this rotation, though many rotation techniques are well known as described in the regular U.S. application noted in the Cross-Reference to Related Applications section.

Next, the beam goes through a set of optics to position the beam waist and set the beam size to be appropriate for the zoom optics and the objective lens 305. Note, the zoom optics also modify the angle between the two beams, therefore the angle between the two beams exiting the AOM has to be adjusted depending on the zoom setting to result in the desired spot separation at the focal plane. Next, the laser beams enter the objective lens 305 which provides a pair of focused spots 306, 307 on two links. The two spots are separated by a distance that is approximately equal to the focal length of the lens times the angle between the two beams. In one exemplary embodiment, a 80 MHz AOM center frequency with a sweep range of about 2.3 MHz (77.7 - 82.3 MHz) may be used to produce a spot size of about 1.8 μm on a pair of adjacent links spaced apart by about 3 μm . As mentioned earlier, these links may have a dimension on the order of a laser wavelength (*e.g.*, 1 micron) which, at very high speed operation, require the precision positions of the laser beam and microstructure.

Summary of Some General Aspects of Invention

5 In summary, one aspect of the invention is a method of selective material processing of a microscopic target structure with a pulsed laser beam. The target structure is separated from a substrate by a plurality of layers which form a multi-layer stack. The target structure, layers, and substrate have dissimilar thermal and optical properties. The method includes generating a pulsed laser beam with an energy density; irradiating the target structure with at least one pulse. Undesirable changes to the stack structure and substrate are avoided by selection of at least one pulse characteristic.

10 A portion of the stack may be irradiated with the laser beam during the processing of the target structure, yet undesirable damage to the layers, substrate, and functional circuitry in a plane of the inner layers is avoided.

15 Undesirable damage of the stack structure includes cracking, induced by thermal stress, of inner dielectrics. Undesirable damage to inner layer conductors of the stack includes thermal damage caused by irradiation. Undesirable damage to the substrate may arise from laser irradiation and resulting thermal diffusion.

The dielectric layers may include Silicon Nitride or Silicon Dioxide. The substrate may be Silicon.

20 The target structure is preferably copper, and may have thickness or width below one micron, with a dimension at or below wavelengths of visible light. Alternatively, the target structure may be a metal link, for instance aluminum, titanium, platinum, or gold.

25 An aspect of the invention is selection or control of the spatial and temporal beam characteristics of the pulse, which allows the target structure to be cleanly processed while avoiding undesirable damage to the layers, substrate, and functional circuitry in a plane of the inner layers.

A temporal characteristic of the pulse is the pulse shape. The pulse shape includes a rise time fast enough to efficiently couple laser energy into the target, a duration sufficient to cleanly remove a portion of the target structure, and a fall time fast enough to avoid undesirable damage caused by subsequent optical transmission. A preferred pulse rise time for link processing is less than 1 nanosecond (ns) to about 2 ns. A preferred duration is less than 10 ns. A fall time of less than 3 ns is preferred. The pulse shape may be substantially square, with ringing or variation between the rising and falling edges of about $\pm 10\%$. A single pulse or multiple pulses in the form of a rapid burst may be used. Alternatively, a series of q-switched pulses spaced apart in time, with varying output power if desired, may be combined to form a pulse shape having a fast leading edge with high peak power, followed by a second pulse with lower power. In yet another embodiment of the present invention the q-switched pulses may have approximately the same output power and combined to produce a substantially square pulse shape.

Another temporal pulse characteristic is the pulse power at the leading edge. If the irradiance on the target structure is greater than about 10^9 W/cm², the reflectivity of the target structure is reduced and coupling of the laser energy is improved.

A fast rising pulse characteristic avoids undesirable damage of a dielectric stack of a memory device having a metal target structure. Cracking of the upper corner occurs during the pulse duration which lowers the stress on the lower corner adjacent to underlying layers of the stack.

A spatial characteristic of the beam is the irradiance profile at a controlled beam waist position. The irradiance profile may approximate a circular Gaussian beam, an elliptical Gaussian beam, a rectangular profile in one direction and Gaussian in the orthogonal direction. The beam may be nearly diffraction limited. A spatial shape and beam numerical aperture may be selected to control the interaction of the pulsed laser beam with the target and underlying structures of the 3D device structure to avoid undesirable damage. The material interaction may further be controlled by precision positioning of the beam waist of the pulsed laser

beam. The numerical aperture and beam shape may be selected so the spot size and link size are substantially matched in at least one dimension.

One aspect of the invention is a method of selection of a pulse characteristic based on a model of pulse interaction within a portion of the three-dimensional device structure. The three-dimensional device includes a target structure, stack, and substrate with a dissimilar optical property. A series of structures are disposed at a predetermined spacing to form an array, with at least one structure not designated as a target structure. A specification may further include information regarding the material and spacing of functional circuit elements in a plane of the stack. The method includes determining the optical propagation characteristics of a portion of an incident pulsed laser beam which is not absorbed by the target structure. The method further includes specifying a laser pulse characteristic to avoid undesirable damage to any non-target structures, stack, and substrate.

The interactions mechanisms which result in selection of a pulse characteristic include reflection from the target surface, layer surface and internal reflections, polarization, interference effects, near field diffraction, scattering and absorption or a combination thereof. A thermal model may be used in conjunction with an optical model.

The energy in a pulse used for processing a copper link target structure of a semiconductor memory device may be in the range of about .1-5 microjoules. The energy density corresponds to an area of the irradiance profile of the beam waist. The area may be in the range of less than 20 square microns, and preferably less than 10 square microns.

Another controllable laser pulse characteristic is polarization. The polarization may be controlled or selected based on the relative reflectance of the layers and optical coupling of laser energy into the target structure at a wavelength.

A wavelength of the laser pulse may be selected based on the reflectance of the multi-layer stack (interference effect). The preferred wavelength corresponds to a spectral region where the stack reflection is substantial, for example 60%, and where the internal transmission of within a layer of the stack is high, approaching a maximum. Short wavelengths are preferred for maximum control of the spatial characteristics of the beam (for example, the smallest achievable beam waist with an option for controllably selecting a larger beam waist and depth of focus). The laser wavelength may be fixed, or may be varied with wavelength shifting or harmonic generation. A measurement of the thickness or reflectance may be used to select or adjust the wavelength.

In at least one embodiment, the target structure may be substantially reflective at the laser wavelength. The laser wavelength may be below the absorption edge of the substrate and correspond to an absorbing or reflecting region. The laser wavelength is above the absorption edge of the dielectrics layers of the stack, and corresponds to a substantially maximum transmitting region.

A selected wavelength corresponds to the near UV, visible and near IR spectrum, from below .4 μm to about 1.55 μm . The lower limit may be determined by the absorption of a layer. With silicon substrates, both absorption and reflection increase at shorter wavelengths. For Silicon Dioxide and Silicon Nitride, the internal transmission and single surface reflectance are substantially constant throughout the visible and near IR ranges. The upper limit corresponds to a range of preferred laser wavelengths of laser diodes, optical amplifiers. An amplifier output may be either wavelength preserved or Raman shifted.

Another aspect of the invention is a method of selective material processing of a microscopic target structure of a multi-material, multi-layer device with a pulsed laser beam. The target structure, layers, and substrate have a dissimilar thermal and optical property. The beam has a focused beam waist with a centerline. An alignment pattern is included at one of a plurality of predetermined measurement locations associated with the device. The alignment pattern is covered by at least one layer. The target structure is separated from a substrate by a

plurality of layers which form a multi-layer stack. The method includes measuring the position of the alignment target in at least one dimension; predicting the relative location of the target structure and centerline based on the measurement; inducing relative motion between the target structure and the centerline based on the measurement; generating a pulsed laser beam with an energy density; irradiating the target structure with at least one pulse. Undesirable changes to the stack structure and substrate are avoided with by selection of a pulse characteristic.

The measurement of a position may include a method and system for polarization insensitive detection to avoid spurious measurements resulting from reflected signal variations. The signal variations may result from process induced optical characteristics, including birefringence.

The relative location of the target structure, beam waist, and centerline may be predicted based on multi-parameter least squares fit.

A cleaning process may be used to enhance data used for measurement by removing contaminants which produce multiplicative variations (reflection noise).

Three-dimensional (depth) measurements may be done using the alignment target, wafer, or other suitable material. The measurement may be used to predict the relative location of the target structure relative to the beam waist, the beam waist being located along the centerline of the pulsed laser beam. A surface may be estimated from the three-dimensional measurements. A numerical offset may be introduced to compensate for a depth difference between a measurement location and the target structure, based on the thickness of the stack.

An aspect of the invention includes measurement of the layer thickness or reflectivity at a location, and use of the measurement to control a pulse characteristic. The pulse characteristic may be the pulse energy, pulse width, or wavelength. The location may be a single location on the device or a plurality of locations.

While the best modes for carrying out the invention have been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and embodiments for practicing the invention as defined by the following claims.

WHAT IS CLAIMED IS:

1. A method of laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate, the method
5 comprising:
 - a) generating a pulsed laser beam having a predetermined wavelength and including at least one laser pulse having a predetermined characteristic comprising at least one of a temporal shape and spatial shape;
 - b) relatively positioning the microstructure and a waist of the
10 laser beam in three-dimensional space based on at least a position measurement obtained at a reference location wherein the position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist; and
 - c) irradiating the microstructure with the at least one laser pulse
15 based on the predicted common location at a time wherein the beam waist and the microstructure substantially coincide, wherein the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure and wherein an undesirable change to the inner layers of the stack and substrate is avoided.
2. The method of claim 1 wherein the multi-level device is a damascene semiconductor memory.
- 20 3. The method of claim 1 wherein the predetermined characteristic is a pulse rise time less than 2 nanoseconds.
4. The method of claim 3 wherein the rise time is less than 1 nanosecond.
5. The method of claim 1 wherein the predetermined
25 characteristic is a substantially square pulse having a duration of less than about 10 nanoseconds and a rise time less than about 2 nanoseconds.

6. The method of claim 1 wherein the predetermined characteristic is based on a model of laser pulse interactions with materials of the multi-level, multi-material device.

5 7. The method of claim 3 wherein the stack has at least one outer dielectric layer covering the microstructure, and wherein the rise time initiates cracking of the at least one outer layer and avoids damage of the inner layers of the stack.

8. The method of claim 1 wherein the inner layers include at least 2 pairs of dielectric layers.

10 9. The method of claim 8 wherein the inner layers include at least 4 pairs of dielectric layers.

10. The method of claim 1 wherein pulse energy density at the substrate is less than a damage threshold of the substrate and wherein the maximum pulse energy density at the microstructure is greater than the damage threshold of
15 the substrate.

11. The method of claim 1 wherein the predetermined characteristic is 3D irradiance profile having a beam waist, W_{y0} , which approximates a narrow microstructure dimension, the irradiance profile being characterized by a relative reduction in energy density at the inner layers and the
20 substrate caused by beam divergence, whereby the energy density at the substrate is substantially reduced by at least the beam divergence and inner layer reflections.

12. The method of claim 1 wherein the substrate is a silicon substrate.

13. The method of claim 1 wherein the substrate is a silicon
25 substrate and the predetermined wavelength is about $1.064\ \mu\text{m}$.

14. The method of claim 6 wherein the predetermined wavelength is below an absorption edge of the substrate and pulse energy density at the substrate is reduced by at least one of a plurality of predetermined factors of the model including: (a) beam divergence; (b) stack surface reflection; (c) beam diffraction;
5 (d) stack multiple scattering; (e) internal stack reflection; (f) multi-layer interference; and (g) non-linear absorption within the microstructure.

15. The method of claim 1 wherein peak pulse energy density at the substrate is less than about 1/10 of the maximum pulse energy density at the microstructure.

10 16. The method of claim 8 wherein the dielectric layers comprise silicon nitride and silicon dioxide.

17. The method of claim 1 wherein the predetermined characteristic is based on a physical property of a material of the multi-material device.

15 18. The method of claim 1 wherein the predetermined wavelength is less than 1.2 μm .

19. The method of claim 18 wherein the predetermined wavelength is less than an absorption edge of the substrate.

20 20. The method of claim 1 wherein the predetermined characteristic comprises a non-circular spatial profile based on a preselected numerical aperture and shape of a spot wherein the spot and the microstructure are substantially correlated in at least one dimension, whereby a fraction of laser energy delivered to the microstructure is increased and irradiance of the stack and the substrate with the at least one laser pulse is decreased.

25 21. The method of claim 1 wherein a plurality of closely-spaced pulses irradiate the microstructure during the step of relatively positioning.

22. The method of claim 21 wherein the pulses have a duration in the range of a few picoseconds to several nanoseconds.

23. The method of claim 21 wherein at least one of the pulses is delayed by a delay line and wherein spacing between the pulses is in the range of
5 about 20 - 30 nanoseconds.

24. The method of claim 21 wherein pulse energy of the pulses is about 50% to 70% of pulse energy used for processing the microstructure with a single laser pulse.

25. The method of claim 1 wherein the device includes a plurality
10 of microstructures to be processed and wherein the method further comprises repeating steps a), b) and c) until all of the microstructures are processed.

26. The method of claim 1 wherein pulse energy density at the microstructure is in the range of about .1 - 5 μ joules over an area of less than about 10 - 20 square microns on the microstructure.

27. The method of claim 26 wherein the range is about .1 - 3
15 μ joules.

28. The method of claim 1 wherein the step of generating includes the step of shifting a first wavelength of the laser beam to the predetermined wavelength, wherein pulse energy is coupled into the microstructure more efficiently
20 at the predetermined wavelength than at the first wavelength while avoiding damage to the inner layers and stack.

29. The method of claim 1 wherein the predetermined wavelength is within a spectral region wherein stack intensity reflection is substantially increased when compared to at least one other wavelength.

30. The method of claim 29 wherein the stack intensity reflection exceeds about 60%.

31. The method of claim 30 wherein the stack intensity reflection exceeds about 90%.

5 32. The method of claim 29 wherein the predetermined wavelength is less than the absorption edge of the substrate.

33. The method of claim 1 further comprising:

(1) obtaining information identifying microstructures designated for removal; (2) measuring a first set of reference locations to obtain three-dimensional
10 reference data; (3) generating a trajectory based on at least the three-dimensional reference data to predict a plurality of beam waist and microstructure locations; (4) updating the prediction during the step of relatively positioning based on updated position information, the updated position information being obtained during the step of relatively positioning.

15 34. The method of claim 33 wherein the updated position information obtained during the step of relatively positioning includes data from a position encoder.

35. The method of claim 33 wherein the updated position information obtained during the step of relatively positioning includes data from an
20 optical sensor.

36. The method of claim 1 wherein the reference location is an alignment target of the multi-material device, the alignment target being covered by at least one upper layer of the stack.

37. The method of claim 1 wherein the predetermined
25 characteristic is irradiance profile at the beam waist.

38. The method of claim 37 wherein the irradiance profile approximates a dimension of the microstructure such that a significant percent of laser energy is coupled to the microstructure and background irradiance is reduced.

39. The method of claim 38 wherein the dimension of the
5 microstructure is less than 1 μm .

40. The method of claim 38 wherein the percent is at least 60%.

41. The method of claim 37 wherein the irradiance profile is an elliptical Gaussian.

42. The method of claim 37 wherein the irradiance profile is a top
10 hat along a length of the microstructure and substantially Gaussian along a width of the microstructure.

43. The method of claim 37 wherein the irradiance profile is substantially diffraction limited with an M-squared factor of less than about 1.1.

44. The method of claim 1 wherein the microstructure is a metal
15 link.

45. The method of claim 44 wherein the metal link has a first dimension of less than 1 μm and wherein the predetermined characteristic is a laser spot size less than about 1.5 μm in the first dimension.

46. The method of claim 1 wherein the substrate is a silicon
20 substrate and wherein pulse energy density at the substrate is less than about 1/100 the pulse energy density at the microstructure.

47. A system of laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack

having inner layers which separate the microstructure from the substrate, the system comprising:

means for generating a pulsed laser beam having a predetermined wavelength and including at least one laser pulse having a predetermined
5 characteristic comprising at least one of a temporal shape and spatial shape;

means for relatively positioning the microstructure and a waist of the laser beam in three-dimensional space based on at least a position measurement obtained at a reference location wherein the position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist; and

10 means for irradiating the microstructure with the at least one laser pulse based on the predicted common location at a time wherein the beam waist and the microstructure substantially coincide, wherein the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure and wherein an undesirable change to the inner layers of the stack and substrate is
15 avoided.

48. The system of claim 47 wherein the multi-level device is a damascene semiconductor memory.

49. The system of claim 47 wherein the predetermined characteristic is a pulse rise time less than 2 nanoseconds.

20 50. The system of claim 49 wherein the rise time is less than 1 nanosecond.

51. The system of claim 47 wherein the predetermined characteristic is a substantially square pulse having a duration of less than about 10 nanoseconds and a rise time less than about 2 nanoseconds.

25 52. The system of claim 47 wherein the predetermined characteristic is based on a model of laser pulse interactions with materials of the multi-level, multi-material device.

53. The system of claim 49 wherein the stack has at least one dielectric outer layer covering the microstructure, and wherein the rise time initiates cracking of the at least one outer layer and avoids damage of the inner layers of the stack.

5 54. The system of claim 47 wherein the inner layers include at least 2 pairs of dielectric layers.

55. The system of claim 54 wherein the inner layers include at least 4 pairs of dielectric layers.

10 56. The system of claim 47 wherein pulse energy density at the substrate is less than a damage threshold of the substrate and wherein the maximum pulse energy density at the microstructure is greater than the damage threshold of the substrate.

15 57. The system of claim 47 wherein the predetermined characteristic is 3D irradiance profile having a beam waist, Wy_0 , which approximates a narrow microstructure dimension, the irradiance profile being characterized by a relative reduction in energy density at the inner layers and the substrate caused by beam divergence, whereby the energy density at the substrate is substantially reduced by at least the beam divergence and inner layer reflections.

20 58. The system of claim 47 wherein the substrate is a silicon substrate.

59. The system of claim 47 wherein the substrate is a silicon substrate and the predetermined wavelength is about $1.064\ \mu\text{m}$.

25 60. The system of claim 52 wherein the predetermined wavelength is below an absorption edge of the substrate and pulse energy density at the substrate is reduced by at least one of a plurality of predetermined factors of the model including: (a) beam divergence; (b) stack surface reflection; (c) beam diffraction;

(d) stack multiple scattering; (e) internal stack reflection; (f) multi-layer interference; and (g) non-linear absorption within the microstructure.

61. The system of claim 47 wherein peak pulse energy density at the substrate is less than about 1/10 of the maximum pulse energy density at the
5 microstructure.

62. The system of claim 54 wherein the dielectric layers comprise silicon nitride and silicon dioxide.

63. The system of claim 47 wherein the predetermined characteristic is based on a physical property of a material of the multi-material
10 device.

64. The system of claim 47 wherein the predetermined wavelength is less than 1.2 μm .

65. The system of claim 64 wherein the predetermined wavelength is less than an absorption edge of the substrate.

15 66. The system of claim 47 wherein the predetermined characteristic comprises a non-circular spatial profile based on a preselected numerical aperture and shape of a spot wherein the spot and the microstructure are substantially correlated in at least one dimension, whereby a fraction of laser energy delivered to the microstructure is increased and irradiance of the stack and the
20 substrate with the at least one laser pulse is decreased.

67. The system of claim 47 wherein a plurality of closely-spaced pulses irradiate the microstructure by the means for irradiating.

68. The system of claim 67 wherein the pulses have a duration in the range of a few picoseconds to several nanoseconds.

69. The system of claim 67 wherein at least one of the pulses is delayed by a delay line and wherein spacing between the pulses is in the range of about 20 - 30 nanoseconds.

70. The system of claim 67 wherein pulse energy of the pulses is
5 about 50% to 70% of pulse energy used for processing the microstructure with a single laser pulse.

71. The system of claim 47 wherein the device includes a plurality of microstructures to be processed by the system.

72. The system of claim 47 wherein pulse energy density at the
10 microstructure is in the range of about .1 - 5 μ joules over an area of less than about 10 - 20 square microns on the microstructure.

73. The system of claim 72 wherein the range is about .1 - 3 μ joules.

74. The system of claim 47 wherein the means for generating
15 includes means for shifting a first wavelength of the laser beam to the predetermined wavelength, wherein pulse energy is coupled into the microstructure more efficiently at the predetermined wavelength than at the first wavelength while avoiding damage to the inner layers and stack.

75. The system of claim 47 wherein the predetermined wavelength
20 is within a spectral region wherein stack intensity reflection is substantially increased when compared to at least one other wavelength.

76. The system of claim 75 wherein the stack intensity reflection exceeds about 60%.

77. The system of claim 76 wherein the stack intensity reflection
25 exceeds about 90%.

78. The system of claim 75 wherein the predetermined wavelength is less than the absorption edge of the substrate.

79. The system of claim 47 further comprising:

5 (1) means for obtaining information identifying microstructures designated for removal; (2) means for measuring a first set of reference locations to obtain three-dimensional reference data; (3) means for generating a trajectory based on at least the three-dimensional reference data to predict a plurality of beam waist and microstructure locations; (4) means for updating the prediction based on updated position information.

10 80. The system of claim 79 wherein the updated position information includes data from a position encoder.

81. The system of claim 79 wherein the updated position information includes data from an optical sensor.

15 82. The system of claim 47 wherein the reference location is an alignment target of the multi-material device, the alignment target being covered by at least one upper layer of the stack.

83. The system of claim 47 wherein the predetermined characteristic is irradiance profile at the beam waist.

20 84. The system of claim 83 wherein the irradiance profile approximates a dimension of the microstructure such that a significant percent of laser energy is coupled to the microstructure and background irradiance is reduced.

85. The system of claim 84 wherein the dimension of the microstructure is less than 1 μm .

86. The system of claim 84 wherein the percent is at least 60%.

87. The system of claim 83 wherein the irradiance profile is an elliptical Gaussian.

88. The system of claim 83 wherein the irradiance profile is a top hat along a length of the microstructure and substantially Gaussian along a width of the microstructure.

89. The system of claim 83 wherein the irradiance profile is substantially diffraction limited with an M-squared factor of less than about 1.1.

90. The system of claim 47 wherein the microstructure is a metal link.

91. The system of claim 90 wherein the metal link has a first dimension of less than 1 μm and wherein the predetermined characteristic is a laser spot size less than about 1.5 μm in the first dimension.

92. The system of claim 47 wherein the substrate is a silicon substrate and wherein pulse energy density at the substrate is less than about 1/100 the pulse energy density at the microstructure.

93. A method of laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner dielectric layers which separate the microstructure from the substrate, the method comprising:

generating a pulsed laser beam having a predetermined wavelength and including at least one laser pulse wherein at least reflections of the laser beam by the layers of the stack substantially reduce pulse energy density at the substrate relative to at least one other wavelength; and

processing the microstructure with the at least one laser pulse wherein pulse energy density at the microstructure is sufficient to remove the microstructure while avoiding damage to the substrate and the inner layers of the stack.

94. The method of claim 93 wherein the predetermined wavelength is less than an absorption edge of the substrate.

95. The method of claim 93 wherein the predetermined wavelength is in the range of about $.4\ \mu\text{m}$ - $1.55\ \mu\text{m}$.

5 96. The method of claim 93 wherein the predetermined wavelength is in the range of about $.35\ \mu\text{m}$ - $1.55\ \mu\text{m}$.

97. The method of claim 93 wherein the predetermined wavelength is less than $1.2\ \mu\text{m}$.

10 98. The method of claim 93 wherein the substrate is a silicon substrate and the microstructure is a metal microstructure.

99. The method of claim 98 wherein the metal of the microstructure comprises copper.

15 100. The method of claim 93 wherein pulse energy density at the substrate is further reduced with a predetermined characteristic of the at least one pulse.

101. The method of claim 100 wherein the predetermined characteristic is based on a model of laser pulse material interaction.

102. The method of claim 101 wherein the model is a thermal model.

20 103. The method of claim 101 wherein the model is a multi-parameter model.

104. The method of claim 93 wherein the step of generating includes the step of shifting the wavelength of the laser beam from a first

wavelength to the predetermined wavelength wherein the predetermined wavelength is based on material characteristics comprising at least one of: (1) coupling characteristics of the microstructure, (2) multi-layer interference, and (3) substrate reflectivity.

5 105. The method of claim 104 wherein the predetermined wavelength is a shifted wavelength below an absorption edge of the substrate.

106. A system of laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner dielectric layers which separate the microstructure from the substrate,
10 the system comprising:

means for generating a pulsed laser beam having a predetermined wavelength and including at least one laser pulse wherein at least reflections of the laser beam by the layers of the stack substantially reduce pulse energy density at the substrate relative to at least one other wavelength beyond the absorption edge; and

15 means for processing the microstructure with the at least one laser pulse wherein pulse energy density at the microstructure is sufficient to remove the microstructure while avoiding damage to the substrate and the inner layers of the stack.

107. The system of claim 106 wherein the predetermined
20 wavelength is less than an absorption edge of the substrate.

108. The system of claim 106 wherein the predetermined wavelength is in the range of about $.4 \mu\text{m}$ - $1.55 \mu\text{m}$.

109. The system of claim 106 wherein the predetermined wavelength is in the range of about $.35 \mu\text{m}$ - $1.55 \mu\text{m}$.

25 110. The system of claim 106 wherein the predetermined wavelength is less than $1.2 \mu\text{m}$.

111. The system of claim 106 wherein the substrate is a silicon substrate and the microstructure is a metal microstructure.

112. The system of claim 111 wherein the metal of the microstructure comprises copper.

5 113. The system of claim 106 wherein pulse energy density at the substrate is further reduced with a predetermined characteristic of the at least one pulse.

114. The system of claim 113 wherein the predetermined characteristic is based on a model of laser pulse material interaction.

10 115. The system of claim 114 wherein the model is a thermal model.

116. The system of claim 114 wherein the model is a multi-parameter model.

15 117. The system of claim 106 wherein the means for generating includes means for shifting the wavelength of the laser beam from a first wavelength to the predetermined wavelength wherein the predetermined wavelength is based on material characteristics comprising at least one of: (1) coupling characteristics of the microstructure, (2) multi-layer interference, and (3) substrate reflectivity.

20 118. The system of claim 117 wherein the predetermined wavelength is a shifted wavelength below an absorption edge of the substrate.

119. A method for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate, the method comprising:

providing information regarding material of the structures including the predetermined microstructure and the substrate;

5 determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information; and

determining at least one characteristic of the at least one pulse based on the optical propagation characteristics.

120. The method of claim 119 wherein the information also regards spacing of the structures including the predetermined microstructure and the
10 substrate.

121. A system for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate, the system comprising:

15 means for providing information regarding material of the structures including the predetermined microstructure and the substrate;

means for determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information; and

20 means for determining at least one characteristic of the at least one pulse based on the optical propagation characteristics.

122. The system of claim 121 wherein the information also regards spacing of the structures including the predetermined microstructure and the substrate.

25 123. A method for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate, the method comprising:

providing information regarding material and spacing of the structures including the predetermined microstructure and the substrate;

determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the
5 information; and

determining at least one characteristic of the at least one pulse which avoids undesirable changes in electrical or physical characteristics of the substrate and the other structures based on the optical propagation characteristics.

124. The method as claimed in claim 123 wherein the interactions
10 are selected from a group comprising: reflections from at least one surface of the structures, internal reflections, polarization, interference effects, near field diffraction, scattering and absorption.

125. The method as claimed in claim 123 wherein the step of determining optical propagation characteristics includes correlating irradiance of a
15 structure neighboring the predetermined microstructure with a laser spot dimension.

126. A system for modeling interactions of a pulsed laser beam including at least one laser pulse with a three-dimensional device including a substrate, a predetermined microstructure formed on the substrate and a plurality of other structures formed on the substrate, the system comprising:

20 means for providing information regarding material and spacing of the structures including the predetermined microstructure and the substrate;

means for determining optical propagation characteristics of at least a portion of the laser beam not absorbed by the predetermined microstructure based on the information; and

25 means for determining at least one characteristic of the at least one pulse which avoids undesirable changes in electrical or physical characteristics of the substrate and the other structures based on the optical propagation characteristics.

127. The system as claimed in claim 126 wherein the interactions are selected from a group comprising: reflections from at least one surface of the structures, internal reflections, polarization, interference effects, near field diffraction, scattering and absorption.

5 128. The system as claimed in claim 126 wherein the means for determining optical propagation characteristics includes means for correlating irradiance of a structure neighboring the predetermined microstructure with a laser spot dimension.

10 129. A method of laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate, the method comprising:

generating a pulsed laser beam having a predetermined wavelength and including at least one laser pulse having a predetermined characteristic wherein:

15 a) the predetermined wavelength is below an absorption edge of the substrate; and

b) wherein the at least one pulse has duration less than about 10 nanoseconds, and a repetition rate of 10 KHz or higher;

20 relatively positioning the microstructure and a waist of the laser beam in three-dimensional space based on at least a position measurement obtained at a reference location wherein the position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist; and

25 irradiating the microstructure with the at least one laser pulse based on the predicted common location at a time wherein the beam waist and the microstructure substantially coincide, wherein the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure and wherein an undesirable change to the inner layers of the stack and substrate is avoided.

130. The method of claim 129 wherein the predetermined characteristic includes a q-switched pulse shape.

131. The method of claim 130 wherein the q-switched pulse shape is generated with a microlaser.

132. The method of claim 129 wherein the pulse duration of the at least one laser pulse is in the range of 1-5 nanoseconds.

5 133. The method of claim 129 wherein a plurality of pulses are generated and delayed by a predetermined delay based upon a physical property of a material of the multi-material device.

134. The method of claim 130 wherein the predetermined wavelength is about 1.064 microns.

10 135. A system of laser processing a multi-level, multi-material device including a substrate, a microstructure and a multi-layer stack, the stack having inner layers which separate the microstructure from the substrate, the system comprising:

 means for generating a pulsed laser beam having a predetermined
15 wavelength and including at least one laser pulse having a predetermined characteristic wherein:

 a) the predetermined wavelength is below an absorption edge of the substrate; and

 b) wherein the at least one pulse has duration less than about 10
20 nanoseconds, and a repetition rate of 10 KHz or higher;

 means for relatively positioning the microstructure and a waist of the laser beam in three-dimensional space based on at least a position measurement obtained at a reference location wherein the position measurement is used to obtain a prediction of a common location of the microstructure and the beam waist; and

25 means for irradiating the microstructure with the at least one laser pulse based on the predicted common location at a time wherein the beam waist and the microstructure substantially coincide, wherein the microstructure is cleanly removed with substantially maximum pulse energy density at the microstructure and

wherein an undesirable change to the inner layers of the stack and substrate is avoided.

136. The system of claim 135 wherein the predetermined characteristic includes a q-switched pulse shape.

5 137. The system of claim 136 wherein the q-switched pulse shape is generated with a microlaser.

138. The system of claim 135 wherein the pulse duration of the at least one laser pulse is in the range of 1-5 nanoseconds.

10 139. The system of claim 135 wherein a plurality of pulses are generated and delayed by a predetermined delay based upon a physical property of a material of the multi-material device.

140. The system of claim 135 wherein the predetermined wavelength is about 1.064 microns.

15 141. A multi-level, multi-material device comprising:
a substrate;
a microstructure;
a multi-layer stack having inner layers which separate the microstructure from the substrate, wherein at least one of the inner layers has a predetermined physical parameter based on interactions of a pulsed laser beam with
20 the stack, the laser beam having a predetermined wavelength, wherein undesirable changes to the substrate and the inner layers of the stack are avoided during laser processing with the pulsed laser beam.

25 142. The device of claim 141 wherein the predetermined physical parameter include at least one of layer thickness, layer material, and index of refraction.

143. The device of claim 141 wherein the stack includes a quarter-wave stack of dielectric layers.

144. The device of claim 141 wherein the stack includes a precision spacer layer located between layers of the stack.

5 145. A method for thermal-based laser processing a multi-material device including a substrate and at least one microstructure, the processing occurring with multiple pulses in a single pass operation controlled with a positioning subsystem of a thermal processing system, the positioning subsystem inducing relative motion between the device and laser beam waists, the processing
10 to remove the at least one microstructure without damaging the substrate, the method comprising:

generating a first pulse having a first predetermined characteristic;

irradiating the at least one microstructure with the first pulse wherein a first beam waist associated with the first pulse and the at least one microstructure
15 substantially coincide, the step of irradiating at least initiating processing the at least one microstructure;

generating a second pulse having a second predetermined characteristic, the second pulse being delayed a predetermined time relative to the first pulse; and

20 irradiating the at least one microstructure with the second pulse wherein a second beam waist associated with the second pulse and the at least one microstructure substantially coincide, the step of irradiating the at least one microstructure with the second pulse further processing the at least one microstructure wherein the processing of the at least one microstructure with the
25 first and second pulses occurs during relative motion of the at least one microstructure and the beam waists in a single pass whereby throughput of the thermal processing system is substantially improved.

146. The method of claim 145 wherein the device is a semiconductor memory including a silicon substrate and wherein the at least one

microstructure is a metal link of the semiconductor memory separated from the silicon substrate by at least one oxide layer.

147. The method of claim 145 wherein at least one of the pulses has a duration of greater than a few picoseconds to several nanoseconds.

5 148. The method of claim 145 wherein the pulses are generated by a mode-locked laser system and amplified with an optical amplifier.

149. The method of claim 145 wherein at least one of the pulses is generated by a q-switched microlaser having a pulsewidth less than 5 nanoseconds.

10 150. The method of claim 145 wherein the first and second pulses are propagated along different optical paths so that the second pulse is delayed for the predetermined time relative to the first pulse based on a difference in optical path length.

15 151. The method of claim 145 wherein the pulses have a temporal spacing less than or approximately equal to the predetermined time, and wherein the method further comprises selecting the second pulse to irradiate the at least one microstructure.

20 152. The method of claim 145 wherein the predetermined time is determined by a thermal property of the substrate wherein substrate temperature is substantially reduced after the predetermined time compared to the temperature of the substrate during the step of irradiating the at least one microstructure with the second pulse.

153. The method of claim 152 wherein the substrate temperature is substantially reduced to approximately room temperature.

25 154. The method of claim 145 wherein the first and second predetermined characteristics comprise a substantially square temporal pulse shape

having a rise time of less than about 2 nanoseconds and a pulse duration of about 10 nanoseconds.

155. The method of claim 145 wherein the predetermined time is in the range of about 20 - 50 nanoseconds.

5 156. The method of claim 145 wherein the predetermined time is about 30 nanoseconds.

157. The method of claim 145 wherein two pulses are used to completely process the at least one microstructure, and wherein laser energy of each of the pulses is about 60 - 70% of laser energy required for laser processing the at
10 least one microstructure with a single pulse.

158. The method of claim 145 wherein relative position change between the pulses at the at least one microstructure is less than about 10% of a dimension of the at least one microstructure to be processed.

159. The method of claim 145 wherein at least one of the first and
15 second predetermined characteristics comprises a substantially square pulse.

160. The method of claim 145 wherein at least one of the predetermined characteristics comprises a non-circular spatial profile based on a selected numerical aperture and shape of a spot and wherein the spot and the at least one microstructure are substantially correlated in at least one dimension whereby
20 percent of laser energy delivered to the at least one microstructure is increased and irradiance of the substrate is decreased.

161. The method of claim 145 wherein a spatial beam shape of the second pulse is in the form of a cleaning beam having an energy density lower than energy density of the first pulse.

162. The method of claim 161 wherein the cleaning beam has an attenuated central region and a higher energy outer region so as to remove debris surrounding a target site on the at least one microstructure.

5 163. The method of claim 145 wherein the steps of generating include directing a portion of a laser pulse through an optical subsystem having opposing, spaced-apart, corner cube reflectors and polarization rotators so as to align a pulsed laser beam, and to control delay and amplitude of the second pulse relative to the first pulse.

10 164. The method of claim 145 wherein the steps of generating include providing an optical subsystem having multiple lasers wherein delay between trigger pulses to the optical subsystem determines the predetermined time.

165. The method of claim 145 wherein a fiber optic delay line delays the second pulse for the predetermined time and wherein the predetermined time is about several nanoseconds.

15 166. The method of claim 145 wherein relative position change between the pulses at the at least one microstructure is either greater than about 10% of a dimension of the at least one microstructure to be processed or greater than about $\frac{1}{2}$ of either of the beam waists and further including a high speed beam deflector operatively coupled to the positioning subsystem to compensate for relative
20 motion between the pulses, wherein the second pulse is deflected by the deflector to also substantially irradiate the at least one microstructure with the second pulse.

167. The method of claim 145 wherein the predetermined time is in the range of about 10 ns to 10 μ s.

25 168. The method of claim 166 wherein the beam deflector is a single axis acousto-optic device.

169. The method of claim 145 wherein the first and second predetermined characteristics are based on physical properties of the multi-material device.

5 170. The method of claim 145 wherein the first pulse irradiates a first portion of the at least one microstructure and the second pulse irradiates a second portion of the at least one microstructure and wherein relative position change between the first and second portions of the at least one microstructure is less than 1/4 of either of the beam waists.

10 171. The method of claim 164 wherein the step of providing also provides at least one optical amplifier optically coupled to at least one of the lasers.

172. The method of claim 145 wherein the at least one microstructure and the beam waists are relatively positioned during relative motion based upon three-dimensional information.

15 173. The method of claim 145 wherein the steps of generating includes generating a single pulse and forming the first and second pulses from the single pulse.

174. The method of claim 173 wherein the step of forming delays the second pulse for the predetermined time relative to the first pulse.

20 175. The method of claim 173 wherein the step of forming includes splitting the single pulse with a multi-frequency deflector to form the first and second pulses.

176. The method of claim 175 wherein first and second microstructures are irradiated by the first and second pulses, respectively.

25 177. A system for thermal-based laser processing a multi-material device including a substrate and at least one microstructure, the processing

occurring with multiple pulses in a single pass operation controlled with a positioning subsystem which induces relative motion between the device and laser beam waists, the processing to remove the at least one microstructure without damaging the substrate, the system comprising:

5 means for generating a first pulse having a first predetermined characteristic;

 means for irradiating the at least one microstructure with the first pulse wherein a first beam waist associated with the first pulse and the at least one microstructure substantially coincide, the first pulse at least initiating processing the
10 at least one microstructure;

 means for generating a second pulse having a second predetermined characteristic, the second pulse being delayed a predetermined time relative to the first pulse; and

 means for irradiating the at least one microstructure with the second
15 pulse wherein a second beam waist associated with the second pulse and the at least one microstructure substantially coincide, the second pulse further processing the at least one microstructure wherein the processing of the at least one microstructure with the first and second pulses occurs during relative motion of the at least one microstructure and the beam waists in a single pass whereby throughput of the
20 system is substantially improved.

178. The system of claim 177 wherein the device is a semiconductor memory including a silicon substrate and wherein the at least one microstructure is a metal link of the semiconductor memory separated from the silicon substrate by at least one oxide layer.

25 179. The system of claim 177 wherein at least one of the pulses has a duration of greater than a few picoseconds to several nanoseconds.

180. The system of claim 177 wherein the means for generating includes a mode-locked laser system and further comprising an optical amplifier for amplifying the pulses.

181. The system of claim 177 wherein at least one of the means for generating includes a q-switched microlaser having a pulsewidth less than 5 nanoseconds.

5 182. The system of claim 177 wherein the first and second pulses are propagated along different optical paths so that the second pulse is delayed for the predetermined time relative to the first pulse based on a difference in optical path length.

10 183. The system of claim 177 wherein the pulses have a temporal spacing less than or approximately equal to the predetermined time, and wherein the system further comprises means for selecting the second pulse to irradiate the at least one microstructure.

15 184. The system of claim 177 wherein the predetermined time is determined by a thermal property of the substrate wherein substrate temperature is substantially reduced after the predetermined time compared to the temperature of the substrate during irradiation of the at least one microstructure with the second pulse.

185. The system of claim 184 wherein the substrate temperature is substantially reduced to approximately room temperature.

20 186. The system of claim 177 wherein the first and second predetermined characteristics comprise a substantially square temporal pulse shape having a rise time of less than about 2 nanoseconds and a pulse duration of about 10 nanoseconds.

187. The system of claim 177 wherein the predetermined time is in the range of about 20 - 50 nanoseconds.

25 188. The system of claim 177 wherein the predetermined time is about 30 nanoseconds.

189. The system of claim 177 wherein two pulses are used to completely process the at least one microstructure, and wherein laser energy of each of the pulses is about 60 - 70% of laser energy required for laser processing the at least one microstructure with a single pulse.

5 190. The system of claim 177 wherein relative position change between the pulses at the at least one microstructure is less than about 10% of a dimension of the at least one microstructure to be processed.

191. The system of claim 177 wherein at least one of the first and second predetermined characteristics comprises a substantially square pulse.

10 192. The system of claim 177 wherein at least one of the predetermined characteristics comprises a non-circular spatial profile based on a selected numerical aperture and shape of a spot and wherein the spot and the at least one microstructure are substantially correlated in at least one dimension whereby percent of laser energy delivered to the at least one microstructure is increased and
15 irradiance of the substrate is decreased.

193. The system of claim 192 wherein a spatial beam shape of the second pulse is in the form of a cleaning beam having an energy density lower than energy density of the first pulse.

20 194. The system of claim 193 wherein the cleaning beam has an attenuated central region and a higher energy outer region so as to remove debris surrounding a target site on the at least one microstructure.

25 195. The system of claim 177 wherein the means for generating the first and second pulses include an optical subsystem having opposing, spaced-apart, corner cube reflectors and polarization rotators so as to align a pulsed laser beam, and to control delay and amplitude of the second pulse relative to the first pulse.

196. The system of claim 177 wherein the means for generating the first and second pulses include an optical subsystem having multiple lasers wherein delay between trigger pulses to the optical subsystem determines the predetermined time.

5 197. The system of claim 177 further comprising a fiber optic delay line to delay the second pulse for the predetermined time and wherein the predetermined time is about several nanoseconds.

198. The system of claim 177 wherein relative position change between the pulses at the at least one microstructure is either greater than about 10%
10 of a dimension of the at least one microstructure to be processed or greater than about $\frac{1}{2}$ of either of the beam waists and further including a high speed beam deflector operatively coupled to the positioning subsystem to compensate for relative motion between the pulses, wherein the second pulse is deflected by the deflector to also substantially irradiate the at least one microstructure with the second pulse.

15 199. The system of claim 177 wherein the predetermined time is in the range of about 10 ns to 10 μ s.

200. The system of claim 198 wherein the beam deflector is a single axis acousto-optic device.

20 201. The system of claim 177 wherein the first and second predetermined characteristics are based on physical properties of the multi-material device.

25 202. The system of claim 177 wherein the first pulse irradiates a first portion of the at least one microstructure and the second pulse irradiates a second portion of the at least one microstructure and wherein relative position change between the first and second portions of the at least one microstructure is less than $\frac{1}{4}$ of either of the beam waists.

203. The system of claim 196 further comprising at least one optical amplifier optically coupled to at least one of the lasers.

204. The system of claim 177 wherein the at least one microstructure and the beam waists are relatively positioned during relative motion
5 based upon three-dimensional information.

205. The system of claim 177 wherein the means for generating the first and second pulses includes means for generating a single pulse and means for forming the first and second pulses from the single pulse.

206. The system of claim 205 wherein the means for forming
10 delays the second pulse for the predetermined time relative to the first pulse.

207. The system of claim 205 wherein the means for forming includes a multi-frequency deflector for splitting the single pulse to form the first and second pulses.

208. The system of claim 207 wherein first and second
15 microstructures are irradiated by the first and second pulses, respectively.

209. A method for thermal-based laser processing a multi-material device including a substrate and a microstructure, the method comprising:

generating the at least one laser pulse having at least one
20 predetermined characteristic based on a differential thermal property of materials of the device; and

irradiating the microstructure with the at least one laser pulse wherein a first portion of the at least one pulse increases a difference in temperature between the substrate and the microstructure and wherein a second portion of the at least one
25 pulse further increases the difference in temperature between the substrate and the microstructure to process the multi-material device without damaging the substrate.

210. The method as claimed in claim 209 wherein the first and second portions are portions of a single pulse.

211. The method as claimed in claim 209 wherein the first and second portions are portions of different pulses.

5 212. The method as claimed in claim 209 wherein the first portion of the at least one pulse increases temperature of the microstructure.

213. The method as claimed in claim 209 wherein the first portion is a high density leading edge portion of the at least one pulse.

10 214. The method as claimed in claim 213 wherein the leading edge portion has a rise time of less than two nanoseconds.

215. The method as claimed in claim 214 wherein the rise time is less than one nanosecond.

216. The method as claimed in claim 209 wherein the first and second portions of the at least one pulse are sufficient to remove the microstructure.

15 217. The method as claimed in claim 213 wherein the microstructure is a metal link having reflectivity and wherein the leading edge portion of the at least one pulse reduces the reflectivity of the metal link.

218. The method as claimed in claim 217 wherein the substrate is silicon and the device is a semiconductor memory.

20 219. The method as claimed in claim 212 wherein the second portion of the at least one pulse further increases the temperature of the microstructure.

220. The method as claimed in claim 209 wherein the step of irradiating is completed in a period between 5 and 75 nanoseconds.

221. The method as claimed in claim 220 wherein the period is between 10 and 50 nanoseconds.

5 222. A system for thermal-based laser processing a multi-material device including a substrate and a microstructure, the system comprising:

 means for generating the at least one laser pulse having at least one predetermined characteristic based on a differential thermal property of materials of the device; and

10 means for irradiating the microstructure with the at least one laser pulse wherein a first portion of the at least one pulse increases a difference in temperature between the substrate and the microstructure and wherein a second portion of the at least one pulse further increases the difference in temperature between the substrate and the microstructure to process the multi-material device
15 without damaging the substrate.

223. The system as claimed in claim 222 wherein the first and second portions are portions of a single pulse.

224. The system as claimed in claim 222 wherein the first and second portions are portions of different pulses.

20 225. The system as claimed in claim 222 wherein the first portion of the at least one pulse increases temperature of the microstructure.

226. The system as claimed in claim 222 wherein the first portion is a high density leading edge portion of the at least one pulse.

25 227. The system as claimed in claim 226 wherein the leading edge portion has a rise time of less than two nanoseconds.

228. The system as claimed in claim 227 wherein the rise time is less than one nanosecond.

229. The system as claimed in claim 222 wherein the first and second portions of the at least one pulse are sufficient to remove the microstructure.

5 230. The system as claimed in claim 226 wherein the microstructure is a metal link having reflectivity and wherein the leading edge portion of the at least one pulse reduces the reflectivity of the metal link.

231. The system as claimed in claim 230 wherein the substrate is silicon and the device is a semiconductor memory.

10 232. The system as claimed in claim 225 wherein the second portion of the at least one pulse further increases the temperature of the microstructure.

233. The system as claimed in claim 222 wherein the irradiation is completed in a period between 5 and 75 nanoseconds.

15 234. The system as claimed in claim 233 wherein the period is between 10 and 50 nanoseconds.

235. A method for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined target having a first material to be laser processed, the method
20 comprising:

measuring position of at least one alignment target formed at a predetermined measurement location to obtain a measurement, the at least one alignment target being covered by at least one layer of a second material, the step of measuring including selectively irradiating a portion of a region to be measured
25 with a radiation cleaning beam to remove debris from the region to compensate for

reflectivity variations and reduce multiplicative noise and associated signal variations at a detector;

predicting relative location of the predetermined target and a waist of the laser beam based on the measurement to obtain a predicted relative location;

5 inducing relative motion between the predetermined target and the beam waist based on the predicted relative location;

generating the laser beam including at least one pulse; and

irradiating the at least one pulse into a spot on the predetermined target wherein the at least one pulse is sufficient to process the predetermined target.

10 236. The method as claimed in claim 235 wherein the step of measuring is performed in a polarization insensitive fashion.

237. The method as claimed in claim 235 further comprising estimating locations utilizing a multi-parameter least squares fit algorithm to obtain residuals and wherein the step of predicting includes evaluating the residuals.

15 238. The method as claimed in claim 235 wherein the first material comprises metal and wherein the predetermined target is part of a multi-material device having at least one outer layer of dielectric material.

239. The method as claimed in claim 235 further comprising the steps of measuring layer thickness or reflectivity at at least one location to obtain a
20 layer measurement and utilizing the layer measurement to control a characteristic of the at least one pulse.

240. The method of claim 235 further comprising measuring a layer thickness to obtain a thickness measurement and using at least the thickness measurement for predicting the relative location.

25 241. The method as claimed in claim 239 wherein the characteristic is pulse energy or pulsewidth.

242. The method as claimed in claim 235 further comprising the steps of measuring layer thickness or reflectivity at at least one location to obtain a layer measurement, and utilizing the layer measurement to controllably shift a wavelength of the laser beam.

5 243. The method as claimed in claim 235 further comprising: (a) obtaining information identifying microstructures designated for removal, (b) measuring a first set of reference locations to obtain three-dimensional reference data, (c) generating a trajectory based on at least the three-dimensional reference data to obtain a prediction of beam waist and microstructure surface locations, (d)
10 updating the predicted relative location during relative motion based on updated position information, the updated position information being obtained during the relative motion.

 244. The method of claim 243 wherein the updated position information obtained during the step of relatively positioning includes data from a
15 position encoder.

 245. The method of claim 243 wherein the updated position information obtained during the step of relatively positioning includes data from an optical sensor.

 246. The method as claimed in claim 235 wherein the step of
20 selectively irradiating occurs within orthogonal linear scans in the region to be measured.

 247. The method of claim 235 wherein the at least one alignment target is part of a multi-material semiconductor memory including a substrate and at least one dielectric layer disposed between the substrate and the predetermined
25 target, and wherein power of the radiation cleaning beam is substantially below power required to cause an undesirable change to the predetermined target, the substrate, or the at least one dielectric layer.

248. The method of claim 235 wherein energy of the cleaning beam is in the range .005 to .05 μ joules.

249. The method of claim 235 wherein the measurement is a 3-D measurement.

5 250. A system for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined target having a first material to be laser processed, the system comprising:

10 means for measuring position of at least one alignment target formed at a predetermined measurement location to obtain a measurement, the at least one alignment target being covered by at least one layer of a second material, the means for measuring including means for selectively irradiating a portion of a region to be measured with a radiation cleaning beam to remove debris from the region to compensate for reflectivity variations and reduce multiplicative noise and associated
15 signal variations at a detector;

 means for predicting relative location of the predetermined target and a waist of the laser beam based on the measurement to obtain a predicted relative location;

20 means for inducing relative motion between the predetermined target and the beam waist based on the predicted relative location;

 means for generating the laser beam including at least one pulse; and

 means for irradiating the at least one pulse into a spot on the predetermined target wherein the at least one pulse is sufficient to process the predetermined target.

25 251. The system as claimed in claim 250 wherein measuring is performed in a polarization insensitive fashion.

252. The system as claimed in claim 250 further comprising means for estimating locations utilizing a multi-parameter least squares fit algorithm to

obtain residuals and wherein the means for predicting includes means for evaluating the residuals.

253. The system as claimed in claim 250 wherein the first material comprises metal and wherein the predetermined target is part of a multi-material device having at least one outer layer of dielectric material.

254. The system as claimed in claim 250 further comprising means for measuring layer thickness or reflectivity at at least one location to obtain a layer measurement and means for utilizing the layer measurement to control a characteristic of the at least one pulse.

255. The system of claim 250 further comprising means for measuring a layer thickness to obtain a thickness measurement and means for using at least the thickness measurement for predicting the relative location.

256. The system as claimed in claim 254 wherein the characteristic is pulse energy or pulsewidth.

257. The system as claimed in claim 250 further comprising means for measuring layer thickness or reflectivity at at least one location to obtain a layer measurement, and means for utilizing the layer measurement to controllably shift a wavelength of the laser beam.

258. The system as claimed in claim 250 further comprising: (a) means for obtaining information identifying microstructures designated for removal, (b) means for measuring a first set of reference locations to obtain three-dimensional reference data, (c) means for generating a trajectory based on at least the three-dimensional reference data to obtain a prediction of beam waist and microstructure surface locations, (d) means for updating the predicted relative location during relative motion based on updated position information, the updated position information being obtained during the relative motion.

259. The system of claim 258 further comprising a position encoder for generating data of the updated position information.

260. The system of claim 258 further comprising an optical sensor for generating data of the updated position information.

5 261. The system as claimed in claim 250 wherein the means for selectively irradiating irradiates within orthogonal linear scans in the region to be measured.

10 262. The system of claim 250 wherein the at least one alignment target is part of a multi-material semiconductor memory including a substrate and at least one dielectric layer disposed between the substrate and the predetermined target, and wherein power of the radiation cleaning beam is substantially below power required to cause an undesirable change to the predetermined target, the substrate, or the at least one dielectric layer.

15 263. The system of claim 250 wherein energy of the cleaning beam is in the range .005 to .05 μ joules.

264. The system of claim 250 wherein the measurement is a 3-D measurement.

20 265. In a system for laser processing a target structure of a multi-layer, multi-material device, a method of controlling energy delivered to the target structure, the method comprising:

obtaining at least one measurement at each of at least two predetermined wavelengths;

determining thickness of at least one layer of the device based on the measurements; and

25 controlling energy delivered to the target structure based on the determined thickness to compensate for variations in energy required to process the target structure caused by interference effects of the at least one layer.

266. The method as claimed in claim 265 wherein level of the controlled energy is substantially constant during processing of each microstructure of the device.

5 267. The method as claimed in claim 265 wherein level of the controlled energy is varied to process a plurality of microstructures based on a plurality of thickness measurements over the device.

268. The method as claimed in claim 267 further comprising recording the plurality of thickness measurements for process monitoring.

10 269. In a system for laser processing a target structure of a multi-layer, multi-material device, a control system for controlling energy delivered to the target structure, the control system comprising:

means for obtaining at least one measurement at each of at least two predetermined wavelengths;

15 means for determining thickness of at least one layer of the device based on the measurements; and

means for controlling energy delivered to the target structure based on the determined thickness to compensate for variations in energy required to process the target structure caused by interference effects of the at least one layer.

20 270. The control system as claimed in claim 269 wherein level of the controlled energy is substantially constant during processing of each microstructure of the device.

271. The control system as claimed in claim 269 wherein level of the controlled energy is varied to process a plurality of microstructures based on a plurality of thickness measurements over the device.

25 272. The control system as claimed in claim 271 further comprising means for recording the plurality of thickness measurements for process monitoring.

273. A method for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a predetermined target having a first material to be laser processed, the method comprising:

- 5 measuring position of at least one alignment target formed at a predetermined measurement location to obtain at least one measurement;
 predicting relative location of the predetermined target and a laser beam based on the at least one measurement to obtain a predicted relative location;
 generating a laser beam including at least one pulse;
10 inducing relative motion between the predetermined target and the laser beam based on the predicted relative location;
 updating the predicted relative location during relative motion based on updated position information, the updated position information being obtained during the relative motion; and
15 irradiating the at least one pulse into a spot on the predetermined target to process the predetermined target based on the updated position information.

274. The method of claim 273 wherein the updated position information obtained during the step of relatively positioning includes data from a position encoder.

- 20 275. The method of claim 273 wherein the updated position information obtained during the step of relatively positioning includes data from an optical sensor.

276. The method of claim 273 further comprising measuring a set of reference locations to obtain three-dimensional reference data.

- 25 277. The method of claim 276 wherein the reference locations are measured during a calibration process.

278. A system for precisely relatively positioning a waist of a pulsed laser beam to compensate for microscopic positional variations of a

predetermined target having a first material to be laser processed, the system comprising:

- means for measuring position of at least one alignment target formed at a predetermined measurement location to obtain at least one measurement;
- 5 means for predicting relative location of the predetermined target and a laser beam based on the at least one measurement to obtain a predicted relative location;
- means for generating a laser beam including at least one pulse;
- means for inducing relative motion between the predetermined target
- 10 and the laser beam based on the predicted relative location;
- means for updating the predicted relative location during relative motion based on updated position information, the updated position information being obtained during the relative motion; and
- means for irradiating the at least one pulse into a spot on the
- 15 predetermined target to process the predetermined target based on the updated position information.

279. The system of claim 278 further comprising a position encoder for generating data of the updated position information.

280. The system of claim 278 further comprising an optical sensor

20 for generating data of the updated position information.

281. The system of claim 278 further comprising means for measuring a set of reference locations to obtain three-dimensional reference data.

282. The system of claim 281 wherein the reference locations are measured during a calibration process.

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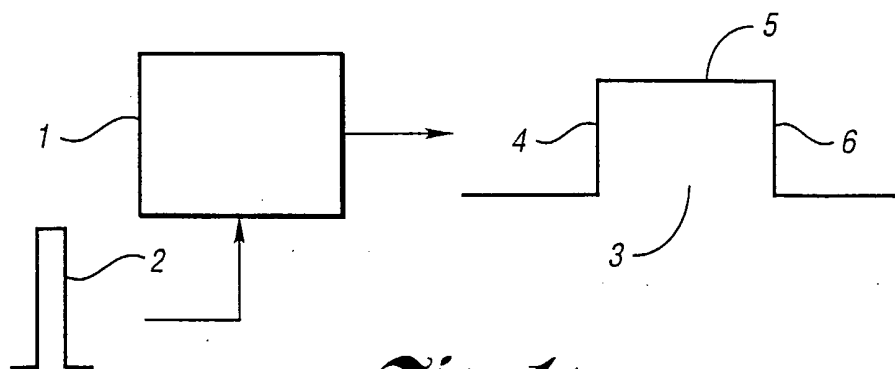


Fig. 1a

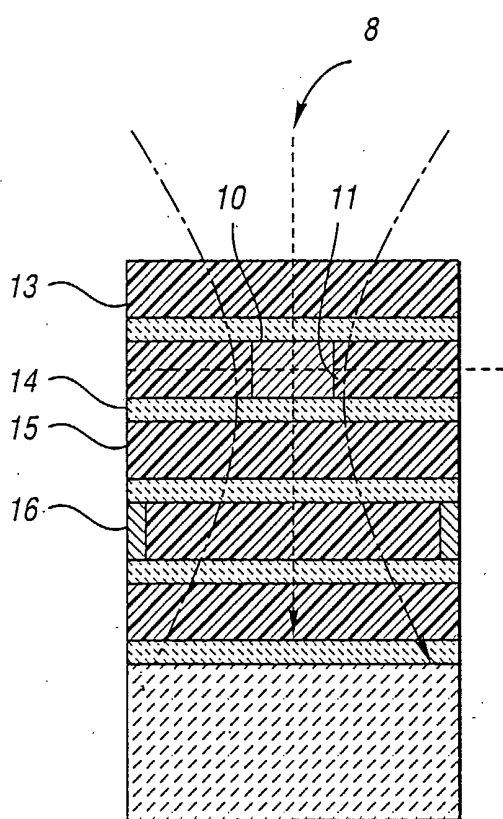


Fig. 1b

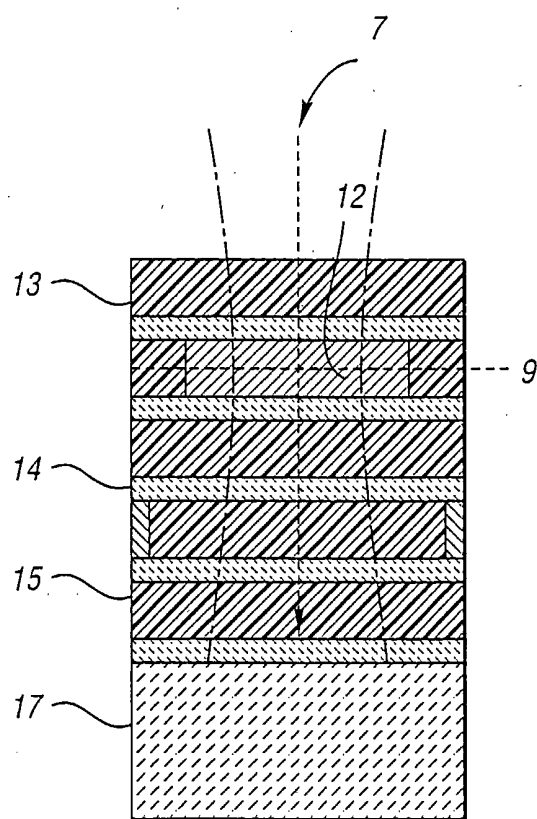


Fig. 1c

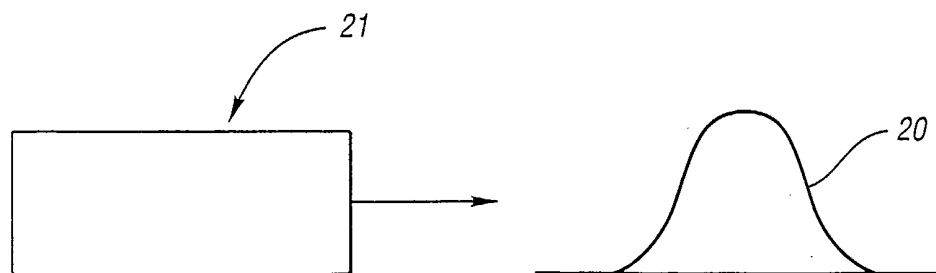


Fig. 2a (PRIOR ART)

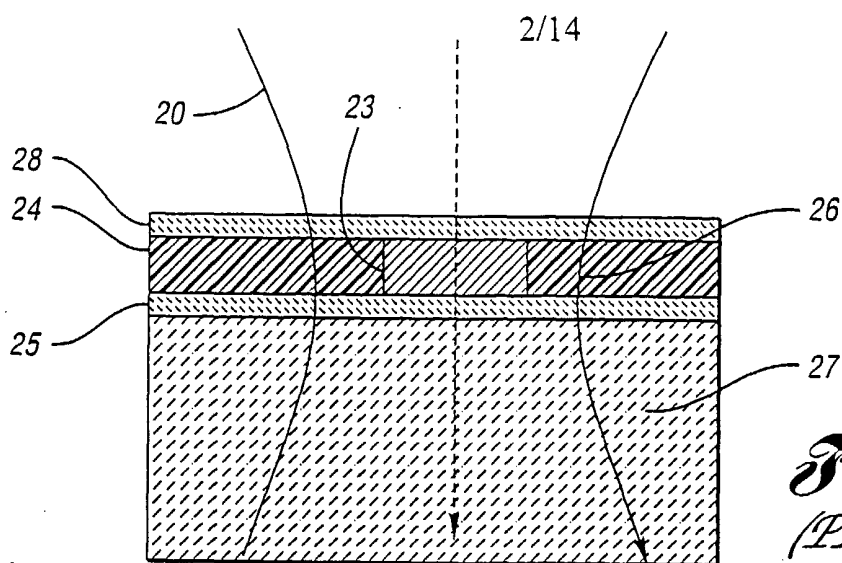


Fig. 2b
(PRIOR ART)

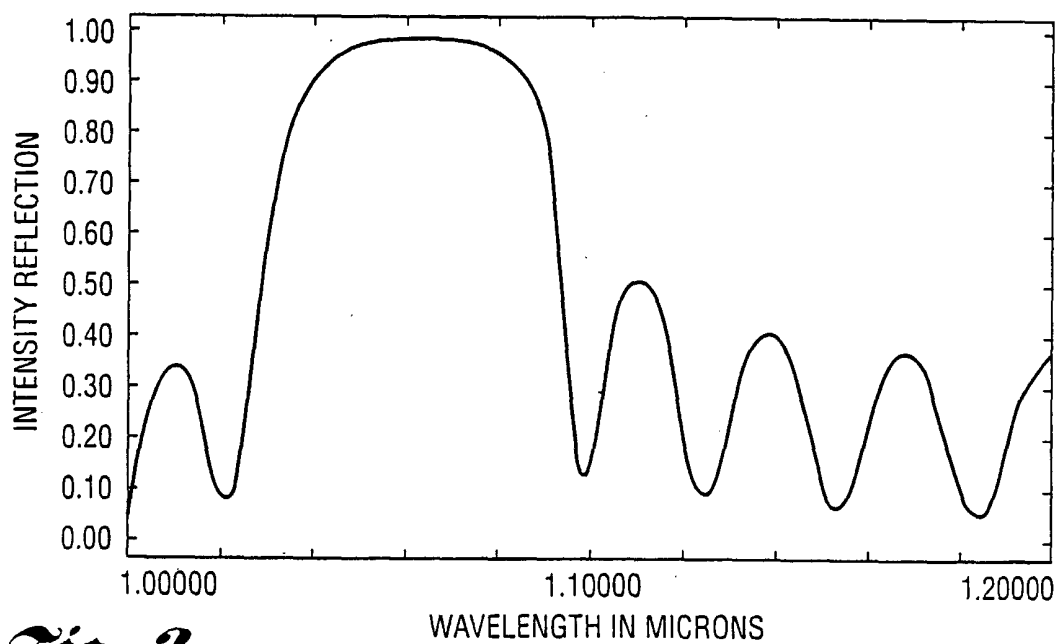


Fig. 3

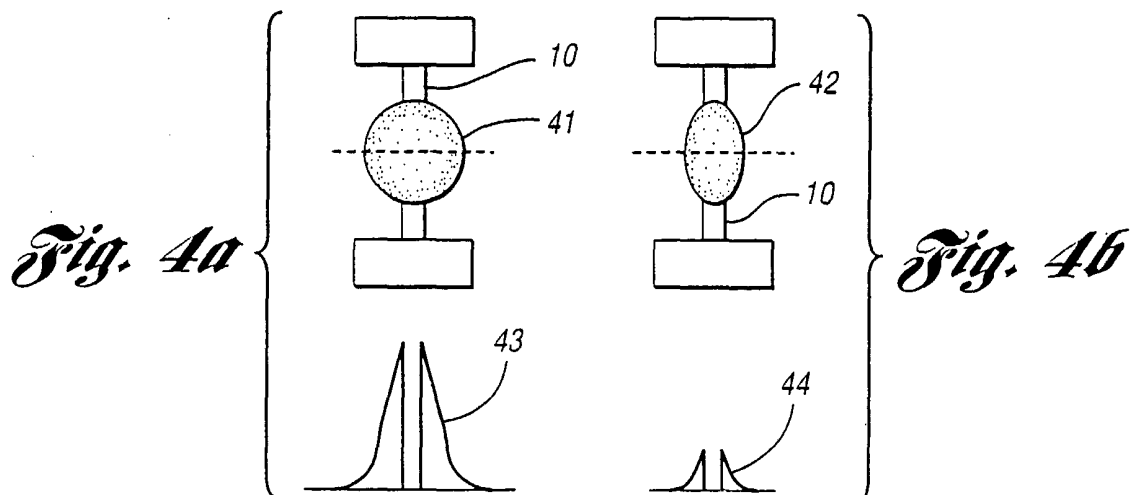
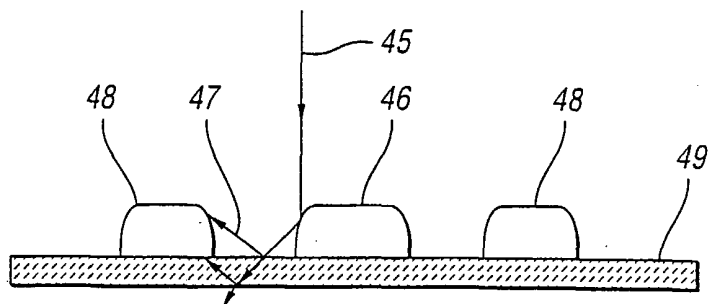
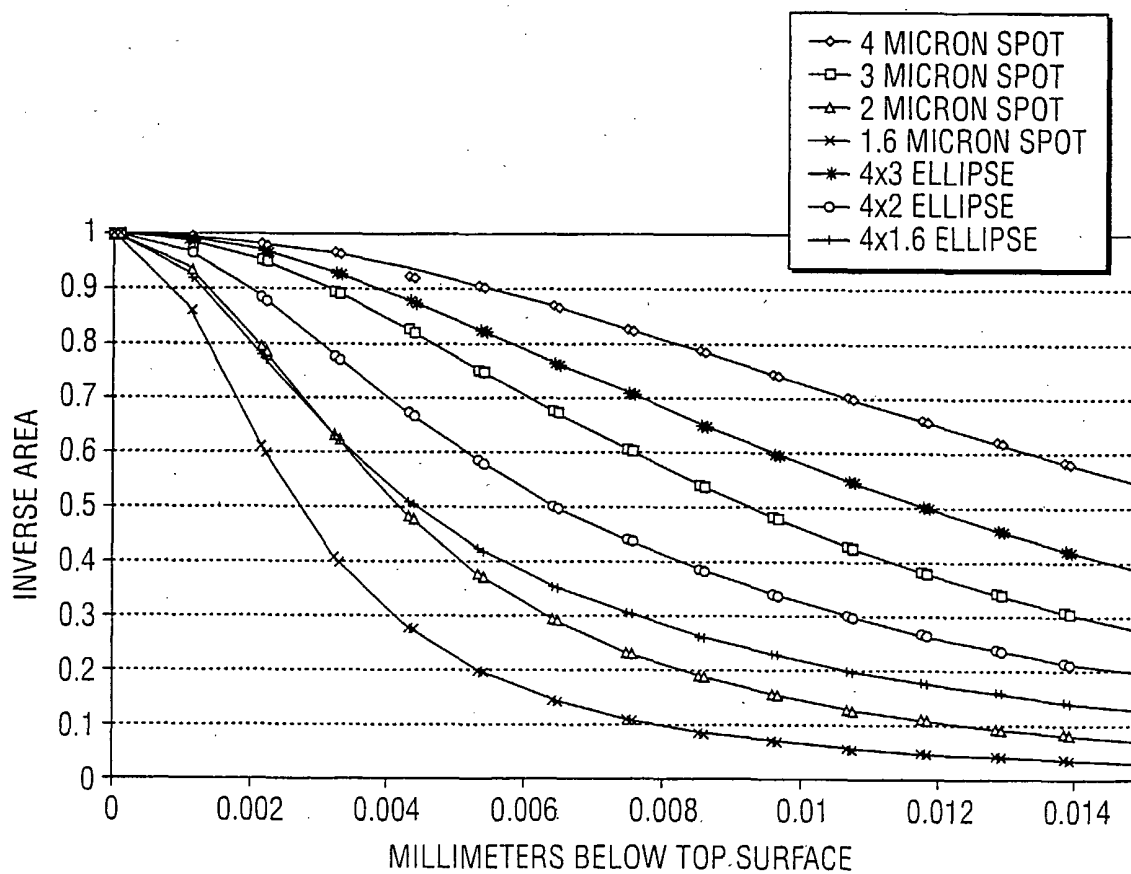


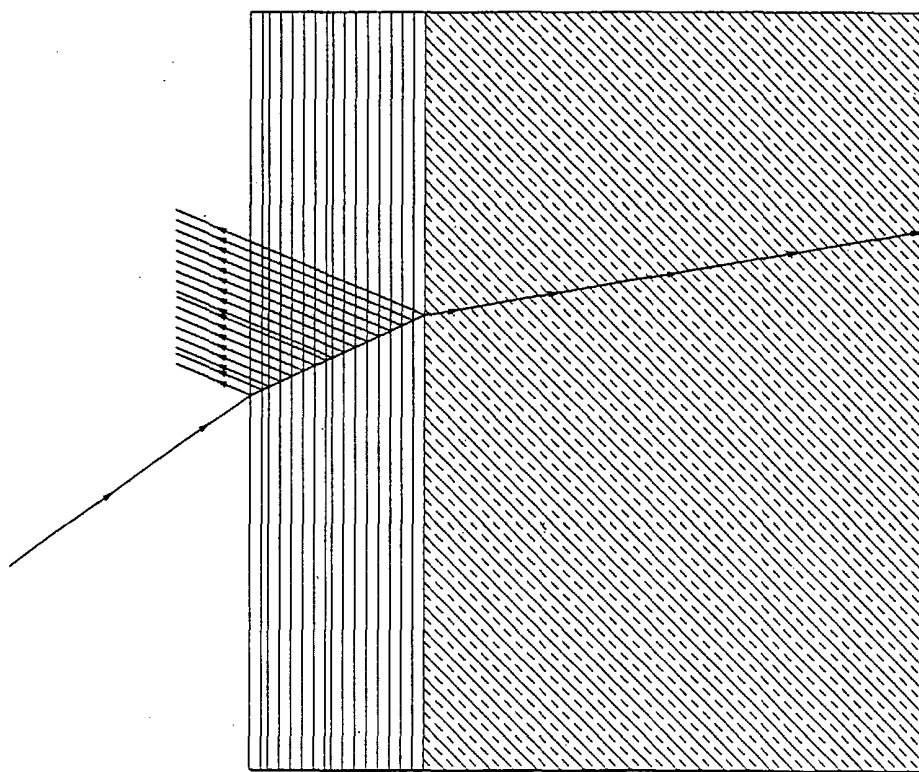
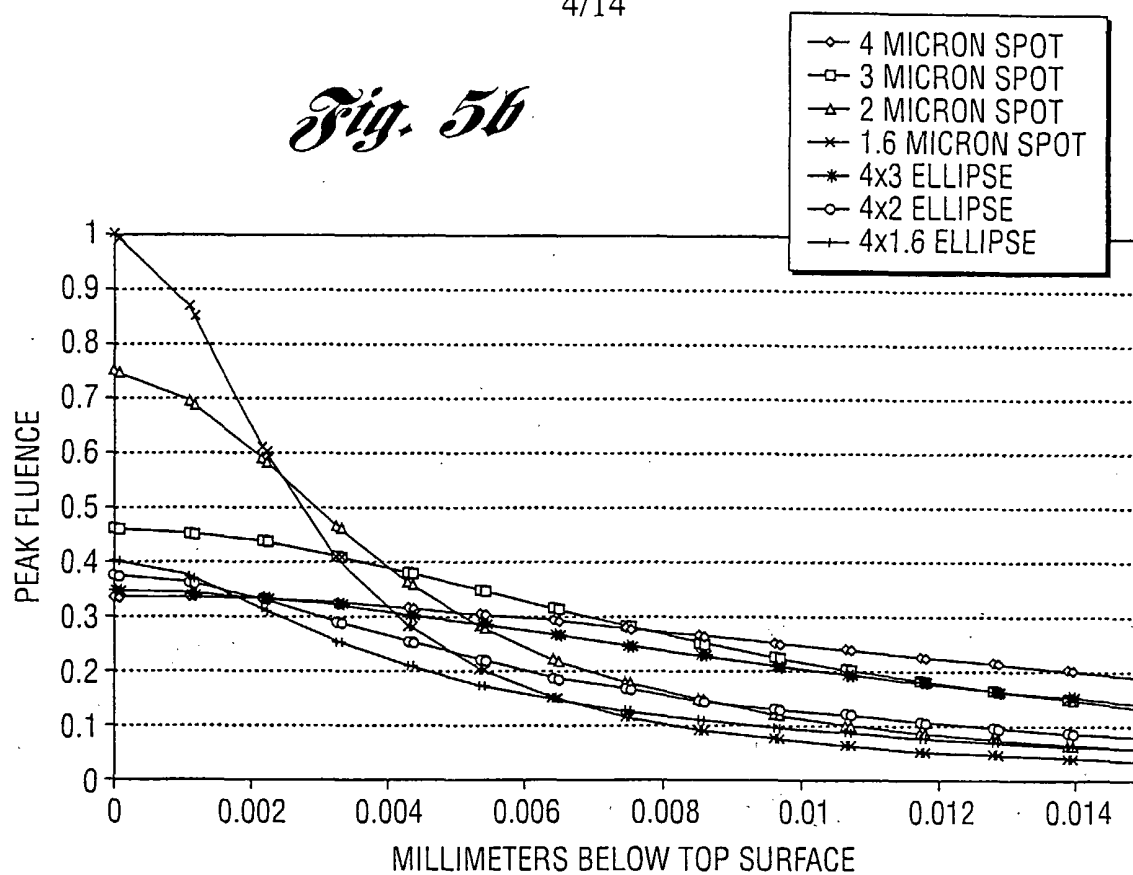
Fig. 4a

Fig. 4b

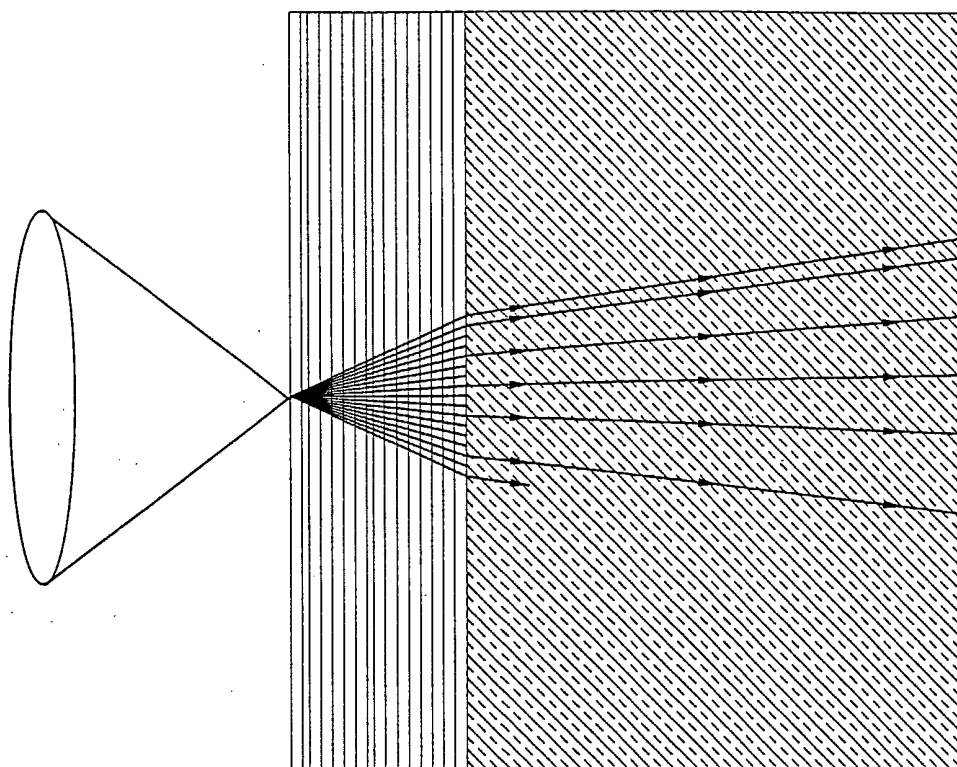
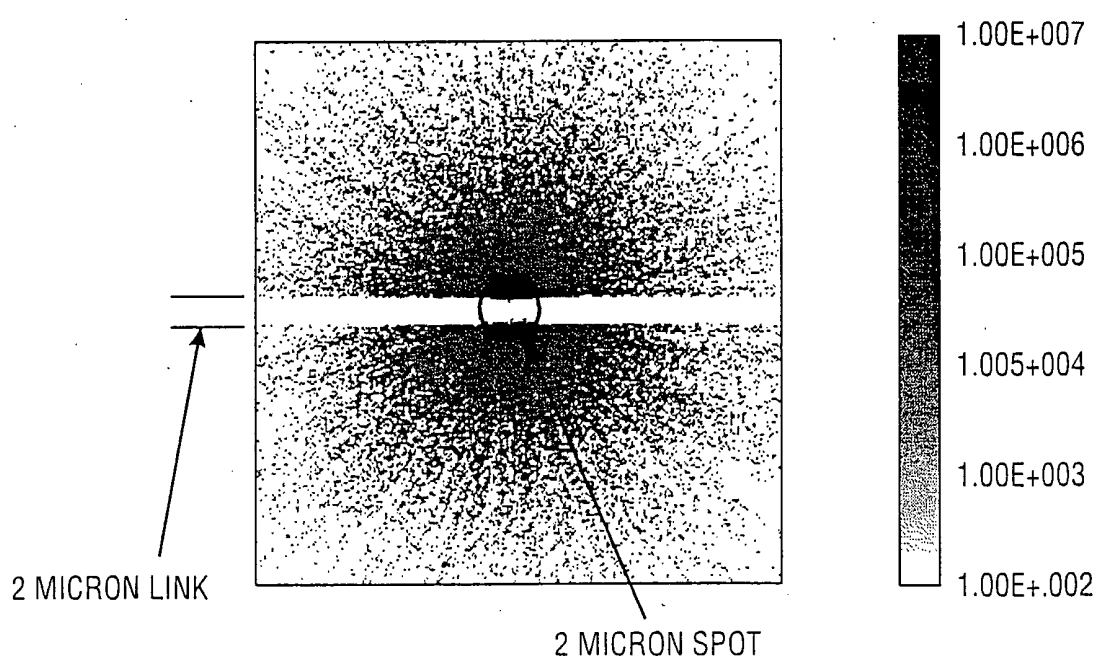
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*Fig. 4c**Fig. 5a*

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Fig. 5b*Fig. 6a*

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*Fig. 6b**Fig. 7a*

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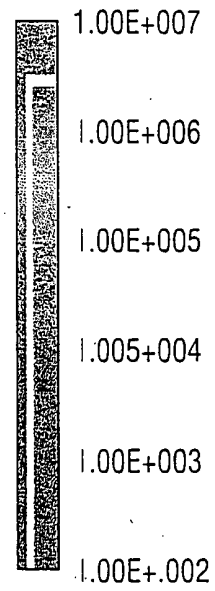
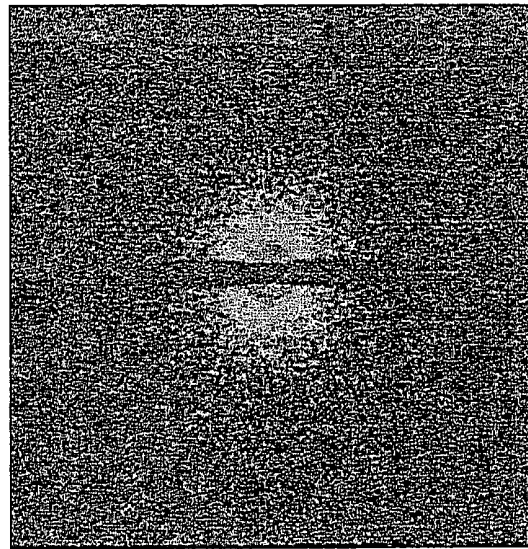


Fig. 7b

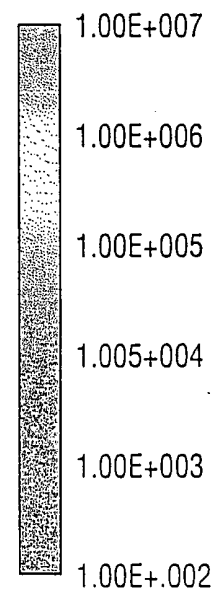
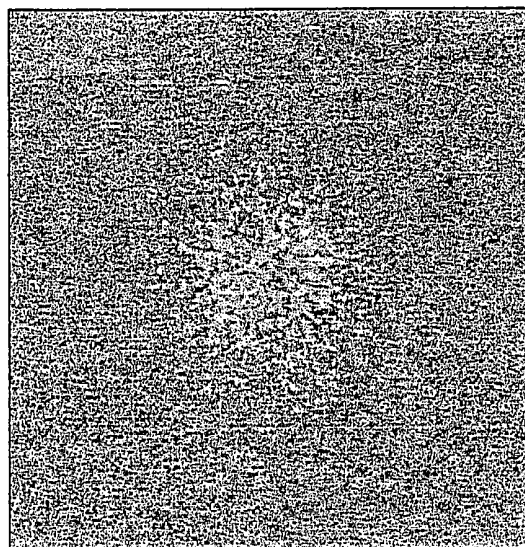


Fig. 8

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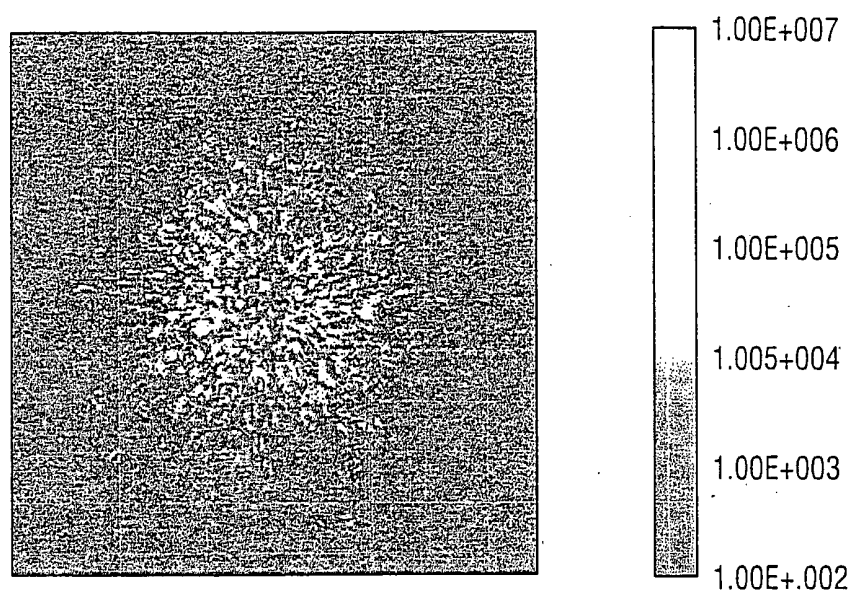


Fig. 9

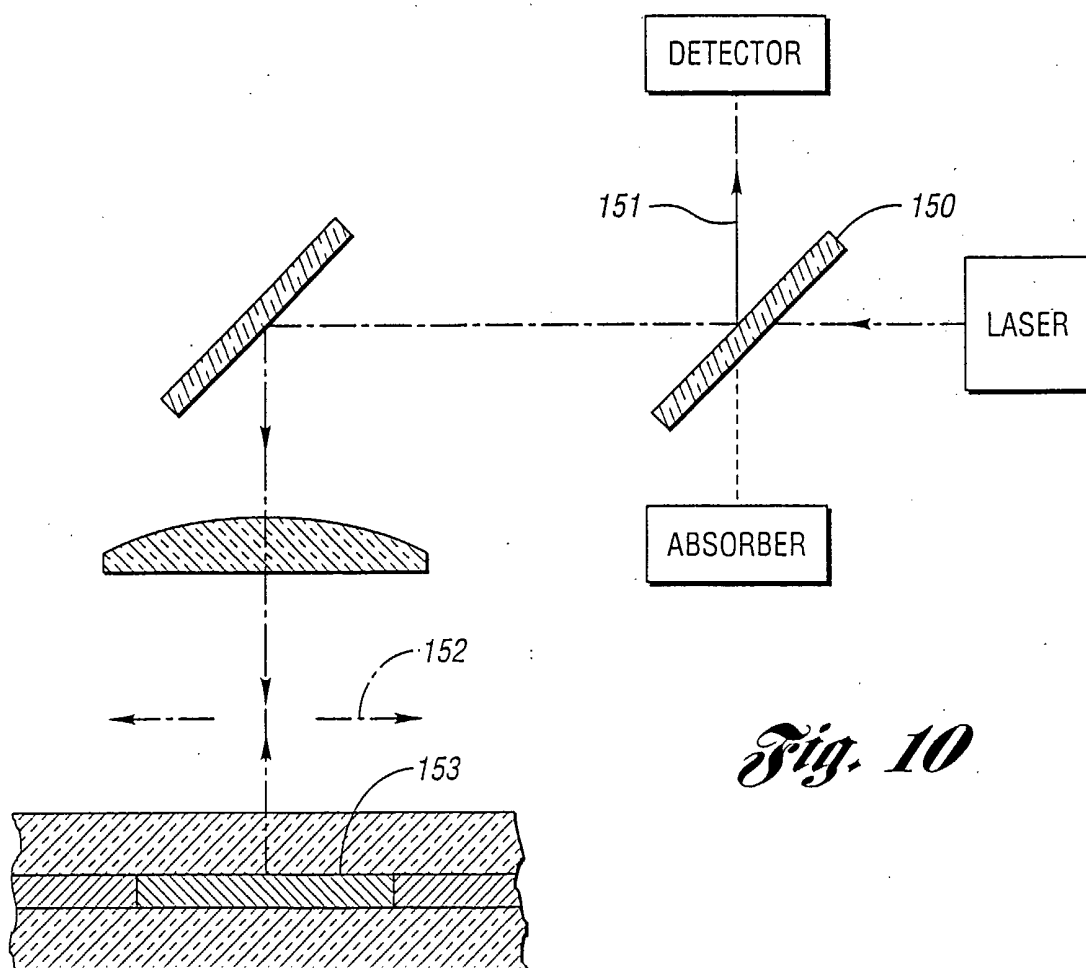
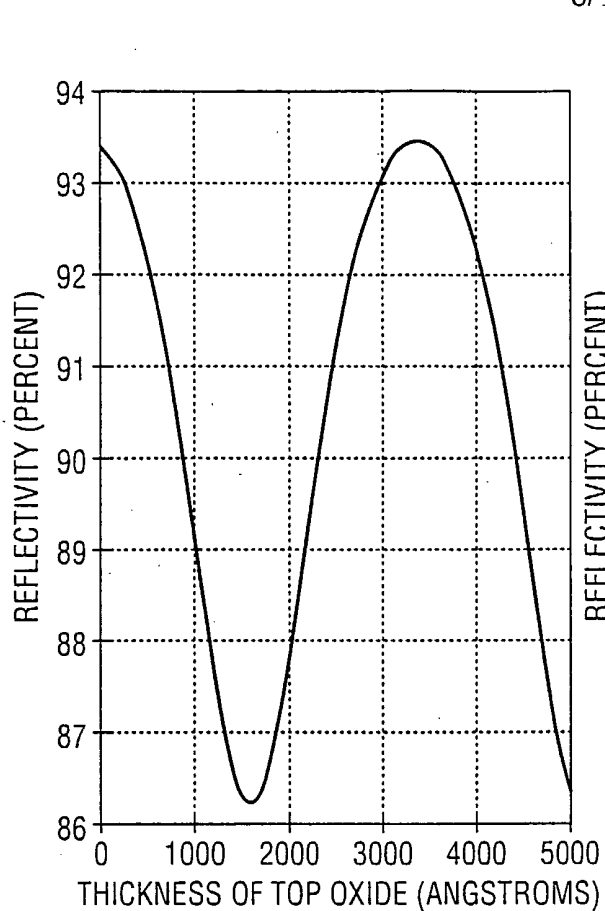
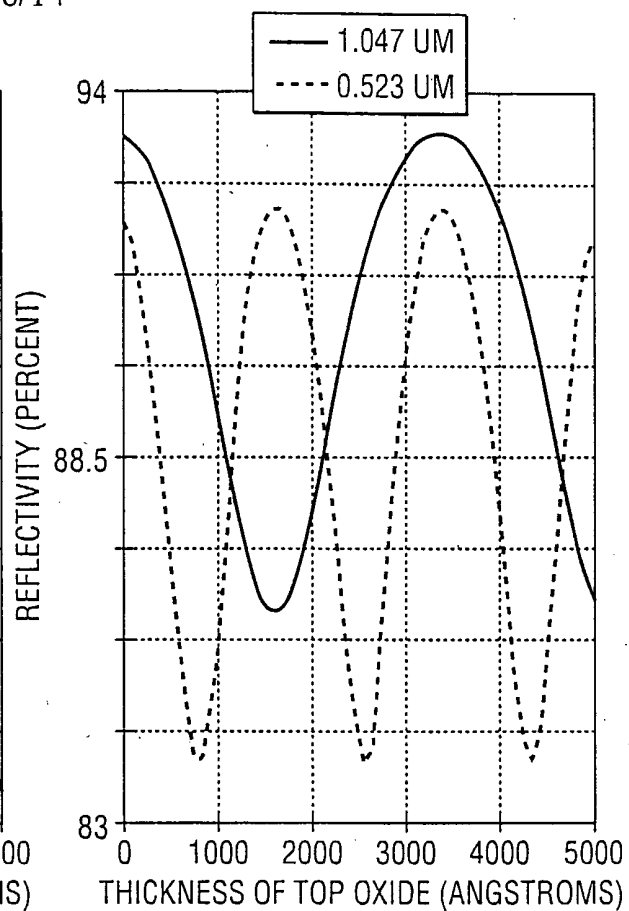
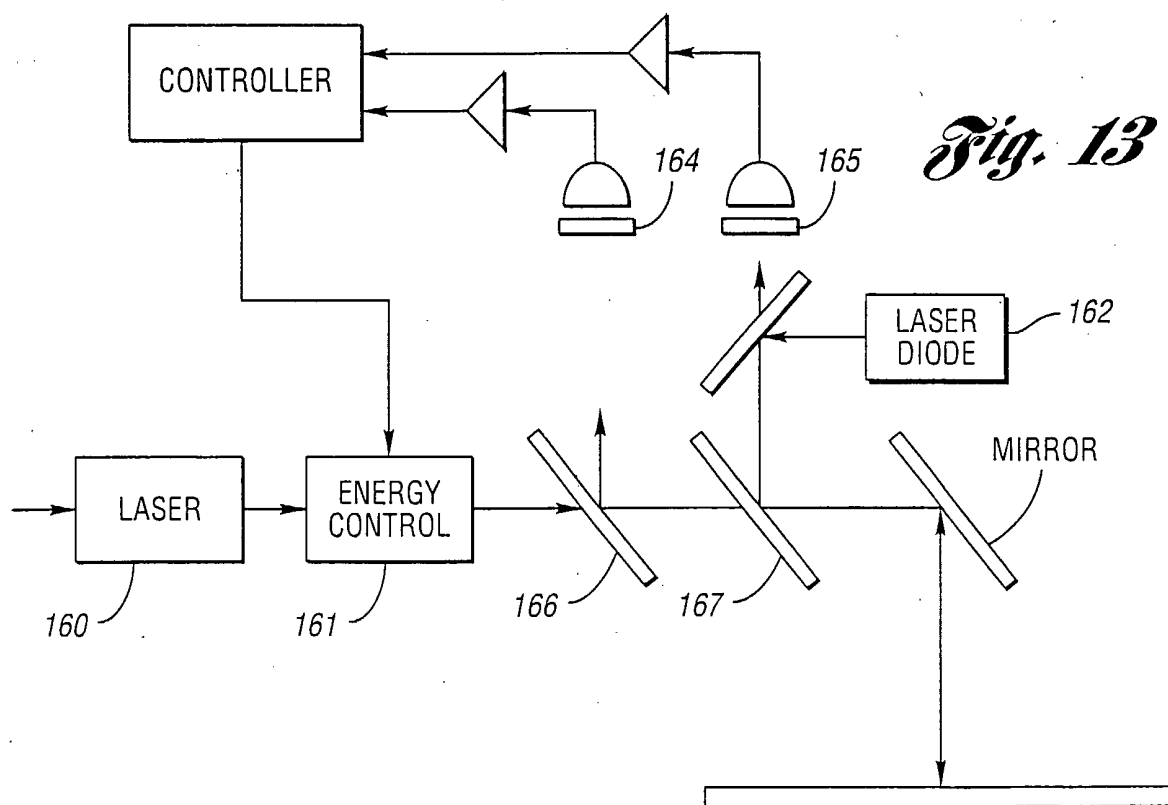


Fig. 10

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*Fig. 11**Fig. 12**Fig. 13*

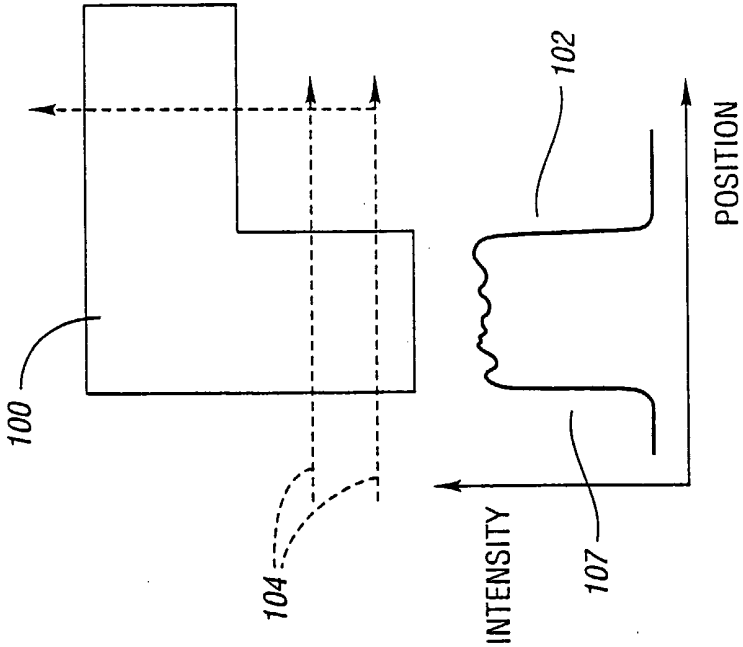


Fig. 14a

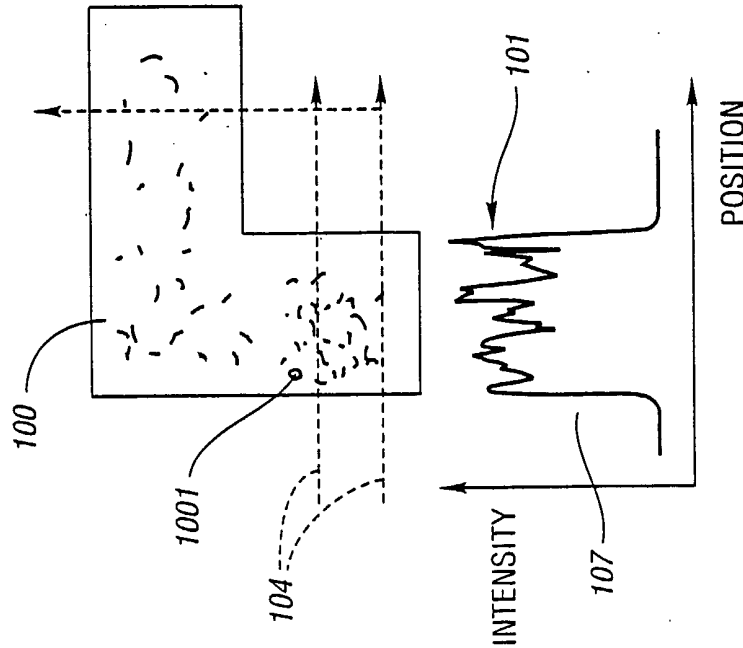


Fig. 14b

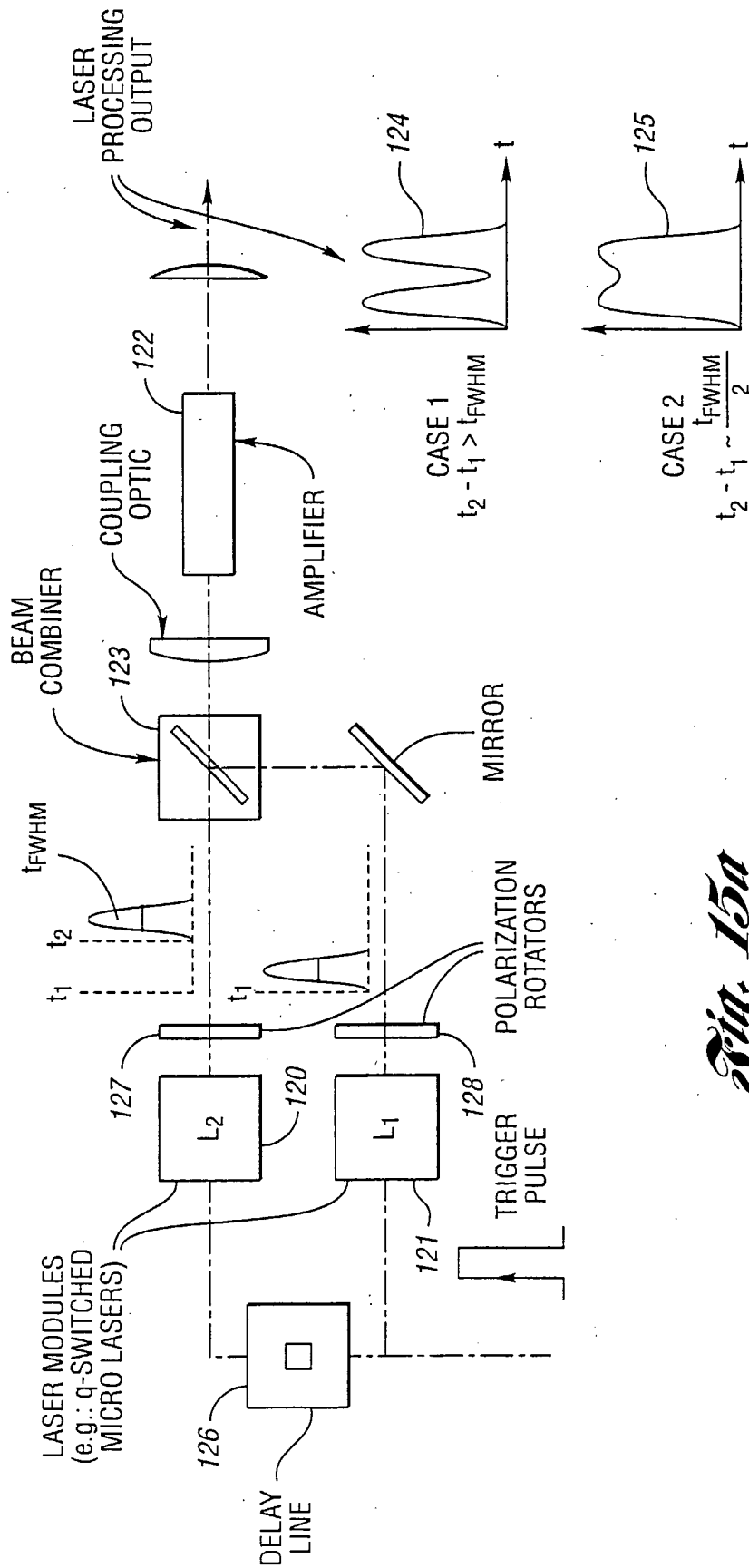
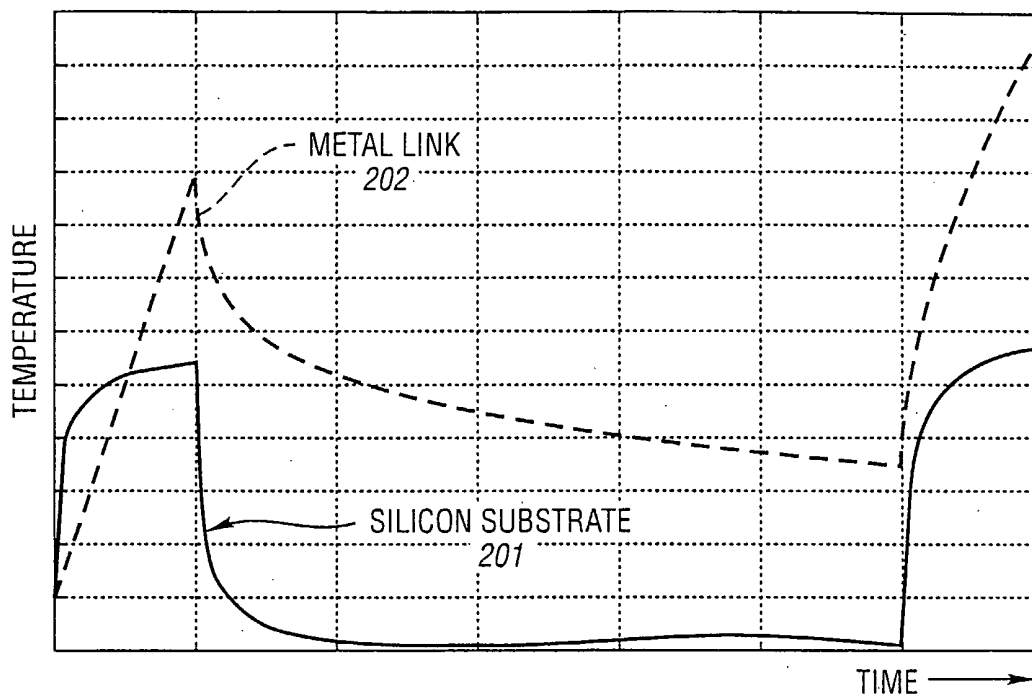
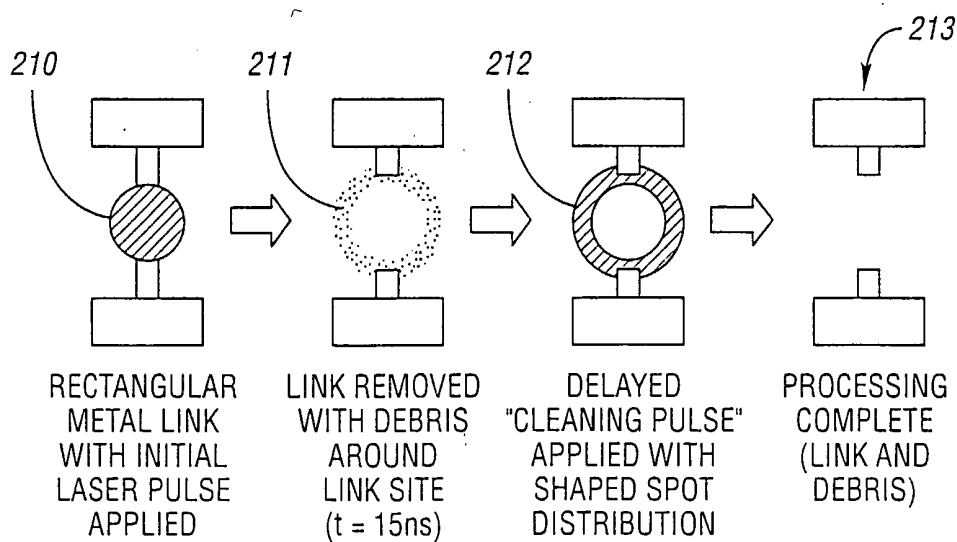


Fig. 15a

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*Fig. 16**Fig. 17*

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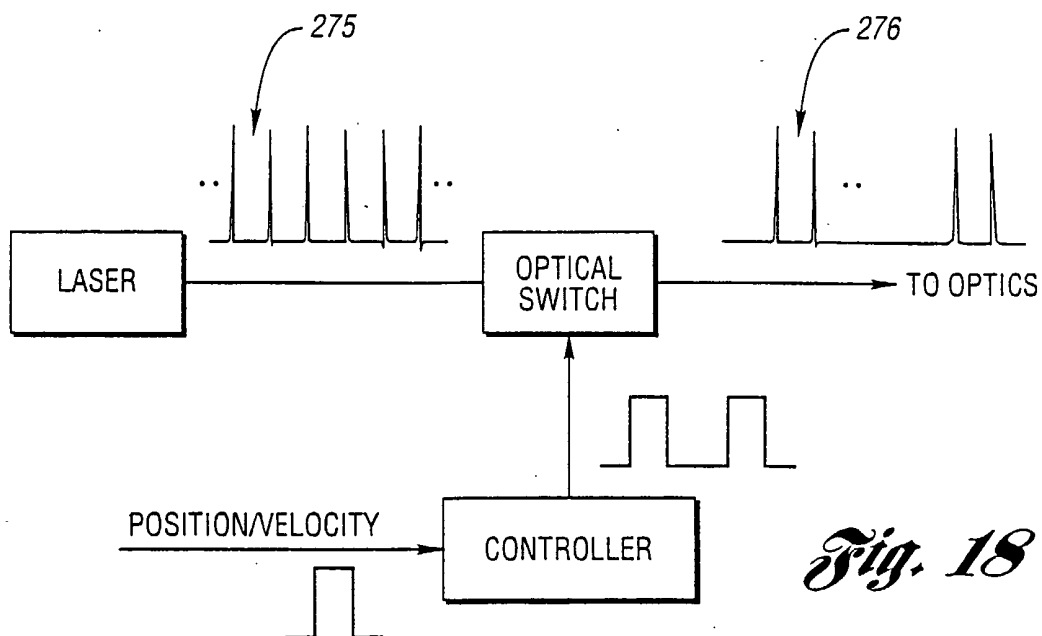


Fig. 18

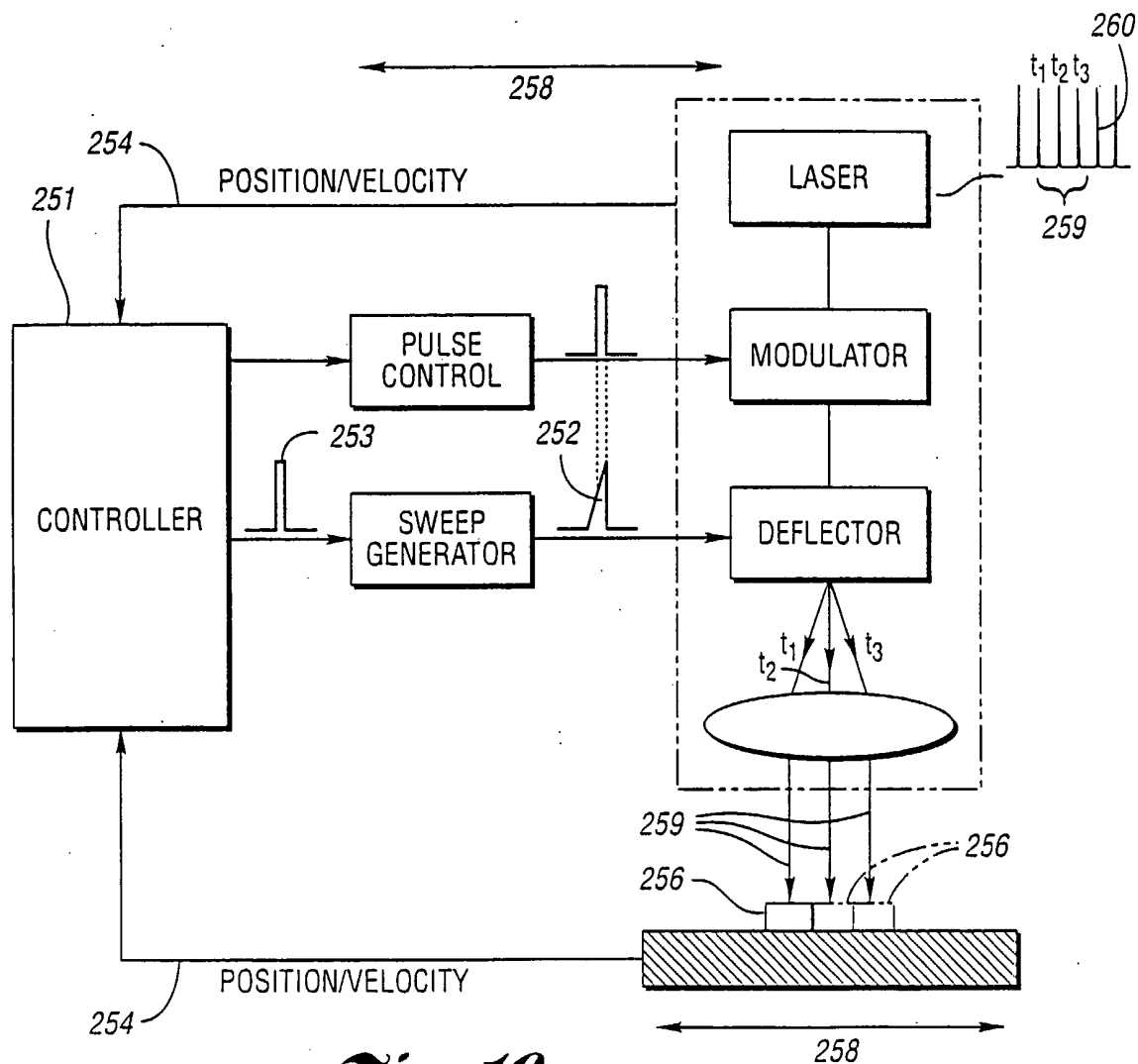
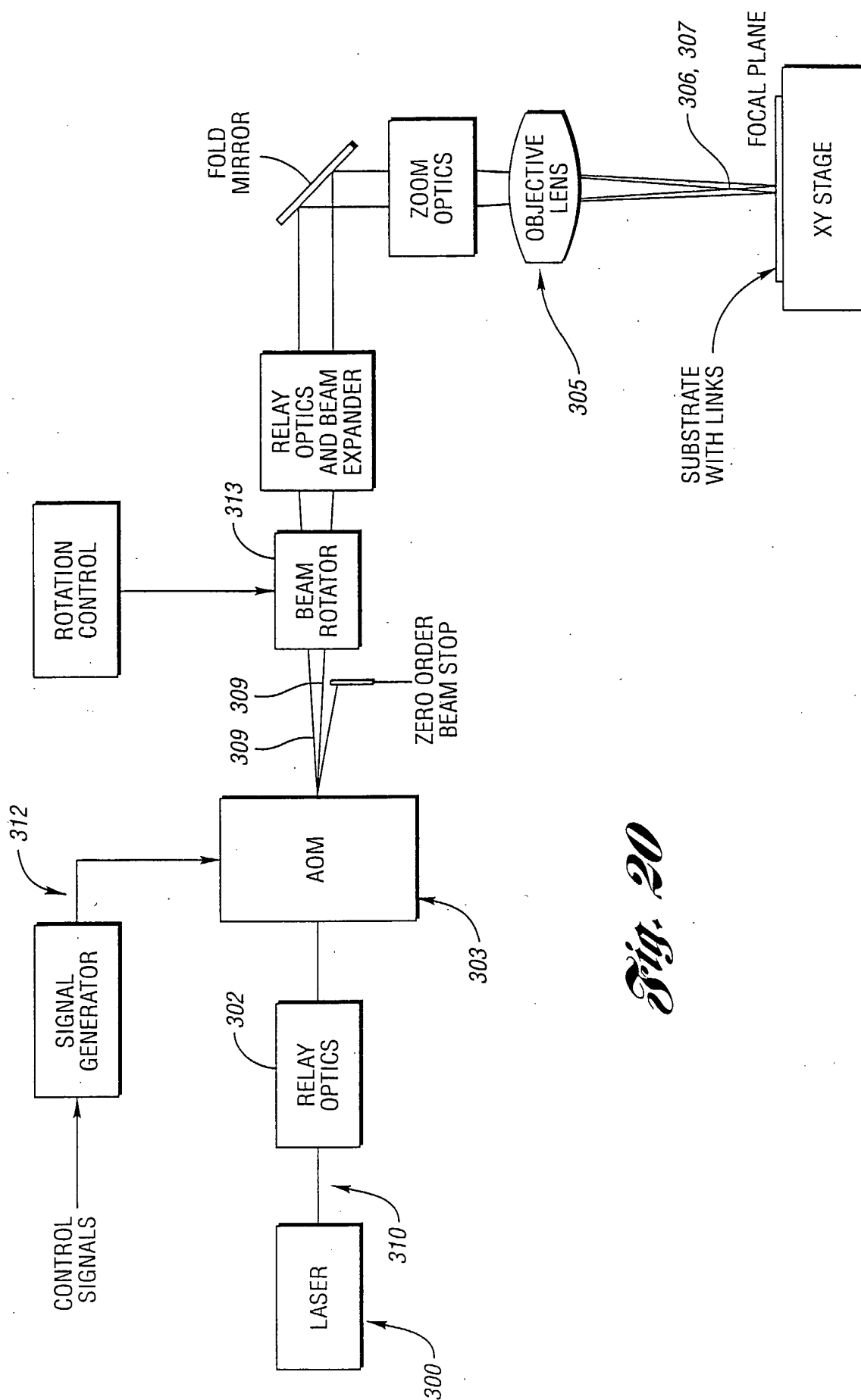


Fig. 19

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*Fig. 20*

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/09665

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : B23K 26/00

US CL : 219/121.61, 121.69, 121.7, 121.71, 121.72, 121.81; 427/96, 97, 554, 555, 556; 264/400; 438/940

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 219/121.61, 121.69, 121.7, 121.71, 121.72, 121.81; 427/96, 97, 554, 555, 556; 264/400; 438/940

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6,103,992 A (NODDIN) 15 August 2000 (15.08.2000), Figure 1, Item 4.	1-282
A	US 5,841,049 A (OWEN et al) 24 November 1998 (24.11.1998), Figure 3a, Item 90.	1-282
A	US 5,294,567 A (DORFMAN et al) 15 March 1994 (15.06.1994), column 2, lines 15-45.	1-282



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&"

document member of the same patent family

Date of the actual completion of the international search

26 July 2002 (26.07.2002)

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