

LASER-BASED METHOD AND SYSTEM FOR PROCESSING TARGETED SURFACE MATERIAL AND ARTICLE PRODUCED THEREBY

CROSS-REFERENCE TO RELATED APPLICATION

5 This application claims the benefit of U.S. provisional application
Serial No. 60/584,268, filed June 30, 2004.

BACKGROUND OF THE INVENTION

1. Field of the Invention

10 The present invention relates to laser marking and texturing,
particularly forming at least semi-permanent or erasable indicia on one or more
materials of a microelectronic device. The materials may include semiconductor
substrates, thin films, metallization, and dielectric layers. One or more embodiments
may also be applied for forming indicia on MEMs, optoelectronic devices, or
biomedical microchips. Various embodiments are useable for various
micromachining or microfabrication applications.

15 2. Background Art

20 Prior to 1999, Silicon wafer marking was used for identification at
wafer level. Initially driven by the Known Good Die, and more recently by
traceability and component identification, laser marking on the backside of the wafer
at the die level has become the trend, and applied to various packaging technologies,
including MCM, Flip Chip, DCA, and CSP. For the past years, research and
development effort occurred to develop such a marking tool for production.

One of the emerging challenges for die marking is the recent
introduction of very thin wafers. Previously, wafer thickness specifications of 300
to 700 microns (μm) were typical. Present requirements for smaller die, both in

terms of area and thickness, are resulting in wafers as thin as 150 μm . Long-term projections are for wafer thickness to be reduced to a feasible limit.

Another challenge is the continuing shrinking of die sizes. For example, die used in DCA (Direct Chip Attach) applications are in the 3mm to 8mm dimension. However, products like the RFID tags can be as small as 0.3mm yet require much of the same information that is included in large die marking. This trend creates the need for further development in die marking to shrink the actual alphanumeric character sizes.

Traditional wafer marking systems are not well suited to present and emerging requirements.

Valuable advancements have been demonstrated, for instance as disclosed in published US Patent Application Number 2003/0060910 entitled "High Speed, Laser-Based Marking Method And System For Producing Machine Readable Marks On Workpieces And Semiconductor Devices With Reduced Subsurface Damage Produced Thereby," assigned to the assignee of the present invention, published 1 April 2004. However, there is a need to produce high contrast indicia while providing for decreased feature sizes – and to form indicia on microelectronic materials, known to have widely varying optical properties.

Desirable advancements for precision laser marking systems includes: increasing mark density (*e.g.*, smaller effective dot size or line width), control over the marking depth, and improved mark repeatability with control of or substantial elimination of a heat affected zone. There is a need for improvement of readability (*e.g.*, mark contrast with the background), preferably, angle independent contrast.

The ideal mark will be formed with little or no material removed, and will provide contrast that will survive through one or more subsequent fabrication steps. Further, shrinking sizes are expected to mandate increasing density requirements, for instance, font sizes less than .3 mm and decreased font spacing.

SUMMARY OF THE INVENTION

An object of at least one embodiment of the invention is to provide a method of forming indicia/texture on at least one material of a microelectronic article. The method includes the step of applying a pulsed laser output to a localized
5 region of the material, the output having sufficient total fluence to initiate ablation within at least a portion of the region and a pulse width short enough such that the region and proximate material surrounding the region are substantially slag-free.

Another object of at least one embodiment of the invention is to provide an article of manufacture produced by the above method.

10 Yet another object of at least one embodiment of the invention is to provide a laser marking/texturing system for carrying out the above method.

In carrying out the above objects and other objects of the present invention, a method for processing targeted surface material within a region of a workpiece while avoiding undesirable changes to adjacent non-targeted material is
15 provided. The method includes generating a pulsed laser output including at least one pulse having a wavelength and a pulse width. The method further includes irradiating the targeted surface material of the workpiece with the pulsed laser output including the at least one pulse to texture the targeted surface material. The pulsed laser output has sufficient total fluence to initiate ablation within at least a
20 portion of the targeted surface material and the pulse width is short enough such that the region and non-targeted material surrounding the region are substantially free of slag.

The textured surface material may include indicia.

The indicia may be at least semi-permanent or erasable.

25 The workpiece may be a microelectronic device and the textured surface material may be a microelectronic material.

The targeted surface material may be at least one of a semiconductor substrate, a thin film, a metal layer and a dielectric layer.

The workpiece may be one of a MEMs device, an optoelectronic device and a biomedical chip.

5 The non-targeted surface material may include indicia.

The indicia may be machine-readable.

The indicia may have a font size less than .3 mm.

The textured surface material may include a microtextured pattern formed on the workpiece.

10 The workpiece may be a semiconductor wafer and wherein the microtextured pattern forms indicia on the wafer.

The method may further include generating a secondary laser output and irradiating the textured surface material with the secondary laser output to process the textured surface material.

15 The textured surface material may include indicia, and the indicia may be erased during the step of irradiating with the secondary laser output.

The textured surface material may be formed on at least one side of the workpiece.

The workpiece may be a semiconductor wafer.

20 The step of generating may be at least partially performed with a femtosecond or picosecond laser.

The pattern may be a bar pattern, an alphanumeric character string, or a logotype.

The pulse width of the at least one pulse may be below about 1 ns.

5 The pulse width may be about 100 ps or less, or may be less than about 10 ps.

The textured surface material may include microtextured surface material.

The microtextured surface material may include nanotextured surface material.

10 The total fluence may be measurable over a spatial dimension of a spot of the output.

15 The textured surface material may include indicia, and the step of irradiating may include the step of directing the laser output in response to at least one control signal that represents a first location of at least a part of the indicia to impinge the region at the first location.

The region may be within the spatial dimension of the spot.

The step of irradiating may substantially increase surface roughness of the targeted surface material within at least a portion of the region.

20 The non-targeted surface material surrounding the region may have a surface with a strong specular reflection component.

Diffuse reflectance of the indicia may be in a range of .5% to 5%.

The total fluence may exceed about .1 J/cm².

The wavelength may be less than an absorption edge of the targeted surface material.

The wavelength may be ultraviolet.

5 The pulse width of the at least one pulse may be in a range of about 15 fs to 500 ps.

The pulse width of the at least one pulse may be in a range of about 100 fs to 50 ps, or may be in a range of about 300 fs to 15 ps.

The targeted surface material may be silicon, or may be a metal or a dielectric.

10 The targeted surface material may be a portion of a dielectric passivation layer. The dielectric of the layer may be an inorganic, organic, or a low-k dielectric.

The targeted surface material may be part of a MEM device.

15 A portion of the indicia may have surface variations in a range of about .25 microns to about 1 micron.

A feature dimension of the indicia may be in a range of several microns to tens of microns, or may be a few wavelengths of the at least one pulse.

20 The step of irradiating may include the step of controlling polarization of the pulsed laser output to enhance or control a characterization of the textured surface material.

The pulsed laser output may include a focused laser processing beam, and the step of irradiating may include the step of relatively moving the workpiece and the focused laser processing beam.

The textured surface material may include a microtextured pattern, and the step of relatively moving may create the microtextured pattern on the workpiece.

5 The step of irradiating may include the step of shaping the spot to obtain a shaped spot.

The shaped spot may have a top-hat irradiance profile.

The shaped spot may have a depressed center with energy concentrated in a perimeter of the shaped spot.

10 The step of irradiating may include the step of controlling an aspect of the spot.

The wavelength may be below an absorption edge of a material of the workpiece.

15 The pulsed laser output may finely texture the targeted surface material and the secondary laser output may coarsely process the textured surface material.

The pulsed laser output may coarsely texture the targeted surface material and the secondary laser output may finely process the textured surface material.

20 The textured surface material may include indicia, and a negative window mark may be created during the step of irradiating with the secondary laser output.

The textured surface material may include a pattern, and the step of irradiating with the secondary laser output may micromachine the pattern.

The step of irradiating with the secondary laser output may trim an electrical or mechanical parameter of the textured surface material.

The secondary laser output may include at least one pulse having a wavelength which is absorbed into the textured surface material.

- 5 The wavelength of the at least one pulse of the secondary beam may or may not be absorbed into the non-targeted material surrounding the region.

- Further in carrying out the above objects and other objects of the present invention, a system for processing targeted surface material within a region of a workpiece while avoiding undesirable changes to adjacent non-targeted material is provided. The system includes a primary laser subsystem which includes a primary laser source for generating a pulsed laser output including at least one pulse having a wavelength and a pulse width. The system further includes a delivery subsystem for irradiating the targeted surface material of the workpiece with the pulsed laser output including the at least one pulse to texture the targeted surface material. The pulsed laser output has sufficient total fluence to initiate ablation within at least a portion of the targeted surface material. The pulse width is short enough such that the region and the non-targeted material surrounding the material are substantially free of slag.
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The primary laser source may include an ultrafast laser.

- 20 The ultrafast laser may be a picosecond laser, or may be a femtosecond laser.

The delivery subsystem may include a controller that accepts data that represents a location of the targeted surface material to be textured and produces at least one position control signal.

- 25 The delivery subsystem may include a positioning subsystem for directing the laser output to the location of the targeted surface material so as to

texture the targeted surface material in response to the at least one position control signal.

The system may further include a secondary laser subsystem which includes a secondary laser source for generating a secondary laser output which
5 irradiates the textured surface material.

The secondary laser output may at least erase, micromachine, weld or actuate the region of the textured surface material.

The secondary laser source may include one of a pulsed, modulated or CW source.

10 Irradiation with the secondary laser output may be below the fluence breakdown threshold of the targeted surface material to heat the region.

Irradiation with the secondary laser output may be above the fluence breakdown threshold of the targeted surface material to effect at least one property change of the targeted surface material.

15 The secondary laser output may include at least one pulse having a wavelength near or exceeding the absorption edge of the material of the workpiece.

The primary laser source may include the secondary laser source or may be separate from the secondary laser source.

20 The delivery subsystem may include a polarization controller for controlling polarization of the laser output.

The primary laser source may include a diode-pumped, solid-state UV laser, and the pulse width may be less than about 20 ns.

The pulse width may be less than 1 ns.

The positioning subsystem may include at least one translation stage to move the workpiece relative to the laser output.

The positioning subsystem may include fine and coarse positioners.

5 The positioning subsystem may include translation and rotation stages to move the workpiece relative to the laser output.

The positioning subsystem may include an optical scanner to move the laser output relative to the workpiece.

The positioning subsystem may include two or more stages and scanners to move the laser output relative to the workpiece.

10 The laser output may be a laser beam having a beam waist. The positioning subsystem may include at least one component for moving the beam waist relative to the workpiece.

The delivery subsystem may include a focusing subsystem.

The focusing subsystem may be a refractive optical subsystem.

15 The system may further include an inspection subsystem for inspecting the textured surface material.

The inspection subsystem may include a machine vision subsystem.

The primary laser source may include a mode-locked oscillator and a diode-pumped, solid-state laser amplifier.

20 The optical scanner may be a two-dimensional, galvanometer-based scanner.

The at least one position control signal may be produced during at least one step of manufacturing an article from the workpiece.

The primary laser subsystem may include a seed laser and a fiberoptic amplifier.

- 5 The primary laser subsystem may further include a frequency-doubled, diode-pumped, solid-state laser.

The primary laser subsystem may still further include a mode-locked oscillator, a diode-pumped, solid-state laser amplifier, and a wavelength shifter.

- 10 The primary laser subsystem may yet further include one of a frequency doubler, a frequency tripler and a frequency quadrupler.

The laser output may have a repetition rate greater than 10 KHz.

The laser output may have an average laser output power in the range of .01W - 2W.

- 15 The textured surface material may include indicia. The system may further include a viewing subsystem for reading the indicia. The viewing subsystem may include an illuminator and an electronic imaging subsystem.

The illuminator may be one of a bright-field, a dark-field, and a combination of both bright- and dark-field.

- 20 Yet still further in carrying out the above objects and other objects of the present invention, an article of manufacture is provided. At least one surface material has discernible indicia formed thereon during at least one step of manufacturing the article. The indicia are formed by a method of selectively irradiating targeted surface material within a region of a workpiece with a pulsed laser output. The indicia are at least semi-permanent and useable during a

subsequent step of manufacturing the article. The region and non-targeted material surrounding the region are substantially slag-free. Surface roughness is increased within at least a portion of the region during the at least one step of manufacturing, thereby reducing reflection of energy used for reading the indicia.

- 5 High reflectance contrast may be obtained between the region and a background of the region over a wide range of viewing angles.

A surface of the background of the region may have a strong specular reflection component.

- 10 Reflectance contrast between the discernible indicia and a background of the region may exceed 30:1 over an angular viewing range of at least 20 degrees.

The indicia may include an alphanumeric indicium having a font dimension .3 mm or finer.

The indicia may include a two-dimensional matrix code.

- 15 The indicia may be useable for one or more steps of manufacturing the article in addition to identification.

The indicia may be distinguishable from a background of the region with a roughness measurement obtained by at least one of SEM (scanning electron microscope) data, and AFM (atomic force microscope) data.

- 20 DIN 4768 roughness measurement standards may be utilized to compare roughness of a portion of the indicia with a background of the region.

The indicia may be distinguishable from a background of the region with a measurement of image contrast.

The indicia may be machine readable, and may appear as a sequence of non-overlapping dots that form a dot matrix code.

The indicia may be usable in at least one of traceability, component identification, and sorting.

- 5 The above objects 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.

BRIEF DESCRIPTION OF THE DRAWINGS

- 10 These and other features, aspects, and advantages of the invention will become better understood with regard to the following description, accompanying drawings and attachments where:

FIGURE 1 is a schematic block diagram showing some elements of a laser processing system corresponding to one embodiment of the present invention
15 wherein a microtextured pattern is formed on a workpiece, for instance, to form indicia on a portion of a semiconductor wafer;

FIGURE 2 is a schematic block diagram showing some elements of a laser processing system corresponding to one embodiment of the present invention wherein a microtextured pattern, which may be formed with the system of Figure
20 1a, is further processed with a secondary beam, for instance to erase a mark;

FIGURES 3 and 4 illustrate some details of first and second sides of semiconductor wafer, an example of a workpiece which may be processed with various embodiments of the present invention;

FIGURE 5 is a schematic illustrating an exemplary microtextured
25 region which may be formed with a femtosecond laser system;

FIGURES 6 and 7 are schematics comparing prior art marks with marks formed in accordance with the present invention, and illustrate improved density of a dot matrix pattern;

5 FIGURES 8 and 9 are schematics comparing prior art marks with marks formed in accordance with the present invention, and illustrate improved density of a bar pattern;

10 FIGURES 10 and 11 are schematics illustrating, by way of example, a prior art laser mark formed on a specular surface, for instance bare silicon, and a corresponding surface profile showing exemplary defects associated with a deep (“hard”) mark – for instance slag and melted zones, debris, and microcracking;

FIGURES 12 and 13 are schematics illustrating, by way of example, a mark formed on the specular surface of Figure 10 using a system of the present invention and an exemplary profile for comparison with Figures 10 and 11;

15 FIGURES 14 and 15 are schematic block diagrams showing some elements of a semiconductor wafer processing system;

FIGURES 16 and 17 illustrate subsystems of a semiconductor wafer processing system corresponding to Figures 14 and 15 in further detail;

20 FIGURES 18 and 19 show some components of an exemplary laser beam positioning system which may be included in Figure 1 or Figure 2 for practicing various embodiments of the present invention;

FIGURE 20 is a schematic block diagram, similar to Figure 16, showing some elements of a semiconductor wafer processing system, specifically, elements related to secondary processing of Figure 2;

FIGURES 21 and 22 illustrate the structure of various laser marks produced with conventional and more recent laser marking systems for further comparison with a marks formed in accordance with the present invention;

5 FIGURE 23 illustrates removing material, for instance, erasing a mark using a secondary processing beam corresponding, for example, to Figure 2;

FIGURE 24 illustrates removing material, for instance, modifying a microtextured pattern, using a secondary processing beam corresponding, for example, to Figure 2; and

10 FIGURES 24-37d illustrate various examples and results wherein silicon wafers having ground, polished, smooth, or rough surfaces are marked in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

For the purpose of the following description of various embodiments of the invention, the following non-limiting guidelines are used:

15 “Ultrafast laser” or “ultrashort laser” generally refers to a pulsed laser providing one or more pulses, each pulse having a duration below 1 ns, for instance 100 ps or less, or typically less than 10 ps;

20 “Microtexture” generally refers to micron sized surface variations, but may also include surface variations of a finer scale, for instance .5 microns or .1 microns; and

“Nanotexture” generally refers to surface variations below one micron in size.

Overview

25 New laser marking technology has been developed to overcome limitations of present laser marking systems. Permanent and high contrast shallow

marks (less than 1 micron) on the backside of wafers are achieved with little or no material removed by using this new laser technology. Viewing of these marks is strongly independent of the viewing angle, a significant advancement. The so-called micro marking technology allows the mark font size to be much less than 0.3 mm.

5 As will become apparent in sections that follow, various embodiments may be also applied to mark erasing, microjoining, laser welding, and microactuation.

 At least one embodiment of the invention may be applied to micro machining of fine, laser-marked patterns.

10 One or more embodiments of the invention may be applicable to laser micro assembly techniques for silicon articles including laser welding and laser actuation of micro device members.

Laser Marking/Texturing Method

 One aspect of the invention features a method of marking a material
15 of a microelectronic device with a pulsed laser output to form high-density, discernible indicia on the material. The method includes: generating a pulsed laser output having at least one pulse with a pulse duration less than about 1 ns and having total fluence sufficient to initiate ablation of a portion of the material, the fluence being measurable over a spatial spot dimension of the output. The method
20 further includes directing the laser output in response to at least one control signal that defines a first location of at least a portion of indicia to be formed on the material, to impinge a localized region of the material at the first location, the localized region being within the spatial spot dimension. The laser output initiates ablation of at least a portion of the material and substantially increases surface
25 roughness within at least the portion of the region. The region and background material that proximately surrounds the region are both substantially slag-free.

A background surface may have a strong specular reflection component.

The diffuse reflectance of the indicia may be in a range of .5% to 5%.

5 The total fluence may exceed about .1 J/cm².

The laser output may have a wavelength less than an absorption edge of the material.

The laser wavelength may be ultraviolet.

The pulse duration may be in the range of about 15 fs to 500 ps.

10 The pulse duration may be in the range of about 100 fs to 50 ps.

The pulse duration may be in the range of about 300 fs to 15 ps.

The material may be silicon.

The material may be a metal or dielectric.

15 The material may be a portion of a dielectric passivation layer, and the dielectric may be inorganic, organic, or a Low-k dielectric.

The material may be part of a MEM device.

A portion of the indicia may have surface height variations in the range of about .25 microns to about 1 micron.

20 A feature dimension of the indicia may be in the range of several microns to tens of microns.

A feature dimension of the indicia may be a few optical wavelengths.

Laser Marking/Texturing System

Another aspect of the invention features a laser marking system. The marking system includes: means for generating a pulsed laser output having at least
5 one pulse with a pulse duration less than about 1 ns and having total fluence over a spatial region of the output sufficient to initiate ablation of a portion of a material to be marked; a controller that accepts data that define indicia to be formed on a material of a microelectronic article and produces at least one position control signal to direct a laser output to mark the material and thereby form the indicia; and means
10 for directing the laser output to a surface location of the material to be marked so as to form discernible, high contrast, high-density indicia on the material surface.

The means for directing may include an optical scanner.

The means for directing may include a positioning subsystem for positioning the material relative to the laser beam in three dimensions.

15 The positioning subsystem may have three or more degrees of freedom.

The optical scanner may be a two-dimensional, galvanometer-based scanner.

20 The means for directing may include an X-Y stage and a beam deflector coupled to the controller.

The position control signal may be produced during at least one step of manufacturing the article.

The means for generating may include a seed laser and a fiber optic amplifier.

The means for generating may include a frequency doubled, diode-pumped, solid-state laser.

The means for generating may include a mode-locked oscillator, a diode-pumped, solid-state laser amplifier, and a wavelength shifter.

- 5 The means for generating may include a frequency doubler, frequency tripler or frequency quadrupler.

The laser output may have a repetition rate greater than 10 KHz.

The average laser output power may be in the range of .01W – 2W.

- 10 The system may further include a viewing system for reading the indicia, including an illuminator and an electronic imaging system.

The illuminator may be bright-field.

The illuminator may be dark-field.

The illuminator may be a combination of bright and dark field.

Article of Manufacture

- 15 One aspect of the invention features an electronic article. The article includes at least one material having discernible indicia formed on the material during at least one step of manufacturing the article. The indicia are formed by a method of selectively irradiating at least one localized material region with a pulsed laser output. The indicia are at least semi-permanent and useable during a subsequent step of manufacturing the article. A marked region and background material that proximately surrounds the region are both substantially slag-free. The surface roughness is increased within at least a portion of the material region, and thereby reduces reflection of energy used for reading the indicia.
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Preferably, the method of selectively irradiating at least one localized material region with a pulsed laser output is the above section entitled "Laser Marking/Texturing Method."

5 High reflectance contrast may be obtained between the region and the background over a wide range of viewing angles.

A background surface may have a strong specular reflection component.

Reflectance contrast between the discernible indicia and the background may exceed 30:1 over an angular viewing range of at least 20 degrees.

10 The indicia may include an alphanumeric indicium having font dimension .3 mm or finer.

The indicia may include a two-dimensional matrix code.

The indicia may be useable for one or more manufacturing steps in addition to identification.

15 The indicia may be distinguished from the background with a roughness measurement obtained by at least one of SEM (scanning electron microscope) data, and AFM (atomic force microscope) data.

DIN 4768 roughness measurement standards may be utilized to compare the roughness of a portion of the indicia with the background.

20 The indicia may be distinguished from the background with a measurement of image contrast.

The indicia may be machine readable.

The indicia may appear as a sequence of non-overlapping dots that form a dot matrix code.

The indicia may be used in at least one of traceability, component identification, and sorting.

5 Laser Processing

Embodiments of the present invention may be used to form indicia on ground, polished, or smooth material surfaces, based on specific application requirements. A surface may be coated. By way of example, the surface may be either side of a semiconductor wafer, or another material used in a step of
10 fabricating a microelectronic device.

With reference to Figure 1, an ultrafast laser source 102 of a laser processing system, generally indicated at 100, generates a laser output 104 which includes one or more pulses. The laser output 104 propagates through delivery optics 106 that focus the output and deliver the beam into a process chamber 110,
15 the chamber 110 being used if the laser processing is to be carried out in a gaseous environment. The process chamber 110 may contain a gaseous processing environment at a pressure, partial vacuum, or temperature as is known in the field of laser material interaction to produce microtextured silicon. For processing in ambient, atmospheric conditions the chamber is not required. The focused beam
20 108 produces a working spot 112 that is incident on the target material, which may be a portion of a silicon semiconductor wafer 114, and produces marked material 116 (not to scale).

With reference to Figures 3 and 4, the wafer 114 may have a bare (unpatterned) backside 117, which may be coated, polished, or rough. Fiducials
25 118 are used for alignment. The topside shown in Figure 3 may have a large number of die 119 and corresponding dense circuit patterns.

An optional secondary laser processing system may be used for further processing. With reference to Figure 2, to erase, micromachine, weld, or actuate the region of the mark, a second laser source 120 generates a secondary beam 122. High absorption within the marked region can support such further processing. For example, the actuation may occur as a result of differential thermal expansion of the material and background subsequent to heating the material with the secondary processing beam. The beam 122 propagates through secondary delivery optics 124 that focus the beam. The secondary laser source 120 may be a pulsed, modulated, or CW source, depending on the application. The focused beam 126 produces a secondary working spot 130 that is incident on the wafer 114 and irradiates the marked material 116. The irradiation may be below the ablation threshold of the marked material to heat the region for actuation or above the threshold to effect material property changes.

In various embodiments, the two laser systems 100, 129 having beam paths 104, 122 may be included in separate systems, or the optical systems may be combined by various well-known methods into a single laser system. There may be two optical axes, one for each beam path, or the beam paths may be combined for a coaxial beam path. A single laser head may produce the beams of the laser sources 102 and 120, or there may be two laser sources. By way of example, it is preferred that the secondary laser 120 has a wavelength near or exceeding the absorption edge of silicon. The choice of integrating into a single system may be based on specific design considerations, for example, workpiece dimensions, laser wavelengths and power, optical design considerations, component costs, available factory floor space, X-Y positioning requirements, etc.

The delivery systems 106 and 124, corresponding to the texturing system 100 and the secondary processing system 129, respectively, will often include some elements operated under computer control, as indicated by lines 107 and 127, respectively. For example, focusing, spot size adjustment, polarization control, and energy control functions may be controlled. Suitable combinations of electro-optic devices, modulators, and opto-mechanical devices for positioning may

be utilized. For instance, either delivery system 106 or 124 may include a polarization controller to enhance or control a mark characteristic.

The ultrafast laser 102 may produce one or more femtosecond pulses. However, picosecond lasers may provide many of the benefits of femtosecond lasers but at reduced cost and complexity. Controlled laser-material interaction at the ultrafast scale can be used to control the contrast of the marks over a wide range to meet specific application requirements. Of further significance is the reduction or elimination of debris, slag, cracking, and other undesirable effects generally associated with traditional marking lasers.

Discrete areas of laser-patterned, microtextured material may be used to create high contrast marking on silicon, especially silicon wafers, and on other materials such as titanium or steel. By way of example, Figure 5 illustrates an exemplary “spiky” textured region 135 with the surface height 136 illustrated by a typical spike. Such nearly periodic and sharp variation in roughness may be produced with femtosecond laser pulses. The spikes may have a height ranging from a fraction of one micron to tens of microns. The surface profile may be strongly dependent on laser parameters including pulse duration (*i.e.*, width), peak energy, spot diameter, and spot irradiance profile. Researchers have postulated that such spike formation involves both laser ablation and laser-induced chemical etching.

Embodiments of the present invention can be used to create microtextured regions having lower amplitude (*e.g.*, sub-micron) surface height variations than exemplified in the above paragraph, but with sufficient variations to create high contrast, slag-free marks. Further, enhanced contrast and absence of debris provides for improved mark density when compared to traditional marking approaches. Figures 10 and 11 are schematics illustrating, by way of example, a prior art laser mark formed on a specular surface, for instance bare silicon, and a corresponding surface profile showing debris and cracking associated with a deep, “hard” mark. Figures 12 and 13 are schematics illustrating, by way of example, a mark formed on the specular surface of Figure 10 using a system of the present

invention. The pulsed laser may be a picosecond laser producing a pulsed output with total energy density (in one or more pulses) sufficient to initiate ablation within a portion of a spot area on the substrate surface. The surface height variations may be tens to hundreds of nanometers, the marked region generally showing significant roughness and eliminating at least strong reflection components.

Figures 6 and 7 are schematics comparing prior art marks with marks formed in accordance with the present invention, respectively, and illustrate improved density of a dot matrix pattern. Figures 8 and 9 are schematics comparing prior art marks with marks formed in accordance with the present invention, respectively, and illustrate improved density of a bar pattern.

Figures 21 and 22 illustrate the structure of various laser marks produced with traditional and more recent laser marking systems for further comparison with a marked substrate produced in accordance with the present invention. Figures 21 and 22, respectively, are side and top schematic views of a mark 250 formed by the assignee of the present invention using a NdYVO₄ laser with a pulse width of about 15 ns at 532 nm. The laser system produced shallow marks having a depth of about 1.5 – 4 microns without substrate cracking. Figure 22 is a top view of a mark 250 illustrating the presence of ejected material 252 adjacent to the mark 250. This recent example corresponds to results disclosed in published US Patent Application Number 2004/0060910 entitled “High Speed, Laser-based Marking Method and System for Producing Machine Readable Marks on Workpieces and Semiconductor Devices with Reduced Subsurface Damage Produced Thereby,” assigned to the assignee of the present invention, and published 1 April 2004. Figure 21 is a side schematic view of a relatively deep traditional “hard” mark 254, about 10 microns in depth, wherein cracking of silicon is observed with relatively deep, laser penetration 256.

In certain applications it may also be of interest to remove or erase a previously-formed, laser mark. The formation of highly-absorbing, microtextured regions provides for such capability because the region may be controllably modified using the secondary laser system configured with appropriate laser parameters.

With bright field visible at near infrared illumination, these textured (marked) areas formed in accordance with the present invention provide high contrast relative to the reflective wafer background surface 115. For instance, the wafer surface 115 may be smooth relative to a visible wavelength, thereby resulting in a strong specular reflection component with negligible diffuse reflection. A textured region may appear opaque, and will preferably have diffuse reflectance corresponding to the darkest shades of "grey scale charts" used for calibrating imaging systems.

By way of example, the diffuse reflectance may be in a range of about .5% to 5%, corresponding to about 6 shades of grey. The contrast provides detection for improved-detection, machine-readable marks such as alphanumeric strings, bar codes, matrix codes, etc. Such indicia may be viewed with a mark inspection system 201, which may be one component of a complete laser processing system as shown in Figure 14 which, by way of example, includes both the marking laser system 100, and the secondary laser processing system 129 of Figures 1 and 2, respectively. The system 129 may be used to erase a mark. Alternatively, a system may include only laser marking and an optional mark inspection system 201 without secondary processing. With an ultrafast (or ultra-violet) source, shallow marks with highly controllable depths are possible that would be advantageous for marking or coding very thin wafers, for instance, with mark dimensions substantially finer than present commercially available systems.

A following section entitled "Marking Examples" and referenced drawing figures show exemplary results using picosecond lasers to produce laser marks on silicon substrates having rough, ground, or smooth surfaces. The readability of the marks is improved over conventional laser marks. The marks appear substantially opaque and the contrast with the background remains high as a function of illumination and viewing angles, for instance, as the relative angle between an illumination source and receiver is varied over 30 degrees. This invariance increase the reliability of machine vision algorithms.

Laser Marking Systems

Various embodiments of the invention provide for high contrast marks on wafers and marks on other microelectronic articles or devices made from silicon. Further application is expected to MEMS and MOEMS devices and for
5 providing marks or other patterns on materials such as Ti and steel.

The marking may be used primarily for identification, or it may be used to change the material's optical properties at discrete sites for functional or subsequent process reasons.

In a complete marking system, wafers to be processed are removed
10 from a wafer carrier by a robotic wafer handling system 205, as illustrated schematically in Figures 14 and 15. Orientation of the wafer is determined by optical alignment, including operation of a pre-aligner 206 and any other required steps, for instance identifying the wafer type with a reader 207.

The laser 102 generates a processing beam. With reference to Figure
15 16, the beam positioning system 106 delivers and focuses the ultrafast processing beam onto a workpiece, which may be a silicon substrate. Interaction of the focused processing beam with the material of the workpiece in an atmosphere or ambient environment creates microtexture on the surface of the workpiece.

Laser pulses 104 (*i.e.*, Figure 1) generated by the ultra-short pulse
20 laser 102 propagate along the optical path 104, and are deflected or otherwise positioned with a beam positioner 220 (Figure 16). The beam positioning will typically be carried out using two galvanometer scan mirrors which generally provide for deflection over a wide angle with a scan lens used to focus the output onto the wafer 114 which is typically mounted on an X-Y stage 208. Each laser
25 pulse (or pulse sequence) forms a microtextured spot of material on the wafer 114. The positioning of the beam is determined by a controller so that a sequence of laser pulses forms characters or other indicia on the wafer 114. When the mark is complete, the wafer 114 is removed from the processing area and reloaded into its

wafer carrier. Alternatively, a secondary processing step may occur with the system 129 before the wafer 114 is transferred.

Relative controlled movement of the workpiece and the focused processing beam selectively creates microtexture that forms discernible patterns on
5 the workpiece.

Various spot-shaping and aligning methods such as shaping by dithering taught by Fillion in U.S. patents 6,341,029 and 6,496,292, and aspect and orientation modification taught by Ehrmann in U.S. patent 6,639,177 and others can be applied to laser microtexturing. For example, top-hat irradiance profile spots can
10 provide indicia with more uniform microtexturing and reduced melting at the ablation threshold transition zone. With a top hat profile, the area of the spot at or above the ablation threshold can be increased without an increase in the pulse energy, thereby efficient microtexturing is achieved. It may be desirable to use a spot with a depressed center and energy concentrated in the perimeter to further
15 limit melting and increase sharpness of the microtexture substrate transition at the kerf edge.

Round spots provide consistent exposure for line elements in any orientation. However, square and rectangular spots can further increase efficiency and uniformity by delivering a uniform dose across an aligned kerf width and to
20 larger areas requiring filling. Control of the aspect of a spot can be used to precisely control the irradiance and spot overlap. For example, maximum pulse energy may be selected and spot length along a trajectory may be expanded or contracted to modify the shape of the area exposed at or above the ablation threshold. The spot may be expanded to expose a larger area at or above the
25 ablation threshold without increasing the kerf width or can allow the kerf width to be reduced without increasing irradiance. The spot may be expanded to allow expose of at least a portion of the spot to an increased number of laser pulses. Conversely, compression of the spot along the kerf may be used to increase the exposure to or above the ablation threshold without decreasing the kerf width or can
30 allow the kerf width to be increased without decreasing irradiance. Compression

of the spot may also be used to allow exposure of at least a portion of the spot to a decreased number of pulses.

The laser may be an ultrafast laser. Generally, the laser parameters will depend of the linewidth to be marked, the material optical properties, and numerous system considerations and features (*e.g.*, overall optical efficiency of the laser processing system). The ultrafast laser may have a wavelength below the absorption edge of the substrate, for example 532 nm for silicon processing. The average power, which relates to the required threshold fluence and repetition rate may be in the approximate range of .01W – 2W for marking silicon wafers using various embodiments of the present invention. The pulse width (duration) may be less than 1 ns. Preferably, the laser pulse width will be in the range of about 100 fs to about 50 ps, and most preferably in the range of about 300 fs to 10 ps.

Certain embodiments may use a diode-pumped, solid-state UV laser with a pulse width less than about 20 ns, and preferably less than 1 ns. Formation of the desired microtexture may utilize gas-assist or a gaseous environment in the chamber 110, as shown in Figure 1, for best results with UV processing.

Figures 16-19 show additional details of an exemplary laser processing system which may be used for laser marking of substrates, for instance marking of silicon wafers (front and/or backside). A positioning subsystem may include one or more translation stages 208 for moving the workpiece relative to the processing beam 108 along at least two axes. Numerous combinations of relative substrate and beam positioning devices are known to those skilled in the art of laser material processing, for instance, semiconductor processing, stereolithography, semiconductor laser repair, laser drilling, or semiconductor wafer trimming.

The features of Figures 7 and 9 (dots and bars, respectively) are typically tens of microns in commercially available marking systems. A laser marking system of the present invention may be used to produce significantly smaller feature sizes, for instance 5-10 micron dots. The features in Figures 7 and 9 may be characterized by a minimum resolvable distance between features of the

pattern. The minimum resolvable distance may be on the order of a wavelength of the pulsed laser output, for instance .25 microns.

By way of example, it may be desirable to form indicia on a portion of a MEM, in a restricted area. By controlling the fraction of the energy above threshold in a merely diffraction-limited spot, sub-micron features may be formed, for instance .25 micron features, or .5-2 micron features if margin is to be provided. As such, the positioning system may include fine and coarse positioners to match or exceed the pattern resolution and provide for ultra-fine patterning. The fine stage may have a travel range on the order of millimeters positioning accuracy substantially finer than 1 micron, for instance .05 microns. The system may also include other auxiliary fine positioners, for instance precision, small-angle, beam deflectors (*e.g.*, an acousto-optic deflector), together with closed loop control. Such positioning systems may be used in embodiments of the present invention for laser marking, patterning, joining, or other applications.

With reference to Figure 17, embodiments of the invention for practicing laser marking and other applications with laser systems 100,129 may include irradiating first and second sides of the workpiece. By way of example, wafer chuck 249 may be mounted to an X-Y stage in a configuration suitable for laser systems 100,129 to irradiate opposite sides of the workpiece surface. The wafer chuck 249 may include a Z-axis translator and capability for tilting the workpiece (rotation about the x-y axes). Such precision translation and rotation stages have been applied in lithography, laser trimming, and similar applications.

With reference to Figures 16, 18, 19 and 20, either or both beam positioning systems 220, 220' may include a two-axis, galvanometer-based, beam scanner 240,242 to move the beam relative to the workpiece. Either beam positioning system 220, 220' may include a combination of two or more stages and scanners to move the processing beam relative to the workpiece in at least two axes. Further, components to position the beam waist relative to the workpiece through movement 246 of one or more optical elements within the secondary laser system may be included. Similarly, components may be included to move the beam waist

relative to the workpiece in at least 3 axes using various combinations of movement
246 of optical system components with z-axis translation 246' using, for example,
a motorized wafer chuck assembly.

Precision galvanometric scanning heads 240,242 are available from
5 GSI Lumonics Corporation (assignee of the present invention), Cambridge
Technologies and Scan Labs LTD. Exemplary options for an associated optical
system are illustrated in Figures 18 and 19 include: (1) a telecentric lens or f-theta
corrected lens 221 with programmable spot size adjustment 222; and (2) a widefield
post-objective system 223 and motorized dynamic focus adjustment 224 (not shown
10 in Figure 16).

The focusing subsystem 106 in the ultrafast system is illustrated as
a refractive optical system. In embodiments where a femtosecond laser system
produces a laser output, an all reflective system may provide for improved
performance as a result of dispersion compensation. For example, an ultrashort
15 pulse may have a wavelength spread of about 8 nm or more about the central
wavelength. Femtooptics, Inc. is a supplier of femtosecond optical components.

Extremely high absorption microtextures may be produced in a non-
ambient atmosphere, with processing carried out in a processing chamber. The
processing atmosphere may containing gases or may be a vacuum to assist the
20 formation of microstructures. However, it is preferred that microstructures are
formed in a open atmosphere of gases, and it is most preferred that the workpiece
is placed in ambient air.

The microtexture created reduces reflected energy off the surface of
the workpiece. Generally, the microtexture created is spike or cone-like structures,
25 on the order of or smaller than the wavelength of light, the surface profiles of which
are illustrated in Figure 5 as an exemplary regular arrangement and Figures 12 and
13 as a microtextured region with reduced height variation (peak amplitude) and
regularity. Very highly absorbing structures have been made in process chambers.
However, moderately absorbing structures (*e.g.*, Figures 12 and 13) are considered

for various embodiments of the present invention, thereby reducing the system requirements needed to create the microtextured regions.

In application to marking, the patterns formed may be alpha-numeric characters. The patterns formed may be logotypes. The patterns formed may be machine-readable. The patterns may be also be human-readable. A font size of
5 finer than .3 mm is achievable using one or more embodiments of the present invention.

The system may include an integral mark inspection system 201 (*i.e.*, Figure 14) to identify the patterns, or the inspection may be included in a separate
10 system or station of a manufacturing process. Commercially available machine vision technology, for instance pattern recognition systems supplied by Cognex, Inc. may be used for mark identification. When compared with conventional wafer marking technologies, laser-based microtexturing has produced high contrast marks, relatively insensitive to illumination conditions, including camera angle and
15 lighting angle over a wide range. Similarly, for certain applications, if the marks result in imagery that is at least weakly dependent upon illumination or viewing angles, the inspection vision system 201 may be implemented (or replaced) with an optional "through the lens" vision system configuration integrated within a galvanometer system, for instance designs corresponding to Figures 18 and 19.

20 The substrate material may be a metal, a silicon wafer (bare or with various coatings). Other exemplary materials include inorganic or organic dielectrics (including low-k materials, metallization, refractory metals, and plastics).

The material to be marked may be part of a multimaterial device, which may include a layer of silicon dioxide on silicon, for instance. The material
25 may be an inorganic or organic dielectric, for instance a passivation layer. The marked areas may be permanent, semi-permanent, or erasable so as to be utilized in the process of making the multimaterial device, for instance, to control or select various fabrication steps. Exemplary devices include a multimaterial semiconductor

memory, damascene structure, processors, peripheral chips, etc., RFID tags, MCMs, and the like.

In one arrangement, allowing for efficient integration into existing systems supplied to the semiconductor industry, an ultra-short pulse laser source is to be included within a commercially soft-mark type of wafer marking system such as the GSI Lumonics WaferMark SigmaClean. Details regarding various laser system alternatives are included in a later section. The soft marks normally created in the wafer marking system are replaced with shallow, low-reflectance, angle-insensitive marks. Integration of the ultra-short pulse laser source requires mechanical and optical changes to couple the laser energy into an optical path of the machine, propagate the beam along the optical path and focus the beam onto the substrate. The integration may be carried out by design practices well-known to those skilled in the art of designing laser beam processing systems.

Material Removal/Erasing a Mark

A highly absorbing marked area may be irradiated for subsequent processing according to various methods of this invention. The secondary irradiation may use lasers that are more weakly absorbed in the substrate, for instance lasers that operate near or beyond the absorption edge of silicon. Various studies have shown increased absorptance within the microtextured regions both in the visible and the NIR. Near and beyond the absorption edge of silicon, high power processing lasers can be used with minimal damage to the normally transmitting substrate. The first ultrafast step may produce fine patterning that is processed with a coarse secondary beam, and conversely, the first step may produce a coarse mark that is finely patterned with the secondary step. The absorbing material may be ablated in a micromachining step with controlled depth.

With reference to Figure 23, this ablation may be for the purpose of removing or erasing the mark, creating a negative "window" mark on an absorbing field, or it may be to micromachine a fine pattern, or trim an electrical or mechanical parameter.

Figure 24 shows a microtextured area that is modified at 420 with secondary irradiation 126. The operations to produce the microtextured region may be carried out within a system as illustrated in Figure 14, or at a different location in the manufacturing process.

5 Figures 2 and 20 illustrate several components which may be used in a secondary processing system and these system components may be similar or identical to those used in the ultrafast system. The laser 120 generates the secondary processing beam. A beam positioning system, which may correspond to any suitable arrangement of optical or mechanical beam positioners, delivers and
10 focuses the secondary processing beam 126 onto a microtextured area of a workpiece. The secondary laser energy is absorbed by the microtexture. The microtexture is heated and the increased temperature is sufficient to cause a phase change in the material.

 The secondary processing laser 120 may be a YAG or CO2 laser.
15 Preferably, the laser 120 is selected to minimize damage to non-microtextured areas. Most preferably, the laser beam 126 is transmitted through the non-microtextured material. For example, if the material is silicon the preferred wavelength may be about 1.2 microns (*e.g.*, using a Raman laser) where the silicon transmission is generally maximized. Alternatively, a commercially available 1.32 micron laser
20 may also be nearly optimum, and such lasers are widely available.

 The beam positioning system may include one or more stages 208 for moving the workpiece relative to the processing beam, in an arrangement similar or identical to Figure 20. The beam positioning system may include a beam scanner 240,242 to move the beam relative to the workpiece and a focusing lens. The
25 specific choice of components and other features (*e.g.*, lens coating) will generally depend on the laser wavelength, spot size requirements, damage threshold considerations, etc.

 The beam positioning system may include a combination of two or more stages and scanners to move the processing beam relative to the workpiece in

at least two axes. The beam positioner may position the beam waist relative to the workpiece through movement 246 of one or more optical elements within the secondary laser system. The beam positioning system may move the beam waist relative to the workpiece in at least three axes. The beam positioning system may
5 move the beam waist relative to the workpiece in at least three axes using various combinations of movement of optical system components with z-axis translation 246' using, for example, a motorized wafer chuck assembly.

The microtextured area may be formed according to an embodiment of the current invention, but is not restricted to ultrashort laser processing.
10 Generally, the microtextured area is to decrease the reflection coefficient of the workpiece material.

The irradiated material may be ablated from the surface to remove the absorbing structure. The irradiated material may be melted and recast to form an area with modified properties.

15 For microtexture formed on materials with a transmission band, it is preferred to select a laser wavelength in the transmission band which is absorbed into the microtexture. In this way, the properties of the microtextured material can be modified and the properties of adjacent material can be left unchanged. The secondary beam may have a wavelength which corresponds to maximum
20 transmission through the non-textured material. For example, if the non-textured region is also silicon, the secondary beam may have a wavelength beyond the absorption edge of silicon, for instance greater than 1.2 microns. If the non-textured material is glass, the wavelength may be in the visible or near IR region. In some applications it may be desirable to use a laser that is absorbed in the microtexture
25 and the adjacent material

Marking Examples

Each of Figures 25 to 36 relates to actual results obtained using a commercially available picosecond laser to form marks on silicon substrates having

ground, polished, or smooth surfaces. Laser and system parameters for some marked regions are as follows:

Figure 25

- ▶ Grinded silicon wafer (with good mark);
- 5 ▶ Marking condition:
 - ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
 - ▶ Average power 460 mw;
 - ▶ 15 μ j pulse energy;
 - 10 ▶ Linear mark speed 100 mm/sec;
 - ▶ Line width 115 μ m;
 - ▶ Energy density 0.15 J/cm²;
 - ▶ Peak power density 10¹⁰ W/cm²;
 - ▶ Overlap: 34.

Figure 26

- ▶ Grinded silicon wafer;
- ▶ Marking condition:
 - ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
 - 20 ▶ Average power 500 mw;
 - ▶ 16.3 μ j pulse energy;
 - ▶ Linear mark speed 100 mm/sec;
 - ▶ Line width 140 μ m;
 - ▶ Energy density 0.16 J/cm².

Figure 27

- ▶ Grinded silicon wafer;
- ▶ Marking condition:
 - ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
 - 30 ▶ Average power 300 mw;

- ▶ 9.8 μj pulse energy;
- ▶ Linear mark speed 16.6 mm/sec;
- ▶ Energy density 0.1 J/cm².

Figure 28

- 5 ▶ Grinded silicon wafer (with good mark);
- ▶ Marking condition:
 - ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
 - ▶ Average power 100 mw;
- 10 ▶ 3.3 μj pulse energy;
- ▶ Linear mark speed 100 mm/sec;
- ▶ Line width 40 μm ;
- ▶ Energy density 0.26 J/cm²;
- ▶ Peak power density 1.7×10^{10} W/cm².

15 Figure 29

- ▶ Polished silicon wafer (with good mark);
- ▶ Marking condition:
 - ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
- 20 ▶ Average power 100 mw;
- ▶ 3.3 μj pulse energy;
- ▶ Linear mark speed 100 mm/sec;
- ▶ Line width 40 μm ;
- ▶ Energy density 0.26 J/cm²;
- 25 ▶ Peak power density 1.7×10^{10} W/cm².

Figures 30a and 30b

- ▶ Silicon wafer (with mark on specular surface);
- ▶ Marking condition:
 - ▶ Wavelength 532 nm;
- 30 ▶ Repetition rate 30 KHz;

- ▶ Average power 7.2 mw;
- ▶ 0.24 μ j pulse energy;
- ▶ Linear mark speed 100 mm/sec;
- ▶ Line width 8 μ m;
- 5 ▶ Energy density 0.12 J/cm²;
- ▶ Peak power density 0.8 x 10¹⁰ W/cm².

Figures 31a and 31b

- ▶ Silicon wafer (with mark on rough surface);
- ▶ Marking condition:
 - 10 ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
 - ▶ Average power 7.2 mw;
 - ▶ 0.24 μ j pulse energy;
 - ▶ Linear mark speed 100 mm/sec;
 - 15 ▶ Line width 8 μ m;
 - ▶ Energy density 0.12 J/cm²;
 - ▶ Peak power density 0.8 x 10¹⁰ W/cm².

Figures 32a, 32b and 32c

- ▶ Silicon wafer (with 15 line mark within .28 mm);
- 20 ▶ Marking condition:
 - ▶ Wavelength 532 nm;
 - ▶ Repetition rate 30 KHz;
 - ▶ Average power 7.2 mw;
 - ▶ 0.24 μ j pulse energy;
 - 25 ▶ Linear mark speed 100 mm/sec;
 - ▶ Line width 8 μ m;
 - ▶ Energy density 0.12 J/cm²;
 - ▶ Peak power density 0.8 x 10¹⁰ W/cm².

The samples were mounted on X-Y stage, and the mark linewidth was varied by adjustment of a combination of the optical system and incident laser energy, the adjustments controlling the energy density incident on the material.

5 The images of the marked material samples were taken using a
“through the lens” (brightfield) microscope system and CCD camera. Various regions were profiled using either a SEM (scanning electron microscope) or AFM (atomic force microscope). Certain marks were also compared with marks formed using a nanosecond laser system. The number of pulses corresponding to a particular linewidth can be computed from the pulse repetition rate, linewidth, and
10 table speed. For instance, Figure 25 corresponds to 34 applied pulses during stage travel corresponding to the linewidth of 115 μm .

The listed laser parameters and results are to be regarded as exemplary rather than limiting. The laser parameters may be optimized or adjusted based on various process conditions, surface roughness figures, presence/absence
15 of coatings, etc. Various refinements and adjustments may provide for further improvements in contrast and density.

Generally, the linewidth corresponds to an effective spot size on the surface wherein the fluence is at or above an approximate ablation threshold of silicon. Hence, if a greater fraction of the spot is above the ablation threshold the
20 linewidth increases. For example, if the spot profile is diffraction limited and Gaussian and the region above threshold corresponds to the FWHM, then the nominal kerf width will be approximately the FWHM.

Also, as a result of a nearly constant fluence threshold for a specific material, larger linewidths, larger spots, generally require more laser energy than
25 small linewidths.

The laser used in the experiments and general laser system specifications are as follows:

- ▶ Commercial pico-second laser from Lumera Laser, Model Staccato;
- ▶ Primary specifications:
 - ▶ Pulse width 15 ps;
 - ▶ Wavelength 532 nm;
 - 5 ▶ Repetition rate 30 KHz;
 - ▶ Average power (see attached results);
 - ▶ Linear polarization;
 - ▶ M-squared less than 1.2.

10 It is noted that whenever linear polarization is used the direction of stage travel was aligned perpendicular to the polarization direction.

Figures 25, 26 and 27 show marks formed on a ground silicon substrate, exemplified by the grind direction (as opposed to uniform, specular background). Figures 26 and 27 provide a rough test of the “process energy window” which represent the energy range over which acceptable processing is achieved. The larger linewidth (140 microns) in Figure 26 corresponds to a larger fraction of the focused spot diameter above the ablation threshold. A slight heat-affected zone (HAZ) is shown in the regions where melting occurs, though insignificant. Undesirable slag, debris, or severely melted zones are absent.

20 Figures 28 and 29 show parameters and results where a 40 micron linewidth was produced in the X and Y directions, respectively. The polarization was perpendicular to the direction of travel.

Figures 30a, 30b, 31a, 31b, 32a, 32b and 32c illustrate improved mark density and a clearly resolved pattern within a .3 mm (.28 mm) region, a result which demonstrates capability to form finer indicia than available in current, commercially-available, laser marking systems. Figure 30a and 30b correspond to a specular wafer background (smooth finish), Figures 31a and 31b correspond to a rough back-side wafer surface, and Figures 32a, 32b and 32c correspond to a polished wafer. The enlarged photos provide some local additional detail, the definition and sharpness reduction believed to be caused by various limitations in the

setup, for instance the camera dynamic range, the high N.A. of the microscope collecting additional scattered light, and other factors. The high contrast images correspond to the approximate magnification to be used by a typical mark reader/inspection system.

5 Figures 33a and 33b compare a high contrast mark obtained with the picosecond system (*i.e.*, Figure 33a) with a mark formed with a typical nanosecond laser-based marking system (*i.e.*, Figure 33b). The nanosecond “dark” mark surface roughness is not significantly altered, whereas the microtexture is formed only within the picosecond mark.

10 Figures 34a, 34b and 34c show SEM images of the marked regions further demonstrating the presence of the microtexture produced with the picosecond system as follows:

Figure 34a

SEM of mark by ps laser;
15 Submicron structures seen.

Figure 34b

SEM of dark mark by ns laser;
No structure seen.

Figure 34c

20 SEM of white mark by ns laser;
Larger ridge structure seen.

25 The nanosecond results show only insignificant roughness (“dark mark” case), the surface roughness variations evident with the picosecond results were not detected in the nanosecond data – neither the “dark” or “hard” marks show the microtexture. The deep marks (traditional “hard marks”) also show highly undesirable ridge formations. Of significance is an observation that even for “dark”

nanosecond marks (which are relatively shallow compared to “hard marks”), the microtexture is not detected in the images corresponding to the nanosecond marking.

Figure 35 shows SEM images obtained from a marked region of a polished wafer. A surface region is shown at three SEM magnifications: 15,000X,
5 6,000X, and 25,000X. The texture boundary between the marked and unmarked region is evident, even with the polished background variations. Further, the marked region, its periphery, and the polished background are all slag-free – ridges and kerf height negligible.

Figures 36, 37a, 37b, 37c and 37d show measurement of a marked
10 region of a polished wafer using an AFM to measure surface heights. Sub-micron structures are evident, with peak heights in the range of tens to hundreds of nanometers. The polished background regions correspond to the semi-specular, strong directional reflectance results shown in earlier figures. A very high contrast is achievable for specular wafer backgrounds providing for clear recognition of
15 textured and non-marked specular wafer regions. In such a case, the indicia may also be clearly distinguished from the background using AFM or SEM measurements which will exemplify the difference in texture.

The examples generally show marked regions which have roughness greater than a reflective background. By way of example, it is also possible to form
20 positive contrast indicia by forming a background which is microtextured, wherein the indicia are highly reflective, and configuring the lighting so that the indicia have positive contrast relative to a dark background. This example may be of interest if, for example, the system throughput is not degraded (or is improved) using the technique (*e.g.*, wherein the total area of the indicia is to be greater than the
25 background area). Further, certain applications may require such “reverse contrast” as part of customer specifications. Other similar variations and alternatives can be carried out without departing from the scope and spirit of the present invention.

Laser Embodiments

The commercially available laser used to produce the high contrast results of the above working example includes a mode locked oscillator and a diode pumped solid-state laser amplifier. Picosecond outputs are available with pulse parameters within a desired range. The choice of a laser system is generally based upon the requirements for pulse energy, repetition rate, average power, pulse width required to irradiate the material to be marked with total energy density sufficient to initiate ablation within the spatial spot size on the material surface. Useful laser wavelengths include near IR, visible (*e.g.*, 532 nm), and ultraviolet. Other factors include size, cost, reliability, and various practical considerations for use in semiconductor production environment, for example. An "off-the-shelf" solution is desirable when available. Preferably, the laser system is compatible with available marking equipment, for instance the commercially soft-mark type of wafer marking system such as the GSI Lumonics WaferMark SigmaClean.

Published U.S. patent application No. 2004/0134894 entitled "Laser-based System for Memory Link Processing with Picosecond Lasers," is assigned to the assignee of the present invention and is hereby incorporated in its entirety herein. Included therein are various exemplary picosecond laser systems which may be used or modified for use in one or more embodiments of the present invention. Of particular interest are: the section entitled "Picosecond Laser Embodiments", Figures 6a-8e, and the corresponding portions of the published application.

Published U.S. patent application No. 2004/0226925 entitled "Laser System and Method for Material Processing with Ultra Fast Lasers," is assigned to the assignee of the present invention and is hereby incorporated in its entirety herein. Included therein are various exemplary femtosecond laser systems which may be used or modified for use in one or more embodiments of the present invention. Of particular interest are: the section entitled "Ultrashort Laser Embodiments," Figures 1-8, and the corresponding portions of the published application.

By way of example, the laser systems of the above-noted incorporated patent applications may be modified for use at shifted wavelengths (*e.g.*, green and UV). The system output, for instance average power and peak energy, may be adjusted to meet the energy density requirements with reduction or increase or
5 amplifier gain as needed to process at a required energy density.

Ongoing developments are expected to lead to increased commercial availability. For example, FCPA system (Fiber based Chirped Pulse Amplification) reported by IMRA America includes 2 microjoules of pulse energy at a repetition rate of 500 KHz, corresponding to 1W average power operation at femtosecond
10 pulse widths.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes
15 may be made without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A method for processing targeted surface material within a region of a workpiece while avoiding undesirable changes to adjacent non-targeted material, the method comprising:
 - 5 generating a pulsed laser output including at least one pulse having a wavelength and a pulse width;
 - irradiating the targeted surface material of the workpiece with the pulsed laser output including the at least one pulse to texture the targeted surface material, the pulsed laser output having sufficient total fluence to initiate ablation
 - 10 within at least a portion of the targeted surface material and the pulse width being short enough such that the region and non-targeted material surrounding the region are substantially free of slag.
2. The method as claimed in claim 1, wherein the textured surface material comprises indicia and wherein the indicia is at least semi-permanent
- 15 or erasable.
3. The method as claimed in claim 1, wherein the targeted surface material is at least one of a semiconductor substrate, a thin film, a metal layer and a dielectric layer.
4. The method as claimed in claim 1, wherein the workpiece is
- 20 one of a MEMs device, an optoelectronic device and a biomedical chip.
5. The method as claimed in claim 2, wherein the indicia are machine-readable and wherein the indicia have a font size less than .3 mm.
6. The method as claimed in claim 1, further comprising generating a secondary laser output and irradiating the textured surface material with
- 25 the secondary laser output to process the textured surface material.

7. The method as claimed in claim 6, wherein the textured surface material comprises indicia and wherein the indicia are erased during the step of irradiating with the secondary laser output.

8. The method as claimed in claim 1, wherein the textured
5 surface material comprises a microtextured pattern and wherein the pattern is one of a bar pattern, a matrix pattern, an alphanumeric character string, and a logotype.

9. The method as claimed in claim 1, wherein the pulse width of the at least one pulse is below about 1 ns.

10. The method as claimed in claim 9, wherein the pulse width
10 is about 100 ps or less.

11. The method as claimed in claim 1, wherein the total fluence is measurable over a spatial dimension of a spot of the output.

12. The method as claimed in claim 11, wherein the textured
15 surface material comprises indicia and where the step of irradiating includes the step of directing the laser output in response to at least one control signal that represents a first location of at least a part of the indicia to impinge the region at the first location.

13. The method as claimed in claim 1, wherein the step of
20 irradiating substantially increases surface roughness of the targeted surface material within at least a portion of the region.

14. The method as claimed in claim 1, wherein the non-targeted surface material surrounding the region has a surface with a strong specular reflection component.

15. The method as claimed in claim 2, wherein diffuse reflectance
25 of the indicia is in a range of .5% to 5%.

16. The method as claimed in claim 1, wherein the total fluence exceeds about .1 J/cm².

17. The method as claimed in claim 1, wherein the wavelength is less than an absorption edge of the targeted surface material.

5 18. The method as claimed in claim 1, wherein the wavelength is ultraviolet.

19. The method as claimed in claim 1, wherein the targeted surface material is silicon.

10 20. The method as claimed in claim 1, wherein the targeted surface material is a metal or a dielectric.

21. The method as claimed in claim 1, wherein the targeted surface material is a portion of a dielectric passivation layer and wherein the dielectric of the layer is an inorganic, organic, or a low-k dielectric.

15 22. The method as claimed in claim 1, wherein the targeted surface material is part of a MEM device.

23. The method as claimed in claim 2, wherein a portion of the indicia has surface variations in a range of about .25 microns to about 1 micron.

24. The method as claimed in claim 2, wherein a feature dimension of the indicia is in a range of several microns to tens of microns.

20 25. The method as claimed in claim 2, wherein a feature dimension of the indicia is a few wavelengths of the at least one pulse.

26. The method as claimed in claim 1, wherein the step of irradiating includes the step of controlling polarization of the pulsed laser output to enhance or control a characterization of the textured surface material.

27. The method as claimed in claim 11, wherein the step of
5 irradiating includes the step of shaping the spot to obtain a shaped spot.

28. The method as claimed in claim 27, wherein the shaped spot has a top-hat irradiance profile.

29. The method as claimed in claim 27, wherein the shaped spot has a depressed center with energy concentrated in a perimeter of the shaped spot.

10 30. The method as claimed in claim 6, wherein the pulsed laser output finely textures the targeted surface material and the secondary laser output coarsely processes the textured surface material.

31. The method as claimed in claim 6, wherein the pulsed laser output coarsely textures the targeted surface material and the secondary laser output
15 finely processes the textured surface material.

32. The method as claimed in claim 6, wherein the textured surface material comprises indicia and wherein a negative window mark is created during the step of irradiating with the secondary laser output.

33. The method as claimed in claim 6, wherein the textured
20 surface material comprises a pattern and wherein the step of irradiating with the secondary laser output micromachines the pattern.

34. The method as claimed in claim 6, wherein the step of irradiating with the secondary laser output trims an electrical or mechanical parameter of the textured surface material.

35. The method as claimed in claim 6, wherein the secondary laser output includes at least one pulse having a wavelength which is absorbed into the textured surface material.

5 36. The method as claimed in claim 35, wherein the wavelength of the at least one pulse of the secondary beam is also absorbed into the non-targeted material surrounding the region.

37. The method as claimed in claim 35, wherein the wavelength of the at least one pulse of the secondary beam is not absorbed into the non-targeted material surrounding the region.

10 38. A system for processing targeted surface material within a region of a workpiece while avoiding undesirable changes to adjacent non-targeted material, the system comprising:

15 a primary laser subsystem include a primary laser source for generating a pulsed laser output including at least one pulse having a wavelength and a pulse width;

a delivery subsystem for irradiating the targeted surface material of the workpiece with the pulsed laser output including the at least one pulse to texture the targeted surface material, the pulsed laser output having sufficient total fluence to initiate ablation within at least a portion of the targeted surface material and the pulse width being short enough such that the region and the non-targeted material surrounding the material are substantially free of slag.

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39. The system as claimed in claim 38, wherein the primary laser source includes an ultrafast laser.

25 40. The system as claimed in claim 38, wherein the delivery subsystem includes a controller that accepts data that represents a location of the targeted surface material to be textured and produces at least one position control signal.

41. The system as claimed in claim 40, wherein the delivery subsystem includes a positioning subsystem for directing the laser output to the location of the targeted surface material so as to texture the targeted surface material in response to the at least one position control signal.

5 42. The system as claimed in claim 38, further comprising a secondary laser subsystem including a secondary laser source for generating a secondary laser output which irradiates the textured surface material.

43. The system as claimed in claim 42, wherein the secondary laser output at least erases, micromachines, welds or actuates the region of the textured surface material.

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44. The system as claimed in claim 42, wherein the secondary laser source includes one of a pulsed, modulated or CW source.

45. The system as claimed in claim 42, wherein irradiation with the secondary laser output is below the fluence breakdown threshold of the targeted surface material to heat the region.

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46. The system as claimed in claim 42, wherein irradiation with the secondary laser output is above the fluence breakdown threshold of the targeted surface material to effect at least one property change of the targeted surface material.

20 47. The system as claimed in claim 42, wherein the secondary laser output includes at least one pulse having a wavelength near or exceeding the absorption edge of the material of the workpiece.

48. The system as claimed in claim 42, wherein the primary laser source comprises the secondary laser source.

49. The system as claimed in claim 42 wherein the primary laser source is separate from the secondary laser source.

50. The system as claimed in claim 38, wherein the delivery subsystem includes a polarization controller for controlling polarization of the laser output.

51. The system as claimed in claim 38, wherein the primary laser source includes a diode-pumped, solid-state UV laser and wherein the pulse width is less than about 20 ns.

52. The system as claimed in claim 51, wherein the pulse width is less than about 1 ns.

53. The system as claimed in claim 41, wherein the positioning subsystem includes at least one translation stage to move the workpiece relative to the laser output.

54. The system as claimed in claim 38, wherein the primary laser source includes a mode-locked oscillator and a diode-pumped, solid-state laser amplifier.

55. The system as claimed in claim 38, wherein the laser output has an average laser output power in the range of .01W - 2W.

56. The system as claimed in claim 38, wherein the textured surface material comprises indicia and wherein the system further comprises a viewing subsystem for reading the indicia, the viewing subsystem including an illuminator and an electronic imaging subsystem.

57. The system as claimed in claim 56, wherein the illuminator is one of a bright-field, a dark-field, and a combination of both bright- and dark-field.

58. An article of manufacture comprising:
at least one surface material having discernible indicia formed thereon
during at least one step of manufacturing the article, the indicia being formed by a
method of selectively irradiating targeted surface material within a region of a
workpiece with a pulsed laser output, the indicia being at least semi-permanent and
useable during a subsequent step of manufacturing the article;
the region and non-targeted material surrounding the region are
substantially slag-free; and
surface roughness is increased within at least a portion of the region
during the at least one step of manufacturing, thereby reducing reflection of energy
used for reading the indicia.

59. The article as claimed in claim 58, wherein high reflectance
contrast is obtained between the region and a background of the region over a wide
range of viewing angles.

60. The article as claimed in claim 58, wherein a surface of the
background of the region has a strong specular reflection component.

61. The article as claimed in claim 58, wherein reflectance
contrast between the discernible indicia and a background of the region exceeds 30:1
over an angular viewing range of at least 20 degrees.

62. The article as claimed in claim 58, wherein the indicia include
an alphanumeric indicium having a font dimension .3 mm or finer.

63. The article as claimed in claim 58, wherein the indicia include
a two-dimensional matrix code.

64. The article as claimed in claim 58, wherein the indicia are
useable for one or more steps of manufacturing the article in addition to
identification.

65. The article as claimed in claim 58, wherein the indicia are distinguishable from a background of the region with a roughness measurement obtained by at least one of SEM (scanning electron microscope) data, and AFM (atomic force microscope) data.

5 66. The article as claimed in claim 58, wherein DIN 4768 roughness measurement standards may be utilized to compare roughness of a portion of the indicia with a background of the region.

10 67. The article as claimed in claim 58, wherein the indicia are distinguishable from a background of the region with a measurement of image contrast.

68. The article as claimed in claim 58, wherein the indicia are machine readable.

69. The article as claimed in claim 58, wherein the indicia appear as a sequence of non-overlapping dots that form a dot matrix code.

15 70. The article as claimed in claim 58, wherein the indicia are usable in at least one of traceability, component identification, and sorting.