

PROCESSING A MEMORY LINK WITH A SET OF AT LEAST TWO LASER PULSES

Technical Field

[0001] The present invention relates to laser processing of memory or other IC links and, in particular, to a laser system and method employing a set of at least two laser pulses to sever an IC link on-the-fly.

Background of the Invention

[0002] Yields in IC device fabrication processes often incur defects resulting from alignment variations of subsurface layers or patterns or particulate contaminants. FIGS. 1, 2A, and 2B show repetitive electronic circuits 10 of an IC device or work piece 12 that are commonly fabricated in rows or columns to include multiple iterations of redundant circuit elements 14, such as spare rows 16 and columns 18 of memory cells 20. With reference to FIGS. 1, 2A, and 2B, circuits 10 are also designed to include particular laser severable conductive links 22 between electrical contacts 24 that can be removed to disconnect a defective memory cell 20, for example, and substitute a replacement redundant cell 26 in a memory device such as a DRAM, an SRAM, or an embedded memory. Similar techniques are also used to sever links to program a logic product, gate arrays, or ASICs.

[0003] Links 22 are about 0.3-2 microns (μm) thick and are designed with conventional link widths 28 of about 0.4-2.5 μm , link lengths 30, and element-to-element pitches (center-to-center spacings) 32 of about 2-8 μm from adjacent circuit structures or elements 34, such as link structures 36. Although the most prevalent link materials have been polysilicon, polycide, disilicide, and like compositions, memory manufacturers have more recently adopted a variety of more conductive metallic link materials that may include, but are not limited to, aluminum, copper, chromide, gold, nickel, nickel chromide, titanium, tungsten, platinum, as well as other metals, metal alloys, metal nitrides such as titanium or tantalum nitride, metal silicides such as tungsten silicide, or other metal-like materials.

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[0004] Circuits 10, circuit elements 14, or cells 20 are tested for defects, the locations of which may be mapped into a database or program. Traditional $1.047\ \mu\text{m}$ or $1.064\ \mu\text{m}$ infrared (IR) laser wavelengths have been employed for more than 20 years to explosively remove conductive links 22. Conventional memory link processing systems focus a single pulse of laser output having a pulse width of about 4 to 30 nanoseconds (ns) at each link 22. FIGS. 2A and 2B show a laser spot 38 of spot size (area or diameter) 40 impinging a link structure 36 composed of a polysilicon or metal link 22 positioned above a silicon substrate 42 and between component layers of a passivation layer stack including an overlying passivation layer 44 (shown in FIG. 2A but not in FIG. 2B), which is typically 500-10,000 angstrom ($\text{\AA}$) thick, and an underlying passivation layer 46. Silicon substrate 42 absorbs a relatively small proportional quantity of IR radiation, and conventional passivation layers 44 and 46 such as silicon dioxide or silicon nitride are relatively transparent to IR radiation. The links 22 are typically processed "on-the-fly" such that the beam positioning system does not have to stop moving when a laser pulse is fired at a link 22, with each link 22 being processed by a single laser pulse. The on-the-fly process facilitates a very high link-processing throughput, such as processing several tens of thousands of links 22 per second.

[0005] FIG. 2C is a fragmentary cross-sectional side view of the link structure of FIG. 2B after the link 22 is removed by the prior art laser pulse. To avoid damage to the substrate 42 while maintaining sufficient energy to process a metal or nonmetal link 22, Sun et al. in U.S. Patent No. 5,265,114 and U.S. Pat. No. 5,473,624 proposed using a single 9 to 25 ns pulse at a longer laser wavelength, such as $1.3\ \mu\text{m}$, to process memory links 22 on silicon wafers. At the $1.3\ \mu\text{m}$ laser wavelength, the absorption contrast between the link material and silicon substrate 42 is much larger than that at the traditional $1\ \mu\text{m}$ laser wavelengths. The much wider laser processing window and better processing quality afforded by this technique has been used in the industry for about five years with great success.

[0006] The $1.0\ \mu\text{m}$ and $1.3\ \mu\text{m}$ laser wavelengths have disadvantages however. The coupling efficiency of such IR laser beams 12 into a highly electrically conductive metallic link 22 is relatively poor; and the practical achievable spot size 40 of an IR laser beam for link severing is relatively large and limits the critical dimensions of link width 28, link length 30 between contacts 24, and link pitch 32. This conventional laser link processing relies on heating, melting, and evaporating link 22, and creating a mechanical stress

build-up to explosively open overlying passivation layer 44 with a single laser pulse. Such a conventional link processing laser pulse creates a large heat affected zone (HAZ) that could deteriorate the quality of the device that includes the severed link. For example, when the link is relatively thick or the link material is too reflective to absorb an adequate amount of the laser pulse energy, more energy per laser pulse has to be used. Increased laser pulse energy increases the damage risk to the IC chip. However, using a laser pulse energy within the risk-free range on thick links often results in incomplete link severing.

[0007] U.S. Pat. No. 6,057,180 of Sun et al. and U.S. Pat. No. 6,025,256 of Swenson et al. more recently describe methods of using ultraviolet (UV) laser output to sever or expose links that "open" the overlying passivation by different material removal mechanisms and have the benefit of a smaller beam spot size. However, removal of the link itself by such a UV laser pulse entails careful consideration of the underlying passivation structure and material to protect the underlying passivation and silicon wafer from being damaged by the UV laser pulse.

[0008] U.S. Pat. No. 5,656,186 of Mourou et al. discloses a general method of laser induced breakdown and ablation at several wavelengths by high repetition rate ultrafast laser pulses, typically shorter than 10 ps, and demonstrates creation of machined feature sizes that are smaller than the diffraction limited spot size.

[0009] U.S. Pat. No. 5,208,437 of Miyauchi et al. discloses a method of using a single "Gaussian"-shaped pulse of a subnanosecond pulse width to process a link.

[0010] U.S. Pat. No. 5,742,634 of Rieger et al. discloses a simultaneously Q-switched and mode-locked neodymium (Nd) laser device with diode pumping. The laser emits a series of pulses each having a duration time of 60 to 300 picoseconds (ps), under an envelope of a time duration of 100 ns.

Summary of the Invention

[0011] An object of the present invention is to provide a method or apparatus for improving the quality of laser processing of IC links.

[0012] Another object of the invention is to process a link with a set of low energy laser pulses.

[0013] A further object of the invention is to process a link with a set of low energy laser pulses at a shorter wavelength.

[0014] Yet another object of the invention is to employ such sets of laser pulses to process links on-the-fly.

[0015] The present invention employs a set of at least two laser pulses to sever an IC link, instead of using a single laser pulse of conventional link processing systems. This practice does not, however, entail either a long dwell time or separate duplicative scanning passes of repositioning and refiring at each link that would effectively reduce the throughput by factor of about two. The duration of the set is preferably shorter than 1,000 ns, more preferably shorter than 500 ns, most preferably shorter than 300 ns and preferably in the range of 5 to 300 ns; and the pulse width of each laser pulse within the set is generally in the range of 0.1 ps to 30 ns, and more preferably from about 25 ps to about 20 ns or 30 ns. Each laser pulse within the set has an energy or peak power per pulse that is less than the damage threshold for the silicon substrate. The number of laser pulses in the set is controlled such that the last pulse cleans off the bottom of the link leaving the underlying passivation layer and the substrate intact. Because the whole duration of the set is shorter than 1,000 ns, the set is considered to be a single "pulse" by a traditional link-severing laser positioning system. The laser spot of each of the pulses in the set encompasses the link width and the displacement between the laser spots of each pulse is less than the positioning accuracy of a typical positioning system, which is typically ± 0.05 to $0.2 \mu\text{m}$. Thus, the laser system can still process links on-the-fly, i.e. the positioning system does not have to stop moving when the laser system fires a set of laser pulses at each link.

[0016] Additional objects and advantages of this invention will be apparent from the following detailed description of preferred embodiments, which proceeds with reference to the accompanying drawings.

Brief Description of the Drawings

[0017] FIG. 1 is a schematic diagram of a portion of a DRAM showing the redundant layout of and programmable links in a spare row of generic circuit cells.

[0018] FIG. 2A is a fragmentary cross-sectional side view of a conventional, large semiconductor link structure receiving a laser pulse characterized by a prior art pulse parameters.

[0019] FIG. 2B is a fragmentary top view of the link structure and the laser pulse of FIG. 2A, together with an adjacent circuit structure.

[0020] FIG. 2C is a fragmentary cross-sectional side view of the link structure of FIG. 2B after the link is removed by the prior art laser pulse.

[0021] FIG. 3 shows a power versus time graph of exemplary sets of constant amplitude laser pulses employed to sever links in accordance with the present invention.

[0022] FIG. 4 shows a power versus time graph of alternative exemplary sets of modulated amplitude laser pulses employed to sever links in accordance with the present invention.

[0023] FIG. 5 is a partly schematic, simplified diagram of one embodiment of a preferred green laser system including a work piece positioner that cooperates with a laser processing control system for practicing the method of the present invention.

[0024] FIG. 6A shows a power versus time graph of a typical single laser pulse emitted by a conventional laser system to sever a link.

[0025] FIG. 6B shows a power versus time graph of an exemplary set of laser pulses emitted by the laser system of FIG. 5 with a step-controlled Q-switch to sever a link.

[0026] FIG. 7 is a power versus time graph of an exemplary RF signal applied to a step-controlled Q-switch.

[0027] FIG. 8 is a power versus time graph of exemplary laser pulses that can be generated through a step-controlled Q-switch employing the RF signal shown in FIG. 7.

[0028] FIG. 9 is a simplified schematic diagram of an alternative embodiment of a laser system that could be employed to implement the present invention.

[0029] FIGS. 10A-10D show respective power versus time graphs of an exemplary laser pulses propagating along separate optical paths of the laser system shown in FIG. 9.

[0030] FIG. 11 is a simplified schematic diagram of an alternative embodiment of a laser system that employs two or more lasers to implement the present invention.

[0031] FIGS. 12A-12C show respective power versus time graphs of exemplary laser pulses propagating along separate optical paths of the laser system shown in FIG. 11.

Detailed Description of Preferred Embodiments

[0032] FIGS. 3, 4, 6B, 8, 10D, and 12C show power versus time graphs of exemplary sets 50a, 50b, 50c, 50d and 50e (generically sets 50) of laser pulses 52a, 52b₁, 52b₂, 52b₃, 52c₁, 52c₂, 52d, and 52e (generically laser pulses 52) employed to sever links 22 in accordance with the present invention. The duration of each set 50 is preferably shorter than about 1000 ns, more preferably shorter than 500 ns, and most preferably in the range

of about 5 ns to 300 ns. Sets 50 are time-displaced by a programmable delay interval that is typically shorter than 0.1 millisecond and may be a function of the speed of the positioning system 62 and the distance between the links 22 to be processed. The pulse width of each laser pulse 52 within set 50 is preferably in the range of about 0.1 ps to about 30 ns and more preferably from about 25 ps to 30 ns or ranges in between such as from about 100 ps to 10 ns or from 5 ns to 20 ns.

[0033] During a set 50 of laser pulses 52, each laser pulse 52 has insufficient heat, energy, or peak power to fully sever a link 22 or damage the underlying substrate 42 but removes a part of link 22 and/or any overlying passivation layer 38. At a preferred wavelength from about 150 nm to about 1320 nm, preferred ablation parameters of focused spot size 40 of laser pulses 52 include laser energies of each laser pulse between about 0.005 μJ to about 1 μJ (and intermediate energy ranges between 0.01 μJ to about 0.5 μJ) and laser energies of each set between 0.01 μJ to about 2 μJ at greater than about 1 Hz, and preferably 1 kHz to 40 kHz or higher. The focused laser spot diameter is preferably 50% to 100% larger than the width of the link 22, depending on the link width 28, link pitch size 32, link material and other link structure and process considerations.

[0034] Depending on the wavelength of laser output and the characteristics of the link material, the severing depth of pulses 52 applied to link 22 can be accurately controlled by choosing the energy of each pulse 52 and the number of laser pulses 52 in each set 50 to clean off the bottom of any given link 22, leaving underlying passivation layer 46 relatively intact and substrate 42 undamaged. Hence, the risk of damage to silicon substrate 42 is substantially eliminated, even if a laser wavelength in the near UV range is used.

[0035] The energy density profile of a set 50 of laser pulses 52 can be controlled better than the energy density profile of a conventional single link-severing laser pulse. With reference to FIG. 3, each laser pulse 52a can be generated with the same energy density to provide a pulse set 50a with a consistent "flat-top" energy density profile. Set 50a can, for example, be accomplished with a mode-locked laser followed by an electro-optic (E-O) or acousto-optic (A-O) optical gate and an optional amplifier.

[0036] With reference to FIG. 4, the energy densities of pulses 52b can be modulated so that sets 50b of pulses 52b can have almost any predetermined shape, such as the energy density profile of a conventional link blowing laser pulse. Sets 50b can, for example, be accomplished with a simultaneously Q-switched and CW mode-locked laser system 60

shown in FIG. 5. Another alternative set 50 that is not shown has initial pulses 52 with high energy density and trailing pulses 52 with decreasing energy density. Such an energy density profile for a set 50 would be useful to clean out the bottom of the link without risk of damage to a particularly sensitive work piece. Sequential sets 50 may have different peak power and energy density profiles, particularly if links 22 with different characteristics are being processed.

[0037] FIG. 5 shows a preferred embodiment of a simplified laser system 60 including a Q-switched and/or CW mode-locked laser 64 for generating sets 50 of laser pulses 52 desirable for achieving link severing in accordance with the present invention. Preferred laser wavelengths from about 150 nm to about 2000 nm include, but are not limited to, 1.3, 1.064, or 1.047, 1.03-1.05, 0.75-0.85 μm or their second, third, fourth, or fifth harmonics from Nd:YAG, Nd:YLF, Nd:YVO₄, Yb:YAG, or Ti:Sapphire lasers 64. Skilled persons will appreciate that lasers emitting at other suitable wavelengths are commercially available, including fiber lasers, and could be employed.

[0038] Laser system 60 is modeled herein only by way of example to a second harmonic (532 nm) Nd:YAG laser 64 since the frequency doubling elements can be removed to eliminate the harmonic conversion. The Nd:YAG or other solid-state laser 64 is preferably pumped by a laser diode 70 or a laser diode-pumped solid-state laser, the emission 72 of which is focused by lens components 74 into laser resonator 82. Laser resonator 82 preferably includes a lasing medium 84, preferably with a short absorption length, and a Q-switch 86 positioned between focusing/folding mirror 76 and output coupling mirror 78 along an optic axis 90. An aperture 100 may also be positioned between lasing medium 84 and output coupling mirror 78. Output coupling mirror 78 is partly reflective and acts as an output coupler but can also or alternatively be adapted to reflect a portion of the light to a semiconductor saturable absorber mirror device (not shown) for mode locking the laser 64. Mirror 78 propagates resonator output 96 along optic axis 98.

[0039] A harmonic conversion doubler 102 is preferably placed externally to resonator 82 to convert the laser beam frequency to the second harmonic laser output 104. Skilled persons will appreciate that where harmonic conversion is employed, a gating device 106, such as an E-O or A-O device can be positioned before the harmonic conversion apparatus to gate or finely control the harmonic laser pulse energy.

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[0040] Skilled persons will appreciate that any of the second, third, or fourth harmonics of Nd:YAG (532 nm, 355 nm, 266 nm); Nd:YLF (524 nm, 349 nm, 262 nm) or the second harmonic of Ti:Sapphire (375-425 nm) can be employed to preferably process certain types of links 22 using appropriate well-known harmonic conversion techniques. Harmonic conversion processes are described in pp. 138-141, V.G. Dmitriev, et. al., "Handbook of Nonlinear Optical Crystals", Springer-Verlag, New York, 1991 ISBN 3-540-53547-0.

[0041] Laser output 104 (regardless of wavelength) can be manipulated by a variety of conventional optical components 116 and 118 that are positioned along a beam path 120. Components 116 and 118 may include a beam expander or other laser optical components to collimate laser output 104 to produce a beam with useful propagation characteristics. One or more beam reflecting mirrors 122, 124, 126 and 128 are optionally employed and are highly reflective at the laser wavelength desired, but highly transmissive at the unused wavelengths, so only the desired laser wavelength will reach link structure 36. A focusing lens 130 preferably employs an F1, F2, or F3 single component or multicomponent lens system that focuses the collimated pulsed laser system output 140 to produce a focused spot size 40 that is greater than the link width 28, encompasses it, and is preferably less than 2 μm in diameter or smaller depending on the wavelength.

[0042] A preferred beam positioning system 62 is described in detail in U.S. Patent No. 4,532,402 of Overbeck. Beam positioning system 62 preferably employs a laser controller 160 that controls at least two platforms or stages (stacked or split-axis) and coordinates with reflectors 122, 124, 126, and 128 to target and focus laser system output 140 to a desired laser link 22 on IC device or work piece 12. Beam positioning system 62 permits quick movement between links 22 on work piece 12 to effect unique link-severing operations on-the-fly based on provided test or design data.

[0043] The position data preferably direct the focused laser spot 38 over work piece 12 to target link structure 36 with one set 50 of laser pulses 52 of laser system output 140 to remove link 22. The laser system 60 preferably severs each link 22 on-the-fly with a single set 50 of laser pulses 52 without stopping the beam positioning system 62 over any link 22, so high throughput is maintained. Because the sets 50 are less than about 1,000 ns, each set 50 is treated like a single pulse by positioning system 62, depending on the scanning speed of the positioning system 62. For example, if a positioning system 62 has a high speed of about 200 mm per second, then a typical displacement between two consecutive

laser spots 38 would be typically less than $0.2\ \mu\text{m}$ and preferably less than $0.06\ \mu\text{m}$ during a preferred time interval of set 50, so two or more consecutive spots 38 would substantially overlap and each of the spots 38 would completely cover the link width 28. In addition to control of the repetition rate, the time offset between the initiation of pulses 52 within a set 50 is typically shorter than 1,000 ns, more preferably shorter than 500 ns, and most preferably between about 5 ns and 300 ns and can be programmable by controlling Q-switch stepping, laser synchronization, or optical path delay techniques as later described. Preferred sets 50 include 2 to 50 pulses 52, and more preferably 2 to 10 pulses 52.

[0044] Laser controller 160 is provided with instructions concerning the desired energy and pulse width of laser pulses 52, the number of pulses 52, and/or the shape and duration of sets 50 according to the characteristics of link structures 36. Laser controller 160 may be influenced by timing data that synchronizes the firing of laser system 60 to the motion of the platforms such as described in U.S. Pat. No. 5,453,594 of Konecny for Radiation Beam Position and Emission Coordination System. Alternatively, skilled persons will appreciate that laser controller 160 may be used for extracavity modulation of laser energy via an E-O or an A-O device 106 and/or may optionally instruct one or more subcontrollers 164 that control Q-switch 86 or gating device 106. Beam positioning system 62 may alternatively or additionally employ the improvements or beam positioners described in U.S. Pat. No. 5,751,585 of Cutler et al. or U.S. Pat. No. 6,430,465 B2 of Cutler, which are assigned to the assignee of this application. Other fixed head, fast positioner head such as galvanometer, piezoelectrically, or voice coil-controlled mirrors, or linear motor driven conventional positioning systems or those employed in the 9300 or 9000 model series manufactured by Electro Scientific Industries, Inc. (ESI) of Portland, Oregon could also be employed.

[0045] FIG. 6A depicts an energy density profile of typical laser output from a conventional laser used for link blowing. FIG. 6B depicts an energy density profile of a set 50c of laser pulses 52c₁ and 52c₂ emitted from a laser system 60 (with or without mode-locking) that has a step-controlled Q-switch 86. Skilled persons will appreciate that the Q-switch can alternatively be intentionally misaligned for generating more than one laser pulse 52. Set 50c depicts one of a variety of different energy density profiles that can be employed advantageously to sever links 22 of link structures 36 having different types and thicknesses of link or passivation materials. The shape of set 50c can alternatively be

accomplished by programming the voltage to an E-O or A-O gating device or by employing and changing the rotation of a polarizer.

[0046] FIG. 7 is a power versus time graph of an exemplary RF signal 54 applied to a step-controlled Q-switch 86. Unlike typical laser Q-switching which employs an all or nothing RF signal and results in a single laser pulse (typically elimination of the RF signal allows the pulse to be generated) to process a link 22, step-controlled Q-switching employs one or more intermediate amounts of RF signal 54 to generate one or more quickly sequential pulses 52c₃ and 52c₄, such as shown in FIG. 8, which is a power versus time graph. With reference to FIGS. 7 and 8, RF level 54a is sufficient to prevent generation of a laser pulse 52c. The RF signal 54 is reduced to an intermediate RF level 54b that permits generation of laser pulse 52c₃, and then the RF signal 54 is eliminated to RF level 54c to permit generation of laser pulse 52c₄. The step-control Q-switching technique causes the laser pulse 52c₃ to have a peak-instantaneous power that is lower than that of a given single unstepped Q-switched laser pulse and allows generation of additional laser pulse(s) 52c₄ of peak-instantaneous powers that are also lower than that of the given single unstepped Q-switched laser pulse. The amount and duration of RF signal 54 at RF level 54b can be used to control the peak-instantaneous powers of pulses 52c₃ and 52c₄ as well as the time offset between the laser pulses 52 in each set 50. More than two laser pulses 52c can be generated in each set 50c, and the laser pulses 52c may have equal or unequal amplitudes within or between sets 50c by adjusting the number of steps and duration of the RF signal 54.

[0047] FIG. 9 is a simplified schematic diagram of an alternative embodiment of a laser system 60a employing a Q-switched laser 64 (with or without CW-mode-locking) and having an optical delay path 170 that diverges from beam path 120, for example. Optical delay path 170 preferably employs a beam splitter 172 positioned along beam path 120. Beam splitter 172 splits a portion of the laser light from beam path 120 and causes a portion of the light to propagate along beam path 120a and a portion of the light to propagate along optical delay path 170 to reflective mirrors 174a and 174b, through an optional half wave plate 176 and then to combiner 178. Combiner 178 is positioned along beam path 120 downstream of beam splitter 172 and recombines the optical delay path 170 with the beam path 120a into a single beam path 120b. Skilled persons will appreciate that optical delay path 170 can be positioned at a variety of other locations between laser 64 and link

structure 36, such as between output coupling mirror 78 and optical component 116 and may include numerous mirrors 174 spaced by various distances.

[0048] FIGS. 10A-10D show respective power versus time graphs of exemplary laser pulses 52d propagating along optical paths 120, 120a, 120b, and 170 of the laser system 60a shown in FIG. 9. With reference to FIGS. 9 and 10A-10D, FIG. 10A shows the power versus time graph of a laser output 96 propagating along beam path 120. Beam splitter 172 preferably splits laser output 96 into equal laser pulses 52d₁ of FIG. 10B and 52d₂ of FIG. 10C (generically laser pulses 52d), which respectively propagate along optical path 120a and optical delay path 170. After passing through the optional half wave plate 176, laser pulse 52d₂ passes through combiner 178 where it is rejoined with laser pulse 52d₁ propagate along optical path 120b. FIG. 10D shows the resultant power versus time graph of laser pulses 52d₁ and 52d₂ propagating along optical path 120b. Because optical delay path 170 is longer than beam path 120a, laser pulse 52d₂ occurs along beam path 120b at a time later than 52d₁.

[0049] Skilled persons will appreciate that the relative power of pulses 52 can be adjusted with respect to each other by adjusting the amounts of reflection and/or transmission permitted by beam splitter 172. Such adjustments would permit modulated profiles such as those discussed or presented in profiles 50c. Skilled persons will also appreciate that the length of optical delay path 170 can be adjusted to control the timing of respective pulses 52d. Furthermore, additional delay paths of different lengths and/or of dependent nature could be employed to introduce additional pulses at a variety of time intervals and powers.

[0050] Skilled persons will appreciate that one or more optical attenuators can be positioned along common portions of the optical path or along one or both distinct portions of the optical path to further control the peak-instantaneous power of the laser output pulses. In addition, different optical paths can be used to generate pulses 52 of the same or different spot sizes within a set 50.

[0051] FIG. 11 is a simplified schematic diagram of an alternative embodiment of a laser system 60b that employs two or more lasers 64a and 64b (generally lasers 64) to implement the present invention, and FIGS. 12A-12C show respective power versus time graphs of an exemplary laser pulses 52e₁ and 52e₂ (generically 52e) propagating along optical paths 120c, 120d, and 120e of laser system 60b shown in FIG. 11. With reference

to FIGS. 11 and 12A-12C, lasers 64 are preferably Q-switched lasers 64 (preferably not CW mode-locked) of types previously discussed or well known in the art and can be of the same type or different types, producing the same or different spot sizes. Skilled persons will appreciate that lasers 64 are preferably the same type and their parameters are preferably controlled to produce similar spot sizes, pulse energies, and peak powers. Lasers 64 can be triggered by synchronizing electronics 180 such that the laser outputs are separated by a desired or programmable time interval. A preferred time interval includes about 5 ns to about 1,000 ns.

[0052] Laser 64a emits laser pulse 52e₁ that propagates along optical path 120c and then passes through a combiner 178, and laser 64b emits laser pulse 52e₂ that propagates along optical path 120d and then passes through an optional half wave plate 176 and the combiner 178, such that both laser pulses 52e₁ and 52e₂ propagate along optical path 120e but are temporally separated to produce a set 50e of laser pulses having a power versus time profile shown in FIG. 12C.

[0053] With respect to all the embodiments, preferably each set 50 severs a single link 22. In most applications, the energy density profile of each set 50 is identical. However, when a work piece 12 includes different types (different materials or different dimensions) of links 22, then a variety of energy density profiles (heights and lengths and as well as the shapes) can be applied as the positioning system 62 scans over the work piece 12.

[0054] In view of the foregoing, link processing with sets 50 of laser pulses 52 offers a wider processing window and a superior quality of severed links than does conventional link processing without sacrificing throughput. The versatility of pulses 52 in sets 50 permits better tailoring to particular link characteristics.

[0055] Because each laser pulse 52 in the laser pulse set 50 has less laser energy, there is less risk of damaging the neighboring passivation and the silicon substrate 42. In addition to conventional link blowing IR laser wavelengths, laser wavelengths shorter than the IR can also be used for the process with the added advantage of smaller laser beam spot size, even though the silicon wafer's absorption at the shorter laser wavelengths is higher than at the conventional IR wavelengths. Thus, the processing of narrower and denser links is facilitated. This better link removal resolution permits links 22 to be positioned closer together, increasing circuit density. Although link structures 36 can have conventional sizes, the link width 28 can, for example, be less than or equal to about 0.5

μm . Similarly, passivation layers 44 above or below the links 22 can be made with material other than the traditional SiO_2 and SiN , such as the low k material, or can be modified if desirable to be other than a typical height since the sets 50 of pulses 52 can be tailored and since there is less damage risk to the passivation structure. In addition, center-to-center pitch 32 between links 22 processed with sets 50 of laser pulses 52 can be substantially smaller than the pitch 32 between links 22 blown by a conventional IR laser beam-severing pulse. Link 22 can, for example, be within a distance of $2.0\ \mu\text{m}$ or less from other links 22 or adjacent circuit structures 34.

[0056] It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiment of this invention without departing from the underlying principles thereof. The scope of the present invention should, therefore, be determined only by the following claims.

Claims

1. A method of selectively removing a target material from locations of selected link structures, each link structure containing an electrically conductive redundant memory or integrated circuit link positioned between a pair of electrically conductive contacts in a circuit fabricated on a substrate, each link having a link width, comprising:

providing to a beam positioner beam positioning data representing one or more locations of electrically conductive links in the circuit, the beam positioner coordinating relative movement between a laser spot position and the substrate;

generating, from a first laser, at least one first laser output pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during a first time interval that is shorter than about 1,000 nanoseconds, the first laser output pulse also having a first laser spot with a spot size that is greater than the link width;

directing, in accordance with the beam positioning data, the first laser output pulse so that the first laser spot impinges a first location of a first electrically conductive link between first contacts;

generating, from a second laser, at least one second laser output pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during the first time interval, the second laser output pulse also having a second laser spot with a spot size that is greater than the link width;

directing, in accordance with the beam positioning data, the second laser output pulse so that the second laser spot impinges the first location of the first electrically conductive link such that the first and second laser spots substantially overlap and the first and second laser output pulses contribute to the removal of target material at the first location;

generating, from the first laser, at least one third laser output pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during a second time interval that is shorter than 1,000 nanoseconds and time-displaced from the first time interval, the third laser output pulse also having a third laser spot with a spot size that is greater than the link width;

directing, in accordance with the beam positioning data, the third laser output pulse so that the third laser spot impinges a second location of a second electrically conductive link between second contacts that is distinct from the first location;

generating, from the second laser, at least one fourth laser output pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during the second time interval, the fourth laser output pulse also having a fourth laser spot with a spot size that is greater than the link width; and

directing, in accordance with the beam positioning data, the fourth laser output pulse to impinge the second location of the second electrically conductive link such that the third and fourth laser spots substantially overlap and the third and fourth laser output pulses contribute to the removal of target material at the second location.

2. The method of claim 1 in which the beam positioner imparts substantially continuous relative movement between the laser spot position and the substrate such that the electrically conductive links are processed on-the-fly.

3. The method of claim 2 in which the electrically conductive links form part of respective link structures, the substrate associated with the link structures has energy and peak power damage thresholds, and each of the laser output pulses has an energy and peak power that are less than the respective energy and peak power damage thresholds.

4. The method of claim 1 in which the electrically conductive links form part of respective link structures, the substrate associated with the link structures has energy and peak power damage thresholds, and each of the laser output pulses has an energy and peak power that are less than the respective energy and peak power damage thresholds.

5. The method of claim any one of claims 1 through 4 in which the laser pulses from each laser completely encompass the link width of the electrically conductive link that the laser pulses process.

6. The method of claim 1 in which the laser output pulses from the first and second lasers propagate along optical paths that share a substantially collinear common portion.

7. The method of any of claims 1 in which the laser output pulses have a pulse width of between about 5 nanoseconds and 20 nanoseconds.

8. The method of claim 1, further comprising:

generating the laser output pulses at a repetition rate such that a delay interval between the first and second time intervals is shorter than 0.1 millisecond.

9. The method of claim 1 in which at least one of the electrically conductive links is covered by an overlying passivation layer.

10. The method of claim 1 in which at least one of the electrically conductive links is not covered by an overlying passivation layer.

11. The method of claim 1 in which at least one of the electrically conductive links comprises aluminum, chromide, copper, polysilicon, disilicide, gold, nickel, nickel chromide, platinum, polycide, tantalum nitride, titanium, titanium nitride, tungsten, or tungsten silicide.

12. The method of claim 1, further comprising generating the laser output pulses at a wavelength between about 150 nm and 2000 nm.

13. The method of claim 1 in which the spot sizes of the laser spots from the laser output pulses of the first and second lasers are the same.

14. The method of claim 1 in which the spot sizes of the laser spots from the laser output pulses of the first and second lasers are different.

15. The method of claim 1 in which the laser output pulses during the first and second time intervals have similar peak power profiles and similar energy density profiles.

16. The method of claim 1 in which each of the laser output pulses during the first time interval has approximately the same energy and approximately the same peak power.

17. The method of claim 1 in which at least two of the laser output pulses during the first time interval have different energies and different peak powers.

18. The method of claim 1 in which a time offset between initiation of the first and second laser output pulses is programmable.

19. The method of claim 1 in which a time offset between initiation of the first and second laser output pulses is within about 5 to 500 ns.

20. The method of claim 1 in which each of the laser output pulses has a laser energy of about 0.005-1 microjoule.

21. A method of selectively removing a target material from locations of selected link structures, each link structure containing an electrically conductive redundant memory or integrated circuit link positioned between a pair of electrically conductive contacts in a circuit fabricated on a substrate, each link having a link width, comprising:

providing to a beam positioner beam positioning data representing one or more locations of electrically conductive links in the circuit, the beam positioner coordinating relative movement between a laser spot position and the substrate;

generating from a laser at least one first laser pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during a first time interval that is shorter than 1,000 nanoseconds;

propagating the first laser pulse along a first optical path;

splitting the first laser pulse into first and second laser output pulses such that the first laser output pulse propagates along the first optical path and such that the second laser output pulse propagates along a second optical path, the first and second laser output pulses also having respective first and second laser spots having spot sizes that are greater than the link width;

directing, in accordance with the beam positioning data, the first laser output pulse so that the first laser spot impinges a first location of a first electrically conductive link between first contacts during the first time interval;

directing the second laser output pulse so that the second laser spot impinges the first location of the first electrically conductive link during the first time interval such that the first and second laser spots substantially overlap and the first and second laser output pulses contribute to the removal of target material at the first location, the second optical path having a characteristic that causes the second laser pulse to reach the first location after the first laser pulse reaches the first location;

generating from the laser at least one second laser pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during a second time interval that is shorter than 1,000 nanoseconds;

propagating the second laser pulse along the first optical path;

splitting the second laser pulse into third and fourth laser output pulses such that the third laser output pulse propagates along the first optical path and such that the fourth laser output pulse propagates along the second optical path, the third and fourth laser output pulses also having respective third and fourth laser spots having spot sizes that are greater than the link width;

directing, in accordance with the beam positioning data, the third laser output pulse so that the third laser spot impinges a second location of a second electrically conductive link between second contacts during the second time interval; and

directing the fourth laser output pulse so that the fourth laser spot impinges the second location of the second electrically conductive link during the second time interval such that the third and fourth laser spots substantially overlap and the third and fourth laser output pulses contribute to the removal of target material at the second location, the second optical path having a characteristic that causes the fourth laser pulse to reach the second location after the third laser pulse reaches the second location.

22. The method of claim 21 in which the beam positioner imparts substantially continuous relative movement between the laser spot position and the substrate such that the electrically conductive links are processed on-the-fly.

23. The method of claim 22 in which the electrically conductive links form part of respective link structures, the substrate associated with the link structures has energy and peak power damage thresholds, and each of the laser output pulses has an energy and peak power that are less than the respective energy and peak power damage thresholds.

24. The method of claim 21 in which the electrically conductive links form part of respective link structures, the substrate associated with the link structures has energy and peak power damage thresholds, and each of the laser output pulses has an energy and peak power that are less than the respective energy and peak power damage thresholds.

25. The method of claim any one of claims 21 through 24 in which the laser pulses from each laser completely encompass the link width of the electrically conductive link that the laser pulses process.

26. The method of claim 25 in which each of the laser output pulses has a laser energy of about 0.005-1 microjoule.

27. The method of any of claims 21 in which the laser output pulses have a pulse width of between about 5 nanoseconds and 20 nanoseconds.

28. The method of claim 21, further comprising:

generating the laser output pulses at a repetition rate such that a delay interval between the first and second time intervals is shorter than 0.1 millisecond.

29. The method of claim 21 in which at least one of the electrically conductive links is covered by an overlying passivation layer.

30. The method of claim 21 in which at least one of the electrically conductive links is not covered by an overlying passivation layer.

31. The method of claim 21 in which at least one of the electrically conductive links comprises aluminum, chromide, copper, polysilicon, disilicide, gold, nickel, nickel chromide, platinum, polycide, tantalum nitride, titanium, titanium nitride, tungsten, or tungsten silicide.

32. The method of claim 21, further comprising generating the laser output pulses at a wavelength between about 150 nm and 2000 nm.

33. The method of claim 21 in which the spot sizes of the laser spots from the laser output pulses of the first and second lasers are the same.

34. The method of claim 21 in which the spot sizes of the laser spots from the laser output pulses of the first and second lasers are different.

35. The method of claim 21 in which the laser output pulses during the first and second time intervals have similar peak power profiles and similar energy density profiles.

36. The method of claim 21 in which each of the laser output pulses during the first time interval has approximately the same energy and approximately the same peak power.

37. The method of claim 21 in which at least two of the laser output pulses during the first time interval have different energies and different peak powers.

38. The method of claim 21 in which a time offset between when the first and second laser output pulses reach the first location is adjustable.

39. The method of claim 21 in which a time offset between when the first and second laser output pulses reach the first location is within about 5 to 500 ns.

40. The method of claim 21 in which each of the laser output pulses has a laser energy of about 0.005-1 microjoule.

41. A method of selectively removing a target material from locations of selected link structures, each link structure containing an electrically conductive redundant memory or integrated circuit link positioned between a pair of electrically conductive contacts in a circuit fabricated on a substrate, each link having a link width, comprising:

providing to a beam positioner beam positioning data representing one or more locations of electrically conductive links in the circuit, the beam positioner coordinating relative movement between a laser spot position and the substrate;

reducing an RF signal to a Q-switch from a high RF level to an intermediate RF level to generate from a laser at least one first laser output pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during a first time interval that is shorter than 1,000 nanoseconds, the first laser output pulse also having a first laser spot with a spot size that is greater than the link width;

directing, in accordance with the beam positioning data, the first laser output pulse so that the first laser spot impinges a first location of a first electrically conductive link between first contacts;

reducing the RF signal to the Q-switch from the intermediate RF level to a smaller RF level to generate at least one second laser output pulse having a pulse width of between about 25 picoseconds and 30 nanoseconds during the first time interval, the second laser output pulse also having a second laser spot with a spot size that is greater than the link width;

directing the second laser output pulse so that the second laser spot impinges the first location of the first electrically conductive link such that the first and second laser spots substantially overlap and the first and second laser output pulses contribute to the removal of target material at the first location;

increasing the RF signal to the Q-switch from the smaller RF level to the high RF level;

reducing the RF signal to the Q-switch from the high RF level to the intermediate RF level to generate from the laser at least one third laser output pulse having a pulse width duration of between about 25 picoseconds and 30 nanoseconds during a second time interval having a set width duration of shorter than 1,000 nanoseconds, the third laser output pulse also having a third laser spot with a spot size that is greater than the link width;

directing, in accordance with the beam positioning data, the third laser output pulse so that the third laser spot impinges a second location of a second electrically conductive link between second contacts;

reducing the RF signal to the Q-switch from the intermediate RF level to the smaller RF level to generate at least one fourth laser output pulse having a pulse width duration of between about 25 picoseconds and 30 nanoseconds during the second time interval, the fourth laser output pulse also having a fourth laser spot with a spot size that is greater than the link width; and

directing the fourth laser output pulse so that the fourth laser spot impinges the second location of the second electrically conductive link such that the third and fourth laser spots substantially overlap and the third and fourth laser output pulses contribute to the removal of target material at the second location.

42. The method of claim 41 in which the beam positioner imparts substantially continuous relative movement between the laser spot position and the substrate such that the electrically conductive links are processed on-the-fly.

43. The method of claim 42 in which the electrically conductive links form part of respective link structures, the substrate associated with the link structures has energy and peak power damage thresholds, and each of the laser output pulses has an energy and peak power that are less than the respective energy and peak power damage thresholds.

44. The method of claim 41 in which the electrically conductive links form part of respective link structures, the substrate associated with the link structures has energy and peak power damage thresholds, and each of the laser output pulses has an energy and peak power that are less than the respective energy and peak power damage thresholds.

45. The method of claim any one of claims 41 through 44 in which the laser pulses from each laser completely encompass the link width of the electrically conductive link that the laser pulses process.

46. The method of claim 45 in which each of the laser output pulses has a laser energy of about 0.005-1 microjoule.

47. The method of any of claims 41 in which the laser output pulses have a pulse width of between about 5 nanoseconds and 20 nanoseconds.

48. The method of claim 41, further comprising:
generating the laser output pulses at a repetition rate such that a delay interval between the first and second time intervals is shorter than 0.1 millisecond.

49. The method of claim 41 in which at least one of the electrically conductive links is covered by an overlying passivation layer.

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50. The method of claim 41 in which at least one of the electrically conductive links is not covered by an overlying passivation layer.

51. The method of claim 41 in which at least one of the electrically conductive links comprises aluminum, chromide, copper, polysilicon, disilicide, gold, nickel, nickel chromide, platinum, polycide, tantalum nitride, titanium, titanium nitride, tungsten, or tungsten silicide.

52. The method of claim 41, further comprising generating the laser output pulses at a wavelength between about 150 nm and 2000 nm.

53. The method of claim 45 in which the laser output pulses during the first and second time intervals have similar peak power profiles and similar energy density profiles.

54. The method of claim 41 in which each of the laser output pulses during the first time interval has approximately the same energy and approximately the same peak power.

55. The method of claim 41 in which the laser output pulses during the first and second time intervals have similar peak power profiles and similar energy density profiles.

56. The method of claim 45 in which each of the laser output pulses during the first time interval has approximately the same energy and approximately the same peak power.

57. The method of claim 41 in which at least two of the laser output pulses during the first time interval have different energies and different peak powers.

58. The method of claim 41 in which a time offset between initiation of the first and second laser output pulses is programmable.

59. The method of claim 41 in which a time offset between initiation of the first and second laser output pulses is within about 5 to 500 ns.

60. The method of claim 41 in which each of the laser output pulses has a laser energy of about 0.005-1 microjoule.

61. A method of selectively removing a target material from locations of selected link structures, each link structure containing an electrically conductive redundant memory or integrated circuit link positioned between a pair of electrically conductive contacts in a circuit fabricated on a substrate, each link having a link width, comprising:

providing to a beam positioner beam positioning data representing one or more locations of electrically conductive links in the circuit, the beam positioner coordinating relative movement between a laser spot position and the substrate;

generating from a laser having a misaligned Q-switch at least first and second laser output pulses having a pulse width of between about 25 picoseconds and 30 nanoseconds during a first time interval that is shorter than 1,000 nanoseconds, the first and second laser output pulses also having respective first and second laser spots having spot sizes that are greater than the link width;

directing, in accordance with the beam positioning data, the first and second laser output pulse so that the first and second laser spots impinge a first location of a first electrically conductive link between first contacts during the first time interval such that the first and second laser spots substantially overlap and the first and second laser output pulses contribute to the removal of target material at the first location;

generating from the laser at least third and fourth laser output pulses having a pulse width of between about 25 picoseconds and 30 nanoseconds during a second time interval that is shorter than 1,000 nanoseconds, the third and fourth laser output pulses also having respective third and fourth laser spots having spot sizes that are greater than the link width; and

directing, in accordance with the beam positioning data, the third and fourth laser output pulse so that the third and fourth laser spots impinge a second location of a second electrically conductive link between second contacts during the second time interval such that the third and fourth laser spots substantially overlap and the third and fourth laser output pulses contribute to the removal of target material at the second location.

62. The method of any one claims 1-20 in which the each laser output pulse has insufficient heat, energy, or peak power to fully sever the link at the respective locations.

63. The method of claim 62 in which the respective sets of first and second laser output pulses and third and fourth laser output pulses are generated at a repetition rate of greater than 1 kHz.

64. The method of any one claims 21-40 in which the each laser output pulse has insufficient heat, energy, or peak power to fully sever the link at the respective locations.

65. The method of claim 64 in which the respective sets of first and second laser output pulses and third and fourth laser output pulses are generated at a repetition rate of greater than 1 kHz.

66. The method of any one claims 41-60 in which the each laser output pulse has insufficient heat, energy, or peak power to fully sever the link at the respective locations.

67. The method of claim 66 in which the respective sets of first and second laser output pulses and third and fourth laser output pulses are generated at a repetition rate of greater than 1 kHz.

68. The method of claim 61 in which the each laser output pulse has insufficient heat, energy, or peak power to fully sever the link at the respective locations.

69. The method of claim 68 in which the respective sets of first and second laser output pulses and third and fourth laser output pulses are generated at a repetition rate of greater than 1 kHz.