US 20060131288A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2006/0131288 A1**

Sun et al. (43) **Pub. Date: Jun. 22, 2006**

(54) **PROCESSING A MEMORY LINK WITH A SET OF AT LEAST TWO LASER PULSES**

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(21) Appl. No.: **11/292,327**

(22) Filed: **Nov. 30, 2005**

Related U.S. Application Data

(63) Continuation of application No. 10/322,347, filed on Dec. 17, 2002, and which is a continuation-in-part of application No. 09/757,418, filed on Jan. 9, 2001, now Pat. No. 6,574,250.

(60) Provisional application No. 60/341,744, filed on Dec. 17, 2001. Provisional application No. 60/223,533, filed on Aug. 4, 2000. Provisional application No. 60/175,337, filed on Jan. 10, 2000.

Publication Classification

(51) **Int. Cl.**
B23K 26/16 (2006.01)

(52) **U.S. Cl.** **219/121.69**

(57) **ABSTRACT**

A set (**50**) of laser pulses (**52**) is employed to sever a conductive link (**22**) in a memory or other IC chip. The duration of the set (**50**) is preferably shorter than 1,000 ns; and the pulse width of each laser pulse (**52**) within the set (**50**) is preferably within a range of about 0.1 ps to 30 ns. The set (**50**) can be treated as a single "pulse" by conventional laser positioning systems (**62**) to perform on-the-fly link removal without stopping whenever the laser system (**60**) fires a set (**50**) of laser pulses (**52**) at each link (**22**). Conventional IR wavelengths or their harmonics can be employed.

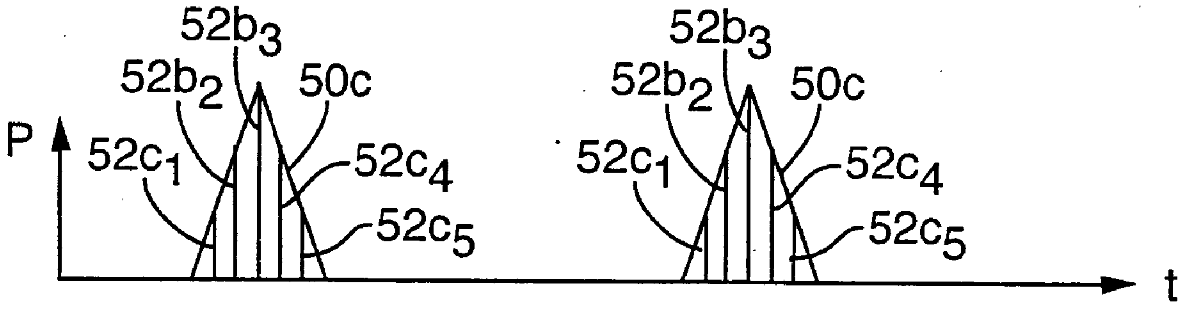


FIG. 1
(Prior Art)

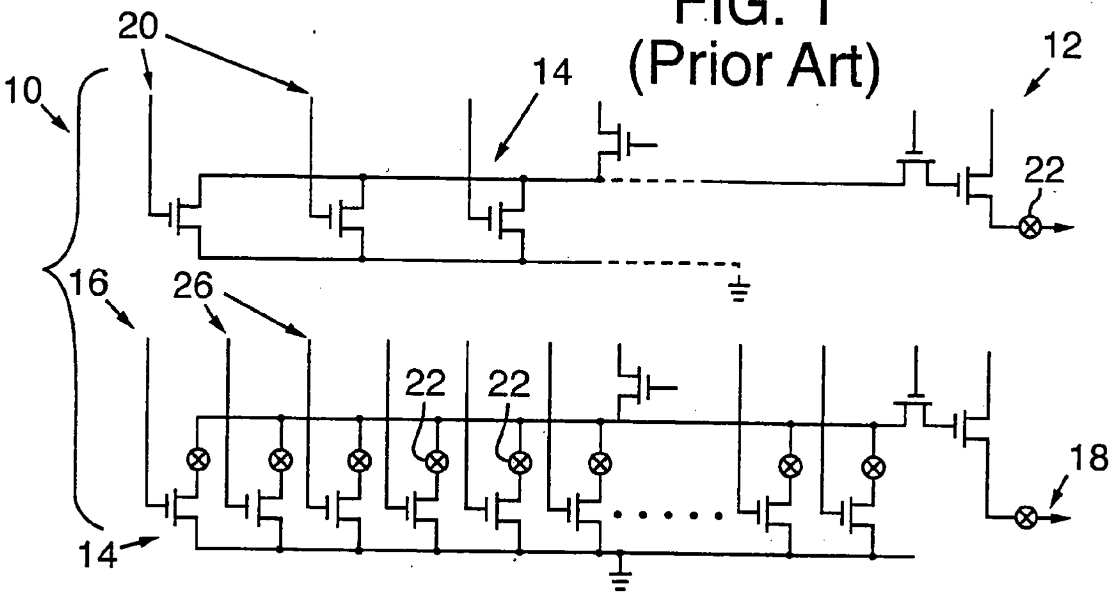


FIG. 2A
(Prior Art)

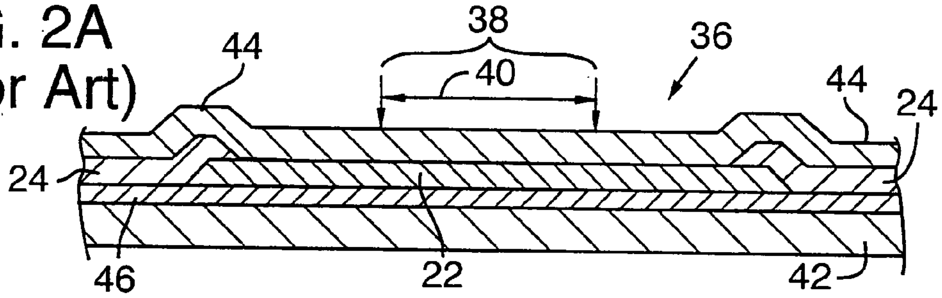


FIG. 2B
(Prior Art)

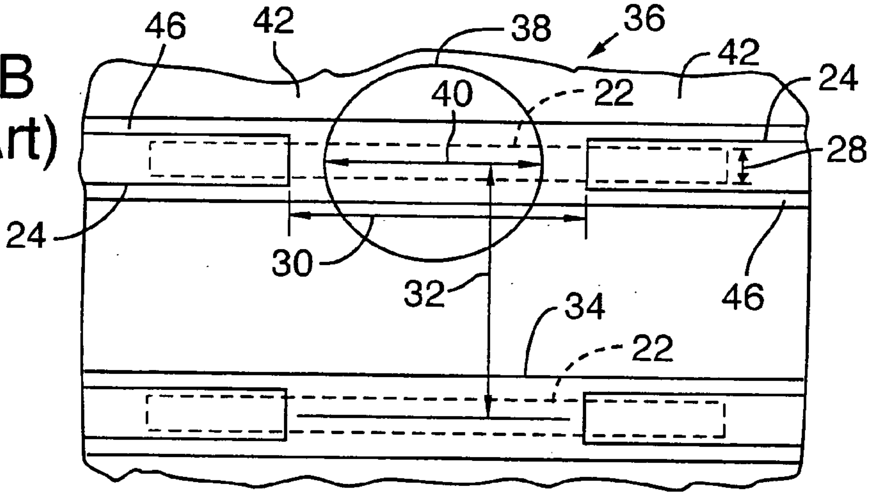


FIG. 2C
(Prior Art)

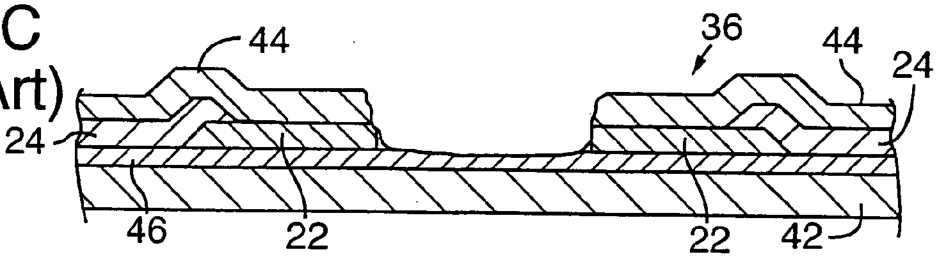
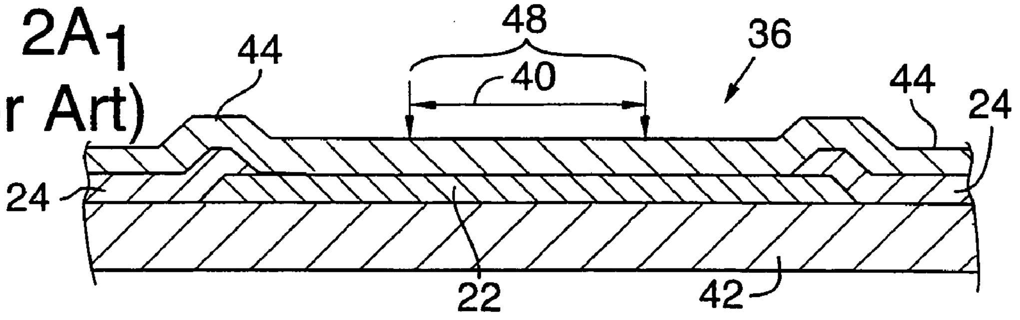


FIG. $2A_1$
(Prior Art)



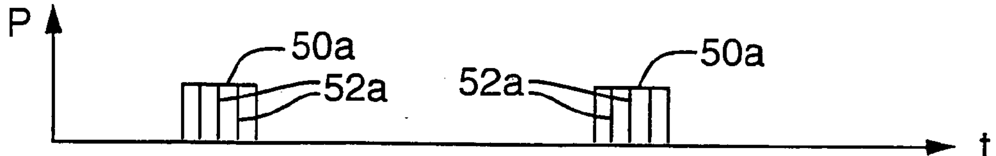


FIG. 3

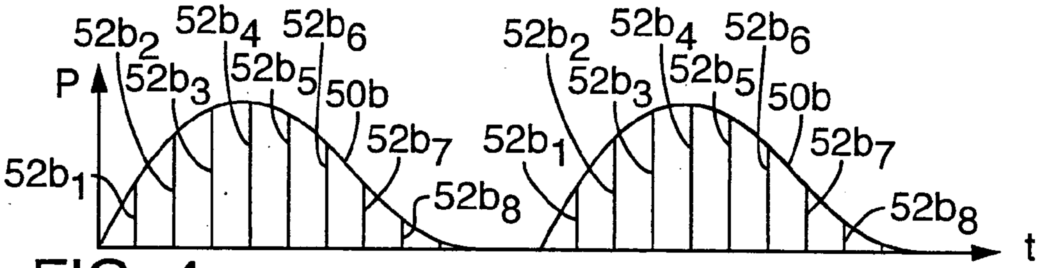


FIG. 4

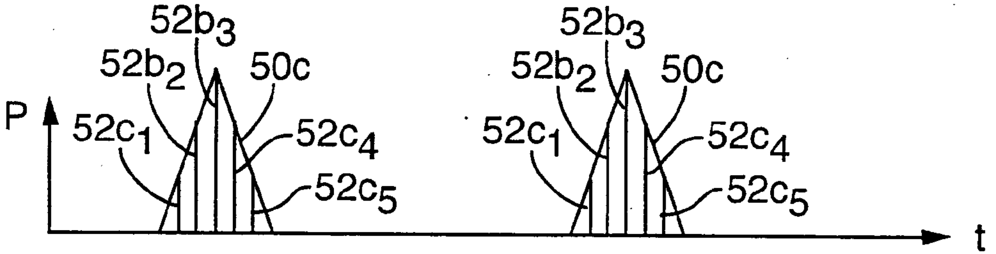


FIG. 5

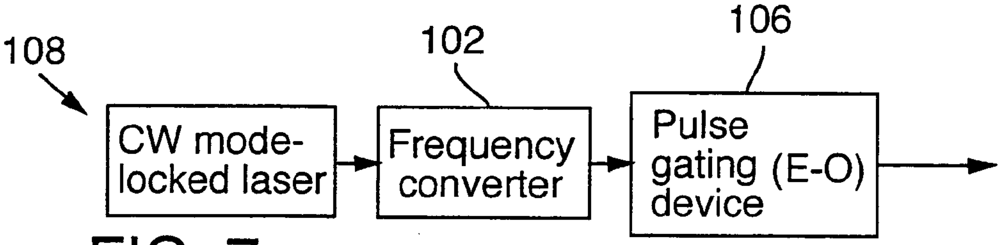


FIG. 7

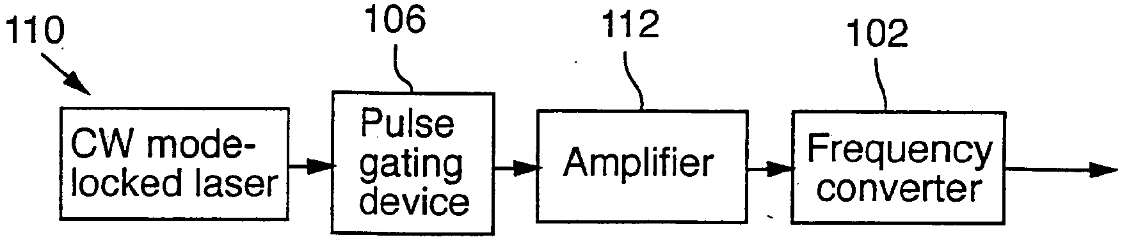


FIG. 8

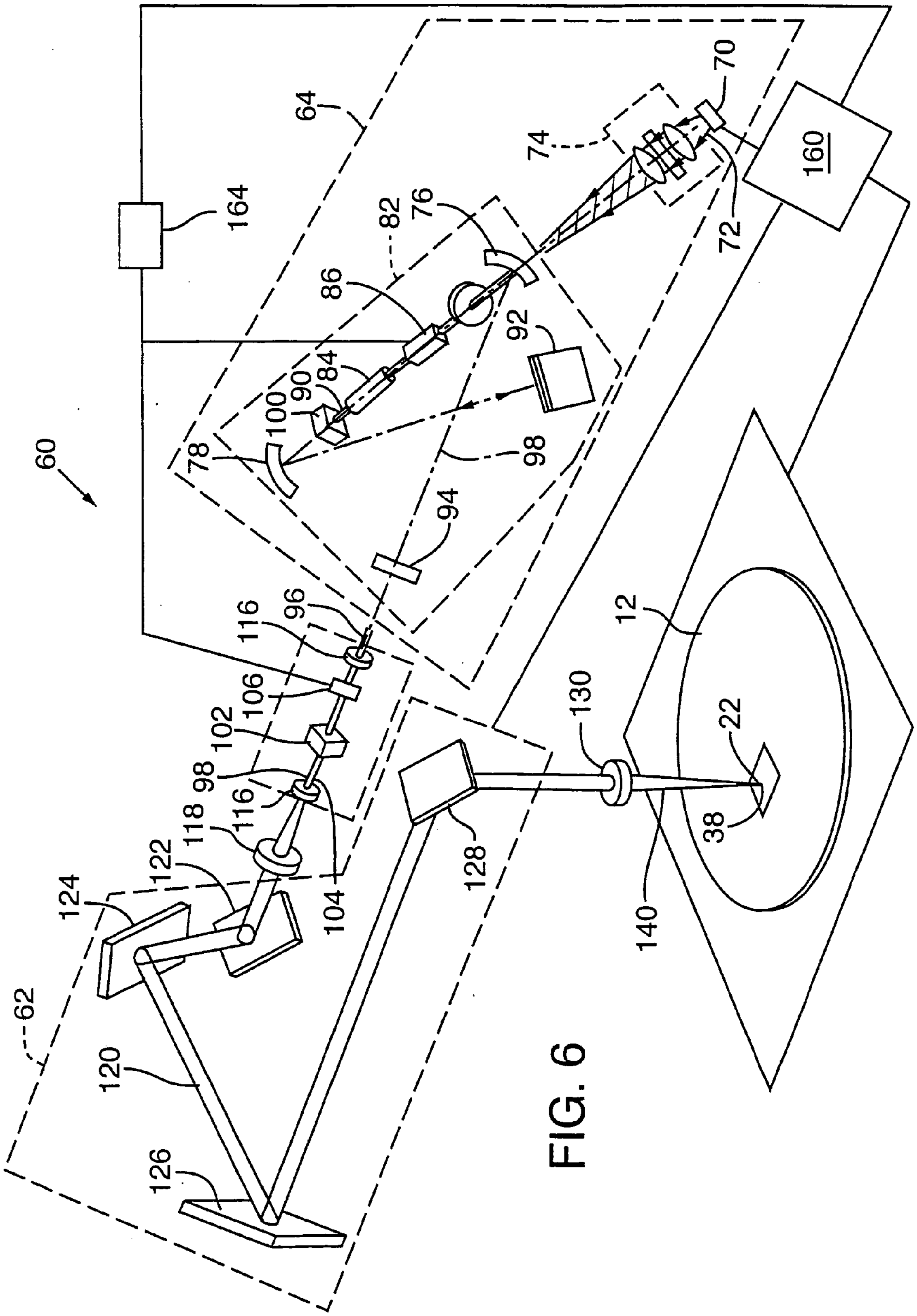

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FIG. 6

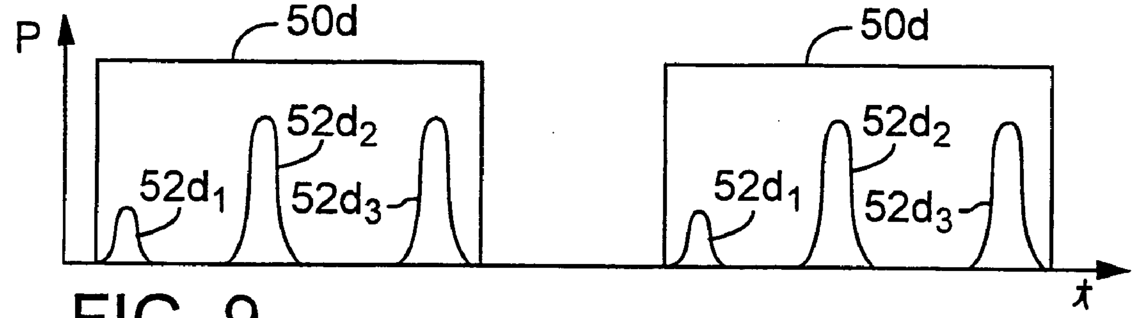

FIG. 9

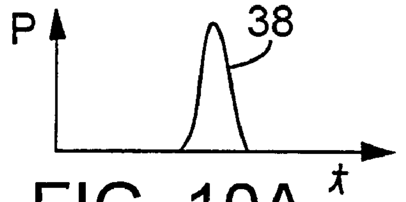

FIG. 10A

FIG. 10B

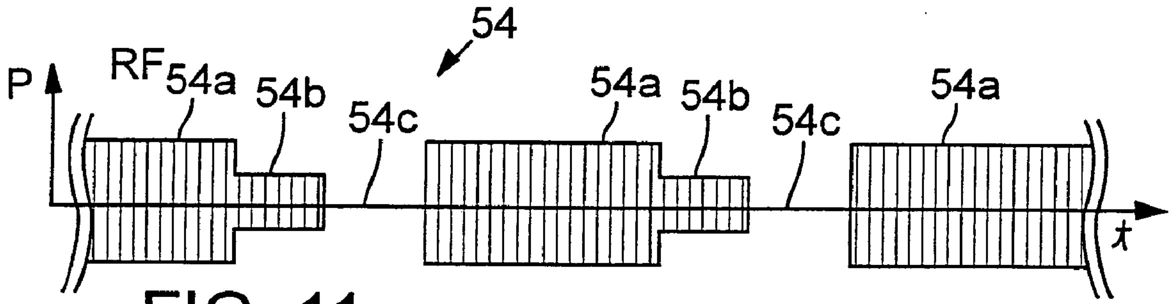

FIG. 11

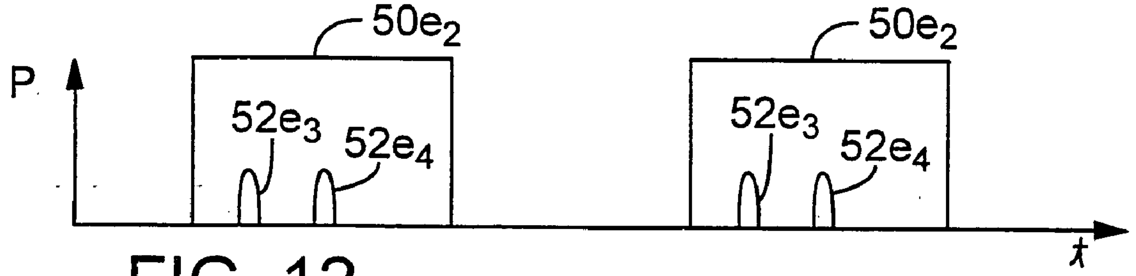

FIG. 12

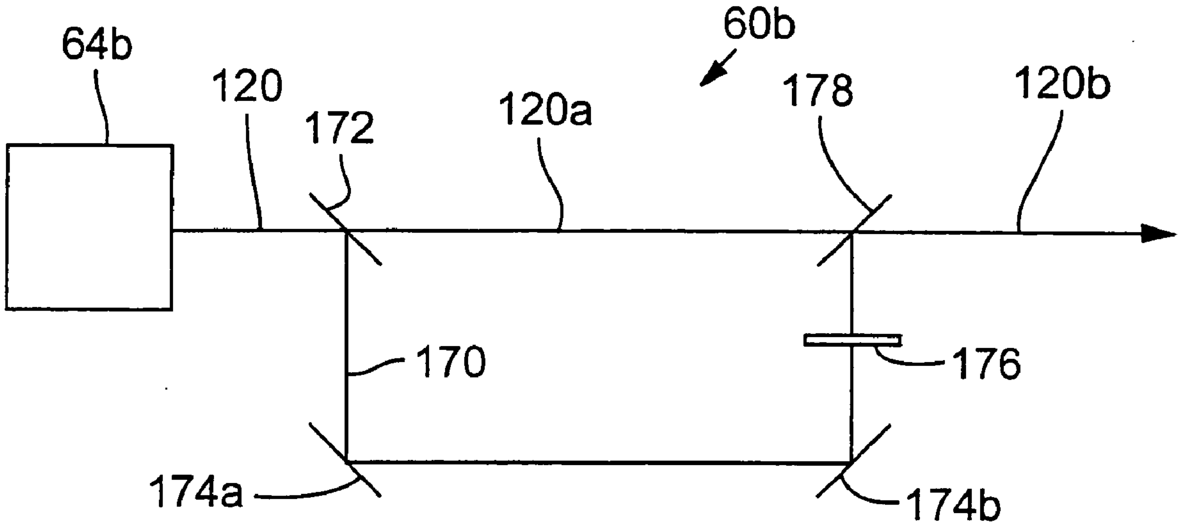

FIG. 13

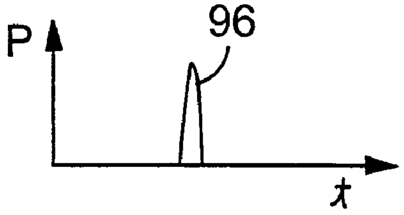

FIG. 14A

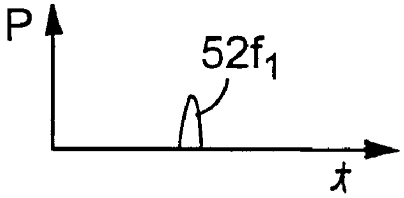

FIG. 14B

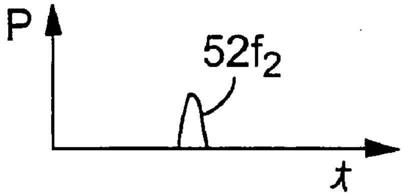

FIG. 14C

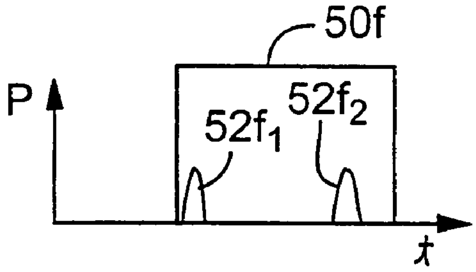

FIG. 14D

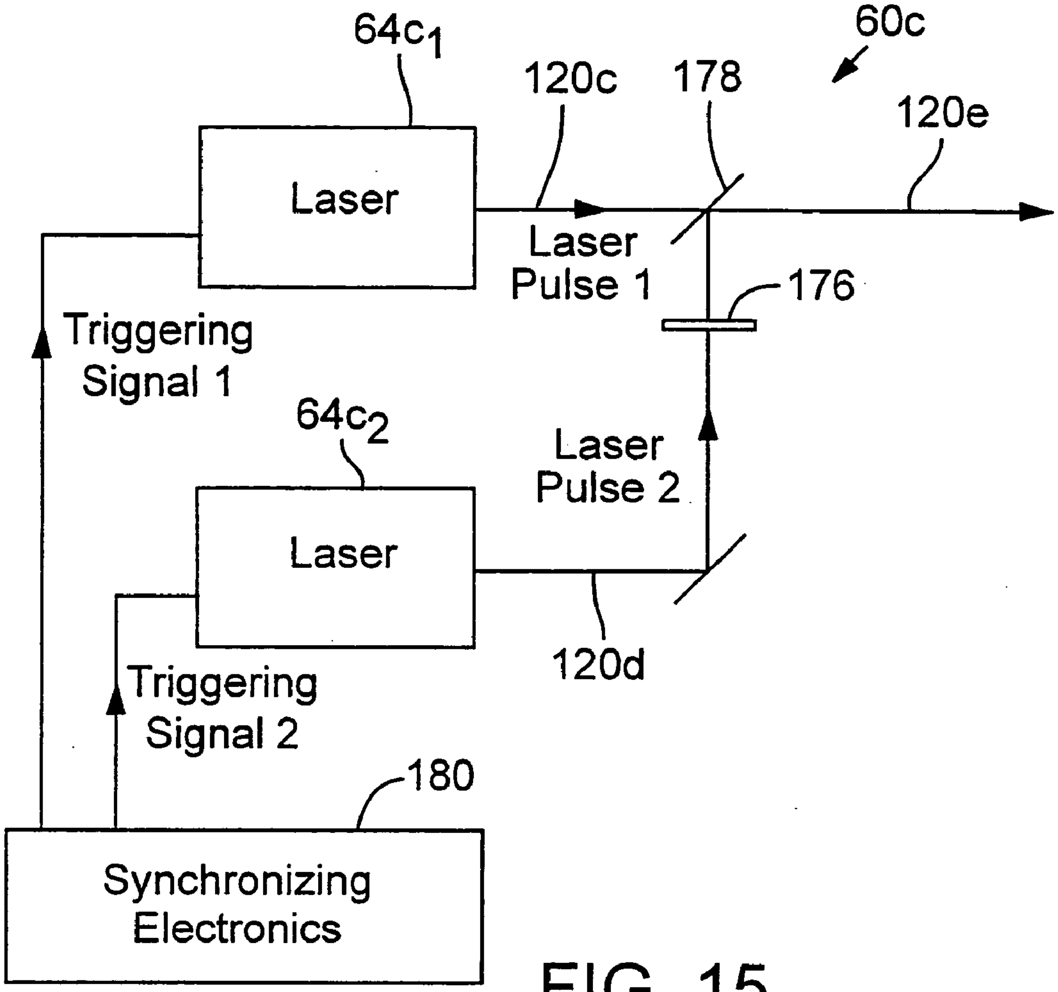

FIG. 15

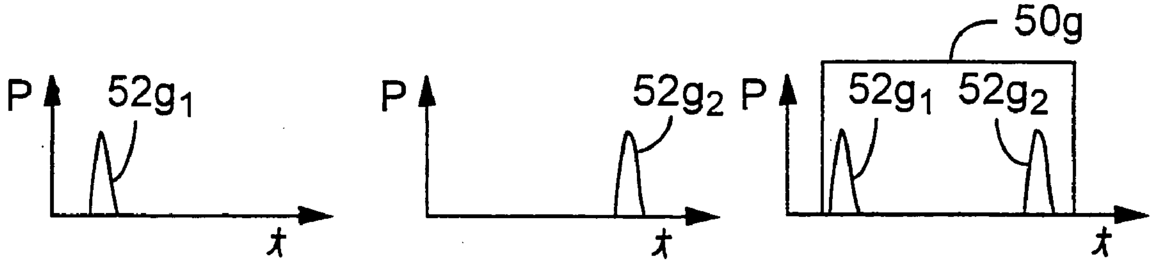

FIG. 16A FIG. 16B FIG. 16C

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

RELATED APPLICATIONS

[0001] This patent application is a continuation of U.S. patent application Ser. No. 10/322,347, filed Dec. 17, 2002, which claims priority from U.S. Provisional Application No. 60/341,744, filed Dec. 17, 2001, and is a continuation-in-part of U.S. patent application Ser. No. 09/757,418, filed Jan. 9, 2001, now U.S. Pat. No. 6,574,250, which claims priority from both U.S. Provisional Application No. 60/223,533, filed Aug. 4, 2000, and U.S. Provisional Application No. 60/175,337, filed Jan. 10, 2000.

TECHNICAL FIELD

[0002] 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

[0003] 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.

[0004] 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 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, gold, nickel, 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.

[0005] 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 μm or 1.064 μm 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 (Å) 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.

[0006] **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. Pat. 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 μm, to process memory links **22** on silicon wafers. At the 1.3 μm laser wavelength, the absorption contrast between the link material and silicon substrate **42** is much larger than that at the traditional 1 μm 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.

[0007] The 1.0 μm and 1.3 μm 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.

[0008] 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.

[0009] 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.

[0010] 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.

[0011] 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

[0012] An object of the present invention is to provide a method or apparatus for improving the quality of laser processing of IC links.

[0013] Another object of the invention is to process a link with a set of low energy laser pulses.

[0014] A further object of the invention is to process a link with a set of low energy laser pulses at a shorter wavelength.

[0015] Yet another object of the invention is to employ such sets of laser pulses to process links on-the-fly.

[0016] The present invention employs a set of at least two laser pulses, each with a laser pulse energy within a safe range, 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 100 femtoseconds (fs) to 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 supporting the link structure. 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 μm. 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 selected link.

[0017] In one embodiment, a continuous wave (CW) mode-locked laser at high laser pulse repetition rate, followed by optical gate and an amplifier, generates sets having ultrashort laser pulses that are preferably from about 100 fs to about 10 ps. In another one embodiment, a Q-switched and CW mode-locked laser generates sets having ultrashort laser pulses that are preferably from about 100 fs to about 10 ps. Because each laser pulse within the burst set is ultrashort, its interaction with the target materials (passivation layers and metallic link) is substantially not thermal. Each laser pulse breaks off a thin sublayer of about 100-2,000 Å of material, depending on the laser energy or peak power, laser wavelength, and type of material, until the link is severed. This substantially nonthermal process may mitigate certain irregular and inconsistent link processing quality associated with thermal-stress explosion behavior of passivation layers **44** of links **22** with widths narrower than about 1 μm. In addition to the "nonthermal" and well-controllable nature of ultrashort-pulse laser processing, the most common ultrashort-pulse laser source emits at a wavelength of about 800 nm and facilitates delivery of a small-sized laser spot. Thus, the process may facilitate greater circuit density.

[0018] In another embodiment, the sets have laser pulses that are preferably from about 25 ps to about 20 ns or 30 ns. These sets of laser pulses can be generated from a CW mode-locked laser system including an optical gate and an optional down stream amplifier, from a step-controlled acousto-optic (A-O) Q-switched laser system, from a laser system employing a beam splitter and an optical delay path, or from two or more synchronized but offset lasers that share a portion of an optical path.

[0019] 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

[0020] **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.

[0021] **FIGS. 2A and $2A_1$**, are fragmentary cross-sectional side views of conventional, large semiconductor link structures, respectively with and without an underlying passivation layer, receiving a laser pulse characterized by prior art pulse parameters.

[0022] **FIG. 2B** is a fragmentary top view of the link structure and the laser pulse of **FIG. 2A**, together with an adjacent circuit structure.

[0023] **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.

[0024] **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.

[0025] **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.

[0026] **FIG. 5** shows a power versus time graph of other alternative exemplary sets of modulated amplitude laser pulses employed to sever links in accordance with the present invention.

[0027] **FIG. 6** is a partly schematic, simplified diagram of an embodiment of an exemplary green laser system including a work piece positioner that cooperates with a laser processing control system for practicing the method of the present invention.

[0028] **FIG. 7** is a simplified schematic diagram of one laser configuration that can be employed to implement the present invention.

[0029] **FIG. 8** is a simplified schematic diagram of an alternative embodiment of a laser configuration that can be employed to implement the present invention.

[0030] **FIG. 9** 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.

[0031] **FIG. 10A** shows a power versus time graph of a typical single laser pulse emitted by a conventional laser system to sever a link.

[0032] **FIG. 10B** shows a power versus time graph of an exemplary set of laser pulses emitted by a laser system with a step-controlled Q-switch to sever a link.

[0033] **FIG. 11** is a power versus time graph of an exemplary RF signal applied to a step-controlled Q-switch.

[0034] **FIG. 12** 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. 11**.

[0035] **FIG. 13** is a simplified schematic diagram of an alternative embodiment of a laser system that can be employed to implement the present invention.

[0036] **FIGS. 14A-14D** show respective power versus time graphs of an exemplary laser pulses propagating along separate optical paths of the laser system shown in **FIG. 14**.

[0037] **FIG. 15** is a simplified schematic diagram of an alternative embodiment of a laser system that employs two or more lasers to implement the present invention.

[0038] **FIGS. 16A-16C** show respective power versus time graphs of exemplary laser pulses propagating along separate optical paths of the laser system shown in **FIG. 16**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0039] **FIGS. 3-5**, **9**, **10**B, **12**, **14**D, and **16**C show power versus time graphs of exemplary sets **50***a*, **50***b*, **50***c*,**50***d*, **50***e*, **50***f*, and **50***g* (generically sets **50**) of laser pulses **52***a*, **52***b*$_1$-**52***b*$_8$, **52***c*$_1$-**52***c*$_5$, **52***d*$_1$,-**52***d*$_3$, **52***e*$_1$-**52***e*$_4$, **52***f*$_1$-**52***f*$_2$, and **52***g*$_1$-**52***g*$_2$ (generically laser pulses **52**) employed to sever links **22** in accordance with the present invention. Preferably, each set **50** severs a single link **22**. Preferred sets **50** include 2 to 50 pulses **52**. 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 in the range of about 100 fs to about 30 ns.

[0040] 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 **44**. 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 and 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.

[0041] 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 UV range is used.

[0042] The energy density profile of each 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 **52***a* can be generated with the same energy density to provide a pulse set **50***a* with a consistent "flat-top" energy density profile. Set **50***a* 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 (**FIG. 8**).

[0043] With reference to **FIG. 4**, the energy densities of pulses **52***b*$_1$-**52***b*$_8$ (generically **52***b*) can be modulated so that sets **50***b* of pulses **52***b* can have almost any predetermined shape, such as the energy density profile of a conventional link-blowing laser pulse with a gradual increase and decrease of energy densities over pulses **52***b*$_1$-**52***b*$_8$. Sets **50***b* can, for example, be accomplished with a simultaneously Q-switched and CW mode-locked laser system **60** shown in **FIG. 6**. Sequential sets **50** may have different peak power and energy density profiles, particularly if links **22** with different characteristics are being processed.

[0044] **FIG. 5** shows an alternative energy density profile of pulses **52***c*$_1$-**52***c*$_5$ (generically **52***c*) that have sharply and symmetrically increasing and decreasing over sets **50***c*. Sets **50***c* can be accomplished with a simultaneously Q-switched and CW mode-locked laser system **60** shown in **FIG. 6**.

[0045] 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.

[0046] **FIG. 6** 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:YVO$_4$, 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.

[0047] 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 lasant **84**, preferably with a short absorption length, and a Q-switch **86** positioned between focusing/folding mirrors **76** and **78** along an optic axis **90**. An aperture **100** may also be positioned between lasant **84** and mirror **78**. Mirror **76** reflects light to mirror **78** and to a partly reflective output coupler **94** that propagates laser output **96** along optic axis **98**. Mirror **78** is adapted to reflect a portion of the light to a semiconductor saturable absorber mirror device **92** for mode locking the laser **64**. 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.

[0048] 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.

[0049] An exemplary laser **64** can be a mode-locked Ti-Sapphire ultrashort pulse laser with a laser wavelength in the near IR range, such as 750-850 nm. Spectra Physics makes a Ti-Sapphire ultra fast laser called the MAI TAI™ which provides ultrashort pulses **52** having a pulse width of 100 femtoseconds (fs) at 1 W of power in the 750 to 850 nm range at a repetition rate of 80 MHz. This laser **64** is pumped by a diode-pumped, frequency-doubled, solid-state green YAG laser (5 W or 10 W). Other exemplary ultrafast Nd:YAG or Nd:YLF lasers **64** include the JAGUAR-QCW-1000™ and the JAGUAR-CW-250™ sold by Time-Bandwidth® of Zurich, Switzerland.

[0050] **FIG. 7** shows a schematic diagram of a simplified alternative configuration of a laser system **108** for employing the present invention. Skilled persons will appreciate that for harmonically converted green and longer wavelength light, the E-O device **106** is preferably positioned after the harmonic conversion converter **102**.

[0051] **FIG. 8** shows a schematic diagram of another simplified alternative configuration of a laser system **110** for that employs an amplifier **112**.

[0052] Skilled person will appreciate that a Q-switched laser **64** without CW mode-locking is preferred for several embodiments, particularly for applications employing pulse widths greater than 0.1 ps. Such laser systems **60** does not employ a saturable absorber and optical paths **90** and **98** are collinear. Such alternative laser systems **60** are commercially available and well known to skilled practitioners.

[0053] Laser output **104** (regardless of wavelength or laser type) 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 F**1**, F**2**, or F**3** 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 link width **28** and the laser wavelength.

[0054] A preferred beam positioning system **62** is described in detail in U.S. Pat. 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.

[0055] 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 μm per second, then a typical displacement between two consecutive laser spots **38** with interval time of 1,000 ns between them would be typically less than 0.2 μm and preferably less then 0.06 μm 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 less than 1,000 ns and preferably between about 5 ns and 500 ns and can also be programmable by controlling Q-switch stepping, laser synchronization, or optical path delay techniques as later described.

[0056] 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 Koneeny 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, Oreg. could also be employed.

[**0057**] With reference again to **FIGS. 3-5**, in some embodiments, each set **50** of laser pulses **52** is preferably a burst of ultrashort laser pulses **52**, which are generally shorter than 25 ps, preferably shorter than or equal to 10 ps, and most preferably from about 10 ps to 100 fs or shorter. The laser pulse widths are preferably shorter than 10 ps because material processing with such laser pulses **52** is believed to be a nonthermal process unlike material processing with laser pulses of longer pulse widths.

[**0058**] During a set **50** of ultrashort laser pulses **52**, each laser pulse **52** pits off a small part or sublayer of the passivation layer **44** and/or link material needed to be removed without generating significant heat in link structure **36** or IC device **12**. Due to its extremely short pulse width, each pulse exhibits high laser energy intensity that causes dielectric breakdown in conventionally transparent passivation materials. Each laser pulse breaks off a thin sublayer of, for example, about 1,000-2,000 Å of overlying passivation layer **44** until overlying passivation layer **44** is removed. Consecutive ultrashort laser pulses **52** ablate metallic link **22** in a similar layer by layer manner. For conventionally opaque material, each ultrashort pulse **52** ablates a sublayer having a thickness comparable to the absorption depth of the material at the wavelength used. The absorption or ablation depth per single ultrashort laser pulse for most metals is about 100-300 Å.

[**0059**] Although in many circumstances a wide range of energies per ultrashort laser pulse **52** will yield substantially similar severing depths, in a preferred embodiment, each ultrashort laser pulse **52** ablates about a 0.02-0.2 μm depth of material within spot size **40**. When ultrashort pulses are employed, preferred sets **50** include 2 to 20 ultrashort pulses **52**.

[**0060**] In addition to the "nonthermal" and well-controllable nature of ultrashort laser processing, some common ultrashort laser sources are at wavelengths of around 800 nm and facilitate delivery of a small-sized laser spot. Skilled persons will appreciate, however, that the substantially nonthermal nature of material interaction with ultrashort pulses **52** permits IR laser output be used on links **22** that are narrower without producing an irregular unacceptable explosion pattern. Skilled persons will also appreciate that due to the ultrashort laser pulse width and the higher laser intensity, a higher laser frequency conversion efficiency can be readily achieved and employed.

[**0061**] With reference **FIGS. 9-16**, in some embodiments, each set **50** preferably includes 2 to 10 pulses **52**, which are 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. These typically smaller sets **50** of laser pulses **52** may be generated by additional methods and laser system configurations. For example, with reference to **FIG. 9**, the energy densities of pulses **52***d* of set **50***d* can accomplished with a simultaneously Q-switched and CW mode-locked laser system **60** (**FIG. 6**).

[**0062**] **FIG. 10A** depicts an energy density profile of typical laser output from a conventional laser used for link blowing. **FIG. 10B** depicts an energy density profile of a set **50***e* of laser pulses **52**e_2 and **52**e_2 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 **50***e* 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 **50***c* 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.

[**0063**] **FIG. 11** 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 **52**e_3 and **52**e_4, such as shown in **FIG. 12**, which is a power versus time graph.

[**0064**] With reference to **FIGS. 11 and 12**, RF level **54***a* is sufficient to prevent generation of a laser pulse **52***e*. The RF signal **54** is reduced to an intermediate RF level **54***b* that permits generation of laser pulse **52**e_3, and then the RF signal **54** is eliminated to RF level **54***c* to permit generation of laser pulse **52**e_4. The step-control Q-switching technique causes the laser pulse **52**e_3 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) **52**e_4 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 **54***b* can be used to control the peak-instantaneous powers of pulses **52**e_3 and **52**e_4 as well as the time offset between the laser pulses **52** in each set **50**. More that two laser pulses **52***e* can be generated in each set **50***e*, and the laser pulses **52***e* may have equal or unequal amplitudes within or between sets **50***e* by adjusting the number of steps and duration of the RF signal **54**.

[**0065**] **FIG. 13** is a simplified schematic diagram of an alternative embodiment of a laser system **60***b* employing a Q-switched laser **64***b* (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** diverts a portion of the laser light from beam path **120** and causes a portion of the light to propagate along beam path **120***a* and a portion of the light to propagate along optical delay path **170** to reflective mirrors **174***a* and **174***b*, 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

120*a* into a single beam path **120***b*. Skilled persons will appreciate that optical delay path **170** can be positioned at a variety of other locations between laser **64***b* 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.

[**0066**] **FIGS. 14A-14D** show respective power versus time graphs of exemplary laser pulses **52***f* propagating along optical paths **120**, **120***a*, **120***b*, and **170** of the laser system **60***b* shown in **FIG. 13**. With reference to **FIGS. 13 and** **14**A-14D, **FIG. 14A** 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 **52**f_1 of **FIG. 14B and 52**f_2 of **FIG. 14C** (generically laser pulses **52***f*), which respectively propagate along optical path **120***a* and optical delay path **170**. After passing through the optional half wave plate **176**, laser pulse **52**f_2 passes through combiner **178** where it is rejoined with laser pulse **52**f_1 propagate along optical path **120***b*. **FIG. 14D** shows the resultant power versus time graph of laser pulses **52**f_1 and **52**f_2 propagating along optical path **120***b*. Because optical delay path **170** is longer than beam path **120***a*, laser pulse **52**f_2 occurs along beam path **120***b* at a time later than **52**f_1.

[**0067**] 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 **50***c*. Skilled persons will also appreciate that the length of optical delay path **170** can be adjusted to control the timing of respective pulses **52***f*. 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.

[**0068**] 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. Similarly, additional polarization devices can be positioned as desired along one or more of the optical paths. In addition, different optical paths can be used to generate pulses **52** of different spot sizes within a set **50**.

[**0069**] **FIG. 15** is a simplified schematic diagram of an alternative embodiment of a laser system **60***c* that employs two or more lasers **64**c_1 and **64**c_2 (generally lasers **64**) to implement the present invention, and **FIGS. 16A-16C** show respective power versus time graphs of an exemplary laser pulses **52**g_1 and **52**g_2 (generically **52***g*) propagating along optical paths **120***c*, **120***d*, and **120***e* of laser system **60***c* shown in **FIG. 15**. With reference to **FIGS. 15 and** **16**A-**16**C, lasers **64** are preferably Q-switched (preferably not CW mode-locked) lasers of types previously discussed or well-known variations and can be of the same type or different types. 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.

[**0070**] Laser **64**c_1 emits laser pulse **52**g_1 that propagates along optical path **120***c* and then passes through a combiner **178**, and laser **64**c_2 emits laser pulse **52**g_2 that propagates along optical path **120***d* and then passes through an optional half wave plate **176** and the combiner **178**, such that both laser pulses **52**g_1 and **52**g_2 propagate along optical path **120***e* but are temporally separated to produce a set **50***g* of laser pulses **52***g* having a power versus time profile shown in **FIG. 16C**.

[**0071**] 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**.

[**0072**] 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.

[**0073**] 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.

[**0074**] Similarly, passivation layers **44** above or below the links **22** can be made with material other than the traditional SiO2 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 μm or less from other links **22** or adjacent circuit structures **34**.

[**0075**] 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.

1. A laser system for severing a conductive link in an integrated circuit (IC), comprising:

a laser source operable to generate at least two laser pulses, the laser pulses including a first laser pulse and a second laser pulse, and each of the first and second laser pulses producing a laser spot at the integrated circuit; and a beam positioning system operable to utilize position data representative of locations of one or more conductive links and to coordinate directing the laser pulses to a selected conductive link, wherein the laser spots are in movement relative to the selected conductive link while the laser pulses are directed to the selected conductive link, the first and second laser pulses are sequentially directed to the selected conductive link, and the laser pulses sever the selected conductive link.

2. The system of claim 1, comprising a focusing lens between the laser source and the integrated circuit, wherein the focusing lens is in relative movement with respect to the selected conductive link while the laser pulses are directed to the selected conductive link.

3. The system of claim 1, wherein the beam positioning system is operable to direct a first set of two or more laser pulses and a second set of two or more laser pulses to sever respective conductive links, wherein the laser pulses in the first and second sets have different energy density profiles.

4. The system of claim 1, comprising a laser pulse gating device between the laser source and the integrated circuit.

5. The system of claim 1, wherein the selected conductive link comprises a link of a memory device or a logic device.

6. The system of claim 1, wherein a passivation layer overlies the selected conductive link.

7. The system of claim 6, wherein at least one of the laser pulses removes a 0.01-0.2 micron thickness of the passivation layer overlying the selected conductive link.

8. The system of claim 1, wherein the beam positioning system is operable to direct a first set of at least two laser pulses to sever a first selected conductive link and a second set of at least two laser pulses to sever a second selected conductive link, wherein a repetition rate between the first and second sets is greater than about 1 Hz.

9. The system of claim 8, wherein the repetition rate is less than about 5 kHz.

10. The system of claim 1, wherein the first and second laser pulses have substantially the same energy characteristics.

11. The system of claim 1, comprising an amplifier between the laser source and the integrated circuit.

12. The system of claim 1, wherein a burst comprising the laser pulses has a width less than 500 ns.

13. The system of claim 12, wherein the burst comprises 2 to 50 of the laser pulses.

14. The system of claim 1, wherein the second laser pulse starts after the end of the first laser pulse.

15. The system of claim 1, wherein each of the laser pulses have energy characteristics, and the number of laser pulses and the energy characteristics of each of the laser pulses are determined as a function of the thickness of the selected conductive link to be severed.

16. The system of claim 1, wherein the selected conductive link has a width less than or equal to about 1 μm.

17. The system of claim 1, wherein the selected conductive link is comprised of a chromide, aluminum, copper, polysilicon, disilicide, gold, nickel, nickel chromide, platinum, polycide, tantalum nitride, titanium, titanium nitride, tungsten, or tungsten silicide material.

18. The system of claim 1, wherein the laser spots have spot sizes that are the same.

19. The system of claim 1, wherein the laser source includes a mode locked laser.

20. The system of claim 1, wherein the laser spots overlap at the selected conductive link.

21. The system of claim 1, wherein each of the first and second laser pulses has a single peak pulse shape.

22. The system of claim 1, wherein the laser pulses have a wavelength about 200 to 1320 nm.

23. The system of claim 1, wherein the laser pulses have an ultraviolet (UV) or near UV wavelength.

24. The system of claim 1, wherein the laser pulses have a total energy of about 0.01 μJ to 10 mJ.

25. The system of claim 1, wherein at least one of the laser spots has a spot size that is greater than a width of the selected conductive link.

26. The system of claim 1, comprising at least two stages in a split-axis configuration operable to move the selected conductive link relative to the laser spots.

27. The system of claim 1, comprising at least two stages in a stacked configuration operable to move the selected conductive link relative to the laser spots.

28. The system of claim 1, wherein the laser source includes a Q-switched laser.

29. The system of claim 28, wherein the Q-switched laser includes a misaligned Q-switch.

30. The system of claim 1, comprising a device operable to change an energy characteristic of at least one of the initial laser pulses wherein the device is located between the laser source and the integrated circuit.

31. The system of claim 1, wherein the laser source includes an A-O, Q-switched, solid-state laser having an A-O Q-switch that is step controlled such that an RF signal to the Q-switch is reduced from a high power level to an intermediate level to generate the first laser pulse, and the RF signal to the Q-switch is reduced from the intermediate RF level to a smaller RF level to generate the second laser pulse.

32. The system of claim 1, wherein at least one of the laser pulses has a pulse width of less than 25 picoseconds.

33. The system of claim 1, wherein the selected conductive link is not covered by an overlying passivation layer.

34. The system of claim 1, wherein at least one of the laser pulses removes a 0.01-0.03 micron thickness of the selected conductive link.

35. A laser system for severing a conductive link in an integrated circuit (IC), comprising:

a laser source operable to generate at least two laser pulses, the laser pulses including a first laser pulse and a second laser pulse, and each of the first and second laser pulses producing a laser spot at the integrated circuit; and

a beam positioning system operable to utilize position data representative of locations of one or more conductive links and to coordinate directing the laser pulses through a focusing lens to a selected conductive link, wherein the focusing lens is in relative motion with respect to the selected conductive link while the laser pulses are directed to the selected conductive link, the first and second laser pulses are sequentially directed to the selected conductive link, and the laser pulses sever the selected conductive link.

36. A laser system for severing a conductive link in an integrated circuit (IC), comprising:

a laser source operable to generate at least two laser pulses, the laser pulses including a first laser pulse and a second laser pulse, and each of the first and second laser pulses producing a laser spot at the integrated circuit; and

a beam positioning system operable to utilize position data representative of locations of one or more conductive links and to coordinate directing the laser pulses to a selected conductive link provided above at least one platform, wherein the laser spots are in movement relative to the selected conductive link while the laser pulses are directed to the selected conductive link, the platform is in motion while the laser pulses are directed to the selected conductive link, the first and second laser pulses are sequentially directed to the selected conductive link, and the laser pulses sever the selected conductive link.

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