The State of the Art and Future Prospects for Laser Direct-Write for Industrial and Commercial Applications

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Abstract

Laser direct-write (LDW) is an established technology for manufacturing electronic and optoelectronic appliances such as cellular telephones, digital cameras, and notebook-type personal computers. One of the most successful applications is laser drilling of via holes on printed circuit boards for the manufacture of cellular telephones. Other practical applications include marking, dicing, trimming, repairing, patterning, bending, and rapid prototyping. In this article, the state of the art of LDW for industrial applications in Japan, the United States, and Europe is reviewed, and its future prospects are discussed.

Overview of LDW in Industry

Recently, increasing demand for small size, light weight, and high speed in electronic appliances such as cellular telephones, digital cameras, and notebook-type personal computers (PCs) is establishing laser direct-write (LDW) as an attractive technology in the microelectronics and optoelectronics industries due to its excellent features of high speed, high flexibility, high precision, high reliability, and use of fewer chemicals and fewer process steps compared with conventional semiconductor processing based on photolithography. Table I summarizes representative applications of LDW in microelectronics and optoelectronics.

One of the biggest markets for LDW is laser drilling of via holes for stacked or built-up printed circuit boards (PCBs). Built-up PCBs are primarily used in cellular telephones, digital video cameras, and digital still cameras.[1] Currently, ~250–300 production systems for high-throughput laser drilling of via holes are put in operation each year worldwide, and the number is expected to increase.[2] Back in 1998, most of the $1 billion total output of PCBs in the world was produced in Japan, while in 2005 the output increased to $7 billion, but Japan's share was reduced to 40%. Taiwan, China, and South Korea generated 50%, and the remaining 10% was produced in Europe, the United States, and other countries. Currently, pulsed CO_2 lasers are mainly used for drilling via holes with diameters in the range of ~75–150 μm, but in several years, these will be replaced by UV Nd:YAG lasers as via-hole diameters smaller than 50 μm become commonplace.

The other important markets for LDW are photomask repair, memory repair, marking, trimming, patterning of solar cells, microwelding, and rapid prototyping.[3] The repair of photomasks is driven by two different applications, large-scale integration (LSI) in semiconductor integrated circuits and in liquid-crystal displays (LCDs). High-precision repair with accuracy better than ±0.1 μm is required for LSI photomasks, while high-throughput repair is necessary to process LCD masks exceeding 600 mm. Opaque defects are repaired by ablation of excess material, while clear defects are corrected by laser chemical vapor deposition (LCVD). Memory repair using LDW is also becoming necessary in order to improve yields in 64-Mbit and 256-Mbit dynamic random-access memories (DRAMs).

It should be noted that the largest share of laser-based manufacturing systems installed in industry is dedicated to laser marking of semiconductor wafers, integrated circuit (IC) packages, chip-scale packages (CSPs), and other components (see Table I).[4] Recently, the introduction of laser marking systems to production lines in the electronics and semiconductor industries has rapidly enhanced labeling of IC packages and wafers. Laser trimming of small-size chip resistors and ultralow-resistance resistors is also a growing application for the manufacture of cellular telephones, digital video cameras, and notebook PCs. Laser patterning is now a popular method to produce large-scale solar cell modules based on amorphous Si.[5] Laser spot welding is already used for diverse applications such as assembling electronic guns for cathode-ray tube monitors, optical modules, miniature signal relays, and magnetic head suspensions in hard disks. Additionally, laser seam welding is used to assemble lithium-ion batteries, fuel injectors, pressure sensors, and other microelectronic components. Three-dimensional (3D) rapid prototyping techniques such as stereolithography and selective laser sintering find many practical applications in design verification, function and performance evaluation, and production of working models for direct injection-molding dies and patient-specific medical models.

CO_2 and solid-state lasers are still the dominant laser sources for the aforementioned industrial applications, with excimer lasers being used in high-precision applications like inkjet nozzles and indium tin oxide (ITO) patterning. Fiber lasers are becoming more available and

Table I. Representative Applications of Laser Direct-Write in Microelectronics and Optoelectronics.

Process	Applications	Typical Lasers Used
Ablation	Photomask repair	Q-switched solid-state laser, ultrafast laser
	Memory repair	Q-switched solid-state laser, fiber laser
	TFT-LCD repair	Q-switched solid-state laser
	Color filter repair	Q-switched solid-state laser
	Electric circuit patterning (MIDs, GPS antennae, etc.)	THG Q-switched Nd:YAG laser
	Quartz oscillator tuning	Q-switched solid-state laser
	ITO patterning for displays	Q-switched solid-state laser
	Patterning of a-Si solar cell modules	Q-switched solid-state laser, excimer laser
Drilling	Via holes in printed circuit boards	Pulsed CO_2 laser, THG Q-switched Nd:YAG laser
	Via holes in IC interconnects	THG Q-switched solid-state laser, excimer laser
	Inkjet nozzle formation	Excimer laser, Q-switched solid-state laser including SHG and THG, ultrafast laser
	Microfluidics	Excimer laser, CO_2 laser, Q-switched solid-state laser
	Ceramic substrates	CO_2 laser
	Small hole drilling for drug delivery packages	Excimer laser
Marking	IC package marking	Q-switched solid-state laser
	Electronic component marking	Nd:YAG laser, CO_2 laser, excimer laser
	Keyboard and keypad marking	Q-switched solid-state laser
	Si wafer marking	Q-switched solid-state laser
	Chip-scale package marking	Q-switched solid-state laser including SHG
	Glass substrate marking	Q-switched solid-state laser including SHG and THG, CO_2 laser
	General-purpose marking	Q-switched solid-state laser, CO_2 laser
	CD label marking	Q-switched solid-state laser
	Inner-layer or subsurface glass marking	Q-switched solid-state laser including THG
Dicing	Thin Si wafer dicing	Q-switched solid-state laser, etc.
	Sapphire wafer dicing	THG Q-switched Nd:YAG laser
	Solar panel dicing	Q-switched solid-state laser, fiber laser

are poised to rapidly replace diode-pumped solid-state (DPSS) lasers in some applications, due to their unique characteristics, including better beam quality, pulse shaping capability, better reliability, small footprint, long lifetime, and eventually, lower cost. Currently, one can find fiber lasers being used in marking, drilling, and welding applications, and the trend is going to continue.

Diode lasers are another interesting laser source to watch. Traditionally, the beam and power from diodes have been considered inadequate for materials processing. As improvements are made in both the beam quality and power available directly from the diodes, some applications such as surface modification and welding will immediately benefit. Diode lasers are now used to treat metal surfaces for medical devices and automotive parts.

It is obvious that the large number of industrial applications for LDW combined with the development of new laser sources provides many interesting possibilities. Some of the novel applications being developed in Japan, the United States, and Europe are described in the following sections.

Industrial Applications of LDW in Japan

In Japan, almost all the applications summarized in Table I are being pursued. We have chosen to highlight three techniques that exemplify the unique advantages of LDW for industrial applications.

The first technique is known as stealth dicing, and it shows the high speeds and improved precision achievable with LDW compared with standard wafer dicing processes. The second technique is called microscopic integrated processing, and it demonstrates the unique ability of LDW to generate 3D patterns of arbitrary shapes, which is not possible with traditional photolithographic processes. The final technique illustrates how LDW can achieve high throughput despite its serial nature by utilizing multibeam parallel processing approaches.

Recent demands for higher densities and complex functions in semiconductor devices are bringing about numerous difficulties with current wafer dicing technologies. Hamamatsu Photonics developed the stealth dicing technique, in which a Q-switched solid-state laser beam at a wavelength transparent to the wafer is scanned across its surface while focused at a point

Table I (*Continued*)

Process	Applications	Typical Lasers Used
Cutting	FPD glass substrate cutting	CW CO_2 laser
	Medical stent fabrication	Q-switched solid-state laser, fiber laser
	Ceramic substrate scribing	CO_2 laser
Chemical vapor deposition	Photomask repairing	THG Q-switched Nd:YLF laser
	LCD panel repairing	THG Q-switched Nd:YLF laser
Bending	Adjustment of magnetic head components	Q-switched Nd:YAG laser
Trimming	Wafer trimming (thin film and fuse)	Q-switched solid-state laser including SHG
	Chip resistor trimming (thick and thin films)	Q-switched solid-state laser including SHG
	Embedded printed circuit board trimming	Q-switched solid-state laser including SHG and THG
Microwelding	Electronic guns, optical modules, miniature signal relays, magnetic head suspensions for hard disks, razors, pacemakers, lithium-ion batteries, fuel injectors, and pressure sensors	Solid-state laser, diode laser, fiber laser
Surface treatment	Medical devices	Solid-state laser, diode laser
Stereolithography	3D rapid prototyping (design verification, working model, function and performance evaluation, direct injection molding die, medical model, etc.)	He-Cd laser
Selective laser sintering	3D rapid prototyping (design verification, working model, function and performance evaluation, direct injection molding die, medical model, etc.)	CO_2 laser

Abbreviations:
CD – compact disc
CW – continuous wave
FPD – flat-panel display
GPS – global positioning system
IC – integrated circuit
ITO – indium tin oxide
LCD – liquid-crystal display
MID – molded interconnect device
SHG – second harmonic generation
TFT – thin-film transistor
THG – third harmonic generation
YAG – yttrium aluminum garnet
YLF – yttrium lithium fluoride

below the surface.[6] The extremely high peak power density localized only in the vicinity of the focal point induces multiphoton absorption and then forms damaged layers inside the wafer. The wafers after stealth dicing are easily separated into individual chips or bare dies by the same tape-expanding process commonly used in conventional diamond blade dicing. Figure 1 shows images of the front side edge of chips diced from 100-μm-thick Si wafers by blade dicing and stealth dicing. It should be noted that the process speed of 300 mm/s for stealth dicing is three times faster than blade dicing, and that the stealth-diced chip shows little kerf loss (the volume removed by dicing). Neither chipping nor cracking is evident. Furthermore, stealth dicing is a completely dry process that provides high-speed, high-quality dicing at a low operating cost. The stealth dicing technique was initially developed for dicing of ultrathin semiconductor wafers but can be applied to normal thickness, low-*k* devices and microelectromechanical systems (MEMS) wafers.

Matsushita Electric Works Ltd. has developed an LDW technique called microscopic integrated processing technology (MIPTEC) for the manufacture of molded interconnect devices.[7] The procedure consists of five steps (Figure 2): (1) molding of the insulator substrates, (2) chemical plating of the substrates with thin metal films, (3) 3D laser patterning of the metal thin films, (4) electroplating of desirable regions with thick metal films, and (5) soft etching to remove chemically plated metal thin films where metal deposition by the electroplating (step 4) is not carried out. The 3D patterning using a five-axis stage was realized by control of the laser focal plane using a dynamic focusing system as well as control of the laser irradiation parameters. As a result, fine line and space resolution of 30 μm on 3D substrates with a height of up to 10 mm has been achieved. This technique was successfully applied to the manufacture of optical converter assemblies, passive infrared motion sensors, camera modules (Figure 3), and global positioning system antennae for cellular telephones.

In order to achieve high throughput in mass production using LDW techniques, multibeam parallel processing is indispensable. Diffractive optics are a competitive and cost-effective solution for the implementation of multibeam LDW tools. Seiko Epson Corp. is adopting diffractive optics

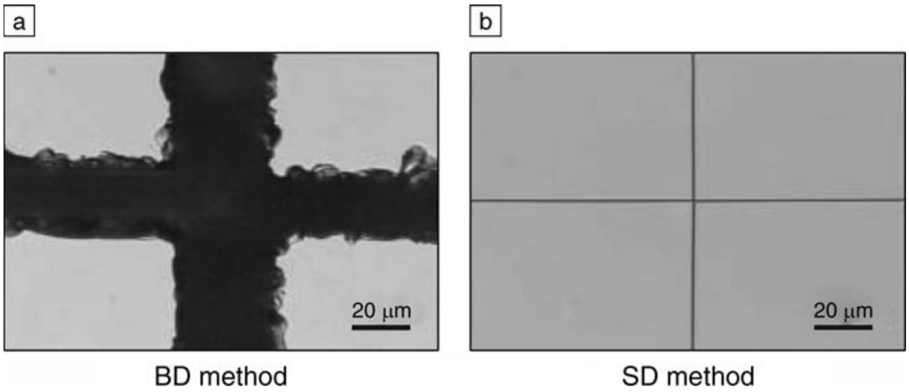

Figure 1. Optical microscope images of the front side edge of chips diced from 100-µm-thick Si wafers by (a) diamond blade dicing (BD) and (b) stealth dicing (SD) methods. (Courtesy of Hamamatsu Photonics.)

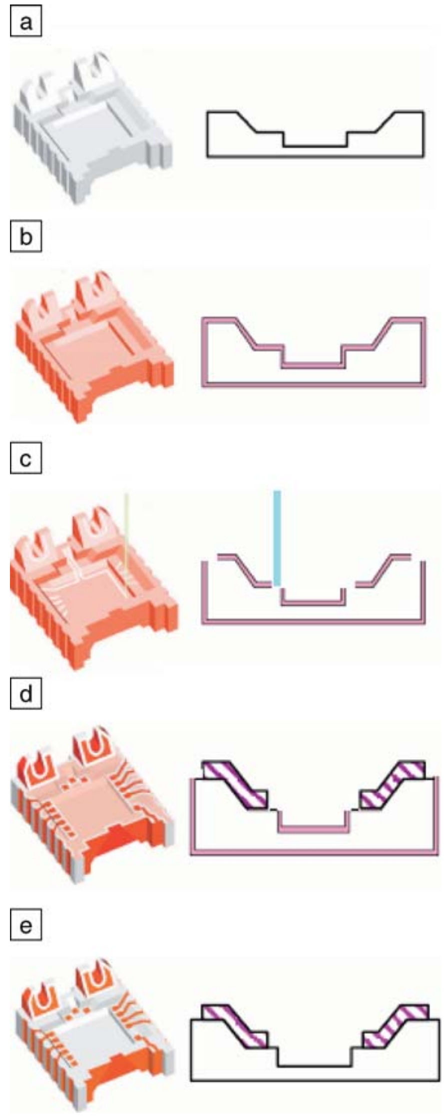

Figure 2. (a)–(e) Schematic illustrations showing the five steps in the microscopic integrated processing technology (MIPTEC) process. (Courtesy of Matsushita Electric Works Ltd.)

for mass production applications such as (1) laser drilling of silicon wafers to form microcavities in nozzles for inkjet printers using a diffractive array illuminator (Figure 4), (2) laser cutting of metal films on LCD panels for cellular telephones using diffractive focusing optics, (3) laser soldering of quartz oscillators onto printed circuits set in wristwatches using a diffractive beam duplicator, and (4) laser sealing of packages using diffraction patterns to house electronic components.[8]

Industrial Applications of LDW in the United States

In the United States, industrial applications of LDW can be found in almost all areas listed in Table I. Major applications in the semiconductor and electronics industries include, as mentioned earlier, laser marking of microelectronic components and semiconductor wafers, drilling of via holes in PCBs, trimming in chip resistors and wafers, memory repair, hole formation in inkjet nozzles, ceramic substrate drilling, and dicing. Other applications include substrate annealing, marking and patterning of ITO layers for the display industry, and manufacturing of medical devices such as tubular stents and small hole drilling in drug delivery packages. Following are some examples illustrating LDW applications in the semiconductor and electronics industries and the progress made in the last few years.

LDW applications for semiconductor memory repair typically employ DPSS lasers or fiber lasers. These lasers are used for ablating polysilicon or metal links to redundant elements on DRAMs.[9,10] This process is known as laser fuse processing and allows fast and effective replacement of defective elements with redundant ones, thus improving overall device yield. Typical DPSS lasers can be fired at rates of up to 100 kHz, and each repair usually requires only a single laser shot. More recently, shaped-pulse fiber lasers are being used for this same application. Performing laser fuse processing with a shaped laser pulse allows adjustment of the pulse width, enhancing the process window for blowing the redundant metal fuses or links while minimizing damage to the surrounding substrate. This improves process yields, especially in metal links where coupling of the laser energy into the metal film layer can be greatly improved by the fast rise time of the fiber laser pulse.

A well-known application in the semiconductor industry of LDW using ultrafast lasers is the repair of chromium-on-fused-silica photomasks for deep-UV photolithography. Femtosecond lasers are well suited to repairing photomasks. Ultrafast-laser-based photomask repair tools are now operating at IBM's mask-making facility in Burlington, Vermont.[11–13] These tools are among the first applications of femtosecond technology in a semiconductor manufacturing environment. Figure 5 shows a chromium-on-glass photomask before and after repair with an ultrafast laser. It shows absorber material removed without damage to the underlying glass substrate and without leaving any debris. More details on this and other LDW applications using ultrafast lasers can be found in the August 2006 issue of *MRS Bulletin.*

Laser marking of silicon wafers has been the industry standard for decades. The semiconductor industry requires total traceability from ingot to die. Traditionally, lasers with wavelengths near 1 µm have been used to generate both soft marks and hard marks. Recently, wafer marking at the die level has been introduced, due to the development of chip-scale package technology and the need for total traceability down to the individual die level.[14] A green laser (532 nm) is chosen over the traditional 1-µm laser because of its ability to write in smaller fonts with less thermal impact. Figure 6 shows a 200-mm wafer with dies marked by a laser.

On-chip resistor trimming by lasers has been another standard of the electronics industry for many years.[15] More recently, driven by the low cost of embedded technologies, laser trimming of embedded components on PCBs has been introduced.[16,17] Figure 7 shows a green probe card with 26 probe tips connecting to an

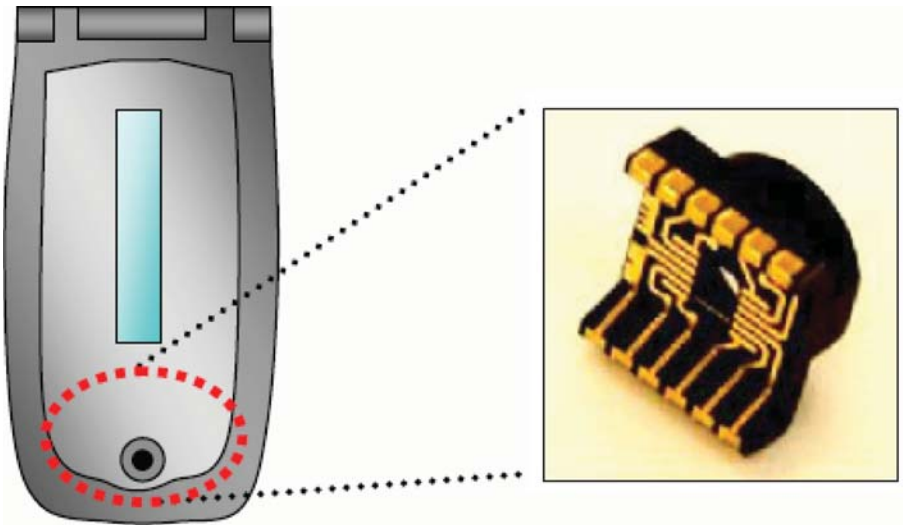

Figure 3. (left) Schematic illustration of a cellular telephone, showing the placement of a camera module (shown at right) whose size is approximately 5 mm 3 5 mm manufactured by the microscopic integrated processing technology (MIPTEC) process. (Courtesy of Matsushita Electric Works Ltd.)

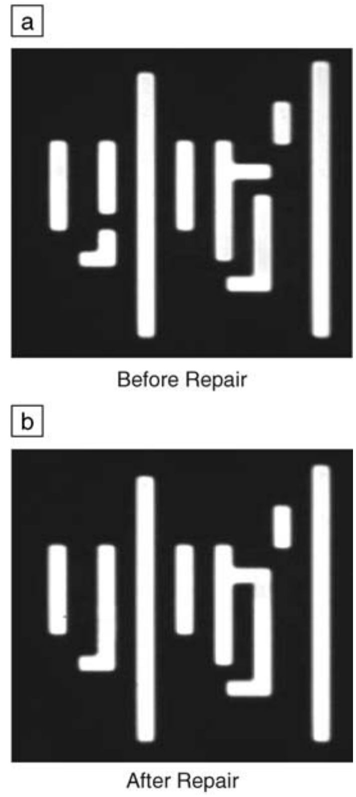

Figure 5. A chromium-on-glass photomask (a) before repair and (b) after repair with an ultrafast laser. No debris or damage to the underlying substrate was observed. Line width: 750 nm. (Courtesy of IBM.)

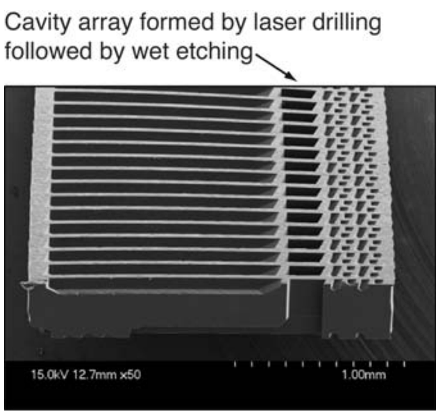

Figure 4. Optical photograph of a cavity array for inkjet printing fabricated in a 400-mm-thick Si substrate by laser drilling using diffractive optics followed by anisotropic wet etching in a KOH solution. (Courtesy of Seiko Epson Corp.)

embedded PCB subsystem ready to be trimmed by a laser directed from above.

Our last example is the application of LDW to drill inkjet nozzles of specific shapes. For the first time in mass production, picosecond lasers are being used by Panasonic U.S. to produce inkjet nozzles in the shape of microfunnels.[18] The picosecond laser, together with a PC-controlled scanning mirror, can fabricate the holes reproducibly, precisely, and fast. Figure 8 is a scanning electron micrograph of a funnel hole drilled by a picosecond laser in stainless steel.

Industrial Applications of LDW in Europe

European industry has made significant advances in LDW technology in recent years, both in terms of laser sources and new applications. The need for direct-write lasers operating in new regimes of power and/or pulse duration has led to a number of startup laser companies in the fiber laser and DPSS laser sectors. Some of these ventures, such as SPI Lasers, a spin-off from the University of Southampton in the United Kingdom, have achieved impressive growth. SPI has focused mainly on medium-power (up to 100 W), continuous-wave modulated fiber lasers,[19] which are ideal for finer direct-write metal machining applications such as cutting of medical stents[20] (Figure 9) and solder paste stencils for electronics manufacturing. New short-pulse and ultrashort-pulse fiber lasers are also becoming available in this power range, and it is anticipated that these will have an impact on other application areas previously associated with fundamental DPSS lasers. On the DPSS side, advances have been made in the area of high-power lasers. For example, the Imperial College London spin-off company Powerlase has recently developed a range of high-M^2 (which is a measure of beam quality, or how tightly a beam can be focused under specific conditions), Q-switched lasers with average powers of up to 800 W, opening up new opportunities for LDW in large-area industrial applications such as ITO patterning for flat-panel displays.[21] Such higher-power lasers allow LDW techniques to be competitive with other processes for large-area applications in terms of speed, throughput, and cost. Some specific examples of emerging LDW applications in Europe are provided below.

Machining of solar panels is a major application for DPSS lasers, particularly in Germany. Laser scribing, either at 1.06-µm or 532-nm wavelengths, can be used to pattern all the layers in a thin-film solar cell of the type shown schematically in Figure 10. The transparent conductive oxide (TCO) layer is patterned in the infrared, while the semiconductor and interconnect metal layers are patterned in the green. Problems with poor edge quality, encountered in early work using quasi-Gaussian beams, have been overcome by using appropriate beam shaping and delivery optics to produce uniform illumination in the laser spot. For example, Figure 10 shows a high-quality 50-µm-wide line scribed in an ITO layer on glass. High-throughput machining is achieved by combining beam scanning with workpiece motion,[22] as in large-area display applications.

Micromachining of silicon is becoming an important application area for visible and UV DPSS lasers. The main applications currently are the cutting of through-wafer ink channels in inkjet printer chips,[23] where laser machining provides a cleaner and more precise alternative to powder-blasting, and the drilling of via holes for advanced microelectronics packaging[24] (see Figure 11). In the latter application, the laser-drilled vias may be metallized to provide through-wafer electrical interconnection or enhanced heat transfer in high-density 3D "stacked die" assemblies.

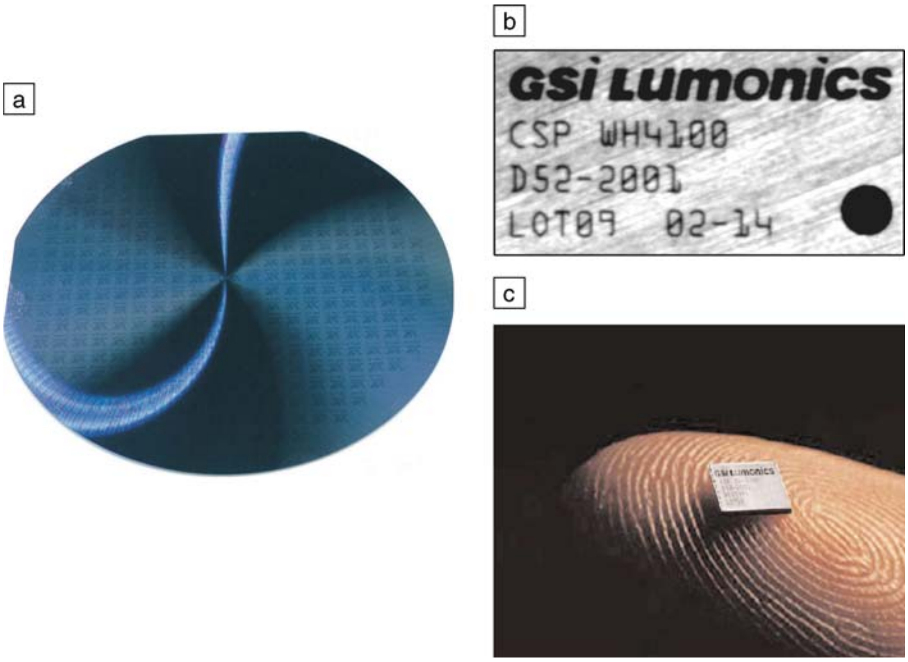

Figure 6. (a) 200-mm wafer with laser-marked dies. There are 400 laser-marked dies on this wafer. (b) Examples of die marks. The die is 3 mm wide. The same die is shown in both (b) and (c). (Courtesy of GSI Group.)

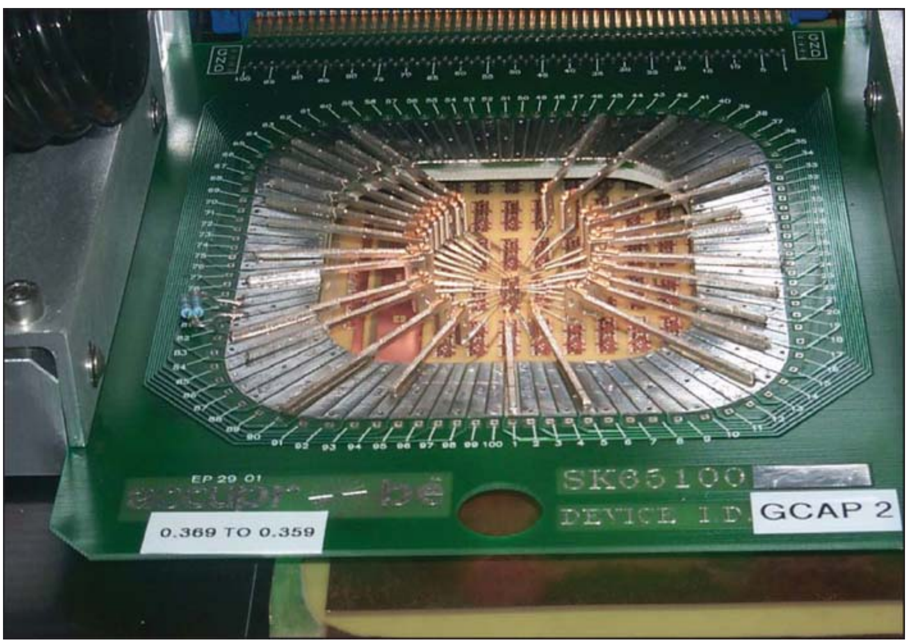

Figure 7. A test subsystem of an embedded PCB laser trimming system showing a green probe card (200 mm 3180 mm) with 26 probe tips testing a portion of the PCB while being laser trimmed. (Courtesy of GSI Group.)

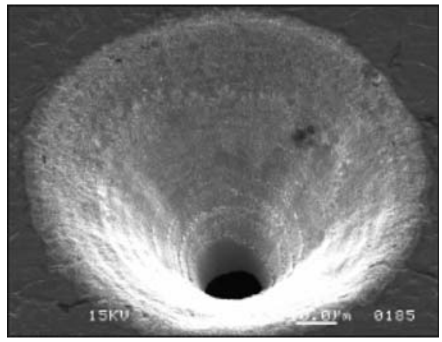

Figure 8. Scanning electron micrograph of a funnel hole drilled by a picosecond laser in stainless steel.[18] The size marker reads 10.0 μm.

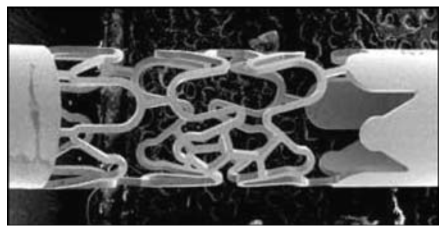

Figure 9. Stent cut by fiber laser in Type 304 stainless steel tube (1.8 mm outer diameter). (Courtesy of SPI Lasers.)

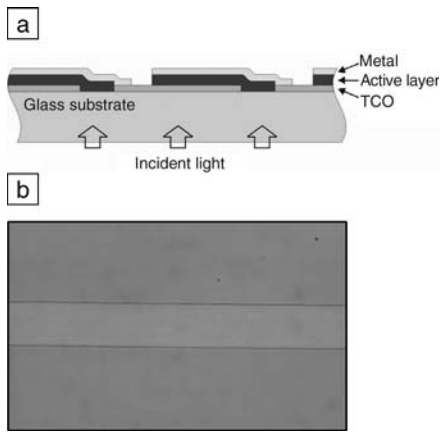

Figure 10. (a) Schematic cross section of thin-film solar panel showing series-connected cells, and (b) optical micrograph showing a 50-mm-wide line scribed in ITO on glass using fundamental Nd:YAG laser. TCO is a transparent conductive oxide layer. (Courtesy of Exitech Ltd.)

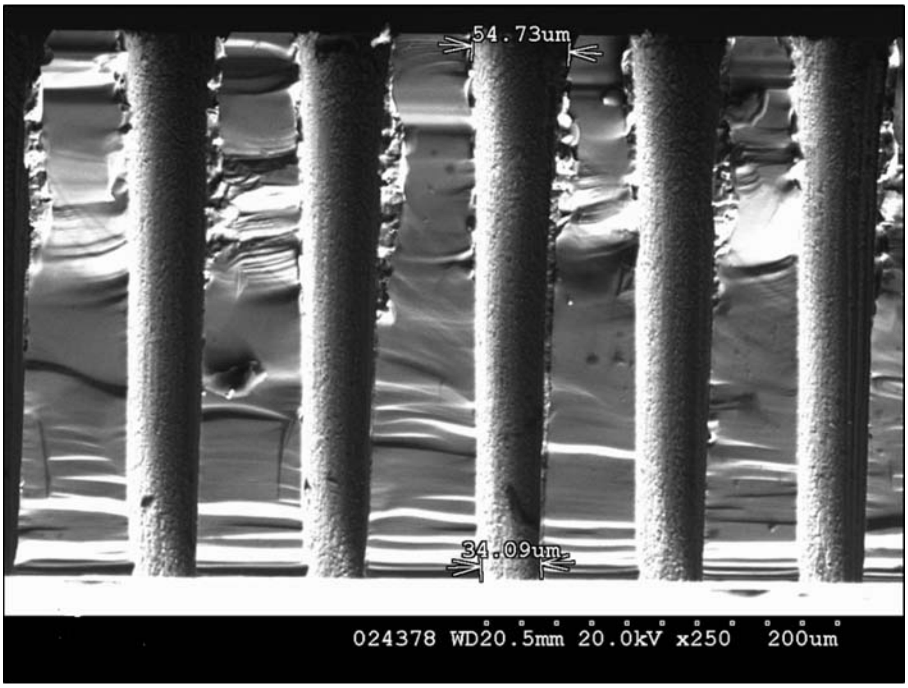

Figure 11. High-aspect-ratio, through-wafer via holes in 300-µm-thick silicon, machined using a 355-nm wavelength Q-switched diode-pumped solid-state laser. (Courtesy of XSiL Ltd.)

Dicing of semiconductor substrates is another area that is being aggressively pursued by several European equipment suppliers, most notably XSil (Ireland) and Synova (Switzerland). Dicing by LDW allows narrower, cleaner cuts than can be achieved by conventional sawing using diamond cutting wheels, as well as the possibility of irregular die shapes and sizes and the ability to handle thin or brittle substrates.[24,25] Minimization of ablation debris is a key issue with any process of this kind. The Synova approach, known as laser microjet, which uses a fine water jet to guide the laser light to the workpiece, potentially offers an advantage in that the water jet also serves to remove debris from the machining site. On the other hand, dry processes, if sufficiently clean, such as the stealth dicing process described earlier, are a highly attractive prospect, particularly for MEMS, which may have delicate moving parts that would need protection in a wet dicing process.

New applications are continually emerging in the MEMS/microsystems domain, particularly in areas such as bio/chemical sensors, microfluidic chips, and rf MEMS devices.[23] These are application areas that require processing of non-silicon materials, such as polymers and glasses, where traditional MEMS processes are not available. Examples are LDW of fluidic channels and via holes for ground connections in rf devices. LDW is also being considered for localized processing of MEMS structures, for example, to trim by removal of bulk material, or to pattern thin metal films on part-fabricated structures that are difficult to process conventionally because of extreme topography and/or fragility.

Future Prospects for LDW

The previous sections illustrate a few of the numerous industrial applications of LDW across Japan, the United States, and Europe, underscoring its growth potential. As the examples show, LDW techniques are driven by industrial applications, particularly in the semiconductor and microelectronics industries, where novel approaches are required in order to satisfy new product cycles that demand improvements in precision and reliability while maintaining high throughput and keeping costs low. Despite the criticism that LDW techniques are limited by their serial nature and the high capital cost associated with lasers, beam optics, and motion systems, this article demonstrates that these limitations can be surmounted with the proper approach and/or laser system. In particular, progress in high-efficiency, high-average-power, and high-repetition-rate laser systems, together with improvements in beam optics, has enabled much of the competitiveness. Continued improvements will open the door to other applications. For instance, fiber lasers are a promising tool for microwelding, cutting, rapid prototyping, and microbending applications, given the high-quality and alignment-less characteristics of their beam, combined with their high efficiency, long lifetime, and small size and weight. Ultrafast and beam-shaping systems can be used in 3D internal modification/microfabrication by multiphoton absorption, and make possible the development and manufacture of 3D integrated microsystems such as photonic devices[26] and biochips.[27] Commercial applications of these lasers are recent, and we expect them to become much more important for industrial applications in the near future. Finally, it should be noted that LDW hybrid techniques such as the previously described laser microjet are attractive for improving process quality and efficiency. Because of this, laser microjet systems are now commercially available for cutting, scribing, and microstructuring of various kinds of materials. These examples show that as long as the development of novel laser processing technologies and advanced laser systems continues, laser direct-write processes will continue to play a role at the forefront of laser materials processing solutions for industrial applications.

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