Laser etching for flip-chip de-bug and inverse stereolithography for MEMS

OVERVIEW A current generation of laser microchemical etching systems removes bulk silicon with several-micron resolution at a rate of 100,000µm³/sec. With no further steps, these systems leave behind perfect mirror-smooth surfaces. Furthermore, it is a 3-D direct write process. These systems could, therefore, become as fundamental in pattern generation as electron beam lithography, but applied to original generation of 3-D masters from CAD. In other applications, laser micromachining systems solve immediate problems such as thinning of flip-chip die for chip repair or advanced testing. Thinning the device prepares it for infrared or photoemission techniques, or permits device modification to be applied from the backside through the silicon substrate.

Laser induced etching of silicon can be accomplished using a diverse and fascinating variety of physical mechanisms [1–6]. In the early 1980s, researchers explored a combination of transport-enhanced and electrochemical methods in many traditional wet solutions, such as KOH-based processes [2]. Other scientists investigated true surface photochemical conditions and applied such effects as light-enhanced diffusion of adsorbed chlorine, photocarrier-assisted desorption of etch products, and gas-phase photochemical generation of halogen atoms [1, 3]. Some of these surface and gas phase photochemical mechanisms show complex lattice orientation and doping dependencies.

The mechanism of most current practical application is based simply on melting silicon in the presence of high-pressure chlorine [1–6]. In this article we review this important process and its intrinsic characteristics.

We then outline two applications that have become possible due to the emergence of fully engineered commercial laser microchemical (LMC) etching systems.

Daniel Ehrlich, Scott Silverman, Richard Aucoin, Michael Burns
Revise Inc., Burlington, Massachusetts

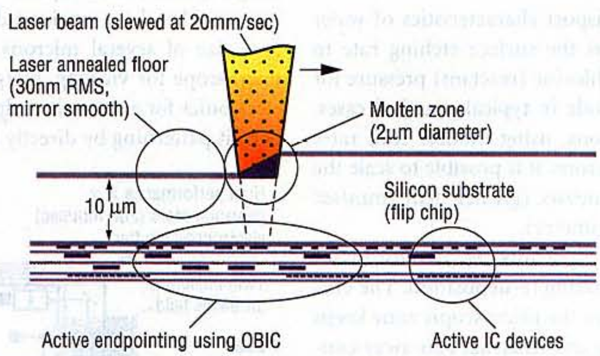

Figure 1. The mechanism for laser microchemical etching of silicon. A visible-wavelength laser melts a microscopic zone on the backside of a silicon die. The molten zone reacts instantaneously with a chlorine ambient to form volatile silicon chloride.

Laser chemical etching of silicon

For most current applications, LMC etching of silicon is applied in the arrangement illustrated in Fig 1. Material is locally melted in a microscopic zone using a tightly focused rapidly scanned laser spot. The (visible) laser light is strongly absorbed in the silicon and, because of the excellent thermal conductivity of the substrate, it is possible to confine the molten zone to a volume of a few cubic microns. Therefore, silicon can be melted in a central zone while, just a few beam diameters from the center, the temperature rise (several hundred degrees) is not large enough to modify lattice order or dopant distributions.

In the presence of high-pressure chlorine, the molten silicon reacts with an efficiency of order unity per surface collision to form silicon dichloride. The dichloride then subsequently reacts in the vapor phase to the stable tetrachloride. The silicon/chlorine reaction becomes limited by mass transport. However, the microscopic volume of the laser-induced reaction permits an increase of many orders of magnitude in the diffusion-limited rate relative to conventional wafer processing.

Figure 2 illustrates this as modeled for purely diffusive transport of fresh chlorine in (or silicon chlorides out of) the microscopic zone. As the chlorine reactant pressure is increased, etching (directly proportional to the reaction flux) increases linearly for a time then saturates as the nonlinear effect of gas diffusion limits long-range transfer of reactant gas. In the common parlance of wafer processing, this is due to the formation of a depleted "boundary layer."

Figure 2 illustrates the enormous benefit of scaling the reaction zone size (w_o) to smaller zone diameters. Physically, this is due to beneficial three-dimensional diffusive transport, as

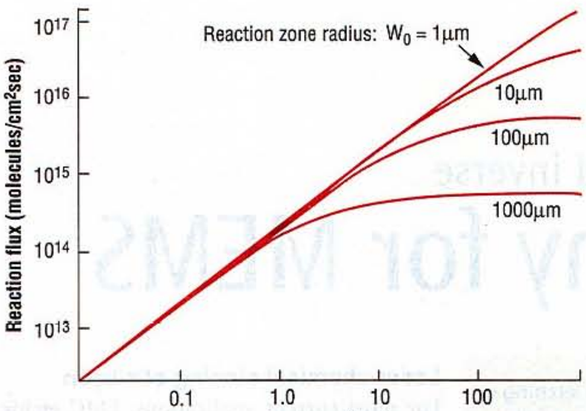

Figure 2. Scaling behavior of silicon etch rate (reaction flux) as a function of increasing pressure, plotted for laser defined reaction zones of different diameter. Note that much higher etch rates are possible in the small zones of a tightly focused laser since there is a greatly reduced boundary layer effect. This results in a vertical etch rate orders of magnitude greater than for full wafer processing.

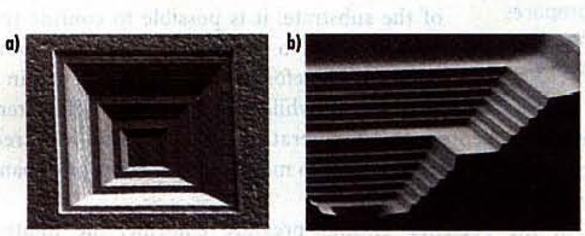

Figure 3. SEMs of a stepped via etched into silicon, showing a) the top view and b) a cross-section. Each terrace corresponds to an etch depth of 6μm. The laser is refocused and stepped into the wafer after each terrace. (Source: Revise Inc.)

opposed to one-dimensional transport characteristics of wafer processing. The small zone allows the surface etching rate to continue to scale favorably with chlorine (reactant) pressure for more than two orders of magnitude in typical practical cases. For most practical implementations, using modest scan rates and a spot diameter of several microns, it is possible to scale the etch rate to greater than 100,000μm^3/sec (greater than 1mm/sec vertical rate until shadowed by geometry).

Hence the chemical ambient permits an extraordinary micromachining rate while eliminating re-deposition. The efficient heat dissipation possible from the microscopic zone keeps these reactions from degenerating into thermal run-away conditions, and therefore excellent spatial control is also retained.

Surface morphology, quality, and chemical selectivity

In the reaction of Fig. 1, a small volume of silicon is locally melted. At the chlorine pressures typically used (100–400 torr), the majority of this volume reacts nearly instantaneously and is carried away as volatile chlorides. A small remaining portion of the molten material recrystallizes and grows epitaxially to the unmelted substrate.

The most important property for many applications is surface smoothness. The efficient chemistry and minor regrowth leave a mirror smooth surface, with a surface roughness under typical scan conditions of less than 30nm RMS (measured by white light interferometry or stylus). When special care i taken using a chemical polishing ambient, it is possible t obtain local smoothness even significantly better than thi value. Since the process is typically raster scanned so that clean 1 to 8μm-thick layer of silicon is removed, layers can b removed iteratively with a laser refocusing operation after eacl layer. The scan pattern of each layer can be adjusted from 3-D model, thereby permitting fully 3-D shapes to be cut laye by layer. This strategy is termed Inverse Stereolithograph in analogy with the well-known process of additive three dimensionsal model making.

The steepness of the maximum sidewall angle is determine by a complex combination of parameters that include Gauss ian beam diffraction, polarization, and the geometry of th molten zone shape (which depends on the laser power an scan properties). For deep structures, an angle of about 15° of substrate normal is easy to achieve and is very suitable for chi modification and for MEMS replication processes.

Figure 3 illustrates this with a typical structure in which rough saw-cut substrate has been machined to mirror smoothness. The etching mechanism is highly sensitive to th chlorine chemistry as well as the optical properties of th substrate. A particularly useful "etch stop" layer is silico dioxide, which is both inert to chlorine and transparent to th visible-wavelength laser.

Anatomy of a laser microchemical instrument

Fully integrated LMC processing tools have been available to th industry for only a few years. The essential features are shown i Fig. 4. A visible-wavelength CW laser beam of 8–10W is precon ditioned and passed through an electro-optic beam blanker an a high-speed scanner capable of sub-μm positioning. Final focus ing is with a long working-distance microscope objective to spot size of several microns. The system incorporates a ligh microscope for viewing, merged with the laser path, and activ electronics for electronic endpoint detection. Software interface permit patterning by directly importing files from a commerci

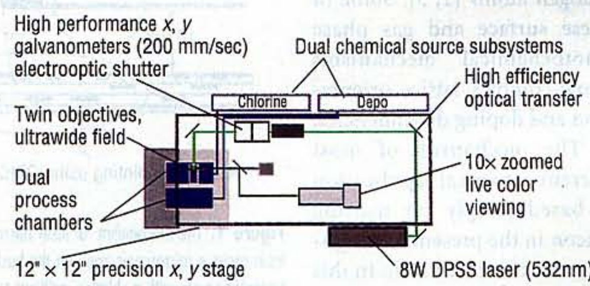

Figure 4. Typical optical layout of a laser microchemical etcher. High-speed deflection and micron-scale positioning accuracy in *x*, *y*, and *z* directions are required for many applications.

3-D CAD/CAM package and navigation using the most widel used computer aided verification (CAV) software. The syste safely handles the process gas.

In the end, a properly engineered system containing th control and automation expected by semiconductor labs leads t

continued on page 14

a total system that is about the same complexity as a focused ion beam (FIB) system (see Fig. 5). A system is often configured to allow both chemically assisted micromachining and laser chemical vapor addition (deposition of metal conductors).

Inverse stereolithography and MEMS

Microelectromechanical systems (MEMS), as their name implies, typically contain a mechanical component. Designers of macroscopic mechanical systems have traditionally made excellent use of three dimensions for structures. Surprisingly, designers of MEMS have typically not had this capability. In fact, all photoresist-based fabrication, including x-ray techniques (e.g., "LIGA"), are at best capable of anisotropic extrusions into the wafer plane.

As a result, few MEMS devices have had truly 3-D design freedom. Areas where this is an obvious constraint are, for example, micro-optics and micro-fluidics. Curvature into the third dimension for the macroscopic counterparts of conventional optics or conventional fluidics is taken for granted.

Figure 5. A fully engineered laser microchemical etching system, including high-speed precision patterning capability, ease of use, and safety features similar to a focused ion beam tool. These systems have migrated to the use of diode pumped solid state lasers as primary beam sources and have therefore become economic in footprint and utilities requirements. (Source: Revise Inc.)

The laser microchemical approach, because of its high degree of control in layer by layer micromachining, offers a method to significantly expand micromachining of silicon into 3-D. The method employed is very similar to the well known technique of stereolithography, in which plastic structures are built up layer by layer from a 3-D data file. However, the structure is much smaller than is typical of most stereolithography applications, and the pattern is cut as relief into silicon. (Examples are shown in Figure 6.) The silicon microstructure can be used directly or can be converted to a replication tool using plating, stamping and micro-molding.

The total laser exposure time to remove a 1000µm cube of silicon (with several-micron pattern detail) is nominally 10 seconds. Scan overhead to provide for beam turning and to guarantee uniform velocity will typically add significantly to this time.

Nonetheless, the speed of the laser reaction is far higher than any other means of 3-D mastering in the regime below 25µm, where machine tools have very limited use. The method has also been applied to release of proof-masses and to die-by-die trimming of MEMS at the wafer level.

Application to flip chip modification and testing

Although the basic work on laser microchemical etching of silicon was done at the universities and several industrial research labs [1–7], the first large commercial application was the result

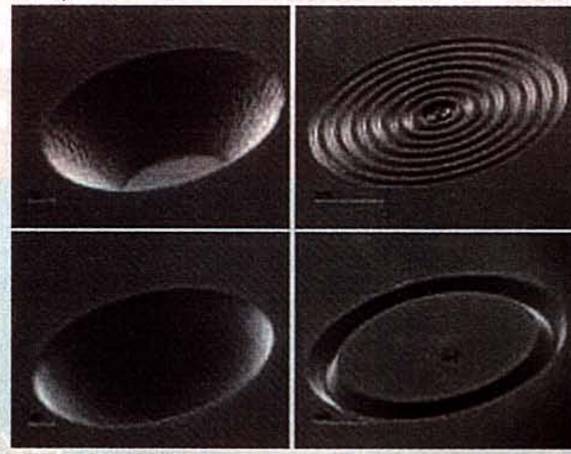

Figure 6. Simple 3-D shapes etched into silicon using the inverse stereolithography capability of a laser microchemical etcher. The capability to create curvature into the substrate is particularly valuable for MEMS and micro-optics applications. (Source: Revise Inc.)

of work by Winer and colleagues at Intel [8]. As early as 199 the Intel group was looking for a process to debug/modify flip chip microprocessors in order to optimize prototypes an enhance fab yields. Although much of the strategy for devic modification in flip-chip packages was nominally the same a for conventional wire-bonded parts, a key difference was th need to locally thin the inverted die. Once the die was thi enough to allow precision focused ion beam (FIB) machinin fairly standard strategies could be applied. The Intel group ha thoroughly documented the limits of mechanical thinning c parts by grinding and global etching, and had also documente the implications of global thinning to heat dissipation an device damage. They were convinced that an "intermediate step was needed to locally thin the flipped die. The need was fo a process that would start with a packaged die, globally thin to several hundred microns, and then etch flat-bottome "trenches" to create a thin region as close as possible to th active diffusions (about 10µm remaining thickness). The lase microchemical etching method was selected as the best metho from a diverse array of candidates. Since the introduction of th method by Intel, a large number of groups have now adopte more or less the same approach.

Local laser thinning is applied only after the part has bee thinned as much as possible by polishing or use of a numeri cally controlled milling machine. Typically, a globally thinne die in its flip-chip package (100–200µm remaining thickness) i put into a laser system. The die is navigated to the approximat circuit region of interest and a laser trench — typically hun dreds of microns in lateral dimensions — is made. Precise reg istration is typically not required, since the laser process is s fast that the trench can be oversized to allow for a location erro

The challenge is to stop the laser etching at a predetermine thickness remaining; this thickness should be sufficiently small t allow reasonable FIB machining time and reasonable FIB regis tration accuracy in the subsequent steps, without the laser punching through to the diffusions. This is accomplished by method that uses active endpoint detection with an optical bea

continued on page 15

induced current (OBIC) signal that is generated on the power and ground networks of the IC itself [7]. While under laser exposure, photocarriers diffuse to the IC junctions in competition with recombination in a manner that is highly dependent on thickness. When the photocurrent induced by the laser reaches a threshold value, an electro-optic shutter blanks the laser and etching ceases.

Once the laser-etched trenches are produced through the backside of the semiconductor part, processing proceeds much as it has does for noninverted die. A combination of testing and circuit surgery is done with heavy use of focused ion beams and optical diagnostics. It is noteworthy that ICs are getting so complex in metal layer count that backside access to the circuit is actually easier than frontside access in many cases, even when not required by a flip-chip package.

Conclusion

Laser direct-write microchemical processing is unique in combining high speed and great precision. The reaction of chlorine on silicon occurs with order unity reaction efficiency. It is a true interface reaction leading to controlled material removal without a significant ablative component. The laser process benefits from the fortuitous scaling of mass transport with reaction size and the excellent heat transport of the substrate, the latter allowing the reaction to remain small. As a result, the laser reaction of chlorine on silicon is among the very fastest known controlled interface reactions (among all fields and all applications); it also maintains properties that are close to ideal for micro-machining.

Prerequisites for control of this chemistry are a highly competent beam scanning system, good dose control, and active endpoint detection and calibration. In fact, state-of-the-art laser microchemical systems resemble a scanning electron or ion-beam system in beam control, absolute navigation, process monitoring, and operator safety features. This technology appears suitable for micromachining technology for a broad range of applications, and it has also found a niche as a result of an industry-wide trend to flip-chip packaging. ■

References

1. D.J. Ehrlich, J.Y. Tsao, "Laser Microfabrication: Thin Film Processes and Lithography," Academic Press, 1989.
2. R.J. Von Gutfeld, R.T. Hodgson, "Laser Enhanced Etching in KOH," *Appl. Phys. Lett.*, Vol. 40, pp. 352–354, 1982.
3. F.A. Houle, "Mechanism of Laser Enhanced Etching of Silicon," *Mat. Res. Soc. Symp. Proc.*, Vol. 29, pp. 203–209, 1984.
4. D.J. Ehrlich, R.M. Osgood, T.F. Deutsch, "Laser Chemical Technique for Rapid Writing of Surface Relief in Silicon," *Appl. Phys. Lett.*, Vol. 38, pp. 1018–1020, 1980.
5. T.M. Bloomstein, D.J. Ehrlich, "Stereo Laser Micromachining of Silicon," *Appl. Phys. Lett.*, Vol. 61, pp. 708–712, 1992.
6. T.M. Bloomstein, D.J. Ehrlich, "Laser-Chemical Three-Dimensional Writing of Microelectromechanics and Application to Standard-Cell Microfluidics," *J. Vac. Sci. Technol. B10*, pp. 2671–2674, 1992.
7. S. Silverman, R. Aucoin, D.J. Ehrlich, K. Nill, "OBIC Endpointing Method for Laser Thinning of Flip-Chip Circuits," *Proceeding of the 24th International Symposium for Testing and Failure Analysis*, pp. 461–464, 1998.
8. R. Livengood, et al., "Advanced Micro-Surgery Techniques and Material Parasitics for Debug of Flip-Chip Microprocessors," *Proceeding of the 25th International Symposium for Testing and Failure Analysis*, pp. 477–483, 1999.

Daniel Ehrlich is the founder and president of Revise Inc. He has managed the submicrometer technology group at MIT Lincoln Laboratory and is the current director of the Bio-MEMS Laboratory at the Whitehead Institute for Biomedical Research/MIT. He is the author of 240 publications and 15 US patents. *Revise Inc., 79 Second Ave., Burlington, MA 01803; ph 781/272-9888, fax 781/221-1482, email ehrlich@revise.com.*

Scott Silverman received his BSEE from Rensselaer Polytechnic Institute. He has 14 years of experience in the semiconductor industry, specializing in advanced lithography. He is currently the chief operating officer at Revise Inc.

Richard Aucoin received his BS in physics from the University of Massachusetts in 1978 and joined Revise Inc. in 1996, working on applications development. Prior to joining Revise, he worked on process development in various semiconductor systems, including CMOS, GaAs, InP, and MEMS devices for NASA's Chandra telescope.

Michael Burns has worked on superconductor and semiconductor technology for 23 years. He is the author of seven issued US patents and more than 53 publications in the superconductor, semiconductor, and biotechnology fields. He is also the holder of six copyrights for software ranging from Auger spectroscopy control and collection to computer security.