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 100,000 µm³/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 micro-machining 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 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 (wₚ) to smaller zone diameters. Physically, this is due to beneficial three-dimensional diffusive transport, as

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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: Ruvim 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 100,000μm²/sec (greater than 1nm/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 is taken using a chemical polishing ambient, it is possible to obtain local smoothness even significantly better than this value. Since the process is typically raster scanned so that a clean 1 to 8μm-thick layer of silicon is removed, layers can be removed iteratively with a laser refocusing operation after each layer. The scan pattern of each layer can be adjusted from a 2-D model, thereby permitting fully 3-D shapes to be cut layer by layer. This strategy is termed Inverse Stereolithography in analogy with the well-known process of additive three dimensional model making.

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

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

Anatomy of a laser microchemical instrument
Fully integrated LMC processing tools have been available to industry for only a few years. The essential features are shown in Fig. 4. A visible-wavelength CW laser beam of 5–10W is pre-conditioned and passed through an electro-optic beam blanker and a high-speed scanner capable of sub-μm positioning. Final focusing is with a long working-distance microscope objective to spot size of several microns. The system incorporates a high efficiency optical transfer and a high-speed deflection and micrometer-scale rasterization for imaging. The system incorporates an automatic 12" x 12" precision x, y stage, dual chemical source delivery systems, and a high-speed galvanometer (200 mm/sec). The system utilizes a dual 8W DPSS laser (532nm) and a high efficiency optical transfer. 3-D CAD/CAM package and navigation using the most widely used computer aided verification (CAV) software. The system safely handles the process gas.

In the end, a properly engineered system containing the control and automation expected by semiconductor fabs lead to...
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.

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 1000-μm 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.

Nevertheless, the speed of the laser reaction is far higher than any other means of 3-D mastering in the regime below 25 μm, 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 of work by Winer and colleagues at Intel [8]. As early as 1991 the Intel group was looking for a process to debug/modify flip chip microprocessors in order to optimize prototypes and enhance fab yields. Although much of the strategy for device modification in flip-chip packages was nominally the same as for conventional wire-bonded parts, a key difference was the local need to thin the inverted die. Once the die was thin enough to allow precision focused ion beam (FIB) machining, fairly standard strategies could be applied. The Intel group has thoroughly documented the limits of mechanical thinning (parts by grinding and global etching, and had also documented the implications of global thinning to heat dissipation and device damage. They were convinced that an “intermediate step was needed to locally thin the flipped die. The need was for a process that would start with a packaged die, globally thin it to several hundred microns, and then etch flat-bottomed “trenches” to create a thin region as close as possible to the active diffusions (about 10 μm remaining thickness). The laser microchemical etching method was selected as the best method from a diverse array of candidates. Since the introduction of this method by Intel, a large number of groups have now adopted or used the same approach.

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

The challenge is to stop the laser etching at a predetermined thickness remaining: this thickness should be sufficiently small to allow reasonable FIB machining time and reasonable FIB registration accuracy in the subsequent steps, without the laser punching through to the diffusions. This is accomplished by a method that uses active endpoint detection with an optical beam...
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-etching trenches are produced through the backside of the semiconductor part, processing proceeds much as it 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


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