Laser Stereo Micromachining at One-Half Million Cubic Micrometers Per Second

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Abstract/Summary

We have recently demonstrated three-dimensional (3-D) micromachining of silicon using a chlorine-based microchemical reaction.[1] This technology achieves the necessary high degree of localization through rate nonlinearities near silicon melting. Applications are high-speed 3-D mastering and device prototyping directly from the computer-aided design environment, with no hard tooling. Figures 1–2 illustrate typical results.

Previous work has concentrated on the limiting case of slow linear scans where mass and heat transport profiles are indistinguishable from the static steady state. In this paper, we will report our findings on laser microchemical etching under conditions where transport distributions do not develop quasi-stationary profiles. Increasing the scanning velocity into this regime markedly changes the reaction dynamics. It is predicted that improvements in removal rate and surface quality will occur in this regime as the reaction zone is swept through fresh reactive gas and the melt zone extends less deeply into the bulk. Beneficial reaction zone narrowing, along with a general stabilization of dimensional control, should also occur. The chemistry used in our 3-D etching is innately among the fastest known solid/vapor interface reactions. Our study is therefore a test case for the more generally predicted benefits of using beam reactions in the transient transport regime.

This work has important implications for laser processing in the field of microelectromechanical systems and micromolding. In comparison with microelectronic applications, significantly larger volumes of material must be removed. This is expected to push laser-induced microchemical technology towards larger spot sizes to improve overall processing rates. Quasi-stationary transport profiles are, however, nonoptimal since overall removal rates can be improved only at the expense of dimensional accuracy and surface quality. Velocity-dependent transport processing is not expected to sacrifice these key aspects of the machining process and provides wider process latitude through the addition of a new process variable.

To study the laser reaction in the velocity-dependent transport domain, we have designed and constructed a new galvanometer-based laser scanning system. The output of a 15-W argon-ion laser is focused to a spot size on the order of 10 μm. In our current arrangement, the beam can be swept across the surface at rates exceeding 10 m/s. This corresponds to a laser beam residence time of approximately 1 μs, whereas characteristic mass and thermal transport times develop on a 10-μs time scale. We will report the current state of the art in terms of processing speed, resolution, and

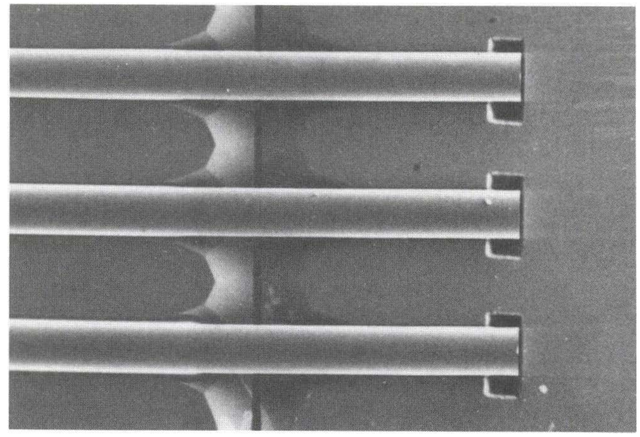

Figure 1. To improve coupling between an optical fiber and semiconductor laser, the faceted ends of the V-grooves are etched in a 100-Torr chlorine ambient using 10 W of laser power focused to a 10-μm spot size. The V-grooves are 310 μm wide and 110 μm deep. The laser etched side-wall has a slope of 3°.

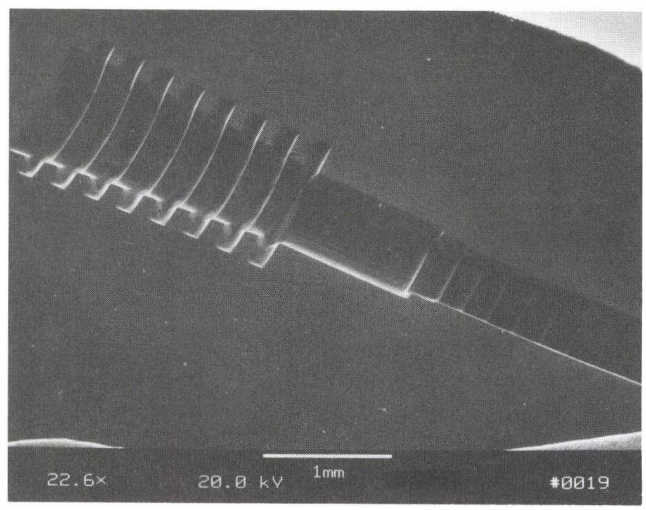

Figure 2. Prototype of the initial stage of a 490 Ghz circular to rectangular waveguide mode-matching structure.[2] The total length of the structure shown is 4 mm and the maximum depth is 500 μm. The total volume of the structure is approximately 5×10^8 $\mu m^3/s$ and requires surface roughness values less than 0.2 μm.

surface flatness. A volumetric removal rate of 5×10^5 $\mu m^3/s$ can now be achieved by optimized scan speed and pressure conditions. Similarly, a surface roughness average of less than 0.1 µm can be achieved on laser-etched surfaces.

Equipment

The scanning system uses a high-performance x-y galvanometer scanner to deflect the output of a 15-W argon-ion laser running multiline (488- to 514-nm wavelength). The output of the laser is expanded to 16 mm and focused to a 10-µm spot through a 250-mm-focal-length lens. The beam is introduced through a quartz cover glass into a stainless steel sample cell which is backfilled with chlorine gas. The sample is biased to 300 °C using a halogen lamp incident on the back side of the wafer. The sample surface is observed through the focusing optic with a charge-coupled-device camera.

The galvanometer is scanned up to angular velocities of 40 rad/s. This translates to linear velocities on the surface of 10 m/s with the current focusing optic. These optical and scan parameters were chosen to allow changes in thermal and mass transport dynamics to be evident. The mass diffusion coefficient of chlorine and the thermal diffusion coefficient of silicon near melt are both approximately 0.1 cm^2/s. For a reaction zone on the order of the spot size, the characteristic transport time, $\tau_{transport} \approx \omega_o^2/D$ where ω_o is the spot size and D is the diffusion coefficient, is approximately 10 µs. The resident time of the laser beam is $\tau_{residence} \approx \omega_o/v_s$ and is a factor of ten below the transport time for scanning velocity v_s, equal to 10 m/s.

Results

Boxes and lines were etched under several different scanning velocities ranging from 32 to 1000 cm/s to measure volumetric removal rates and lateral resolution. The transition from quasi-stationary to velocity-dependent transport conditions occurs around 100 cm/s. Figure 3 shows a graph of linewidth versus power for single passes of the laser across the surface. Results were obtained using an optical linewidth measurement system. For example, note that at the highest power, the linewidth is reduced by about a factor of three at increased scan speed. Figure 4 shows the corresponding volumetric removal rates for etched boxes taken at 1000 Torr of chlorine. Approximately the same volumetric removal rate occurs at higher powers although the resolution is better in the faster scan case. A slight improvement in rate, more pronounced at high scan velocity, is observed at 1520 Torr of chlorine. A simple model is being developed which incorporates both diffusional and convective components to the mass fluxes near the reaction zone. It predicts continued etch rate improvements as the pressure is increased in the fast scan limit . We are continuing to study the pressure dependence of the removal rate.

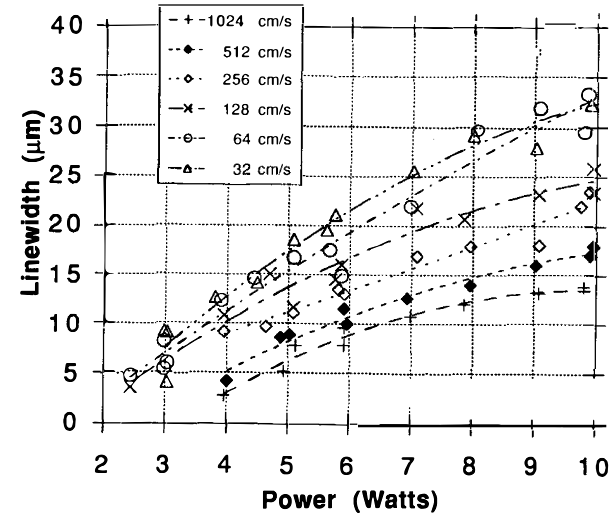

Figure 3. Linewidth of laser etched zone versus laser power. Data is presented for scan velocities of 32, 64, 128, 256, 512, and 1024 cm/s. The lower slope which occurs in the fast scan case should enable smaller features to be written with less sensitivity to laser power fluctuations.

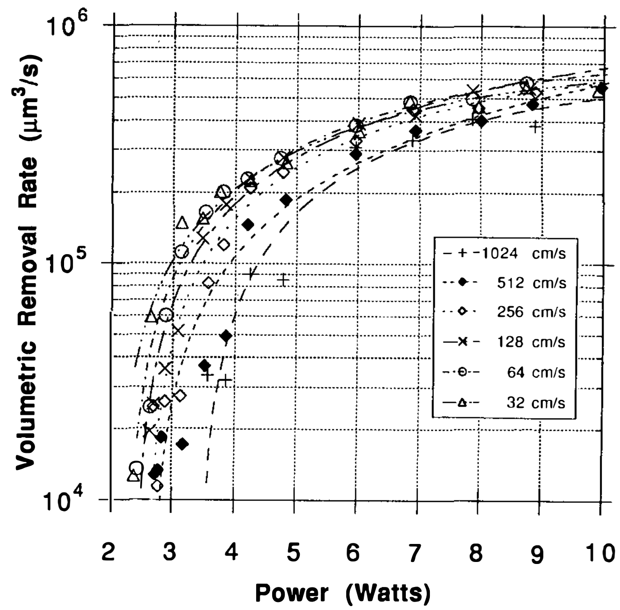

Figure 4. Volumetric removal rates versus laser power for the same variation of scan rate shown in Figure 3. At 4 Watts laser power, the slow scan case has roughly a 13-µm linewidth, but less than half the removal rate of the fast scan case. At higher powers, roughly the same removal rates occur at all scan velocities. Typically, tens of rasters were performed in etching the boxes for the volumetric removal rate measurements. Little variation in volumetric removal rate occurred when the number of rasters was halved or doubled.

Average surface roughness values in the several tens of nanometers are typically measured under all scanning conditions with in general the smoothest surfaces occurring in the fastest scan case. At slow speeds (32–100 µm/s), the periodic nature of the surface texture is evident from the overlapping line scans. At intermediate speeds (100–500 µm/s), the surfaces have a wavy texture when viewed under Nomarski microscopy. This may be due to nonlinear optical coupling effects between the incident power and the highly reflective molten portion of the reaction zone. In the fastest scan case, this effect appears to be reduced. One benefit from faster scanning is the significantly higher depth resolution. Thin shavings less than 0.1-μm thick are removed per scan at the highest etch rates. Detailed studies are now in progress to characterize the laser-affected surface.

Conclusions

We have achieved etch rates of 5×10^5 cm^3/s at lateral resolutions from 13 to 33 μm. We are continuing to study the pressure dependence of the reaction rate. Average surface roughness in the range of tens of nanometers has been achieved.

Reference

1. T. M. Bloomstein and D. J. Ehrlich, *J. Vac. Sci. Technol. B* **10**, 2671 (1992).
2. C.K. Walker, T. M. Bloomstein, D. J. Ehrlich, to be published.

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