

Silicon Micromachining Using *In Situ* DC Microplasmas

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Abstract—This paper reports on the generation of spatially confined plasmas and their application to silicon etching. The etching is performed using SF_6 gas and dc power applied between thin-film electrodes patterned on the silicon wafer to be etched. The electrodes also serve as a mask for the etching. The typical operating pressure and power density are in the range of 1–20 Torr and 1–10 W/cm^2 , respectively. The plasma confinement can be varied from $<100 \mu\text{m}$ to $>1 \text{cm}$ by varying the electrode area, operating pressure, and power. High power densities can be achieved at moderate currents because the electrode areas are small. Etch rates of 4–17 $\mu\text{m}/\text{min.}$, which enable through-wafer etching and varying degrees of anisotropy, have been achieved. The etch rate increases with power density, whereas the etch rate per unit power density increases with operating pressure. Scaling effects are explored for varying sized mask openings. Plasma resistance measurements and electric field modeling are used to provide an initial assessment of the microplasmas. [570]

Index Terms—dc plasma, dry etching, microplasma, micromachining, semiconductor plasma.

I. INTRODUCTION

PLASMA processing is extensively utilized in semiconductor processing applications, and is the dominant silicon etching technique. Silicon etching is commonly performed in parallel plate reactors by applying RF power (typically at 13.56 MHz) between two electrodes placed several centimeters apart. The silicon wafer is located on the powered electrode for reactive ion etching. The operating pressure and power are in the range of 10–500 mtorr and 10–500 mW/cm^2 , respectively. Since the plasma exists globally across the wafer, the etch is selectively masked by a thin film of photoresist, SiO_2 , or metal which is patterned on the wafer surface. More recently, fast anisotropic etches have been demonstrated by alternative plasma etchers utilizing electron cyclotron resonance (ECR) [1] and inductively coupled plasmas (ICP) [2]. All of these options, however, employ a single plasma that acts over the entire surface area of a wafer. Creating several different etch depths or profiles in a single die mandates the use of a like number of masking steps.

In this paper, we report on silicon etching using *in-situ* microplasmas [3]. The microplasmas are powered by two metal electrodes separated by a dielectric in a tri-layer stack on the wafer surface (Fig. 1). The power density is approximately $100\times$ higher than in conventional plasmas. In addition, dc

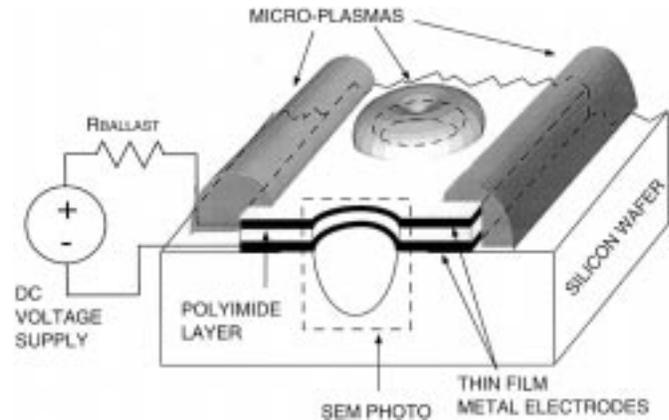


Fig. 1. Schematic illustrating the generation of an *in-situ* microplasma.

power is used to etch silicon substrates. This eliminates the need for matching impedance networks associated with RF driven plasmas. Plasma confinement can be varied from a few tens of microns to more than a centimeter by changing operating conditions. The electrodes may also serve to mask the etch in regions where the microplasma is ignited. The etch dimensions are consequently confined to the openings in the mask, as with conventional etchers. Localized through-wafer etching has been demonstrated with this technique, and etch rates greater than 17 $\mu\text{m}/\text{min.}$ have been recorded using SF_6 .

II. EXPERIMENTAL RESULTS

Test samples are fabricated by a two-mask process sequence. First, a metal–polyimide–metal electrode stack is deposited on the wafer. The first lithography mask is used to pattern the upper metal layer and the polyimide. The second mask is then used to pattern the lower metal layer and simultaneously re-pattern the upper metal as well. Metal layers that have been investigated include chrome, aluminum, titanium, and nickel. Following the microplasma etch, the electrode stack can be stripped by sacrificing the lower metal electrode in the appropriate wet etchant.

In the electrical set-up, the pads for the two *in-situ* electrodes are contacted by probes and connected to a dc power supply across a series ballast resistor, which provides a means to control the plasma current. As shown in Fig. 1, the upper electrode serves as the anode, whereas the lower electrode is connected to the ground, in order to direct the positive ions in the plasma toward the Si substrate. Typical bias values range from 300–600 V, depending on the ambient gas used and target etch rate. The silicon is shielded from the electric field by the grounded cathode. The relatively small electrode areas for *in-situ* microplasmas

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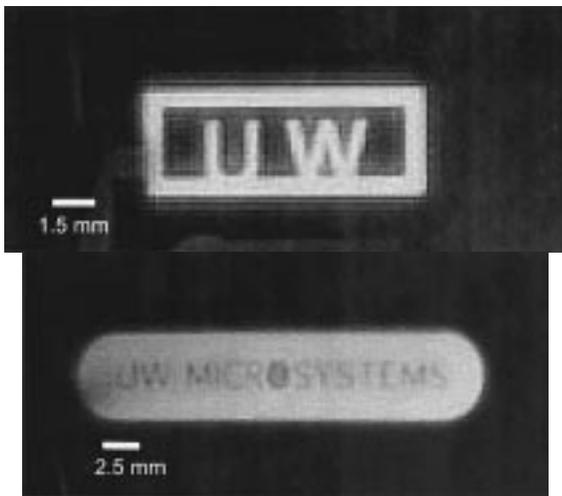


Fig. 2. Local confinement of N₂ microplasmas at 1–20 Torr and –360 V dc. (a-upper): Narrow electrodes with wide gaps; (b-lower): Wide electrodes with narrow gaps.

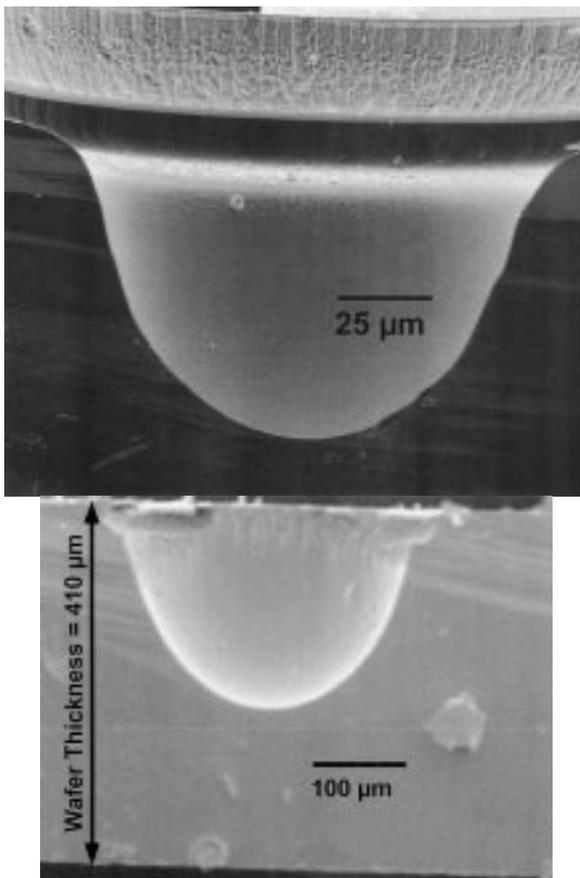


Fig. 3. (a-upper): A 92 μm deep etch through a 150 μm ϕ circular opening (2.7 Torr, 3.2 W/cm², 20 min.). (b-lower): A 233 μm deep etch (50 min.).

allow power densities in the range of 1–10 W/cm² to be achieved without drawing high currents.

Relatively large operating pressures of 1–20 Torr are used to spatially confine the plasma. This can permit several microplasmas with different etch characteristics to operate simultaneously on a wafer. The spatial self-confinement of microplasmas is shown in Fig. 2 as a glow that is localized

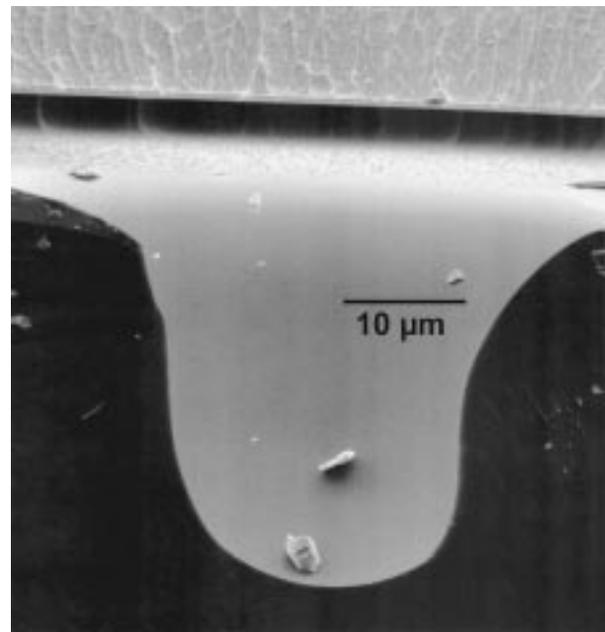


Fig. 4. A 33 μm deep etch through a 50 μm ϕ opening (2.9 Torr, 7.3 W/cm², 3 min.).

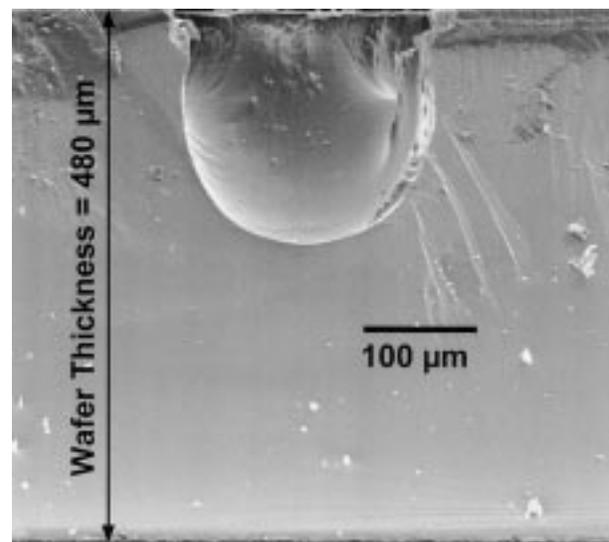


Fig. 5. A 207 μm deep etch through a 280 μm wide slit opening (5.2 Torr, 6.8 W/cm², 24 min.).

to the *in-situ* electrodes. In this experiment, the ambient gas was N₂, and the bias voltage was –360 V, which has opposite polarity to the bias normally used for etching. By varying the power and pressure the confinement can be changed from <100 μm to >1 cm.

Typical etch profiles achieved by microplasmas are shown in Figs. 3–5. In each of these cases the etch was performed through openings in the *in situ* electrodes using a partial pressure of SF₆. Fig. 3(a) shows a 92-μm deep etch through a circular opening of 150 μm diameter, that was achieved in 20 min. at 2.7 Torr, with a power density of 3.2 W/cm² averaged over the electrode area. The sidewall angle was 21° off vertical. The electrode metal used in this case is aluminum. Fig. 3(b) shows a 233 μm

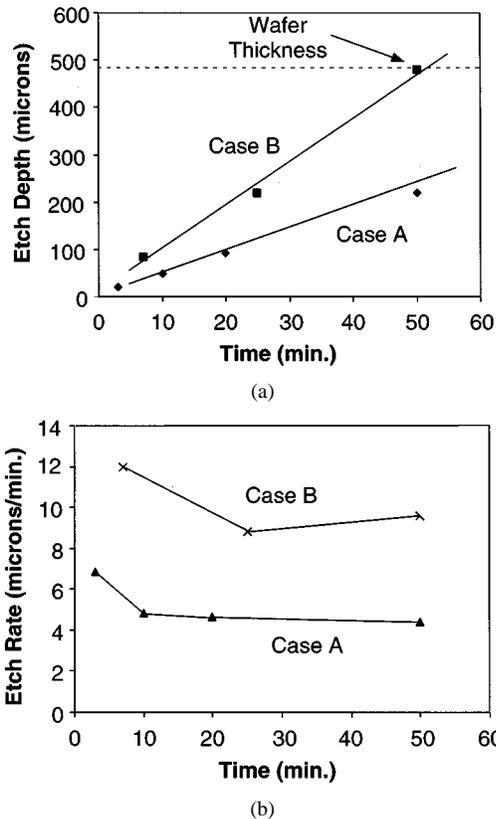


Fig. 6. (a-upper): Etch progression for two cases described in the text. Through-wafer etches can be achieved in <1 hour. (b-lower): A cumulative average etch rate of 4–10 $\mu\text{m}/\text{min.}$ has been sustained, although initial values are higher.

deep etch that was achieved in 50 min. using the same parameters. Fig. 4 shows a 33 μm deep etch through a 50 μm diameter opening achieved in 3 min. at 2.9 Torr and 7.3 W/cm^2 . The sidewall angle is nearly vertical in certain locations of the profile. The electrode metal for this case was also aluminum. Fig. 5 shows the cross-section of a 207 μm deep etch through a 280 μm wide, 2.2 mm long slit opening. The electrode metal used in this case was titanium. The etch was achieved in 24 min. at 5.2 Torr and 6.8 W/cm^2 . The sidewall angle of this etch is also nearly vertical in certain locations of the profile. The profiles shown in Figs. 3–5 indicate that varying degrees of anisotropy can be achieved by changing the operating conditions of microplasma.

The etch rate of Si in SF_6 microplasma was studied as a function of several operating parameters (Figs. 6–8). Fig. 6 shows the dependence of the etch depth and the cumulative average etch rate on the duration of the etch. These etches were performed under two sets of conditions: case A used 2.7 Torr pressure, 1.6 W/cm^2 power density, and aluminum electrodes with circular openings of 350 μm diameter; case B used 5.2 Torr, 6.8 W/cm^2 , and titanium electrodes with 280 μm wide slit openings. Case A achieved etch rates of 4–7 $\mu\text{m}/\text{min.}$, whereas Case B achieved etch rates of 9–12 $\mu\text{m}/\text{min.}$ In both cases the etch rate was significantly higher for the first few minutes, and then rapidly settled at a lower value that was stable for 50 minutes. Although the reasons for the higher initial etch rate remain to be determined, it is noteworthy that the electric field above the exposed Si is

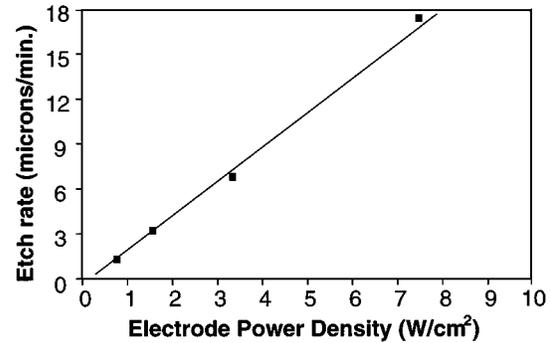


Fig. 7. The etch rate is proportional to electrode power density. (All 3 min. etches at 2.7 Torr.)

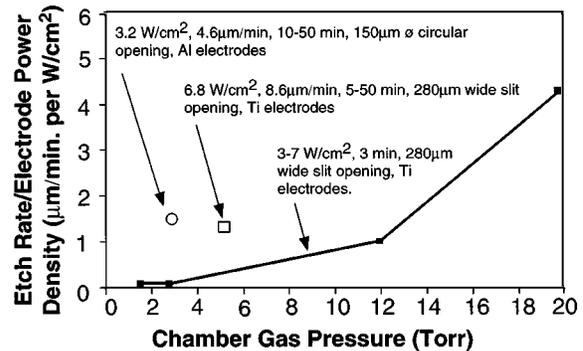


Fig. 8. The ratio of the etch rate to the electrode power density increases with chamber pressure.

highest for the first few minutes of an etch, during the time that the etched depth is relatively small. This is shown as a modeling result in the next section.

Fig. 6(a) also indicates that under the conditions of case B, it was possible to etch through a wafer in less than an hour. Through-wafer etches were routinely achieved with the use of titanium electrodes, which developed considerably less damage than aluminum from sputtering in exposed regions of the cathode. This is consistent with trends seen in conventional etchers [4].

Fig. 7 shows the dependence of the etch rate on electrode power density. All the etches shown in this figure were performed for three minutes at 2.7 Torr using aluminum electrodes with circular openings of 350 μm diameter. It is clear that the etch rate increases linearly with power density within the operating regime explored. The highest etch rate achieved is 17.4 $\mu\text{m}/\text{min.}$ The relatively high etch rates are facilitated in part by the high power densities. Since the electrode area for microplasma is generally $\ll 1 \text{ cm}^2$, these power densities can be achieved at moderate current levels.

Since the etch rate is linearly related to electrode power density, it is worthwhile to evaluate the etch rate per unit power density as a figure of merit for the efficiency of the etch. Fig. 8 shows this parameter as a function of chamber pressure for three minute long etches performed through a 280 μm wide slit opening in titanium electrodes. As the pressure is increased, the power necessary to sustain the plasma increases from 3 to 7 W/cm^2 . Despite this, the ratio of the etch rate to power density increases from 0.15 to 4.23 $\mu\text{m}/\text{min. per W}/\text{cm}^2$ as the pressure

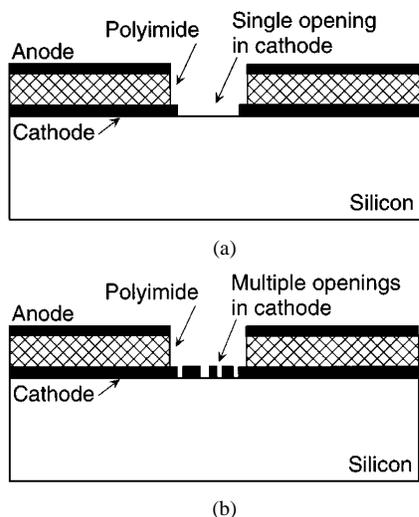


Fig. 9. (a-upper): The single cavity configuration of Fig. 1. (b-lower): The shared anode configuration.

is changed from 2 to 20 Torr. Higher ratios achieved by other operating parameters are also shown in Fig. 8.

An alternate arrangement of the electrodes is called the shared anode configuration. In the electrode arrangement of Fig. 1, which is also shown as a cross-section in Fig. 9(a), the entire electrode stack forms a barrier that masks the protected areas from the local microplasma. However, when the lateral dimensions of the trench are small, it is easier to fabricate an electrode arrangement in which the lower metal serves this purpose alone, resulting in a shared anode arrangement of Fig. 9(b).

The variation of etch rates with lateral dimensions of the mask opening was explored in the shared anode configuration. The openings were 1.75 mm long and ranged in width from 106 μm to 5.6 μm . The normalized etch rates for a 3 minute etch performed at 7.2 W/cm^2 power density are plotted in Fig. 10. Under these circumstances, the 95% reduction in slit width is related to a 14% monotonic reduction in etch rate.

III. PLASMA MODELING

In plasmas having power density that is typically used for semiconductor processing, ion-electron pairs are vastly outnumbered by neutral species [5]. As a consequence, when the applied voltage is increased, the energy increase results in appreciably more electron-neutral collisions than electron-electron collisions. This increases the plasma density, but does not substantially increase the electron temperature. The higher plasma density then results in a larger plasma current, which is observable as a drop in plasma resistance with an increase in the power density. Fig. 11 plots the measured resistance of the microplasmas as a function of the power density. The measurements for Fig. 11 were obtained at 2.7 Torr using thin film aluminum electrodes of 0.2 cm^2 area.

Under the conditions described in the preceding section, the etching is believed to be performed by ions which are pulled away from the sheath that exists above the electrode stack by the electric field associated with the openings in the stack. Results from a preliminary effort at modeling the electric field

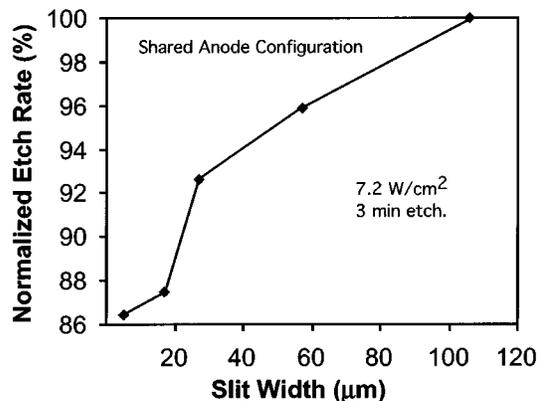


Fig. 10. Normalized etch rate for varying etch widths in the shared anode configuration.

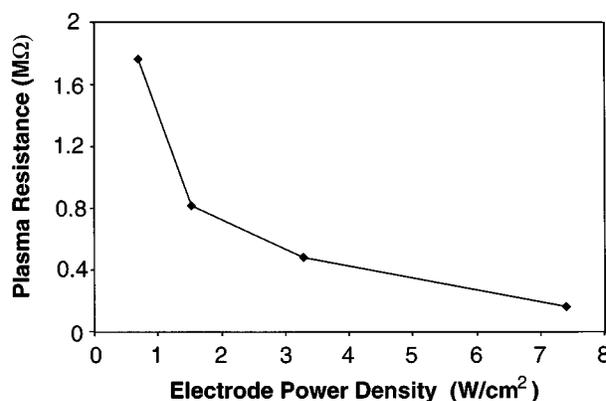


Fig. 11. The plasma resistance decreases with the power density.

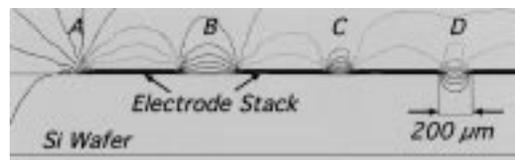


Fig. 12. Equipotential contours showing variations of the local electric field with mask openings of varying widths (A-C) and with etch progression (D).

are shown in Fig. 12. The simulations were performed using MAXWELL, and neglect the conductivity and charge distribution of the plasma. The geometry assumes openings of various widths in a 30 μm thick metal-polyimide-metal electrode stack on a 500 μm thick silicon wafer. The relative dielectric constant of the polyimide is 3.5, and the resistivity of the metal is zero. The figure shows equipotential contours which are crowded progressively closer together in openings A, B, and C, suggesting that the electric fields are higher above narrow openings. At the same time, the local electric field extends to greater heights above the wider gaps. The difference between the contours at locations C and D, which are of the same width but represent shallow and deep etches, respectively, suggest that the electric field is reduced as an etch progresses. This may be correlated to the observation made in the preceding section that the initial etch rate is higher than the cumulative average rate.

IV. CONCLUSIONS

This effort has demonstrated the use of microplasmas for the etching of silicon. The microplasmas were generated by dc power applied to *in-situ* electrodes patterned on the silicon wafer that also served as an etch mask and a shield against the applied potential. Short etches at rates exceeding $17 \mu\text{m}/\text{min}$. and sustained etch rates in the range of $4\text{--}10 \mu\text{m}/\text{min}$. were demonstrated, and through-wafer etches were achieved using SF_6 . The typical operating pressure and power density were in the range of 1–20 Torr and $1\text{--}10 \text{ W}/\text{cm}^2$, respectively. Varying degrees of anisotropy were achieved by changing the etch conditions. The etch rate depended linearly on the electrode power density. The power efficiency of the etch rate increased with pressure. In the shared anode configuration, the etch rate of $5 \mu\text{m}$ wide trenches was 14% lower than that of $106 \mu\text{m}$ wide trenches. The plasma resistance decreased with increasing power density, in compliance with theoretical expectations.

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