Deep Reactive Ion Etching (DRIE)

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The etching approach described herein is counted among the present state of the art techniques utilized in the current trend toward miniaturization of sensors and actuators. The ability to microfabricate deep trenches in silicon substrates while maintaining high selectivity to masking material, good profile control and low nonuniformity across a wafer has been revolutionized with the current generation of deep-reactive-ion-etching (DRIE) tools. These deep-silicon-etching machines can easily achieve rates in the excess of 3µm/min, selectivities to photomasking materials greater than 70:1 (at least twice as much for silicon dioxide), excellent profile control (see figure 1) and non-uniformities across the wafer of 5% of less.

These high-density plasma tools can use two distinct gas-feeding approaches: standard and time multiplexing. The standard approach, all gas species are flowed at the same time, and the etching results depend on the glow discharge having both one species of radicals to proceed with the etch, and another species of radicals for protecting the sidewalls during operation.

In the time-multiplexing scheme, the etching and passivating gases used are flowed independently one at a time (see figure 2), and the machine alternates between an etching cycle and a passivating cycle.
During the etching cycle step a shallow trench is formed in the silicon substrate, with an isotropic profile characteristic of fluorine-rich glow discharges. The typical duration of these steps is \( \leq 12 \)s. During the passivation cycle, a protective fluorocarbon film is deposited on all surfaces. The duration of the step is usually \( \leq 10 \)s and shorter than the etching cycle. In the subsequent etch step, ion bombardment promotes the preferential removal of the film from all horizontal surfaces, allowing the profile to evolve in a highly anisotropic fashion (see figure 3). This separation of etching and passivating cycles is known as the Bosch process, after the German company that developed and patented this technique. In a typical configuration sulfur hexafluoride (SF\(_6\)) is flowed during the etching cycle and octafluorocyclobutane (C\(_4\)F\(_8\)) during the sidewall protection cycle.

![Flow Rate Diagram](image)

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This process, succinctly described as time-multiplexed deep etching (TMDE), offers the advantage of exploiting the high silicon etching rate of fluorinated chemistries, such as SF\(_6\). For all practical purposes, TMDE users have to deal with to different glow discharges: one for silicon etching and another for sidewall passivation.
TMDE tools can also be operated in a continuous mode flowing only SF₆ or C₄F₈. Fully isotropic profiles can be obtained using only SF₆, with silicon etching rates in excess of 6 µm/min and selectivity to soft photoresist masks larger than 150:1. This fluorine-rich, high-density plasma has been exploited for etching structures without stringent profile requirements. Similarly, by using only a continuous C₄F₈ glow discharge, low surface-energy, pinhole-free, fluorocarbon films with various mechanical, optical and electrical characteristics can be deposited. The list of application for such films is very large: for orienting liquid crystal, as anti-corrosion films, as solid lubricants and for anti-stiction purposes. Their low dielectric constant can be exploited in tuning and resonant circuits or, in conjunction with high-conductivity metals, to realize electrical circuits with low RC-constants. Because of their low conductivity, fluorocarbon films are also applicable as electrical insulators. These films can be used as anti-reflection coatings, and, under specific deposition conditions, they can also serve as scratch-resistant films.

The high silicon etching rate of TMDE, combined with the possibility of employing soft masking materials, for instance photoresists, and the ability to control the profile of etched devices, provides another alternative for producing high-aspect-ratio structures (HARS). Compared with LIGA (German acronym for lithography-electroplating-injection-molding), for instance, TMDE not only does not require a synchrotron radiation source, but it is also more compatible with integrated circuit technology and other cleanroom micro-fabrication process. LIGA, however, offers characteristics not surpassed by any other technology, namely, the production of metallic structures with the highest aspect ratio and with reasonably smooth surfaces.

**Etching considerations**

Surface roughness issues are particularly important in TMDE tools. Because of alternate etching and passivating cycles and the spontaneous nature of the etch in fluorinated chemistries, structures fabricated using TMDE exhibit a characteristic scalloped sidewall roughness (see figure 4 and 5) that can be unacceptable in some applications. It is possible to minimize the depth of those scallops by varying the operation conditions during dry processing. The depth of the scallops is due mostly to the spontaneous etching of silicon by fluorine. The height reflects not only the spontaneous etching of silicon but also the contribution due to ion bombardment induced etching and physical sputtering.
Another source of surface roughening during TMDE is the uneven recession of the masking material that transfers vertical striations into the sidewalls (see figure 6). The use of hard materials, like silicon dioxide, helps alleviate this problem.

**Figure 4.** SEM micrograph showing the characteristic scalloping encountered on silicon sidewalls etched using TMDE.

**Figure 5.** The characteristic scallops produced during TMDE are distinguishable in these columns as a series of rings on the sidewalls.

**TMDE characterization**

This work was performed using a Surface Technology System multiplex (ICP). Vacuum pumping of the etching chamber is done by a turbo pump with a pumping speed of 880 l/s.

The equipment includes two independent 13.56 MHz RF power sources: a 1000W supply for a single-turn coils around to create the plasma, and a 300W supply connected to the wafer electrode to vary the RF bias potential of the wafer with respect to the plasma. The efficient inductive power coupling of the coil to the plasma allows high-density plasmas to be maintained.
The system has a single feed for etching and passivating gases located on top of the etching chamber, and backside helium pressurization is used to provide good heat transfer between the wafer and the electrode to maintain a constant and sufficiently low wafer temperature, around 40ºC.

In the standard mode of operation the position of the throttle or automatic pressure control (APC) valve is fixed and the pressure is determined by the respective gas flow rate. Higher values of the APC valve position in degrees correspond to higher pressures. The residence time, $\tau$, which is proportional to $pV/f$ (where $p$ is the pressure, $V$ the chamber volume and $f$ the gas flow rate), is important in relation to the removal rate of etch products in the process chamber with the corresponding effect on reactant concentration. Thus, high APC setting or low flow rate can both have deleterious effects on etching characteristics.

### Silicon etching rate

Figure 7 shows the etched depth achieved as a function of applied coil power (W) and SF₆ flow rate (sccm) for samples exposed for 10 min to the glow discharge. All
measurements graphed in figure 7 were taken for trenches of nominal width 64 µm. The adjusted $R^2$ of the quadratic model for this response is 0.91, indicating that the fit is reasonably good. The silicon etching rate increases with coil power as the ion flux density increases. Similarly, the etching rate increases with increases in SF$_6$ flow rate because of increases in the concentration of the etchant species (F) and because of a reduction of etching (SiF$_4$) that redeposit. Although not shown here, silicon etching rate can also be increased by increasing the applied electrode power during the etching cycle. This is due to the increase in bombardment energy that is reflected in higher etching rates. Pressure also has a significant influence on etching rate, which initially increases with pressure due to high (F) concentrations, but as pressure is increased even further, the ion energy and/or flux is reduced and the etching rate drops.

**Photoresist etching rate**

![Figure 8. Photoresist removal (Å) as a function of electrode power (W) and coil power (W). The adjusted $R^2$ for this variable is 0.88.](image)

Low photoresist removal rate is necessary for a robust operation. Figure 8 shows the photoresist etching rate dependence on applied electrode and coil power with TMDE suppressed. The total thickness of the masking material removed is obtained by measuring the film thickness with an optical interferometer before and after etching.

The photoresist etching rate increases with applied electrode power because of increase in ion bombardment energy; therefore, increasing ion bombardment improves the etching anisotropy but lowers the selectivity. During TMDE operation, this response is also sensitive to pressure and the duration of the etching and passivating cycles.

Although photoresist etching rate decreases as the pressure is increased there are several other important implications associated with large settings of the APC, namely, the sputtering and redeposition of the masking material which promotes the formation of micro-columns or grass, the damage of structures and excessive polymer deposition. These considerations limit the range of useful settings for the throttle valve to no more than 75°.

The duration of the active etching cycle determines the exposure time of the masking material during the etch and therefore the longer the cycle, the more photoresist is etched. Similarly, during the passivating cycle the thickness of the polymerization film increases
with time, thereby decreasing the photoresist removal rate with increasing passivation cycle time.

**Uniformity**

The variation of etching rate uniformity with SF6 flow rate and pressure is shown in figure 9. Plotted values were obtained by comparing the depth of the trenches of nominal width of 64 µm in the middle of the wafer, with trenches located 3 cm away according to 100(1-d/d_{middle}), where d/d_{middle} are the respective measured depths. This variable determines the extent of overetching required to achieve a prescribed depth across the wafer. Although this response is influenced by the temperature uniformity across the wafer, the local rates of plasma density loss and formation, the exposed area, the feature density etc, we can significantly simplify this picture by focusing on plasma formation. Thus, the plasma density being higher at points closer to the RF power coil or heating source, promotes local increases in the etch rate.

![Figure 9. Variation of etching depth uniformity with SF6 flow rate (sccm) and APC valve position (in degrees).](image)

Therefore, for most operating conditions the etching rate will be higher on the periphery of the wafer compared with points closer to the center of the wafer. Uniformity benefits from lower APC valve setting because the diffusivity varies inversely with the pressure. Also, uniformity benefits from lower SF6 flow rates because for a fixed position of the APC valve, pressure decreases when the flow rate decreases.

**Anisotropy and profile control**

This response is of importance in every application, and the ability to tailor the slope of trench walls is one of the more important characteristics of the deep silicon etching tools. It is feasible to obtain anisotropic profiles with positive slopes as well as with reentrant profiles.

In general the combination of ion bombardment in conjunction with the formation and preservation of protective films on the sidewalls allow us to achieve prescribed
anisotropic and selectivity targets. This is clearly illustrated, for instance, in the duration of the etching cycle with respect to the passivating cycle. Specially, an etching cycle too long with respect to the passivating cycle will promote reentrant profiles because the etch continues longer after the protecting film has been removed.

Similarly, an etching cycle too short will not remove completely the deposited passivating films producing walls with significant surface roughness and other detrimental artifacts such as micromasking and grass formation. Thus, settings that promote the deposition of thicker passivating films, i.e. higher pressure, or that promote the efficient removal of such films, i.e. higher coil or electrode power, have significant impact on anisotropy. For instance, with higher pressure settings the average ion energy is reduced, the angle of incidence of ions increases and the anisotropy deteriorates. A similar observation is made with increases in SF$_6$ flow rate when operating with a fixed position for APC valve. As the flow rate increases, the pressure rises and the anisotropy deteriorates.

In addition to carefully selecting the operating conditions to obtain targeted profiles, it is also possible to include steps in the Bosch process where the sample is exposed to oxygen plasma to create a thin layer of protective oxide on all sidewalls. The removal rate of silicon dioxide is smaller than of fluorocarbon films, thus, additional protective films help in achieving better profile control.

Applications.

- Sensors and Actuators
- Micro-fluidic Systems
- Micro-optic Components
- Micro-molds

Conclusion.

The ability to microfabricate deep trenches in silicon substrates while maintaining high selectivity to masking material, good profile control and low nonuniformity across a wafer has been revolutionized with the current generation of deep reactive ion etching rates in excess of 10 µm/min. and 450:1 selectivities can be achieved.

References:

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