Etching Characteristics and Profile Control in a Time Multiplexed Inductively Coupled Plasma Etcher

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ABSTRACT

This paper reports on a complete designed experiment of a deep reactive ion etch process in which matrices of 8 and 4 variables were explored in order to optimize uniformity, anisotropy, Aspect Ratio Dependent Etching (ARDE), photoresist and silicon etching rate. A database results from these experiments which permits customization of operating conditions to obtain desired etch characteristics.

INTRODUCTION

Until the advent of high density plasma etchers, the options for fabricating High Aspect Ratio Structures (HARS) in silicon, such as reactive ion etching (RIE) and electron cyclotron resonance (ECR), had limited success in fulfilling the requirements of high etch rate, good selectivity to masking material, anisotropy and compatibility with other processes. A recent alternative that is satisfying the need of such processes is the time multiplexed deep etcher (TMDE) patented by Robert Bosch GmbH [1]. This approach utilizes an etching cycle flowing only SF_6 (figure 1), and then switches to a sidewall passivating cycle using only C_4F_8 .

Figure 1. Graph showing the gas flow cycles during plasma etching. Note the overlaps caused by the finite time response of the flow controllers.

During the subsequent etching cycle, the passivating film is preferentially removed from the bottom of the trenches due to ion bombardment, while preventing etch of the sidewalls. The final result is anisotropic sidewalls that exhibit scalloping (figure 2), with peak to valley amplitudes as low as 50 nm. Higher electrode power to pressure ratios and shorter etching cycles reduce this effect.

Figure 2. Micrograph view of an anisotropic etch (left) and the scalloping observed on the walls due to the periodic etch/deposition.

The success of Bosch's TMDE scheme, hinges upon the deposition of the inhibiting films. These films prevent the etching of the sidewalls by SF_6 discharges that contain large concentrations of atomic fluorine that spontaneously etches silicon. SF_6 discharges lack polymer forming species to block spontaneous etching [2].

By suppressing the time multiplexing, the equipment can be run with continuous flows of SF_6 or C_4F_8 . With SF_6 it is possible to achieve isotropic etch rates as high as 1380 Å/sec. Using C_4F_8 , teflon-like films can be deposited for use as anti-stiction films.

EXPERIMENTAL DETAILS

This work was performed using a Surface Technology Systems Multiplex ICP. The equipment includes two independent 13.56 MHz RF power sources: a 1000 W supply for a single-turn inductive coupling coil around the etching chamber to create the plasma, and a 300 W supply connected to the wafer electrode to vary the RF bias

(a)

(b)

Figure 5. Trenches of width 8.32 μm in (a) and 35.3 μm in (b). Their measured depth differs by only 0.3 μm .

Uniformity values were obtained by comparing the depth of trenches of nominal width of 64 μm in the middle of the wafer, with trenches located 3 cm away. This variable is important because of its influence in determining the overetch time needed to completely clear features throughout the wafer. In the low electrode power region (~ 8 W), this variable benefits from lower SF_6 flow rate, while in the mid to high applied electrode power regions (~ 12 W), it is necessary to increase the SF_6 flow rate. In general, lower operating pressure settings are

beneficial for this response because the diffusivity varies inversely with the pressure.

Anisotropy is of importance in every application, and the ability to tailor the slope of trench walls is one characteristic of this deep silicon etching tool. As expected, anisotropy has a well defined dependence on applied electrode power and chamber pressure [9]. Anisotropy increases as the applied RF-bias electrode power is increased.

With pressure the behavior of this response is different. Initially, anisotropy increases with pressure increases, as thicker polymer films are deposited protecting the sidewalls. However, as the pressure is increased even further, the reduction in the average ion energy as well as the increase in the ion angle of incidence combine to produce deleterious effects on anisotropy.

It was also observed the relevance of SF_6 flow rate in tailoring the anisotropy. In general, higher SF_6 flow rates decrease the anisotropy and promote surface roughening (figure 6).

Figure 6. Micrographs of trenches etched in 10 minutes with an SF_6 flow rate of 85 sccm (left) and 125 sccm (right) respectively.

Among the applications of the obtained information is the etching of deep narrow trenches like the one shown in figure 7. In that figure, the trench presented has an average width of 12 μm and a measured depth of 404 μm . Narrower trenches and submicron thin walls are also possible and this is shown in figure 8.

Other applications include the utilization of the passivation films to control the notching effect when etching SOI wafers. This is accomplished by depositing a thicker polymer film when approaching the buried dielectric layer (figures 9).

CONCLUSIONS

The observed behavior presented in this report is an important tool to locate and optimize operating conditions to etch high aspect ratio structures. The performance of this deep reactive ion etcher allows the tailoring of etch rates of 4+ $\mu\text{m}/\text{min}$ with anisotropic profiles, nonuniformities of less than 4 % across the wafer, and ARDE control with a depth variation of less than 1 μm for trenches of dissimilar width.

potential of the wafer with respect to the plasma. This arrangement permits the independent control of the energy of the ions reaching the substrate as well as the ion flux [3].

Backside helium pressurization is used to provide good heat transfer between the wafer and the electrode to maintain a constant wafer temperature. Low temperatures reduce the etching rate of the photoresist, thereby allowing its use as a mask for etching silicon. The photoresist can also be used as a bonding material for mounting the device wafer to a handle wafer during processes requiring etching through a wafer [4]. This mounting is required to prevent helium leaks into the chamber. Device wafers can also be mounted on quartz wafers for visual verification of the etch completion.

It is possible to operate with a predetermined common pressure for both etching and passivating active cycles, or with a fixed angular position for the opening of the automatic pressure control valve (APC). In the first case the position of the throttle valve (or APC valve) varies as the gas flow changes during each cycle. In the latter case, the position of the throttle valve is fixed and the pressure is determined by the gas flow rate. The results presented in this report used this latter approach. Higher values of the APC valve position in degrees correspond to higher pressures. However, the trip pressure is fixed at 90 mT creating an upper pressure limit in these experiments.

For the eight-variable experiment the samples were prepared in the following fashion: 4" single crystal silicon <100> wafers were coated with photoresist AZ4620 (Hoechst Celanese, Sunnyvale, CA) spun at 3000 rpm (thickness $\approx 6 \mu\text{m}$) and baked in a convection oven at 90°C for 30 minutes. The samples were then exposed in a contact aligner with a wavelength of 320 nm and power density of 6 mW/cm^2 , developed with AZ440 (Hoechst Celanese, Sunnyvale, CA), and baked again at 90°C for 30 minutes. We used an SEM to study each etched sample. The etching time for these samples was fixed at 30 minutes each.

In order to obtain information on the influence of coil power during etching, an additional four-variable experiment was also performed. This matrix consisted of samples prepared in the following fashion: 4" single crystal silicon <100> wafers were coated with photoresist OCG 825 (Shipley, Marlboro, MA), with viscosity 20 cs, baked and exposed in the same fashion but developed with OCG 934 (1:1). In this case the expected photomasking material thickness is approximately 1 μm . We used an optical interferometer to measure the thickness of the photoresist layer before and immediately after etching each sample, and a profilometer to measure the depth of the etched trenches. All etches had a duration of 3 minutes.

These sets of experiments are adequate to fit a quadratic model and were analyzed using commercial software. The systematic investigation produced response surfaces [5] that enable us to predict appropriate operating conditions for different processing requirements.

MEASURED PERFORMANCE

The etching rate of silicon has a predominant dependence on applied coil power (figure 3), because this input determines the degree of ionization and dissociation of the glow discharge. Although not seen in figure 3, this response also benefits from higher SF_6 flow rates as well as higher applied electrode power settings. Increasing electrode power during the etching cycle

increases primarily the ion bombardment energy and secondarily the ionization and dissociation of the discharge, all of which increase the etching rate. For low SF_6 flows, power increases only have a marginal effect on etching rate. At low flows the concentrations of products (SiF_4) that dissociate and redeposit increases [6].

The etching rate dependence on trench width, also known as ARDE [7, 8], varies with operating conditions (figure 4) and, therefore, it is also feasible to control this effect. ARDE benefits with high SF_6 flow rates because of the reduction of product species in the discharge that contribute to redeposition. An example that exhibits small ARDE is shown in figure 5. This was accomplished by using an SF_6 flow rate of 140 sccm.

Figure 3. Silicon etching rate ($\mu\text{m}/\text{min}$) dependence on applied RF-bias electrode power (W) and RF-inductive coil power (W).

Figure 4. Aspect Ratio dependent Etching variation with trench width for different operating conditions.

Low photoresist etching rate is necessary for robust operation. This response is strongly influenced by the applied electrode power, because this variable determines the ion bombardment energy. Lower electrode power settings are always favorable for achieving high selectivities. Furthermore, higher pressure settings also benefit this response.

Figure 7. Micrograph of a trench etched applying 600 W during the passivation cycle and 750 W during the etching cycle.

Figure 8. Micrograph of a trench 1.85 μm wide and 63.6 μm deep on the left, and a wall 0.8 μm thick and 47.4 μm tall on the right.

Figure 9. The footing effect appears when the etch stops on a buried oxide layer. It is clearly seen in the left micrograph. This effect can be suppressed controlling the passivation films as shown in the right micrograph.

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