The opening effect, that means the reduction of conductivity by stimulated electron-hole recombination is strongly dependent on the value of the direct recombination rate coefficient. Rate equation calculations with $k_d \approx 10^{-10}$ cm$^3$ s$^{-1}$, characteristic for pure GaAs (Ref. 15) showed that with the same laser power and duration the conductivity drop is four orders of magnitude less than for $k_d = 10^{-7}$ cm$^3$ s$^{-1}$. Generally, the faster the electron-hole pair recombination, the less laser energy is required to open the semiconductor switch.

In all these calculations it was assumed that during the switching process transitions between impurity levels can be neglected. Second, it was assumed that nonlinear processes do not contribute to the population of energy levels. For high-power switches triggered by high-power lasers, multiphoton process impose limitations on the maximum obtainable switch current density. Another limitation is given by impurity interactions and cluster formations at high-impurity concentrations.

The outstanding features of the described switch are that it can be turned on and turned off on command without jitter on a nanosecond and faster timescale and that it does not require external energy to sustain the conductivity in the on state. The application of this type of switch is not limited to pulsed power systems, but can be extended to any system where bistable elements with fast temporal response and optical control are required.

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# Anisotropic plasma-chemical etching by an electron-beam-generated plasma

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Anisotropic etching of $SiO_2$ has been achieved with a plasma generated by a broad-area low-energy (150–300 eV) electron beam in a He + $CF_4$ atmosphere. Etch rates of up to 330 Å/min for $SiO_2$ and 220 Å/min for Si were obtained. Etching occurred with good uniformity over the entire area exposed to the electron-beam-generated plasma. The fluxes of energetic charged particles to the sample surface are discussed in relation to their possible contribution to the etching process.

We report the first experimental demonstration of anisotropic etching of $SiO_2$ achieved with the assistance of an electron-beam-generated plasma. It has been previously shown that enhancement of $SiO_2$, $Si_3N_4$, and Si etching is obtained through the use of energetic electrons.[1–3] In comparison with ion beams of the same energy, beam electrons induce less crystalline damage.[1] Consequently, low-energy electron-beam-assisted etching has been proposed as source of low-damage etching.

Coburn and Winters demonstrated that $Si_3N_4$ and $SiO_2$

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are readily etched in a $XeF_2$ atmosphere when assisted by a 1500-V, 50 mA/cm$^2$ small-area electron beam[2]. The nonthermal increase in the rate of plasma-chemical etching of Si and $SiO_2$ in a $CF_4 + O_2$ atmosphere under bombardment by 200-eV electrons was reported by Kireev *et al.*[3] These experiments have demonstrated an increase in etch rate in the presence of an electron beam, but did not describe the etched profiles.

Here we report the anisotropic etching of $SiO_2$ in a $He + CF_4$ plasma created by a low-energy (150–300 eV) broad-area electron beam. Single-crystal (100) Si has also been etched in the same environment. In our experiment, a 1.9-cm-diam electron beam was used to decompose $CF_4$ molecules into reactive radicals and provide a directed flux of energetic electrons to the sample surface.

A schematic diagram of the experimental setup is shown in Fig. 1. A novel hollow cathode discharge electron gun was developed to produce a well-collimated beam of electrons in a $He + CF_4$ atmosphere at pressures up to 0.1 Torr. In this environment, our electron source can produce dc electron beams with current densities up to 15 mA/cm$^2$ at energies between 100 and 1000 eV. Details of the design, operation, and characterization of the broad-area low-energy electron source are discussed in another publication.[4] The electron source and a water-cooled sample support platform are enclosed in a cross-shaped stainless-steel vacuum vessel with 10-cm-diam ports. The samples to be etched were placed on the platform so that the beam strikes at normal incidence. The platform was maintained at the same potential as the outer grid of the electron source to form a nearly field-free negative glow region between the sample and the electron gun. The distance between the electron gun and the sample was adjustable, and tests at 0.7, 1.4, and 2.2 cm were performed. The chamber was evacuated to $10^{-3}$ Torr with a rotary pump, and a rotameter-controlled flow of gases was established. Helium was flowed through the hollow cathode of the electron source to make the operation of the discharge relatively independent of the reactive gas in the etching region. $CF_4$ was flowed into the reaction chamber at a rate of 490 sccm, which is large enough to ensure that the etch rate is not limited by an insufficient amount of reactant gas.

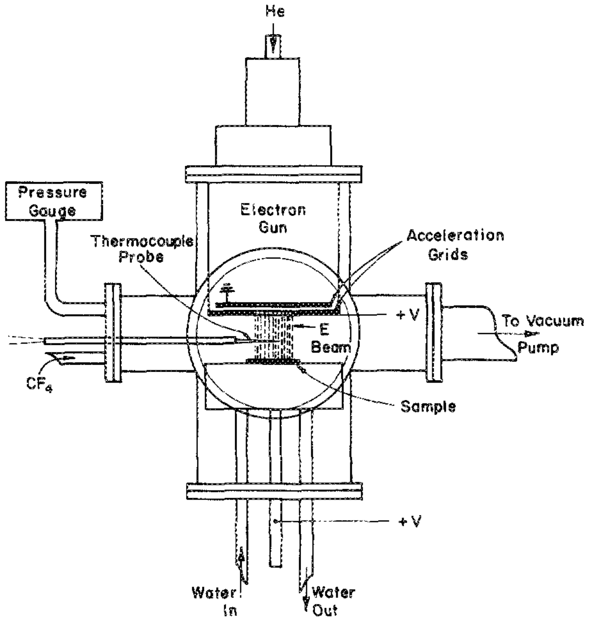

FIG. 1. Schematic diagram of the experimental setup. The thermocouple probe was used to monitor beam power density. A second thermocouple (not shown) was soldered with indium to a Si sample to measure wafer temperature.

Both $SiO_2$ and Si were readily etched in a 50-mT He + 30-mT $CF_4$ environment under a variety of electron beam conditions. $SiO_2$ films, 1.5 $\mu$m thick, were thermally grown over a (100) Si substrate. The Si substrates were 15–20-$\Omega$-cm boron-doped (100) silicon wafers. For the etch profile studies, masking was done with AZ-5214 resist that was deep UV ($\lambda = 254$ nm) stabilized and hard baked for 60 min at 150 °C to insure mask integrity during eteching.

Figure 2 shows a linear dependence of the etched step height in $SiO_2$ and Si as a function of etching time. The constant slopes give etching rates of 175 and 85 Å/min, respectively. The samples were etched at 2.2 cm from the gun with an electron beam current density of 3.0 mA/cm$^2$ and an acceleration voltage of 175 V.

The etch rate dependencies of $SiO_2$ and Si as a function of electron beam current denstiy and energy were studied. Substrate heating imposes a limitation on the maximum values of the electron beam current density and energy. Excessive heating causes photoresist reticulation and degradation and thermal etching. The electron beam current was monitored during the etching by measuring the current collected by the acceleration grid. The beam current density at the sample position was previously measured with a calorimeter and correlated to the acceleration grid currents.

Figure 3(a) shows the increase of the etch rates of $SiO_2$ and Si as a function of electron beam current density. The data were taken for an electron beam acceleration voltage of 175 eV. While the etch rate of $SiO_2$ was found to increase linearly with electron beam current density in the entire range investigated, the etch rate of silicon increased at a larger rate at high (> 3 mA/cm$^2$) beam current densities. A linear increase in the etch rate might be expected since the rate of production of reactive radicals by electron impact collisions increases linearly with current density. Also, an increase in the dissociation rate of adsorbed radicals and

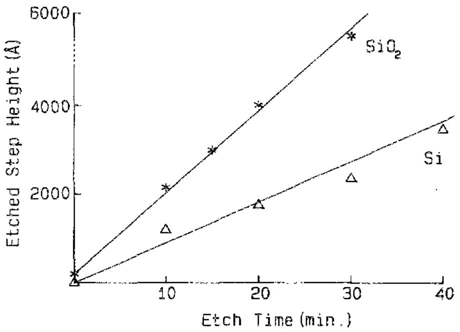

FIG. 2. Variation of the etched step height as a function of time for $SiO_2$ and Si. The atmosphere was 50-mT He + 30-mT $CF_4$, the electron beam current density at the sample position was 3.0 mA/cm$^2$, the acceleration voltage was 175 V, and the sample was positioned 2.2 cm from the gun.

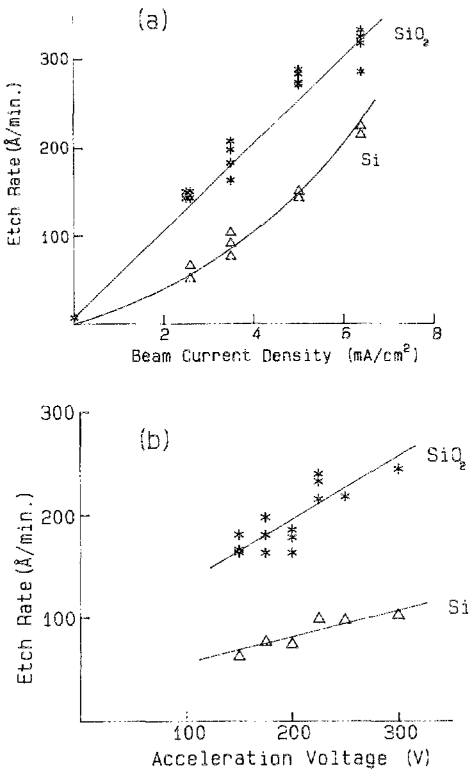

FIG. 3. (a) Etch rate of $SiO_2$ and Si as a function of electron beam current density at the sample. The beam energy was 175 V. (b) Etch rate of $SiO_2$ and Si as a function of electron beam energy. The beam current density at the sample position was 3.0 mA/cm², the atmosphere was 50-mT He + 30-mT $CF_4$, and the distance between the gun and sample was 2.2 cm. The small $SiO_2$ etch rate in the absence of the electron beam was a consequence of 30 min of exposure of the sample to plasma diffusing from the electron gun without beam acceleration voltage applied.

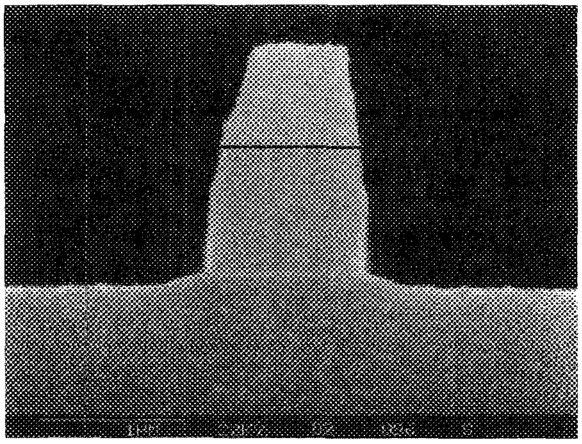

FIG. 4. Etched profile in $SiO_2$. The feature was etched at 150 V for 90 min in He + $CF_4$ atmosphere at a distance of 0.7 cm from the gun. The upper layer, designated by the line, is AZ-5214 photoresist. Below the line is a $SiO_2$ film on a Si substrate.

electron-stimulated desorption of etching products[5–6] should result from an increased electron beam flux. The additional increase in the Si etch rate is probably due to the thermal component of the etching. Measurements of the wafer temperature under the corresponding beam conditions show an increase in wafer temperature from 60 °C at 2.5 mA/cm² to 148 °C at 6.4 mA/cm².

Figure 3(b) illustrates the etch rate dependence as a function of the electron beam energy in the range between 150 and 300 eV, for a constant electron beam current density of 3.0 mA/cm² incident on the sample. Both the $SiO_2$ and Si etch rates increase with beam energy in this range, but the Si rate increase is less pronounced. Collisional production of the etching radicals in the electron-beam-generated plasma decreases slightly over the energy range investigated.[7] Subsequently, the etch rate would be expected to decrease. The observed increase might be due in part to secondary electrons emitted from the sample surface,[1] which can contribute to the creation of reactive radicals.

The anisotropic profile of an etched $SiO_2$ feature 1.0 $\mu$m wide is shown in Fig. 4. No resist undercut was observed in the Si profiles, however the sidewalls were significantly sloped.

In previous electron-beam-assisted etching experiments, the observed enhancement of the etching rates was attributed to beam electrons.[2,3] Nevertheless, the contribution of energetic ions possibly existing in the electron beam plasma used here and in some of the experiments reported in the literature[3] cannot be ignored. There are two mechanisms which could potentially contribute to the anisotropic etching observed in the experiments reported here: direct surface impingement by beam electrons and bombardment by negative ions created by electron attachment and dissociation in the source and accelerated through the potential difference between the grids of the electron gun. The bombardment of the surface by positive ions accelerated across the plasma sheath formed between the bulk of the electron-beam-generated plasma and the sample is unlikely to play a significant role. The voltage drop across the plasma sheath was calculated from a simple model of the sheath to be less than 1.0 eV. This is a consequence of both the low energy ($\simeq$0.1 eV) of the thermalized secondary electrons created by ionization in the beam generated plasma[8] and the secondary electrons emitted from the substrate surface. In this energy range, the secondary electron emission (SEE) coefficients of $SiO_2$, Si, and resist polymer are greater than one.[9] Emitted secondary electrons serve to neutralize the substrate surface and lower the sheath potential.[9] Further measurements, including that of the electron temperature in the He + $CF_4$ electron-beam-generated plasma, are still required to verify our assumptions and to determine with certainty the role of energetic positive ions in the etching process.

The contribution of negative ions cannot be easily neglected since the reactant gas can diffuse upstream into the electron source and result in their formation. While $CF_4$ practically does not capture thermal electrons,[10,11] the decomposition products of the molecule could result in a significant concentration of negative ion species, mainly $F^-$.[12–14] In order to estimate the possible energetic negative ion flux, we introduced an electrostatic probe into the electron source plasma above the acceleration grids. From the Langmuir probe trace, it is possible to obtain rough measurements of the negative ion density to electron density ratio.[13] The ion saturation current portion of the probe trace enabled us to calculate the positive ion density, and the density of negative ions was obtained from the condition of quasineutrality of the plasma. This technique does not allow an accurate measurement of the ion density to be made. However, it can be used to set an upper limit for the presence of a negative ion current. Measurements made at typical electron source operating conditions gave an electron density of $1\times10^{10}$ cm$^{-3}$ and indicated that the negative ion density could be of the same order. Considering the F$^{-}$ to electron mass ratio, the maximum energetic ion flux is estimated to be 1% of the electron beam current density and could consequently amount to ion beam current densities of up to 60 $\mu$A/cm$^2$. Even if the negative ion flux is expected to be approximately 100 times smaller than the measured electron beam flux, it cannot be completely neglected since, from previous experiments in XeF$_2$, the yield of ions was measured to be an order of magnitude larger than that of beam electrons.[1] Further studies are required to determine the relative role of negative ions in assisting anisotropic etching in electron-beam-generated plasmas.

In summary, we have demonstrated anisotropic etching of SiO$_2$ in a He + CF$_4$ electron-beam-generated plasma. Etching was observed to occur over the entire surface exposed to the electron beam with good uniformity and can be scaled to larger areas with electron guns currently available.[4] The possible contribution of energetic ions in electron-beam-assisted etching experiments cannot be neglected and should be more carefully studied.

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# Dielectric measurements on substrate materials at microwave frequencies using a cavity perturbation technique

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A cavity perturbation resonance technique suitable for microwave measurements on substrate materials is discussed. The technique makes use of thin rectangular samples placed in a rectangular waveguide cavity ($Q\sim5000$). The availability of advanced microwave measurement equipment makes it possible to record experimental data at several frequencies (five in this present case). The estimated accuracy of measurements is $\pm2\%$ for dielectric constant and $3\times10^{-4}$ for dielectric loss. Results are reported in the 8.2–12.4-GHz frequency range for alumina and specially prepared silica.

Higher computer speeds and increasing use of microwaves in advanced navigation and domestic appliances require that electrical properties of materials be known at high frequencies. Substrates in microwave integrated circuits and packaging system assemblies have dielectric constants in the range from 2 to 10 and dielectric losses ($\tan\delta$) lower than $10^{-3}$. Therefore, a measurement technique which can measure dielectric parameters with high precision and accepts thin specimens is highly desirable.

Among the reflection-transmission measurement methods at microwave frequencies, a widely used one is that developed by Roberts and von Hippel.[1] The technique loses accuracy for thin sheet specimens encountered in substrate and packaging materials.[2] Chao[3] has discussed other sources of error occurring in short-circuit line methods in general. Alternative techniques have been worked out for thin specimens.[4–8]

Cavity perturbation methods have been widely used in the measurement of dielectric parameters of materials. The perturbation theory of resonant cavities was first proposed by Bethe and Schwinger.[9] The assumptions were further redefined by Spencer, LeCraw, and Ault[10] and Waldron.[11]

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