Broad-area electron-beam-assisted etching of silicon in sulfur hexafluoride

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Silicon etching rates up to 250 Å/min have been observed in an electron-beam-generated He plus SF_6 plasma. The etch rate was found to increase linearly with electron beam current density and to be practically independent of the electron acceleration voltage in the range investigated (170–260 V). Profiles of the resulting features show that etching is anisotropic with a vertical-to-horizontal ratio of 2.5 to 3.

Energetic ions, formed into a beam by an ion source or accelerated in a plasma sheath, are commonly used to assist the etching of microelectronic materials.[1–3] In contrast, the application of low-energy electrons to this process has remained undeveloped. Low-energy ($\leqslant 1$ keV) electrons can be used to induce gas-phase and surface chemical reactions with reduced surface damage.[4] Consequently, the use of beams of these electrons have been studied by our group to determine its feasibility as a new tool to assist in the etching of microelectronic and optoelectronic materials.

For this purpose, we have recently developed a broad-area, low-energy (100–1000 eV) electron source capable of producing beams in a reactive gas atmosphere with independent electron energy and beam current density control.[5] In this source, a plasma is created by a hollow cathode discharge, from which a beam is formed by accelerating the constituent electrons through a potential drop applied between two grids by an external power supply. The design of this electron source and its operation characteristics have been described in detail in a recent publication.[5]

This novel electron source has been used to demonstrate that anisotropic etching of SiO_2 films can be obtained in an electron-beam-generated plasma containing CF_4.[6] Here we report the results of studying the etching of silicon samples in a He plus SF_6 plasma created by a broad-area ($\simeq 3$ cm^2) electron beam. In these experiments the electron beam serves two purposes: it creates reactive radicals by electron impact dissociation of SF_6 and it provides directed energy to the wafer surface to assist surface reactions.

The materials etching was performed in a stainless-steel chamber where a 1.9-cm-diam electron beam created by the source was directed normal to the wafer surface. The wafer samples were positioned on a water-cooled stainless-steel platform maintained at the same potential as the accelerating grid of the electron source. This resulted in a relatively field-free negative glow region being created between the electron gun and the wafer platform. The distance between the electron source and the wafer sample was maintained at 2.2 cm.

The chamber was evacuated to 10^{-3} Torr with a rotary pump and the He and SF_6 gas flows were stabilized and controlled via rotameters. Helium was introduced through the hollow cathode of the electron source for discharge operation. This flow enabled the discharge to be operated relatively independent of the reactive gas in the etching region. The reactant SF_6 flowed into the system at ~ 500 std. cm^3/min (sccm) through a lateral port, slightly above the level of the wafer surface. This flow rate was sufficiently large to prevent measurable gas depletion effects. All the tests reported here were performed at a chamber pressure of 55-mTorr He + 7 mTorr SF_6. A more thorough description of the etching apparatus is given in Ref. 6.

The etching procedure consisted of stabilizing a hollow cathode discharge within the body of the electron source for a period of 45 min before applying the acceleration voltage to the external grid to generate the electron beam and initiate the electron-beam-induced etching processes. This preliminary discharge operation was found to be necessary to insure stable beam operation during the following etching tests. The electron beam energy was set by adjusting the voltage difference applied between the two grids of the electron source.[5] The electron beam current was monitored by measuring the current collected by the accelerating grid, which had a transmissivity of 30%.

The semiconductor material etched was (100) oriented 15–20 Ω cm boron-doped silicon. Masking for determination of the etch rates was performed by covering the samples with a piece of the same silicon material. For the tests to determine feature anisotropy, an AZ-4210 photoresist mask was used. The photoresist was deep UV ($\lambda = 254$ nm) stabilized and hard baked for 60 min at 150 °C to insure mask integrity during etching.

The etch rate behavior was examined using a stylus profilometer for various beam energies and current densities. The ranges of acceleration voltages and beam current densities were chosen to prevent damage to the photoresist mask and substrate surface due to excessive heating. All etch tests lasted for 30 min. Figure 1 shows the variation of etched step

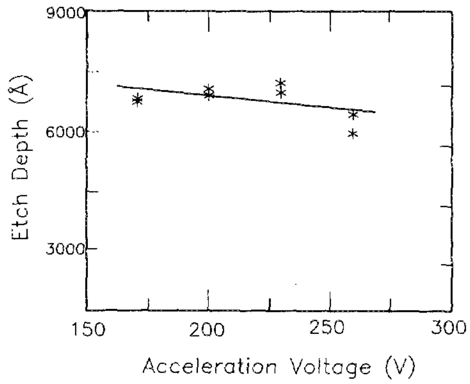

FIG. 1. Silicon etched step height as a function of the accelerated voltage. The grid current was 16 mA, the background pressure 55-mTorr He + 7-mTorr SF_6, and the etch time 30 min following the source pretreatment described in the text.

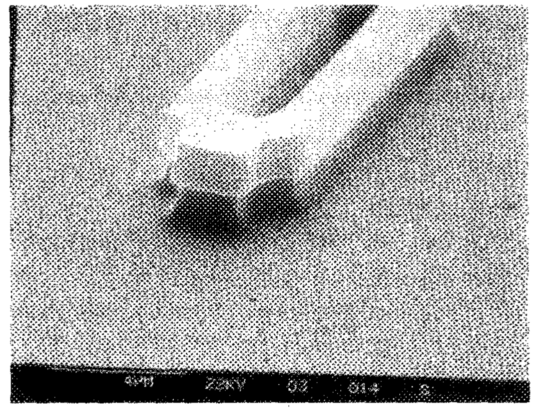

FIG. 2. Silicon etched step height as a function of grid current. The acceleration voltage was maintained at 170 V, the background pressure 55-mTorr He + 7-mTorr SF_6, and the etch time 30 min following the source pretreatment described in the text.

height with respect to electron acceleration voltage over the range 170–260 V. The current collected by the acceleration grid was maintained at a constant value of 16 mA throughout this series of tests. The etched step height is practically independent of electron beam energy in this range and has an approximate value of 6900 Å. The negligible dependence of the silicon etched step height on the electron energy is because the resonances for all important gas-phase and surface reactions occur at electron energies below 170 eV. Consequently, the range of the acceleration voltage examined does not coincide with a region of significant change in the reaction processes. While it would be desirable to extend the study to a broader energy range, in practice, this is limited by the increased scattering of the beam electrons in collisions with the gas molecules at lower energies and excessive wafer heating at higher energies.

The variation of etched step height with beam current density as monitored through the grid current is illustrated in Fig. 2. For this series of tests, the acceleration voltage was maintained at 170 V. As shown, the step height increases linearly with increasing grid current, as does the beam current density, to reach a maximum value of 10 100 Å. The dependence of the etch rate on electron beam current density is similar to results previously observed in the etching of SiO_2 by an electron-beam-generated He plus CF_4 plasma.[6] This behavior can be explained by the assumed linear dependence of the production of reactive radicals in the gas phase and the rate of electron-induced surface reactions on the electron flux. The nonzero intercept of the step height at zero current in Fig. 2 has been attributed to plasma–chemical etching caused by reactive radicals diffusing from the electron source before the electron beam is created. Subtracting this contribution from the total etch step height, the electron-beam-assisted etch rate is calculated from Fig. 2 to vary between 50 and 250 Å/min.

The profiles of the etched Si features were examined using a scanning electron microscope (SEM). The features were observed to exhibit relatively vertical sidewalls, with a vertical-to-horizontal etching ratio of 2.5 to 3. The micrograph in Fig. 3 shows a field view of the etched feature.

In conclusion, we have demonstrated that broad-area electron-beam-assisted etching of silicon in an He plus SF_6 atmosphere yields anisotropically etched features. The etch rate increases linearly with electron beam current density and is practically independent of the beam acceleration voltage in the range (170–260 V) investigated. However, additional studies are needed to obtain a more detailed understanding of the gas-phase and surface reaction mechanisms that produce anisotropic etching with the assistance of an electron beam.

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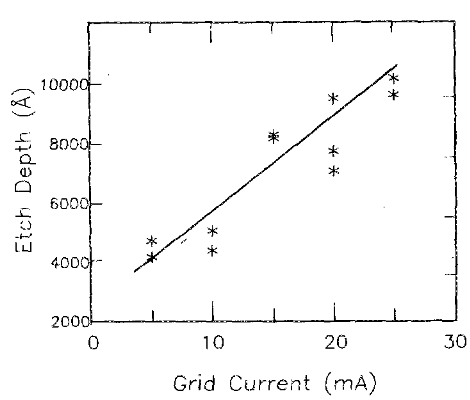

FIG. 3. SEM view of a 1.2-μm-wide, 1.3-μ-deep, etched silicon feature with the photoresist mask intact. The etching was performed with an acceleration voltage of 170 V, a grid current of 16 mA, and a background pressure of 55-mTorr He + 7-mTorr SF_6.

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