

# Low-energy broad area electron beam for etching microelectronic materials

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(Received 6 March 1987; accepted for publication 19 May 1987)

We have generated beams with electron current densities of more than 10 mA/cm<sup>2</sup> at energies between 150 and 900 eV using a plasma source. This electron source can be operated at background pressures between 0.01 and 0.1 Torr in helium and with the addition of various gases, producing electron beams up to 3.8 cm in diameter. The broad area beam can be used to induce gas phase and surface reactions and has been successfully used to achieve anisotropic etching of SiO<sub>2</sub> films in the reactant gas CF<sub>4</sub>.

## I. INTRODUCTION

We describe a low-energy (100–1000 eV) broad area electron source that has been successfully used to anisotropically etch SiO<sub>2</sub> films in a CF<sub>4</sub> environment. The electron source can be operated in various gases at pressures between 0.01 and 0.1 Torr, and offers independent control of the electron beam energy and current. The broad area electron beam can be used to excite, ionize, and dissociate molecules, subsequently inducing chemical reactions in the gas phase or on surfaces. The source finds applications in areas of microelectronic materials processing, such as deposition and etching.

Previously, broad area electron beams have been produced in a gaseous environment by using a simple two electrode glow discharge configuration.<sup>1</sup> This type of electron gun uses electron emission produced by ion bombardment at the cathode and the subsequent acceleration of the electrons in the voltage drop of the cathode sheath to form the beam. These glow discharge electron guns can produce high current-density beams operating at pressures between 0.1 and a few Torr and have been successfully used in electron beam induced chemical vapor deposition.<sup>2,3</sup> However, ambient pressure, electron beam current, and electron beam energy cannot be independently controlled in these sources. Also, the production of well-defined electron beams using glow discharges is limited to energies greater than 800 eV. In some applications, such as electron beam assisted etching, a high-energy beam produces undesirable effects, such as wafer heating and mask damage.

More recently, another type of source, capable of producing an electron beam of controllable energy between 100 and 1000 eV was developed by Kaufmann and Robinson.<sup>4</sup> The beam produced by this source is 0.3 cm in diameter at the gun and diverges as it propagates in the chamber. At 10 cm from the gun, the electron beam produced has a Gaussian profile (2-cm FWHM) with current densities up to 8 mA/cm<sup>2</sup> at 300 V. The operation of this source in argon was limited by gas breakdown to background pressures below 0.001 Torr.

The electron source described herein operates at higher pressures and has been successfully used in a He plus CF<sub>4</sub>

atmosphere at pressures of up to 0.1 Torr to anisotropically etch SiO<sub>2</sub> films. This source produces a collimated cylindrical beam up to 3.8 cm in diameter.

## II. ELECTRON GUN STRUCTURE AND OPERATION

The operation of the electron source is comprised of two processes. One is the formation of a plasma by a hollow cathode discharge. The second is the acceleration of the electrons from this discharge by an electric field sustained between two grids.

The structure of this source is shown schematically in Fig. 1. The hollow cathode is a 1.0-cm-i.d. stainless-steel tube that has a cylindrical insert made of 0.025-mm-thick tantalum foil at the end. Upon heating, the tantalum foil acts as a thermionic emitter. Heating is provided mainly by the bombardment of the foil by ions, which are accelerated in the cathode fall region of the discharge, and fast neutrals created by charge transfer. The heating is enhanced by the poor thermal and good electrical contact between foil and cathode tube. Since the cathode is self-heated, no external heaters were used. Helium gas flows through the hollow cathode at approximately 485 sccm. A negative potential difference of approximately 1.2 kV between the cathode and an anode is required to initiate the discharge. After breakdown, a maintenance voltage of approximately 300 V is required to operate the discharge under typical conditions.

The hollow cathode and the anode are separated by a 1.0-cm-thick boron-nitride disk which has an orifice 0.05 cm in diameter in the center. The restricted helium flow through the orifice causes a pressure difference between the hollow cathode and the reaction chamber. In this way the helium pressure in the cathode region can be maintained at a significantly higher pressure than that in the reaction chamber. For example, the cathode pressure is 2.6 Torr when the reaction chamber pressure is maintained at 16 mT. The entire cathode structure is enclosed in a water-cooled stainless-steel jacket. This enclosure and the helium flow through the orifice keep the hollow cathode discharge free of damage that would be inflicted by highly reactive gases that may be introduced downstream of the electron source. The helium flow through the orifice also allows the discharge to be maintained relatively independent of the concentration of chemically reactive gases in the system.

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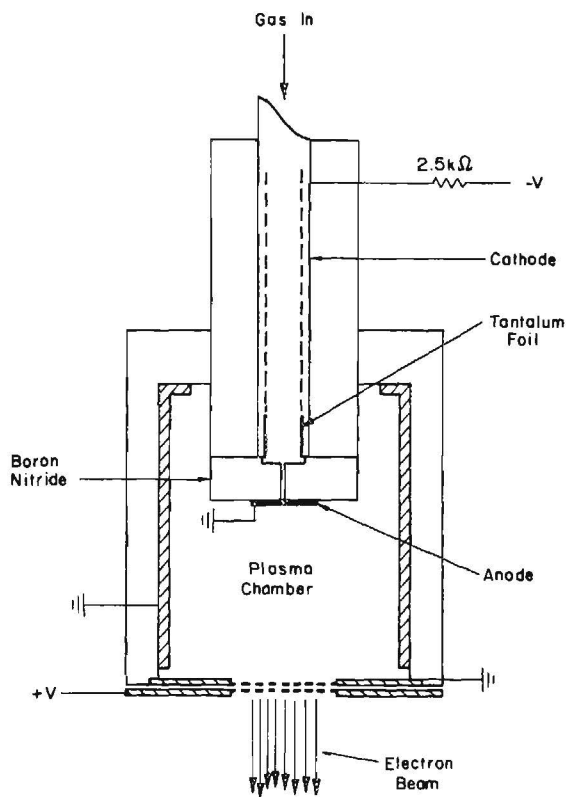


FIG. 1. Schematic diagram of the electron source.

The plasma from the hollow cathode discharge expands into a 5.4-cm-diam stainless-steel chamber. Electrons from this plasma diffuse to a gap formed by two stainless-steel grids, where they are accelerated to form the electron beam. The grids are made of a 42-mesh stainless-steel screen, which has a transmissivity of 59.7%. The screen is mounted on stainless-steel plates. Two sets of grids with aperture diameters of 1.9 and 3.8 cm were alternatively used to produce collimated beams of those dimensions. The distance between the grids is kept to 2.0 mm to avoid Paschen electrical breakdown at the operating pressures. Breakdown was never observed at extraction voltages up to 1000 V under normal operating pressures ( $< 0.1$  Torr) in a He plus  $\text{CF}_4$  atmosphere. It should be possible to operate the gun at even higher accelerating voltages, but at 1000 V and large electron beam current densities, the acceleration grid starts to glow. Output of greater electron beam power can probably be achieved by using sets of grids in which the holes are carefully aligned.

The hollow cathode discharge was maintained by a negative potential applied to the cathode. The anode was connected to ground through the plasma chamber, which was grounded by an external connection in the gun housing. A positive voltage was applied between the acceleration grid and ground to extract the electrons and create the beam, as shown in Fig. 1. For some applications, it might be more convenient to ground the extraction grids and to float the hollow cathode supply. The inner grid can be grounded or supplied with a bias voltage to provide control of the electron beam current. Alternatively, the electron beam current can be controlled by varying the hollow cathode discharge cur-

rent. The results of the variation of these parameters will be discussed in the next section.

### III. PERFORMANCE AND APPLICATION

Figure 2 shows a well-defined 400-eV cylindrical electron beam 1.9 cm in diameter produced in a background atmosphere of 50 mTorr of helium. Visual inspection showed the beam to be well-collimated in all tests. We found the beam divergence to be small, typically less than  $3^\circ$  at 0.7 cm from the acceleration grid. This value was determined by measuring the image of the screen pattern on the wafer surface.

The electron beam current densities obtained at acceleration voltages between 150 and 900 V are shown in Figs. 3(a) and 3(b). The electron beam currents have been measured with a copper calorimeter placed 1.0 cm from the acceleration grid. The measurements were made by determining the heat gained by the calorimeter from the beam as a function of time and correcting the values for heat losses. This correction was experimentally determined from the cooling rate of the calorimeter when the beam was shut off.

Figure 3(a) shows that electron beam current densities larger than  $1 \text{ mA/cm}^2$  were obtained at energies between 150 and 900 eV in 50 mTorr of helium with a hollow cathode discharge current of 50 mA. Considerably larger electron beam current densities were obtained when  $\text{CF}_4$  was introduced to the reaction chamber, as illustrated in Fig. 3(b). The increase in current density obtained while operating the gun in the presence of  $\text{CF}_4$  is attributed to the larger electron impact ionization cross section of the molecular gas,  $3.52 \times 10^{-16} \text{ cm}^2$  at 100 eV (Ref. 5) as compared with  $3.6 \times 10^{-17} \text{ cm}^2$  for He at the same energy.<sup>6</sup> This characteristic results in a denser plasma in the plasma chamber and, consequently, in a more intense beam.

The electron beam current can be controlled independently of the accelerating voltage either by varying the discharge current or by applying a potential bias to the inner grid. By the former procedure, the density of the source plasma is controlled. The electron beam current variation obtained for a 200-eV beam by varying the discharge current between 15 and 90 mA is illustrated in Figs. 4(a) and 4(b)

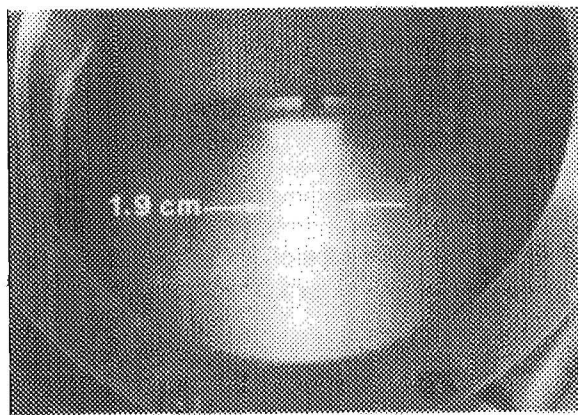


FIG. 2. 400-eV electron beam generated in helium at a pressure of 50 mTorr, a discharge current of 50 mA, and with the inner grid grounded.

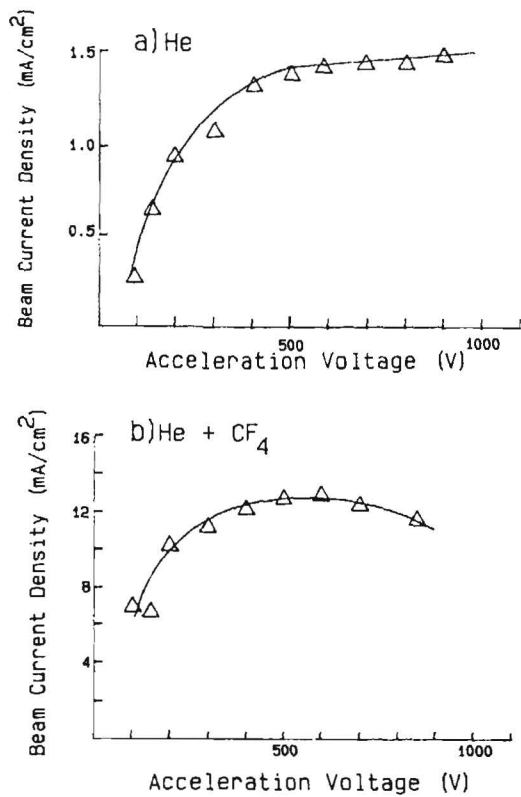


FIG. 3. Electron beam current density as a function of the voltage applied to the external (acceleration) grid. The inner grid was grounded and the discharge current was at 50 mA. (a) Background pressure of 50-mT He. (b) Background pressure of 50-mT He + 30-mT CF<sub>4</sub>.

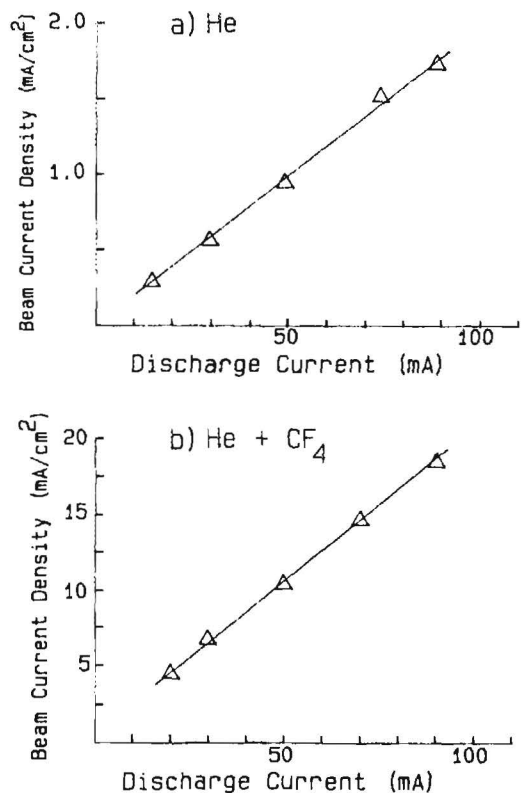


FIG. 4. Electron beam current density as a function of the hollow cathode discharge current. Electron beam energy was 200 eV and the inner grid was grounded. (a) Background pressure of 50-mT He. (b) Background pressure of 50-mT He + 30-mT CF<sub>4</sub>.

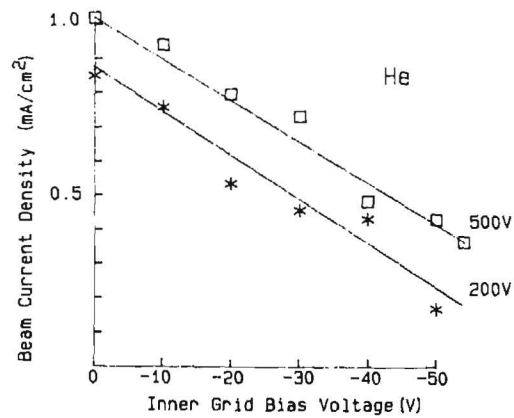


FIG. 5. Electron beam current density as a function of inner grid bias voltage for acceleration voltages of 200 and 500 V. The background pressure was 50-mT He and the discharge current was 50 mA.

for a helium and a He plus CF<sub>4</sub> mixture, respectively. Figure 5 shows the electron beam current variation obtained by operating the hollow cathode discharge at a fixed current of 50 mA and applying a negative bias to the inner grid. The potential applied to the inner grid controls the electron flux from the discharge to the acceleration gap and provides an alternative method of controlling the beam current.

The electron beam current-density distribution across the beam diameter was measured with a Faraday cup. The Faraday cup is composed of a graphite current collector surrounded by a machinable ceramic shield and which has an orifice 0.3 cm in diameter. To ensure that only energetic electrons are collected, a 12-V negatively biased screen is placed in front of the collecting surface. Figure 6 shows the transverse beam profiles measured in helium at a distance of 0.7 cm from the acceleration grid for both a 1.9-cm-diam and a 3.8-cm-diam grid aperture.

As the beam propagates in the background gases, it loses energy and disperses due to collisions with the gas molecules. The variations of the electron beam current density as a function of the distance from the acceleration grid were determined by calorimetric measurements and are illustrated in Figs. 7(a) and 7(b).

We have used the electron beam source to demonstrate a new method of anisotropically etching microelectronic materials over broad areas. Ion beams created by an ion source or in a plasma sheath are commonly used to assist in the etching of microelectronic materials.<sup>7,8</sup> Previously, Coburn

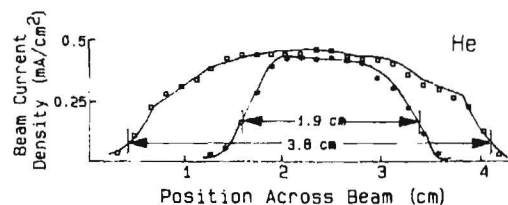


FIG. 6. Transverse profiles of the electron beam in terms of the current density for a 1.9-cm extraction aperture and a 3.8-cm extraction aperture. The profiles were measured 0.7 cm from the external grid, with a beam energy of 200 eV, a background pressure of 77-mT He, a discharge current of 50 mA, and the inner grid grounded.

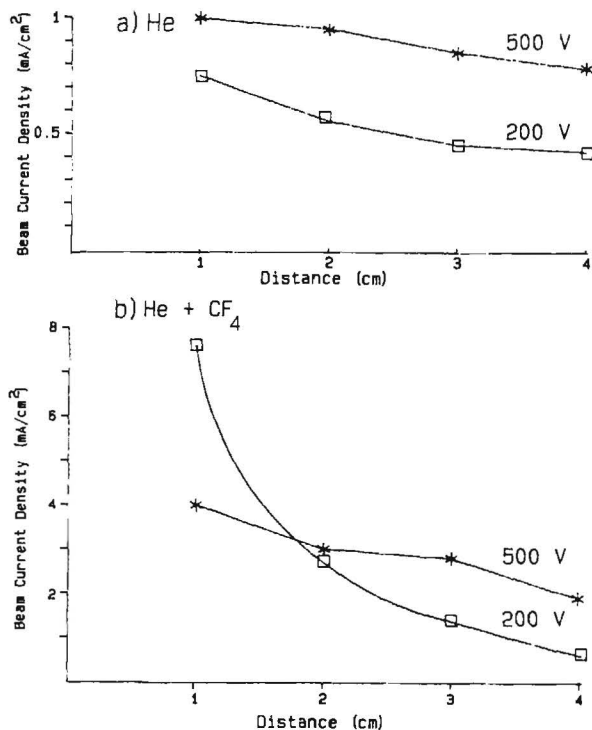


FIG. 7. Electron beam current density in the axis of the beam as a function of the distance from the external grid for electron beam energies of 200 and 500 eV. The discharge current was 50 mA and the inner grid was grounded. (a) Background pressure at 50-mT He. (b) Background pressure of 50-mT He + 30-mT CF<sub>4</sub>.

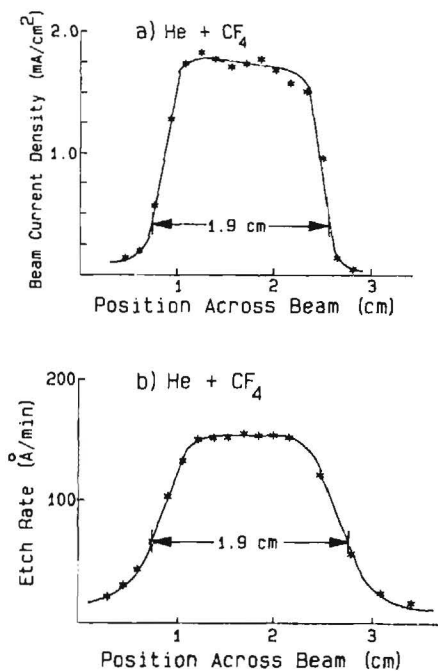


FIG. 8. (a) Transverse electron beam profile of beam current density. The electron beam energy was 200 eV, the discharge current was 50 mA, the inner grid was grounded, and the background pressure was 77-mT He + 45-mT CF<sub>4</sub>. The profile was measured at 0.7 cm from the electron gun. (b) SiO<sub>2</sub> etch rate as a function of the transverse position in the beam. The sample was positioned 0.7 cm from the gun. The electron beam energy was 170 eV, the discharge current was 50 mA, and the background pressure was 50-mT He + 30-mT CF<sub>4</sub>.

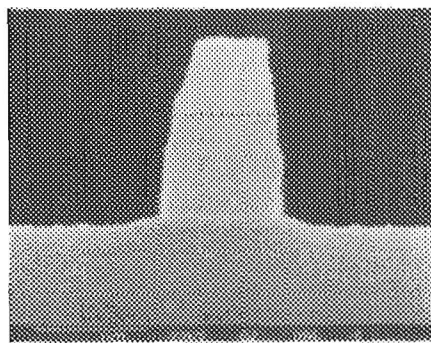


FIG. 9. SEM micrograph of an etched SiO<sub>2</sub> feature (width: 1 μm) on a Si substrate. The region above the dashed line is a positive photoresist mask. The mask is covering an SiO<sub>2</sub> film. Also, the boundary between the SiO<sub>2</sub> and a silicon substrate is visible. The sample was etched at 0.7 cm from the gun, with a beam energy of 150 eV, a discharge current of 50 mA, and a background pressure of 50-mT He + 30-mT CF<sub>4</sub>.

and Winters<sup>9</sup> used the small ( $9.0 \times 10^{-4}$  cm<sup>2</sup>) diameter electron beam in an Auger spectrometer to demonstrate that energetic (1.5 keV) electrons can assist XeF<sub>2</sub> in the etching of SiO<sub>2</sub>.

We have achieved anisotropic etching of photoresist patterned thermally grown SiO<sub>2</sub> films over an area approximately equal to the beam area (2.85 cm<sup>2</sup>). We used our electron source to enhance the etching process in two ways. First, the energetic beam electrons collide with the CF<sub>4</sub> background gas to create reactive radicals which diffuse to the wafer surface and react with the SiO<sub>2</sub> to form precursors of volatile compounds. Second, the beam provides a directional energy flux to the surface of the film, dramatically enhancing the etch rate in the vertical direction.

The beam current density distribution of a 200-eV beam in a He plus CF<sub>4</sub> atmosphere is illustrated in Fig. 8(a). This distribution can be compared with the etch rate profile of a SiO<sub>2</sub> sample shown in Fig. 8(b). The electron beam generated plasma is confined to the region defined by the beam and, consequently, the etch rate decreases significantly in the substrate region outside the electron beam.

Figure 9 is a SEM micrograph of an etched profile of a SiO<sub>2</sub> layer (feature width: 1.1 μm) achieved by placing the sample perpendicular to a 150-eV beam. The sample was etched for 90 min at a distance of 0.7 cm from the gun, in an atmosphere of 50-mT He and 30-mT CF<sub>4</sub>.

#### IV. CONCLUSIONS

In summary, we have developed a broad area electron source capable of operating at background pressures between 0.01 and 0.1 Torr, and providing current densities of more than 10 mA/cm<sup>2</sup> at beam energies between 150 and 900 eV. The electron beam current, beam energy, and background pressure can be independently controlled. The gun has successfully operated for several hundred hours in He plus CF<sub>4</sub> atmosphere while being used to anisotropically etch microelectronic materials. The electron source can be used to induce gas phase and surface chemical reactions for a large number of applications.

## ACKNOWLEDGMENTS

The authors wish to thank Sylvia Rogers for her assistance in the evaluation of the gun parameters and Tricia Douglas and Timothy Ash for their assistance in the etching experiments. This work was funded by NSF Grant No. CPE-84.08304 and an NSF Presidential Young Investigators Award.

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