Radial optical emission profiles of radio frequency glow discharges

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Radial optical emission profiles are determined from Abel inverted emission spectroscopy of a parallel plate radio frequency system known as a GEC Reference Cell. These profiles in general show a nonuniform plasma, annular in shape. Etching results of silicon wafers also follow this annular pattern. This effect is explained by numerically computed large radial and axial electric fields near the edge of the electrodes, produced by the presence of the grounded dark shields.

The increased use of rf glow discharges in microelectronics fabrication has resulted in the need for greater understanding and control of plasmas. Many factors can affect the behavior of the plasma. One of the most important is the geometry of the discharge chamber; minor alterations in design can result in large variations in plasma parameters and, hence, in the etching results. In industry, it has been known that even apparently identical commercial etchers can behave differently.

Due to the number of different systems used for experiments in the past it was difficult to compare data from machines of differing geometries. Similarly, it was difficult to directly compare results from the codes developed to model these different machines. For this reason, a number of the participants at the 1988 Gaseous Electronics Conference agreed that a standardized discharge chamber was needed so that models and measurements could be done with identical systems at different locations. The initial designs for this GEC Reference Cell were drawn up at Sandia National Laboratory in 1989.[1,2]

The GEC Reference Cell is a parallel plate system with 4 in. diam aluminum electrodes and a 1 in. plate spacing. The electrodes are surrounded by grounded stainless-steel dark shields, separated from the electrode by an insulator, in this case Teflon. Gases are introduced into the chamber through the upper electrode in a shower head design. Additional design information can be found in Refs. 1–3. The lower electrode of the Reference Cell used for this work is powered with a 500W ENI AGC-5 13.56 MHz power supply and ENI MW-5 tuning network, while the upper electrode is grounded. This system has been shown to produce similar current and voltage characteristics as other GEC Reference Cells.[3]

One property of discharges that is especially important in the processing of semiconductor materials is plasma uniformity across the electrode; spatial variations of the plasma result in nonuniform etch rates across the wafer. Maintaining uniformity is especially critical as wafer sizes increase. To assess the uniformity of the discharge in the GEC Reference Cell, we have chosen to examine the optical emission of the discharge. By measuring the emission intensity at distinct points across the discharge, the emissivity of the plasma as a function of radius can be determined with a mathematical technique known as Abel inversion.

The optical emission of discharges at several pressure and power conditions were recorded for a number of points across the electrode at various heights. This was achieved by imaging parallel light rays from the emission on to a photodiode array, rotated by 90°, by way of one meter spectrograph. The light from a 4.25 in. diam quartz window was telescoped down by using two lenses with focal lengths of 100 cm and 12 cm placed 112 cm apart from each other. A small iris, about 1 mm in diameter, was placed at the common focal point between the two lenses to block out nonparaxial rays. Two prisms rotated the light by 90° before it entered the 1 cm high entrance slit of the spectrograph. A photodiode array at the exit port, rotated by 90°, was used to record the intensity of the rays at one wavelength. This allowed the simultaneous recording of the intensity at a fixed wavelength at 1024 spatially distinct points horizontally across the discharge. The optics were moved vertically to map out the whole interelectrode area. See Ref. 4 for details of the optical system.

Argon discharges at pressures of 0.1–1.0 Torr and at peak-to-peak voltages of 75–200 V were investigated. At each pressure and voltage the Ar I 750 nm spectral line was recorded at heights of 2.0, 6.0, 10.0, 14.0, 18.0, and 22.0 mm above the lower electrode. The 428 nm Ar II line was also investigated at these same conditions.

The intensity data had a low signal to noise ratio and therefore required smoothing prior to further analysis. Of the many smoothing techniques investigated, a polynomial fit was found to retain the spatial information without following the noise in the data. A major benefit of using a polynomial to describe the data is that an analytic expression for the Abel inversion is then known. This eliminates the numerical instabilities and problems with singularities at the origin, that plagued other smoothing and inversion techniques.

As was mentioned earlier, the window was 4.25 in. in diameter permitting a view just to the electrode edge. However, the discharge extended past the electrode region beyond the edge of this port. The discontinuity in the data at the window edge resulted in a polynomial fit with an unphysically steep slope at electrode edge. To account for the discharge extension, the emission data was linearly extrapolated 2/3 in. from the edge of the electrode. This agrees well with emission data from NIST.[5] Assuming a cylindrically symmetric, optically thin plasma, Abel's integral equation can be used to transform the measured intensity into the radial emission profile of the plasma. Typical re-

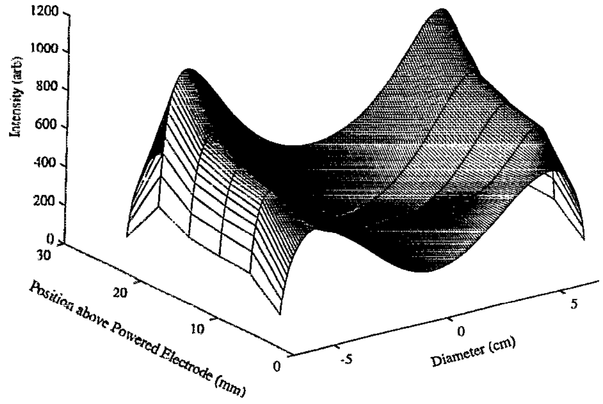

FIG. 1. Radial and axial optical emission profiles of an Ar I line at 750.4 nm at 1.0 Torr with a $V_{p\text{-}p}=75.0$ V.

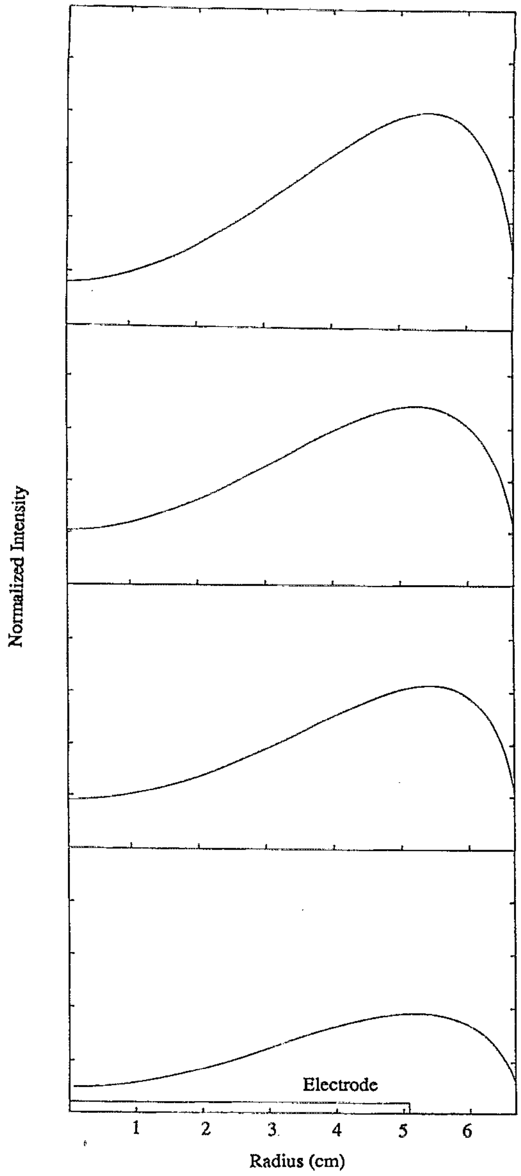

FIG. 2. Radial emission profiles from the Abel transformed data of the 750.4 nm Ar I for pressures of 1.0, 0.5, 0.25, and 0.1 Torr (from top to bottom, respectively) with a $V_{p\text{-}p}=150.0$ V.

sults for 750 nm Ar I line are shown in Figs. 1 and 2. The results obtained without the edge extrapolation were very similar although the radial emission erroneously went to zero at the window radius.

Figure 1 shows a three-dimensional view of the radial and spatial profile of the plasma at 1.0 Torr with a peak-to-peak voltage of 75 V. The nonuniformity of the plasma can clearly be seen from this data set. Figure 2 displays a two-dimensional view of the plasma at 2 mm above the cathode for several pressures. As indicated by this figure the edge enhancements of the plasma are greater at higher pressures. As expected, the center of the plasma is the most uniform. Results from the Ar ion line at 428 nm were similar.

We would like to postulate an explanation for the annular structure of the plasma that has been observed in the measurements described above. The GEC Reference Cell upper and lower electrodes are surrounded by cylindrical dark shields, grounded conductors separated from the sides of the electrodes by 3 mm of Teflon. Because the lower electrode potential is driven as much as 200 V above or below ground there will be a strong electric field across this Teflon filled gap, and also in the nearby plasma. This locally enhanced field could be responsible for accelerating electrons near the electrode edge to much higher energies than the weaker and nearly uniform field in the center of the cell.

We have computed the electric field throughout the GEC Reference Cell chamber by using the Poisson solver section of the MAGIC particle-in-cell code, developed by Mission Research Corporation for the Air Force Office of Science Research.[6] Figure 3 shows the peak axial and radial electric fields as a function of radius at an axial location 3.2 mm above the surface of the lower electrode, for an imposed rf potential of 200 V peak-to-peak; the field intensification in the region of the electrode edge and dark shield are very evident. The field intensification near the dark shield around the upper electrode (not shown) is very small because both that electrode and dark shield are grounded. However, because the imposed field is nonuniform and oscillates at 13.56 MHz there will be a strong ponderomotive effect, which will tend to drive the high energy electrons created near the lower electrode dark shield axially (as well as radially) toward the upper electrode. Thus, there do seem to be mechanisms available in the nonuniform rf electric field imposed on the system to account for increased argon excitation at the electrode radius. While this analysis does not include the self-consistent effects from the presence of the plasma, it does suggest that the electric field enhancement near the lower electrode edge could result in increased excitation of the plasma near the electrode edge. This is consistent with our experimental observations.

Young and Wu[7] modeled a system very similar to this system using a 2D fluid model. Although ungrounded sidewalls at the electrode radius were assumed, the model resulted in increased ionization rates at the edges of the elec-

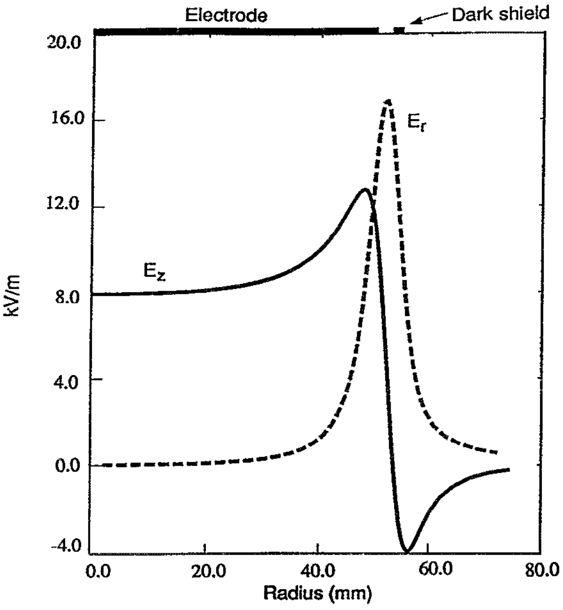

FIG. 3. Radial and axial electric fields as a function of radius at an axial position 3.2 mm above the lower electrode for an applied voltage of 200 V.

trodes. Olthoff *et al.*[5] at NIST examined the optical emission of their GEC Reference Cell with a different optical collection technique and found similar nonuniform plasma results.

Etch uniformity was also examined in the GEC Reference Cell. Figure 4 shows the results of a silicon wafer etched with 20 sccm of CF_4/O_2 at 250 mTorr and 280 V (15 W). While the central region of the wafer showed relatively uniform etching, the etch depth increased rapidly at the edges. A similar etching enhancement at the edges was noticed when the wafer was placed on a quartz plate during the etch. This seems to indicate that the increased etching at the edges was due to a nonuniformity in the plasma and not due to a fluorine loading effect. The nonuniformity of this discharge was directly witnessed in the etches verifying spatially resolved optical emission spectroscopy as a viable predictor for etch uniformity.

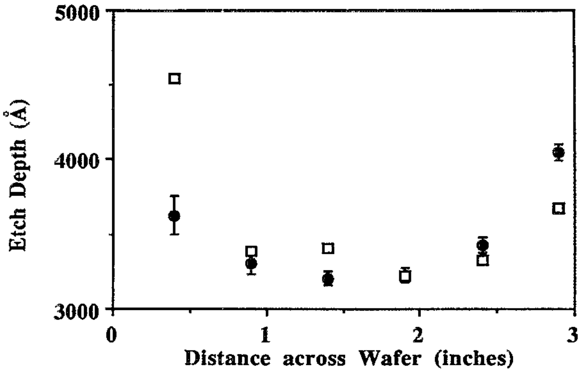

FIG. 4. Etch depth of Si wafer etched in 20 sccm CF_4/O_2 at 250 mTorr and 15 W. Measurements taken across wafer in (●) *x* and (□) *y* directions.

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