Plasma vacuum ultraviolet emission in an electron cyclotron resonance etcher

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This work investigates the vacuum ultraviolet (VUV) emission from various feed gases producing plasmas in an electron cyclotron resonance etcher. Absolute measurements of plasma VUV emission at typical pressures for processing between 0.5 and 5 mTorr, and microwave powers between 700 and 1300 W, show levels of irradiance at the wafer position of the order of tenths of mW/cm^2 and integrated photon fluxes in the 10^{14} $photons/cm^2\,s$ range. The reported level of VUV emission is sufficient to induce radiation damage in typical metal–oxide–semiconductor devices in the form of flatband voltage shift and inversion of lightly doped substrates. © *1999 American Institute of Physics.* [S0003-6951(99)04718-X]

During the last decade, the problem of gate oxide damage from plasma processing of metal–oxide–semiconductor (MOS) devices has been widely studied, because it is increasingly perceived as a threat for the production of advanced integrated circuits. As gate oxide thicknesses approach 20 Å for advanced MOS processes, sources of damage considered minor in the past now hold the potential to degrade device reliability and performance, and the relative impact of different damage mechanisms may also change.

Although charging of floating gates is considered to be the most important MOS damage mechanism, gate oxides may also be damaged during plasma processing by x-ray, vacuum ultraviolet (VUV), and ultraviolet irradiation.[1–3] High-energy photons ($h\nu>9$ eV) can be generated from recombination and relaxation processes in the plasma. Depending on the energy of the incident photons, two cases that may introduce damage can occur: (1) photons with energies higher than the band gap of SiO_2 (~ 9 eV) generate electron–hole pairs in the oxide,[4] and (2) photons with energies lower than the SiO_2 energy gap but greater than 4.2 eV (the height of the minimum energy barrier between the Si substrate valence band and the oxide conduction band) cause electron injection from the silicon surface into the oxide through the photoelectric effect. In case (1), it has been established that electron–hole-pair generation increases the bulk and interface trapped-charge density, which will affect device reliability accordingly.[5,6] In case (2), there is a controversy: while some studies show a similar phenomenon to the one proposed,[7,8] others report that photocarrier injection from the substrate is beneficial, proposing that it anneals the positive interface charge[9] through a recombination process. Consequently, it is apparent that characterizing the plasma VUV irradiation impinging on the wafer surface during processing both qualitatively and quantitatively is essential for understanding radiation damage in MOS devices. This is the key goal of this work.

The electron cyclotron resonance (ECR) plasma etching system employed in this study incorporates a 1.5 kW microwave plasma source and a pair of magnets arranged in a vertical magnetic-mirror configuration.[10] The wafer stage is located 19 cm below the resonance region, and is provided with a radio frequency connection, electrostatic clamping, and helium backside cooling. For this work, neutral pressure was varied between 0.5 and 5 mTorr, microwave power between 700 and 1300 W, and wafer bias power between 0 and 100 W. The plasma parameters (i.e., density, electron temperature and plasma potential) were monitored using a Langmuir probe[11] diagnostic, with the probe located 5 cm above the center of the wafer.

Directly connected to the processing chamber, a 1 m normal incidence vacuum monochromator[12] recorded plasma emission spectra over the range of 400–3000 Å, with a resolution of 0.2 Å. The monochromator uses a 998.9 mm tripartite gold-plated concave grating, with 1200 grooves/mm, blazed for 800 Å. All the motions for slit adjustments and grating scanning and focusing are carried through a metal bellows, allowing the monochromator to reach operating pressures in the 10^{-6} Torr range. The photon flux is detected with a photomultiplier through a window coated with sodium salicylate, which is used as a scintillator. The monochromator samples the ECR plasma along a line passing 5 cm above the surface of the wafer. Through a sequence of collimators, it subtends a small solid angle.

In order to perform absolute intensity measurements of plasma VUV emission, the monochromator has been calibrated with a synchrotron beam having a continuous spectrum in the range of 400–3000 Å, using the facilities of the Synchrotron Radiation Center, at the University of Wisconsin–Madison. The output of the monochromator observing the synchrotron beam was compared to that obtained from calibrated silicon photodiodes of the type AXUV-100, manufactured by International Radiation Detectors Inc., when they were used to observe the same beam. Theoretical calculations of the grating efficiency were made and fitted to experimental values. The monochromator showed a maximum efficiency of 3.85×10^{-17} A s (amperes seconds) per photon in the first order, at a wavelength of 1175 Å, with an error of $\pm 20\%$.

Understanding the damage mechanism produced by plasma VUV irradiation of oxide films requires the exposure of MOS structures or bare SiO_2 to multiple-wavelength ra-

TABLE I. Wavelength, photon energy, and photon flux at specified wavelengths, integrated photon flux, and irradiance of plasma VUV emission. All numbers are calculated at the center of the wafer stage.

Gas	Wavelength (Å)	Energy (eV)	Photon flux at λ_0 ($\times 10^{12}$ cm^{-2} s^{-1})	Integrated photon flux ($\times 10^{13}$ cm^{-2} s^{-1})	Irradiance (mW/cm^2)
He[a]	584.3	21.2	0.177	1.65	0.093
N_2	1200	10.3	0.57	15.0	0.27
	1492	8.3	0.55		
O_2	1305	9.5	1.56	5.07	0.167
Ne[b]	735.9	16.8	1.65	4.28	0.21
	743.7	16.7	0.49		
Ar	1048.2	11.8	9.40	36.4	0.96
	1066.6	11.6	20.2		
Kr	1164.8	10.6	6.16	26.2	0.74
	1235.8	10	13.6		
Xe	1469.6	8.4	19.7	42.8	1.02

[a]Mixture of He and O_2 4:1.
[b]Mixture of Ne and O_2 3:1.

diation. To cover such a broad spectrum, several feed gases were used to produce ECR plasmas at the same neutral pressure of 2 mTorr and microwave power of 1000 W. The most intense emission lines for these plasmas are listed in Table I (stable plasmas could not be created for pure He or Ne; therefore, a mixture with O_2 was used). It is notable that, for these conditions, all the significant lines are atomic and most of the radiation is emitted in the range of 500–1500 Å (~25–8 eV), with little to no emission between 1500 and 3000 Å.

To determine the photon flux impinging on the wafer surface, we consider uniform plasma with a hemispherical shape, located above the horizontal plane of the wafer. For this geometry, the photon flux at the center of the wafer can be calculated from the emission spectra at each wavelength. The photon flux, the integrated flux, and the irradiance of each plasma type are listed in Table I. However, the assumption of a uniform emission from the plasma is not strictly correct for the ECR, due to the higher plasma density and electron temperature in the ECR resonant region. To determine the effect of the source emission, we employed a planar gold mirror, positioned at an angle of 45° with respect to the wafer surface, to reflect light from the resonant region into the monochromator. Measurements of the source radiation reflected by the mirror showed that the source emission is between three to four times higher than bulk plasma emission for Ar lines of 1048 and 1066 Å, at pressures between 1 and 3 mTorr, for 1000 W of microwave power. Considering the dimensions of the ECR source, the irradiance at the center of the wafer may increase up to 15% in this case. Therefore, the data presented in Table I should be regarded more as a minimum value.

The plasma emission intensity was characterized as a function of microwave power, neutral pressure and wafer bias power. While wafer bias power did not show a strong influence, accounting for only a 10% variation in the emission intensity for a change between 0 and 100 W, microwave power and neutral pressure are the dominant driving factors. Figure 1(a) shows a linear dependence of plasma VUV emission with microwave power. By contrast, the emission has a nonlinear dependence on neutral pressure with a maximum at about 3 mTorr. Either a change in plasma parameters (plasma density and electron temperature) or a stronger absorption of the radiation in the plasma itself could explain the decreasing intensity at higher pressures. The two possibilities have been studied separately. Langmuir probe measurements of plasma density and electron density were performed, and they showed a monotonic increase in the density with both microwave power and neutral pressure [Fig. 1(b)]. The electron temperature was also seen to decrease with increasing pressure [Fig. 1(c)]. Although the electron density increased with pressure, the electron distribution function, extracted from the Langmuir probe traces, displayed a lower population of electrons with energies higher than 10 eV at higher pressures (Fig. 2), which points to a lower ultraviolet emission.

In addition, re-absorption of the radiation in the plasma was also considered. Most of the strong emission lines are generated by excited atoms relaxing to the ground state. The majority of the atoms in the plasma are at the ground state and, consequently, they are able to absorb the emitted photons. A rough estimate of the absorption mean free path of the emitted photons for these pressures yields numbers of the order of centimeters, which are within the radial dimensions of our etcher. Thus, both effects contribute to the decrease in ultraviolet emission at high pressures.

The implications of the VUV radiation intensity reported in this work may be analyzed by considering the effective positive charge generated in SiO_2 that is exposed to VUV radiation. Yunogami *et al.*[2] have measured the effective positive charge generation yield of a SiO_2 specimen, irradiated by VUV photons with an energy between 8.8 (SiO_2 band gap energy) and 21 eV, to be in the range of 10^{-3}–10^{-2}. The integration of our VUV spectra in this case yields a minimum effective positive charge production rate of 2.15×10^{12} cm^{-2} s^{-1} for an Ar plasma at 1000 W microwave power and a pressure of 2 mTorr. A similar calculation for an oxygen plasma yields a production rate of 1.3 $\times 10^{11}$ cm^{-2} s^{-1}. Although a significant flatband voltage shift in a typical MOS device would be achieved only for an

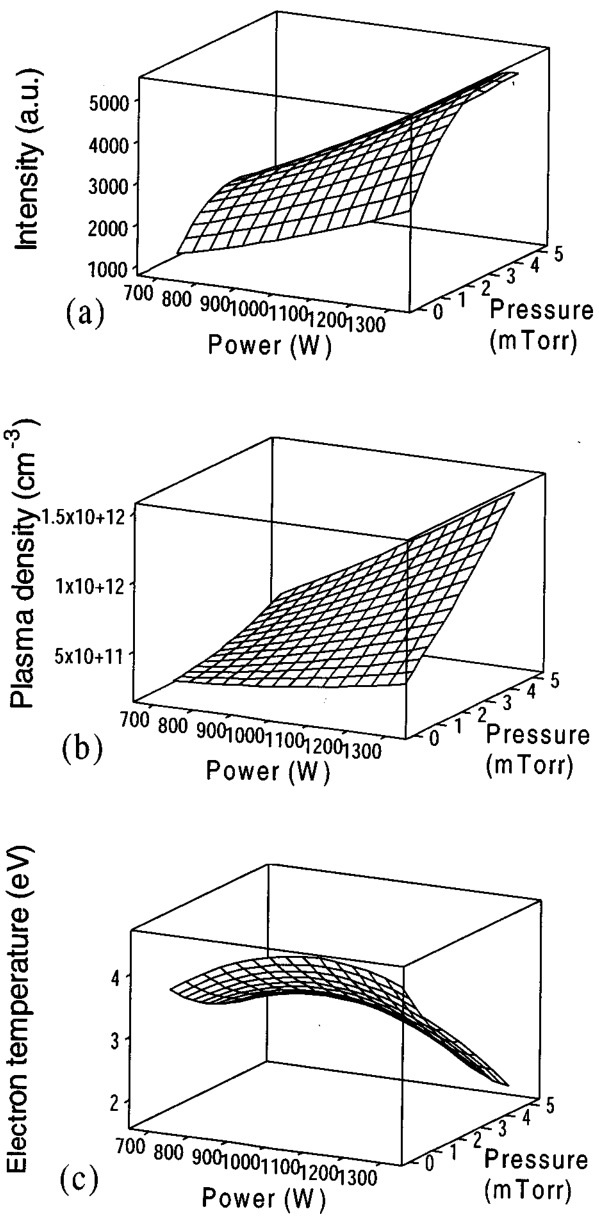

FIG. 1. Emission intensity of Ar 1066.6 Å as a function of microwave power and neutral pressure at 0 W wafer bias power (a), the corresponding plasma density (b), and electron temperature (c).

exposure of minutes, the inversion of lightly doped substrates beneath a layer of oxide can be attained in seconds. Therefore, we believe that plasma VUV emission should be weighed with respect to the particular conditions of each processing step in order to minimize the overall damage induced during manufacturing of semiconductor devices.

In summary, we measured VUV emission spectra for plasmas made with several types of feed gas in an ECR etcher. The irradiance of each of these plasmas at the center of the processed wafer has been calculated to be as high as 1 mW/cm^2 with an integrated photon flux in the order of 10^{14} photons/cm^2 s. Thus, implications of these levels of VUV radiation should be considered as part of the overall plasma processing induced damage to semiconductor devices.

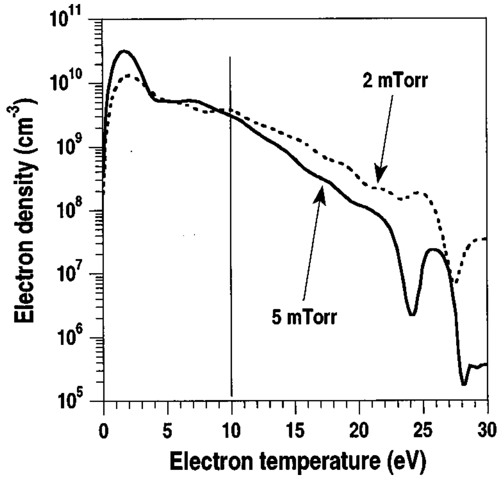

FIG. 2. Electron distribution functions of an Ar plasma at 1000 W microwave power and 0 W wafer bias power show a lower high energy electron population at higher pressures.

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