

X rays in electron-cyclotron-resonance processing plasmas

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Electron-cyclotron-resonance processing plasmas have been shown to produce low-energy x rays. X radiation was detected in nitrogen and CF_4 plasmas from energies of 1–17 keV for microwave powers up to 1000 W. The x-ray flux decreased with increasing pressure over the range of 0.5–3.5 mTorr. Temperatures of the hot electrons responsible for creating the x rays were estimated from the slopes of the x-ray spectra and decreased with increasing pressure. The measured x-ray flux decreased substantially when the magnetic field configuration was changed. Measurable x radiation is produced whenever a field line that passes through the cyclotron resonance surface intersects the vacuum chamber walls and/or other solid surfaces inside the source chamber.

Electron-cyclotron-resonance (ECR) plasma systems are currently being investigated for applications in plasma etching¹ and plasma-enhanced chemical vapor deposition (PECVD).¹ Uniformity of the plasma, and its resulting processing especially in the presence of a diverging magnetic field, are important issues for many types of processes. Charged-particle and high-energy photon fluxes² to a substrate may be of concern in ECR processing devices since radiation damage caused by these fluxes can be detrimental to various layers of a microelectronic circuit.

The major advantage of electron-cyclotron-resonance heating is that it provides an efficient method of energy transfer directly to the electrons from the electromagnetic field, thus allowing higher charged-particle densities at lower operating pressures. There are two types of processes through which the transfer of energy from the electromagnetic field to the electrons takes place: (1) the cyclotron resonance itself, which occurs when the local value of the electron cyclotron frequency is equal to the driving frequency, thus bringing electrons into phase coherence with the electromagnetic field and causing them to continuously gain energy, and (2) a “stochastic” heating process resulting in a “spread” in the velocity distribution as electrons pass through the resonant layer in a nonuniform magnetic field. In a typical plasma, both processes take place. For a given electron, the process which is dominant depends upon the length of time that the electron spends in the region of resonance, which is related to both the gradient of the magnetic field at the resonance and the velocity of the electron parallel to the magnetic field.

Equation (1) shows the change in energy of the electron perpendicular to the magnetic field, ΔW_{\perp} , in a single pass through the resonance zone in a nonuniform magnetic field of the type usually found in ECR processing systems:³

$$\Delta W_{\perp} = q_e v_{\perp} E_{\perp} \tau_{\text{eff}} \cos \theta + \left(\frac{q_e^2}{2m} \right) \tau_{\text{eff}}^2 E_{\perp}^2, \quad (1)$$

$$\text{where } \tau_{\text{eff}} = \left(\frac{2\pi}{v_{\parallel} \omega_c'} \right)^{1/2}.$$

Here, E_{\perp} is the component of the microwave electric field which rotates in the same direction as the electron’s orbital motion (right-circularly polarized), q_e and m are the elec-

tron’s charge and mass, v_{\perp} and v_{\parallel} are the velocities parallel and perpendicular to the magnetic field at the resonance location, and θ is the phase between E_{\perp} and the electron motion as the electron enters the resonance zone. ω_c is the cyclotron frequency, qB/m rad/s, where B is the magnetic field. ω_c' is the axial gradient of the magnetic field at the resonance, and τ_{eff} is the effective time spent by an electron in cyclotron resonance with the microwaves. The first term in Eq. (1) represents the stochastic heating and the second term describes the resonant heating.

In the limit where the resonant heating is the dominant process, the orbit radius in the absence of collisions is⁴

$$r = \frac{E_{\perp}}{B} t. \quad (2)$$

Even without collisions, however, the velocity and orbit radius cannot increase without limit because either the electron will hit the wall of the vacuum chamber or the relativistic mass change will shift the cyclotron frequency and take the electron out of or shift the location of the resonance.

In an ECR processing plasma, the electron speed distribution tends to have the “bulk” of the electrons at lower energies and an exponentially decaying “tail” at higher energies. A Maxwellian-like distribution that exhibits this feature is shown below:

$$f(E) = n \left(\frac{1}{\pi kT} \right)^{3/2} 2\pi E^{1/2} \exp\left(-\frac{E}{kT}\right). \quad (3)$$

T is the temperature of the Maxwellian and n is the density of the electrons. Often in ECR plasmas, the exponential “tail” may need to be represented as the sum of two or more exponentials with different “temperatures.”

For a given electron to gain energy through the resonant process, it must be brought into phase coherence with the electromagnetic field. For this to occur, the following inequality must be satisfied:

$$\frac{1}{2} q E_{\perp} \lambda > KE_i, \quad (4)$$

KE_i is the initial kinetic energy of the electron and λ is the electron mean free path. In steady state, the energy of an electron is a balance between the energy gained by cyclotron heating and the energy lost through collisions with

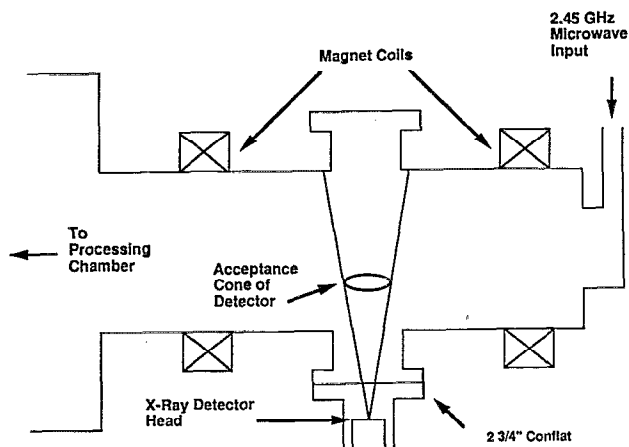


FIG. 1. Electron-cyclotron-resonance experimental system.

other species such as ions and neutral particles. However, if Eq. (4) is satisfied, and the collision frequency drops as the energy increases between collisions, then these resonant electrons will “run away” from the bulk portion of the electron velocity distribution and become energetic enough so that they emit x rays by collisions with solid materials (wall bremsstrahlung) or with ions and/or neutral particles (free-free bremsstrahlung). Such x rays have been seen in ECR fusion plasmas.⁵⁻⁷ Wall bremsstrahlung dominates until very high temperatures and densities are achieved.⁸ Each electron which emits an x-ray photon cannot emit a photon of higher energy than that of the electron itself, and thus the energy spectrum of the emitted x rays can be thought of as a lower bound of the energy distribution of the hot electrons.

Based on the above discussion, the minimum energy for runaway electrons, assuming that the collisional loss processes are due to collisions with gas molecules,⁹ is

$$KE_{\text{runaway}} > 5 \times 10^{-16} \frac{n}{E}, \quad (4)$$

where n is the gas density in particles/m³, E is the electric field in V/m, and the energy is in eV. For a pressure of 1 mTorr, runaway can occur for a 100-eV electron when the microwave electric field is greater than 175 V/m. This is relatively easy to achieve in ECR processing plasmas, especially near the outside plasma edge. Equation (3) is most easily satisfied for those electrons whose energies are in the high-energy tail of the velocity distribution.

In this letter, we describe x-ray measurements made in an ECR processing device. The relative intensity and energy spectrum of the x rays which are produced by electron collisions with the chamber walls are examined as a function of microwave power and pressure as well as the location of the cyclotron resonant layer.

The ECR system used for these measurements is shown in Fig. 1. The microwaves were produced with a 1-kW, 2.45-GHz magnetron, coupled to a 15.2-cm-diam source chamber 33 cm long. The chamber has four ports placed at 90° around the chamber at its midplane. The x ray detector was mounted in one of these ports.

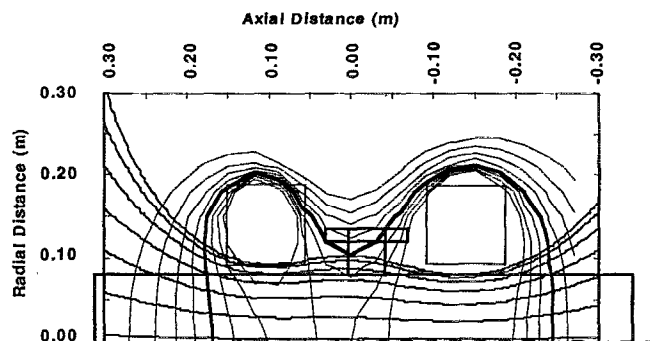


FIG. 2. Surfaces of constant magnetic field and magnetic field lines superimposed over the processing chamber and magnet coil cases. The solid line is the 875 Gauss cyclotron resonance line.

Two separately excited circular magnet coils were equally spaced on each side of the chamber midplane. The source chamber was connected to a larger processing chamber downstream in a region of diverging magnetic field. The chamber base pressure was 5×10^{-5} Torr. The gas flow was 10 sccm and operating pressures were set between 0.5 and 3.5 mTorr using a throttle flap in the inlet to the diffusion pump. The operating pressures were measured by a capacitance manometer and, based on the conductance of the tubulation between the chamber and the gauge, are accurate to within a factor of 2 of the pressure in the chamber itself.

The x-ray detection apparatus consists of a lithium-drifted silicon, Si(Li), detector diode, a pulse processor, and a pulse-height analyzer with an 8- μm -thick beryllium window.

The detector was mounted on a sliding seal. Initial measurements were taken with the detector located 7.2 cm from the edge of the chamber and over 1 min of “live-time” counting. The count rates became very large at pressures below 1 mTorr. Testing with an iron-55 source showed that the magnetic field did not affect the spectrum. X rays were cut off when a 1.25-mm-thick Pyrex shield was placed in front of the diode.

Constant magnetic-field magnitude contours computed from the Biot-Savart law are shown in Fig. 2 for magnet coil currents of 185 and 119 A. The surfaces of constant magnetic field shown differ by 100 G. The figure shows that the resonant surface exists inside the chamber both on and off the axis. A number of magnetic field lines pass through the resonant surface and can carry electrons directly to the walls of the chamber where they produce x rays which then travel to the detector.

At 2.45 GHz, the cyclotron period is 4.08×10^{-10} s. From Fig. 2 it can be ascertained that, as a practical matter, the resonant gain is of the order of 1 mm in width. If we assume that the velocity of an electron parallel to the magnetic field is of the order of 1 eV (4.2×10^5 m/s), it travels 1 mm in 2.38×10^{-9} s. Thus, in travelling through 1 mm, the electron can make more than ten cyclotron periods which is more than enough for a resonant interaction. As a result, in this device, the bremsstrahlung is produced by those electrons which undergo resonant heating

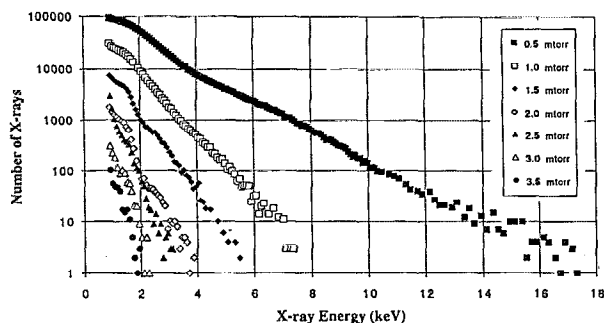


FIG. 3. X-ray spectra for 1000 W of microwave power in nitrogen using pressure as a parameter.

in a single pass through the resonant region. Note that the heating process is initially perpendicular to the magnetic field, so that the parallel motion is basically unaffected by the heating process until after collisions are made.

X-ray spectra for nitrogen plasmas produced with 1000 W of microwave power are shown in Fig. 3. The figure shows that the rate of x-ray production decreases with increasing pressure. It can also be seen that the slope of the spectrum of the x rays increases (implying decreasing average energy) with increasing pressure. This occurs because as the pressure is increased, the electrons collision frequency increases and the electrons do not gain as much energy between collisions. An estimate of the temperature of the electron tail of the distribution can be made by assuming that both the x rays and the electrons have a Boltzmann energy distribution of the form $\exp(-E/kT_e)$. Finally, since the density of particles also increases, then, as per Eq. (4), fewer electrons can run away and the total number of x rays decreases.

The detected x-ray flux from the chamber walls could be significantly changed regardless of pressure by changing the magnet coil currents. For example, decreasing one coil current from 185 to 145 A or decreasing the other coil current from 119 to 70 A moved the resonant region away from the region near the walls of the chamber that are within the acceptable angle of the detector and the measured x-ray flux decreased.

Similar data have been obtained for a CF_4 plasma.

When the detector was moved closer to the vacuum chamber, the count rate decreased. Under this condition, the detector only observed the port region of the chamber. This implies that the x rays were produced primarily by hot electrons incident on the vacuum chamber walls.

In conclusion, ECR processing plasmas are capable of producing soft x rays with energies ranging from below 1 to 17 keV over a pressure range of 0.5–3.5 mTorr. The x-ray flux is decreased as the pressure was increased. Furthermore, the x rays are produced whenever the magnetic field lines that pass through the resonant surfaces intercept the walls or other components of the vacuum chamber in the plasma production region which are within the field of view of the detector.

One concern raised by this observation is the potential for damage to semiconductor devices fabricated in such

systems. A number of researchers have investigated the effects of soft x radiation on metal-oxide-semiconductor (MOS), bipolar, and silicon-on-insulator structures.^{10–13} Dunn¹⁰ reports that *n*-channel metal-oxide-semiconductor field-effect transistors (MOSFETs) on fully processed wafers exposed to 1–2 keV x rays without any resist or blocking layers at a dose of 1500 mJ/cm² exhibit a decrease in device lifetime of a factor of 10 for certain operating conditions. This can be improved if a reoxidized nitrided silicon dioxide is used rather than a conventional oxide.¹⁰ In addition, Hsu *et al.*¹¹ report increased hot-electron-induced instability in *p*-channel MOSFETs patterned using x-ray lithography. They attribute this to residual neutral electron traps generated by the x-ray exposure. These traps are not completely removed by post-metallization annealing. Although initial estimates of the x-ray flux produced here appear to be smaller than the values reported in Ref. 10, an absolute calibration of the x-ray detection system was not feasible. In addition, the level of the x-ray flux needed for damage during ECR processing has not yet been determined. However, the x rays produced are sufficient to blacken x-ray film which was shielded from the plasma and visible and ultraviolet light after an exposure of 2–5 min. This therefore represents the lower limit of the flux.

One may therefore need to exercise caution when using an ECR system for plasma processing so that the soft x rays are not allowed to strike the substrates being processed and cause damage. The x-ray flux to a substrate can be altered by adjusting the neutral gas pressure and/or by adjusting the magnetic field configuration. In addition, if x-ray exposure must occur, additional work needs to be done to determine if this results in undesirable levels of damage.

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