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SHELL STRUCTURE OF A HOT-ELECTRON PLASMA

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There have been reports[1-4] on some interesting features of hot-electron plasmas generated by microwave discharge in mirror geometries. It has been believed that the production and heating of the hot-electron plasma takes place mainly in the electron-cyclotron resonance region[5] within the mirror machine. In this Letter we report experimental evidence that, when microwave power is fed across the magnetic flux lines, the hot electrons form a closed-shell structure and that while the plasma is created mostly at the electron-cyclotron fundamental resonance, subsequent electron heating is performed at the electron-cyclotron harmonic resonance.

The hot-electron plasma device at the Institute of Plasma Physics is called TPM[6] for "Test Plasma by Microwave Discharge." The device consists of ten sectionalized coils, which permit mirror ratios from 2.5:1 to 3.5:1, and of a stainless-steel vacuum tank (30 cm diam × 40 cm length) serving as a multimode microwave cavity, which is evacuated by two vacuum pumps connected to the cavity through circular apertures (12 cm diam) in the end walls (Fig. 1). The base pressure in the vacuum tank is 6×10^{-7} Torr and relatively high-pressure helium $[(1-6)\times10^{-4}$ Torr$]$ is admitted in steady flow during operation. The 6.4-GHz microwave source for the discharge is a 20-msec pulse, having a power up to 5 kW at a repetition rate of five pulses per second. The microwave power is introduced radially through two opposite pairs of waveguide ports in the cavity wall. The plasmas produced at power levels above 3 kW are observed to be very similar to one another in electron temperature and electron density. The hot-electron temperature is determined to be about 150 keV from x-ray spectra. This temperature value is observed to be almost constant during the first 140 msec of the quiet afterglow. An R-band microwave interferometer indicates an electron density of about 2×10^{12} electrons/cm^3 during the microwave discharge.

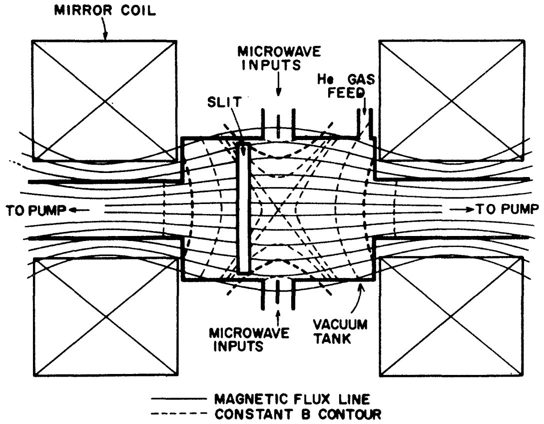

FIG. 1. Schematic diagram of the TPM machine. The bold hyperbolalike dashed lines show the second-harmonic resonance zone and those across the flux lines indicate the fundamental electron-cyclotron resonance region.

In order to determine the radial density profile of the hot electrons of the TPM, the radial emission of x rays from the plasma is observed by scanning with an x-ray telescope along a slit in the cavity wall. Two vertical slits (14 cm × 30 cm) positioned 7 cm off the midplane in the cavity wall, facing each other diametrically, are used for observing the contained plasma along its diameter across the magnetic flux lines. The slits are covered with 5-mm-thick Pyrex glass plates. The total number of photons of the x-ray bremsstrahlung is observed with a 2-cm^2 NaI scintillator. The solid angle subtended by the crystal through the collimator is about 10^{-5} sr and it collects photons from a cylindrical volume of plasma approximately 10 cm long with a cross section of 3 cm^2. The collimation system excludes any reception of unwanted x rays from the cavity walls.

When the x-ray telescope is moved (0.05 cm/sec) along the slit, it is possible to calculate the radial distribution of x-ray emission by using Abel's transformation. This distribution

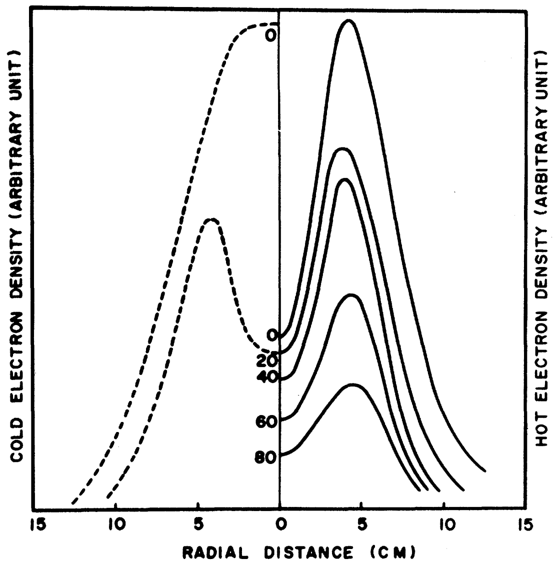

FIG. 2. Plot of the radial density distribution of the electrons, after Abel's transformation. The dashed curves in the left half are related to the cold electrons and the solid curves in the right half to the hot electrons. Parameters are the times (msec) after the front of the heating microwave pulse, of 20-msec duration. Each observation is made for 20 msec.

is directly proportional to that of the hot-electron density.

The hot electrons appear to be bunched in a shell structure both during the microwave discharge and in the afterglow of the plasma as seen in Fig. 2. The radius of the shell increases with the magnetic field. The shell structure is a peculiar feature of this microwave-produced hot-electron plasma. For analyzing the reciprocal influence of the hot and cold electrons, the density and temperature profile of the cold electrons is measured. The measurement is done by using optical techniques. By measuring the intensity ratio of singlet to triplet helium lines (4713 and 4921 Å) across the diameter of the cavity, and by making use of a collimator system similar to the one used for analyzing the hot electrons, the profile of the temperature of the cold electrons was found to be flat across the diameter. The value found for the temperature is about 20 eV. Making the reasonable assumption that the total light intensity is proportional to the cold-electron density, the profile of the cold electrons is found by using a technique in the optical region completely analogous to the one used in the x-ray region for obtaining the hot-electron density profile. As shown in Fig. 2, while the microwave power is applied, the density distribution of the cold electrons has the shape of a bell centered on the axis of the machine, while after the power has been removed, the center of the bell is depleted to form a shell.

After the termination of the microwave pulse, the density of the cold electrons decreases to about one-fifth of the initial value within 1 msec. At that time the bell-shaped profile is strongly depleted. From this time on, the cold electrons present in the plasma are those produced by ionization of neutral atoms by the hot electrons present in the shell. The decay of this new cold-electron distribution is determined now by the longer lifetime (30-100 msec) of the hot electrons, which depends on the background gas pressure. By equating the loss rate to the creation rate of the cold electrons in the shell, we can estimate the ratio between the hot-electron density and the cold-electron density:

$$n_h/n_c = t_i/t_c,$$

where t_c and t_i are the decay and creation time of the cold electrons. The value of t_i is 10^{-5} sec for 150-keV electrons in helium gas[7] at a pressure of 10^{-4} Torr; the value of t_c is about 2×10^{-4} sec and is determined from the decay-time measurements of cold plasma produced by a low-level microwave discharge. The value found for n_h/n_c is 0.1.

A second measurement of the density of the hot electrons is made as a function of time by counting with a pulse-height analyzer the number of photons of x-ray bremsstrahlung from the plasma; a microwave interferometer is used for measuring the density of the cold electrons. The density ratio obtained by this measurement has the value 0.05 independent of time in good agreement with the theoretical value previously found. The fact that this ratio is constant in time is the proof that after the microwaves are turned off, the only source of cold electrons in the plasma is the ionization of neutral atoms due to the hot electrons in the shell; in this way the afterglow of the cold electrons is bound to the afterglow of hot electrons, and the spatial distribution of the cold electrons across the diameter of the cavity becomes a shell situated in the same position as the hot-electron shell. These results imply that the production and the heating of the plasma are not achieved in the same region of the magnetic mirror.

For analyzing this effect further, a new set of measurements is made. While sweeping the magnetic field intensity, the x-ray emission, the total light intensity, the X-band microwave noise, and the plasma density are measured simultaneously. The plasma is not created unless the electron-cyclotron resonance zone is inside the cavity. When the magnetic field is decreased, the electron-cyclotron resonance zone appears first in the midplane and then the plasma discharge starts. A further decrease in the magnetic field intensity does not bring any appreciable change in the plasma density as long as the resonance zone stays in the cavity as can be seen in Fig. 3. This result is consistent with the observation of the total light intensity, which does not show any appreciable change. On the contrary, the x-ray intensity and the microwave noise power, both proportional to the density of the hot electrons, show a resonant increase when the electron-cyclotron harmonic frequencies, associated with the magnetic field intensity in the midplane, reach the heating microwave frequency. A small resonance increase is found also at the third harmonic (Fig. 3). The electrons will then be heated in those regions of the magnetic field where the resonance conditions are satisfied, and later they will spread along the magnetic lines of force. This is the process that confines the hot electrons in a shell. The location of the hot-electron shell corresponds to the throat of the single-lobe hyperboloid-shaped surface of constant magnetic field intensity, which provides the second harmonic resonance (Fig. 1). As the magnetic field is increased, the radius of the throat increases and the radius of the hot-electron shell is observed to follow this growth. Fessenden[3] observed x rays generated at the end walls of a resonant cavity in a ring-shaped area. He observed that the diameter of the ring increased with magnet current. This fact indicates a possible observation of the hot-electron shell produced at the second harmonic resonance.

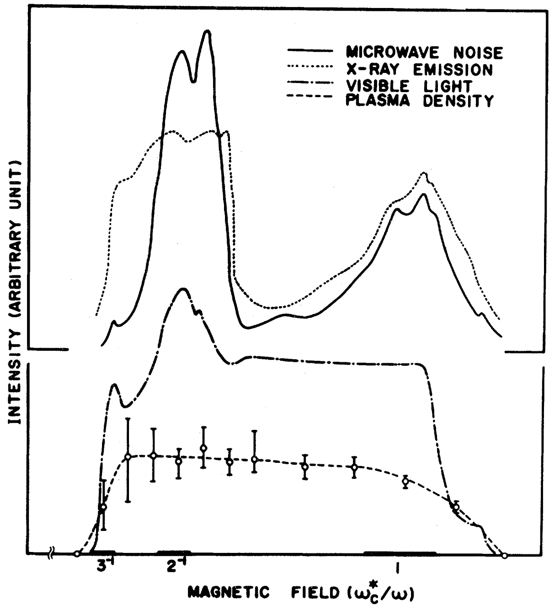

FIG. 3. Variation of the intensities of the X-band microwave noise, x-ray emission, visible light, and plasma density as a function of the magnetic field. The first two quantities are related to the hot electrons and the others to the cold electrons. The ordinate is the electron-cyclotron frequency associated with the magnetic field in the midplane of the mirror field normalized to the frequency of the heating microwave power. The harmonic resonances stay within the midplane during the length of the bold bars in the ordinate.

We summarize our conclusions as follows: In a plasma produced by microwave power injected radially across the lines of force of the magnetic mirror, the relatively cold, primary electrons are produced in the electron-cyclotron resonance zone within the cavity. The diameter of the primary cold plasma is determined by the intersection of the resonance zone with the end wall of the cavity (see Fig. 1). The resonance zone of the second harmonic of the electron-cyclotron frequency forms a hyperboloidlike surface (see Fig. 1) where the primary electrons are heated. The heated electrons confine themselves in a shell-shaped region.

After the microwave power has been removed, the cold electrons escape from the magnetic bottle rapidly. The hot electrons, however, because of their larger transverse kinetic energy, are trapped for a long time within the shell. They ionize neutral helium atoms and consequently the production of cold electrons continues in the shell even after the power has been completely removed. Therefore, during the afterglow, the cold electrons stay in the same shell as the hot electrons (see Fig. 2). The radius of the shell is essentially equal to the radius of the resonance zone of the second harmonic.

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ANOMALOUS WIDTH OF SOME PHOTOEXCITATION LINES OF IMPURITIES IN SILICON*

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The purpose of this Letter is to report experimental results on an unusual broadening of an excitation line of gallium acceptor and of bismuth donor in silicon. Experimental evidence is presented which suggests that the optical phonons play an important role in governing the lifetime of the excited states involved when the energy of the transition equals that of the optical phonons.

One of the remarkable features of the excitation spectrum of gallium acceptors in silicon[1,2] is that the excitation line with the second lowest energy, line 2, is at least an order of magnitude broader than any of the other lines of the spectrum. This is in contrast to the spectra of the other group-III impurities where line 2 is very prominent and just as sharp as the other lines. From the correspondence between the various acceptor spectra, line 2 of gallium is expected to occur at about 63 meV. In view of the proximity of this energy to the Raman energy of silicon, 64.8 meV,[3] we wish to suggest that the anomalous width of this transition is a consequence of a lifetime broadening of the excited state by the emission of an optical phonon of an energy close to that of the transition. It is significant that line 3 of aluminum acceptor in silicon is also expected to occur at ~63 meV; this line has not been observed. Another impurity in silicon whose excitation spectrum has lines with energies close to those of the optical phonons is the group-V donor, bismuth.[4-6] In particular, the $1s(A_1)\rightarrow 2p_{\pm}$ transition has an energy of 64.57 meV which is almost coincident with the Raman energy. However, as can be seen from Fig. 1, this line is sharp and shows no evidence of broadening. It is in fact found to be just as sharp as the $3p_0, 3p_{\pm}, \cdots$ lines. Per contra, the $2p_0$ line is anomalously broad and is asymmetric. The energy of this line is 59.51 meV, which is significantly close to the energy of the TO⟨100⟩ phonons of silicon, i.e., 58.7 ± 1.2 meV.[7] It is well known that for silicon the shallow acceptor states are constructed from the Bloch functions at the top of the valence band, while those of the shallow donors are associated with the conduction-band minima along ⟨100⟩. This might account for the difference in the optical-pho-

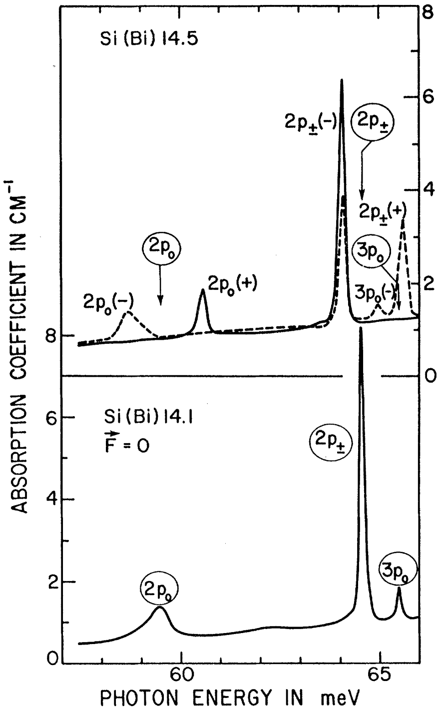

FIG. 1. Part of the excitation spectrum of bismuth impurity in silicon using liquid helium as coolant. Carrier concentration at room temperature $= 4.5\times10^{14}$ cm^{-3}. The upper curve is measured with a compressive force, $\vec{F}$, along [110] and the direction of propagation of the light, $\vec{q}$, along $[1\bar{1}0]$. The dashed curve is for the electric vector $\vec{E}\parallel\vec{F}$, while the full curve is for $\vec{E}\perp\vec{F}$. The vertical arrows together with their encircled labels indicate the zero-stress positions of the lines shown in the lower curve.