II. MICROWAVE GASEOUS DISCHARGES*

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A. MICROWAVE PLASMA CONDUCTIVITY

In microwave studies of gaseous discharges frequent use is made of the expression for the plasma conductivity which was first derived by Margenau (1)

$$\sigma = -\frac{4\pi}{3}\frac{ne^2}{m}\int \frac{1}{(\nu_m + j\omega)}\frac{\partial f}{\partial v} v^3\, dv \tag{1}$$

where ν_m is the electron collision frequency for momentum transfer, ω is the radian frequency of the microwave field, and f is the electron distribution function. Equation 1 was derived for a uniform infinite plasma. Since uniform infinite plasmas are not realized experimentally, questions arise concerning the limits of validity of Eq. 1 with respect to pressure, density gradients, space-charge fields, and so on. We have studied this problem for two cases: (a) the electron mean free path is assumed small compared with the extent of the microwave field and with the dimensions of the plasma container, but the effect of density gradients and space-charge fields is considered; (b) the electron mean free path is large compared with the extent of the field, but the density is assumed uniform.

In case (a) the problem was studied in the usual manner with the aid of the Boltzmann transport equation — without, however, neglecting the time-varying part of the isotropic distribution function. We find that in the presence of density gradients and space-charge fields the microwave current is given by

$$J_1 = \frac{e^2}{m(\nu_m + j\omega)}\left[n_o E_1 + n_1 E_o\right] + \frac{e}{(\nu_m + j\omega)}\frac{\left\langle v^2\right\rangle_1}{3}\nabla n_1 \tag{2}$$

with ν_m assumed independent of energy. The subscripts zero and one denote dc and ac quantities, and $\left\langle v^2\right\rangle_1/3$ is related to the ac diffusion coefficient. The first term on the right-hand side of Eq. 2 is the one commonly used to obtain the plasma conductivity. We find that the other terms are small compared with the first when the following inequality is satisfied

$$\frac{e}{m}\left|\frac{E_o}{(\omega_p^2 - \omega^2 + j\,\nu_m\omega)}\left(\frac{\nabla n_o}{n_o}\right)\right| \ll 1 \tag{3}$$

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where ω_p is the plasma frequency. For microwave plasmas under conditions of ambipolar diffusion Eq. 3 reduces to

$$\frac{\langle v^2 \rangle_o}{3} \left| \frac{1}{(\omega_p^2 - \omega^2 + j\,\nu_m\,\omega)} \left(\frac{\nabla n_o}{n_o} \right)^2 \right| \ll 1 \tag{4}$$

where $\langle v^2 \rangle_o/3$ is related to the dc diffusion coefficient. When $\omega_p < \omega$, Eq. 4 yields the condition

$$\frac{\nabla n_o}{n_o} \ll \frac{1}{\ell_D} \tag{5}$$

where ℓ_D is the Debye length. The condition given by Eq. 5 is less stringent when $\omega_p > \omega$. When $\omega \approx \omega_p$, inequality 4 yields a lower limit on pressure below which Eq. 1 may be incorrect.

For dc plasmas, when $\omega \approx \omega_p$ the inequality to be satisfied is

$$\frac{v_d}{\omega} \frac{\nabla n_o}{n_o} \ll 1 \tag{6}$$

where v_d is the electron drift velocity. Inequality 6 states that the distance drifted in one period of the ac field must be small compared with $(n_o/\nabla n_o)$.

In case (b), wherein the mean free path is large compared with the extent of the field, the usual method of expanding the distribution function in spherical harmonics in velocity and in Fourier series in time, and terminating each expansion after the first two terms, is not adequate. A more fruitful approach is to consider the motion of the individual plasma electrons by using small-signal analysis and averaging over the velocity distribution function.

If a uniform ac field E_1 is maintained between the planes $z = 0$ and $z = d$ in a uniform plasma, we find that the average conductivity of the gap is given by

$$\sigma = -\frac{4\pi}{3} \frac{ne^2}{m} \int v^3 \frac{\partial f}{\partial v} \left[\frac{1}{\nu_m + j\omega} - \frac{3v}{4d} \frac{1}{(j\omega + \nu_m)^2} \right] dv \tag{7}$$

In obtaining Eq. 7, terms of the order $\exp(-3\omega^2 d^2/\langle v^2 \rangle)^{1/4}$ were neglected compared with unity. This limits the validity of Eq. 7 to those cases in which the average electron spends more than three cycles of the ac field in the gap. When $(\nu_m/\omega)^2$ and $(v/d\omega)^2$ are small compared with unity, Eq. 7 is analogous to Eq. 1 if an effective collision frequency ν'_m is defined as

$$\nu'_m = \nu_m + \frac{3}{4} \frac{v}{d} \tag{8}$$

Equation 8 indicates that, when the extent of the ac field is small compared with the mean free path, the width of the gap defines, as far as the microwave field is concerned, an effective mean free path. The factor 4/3 comes in because the electrons enter the gap obliquely. We also find that the smallness of the gap does not alter the energy-storing ability of the plasma electrons.

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References

1. H. Margenau, Phys. Rev. 69, 508 (1946).

B. HIGHLY IONIZED PLASMAS

In a further attempt to produce a highly ionized microwave plasma in hydrogen a microwave system similar to that described previously (1) but capable of supplying cw power of 1000 watts was assembled. It was necessary to construct a variable attenuator capable of dissipating 1000 watts with negligible insertion loss. It was possible to use a probe for coupling into the microwave cavity by surrounding the probe with a Teflon shield.

The cavity was designed to resonate in the TE_{111} mode at S-band, and in the TE_{011} and TM_{111} modes at C-band. The last two modes are utilized to measure the electron density. Preliminary attempts have yielded degrees of ionization of approximately 0.5 per cent at a pressure of 10^{-3} mm Hg.

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References

1. Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., Jan. 15, 1957, p. 17.

C. HIGH-CURRENT PROTON SOURCE

Construction was completed and initial testing has begun on a high-current proton source.

The source employs hydrogen gas at a pressure of 10^{-3} mm Hg that is ionized by the action of 100-mc rf power. The protons are extracted from the ionized hydrogen and focused into a beam by electrodes whose shape was determined by considering the space-charge field of the proton beam. The focusing was satisfactory.

A magnetic field which is applied parallel to the axis of the beam serves three purposes. First, it helps contain the beam. Second, it reduces electron loss in the ionized gas region, which results in a higher plasma density and consequently gives a higher proton density. Third, as the ionizing electric field is applied perpendicular to the magnetic field, it provides an efficient means of transferring energy to the electrons by cyclotron resonance.

An attempt will be made to correlate the effect of gas pressure, accelerating voltage, rf power, and magnetic field upon beam current.

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