II. MICROWAVE GASEOUS DISCHARGES

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A. HIGH-DENSITY MICROWAVE GASEOUS DISCHARGES

Because of the low repetition frequency (8 per sec) of the high-power 100 Mc/sec discharge pulses (Quarterly Progress Report, Research Laboratory of Electronics, M. I. T. April 15, 1953) usual methods of measurement of power and standing-wave ratio are not satisfactory. Consequently, a circuit has been developed which produces pulses on an oscilloscope proportional to either the power incident on the cavity or reflected from it. An additional circuit, including a Brown converter, switches alternately one and then the other pulse to the oscilloscope. The standing-wave ratio can be deduced from the ratio of the pulses, and the power absorbed by the cavity is proportional to the difference, as indicated in Fig. II-1. By applying a continuous wave signal to the dc amplifier, the oscilloscope deflection can be calibrated in terms of a wattmeter.

Preliminary observations have been performed with discharges up to 250 watts in hydrogen in the pressure range of 1 to 200 mm Hg. It was found that the higher the power in the discharge, the more difficult it was to match the cavity to the line and the higher the standing-wave ratio. The appearance of a high-power discharge at 30 mm pressure is shown in Fig. II-2. It shows the bright bounding regions and the dull interior where the density is above that for plasma resonance. Near the edge of the discharge the bright region penetrates further because there the density is lower. At lower pressures (for example, 2 mm) it seemed more difficult to exceed plasma resonance. This may be because the bounding sheath becomes thicker at lower pressures and tends to fill the small cavity gap. If this is the case, a cavity with a larger gap should solve this problem.

However, it will be easier to investigate this quantitatively when the technique mentioned in the previous Quarterly Progress Report is in operation. As shown in Fig. II-3,
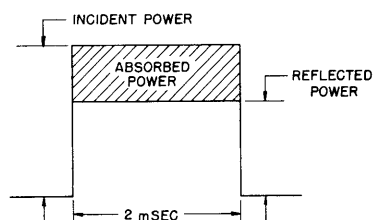

Fig. II-1

Oscilloscope pulse giving standing-wave
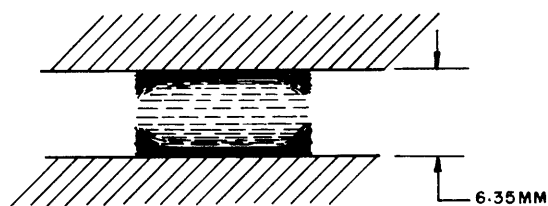ratio and power absorbed by the cavity.

Fig. II-2

High-power discharge in
30 mm Hg of hydrogen.

OSCILLATOR — CAVITY — DETECTOR
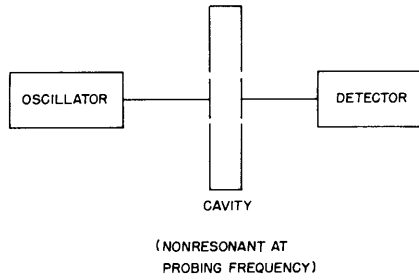
CAVITY

(NONRESONANT AT
PROBING FREQUENCY)

Fig. II-3

Illustration of method of density measurement using plasma resonance.

the probing signal is transmitted through the discharge and picked up by a detector. Disks flush with the cavity wall have been found to be satisfactory transmission elements. However, it is desirable to make these as small as possible to provide a localized probe and to minimize any perturbation of the discharge caused by the disks. This introduces the problem of sensitivity, particularly as the glass seals (necessary for a vacuum cavity) reduce the transmission by 20 db.

B. MEASUREMENT OF COLLISION CROSS SECTION

A study of increasing the average electron energy in the afterglow of a discharge by means of an external electric field has been made. The nonuniformity of the electric field in a microwave cavity adds to the complexity of the problem. In order to interpret the measurements of $(1/p_o)(\sigma_r/\sigma_i)$ correctly, it is necessary to know the correct density distribution. Hence the problem of ambipolar diffusion for the case of a nonuniform energy distribution must be solved. The following assumptions are made: (a) $\nu_c^2 \ll \omega^2$; (b) The energy lost due to energy gradients and diffusion is negligible compared to the energy lost to collisions so that the electron distribution is Maxwellian with an electron temperature

$$T_e = T_g + \frac{M}{3k}\left(\frac{e}{m}\right)^2 \frac{E_{rms}^2}{\omega^2}$$

where

$$E_{rms}^2 = E_{o(rms)}^2 \cos^2 \pi \frac{y}{B} \cos^2 \pi \frac{z}{C}$$

and B and C are the dimensions of the cavity; (c) $\nu_c = bv^h$ and (d) $n = n_o e^{-\gamma t}$ for the variation of electron density with time.

From the equations governing the flow of electrons and ions under conditions of ambipolar diffusion, the following equation is obtained:

$$\left(1 + \frac{T_e}{T_g}\right)\nabla^2 n + \left(2 - \frac{h}{2}\right)\vec{\nabla}n \cdot \vec{\nabla}\frac{T_e}{T_g} + n\left[\left(1 - \frac{h}{2}\right)\nabla^2 \frac{T_e}{T_g} + \frac{\gamma}{D_+}\right] = 0$$

By separation of variables, one can write that $n = n_o \, m(y,z) \, p(x)$. The function $p(x)$ is a cosine distribution and $m(y,z)$ is determined from the above equation after the
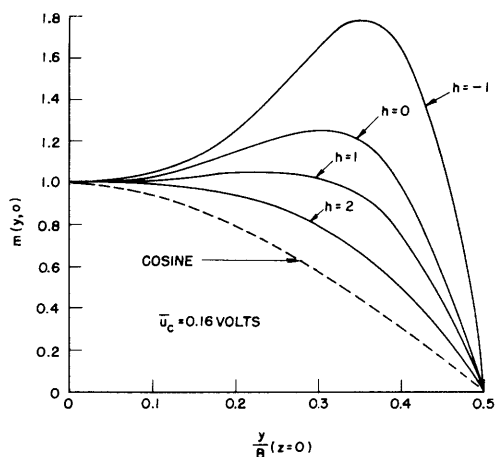
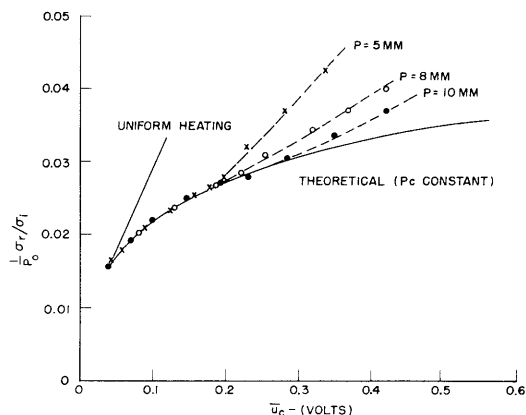Fig. II-4

Density distribution for varying values of h.

Fig. II-5

$(1/p_o)(\sigma_r/\sigma_i)$ as a function of $\bar{u}_c$.

variables have been separated. The differential equation for m(y, z) is transformed to a difference equation and the problem is solved numerically using a two-dimensional net. A typical set of results is shown in Fig. II-4. The curves give m(y, 0) for different values of h for an average electron energy of 0.16 volts at the center of the cavity. The curves are compared to a cosine distribution which would be the case when a uniform heating field is applied. Inasmuch as $(1/p_o)(\sigma_r/\sigma_i)$ depends upon the average of the density distribution for the case of nonuniform heating fields, the correct density distribution must be chosen.

Measurements of $(1/p_o)(\sigma_r/\sigma_i)$ were taken as a function of gas pressure and heating field in helium. The results are shown in Fig. II-5. The average electron energy at the center of the cavity is designated by $\bar{u}_c$. The theoretical curve is drawn for the case of P_c = constant (h=1). The deviations from the theoretical curve depend on pressure, the greater deviation occurring at the lower pressure.

The reason for the discrepancy is that assumption (b) is no longer valid and the presence of energy gradients becomes important and the electron energy tends to become uniform throughout the cavity. Hence $(1/p)(\sigma_r/\sigma_i)$ will approach the value for uniform heating. The curve for uniform heating was obtained experimentally by increasing the gas temperature thermally.

C. HOT PROBE STUDIES

The purpose of this program is to develop techniques pertinent to the application of hot probes to the study of microwave gas discharges. Current techniques of measurement have been unable to determine the space potential at a given point in the cavity.

Standard double-probe methods are inherently unable to do this because the probes are allowed to float; that is, the net current to the probes is zero. Recent attempts to apply the results of Langmuir probe measurements to the determination of the space potential have been unsucessful because of the lack of electron current saturation to the probe. Consequently, a modification of the hot-probe technique used by Ernst is being investigated to see if this will work in a microwave cavity.

A hot probe is an electrode which is heated to a temperature where thermionic emission is appreciable. When such a probe is below the space potential, the electron current to it is smaller than that to a cold probe of identical dimensions; the difference between the two curves is due to the thermionic emission of the former. Since, when the probe potential becomes greater than the space potential, the thermionic emission decreases exponentially, the difference between the current drawn by a probe when hot or cold should be zero when the probe potential is higher than space potential (this analysis neglects contact differences of potential).

This effect will be investigated in a rectangular cavity resonant at 9.8 cm in the TM_{110} mode. The probe, a 1-cm length of 0.003-inch tungsten wire, is heated by square current pulses, and the probe current is measured when the heating current is off so that the probe is an equipotential surface. The probe will be operated both hot and cold; and the difference between the two currents will be found by balancing a potentiometer when the probe is cold and then determining if it is balanced when the probe is warm. Experimental verification of this effect will take place shortly.

D. ELECTRON-ION RECOMBINATION IN HYDROGEN

A cavity and a quartz bottle have been designed with relative dimensions such that some of the higher diffusion modes were suppressed, as mentioned in the Quarterly Progress Report of January 15, 1953. However, measurement of the electron density decay curves in the afterglow still gave no indication of pure diffusion or recombination. The only conclusion could therefore be that the hydrogen used contained impurities in large enough quantities to give a dominating loss mechanism in form of attachment or formation of negative ions.

We had used palladium leaks to introduce the hydrogen into the vacuum system. However, when improving the vacuum system such that smaller leaks could be detected, it was found that in most cases small leaks developed in the wall of the palladium tubing the very first time the palladium came in contact with a hydrogen atmosphere. This, of course, accounted for some of the impurities. Thereafter we tried commercial spectroscopically pure hydrogen and found that it generally contained more impurities. Two things therefore had to be done in order to secure a pure hydrogen atmosphere: (a) improve the vacuum system and (b) find a source of pure hydrogen. For the

latter we used uranium hydride. A quartz tube containing filings of uranium was connected to the vacuum system via a high-vacuum metal valve. The vacuum system was baked at 450°C while the uranium could be baked at 800°C. A holding vacuum of less than 10^{-9} mm Hg was reached. Hydrogen was then let into the system and formed UH_3 at about 100°C. When the hydride was heated up to about 250°C, most of the hydrogen was released, and experiments showed this to be much purer hydrogen than that used earlier. The vacuum system was further improved to attain as high as possible pumping speed between the liquid air trap and the quartz bottle containing the microwave discharge.

In spite of large improvement in terms of purity, the loss of electrons in the afterglow was still influenced by attachment at pressures above 1 mm Hg. It was noticed that when receiving a discharge in the quartz bottle, large amounts of some condensable material, probably water and carbon dioxide, were collected in the top of the liquid air trap. This occurred in spite of a very thorough baking of the quartz bottle before introducing the hydrogen. We therefore ran a continuous discharge in the quartz bottle for approximately 24 hours while baking the rest of the system. In this way we were able to produce a pure enough hydrogen atmosphere so that measurements of the decay curves could be made up to 17 mm Hg without any apparent sign of attachment. The $D_a p$ (ambipolar diffusion coefficient times pressure) for hydrogen in this pressure range was found to be between 675 to 775 cm^2 mm Hg/sec, and as far as we could determine from the experimental result there was no sign of recombination. On the other hand, it was found that higher diffusion modes have quite an influence on the decay of the electron density. Roughly, we found a correlation between the amount of higher modes in the light distribution as a function of coordinates and the amount of higher modes in the electron density decay. The initial spatial distribution of electrons was arranged so as to contain as small an amount of higher diffusion modes as possible. In this case the decay of the fundamental mode could be measured up to 17 mm Hg. Typical data are shown in Fig. II-6.

E. PROBE STUDIES

The experiment described in the Quarterly Progress Report of January 15, 1953, was continued. In computing central electron densities in steady-state microwave gas discharges from the shift in the resonant frequency of the cavity, it is usually assumed that the electron density distribution is sinusoidal. It was found that this assumption is no longer correct above pressures of 1 mm Hg in hydrogen. By graphically integrating the experimental electron density distribution, as found by moving double probes across the discharge in a rectangular quartz bottle, it was found that the central electron density might be lower by a factor up to two compared to values obtained by integrating a sinusoidal distribution. Thus it is necessary to plot the density distribution for every
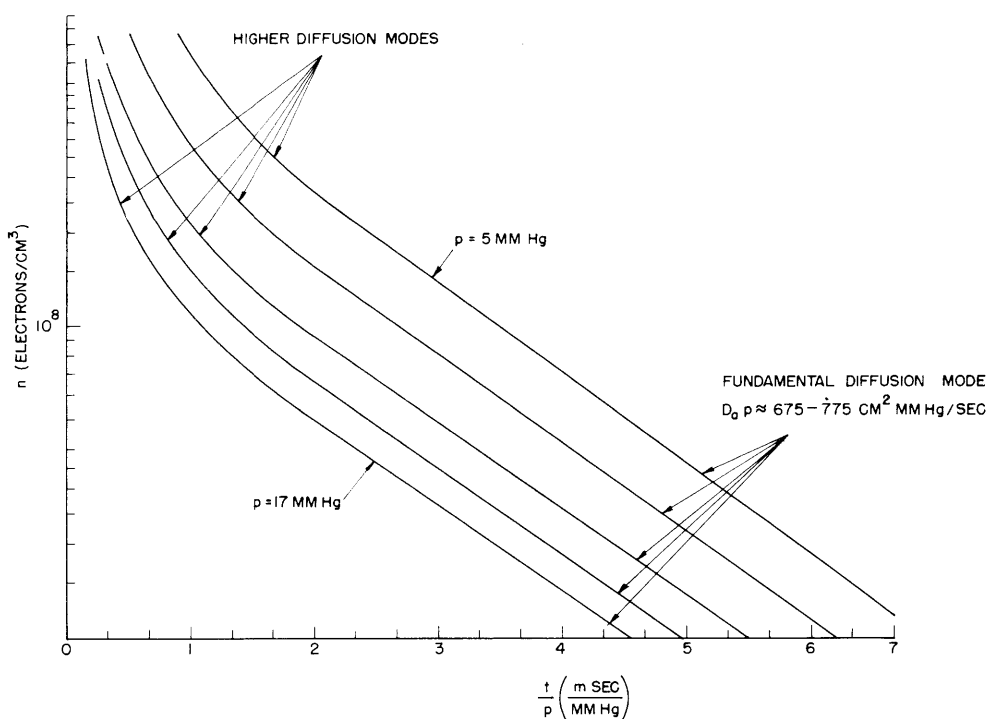
Fig. II-6

Decay of the electron density in the afterglow of a hydrogen discharge.

point for which a comparison between probes and microwaves is desired. Probes made of 5-mil tungsten wire gave fair agreement with microwave determinations of central electron densities.

Since double probes yield only positive ion densities, an attempt was made to use a single probe in an all-metal rectangular vacuum cavity and thus attain electron saturation. The expected electron saturation current to the single probe was kept small compared to the diffusion current to the walls so that the probe should not influence the plasma appreciably. This was accomplished by using very small probes. However, even when the computed electron saturation current to the probe was smaller than 1 percent of the total diffusion current to the walls, no saturation was observed near plasma potential.