PLASMA QUENCHING BY ELECTRO-NEGATIVE GAS SEEDING

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(Received 22 March 1963)

The purpose of this note is to describe some recent experimental measurements in which rather striking alterations of the properties of a supersonic plasma stream have been achieved by seeding the plasma with an electro-negative gas. The application of seeding techniques to various plasma systems is well known and to data the major emphasis in this work has been on generating plasmas of increased ionization by seeding (particularly with the alkali metals).[1]

In the present investigation the aim has been to seed supersonic plasma streams with electro-negative gases to reduce the electron density in the system. The results of such studies are of particular interest because of their possible application to re-entry and space communication problems. In particular, the seeding of argon plasma streams with sulfur hexafluoride (SF_6) has been studied under various conditions. The choice of SF_6 for this purpose was based on its exceptionally high electron capture cross section for low-energy electrons[2] and its stable chemical properties.

The experiments reported here were carried out in a radio-frequency excited (electrodeless discharge), low-density plasma tunnel using argon gas at velocities of approximately Mach 2. The static stream pressure was one Torr and the diameter of the stream at the exit of the nozzle was 1.7 cm. Under these conditions, the argon flow rate in the tunnel was 1.4 liter-atmosphere/minute. Double-probe[3] measurements indicate that the electron density at the nozzle exit is in the range of 10^{12} to 10^{13} electrons/cm^3.

The basic arrangement for seeding the argon plasma with SF_6 is illustrated by the schematic diagram in Fig. 1. The small ceramic seeding tube (0.2 mm i.d., 0.5 mm o.d.) is introduced in the plasma stream from the side so that the orifice is positioned in the center of the stream at a distance of 1.0 cm from the nozzle exit.

In a first set of measurements, the back-scattering of a microwave signal (9.2 Gc/sec) from the plasma stream was measured as a function of the amount of SF_6 introduced into the argon flow. In order to ensure that only microwave scattering from the plasma would be observed, the rf power used to excite the plasma was modulated at one Kc/sec and only this component of the reflected microwave signal was detected.

In Fig. 1 is shown a series of curves of the signal back-scattered from the plasma stream as a function of the position of the seeding tube in the plasma. These curves were obtained by sweeping the tube across a constant argon stream at various injection rates of SF_6. The ratio SF_6/A in Fig. 1 refers to the relative rate of SF_6 molecules injected, to that of argon atoms flowing through the nozzle. It is seen that for a ratio of SF_6 to argon of 3.7×10^{-4}, the back-scattered signal from the plasma is essentially reduced to zero thus indicating a very large drop of electron density in the plasma resulting from the capture

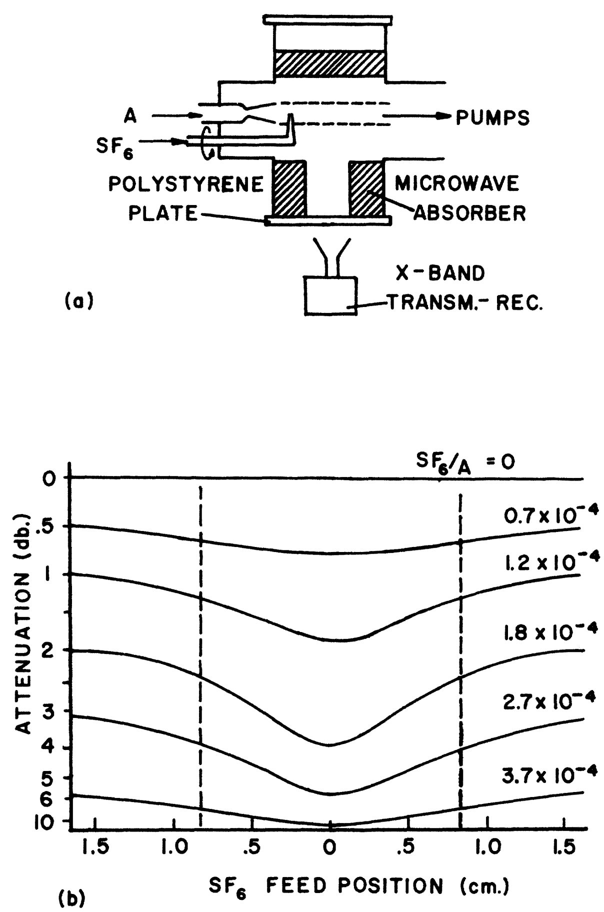

FIG. 1. Effect of SF_6 seeding on microwave back-scattering from the plasma stream. (a) shows a schematic diagram of the apparatus, (b) shows the microwave return as the seeding tube is swept through the stream at different SF_6 injection rates.

of the electrons by SF_6.

Similar tests were carried out using air and oxygen as the seeding gas and even for injection rates an order of magnitude larger than those used for SF_6, no appreciable effect was observed on the back-scattering of the microwave signal.

In a second series of measurements the properties of the flowing plasma were examined by sweeping a double probe across the stream. The double probe was introduced into the plasm stream as shown in the schematic diagram of Fig. 2. The probe could be moved both along and across the stream thus enabling the sampling of the plasma before and after the point of seeding. The probe unit was made of two parallel tungsten wires (0.75 mm diameter) 0.4 mm apart, imbedded in a ceramic rod and protruding 0.5 mm. A sufficiently large constant voltage was applied between the electrodes to insure that the probe unit was operating under conditions of ion saturation current.

Figure 2 shows the effect of SF_6 seeding on the probe current as a function of the probe position across the stream. These measurements were performed in a steady argon plasma stream with a SF_6/A ratio of 4×10^{-4}. In one case the probe is located 0.5 mm upstream from the seeding tube and in the other it is 1.0 cm downstream. In the first case it is seen that the ion concentration at the center of the stream, as indicated by the probe saturation current, is essentially not affected. However, the ion concentration at the edge of the stream is reduced because of the presence of the small amount of SF_6 gas which has diffused from the stream into the test section. When the probe is located downstream from the feed the effect of seeding is very pronounced. It is seen that the probe current at the center of the stream is reduced by seeding to about 6% of its value in the unseeded stream. Measurements further downstream show that this percentage decreases to zero in a distance of a few centimeters. The two maxima near the edge of the stream are real and define the "shadow" of the SF_6 stream being swept by the argon flow. The quenching of the plasma can also be observed visually as a dark region in the luminescent plasma behind the seeding point. Similar tests have been carried out by seeding the argon plasma with air and oxygen and no appreciable change has

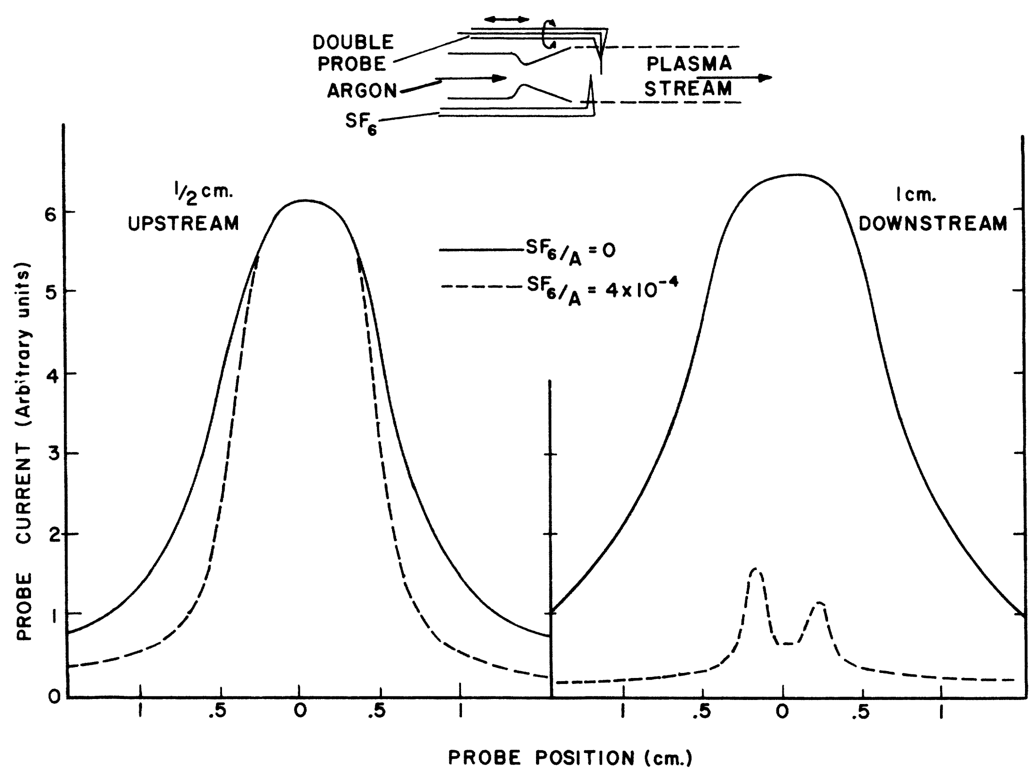

FIG. 2. Double-probe measurements of the plasma flow showing the effect of SF_6 upstream and downstream from the point of seeding.

been found in the ion concentrations across the stream even with seeding flow rates ten times greater than those used with SF_6.

These results seem to indicate that when the argon plasma is seeded by very small amounts of SF_6 not only the electron density (as shown by the microwave measurements) but also the positive-ion density is markedly reduced. This conclusion is based on the fact that the double-probe saturation current is a measure of the ion density in the plasma and a simple replacement of electrons by negative ions should not radically change the probe saturation current. Even including the effect of the low mobility of heavy negative ions in the plasma, the very large changes in probe current that have been observed can only by explained by a reduction in the ion density. This suggests that the capture of electrons in the plasma by SF_6 to form negative ions is quickly followed by a charge exchange process between the argon positive ions and the SF_6 negative ions. In addition, the efficiency of both these processes appears to be very high since the SF_6/A ratio is of the same order of magnitude as the ratio of electron to argon concentration in the unseeded plasma.

The authors wish to express their appreciation to Dr. M. P. Bachynski, for the many useful discussions concerning this investigation.

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[3]E. O. Johnson and L. Malter, Phys. Rev. 80, 58 (1950).

EXCITON-INDUCED IMAGES OF PHONON SPECTRA IN ULTRAVIOLET REFLECTANCE EDGES

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(Received 25 March 1963)

Ultraprecise measurements of the ultraviolet reflectance of a number of semiconductors have been reported by Lukeš and Schmidt.[1,2] The relative accuracy of the reflectance is apparently 0.03% and of the spectral resolution 0.003 eV. Their results for Si at 359°K (Fig. 1) show a hyperfine splitting of the M_1 absorption edge at 3.350 eV into subsidiary edges at 3.310, 3.333, 3.367, 3.387, 3.404, 3.419, and 3.436 eV. Similar splittings which are seen in various absorption edges of other semiconductors are collected in Table I.

Here we observe that this structure is exactly what one expects when multiphonon transitions are taken into account. Consider first the direct transitions between conduction band i and valence band j. If we have an M_0 threshold at energy E_0, the form of the imaginary part of the dielectric constant ϵ_2 is[3]

$$\epsilon_2(\nu) = C(h\nu - E_0)^{1/2}, \qquad (1)$$

while that of an M_1 edge[4] at E_1 is

$$\epsilon_2(\nu) = C_1 - C_2(E_1 - h\nu)^{1/2} \quad h\nu \lesssim E_1, \qquad (2)$$

$$= C_1 + C_3(h\nu - E_1) \quad h\nu \lesssim E_1. \qquad (3)$$

The M_0 direct edge (1) is associated with a sphe-

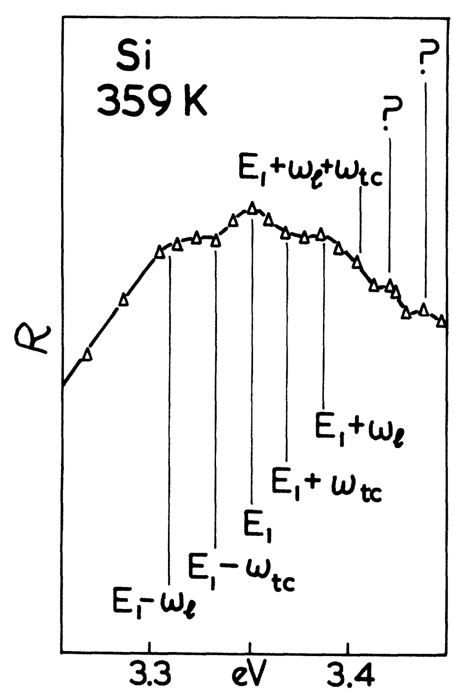

FIG. 1. Ultraviolet reflectance of Si near 3.35 eV at 359°K. The longitudinal acoustic phonon frequency is ω_l, the transverse acoustic ω_{tc}, and E_1 is the no-phonon intrinsic M_1 reflectance edge energy.