Electrical Conduction through Radiation-Produced Plasmas in Inert Gas Thermionic Diodes

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Properties of thermionic diodes containing inert gases at pressures from 1 to 600 Torr have been determined during irradiation with gamma rays and 1-MeV electrons at dose rates to 3×10^8 rads/h. Anode current maxima were observed at applied potential less than 4 V in tubes containing argon, krypton, or xenon, the gases having Ramsauer minima in their scattering cross sections. Negative resistance in the tube characteristics was not observed with helium, neon, or nitrogen which do not have scattering cross-section minima. Negative resistance was observed in diodes having both planar and cylindrical geometry. With all of the rare gases, initiation of breakdown occurred during irradiation at applied potentials less than the ionization potentials of the gases. The diode current at a constant anode voltage increased linearly with dose rate at low radiation intensities and approximately as the square root of dose rates at higher intensities.

ELECTRICAL conductivity measurements in high-pressure inert gas thermionic diodes[1–3] have led to observations of phenomena not heretofore reported. One of the most interesting results of these studies is that a simple thermionic diode has been found to be a useful tool for analyzing extremely small fractional ionization effects in inert gases in the pressure range 1–700 Torr. Recently it has been shown[3] that thermionic diodes containing radioactive krypton as the ambient gas displayed negative resistance characteristics, which were attributed to the Ramsauer minimum in the scattering cross section of krypton for electrons of low energy. Further experiments, reported here, were designed to give a better understanding of the observed phenomena.

EXPERIMENTAL TECHNIQUES

Experimental tubes used in these measurements are illustrated in Fig. 1. The two diodes are the same except that (a) has cylindrical geometry and (b) has planar geometry. The only impurities detected by mass spectrometric analysis in the spectroscopic grade rare gases used for these experiments were 0.006 mole percent helium in the neon and 0.01 mole percent xenon in the krypton. Tubes were evacuated and filled with the appropriate gas by means of the ultrahigh vacuum and gas handling system shown in Fig. 2 of reference 1. The tubes were processed by a procedure similar to that described for natural krypton in reference 3. Diodes employing xenon, krypton, and argon were filled initially to a pressure of about 600 Torr and the lower pressures were obtained by controlling the temperature of cold finger F, in Fig. 1, a procedure similar to that employed previously.[3] To obtain the pressure range of 10–200 Torr argon, the cold finger was cooled with a mixture of liquid and solid nitrogen which was subsequently allowed to warm slowly. Higher pressures of argon and the desired pressures of krypton and xenon were obtained by inserting the cold finger into a massive copper cylinder cooled with liquid nitrogen and allowed to warm slowly. To obtain data on neon-filled diodes as a function of pressure, six separate tubes having identical dimensions were employed.

Electrical characteristics of the tubes were measured using a circuit similar to that employed earlier (Fig. 3

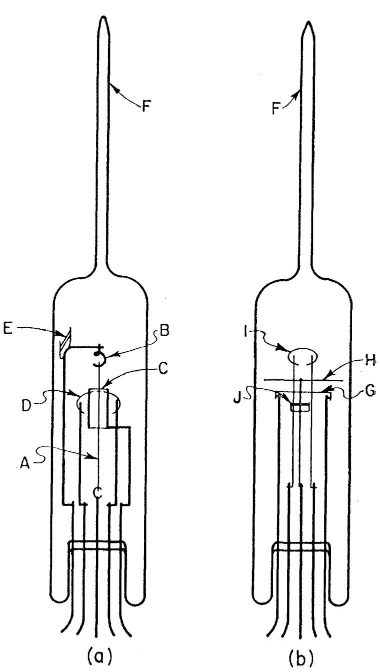


FIG. 1. (a) Cylindrical diode thoriated tungsten filament, A, is 0.01 in. in diameter and 3.5 cm long, supported by tantalum spring, B. The tantalum anode, C, is 1 cm diameter and 1.25 cm long. D is a 0.01-in.-diam tungsten filament used for degassing the anode by electron bombardment and E is a Kemet barium getter. F is a Pyrex glass cold finger appendage used for controlling the vapor pressure of the inert gas contained in the glass envelope. (b) Planar diode, G, is a 0.001-in.-thick thoriated tungsten ribbon 16 mm long and 3 mm wide. The anode, H, is of 0.003-in. tantalum sheet 1×3 cm. I is a 0.01-in.-diam tungsten filament used for degassing the anode. J is a Kemet barium getter and F is a cold finger appendage as in 1(a).

[1] R. Forman, J. Appl. Phys. **32**, 1651 (1961).
[2] R. Forman, Phys. Rev. **123**, 1537 (1961).
[3] R. Forman and J. A. Ghormley, J. Appl. Phys. **33**, 3057 (1962).

TABLE I. Calculated dose rates and rates of ion formation in rare gases exposed in Pyrex vessels to cobalt-60 gamma radiation at a measured dose rate, in water, of 1.63 Mrad/h (1.63×10^8 ergs/g-h).

Gas	Dose rate (Mrad/h)	Rate of ion formation Ion pairs/cc-sec at 50 Torr gas pressure
Helium	1.57	0.80×10^{10}
Neon	1.38	3.6×10^{10}
Argon	1.19	10.2×10^{10}
Krypton	1.00	16.8×10^{10}
Xenon	0.91	26.4×10^{10}

of reference 1) except an Autograf, Model 35, X-Y recorder was used in the anode circuit to facilitate the measurements.

A cobalt-60 gamma-ray source was employed for dose rates up to 10^6 rad/h (one rad=100 ergs/g), and a Van de Graaff electrostatic generator was used for high dose rates. The gamma-ray source was similar to one described previously[4] and consisted of 2400 Ci of cobalt-60, 12 to 16 in. from the bottom of a 12-in.-diam 12-ft.-deep water-filled well. The cobalt was arranged in a cylindrical array surrounding a dry $1\frac{3}{4}$-in.-diam central tube in which the diodes were irradiated. The dose rate (in water) at the center of the source was determined by means of ferrous sulfate dosimetry.[5] In calculating the dose rate in the various gases it was assumed that the range of secondary electrons was large compared with the dimensions of the tubes and, therefore, that the contribution of electrons originating in the gas (and elements of the tubes) was negligible compared to the contribution from electrons originating in the Pyrex glass envelopes. The dose rate in Pyrex was 1.46 Mrad/h and the maximum dose rates in the rare gases are given in Table I. The position of maximum intensity was 14 in. from the bottom of the central sample tube and the relative dose rates at other positions along the axis of this tube were determined by means of a small ionization chamber. Any desired dose rate below the maximum could be obtained by choosing the appropriate vertical position within the sample tube. Dewar vessels were designed to fit into the space available in the traveling carriage of the Co^{60} source. They contained the coolants and heat sinks which were used to control the temperature of cold fingers, controlling the diode gas pressures.

An electron beam from the High Voltage Engineering 1-MeV Van de Graaff electrostatic generator at the Sterling Forest Laboratory of Union Carbide Nuclear Company was used for dose rates up to 3×10^8 rad/h. Electrons entered a krypton-filled diode through a thinned portion (~0.2 mm) of the glass envelope. The dose rate as a function of electron beam current was determined by first observing the characteristics of the diode while it was subjected to gamma radiation at 1 Mrad/h, then experimentally, finding the electron beam current required to give the same characteristics. It was assumed that the dose rate was proportional to electron beam current.

Before irradiation, filament temperatures were determined as a function of filament current and gas pressure by means of a Pyro Micro-Optical pyrometer. Diodes were not accessible for pyrometer measurements during irradiation and darkening of the glass by the radiation prevented measurements after irradiation. By determining the pressure and choosing the appropriate filament current, it was possible to obtain any desired filament temperature during irradiation.

RESULTS AND DISCUSSION

Figure 2 shows current-voltage characteristics of a krypton-filled cylindrical diode during irradiation with

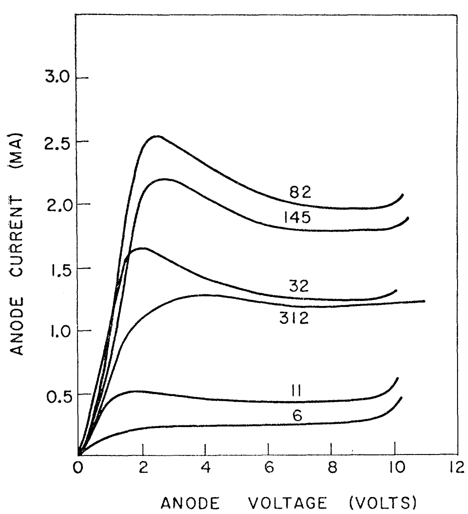


FIG. 2. Anode current-voltage characteristics of krypton-filled cylindrical diode. The data were obtained at a filament temperature of 1650°C brightness and gamma radiation dose rate of 0.25 Mrad/h. The other parameter is krypton pressure in Torr.

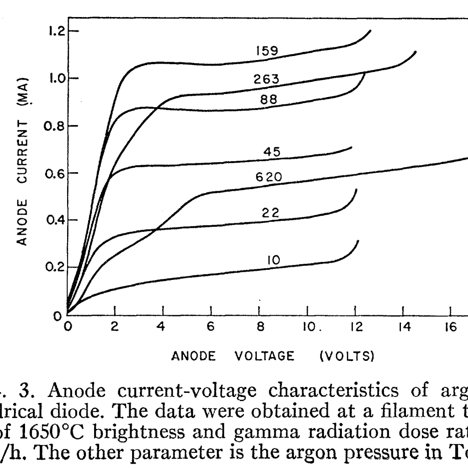


FIG. 3. Anode current-voltage characteristics of argon-filled cylindrical diode. The data were obtained at a filament temperature of 1650°C brightness and gamma radiation dose rate of 0.3 Mrad/h. The other parameter is the argon pressure in Torr.

[4] M. Burton, J. A. Ghormley, and C. J. Hochanadel, Nucleonics **13**, 74 (1955).

[5] S. C. Lind, C. J. Hochanadel, and J. A. Ghormley, *Radiation Chemistry of Gases* (Reinhold Publishing Corporation, New York, 1961), p. 59.

gamma rays at pressures from 6 to 312 Torr. The data of Fig. 2 were obtained at a dose rate of 0.25 Mrad/h, but the same general characteristics were observed at other dose rates between 0.050 and 1.00 Mrad/h.

At low pressure (below 6 Torr) the current-voltage characteristic obeys a space-charge relation[2] and increasing pressure tends to decrease current. This same trend was found previously with radioactive krypton gas.[3] On increasing the pressure further, the current begins to increase rapidly at low anode voltages, and negative resistance (decrease in current with increase in voltage) appears. Increasing the pressure above 6 Torr brings about an increase in current at any given voltage and the negative resistance becomes more apparent. Above about 82 Torr, further increase in pressure leads to a decrease in current and eventual disappearance of the negative resistance. As pressure increases, the current maximum consistently moves toward higher voltages.

The characteristics of a xenon-filled diode are similar to those observed with krypton except that with xenon, (a) the negative resistance effect first appears at a lower pressure and disappears at a lower pressure, and (b) the pressure at which highest current occurs is lower.

Current-voltage characteristics of an argon-filled cylindrical diode are shown in Fig. 3. The negative resistance is barely perceptible in argon and appears only in the pressure range from about 90 to 200 Torr. At higher pressures a reproducible shoulder appears on the current-voltage curve as shown for 620 Torr in Fig. 3.

The results obtained from neon-filled diodes, Fig. 4, show no negative resistance. Pressures examined range from 12 to 600 Torr at dose rates from 0.07 to 1.4 Mrad/h.

A helium-filled diode was examined at only one pressure, 50 Torr. Its characteristics are similar to those of neon with no negative resistance.

Figure 5 shows the effect of radiation dose rate on the characteristics of a krypton-filled diode at constant pressure. The current increases, approximately, linearly with dose rate up to 0.5 Mrad/h but doubling the dose rate from 0.5 to 1.0 Mrad/h results in only 50% increase in current.

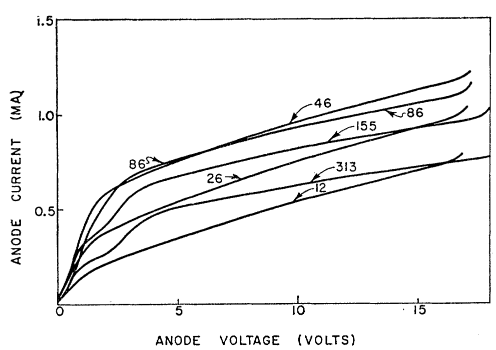


FIG. 4. Anode current-voltage characteristics of neon-filled cylindrical diodes. The data were obtained at a filament temperature of 1650°C brightness and gamma radiation dose rate of 1.38 Mrad/h. The other parameter is the neon pressure in Torr.

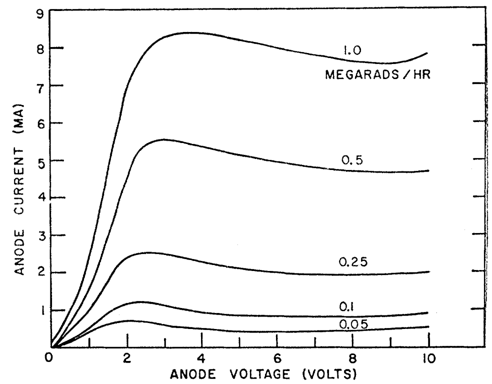
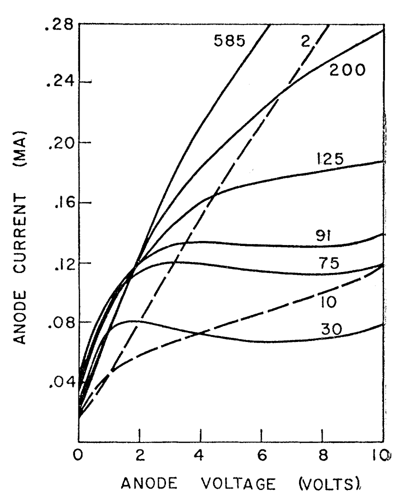


FIG. 5. Anode current-voltage characteristics of krypton-filled cylindrical diode (same tube as Fig. 2) at approximately constant pressure (85±10 Torr) with gamma radiation dose rate in megarads/h as the variable parameter. The filament temperature is 1650°C brightness.

All of the experiments discussed thus far were carried out with diodes having cylindrical geometry. Enhancement of electron currents by positive ions in thermionic diodes at low pressures depends on electrode geometry.[6] An obvious question that can be raised is whether in high-pressure diodes the observed negative resistance is associated with the cylindrical geometry. To answer the question, a diode with planar geometry as shown in Fig. 1(b) was constructed and filled with krypton. It is obvious from the characteristics of this tube shown in Fig. 6 that negative resistance occurs with planar geometry also.

Characteristics of a krypton-filled cylindrical diode subjected to higher radiation intensities from the electron beam of a Van de Graaff generator as shown in Fig. 7 (20 Torr pressure) and Fig. 8 (2 Torr). In each case, current monotonically increased with increasing

FIG. 6. Anode current-voltage characteristics of krypton-filled planar diode. The data were obtained at a filament temperature of 1750°C brightness and gamma radiation dose rate of 0.25 Mrad/h. The other parameter is pressure of krypton in Torr.



[6] K. H. Kingdon, Phys. Rev. 21, 408 (1923).

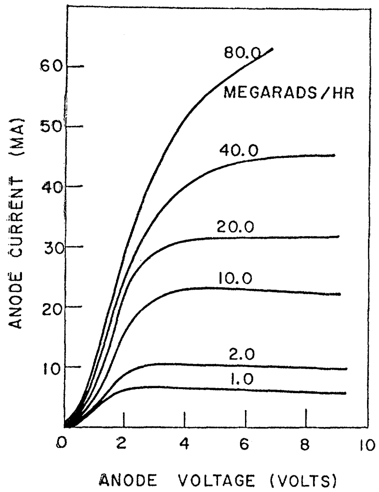


FIG. 7. Anode current-voltage characteristics of krypton-filled cylindrical diode at a pressure of 20 Torr with electron beam radiation dose rate in megarads/h as the variable parameter. The filament temperature is 1750°C brightness.

dose rate, but at the higher pressure the negative resistance was not observed at dose rates above 20 Mrad/h. It should be noted that 50 mA of current in this tube corresponds to a rather high cathode current density of 0.5 A/cm^2 assuming that the effective emitting length of the filament is the same as the anode length. At the lower pressure the diode current was lower but negative resistance was observed even at the highest dose rate.

To complete the picture, it was felt that comparative data should be obtained using a diatomic gas ambient such as nitrogen. These data for a cylindrical diode are shown in Fig. 9. There are three interesting features which should be noted: (1) the anode currents were much lower than those obtained in identical tubes with an inert gas ambient, (2) no negative resistance effects were observed, and (3) no early breakdown was observed in the nitrogen ambient although it was always observed in this pressure range for inert gas-filled diodes when the radiation dose rate was high enough. Data similar to that shown in Fig. 9 were obtained in nitrogen ambients covering the range of pressure from 1–360 Torr.

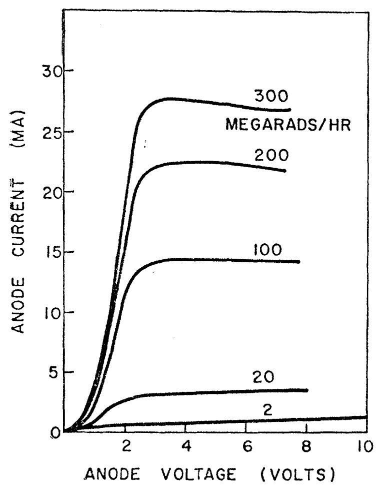


FIG. 8. Anode current-voltage characteristics of krypton-filled cylindrical diode at a pressure of 2 Torr with electron beam radiation dose rate in megarads/h as the variable parameter. The filament temperature is 1750°C brightness.

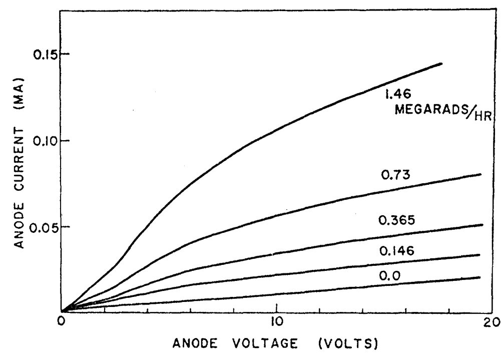


FIG. 9. Anode current-voltage characteristics of a nitrogen-filled cylindrical diode at a pressure of 168 Torr with gamma radiation dose rate in megarads/h as the variable parameter. The filament temperature is 1750°C brightness.

The experimental data are qualitatively consistent with a theory developed by one of the authors and described in detail elsewhere.[7] The theory assumes that the plasma between electrodes is essentially a conductor whose charge density monotonically increases with increasing gas pressure and radiation dose rate. It is further assumed that current through the plasma is determined by the charge density and the drift velocity attained by electrons in traversing the space between cathode and anode. The theory shows that diodes containing the gases xenon, krypton, and argon display negative resistance characteristics as a result of the difference in elastic scattering for low- and high-energy electrons (Ramsauer effect).

[7] R. Forman, preceding paper [Phys. Rev. **128**, 1487 (1962)].