I. PHYSICAL ELECTRONICS

Prof. W. B. Nottingham
J. M. Bailey
A. R. Hutson
H. S. Jarrett
R. F. Lucy
R. N. Noyce
W. E. Spicer
L. E. Sprague
T. F. Wichmann

A. ELECTRON-EMISSION PROBLEMS

1. Magnetic Velocity Analyzer Investigation of Thermionic Emission from Tungsten

Some auxiliary experiments on vacuum technique led to the discovery and observation of a gas absorption and emission effect in tungsten filaments. The effect was observed in the filaments of the Bayard-Alpert type ionization gauge which was sealed off with the "dummy" tube previously described (Quarterly Progress Report, p. 2, April 15, 1951). The vacuum processing of the tube consisted of alternate baking and outgassing. A side tube contained two coils of KIC getter wire welded across a two-lead press and fired before the tube was sealed off. During the firing of the getter both ionization gauge filaments were hot and a blue-green discharge was observed in the getter side-tube. Firing of the getter raised the pressure in the tube from 4×10^{-8} mm to 2×10^{-6} mm and seemed to contaminate the gauge since it had to be completely outgassed before a pressure of 8×10^{-9} mm, at which the tube could be sealed off, was reached. The pressure after seal-off was 6×10^{-9} mm.

In the following discussion of the gas effect, the gauge filaments will be called f_1 and f_2 (either filament could be used to supply the electron current for operation of the gauge). The first observation of the gas effect occurred with f_2 emitting 5 ma to operate the gauge. As the temperature of f_1 was slowly decreased from about 2000°K the pressure in the tube nearly doubled and then fell back to a little less than the original value. The same variation of pressure with the temperature of the nonemitting filament was found upon slowly increasing the temperature to 2000°K. The maximum tube pressure occurred at a filament temperature of about 1200°K and was about 10^{-8} mm. The background pressure in the tube was about 6×10^{-9} with the filament either hot or cold.

Holding f_1 at 1200°K for ten days reduced the magnitude of the gas emission until it could no longer be observed. However, upon reversing the functions of f_1 and f_2, f_2 showed the same emission of gas at about 1200°K. f_2 was allowed to stand by at about 1200°K while the gauge was running for three weeks. At the end of this period, f_2 no longer showed the effect. A second reversal of operation showed that f_1 once again gave off gas in the 1200° region. It appeared as though f_1 had absorbed some of the gas driven out of f_2. This absorption occurred with f_1 hot, as it had to supply the electron emission for the operation of the gauge.

By biasing the gas-emitting filament positive with respect to the electron collector and ion collector and turning off the other filament, one would expect to detect any ion emission associated with this gas effect. No ion emission was detected in the gas-effect temperature range.

A possible explanation for this gas effect might be as follows. The gas concerned has a solubility in tungsten that is a strong function of the temperature, the solubility going up with increasing temperature. If the tungsten is nearly saturated at some high temperature and the temperature is then lowered, gas is expelled as long as it can diffuse to the surface. At temperatures below about 1200°K, the diffusion becomes so small that the gas is effectively frozen into the tungsten lattice.

A. R. Hutson

2. The Distribution of Energies of Photoelectrons Emitted from Germanium Deposited on a Molybdenum Substratum

Investigation of the photoelectric emission from germanium has been completed and a report of this study is available as a thesis publication. A technical report is being prepared. The method of study reported in more detail in previous Progress Reports involved the use of a tube structure which had a molybdenum sphere upon which the germanium was deposited before it was slid along a supporting wire to the center of a collecting sphere. Light from various ultraviolet sources was used to excite the photoelectrons and the yield as a function of wavelength was investigated. In addition, at selected wavelengths, the energy distribution of the electrons was determined by retarding potential methods.

The work function of the molybdenum sphere when clean was found to be 4.33 ev. This value of the photoelectric work function is higher by 0.2 ev than that reported by Roehr and DuBridge.

After the germanium was deposited on the molybdenum surface a work function determination yielded a value of 4.86 ev before heat treatment and 4.94 ev after heating. The distribution in energy of the electrons was very similar to that obtained from typical metals although differences were definitely evident.

H. S. Jarrett
(report prepared by W. B. Nottingham)

3. Photoelectric Study of Surface States on Insulators

The study of photoelectric emission from insulators requires a tube which meets two difficulties. First, since photoelectric emission is a surface phenomenon, the problem of obtaining and maintaining a clean surface arises. Second, the currents involved in emission from insulators are necessarily small because of the low absorption of light in the energy range being investigated. The tube has to be capable of separating this current from others arising during operation.

The first tube for the study of emission from quartz has been constructed, and is now being vacuum-processed. This tube has provision for heating the crystal by electron bombardment to clean the surface. It is hoped that a low enough pressure may be obtained so that the contamination of the surface will proceed slowly enough to be watched if it occurs. The current to the surface is measured by capacitive coupling to an electrode plated on the back side of the crystal. This electrode is carefully shielded by three auxiliary electrodes so that any emission from the back electrode may be identified.

R. Noyce

4. The Influence of Electric Field and Temperature on Field Emission from Tungsten

A photographic study has been made of the alteration in field-emission patterns produced by the application of high voltage to the tube while the filament and the field-emission point were raised to various temperatures in the range from 1100°K to 1900°K. Some typical patterns are shown in the reproductions of Fig. I-1.

A close inspection of these figures shows deviations from the normal tungsten pattern that have resulted from the application of the high field. Although it was the original intention to obtain a more quantitative record of these phenomena, various difficulties interfered with the completion of the program at this time. It will probably be undertaken at a later date. In the meantime the detailed information obtained is available in the thesis report now on file.

W. E. Spicer, Jr., T. F. Wichmann
(report prepared by W. B. Nottingham)

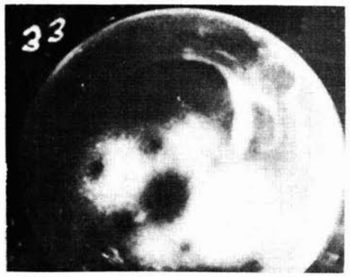
B. STUDIES WITH GAS DISCHARGE

1. Probe Measurements in a Low-Pressure Mercury Arc

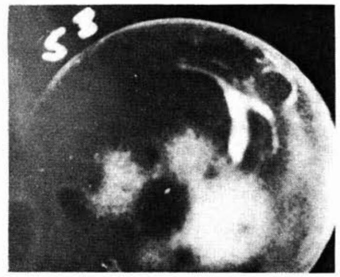
Langmuir probe measurements have been made in a mercury-arc discharge tube in the pressure range from 1.8 to 33 μ, and with arc currents from 200 ma up to 6 amp. The experimental tube has a pool-type mercury cathode, and was designed so that the plasma in which the probes were located was maintained in a side arm of the tube, 48 cm long, and was well shielded from disturbances at the cathode.

With a 4-amp plasma current, mid-curve bends or "kinks" occurred in the probe characteristics and a disturbance in the plasma was indicated by an oscilloscope when the pressure was below 16 μ. Both the kinks and the disturbance disappeared when the pressure was raised above 16 μ. The critical pressure at which the plasma disturbances disappeared was higher for lower plasma currents.

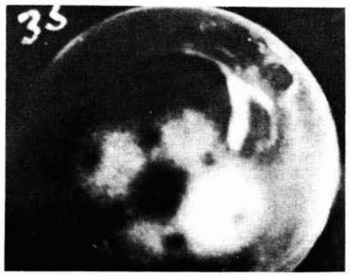
For a given pressure, the kinks in the probe characteristics occurred at the same probe potential, regardless of the plasma potential where the probe was located. This invariance is illustrated by Fig. I-2 which shows that the kink is higher on the probe



3000 volts, 1300°K.

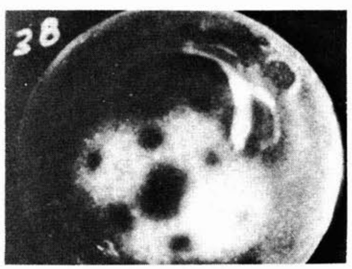


5000 volts, 1300°K.

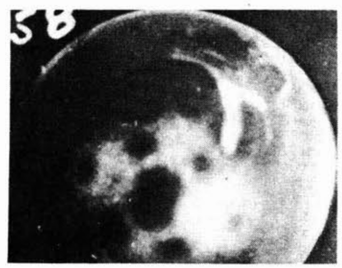


3000 volts, 1500°K.

5000 volts, 1500°K.



3000 volts, 1800°K.



5000 volts, 1800°K.

Fig. I-1

Patterns showing the effect of heating the point to the same temperature with different applied voltages.

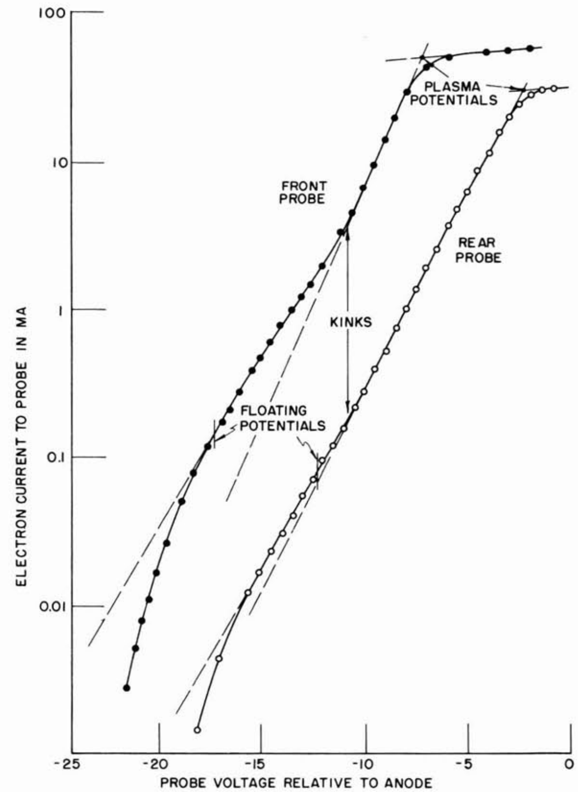


Fig. I-2

Typical probe characteristics. 30°C (3.4 microns), 4-amp plasma current.

characteristic for the front probe than for the rear probe. Note that the plasma potentials for these two probes differ in the expected manner and measure the potential drop along the plasma.

These kinks have been interpreted as an excess group of electrons generated by a form of plasma oscillation localized near the mouth of the side arm of the tube containing the plasma. The indicated energies of the excess group are greater at higher pressures, and the oscillations creating the group seem also to be the source of the plasma disturbances observed.

In addition to the kinks in the probe characteristics, there exist in the probe voltage regions around and below the floating potential downward bendings of the characteristics, which are attributed to the loss of energetic electrons to the tube walls and to inelastic collisions with mercury atoms. These depletions existed at all pressures.

The probes were flashed red-hot before each current measurement, and the probe work function was found to increase as the probe cooled off, indicating the adsorption of some gas other than mercury on the probe surface.

Each probe was equipped with a variable-potential shield, both to avoid the distortion of potential in the vicinity of the probe, which may result from the charging-up of dielectric shields, and to make possible detailed studies of the formation of space-charge sheaths around the probes. With the probe and sheath at the same potential, the increase of effective probe area due to a thickening space-charge sheath as the probe was made very negative or positive with respect to the plasma was avoided. It was found, however, that even under these conditions, the electron or ion current collected still increased as the probe was run more positive or negative, respectively. This result gives direct support to the Langmuir-Tonks theory, which says that the influence of the probe in a plasma extends beyond the space-charge sheath.

A more detailed account of the results obtained is given in "Langmuir Probe Characteristics in a Low-Pressure Mercury Arc", a Master's thesis submitted to the M.I.T. Department of Physics by the author in May, 1951.

J. M. Bailey

C. EXPERIMENTAL TECHNIQUES

1. Ionization Gauge Studies

Studies made with two Bayard-Alpert gauges, identical in all points of design except for the use of a grid system to close the ends of the electron collector, have indicated that the closed structure is more sensitive than the open type of construction by approximately a factor of two. The theoretical point which is to be investigated involves the direct comparison between these two gauges as the vacuum is improved to the best attainable. The fact that the two gauges give a difference in sensitivity is a direct indication that in the open structure ions are lost out through the ends of the ionization region, whereas with the closed structure these ions are trapped. It is to be anticipated that as the true vacuum gets better and better the fraction of the ions lost out through the ends can be expected to increase. Therefore the open-ended gauge might be expected to indicate a better vacuum than really existed. This hypothesis is being tested but the results to date are too incomplete for reporting.

W. B. Nottingham, L. E. Sprague

2. Magnetron Ionization Gauge

In the design of an ionization gauge for the measurement of very low pressures, the chief obstacle is the "reverse photoeffect", sometimes called the X-ray effect. It is by the production of a spurious current, masking the true ion current, that the reverse photoeffect imposes a low-pressure threshold upon the operation of the gauge. The effect may be described as follows. As each electron is collected at the electron collector, photons are emitted which may produce photoelectrons by striking the ion collector. This photoelectric current is registered upon the external measuring circuit in the same manner as the receipt of ionic charges by the ion collector. Thus, for a given electron collector potential there exists a spurious current in the ion collector circuit which is directly proportional to the electron current. The constant of proportionality is given by the product of the average number of photons per collected electron and the probability that a photon emitted at the electron collector will hit the ion collector and produce a photoelectron. The low-pressure threshold of gauge operation is reached when the ratio of the true ion current to electron current becomes of the same order of magnitude as the ratio of the photon-induced spurious current to the electron current.

The Bayard-Alpert ionization gauge obtained a reduction of the low-pressure threshold by a factor of about 200 compared with that of the previous "standard" gauges. This was accomplished by reducing the area of the ion collector by a factor of 200.

A second approach to the problem of decreasing the low-pressure threshold is to increase the sensitivity of the gauge so that more true ion current is produced for the same electron current at the same gas pressure. A method for increasing the sensitivity of the gauge is to increase the "effective ionizing path length" of the electrons, which may be defined from the following considerations.

If i_+ is the ion current and i_- the electron current, then for a particular gas the ratio of i_+ to i_- is proportional to the pressure p in mm Hg: $i_+/i_- = Kp$. The constant of proportionality, K, is called the sensitivity of the gauge, and depends upon the geometry of the gauge, the type of gas used in calibration, and the operating voltages.

An electron in passing through a gas will produce a certain average number of ionic charges per centimeter of its path. The ionization efficiency, E_i, is the number of ionic charges produced per centimeter of electron path in the gas at 1-mm pressure.

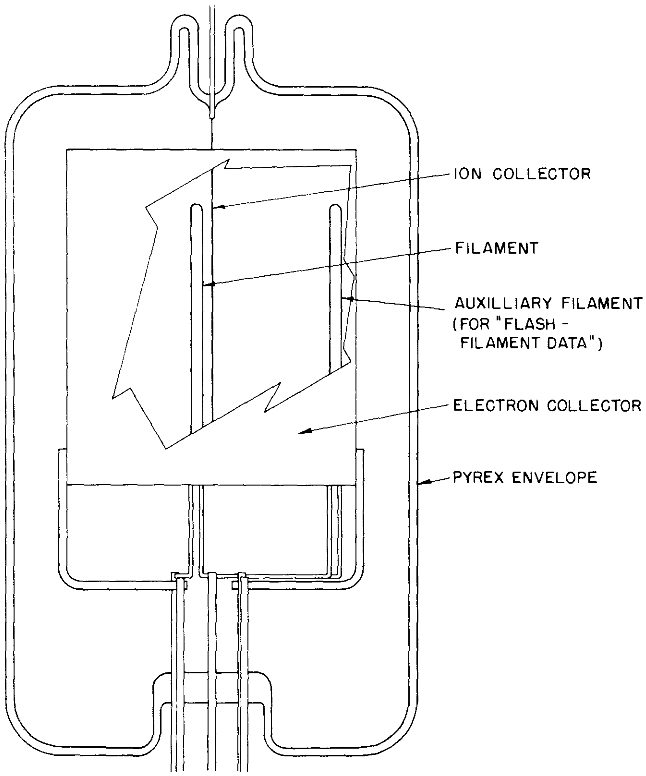


Fig. I-3
Electrode structure of the ionization gauge.

E_i is a function of the electron's kinetic energy. The actual ionic charge produced is proportional to the gas pressure. We may call $\overline{E}_i$ the average ionization efficiency for the range of energies which the electron has en route from filament to electron collector. Then the effective ionizing path length is given by $L = K/\overline{E}_i$.

Since E_i is about 12 for 75 to 160 volt electrons in nitrogen (1), the effective ionizing path length for a Bayard-Alpert type gauge with a K of 12 is one centimeter.

With the hope of increasing the effective ionizing path length while maintaining the small area ion collector used in the Bayard-Alpert gauge, the magnetron ionization gauge was built and tested. Figure I-3 shows that the electron collector consists of a tantalum cylinder; the ion collector is a wire along the axis of this cylinder, and the electron emitting filament is a "hairpin" parallel to the ion collector and very close to it. The name of the gauge is derived from the fact that it is operated with a uniform magnetic field parallel to the axis of the cylinder. The field is provided by a solenoid fitted around the pyrex envelope, or in this experimental work by a pair of Helmholtz coils. The motion of charged particles in a radial electric field and uniform axial magnetic field has been described by A. W. Hull (2). He derived two relations for magnetron cutoff: one for the particles accelerated towards the axis (applicable to the electrons), and one for the particles accelerated away from the axis (applicable to the ions).

For electrons:

$$H = \frac{1}{R_o}\sqrt{\frac{8m}{e}}\, V_e^{1/2}$$

$\left.\begin{array}{l} m = \text{mass of electron} \\ e = \text{charge of electron} \end{array}\right\}$ emu
R_o = radius of filament in cm
V_e = potential difference between electron collector and filament

H is the magnetic field in gauss which will just cut off the current of the particles under consideration.

For ions:

$$H = \frac{1}{\beta R_o'}\sqrt{\frac{8M}{q}}\ V_i^{1/2}$$

M = ionic mass } emu
q = ionic charge } emu
V_i = potential difference between point at which ion is created and the ion collector
R_o' = radius of ion collector
β = R_o'/radial distance at which ion was created.

The ratio of the magnetic field required for ion cutoff to that required for electron cutoff is

$$\frac{R_o}{\beta R_o'}\sqrt{\frac{Me\,V_i}{mq\,V_e}} \quad .$$

Setting V_i equal to the difference of potential between the electron collector and the ion collector, and letting β go to the ratio of the ion collector radius to the electron collector radius, we then set the above expression equal to unity. This tells us the mass of the lightest ion of a given charge which will be collected under conditions of electron cutoff.

The gauge was calibrated with nitrogen in three different modes of operation:

(1) D-C Magnetic Field $\qquad$ K = 80 implies L = 6.6 cm

H = 55 gauss (just greater than electron cutoff value)
V_{ec} = 150 volts
V_{ic} = -200 volts (allowing singly-charged ions of mass greater than 9 atomic units, or doubly-charged ions of mass greater than 18 atomic units to be collected)

The maximum electron current obtainable in this mode of operation was 3 ma, which was probably largely collected on the electron-collector supporting wires.

(2) A-C Magnetic Field $\qquad$ K = 50

Potentials were the same as above, but the magnetic field was sinusoidally varying at a frequency of 60 cps and had an rms value of about 65 gauss. It should be noted that the ratio of ion current to electron current showed practically no change when the d-c magnetic field was changed by as much as 20 percent in the range above electron cutoff.

(3) No Magnetic Field $\qquad$ K = 3 implies L = 0.25 cm

V_{ec} = 150 volts
V_{ic} = -22 volts

In this mode of operation, electron currents as high as 40 ma were tried successfully with no trace of oscillation.

This particular magnetron gauge should have a low-pressure threshold which is lower than that of the Bayard-Alpert type gauge by a factor of three, since the effective ionizing path length is over six times as long and the ion collector area is about twice as large.

Since the operation without magnetic field resulted in an effective ionizing path length of only 0.25 cm, whereas the electrons travelled more than a centimeter with energies in excess of 75 ev, one must conclude that many ions recombine on the glass walls of the tube or on the filament. If in later models the ion collection efficiency can be increased, it is expected that the sensitivities and effective ionizing path lengths of all modes of operation will increase, resulting in a further lowering of the low-pressure threshold.

References

1. K. T. Compton, C. C. Van Voorhis: Phys. Rev. 27, 724, 1926

2. A. W. Hull: Phys. Rev. 18, 31, 1921

A. R. Hutson

3. Design and Construction of Circuits for the Operation of Bayard-Alpert Gauges

An electronic circuit was developed a year ago and described in the thesis by W. S. Attridge and J. B. Thomas for the control and operation of a Bayard-Alpert ionization gauge. This circuit included the following features: (1) means for outgassing the parts of the gauge; (2) a vacuum tube electrometer circuit for the measurements of small currents; (3) a circuit for the integration of small currents; (4) adjustable power supplies so that a wide range of operating parameters would be under control; (5) circuits for automatic regulation of the electron current at chosen values over a very wide range; (6) automatic removal of power in case of vacuum system failure. Although the circuit designed to meet these requirements operated satisfactorily it had certain engineering disadvantages. A detailed analysis of circuit requirements has been completed and an improved circuit designed. A preliminary construction of the improved circuit is now planned for and, following construction and testing, a permanent model will be designed and built.

R. F. Lucy

(report prepared by W. B. Nottingham)