I. PHYSICAL ELECTRONICS

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A. ELECTRON EMISSION PROBLEMS

1. Temperature Dependence of the Fermi Level and Its Relation to Properties of Oxide Cathodes

Studies of the oxide cathode indicate that knowledge concerning the temperature variation of the work-function is vital to the interpretation of experimental data. General considerations indicate that the principal contribution to the temperature coefficient of the work-function comes from the temperature variation of the Fermi level with respect to the bottom of the conduction band rather than the temperature variation of the electron affinity. This latter quantity is defined as the energy difference between the bottom of the conduction band and an electron at rest outside of the electron emitter. It is, therefore, of interest to derive a new equation for the value of the Fermi level as a function of the donor concentration, the location of the donor level, and the temperature. The new equation which serves to relate these quantities is the following:

$$\mu = E - V_T \ln 2 + V_T \ln \left\{ \left[1 + 8\, e^{-\frac{\mu' + E}{V_T}} \right]^{1/2} - 1 \right\} \tag{1}$$

In this equation, the temperature is expressed in its electron-volt equivalent as given in Eq. 2.

$$V_T = \frac{k}{q} T = \frac{T}{11600} \tag{2}$$

A parameter which depends only on the temperature and the donor concentration n_D and is independent of the energy level at which the donor state is located is given by the following equation:

$$\mu' = V_T \left[\ln \frac{1.208 \times 10^{28}}{n_D} - \frac{3}{2} \ln \left(V_T^{-1} \right) \right] \tag{3}$$

The numerical constant of this equation is defined by

$$1.208 \times 10^{28} = \frac{4(2\pi mq)^{3/2}}{h^3} \tag{4}$$

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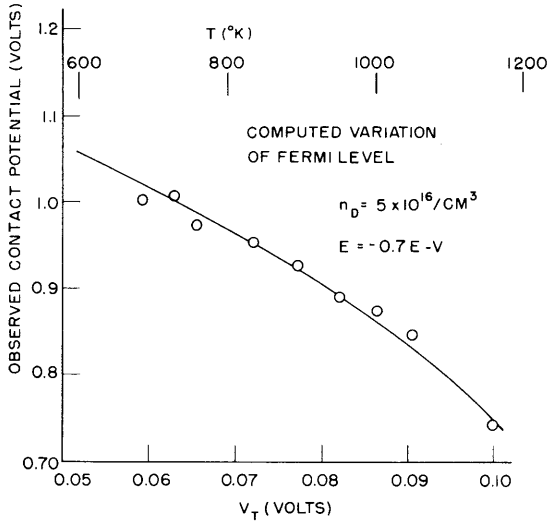

Fig. I-1. Measured contact potential as a function of the temperature compared with the computed curve

In the above equations, μ is the location of the Fermi level with respect to the bottom of the conduction band of a semiconductor in which the energy difference between the filled band and the conduction band is so large that a negligible proportion of the electrons in the conduction band arrive as a result of transitions across the entire forbidden band. The energy level of the donors with respect to the bottom of the conduction band is given by E. The other quantities are Boltzmann's constant k, the charge on the electron q, the mass of the electron m, and Planck's constant h.

Observations have been made on an oxide cathode to determine the observed change in the contact potential as a function of the temperature, which in turn is a measure of the temperature variation of the work-function. The results of these observations are shown by the circles of Fig. I-1. Conductivity studies made on similar cathodes indicate that a suitable choice for the location of the donor state is -0.7 ev with respect to the bottom of the conduction band. If this value is used in Eq. 1 and a density of donors of 5×10^{22} per m^3 (5×10^{16} per cm^3) then the computed variation of the Fermi level fits the experimental data within the accuracy of the measurements.

W. B. Nottingham

B. PHYSICAL ELECTRONICS IN THE SOLID STATE

1. Hall Effect in Lead Sulfide Films

Most of the equipment necessary for a study of the Hall effect has been acquired or constructed. This includes a control circuit to regulate the temperature of the sample. A vacuum tube electrometer, which will be used to measure the sample conduction

current, is near completion. For the high-resistance insulation necessary in this work, Teflon tubing will be used. Its ability to withstand liquid nitrogen temperatures without cracking or losing its high-resistance property makes its use most practicable. A magnetometer was found necessary to determine sufficiently well the magnetic field. A null-type magnetometer has been constructed and is now being modified to allow easy operation and maximum accuracy.

D. H. Dickey

2. Surface Studies on Semiconductors

The design and construction of a device to measure the photoconductivity and the contact potential of a small sample of germanium are now in progress. The contact potential measurement is to be performed by the Kelvin method in respect to a movable tantalum electrode. This device will be used to study the relation between the density of surface traps and the contact potential of the sample. As the sample is very small, the capacitance between it and the tantalum electrode is only around 1 $\mu\mu$f; therefore the present effort is to minimize the capacitance of the connecting leads and to stabilize it, as well as to eliminate as much as possible any stray voltages that may develop in this device.

E. Ahilea

3. Electrical Properties of Clean Germanium Surfaces

The fundamental purpose of this experiment is to obtain information about the existence of hole and electron traps near a clean germanium surface by measuring certain surface-dependent properties of thin samples. The samples are subjected to a combination of ion bombardment and heating similar to that used by the Brown University group under Professor Farnsworth (1). Electron diffraction studies (1, 2) give evidence that this treatment results in a surface free of oxide and other contamination. If the specimen is then maintained in a high vacuum ($\sim 10^{-9}$ mm), a time of the order of one hour is available before a gas can contaminate the surface to an appreciable fraction of a monolayer. During this time, measurements of field effect, noise, photoconductivity, and possibly contact potential will be made. The surface can then be exposed to oxygen or other gases and the same quantities remeasured.

FIELD EFFECT. It is well known that the resistance of a thin specimen of a semiconductor may be perceptibly changed by applying an electric field to its surface. This resistance change is usually smaller than would be the result if all the charge induced on the specimen were free to carry current. This is accounted for by centers assumed to exist near the surface, which immobilize some or all of the charge. The magnitude and time constants of this field effect and its dependence upon the gaseous ambient indicate (3, 4) that normally several types of traps are present. Some, which come to

equilibrium with the bulk very slowly, may exist within a layer of germanium oxide or outside this layer, perhaps in the form of chemically adsorbed atoms or molecules. If the field effect on a freshly bombarded surface no longer showed this slow relaxation this theory would be strengthened. A negative result, however, would not be very instructive as only about 10^{13} traps/cm^2 or one per cent of a monolayer is needed to account for the observed slow relaxation; there is no evidence that as clean a surface as this can be obtained.

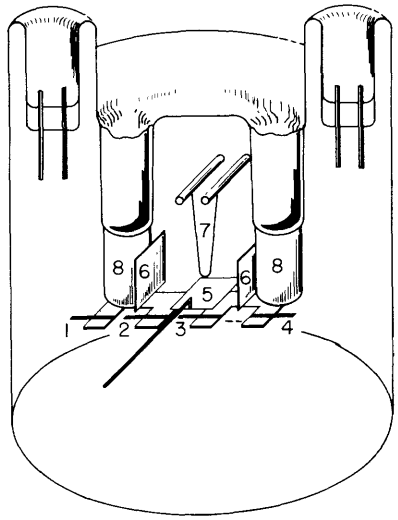

Fig. I-2. Schematic representation of experimental tube

NOISE. Previous measurements of 1/f noise in germanium have been made on etched or sand-blasted surfaces, the true structure of which is not well understood. Since several noise theories have been proposed which involve the existence of ions or an oxide layer on the surface, a measurement of noise on a surface free of such contamination is desirable. One theory (5), which assumes that the same traps participate in both noise generation and field effect, may be tested by observing both noise and field effect on a specimen as it is subjected to various treatments, including cleaning.

PHOTOCONDUCTIVITY. The trap structure at a clean germanium surface will also be investigated by photoconductivity measurements using techniques described elsewhere (6).

EXPERIMENTAL PROCEDURE. The germanium is mounted in the experimental tube (Fig. I-2) in thermal contact with two Kovar cups, 8, which may be filled with a constant-temperature bath. Four leads, 1-4, attached to the specimen permit measurements of its resistance. An electric field may be applied to the germanium surface by means of the tantalum electrode, 5, which is normally about 0.5 mm away from the germanium but can be swung out of the way when the germanium is to be bombarded. Bombardment is done by admitting argon gas to the tube and accelerating electrons from the hot filament, 7, to the electron collector, 6. The ions created by these electrons are then accelerated to the germanium. The germanium is heated in a vacuum for many hours prior to this bombardment and is annealed immediately afterward by heating to about 500°C for a few minutes. This heating is done by passing a current between the first and fourth electrode.

Because of the high temperatures involved, soldering is not possible; the connections to the germanium were originally made by clips or point contacts, but these proved to

be noisy and microphonic. Contacts consisting of tantalum ribbon spot-welded to the germanium (7) have since been adopted and thus far have proven to be quite satisfactory.

The vacuum system is capable of maintaining a pressure of 10^{-9} mm or better after adequate baking and outgassing. A source of considerable difficulty until now has been the system for handling the argon gas. Stopcocks have been abandoned because they evolve excessive amounts of gas even when liquid nitrogen traps are present. A bakeable metal valve purchased from the Granville-Phillips Company has recently been installed. It has not yet been used in a run, but preliminary tests are promising.

H. A. Gebbie, S. H. Autler, A. L. McWhorter

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2. R. M. Burger, Ph. D. Thesis, Brown University, 1955.
3. J. Bardeen and S. R. Morrison, Physica 20, 873 (1954).
4. R. H. Kingston and A. L. McWhorter, Phys. Rev. 98, 1191 (1955).
5. A. L. McWhorter, Technical Report 295, Research Laboratory of Electronics, M.I.T., May 20, 1955.
6. H. A. Gebbie, Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., July 15, 1955.
7. The technique for making these connections was communicated by E. N. Clarke of Sylvania Electric Products Company, Inc.

C. GASEOUS DISCHARGES

1. Probe Measurements, Distribution Functions, and the Einstein Relation

A convenient expression has been obtained for the random particle current density to a retarding plane probe for the spherically symmetric part of the distribution function. The effect of small oscillations on the dc value of the particle current density has been calculated. The Einstein relation between the density diffusion coefficient and the mobility coefficient has been extended to a tensor form which uses correct averaging over a general distribution function. An analysis has been made of the theory of the positive ion current to a negative probe which agrees in form with experimental data.

The random particle current density Γ_R to a retarding plane probe has been calculated for a spherically symmetric distribution function, and the result is given by:

$$\Gamma_R(V) = \frac{1}{4} \int_{v_o}^{\infty} v \left(1 - \frac{v_o^2}{v^2}\right) f(v)\, 4\pi\, v^2\, dv \qquad (1)$$

where $1/2\ m\ v_o^2 = qV$, v_o is the component of the velocity in the direction of the

retarding field, V is the retarding potential, and f(v) is the velocity distribution function. For distribution functions of the form $f(v) = A\, e^{-\alpha v^s}$, the random particle current density to a retarding plane probe is easily obtained from Eq. 1 in terms of incomplete gamma functions

$$\left[\Gamma(x; n) \equiv \int_0^x t^{n-1}\, e^{-t}\, dt\right]$$

$$\Gamma_R(V) = \frac{\pi A}{s} \frac{1}{\alpha^{4/s}} \left[\Gamma\left(\frac{4}{s}\right) - \alpha^{2/s}\, v_o^2 \Gamma\left(\frac{2}{s}\right) + \alpha^{2/s}\, v_o^2 \Gamma\left(\alpha v_o^s;\, \frac{2}{s}\right) - \Gamma\left(\alpha v_o^s;\, \frac{4}{s}\right)\right]$$

For the case of a M-B distribution and a Druyvesteyn distribution the incomplete gamma functions reduce to exponential functions and to error functions, respectively. Another immediate consequence of Eq. 1 is that for any spherically symmetric distribution function, the saturation random particle current density (no retarding potential) is given by $\Gamma_{random} = n\langle v\rangle/4$. It can also be shown that $d^2\Gamma_R/dV^2 = 2\pi q^2/M^2\, f(v_o)$, which is in agreement with Druyvesteyn.

Due to the usual nonlinear variation of Γ_R with V, an alternating voltage superimposed on V (either deliberately injected or as a result of plasma oscillations) will result in an increase in the dc value of Γ_R.

By using both a power series expansion and a Fourier series expansion, the following result has been obtained for the time average of the random particle current density $\overline{\Gamma_R(V, E_o)}$, for the case of a spherically symmetric distribution function, a plane probe, and a retarding potential with a monofrequency oscillation $E_o \sin \omega t$ superimposed.

$$\Gamma_R(V, E_o, \omega t) = \sum_{k=0}^{\infty} (a_k \cos k\omega t + b_k \sin k\omega t)$$

$$\Gamma_R(V, E_o)_{DC} = \overline{\Gamma_R(V, E_o, \omega t)} = a_o = \sum_{m=0}^{\infty} \frac{\left(E_o^2\right)^m}{(\pi)^{1/2}\,(2m)!} \frac{\Gamma(m + 1/2)}{\Gamma(m+1)} \frac{d^{2m}\,\Gamma(V)}{dV^{2m}}$$

where $\Gamma(m)$ is the complete gamma function $\Gamma(\infty; m)$ and should not be confused with the particle current density $\Gamma_R(V, E_o)$. The other components of the Fourier expansion can also be calculated by the same method. The amplitude of the oscillation (E_o) should be less than the magnitude of the retarding potential (V) in order to insure that the probe is not driven into the saturation current region, otherwise a discontinuity appears in

the probe current function and the Fourier expansion takes on a much more complicated form than the above equation.

Work is in progress on an extension of the Einstein relation between the diffusion coefficient D, the mobility coefficient μ, and the average energy $\overline{E}$: $D/\mu = 2/3\ \overline{E}/q$. A detailed calculation has been made of the density diffusion tensor $\mathbb{D}_d$ (as opposed to the temperature diffusion tensor) and of the mobility coefficient μ (valid only for low $-\nabla V/p$). The preliminary results are

$$\mathbb{D}_d = \frac{1}{M} \langle \tau \mathbb{E} \rangle$$

$$\mu = \frac{1}{2} \frac{q}{M} \langle \tau \rangle$$

$$\frac{\mathbb{D}_d}{\mu} = \frac{2}{q} \frac{\langle \tau \mathbb{E} \rangle}{\langle \tau \rangle}$$

where τ, the mean free time between collisions, may be a function of v, and $\mathbb{E}$ is the energy tensor (or dyadic) defined by $\mathbb{E} = \frac{M}{2} \vec{v}\vec{v}$. The average energy tensor $\langle \mathbb{E} \rangle$ is nothing but M/2 times the ratio of the second moment of the distribution factor to the zeroth moment of the distribution function. The m^{th} moment $\left[\vec{v}^{(m)}\right]_M$ of the distribution function is an m^{th} rank tensor defined by $\left[v^{(m)}\right]_M \equiv \int \vec{v}^{(m)}\, f(\vec{v})\, \vec{dv}$, where $\vec{v}^{(m)}$ is a tensor product, and the zeroth moment is the particle density n in configuration space. If the first moment of the distribution function is zero then the temperature tensor $\mathbb{T}$ is related to the average energy tensor by $\mathbb{T} = \frac{1}{k} \langle \mathbb{E} \rangle$, where k is Boltzmann's constant. For a spherically symmetric distribution function the tensor equation reduces to a scalar equation:

$$\frac{\mathbb{D}_d}{\mu} = \frac{2}{3q} \frac{\langle \tau E \rangle}{\langle \tau \rangle} \mathbb{I}$$

where $\mathbb{I}$ is the unit matrix. In obtaining the above result the following/dt expression was derived and used: $\langle v_x^{2p}\, g(v) \rangle = \langle v^{2p}\, g(v) \rangle / (2p + 1)$, which is valid for spherically symmetric distribution functions.

Thus in scalar form the detailed extension of the Einstein relation, for spherically symmetric distribution functions, is given by

$$\frac{D_d}{\mu} = \frac{2}{3} \frac{1}{q} \frac{\langle \tau E \rangle}{\langle \tau \rangle}$$

The theory of the positive ion current to a negative probe in a plasma has been

studied with some success. The experimental saturation ion current to a negative plane probe is much larger (by about a factor of 10) than the current calculated on a random particle current basis. The experimental ratio of saturation positive ion current to saturation electron current $(\Gamma_+/\Gamma_-)_{saturation}$ decreases by about a factor of 2 as the mercury vapor pressure increases by a factor of about 20. To my knowledge, previous theories have not been able to explain or predict such a variation.

A simple model plus certain reasonable assumptions permits the calculation of an expression for $(\Gamma_+/\Gamma_-)_{saturation}$ which changes in the right direction as far as variation with pressure and ion generation (electron energy) is concerned. The model requires (and conversely should give) information about the ion generation in the plasma and the positive ion flow mechanism in the plasma. A preliminary solution has been obtained for the case of usual ion mobility flow $\langle v_+ \rangle = \mu_+ E$ and also for the case of charge exchange limited positive ion flow (important for low energy Hg ions in Hg vapor) where $\langle v_+ \rangle = s_+(E/p)^{1/2}$. It should be possible to obtain information about the ion generation and the charge exchange limited mobility using data obtained from positive and negative probes.

S. Aisenberg

D. EXPERIMENTAL TECHNIQUES

1. Growing Large Single Crystals in Tantalum Ribbon

Over the past year a fairly standard formula for growing crystals in tantalum ribbon has evolved. Still, though, the original stock from which the ribbon is cut must be predisposed to grow crystals. Different batches should be tried if failure results. The most successful tantalum found to date is 0.003-inch stock purchased from Fansteel during the last war and listed as unannealed. With the method to be described, ribbons have been repeatedly grown with a single crystal the entire one-half-centimeter width of the ribbon for more than an inch. The ribbon is cut along the direction of the roll marks. It is then rolled on precision rolls in the same direction until it has increased its length 4 per cent. The ribbon is then weighted with a piece of tungsten rod and mounted in a tube (W. J. Lange, Quarterly Progress Report, Oct. 15, 1954, p. 1) on a mercury system that allows current to be passed through the ribbon from a heavy rod brought in the top of the tube to a pool of mercury whose level is slowly lowered. It is lowered at a constant rate of about 1 cm/hour by pumping through a small leak the air pressure which holds the mercury up. The current is maintained at a value which heats the ribbon to a temperature of about 2000°C as read on an optical pyrometer. When removed from the vacuum and cleaned (cleaning and etching can be accomplished with a small part of HF in concentrated HNO_3 and HCl) the crystal boundaries can readily be seen with proper side lighting with the eye or with a microscope. X-rays show that these crystals

usually have their 211 direction normal to the ribbon with their 110 direction along the ribbon.

W. J. Lange, H. Shelton

2. Use of Single Crystals in Directly Heated Tantalum Ribbon to Determine Work-Functions

Single crystals and especially small ones are easily grown in tantalum ribbons, often merely by heating the ribbon to about 2400°K in high vacuum. The emission from a small area of a single crystal may be selected and directed to the unknown surface by placing a partition with a small hole (about 0.015-inch diameter) opposite the center of a crystal and immersing in a strong (about 3000 gauss) magnetic field. A small positive voltage applied to the partition accelerates the electrons through the hole, reduces space charge effects, and allows the current to the unknown surface to be measured as a function of the retarding potential with respect to the emitting spot.

Voltages are applied to the spot through a potential lead welded to the ribbon or to an appropriate point on an external voltage divider. This point may be easily found when the ribbon is heated on ac, as the retarded current will be a minimum when the point is correct. If the unknown is a single crystal, such as one in another tantalum ribbon, an ideal retarding potential curve is obtained with a knee whose sharpness is determined by the voltage drop across the emitting spot.

If the temperature is obtained from the slope of the plot and the saturation current density is obtained from the saturated current and area of the hole, the true work-function (not the work-function derived from a Richardson's plot) of the emitting crystal can be computed, neglecting any reflection, from the relation

$$i_s = AT^2 e^{-\frac{\phi\, 11610}{T}}$$

where $A = 120$ amp/cm^2/°K^2. The unknown work-function is then known from the contact potential found from the retarding potential plot.

H. Shelton

3. Evaporated Molybdenum As a Getter

The getter used to reduce the partial pressures below 10^{-11} mm Hg for studying clean surfaces has been tantalum evaporated on the walls from a hot filament. Tantalum has proved very effective, but its use requires a certain amount of care. It has to be thoroughly outgassed and will continue to give off gas from some portion of the filament for a very long period of time even at the very high temperatures. Also, since the outgassing and evaporation temperatures are near the melting temperature, care must be

taken not to melt the filament. Easier to use is molybdenum which quickly and easily outgasses completely. A gettered area of about 10 cm^2 has been sealed off with the MassITron for three months and has maintained the partial pressures of all gases other than helium and argon below 10^{-10} mm Hg. The filament is preferably mounted hanging vertically. For a 0.010-inch filament, outgassing is complete in a few minutes with 4.5 amp and evaporates readily with a current of 5 to 5.5 amp. For other diameters use a current altered by the factor $(d/0.010 \text{ inch})^{3/2}$.

H. Shelton

4. Clean-Up of Helium in Ionization Gauges

The clean-up of helium in the Bayard-Alpert ionization gauge has been studied in a series of experiments. The results of these experiments will be published at a later date. Conclusions, from these results, are the following. Single ions of helium are responsible for the observed clean-up. Clean-up depends on the energy of the electrons and the potential at which an ion is formed. Helium atoms are cleaned up only temporarily. A nearly opaque coating of tungsten on the glass does not change appreciably the clean-up rate from that of a newly processed tube.

D. H. Dickey

5. Harmonic Analysis Applied to Thermionic Emission Studies

A new technique has been developed for the analysis of thermionic emission data. The theories of space charge and electron energy distribution indicate that knowledge of the second derivative of the current-voltage characteristic as a function of these quantities would aid in the analysis. An oscillator generates a 1000-cycle wave and a filter eliminates the 2000-cycle component. A small amplitude of this voltage is added to the dc voltage and the second-harmonic component in the current is measured quantitatively by a General Radio Company wave analyzer. This second harmonic is a direct measure of the second derivative needed. A tuned amplifier that suppresses the fundamental 1000-cycle wave and would reduce it 80 to 100 db in comparison with the 2000-cycle output would serve very well instead of the wave analyzer now in use. This arrangement could be made to yield phase information as well as amplitude data. This harmonic generation method is proving to be very useful in the study of the oxide cathode and is to be tried out in connection with probe studies in gas discharges. There must be many other applications in which it could serve. More details will be given in the next quarterly report.

W. B. Nottingham