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Electron Emission from Silicon *p-n* Junctions

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Electron emission from uncoated, reverse biased, silicon *p-n* junctions has been investigated. A junction with a 1-cm diameter and a reverse bias of 0.1 amp gives rise to an emission current, around its perimeter, of the order of 10^{-13} amp. The emission commences at fields which are considerably lower than those required for breakdown and is dependent on the junction bias conditions as well as the lattice temperature. The degree of dependence on the lattice temperature is a function of the bias conditions. A simple mechanism is proposed to explain these phenomena.

INTRODUCTION

WHEN electrons in a semiconductor are in the presence of a high electric field their average kinetic energy is greater than the vibrational energy of the surrounding lattice and the electrons are said to be at a higher temperature[1] than the lattice. If the electron energy exceeds the work function of the surface, emission will be observed even though the lattice itself may be at room temperature. An effect of this nature has recently been observed by Burton[2] who used a reverse-biased silicon *p-n* junction to obtain a high electric field and a cesium layer to lower the work function at the surface. Working with junctions which had a perimeter of several hundred mils, Burton was able to measure emission currents of the order of 5×10^{-5} amp. A similar experiment was performed by Tauc[3] on uncoated silicon *p-n* junctions which showed that this type of junction also gives rise to an electron emission. In the latter experiment the junction is placed several mm from the point of a Geiger counter and the entire apparatus operated in air at normal atmospheric pressure.

In the experiment to be described Tauc's measurements are repeated with the following modifications and extensions: (1) the junction is heated in a vacuum of 10^{-6} mm Hg in order to partially clean the surface. (2) An electron multiplier[4] is used in vacuum to measure the emitted current. (3) Quantitative measurements are taken both with pulsed and dc techniques. (4) The temperature of the junction is varied in order to note its effect on the emission current.

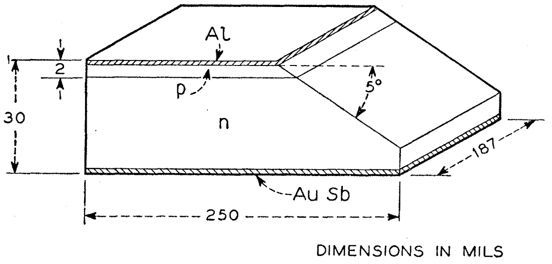

FIG. 1. Schematic of the junction used for emission studies.

It is the primary purpose of this experiment to indicate the junction operating conditions which effect the emission current and to present quantitative data relating the emission and these operating conditions. In addition, various mechanisms are considered as a source of the emission and are discussed in the light of the experimental results.

EXPERIMENTAL

The diode used in the electron emission experiments is shown in Fig. 1. It was fabricated by cutting wafers from a 0.03 ohm-cm *n*-type single crystal, and a *p-n* junction was formed by boron diffusion.[5] Part of the surface was lapped, forming an angle of 5 degrees with the remainder of the surface as shown in Fig. 1. It should be mentioned at this point that lapping was not found to be a necessary condition for a surface to emit electrons. Electron emission can be obtained with etched junctions as well. Furthermore, etching a

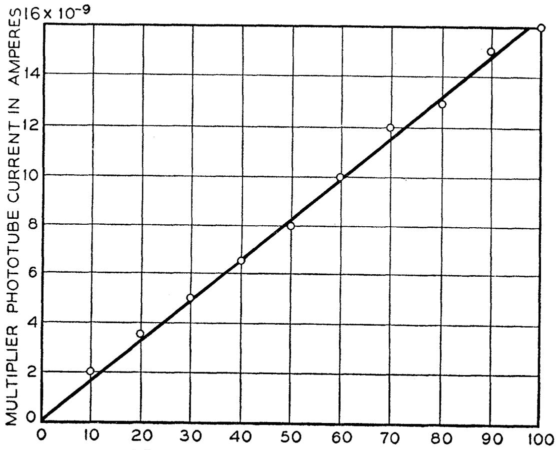

FIG. 2. Light *vs* bias characteristic of junction shown in Fig. 1.

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[1] W. Shockley, Bell System Tech. J. **30**, 990 (1951).

[2] J. A. Burton, Phys. Rev. **108**, 1342 (1957).

[3] J. Tauc, Nature **181**, 38 (1958).

[4] J. S. Allen, Rev. Sci. Instr. **18**, 730 (1947).

[5] The diffusion was kindly performed by C. J. Frosch of this laboratory.

lapped junction does not cause a decided decrease in the emission current. This implies that the emission may be coming from any part of the junction edge and not necessarily from the part which is lapped. The reason for lapping was to make it more convenient to observe the recombination radiation[6,7] coming from the junction edge when the junction is operated in the breakdown region. The recombination radiation appears to come from the lapped edge in the form of a thin filament of uniformly distributed light located at the junction. Superimposed on this filament is a series of bright spots which probably correspond to localized breakdown regions. A 931A photomultiplier with an S-4 response was used to measure the emitted radiation from the diode in Fig. 1 and a quantitative relation was obtained (Fig. 2) between the emitted light and the breakdown current. It is noted that for the range considered a linear relationship exists.

The forward bias characteristic of the junction in Fig. 3 shows the expected exponential behavior and indicates that the ohmic contact resistance is less than 0.01 ohm. This eliminates the possibility that thermionic emission is coming from poor ohmic contacts made to the semiconductor. The reverse characteristic is shown in Fig. 4 where a fairly well defined breakdown region is found. The breakdown is probably characteristic of the doping of the material and not the condition of the surface since much smaller area junctions made from the same material had identical breakdown voltages.

The emission from uncoated silicon *p-n* junction is too weak to measure with a single collector plate and an electrometer. In order to increase the sensitivity of the measurements an electron multiplier was used. This consisted of 16 beryllium copper dynodes mounted on mica spacers. The current in the collector dynode is measured by two methods depending on the magnitude of the emission current. At very low signal levels a pulse counter is used to count the individual pulses which are an indication of the number of particles striking the first dynode. At higher levels of input signal, the current at the output of the multiplier is measured with an electrometer. This requires a knowledge of the gain of the multiplier which was found to be of the order of 10^5.

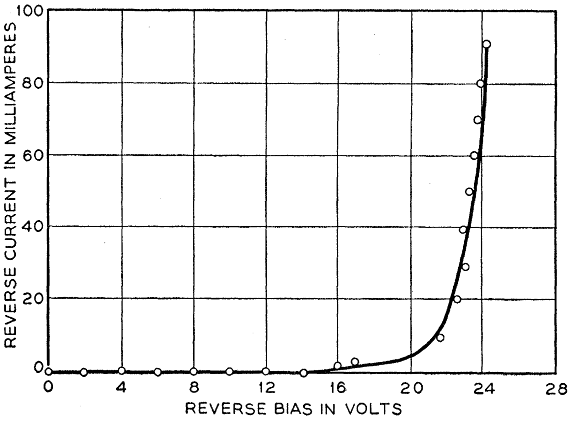

FIG. 4. Reverse bias characteristic of junction shown in Fig. 1.

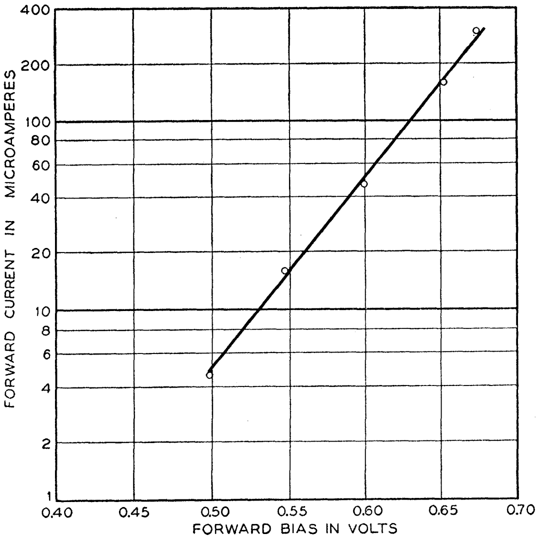

FIG. 3. Forward bias characteristic of junction shown in Fig. 1.

Using the electrometer to measure the multiplier output and plotting this against the breakdown current through the junction, the characteristic shown in Fig. 5 is obtained. When the diode is placed into the vacuum system and the system is pumped down, the initial emission is shown in curve *I*. This emission is unstable and not reproducible. After intermittent

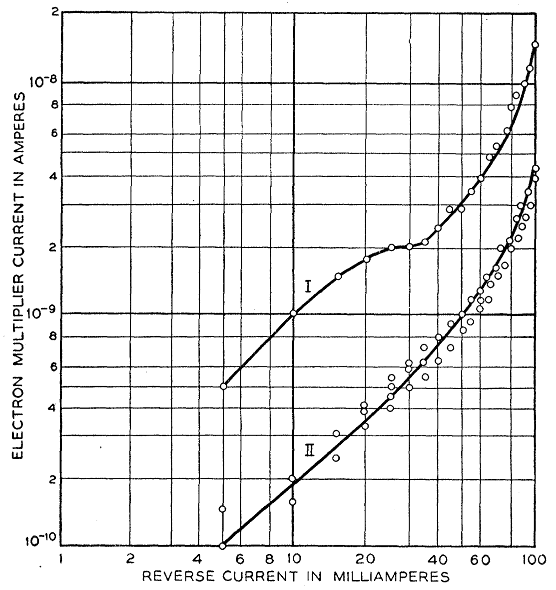

FIG. 5. Electron emission characteristic of junction shown in Fig. 1 taken with an electron multiplier gain of the order of 10^5.

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[6] R. Newman, Phys. Rev. **100**, 700 (1955).

[7] A. G. Chynoweth and K. G. McKay, Phys. Rev. **102**, 369 (1956).

heating of the junction to temperatures of the order of several hundred °C above room temperature for several hours in a vacuum of 10^{-6} mm Hg, the emission decreases to curve II. The latter characteristic is fairly stable and is reproducible over long time periods. It is interesting to note that on the scale used in Fig. 4 there is no noticeable change in reverse bias characteristic even though the baking in vacuum is sufficient to change the electron emission by an order of magnitude. This would tend to imply that, although the conditions on the surface must be changing considerably, the net current through the junction is constant and seems to be solely dependent on the breakdown in the interior of the junction.

The fact that the emission is unstable when it is first placed in vacuum is not surprising since one would expect the emission to be very sensitive to the surface work function which in turn is strongly dependent on the surface conditions. A clean surface is not achieved in this experiment, nevertheless some stability of the surface conditions appears to have been reached after baking, as is evidenced by the electron emission results.

The values obtained for the sample tested above are of the same order of magnitude as the values obtained for several other junctions of comparable properties. Consequently, some estimate of the electron emission densities which can be expected from these types of junctions is of interest. At 100 ma, the measured emission current is of the order of 10^{-13} amp. The computation of the surface area which emits is extremely rough since the emission probably does not take place over the entire junction area but originates at the localized surface breakdown sites. At present there is no way of estimating the extent of these sites. If we consider the emission as originating over the entire junction and use a centimeter as a measure of the junction length and a micron as a measure of the junction width we obtain an emission density of 10^{-9} amp/cm^2 which is probably too low by several orders of magnitude.

One of the factors which severely limits the total emission is the unfavorable geometry used. From one point of view the geometry to be described[8] is more favorable. A very shallow *n* layer is diffused into *p* material so that a *p-n* junction is formed whose entire area is close to the surface. The aim in using this geometry is to enable electrons to escape from the entire area of the junction. By a sensitive weighing and etching technique, the *n* layer was estimated to be 1400 A. There was no measurable emission current down to several electrons per second which is the sensitivity limit of the detection system.[9]

Considering the geometry of Fig. 1 again, let us consider some possible mechanisms to explain the results obtained in Fig. 5. First let us consider the possibility that the emission is thermionic and is due only to lattice heating due to the electrical power dissipated in the junction when it is operated in the breakdown condition. If this is the case, then at first glance one might expect that operating the junction in the forward direction with the same power dissipation as in the reverse direction would yield the same emission current. This experiment was performed and absolutely no emission was found in the forward direction. Had emission been found there would have been strong evidence that lattice thermionic emission is the sole mechanisms, but the negative results do not, by themselves, entirely exclude this possibility. The reason for this is that the distribution of power dissipation along the junction plane is different for the forward and reverse bias conditions. In the reverse bias condition the localized breakdown regions can achieve appreciably higher temperatures than their surroundings.[10] Nevertheless a calculation using Richardson's equation and a 4-ev work function indicates that the expected emission is very many orders of magnitude less than that observed. Therefore unless the work function used is greatly in error, lattice thermionic emission cannot be the sole cause of the measured current. This does not imply that lattice heating, in conjunction with the energy available to the electrons from the electric field has no effect on the emission. This question will be discussed later.

Another possible signal source which must be considered in this type of measurement is the recombination radiation coming from the junction edge. The spectral analysis of this radiation by Chynoweth[7] indicates that there are some photons energetic enough to eject electrons from the beryllium copper surface used in the multiplier. This possibility can be ruled out by comparing the photomultiplier and electron multiplier outputs which are roughly the same. Since the sensitivity of the photomultiplier to light is many orders of magnitude greater than that of the electron multiplier, this implies that the light has a negligible effect on the electron multiplier output.

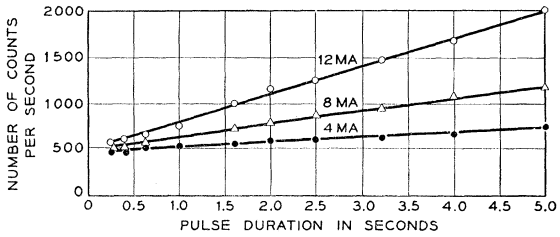

FIG. 6. Pulsed emission characteristic.

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[8] These units were fabricated by R. L. Batdorf and P. W. Foy. The junction depth was measured by R. L. Batdorf and K. H. Mills.

[9] This structure was designed so that breakdown did not occur at the junction perimeter; consequently the type of emission observed in the other units was not seen here.

[10] B. Senitzky and P. D. Radin, J. Appl. Phys. (to be published).

The possibility that the emission is solely a function of the breakdown current is next investigated by means of the following technique. A mercury relay is placed in series with the bias supply and switched on and off by a rectangular pulse of known duration and repetition rate. The resistance in series with the diode is sufficiently high to make the bias supply a constant current source. Whereas the current pulse through the diode is rectangular, the voltage pulse across the diode is not,[10] since the junction heats up and the voltage increases during the intervals that the current is on. The pulse duration is varied from a quarter of a second to 5 sec with a repetition rate of 0.1 cps. A diode with roughly the same doping levels and breakdown voltage as the one shown in Fig. 1 is used. The output of the electrometer is measured with a pulse counter. If the emission is dependent solely on the current flowing through the junction, one would expect to get results which are independent of the duty cycle of the switching pulses. It is immediately apparent from the data shown in Fig. 5 that this is not the case. As a matter of fact, changing the duty cycle, at constant bias current, can change the emission by a factor of three. In all cases the variation is in the direction of an increase in emission with increasing voltage and temperature. For the higher bias currents, a given change in duty cycle gives rise to a greater change in voltage or temperature, therefore the high bias currents in Fig. 6 have a characteristic with greater slope than the low bias currents. These results would seem to indicate that, for this junction at least, the breakdown current is not the predominant factor in determining the emission. The important variable seems to be the temperature or the voltage associated with the breakdown current. If one changes the current in such a manner that the junction has no opportunity to heat up, there appears to be only a small effect on the emission. These results were repeated for other junctions and the following conditions were noted: although some junctions showed a stronger dependence on the dc current at short duty cycles, in all cases there was a decided increase in the emission current with the duty cycle.

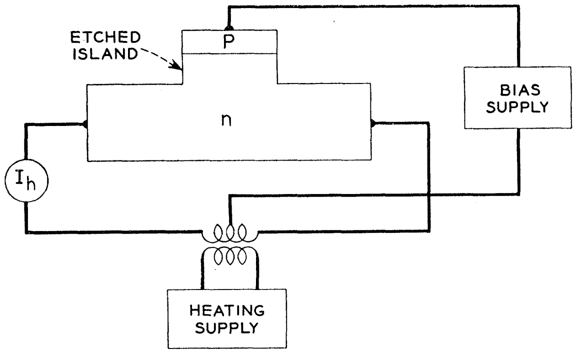

FIG. 7. Schematic of arrangement for lattice temperature variation.

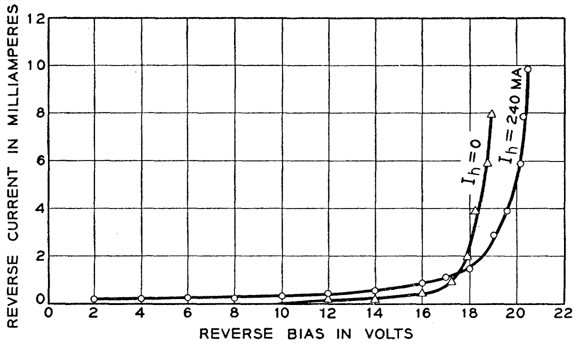

FIG. 8. Reverse bias characteristic for two different lattice temperatures. The $I_h = 240$-ma curve corresponds to a lattice temperature 150°C above room temperature and the $I_h = 0$ curve corresponds to room temperature.

In an attempt to further establish the effect of temperature on the emission a somewhat different geometry[11] was tried in which the temperature of the junction could be independently varied. A schematic representation of the arrangement is shown in Fig. 7. The junction is contained in an island which is etched out from the body of *n* material. The current I_h is an ac current which is used to heat the entire unit. The temperature of the junction itself may be determined by noting the shift in the breakdown voltage corresponding to different values of I_h. The *V*-*I* characteristics for two different settings of the current I_h are shown in Fig. 8. From these an estimate of the temperature differential[12] of 150°C can be made. It should be noted that the temperature referred to is the ambient temperature. In the breakdown region, where there is a considerable degree of self heating[10] due to the current flowing through the junction, the junction temperature is higher than the ambient temperature. Consequently the 150°C temperature differential is only valid for points with the same current.[13] If one considers points with the same voltage, the temperature differential is no longer as great as 150°C but the $I_h = 240$-ma curve is still at a higher junction temperature than the $I_h = 0$-ma curve.[14] The emission for the two ambient temperatures is plotted as a function of voltage in Fig. 9. It is seen that in the prebreakdown region the emission is somewhat higher for the unheated sample than it is for the heated sample, whereas the reverse is true for the breakdown region. The onset of emission occurs at a voltage considerably lower than the breakdown voltage. In some cases it was found that a junction

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[11] The author would like to thank F. G. Allen for this suggestion.

[12] G. L. Pearson and B. Sawyer, Proc. Inst. Radio Engrs. **40**, 1348 (1952).

[13] Since the voltage change between the two curves in the breakdown region is small compared to the breakdown voltage, constant current implies constant power dissipation.

[14] The temperature differential at constant voltage may be estimated from the following two considerations: (1) the temperature differential at the intersection of the two curves is known, and (2) the temperature rise along the separate curves due to self-heating may be computed from the results of reference 10.

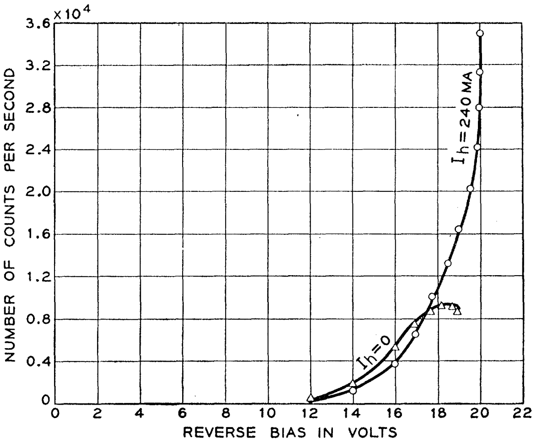

FIG. 9. The electron emission characteristic corresponding to bias conditions shown in Fig. 8.

which exhibits a reasonably sharp breakdown at 20 volts gives rise to emission at 8 volts. This is in accord with the fact that whatever the lower limit is, it must be above the 4-volt work function of the material. The emission at constant current and varying junction temperature can be estimated with the aid of Fig. 8. It is found that in the breakdown region the emission at constant current increases with the junction temperature. This is consistent with the pulsed data shown in Fig. 6.

DISCUSSION

The above experiments indicate that the electron emission from *p-n* junctions is dependent on the electric field, the lattice temperature and the total current flowing through the junction. Although the exact dependence is a function of the particular junction used and the surface conditions of that junction, there is an agreement between different junctions on the general shape of the emission characteristics and also on the order of magnitude of the emission currents. It will be shown by the following rough analysis that the emission currents can be related to the variables mentioned above, namely, the field, temperature and junction current and that the experimental results agree to within an order of magnitude with the predictions of this type of analysis.

An estimate of the probability that an electron gains enough energy from the electric field to escape will be made. We will make the approximate simplifying assumption that the significant contribution to this probability comes from electrons that have travelled the minimum distance required to reach this energy without colliding. Let $1/\tau$ be the probability per unit time that the electron will be scattered. This term is dependent on the various scattering mechanisms that are operative. At low energies the dominant scattering is by acoustical phonons, and at higher energies optical phonon scattering becomes more important.[1] At still higher energies the electrons gain sufficient energy from the field to create electron hole pairs as a result of a collision.[15] At these energies this is the dominant scattering mechanism. If τ is proportional to $\epsilon^{-\frac{1}{2}}$, as it is in many cases where the electron loses only a small fraction of its incident energy as a result of the collision, we can express the probability that an electron will attain the energy ϵ as

$$P(\epsilon)=\exp(-\epsilon/qE\lambda), \tag{1}$$

where λ has the properties of a mean free path independent of the energy. The total probability per unit time of a collision can be taken as the sum of the probabilities for the separate scattering mechanisms so that

$$1/\tau=\textstyle\sum_j(1/\tau_j). \tag{2}$$

If the condition mentioned above is valid, namely, that τ_j is proportional to $\epsilon^{-\frac{1}{2}}$, one can write the probability that an electron attain an energy, ϵ, as

$$P(\epsilon)=\exp\left[-\frac{\epsilon}{qE}\left(\sum_j\frac{1}{\lambda_j}\right)\right]=\exp\left[-\frac{\epsilon}{qE}\left(\frac{1}{\lambda}+\frac{1}{\lambda_i}\right)\right], \tag{3}$$

where the mean free path λ corresponds to acoustical and optical phonon scattering and λ_i is the mean free path for ionization collisions. Because of the magnitude of the electric field, which is approximately 3×10^5 volts/cm, most of the electrons will be energetic enough before their first collision to satisfy the condition that they can only deliver a small fraction of their kinetic energy in a phonon collision. Consequently λ can be taken as a constant, independent of the energy. This is not the case with λ_i where the electron loses a large fraction of its initial energy during a collision. The cross section for this process is zero until a threshold energy of 2.3 electron volts[15,16] is attained. At this point $1/\lambda_i$ rapidly becomes the dominant term in (3). The exponential term giving the probability for an electron to escape can then be written in terms of two factors: one relating to the probability of an electron reaching an energy of $\epsilon_0=2.3$ ev where there is a high probability of an ionizing collision, and another factor which determines the probability that the electron can gain enough additional energy to reach the work function energy Φ. This probability is expressed as

$$P(\Phi)=\exp\{-[(\epsilon_0/qE\lambda)+(\Phi-\epsilon_0)/qE\lambda_i]\}. \tag{4}$$

An approximate estimate, based on a simple Rutherford scattering mechanism, indicates that for the energy range of interest it is not unreasonable to regard λ_i as a constant. The value of λ the mean free path for phonon collisions, can be found by fitting part of the above expression to the data for the ionization con-

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[15] P. A. Wolff, Phys. Rev. **95**, 1415 (1954).

[16] A. G. Chynoweth and K. G. McKay, Phys. Rev. **108**, 29 (1957).

stant.[17,18] If we consider the probability that an electron will gain sufficient energy for pair production and divide this by the distance the electron travels to reach this energy, we obtain the probability of ionization per unit distance

$$\alpha=(qE/\epsilon_0)\exp[-\epsilon_0/qE\lambda]. \tag{5}$$

This agrees with the data when $\lambda=200$ A. Expression (4) gives the probability of an electron escaping when it travels a distance Φ/qE. The probability of escaping per unit distance is therefore $(qE/\Phi)P(\Phi)$. To get the probability of escaping over the entire path, a spatial integration is required, but the problem can be approximated by assuming a uniform field over a path length x_0. The probability of escaping over the entire path length then becomes $(qE/\Phi)P(\Phi)x_0$. This should be multiplied by a geometric factor which takes account of the fact that for a circular junction of radius R only those electrons within a distance λ_i of the perimeter will have a good probability of escaping. This will give rise to a factor λ_i/R. Electrons of energy Φ which do not collide will not leave the material since their motion is tangential to the surface. Of those electrons which have energy Φ and do collide, only the ones that have phonon collisions retain enough energy to escape. The probability for this to occur introduces an additional factor of the order of magnitude of λ_i/λ. The total escape probability for an electron in the junction is consequently given by

$$x_0\left(\frac{\lambda_i^2}{R\lambda}\right)\left(\frac{qE}{\Phi}\right)\exp\left[-\left(\frac{\epsilon_0}{qE\lambda}+\frac{\Phi-\epsilon_0}{qE\lambda_i}\right)\right]. \tag{6}$$

Using the value of α derived above, this can be rewritten as

$$(\alpha x_0)\left(\frac{\epsilon_0}{\Phi}\right)\left(\frac{\lambda_i^2}{R\lambda}\right)\exp\left[-\left(\frac{\Phi-\epsilon_0}{qE\lambda_i}\right)\right]. \tag{7}$$

The emission current, I_e, can then be expressed in terms of the junction current, I, by the equation

$$I_e=I(\alpha x_0)\left(\frac{\epsilon_0}{\Phi}\right)\left(\frac{\lambda_i^2}{R\lambda}\right)\exp\left[-\left(\frac{\Phi-\epsilon_0}{qE\lambda_i}\right)\right]. \tag{8}$$

The above expression can be compared with the experimentally obtained emission current when the junction is biased in the breakdown region where $\alpha x_0=1$, and the value λ_i determined. In order to fit the experimental data a value of λ_i in the neighborhood of 35 A must be chosen. Using this value of λ_i it is clear why the junction which was located 1400 A below the surface did not yield a detectable emission current.

It is difficult to investigate the lattice temperature dependence of (8) because λ_i as a function of temperature is unknown. Nevertheless if we assume that λ_i is not a sensitive function of temperature and concentrate on the effect of α/λ on the emission current, we obtain an expression for dI_e/dT which is proportional to

$$\frac{\alpha}{\lambda^2}\left(\frac{\epsilon_0}{qE\lambda}-1\right)\frac{d\lambda}{dT}. \tag{9}$$

The above expression will be negative for small E, positive for large E and zero for fields of approximately 10^6 volts/cm. Qualitatively this agrees with the observed data, but quantitatively the agreement is only to within an order of magnitude since the field at which the emission is temperature independent is about 3×10^5 volts/cm.

ACKNOWLEDGMENTS

It is a pleasure to thank G. C. Dacey for the helpful discussions relating to the interpretation of the experimental results and W. Wiegmann and P. D. Radin for their able technical assistance in obtaining these results.

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[17] K. G. McKay, Phys. Rev. **94**, 877 (1954).

[18] A. G. Chynoweth, Phys. Rev. **109**, 1537 (1958).