ELECTRON TUNNELING BETWEEN MICROPARTICLES IN THIN DISCONTINUOUS GOLD FILMS

by

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THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

INTRODUCTION

A very thin film of gold deposited on a glass substrate can be seen by an electron microscope to consist of a planar array of small discrete islands constituting a discontinuous film. These islands or microparticles of gold can range anywhere between a few angstroms to as much as 100 Å in diameter and can be separated by a similar distance. The size of the microparticles depends on such factors as the amount of gold deposited on the substrate, the physical structure of the substrate's surface, and the temperature of the substrate during deposition.

If the average thickness of the gold film is allowed to become greater than about 100 Å it will become continuous; i.e., the microparticles of gold will join together to form continuous filaments of gold across the substrate. The electrical conduction mechanism of these thicker films is the same as for the bulk metal. Discontinuous gold films, on the other hand, have electrical properties quite unlike their thicker counterparts because conduction must now take place between isolated microparticles that are separated by a potential barrier. The resistance of a discontinuous film is many orders of magnitude greater than for a thin continuous film. Also, these films exhibit a negative temperature coefficient of resistance at room temperature which suggests a conduction mechanism that depends on the activation energy of the electrons.

The purpose of the research reported in this thesis is to study the conduction of discontinuous gold films as a function of applied voltage, temperature and density of trapping sites in the substrate.

THEORY

Two electron transfer mechanisms exist which could explain the conduction in a gold discontinuous film. One of these is thermionic emission or Schottky emission between the microparticles of gold. Normally thermionic emission fails to explain conduction at room temperature or below because the emission current depends exponentially on the height of the barrier separating the two electrodes. But if the electrodes are microparticles of gold separated by a sufficiently small distance as they are on a discontinuous film the overlap of the image potential between the microparticles will reduce the height of the barrier to an extent that a reasonable current flow is possible. However, Nifontoff (1) has shown that temperatures above 300°K are required before thermionic emission dominates the conduction provided the gaps are not larger than about 100Å. Actually the experimentally observed conductivity of thin discontinuous films at room temperature is many orders of magnitude greater than would be possible if only thermionic emission were to explain the conduction process.

Another possible electron transfer mechanism is tunneling, but, unlike thermionic emission, tunneling by itself cannot explain the negative temperature coefficient of resistance observed in discontinuous thin films because the tunneling current across a potential barrier is relatively independent of temperature.

Neugebauer and Webb (2) attempt to overcome this difficulty by suggesting a mechanism for the creation of charges in the form of electrons or holes which is dependent on the activation energy supplied thermally. For any temperature above absolute zero there exist a certain number of previous neutral microparticles which have acquired a charge having lost or

gained an electron. This number is of the order of $n \sim N e^{-\epsilon/kT}$ where N is the total number of microparticles composing the film and ϵ is the activation energy which is defined as the energy required to change a previous neutral microparticle. This energy is of the order of e^2/r where r is the average linear dimension of the microparticle and e is the electrostatic charge of an electron. Only electrons and holes with at least this energy will be able to tunnel from one microparticle to another without the benefit of an electric field.

The probability of tunneling of an electron from a microparticle with a negative charge to a neighboring, neutral microparticle is

$$P \propto \int_{-\infty}^{\infty} D f_i (1-f_j)\, dE \qquad (1)$$

where D is the transmission coefficient of an electron tunneling through an arbitrarily shaped barrier and f is the Fermi function. The factor $f_i(1-f_j)$ is the distribution of full states in the negatively charged particle times the distribution of empty states in the neutral particle and is used instead of the more familiar (f_i-f_j) because only the tunneling of charges is being considered here and not the tunneling of electrons. The effects of the electrostatic forces between charges are neglected in formulating the above equation.

With no electric field across the film Equation (1) predicts random motion of the charge carriers resulting in no net current flow. However, if a field is applied, the Fermi levels in adjacent particles will shift slightly relative to each other increasing the tunneling probability in the direction of the field and decreasing it in the opposite direction. Thus, the net tunneling probability of charge carriers between particles will be

in the direction of the applied field and will be equal to the difference of the two individual probabilities. This difference can be written as

$$P_{net} = P_{+} - P_{-} \tag{2}$$

where P_{+} is the tunneling probability in the direction of the field and P_{-} is the tunneling probability in the direction opposite the field.

For the purposes of illustration, suppose that there are three microparticles of radius r in the film lined up in the direction of the electric field as shown in Fig. 1. Assume that the two outer microparticles are neutral and the middle microparticle is negatively charged (possesses excess electron). Let R be the distance separating the three particles and V be the applied potential drop between two adjacent particles.

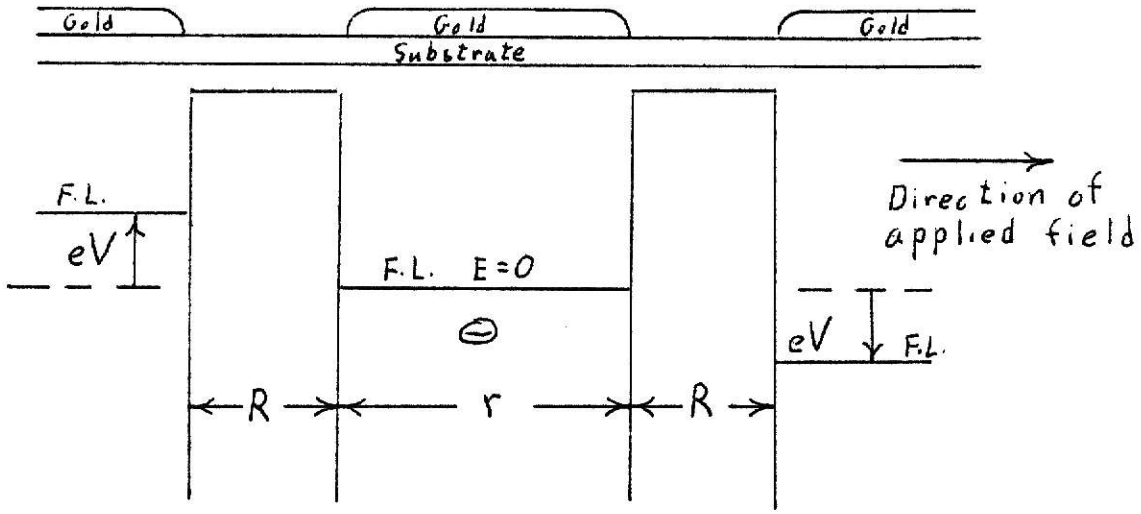


Fig. 1 Relative position of the Fermi level in the three microparticles

The tunneling probability of the charge carrier in the middle microparticle to its neutral neighbor in the direction of the field is

$$P_+ \propto \int_{-\infty}^{\infty} \frac{D}{1+e^{E/kT}} \left[1 - \frac{1}{1+e^{(E+eV)/kT}} \right] dE \qquad (3)$$

and the tunneling probability in the direction opposite of the field is

$$P_- \propto \int_{-\infty}^{\infty} \frac{D}{1+e^{E/kT}} \left[1 - \frac{1}{1+e^{(E-eV)/kT}} \right] dE \qquad (4)$$

In order to maintain an equilibrium concentration of charge carriers and to take D (the transmission coefficient) outside the integral sign one restricts this treatment to low applied fields in which $kT \gg eV$ which is quite sufficient in this case.

After integrating Eq. (3) and (4) and substituting them in Eq. (2) one gets

$$P_{net} \propto D\left(\frac{eV}{1-e^{-eV/kT}} + \frac{eV}{1-e^{eV/kT}} \right) \qquad (5)$$

which reduces to

$$P_{net} \propto DeV \ \text{transitions} \ cm^{-2} \ sec^{-1} \qquad (6)$$

Since the cross-sectional area of an island is $\sim r^2$, the number of transitions per second between two islands is

$$P_r \propto Dr^2 eV \qquad (7)$$

The velocity of a charge carrier can be written as

$$\frac{R}{\tau} = R P_r \text{ cm sec}^{-1} \tag{8}$$

where $\tau = \frac{1}{P_r}$ is the time required for a transition. Using the expression for the mobility of the charge carriers in an applied field V/R,

$$\mu = \frac{R^2 P_r}{V} \tag{9}$$

or

$$\mu \propto D e r^2 R^2 \text{ cm}^2 \text{ sec}^{-1}$$

one can write the conductivity

$$\sigma = n e \mu$$

as

$$\sigma \propto n D e^2 r^2 R^2 \Omega^{-1} \text{cm}^{-1} \tag{10}$$

where

$$n = \frac{1}{r^3} \exp\left(\frac{-e^2/r}{kT}\right) \tag{11}$$

the charge carrier concentration.

This model predicts that the conductivity of discontinuous films is independent of the applied field and varies exponentially on inverse temperature. The data displayed by Neugebauer and Webb in their paper for the conductivity of gold films as a function of both temperature and applied field agrees favorably with their model. However, the conduction data shown for nickel films shows a deviation from Ohm's law at lower temperatures.

Also, the conductivity of the chromium films examined by Milgram and Lu (3) seems to depend on the applied voltage. Another problem is that Neugebauer and Webb fail to explain the necessity of having the charged microparticle play a role in the conduction process nor why electron tunneling between the neutral particles cannot be the predominant mechanism since this type of tunneling would require no thermal activation. One can guess that they needed to invent the charged microparticle phenomenon to explain the temperature dependence in their data. A more plausible explanation for the temperature dependence could be that the "spreading out" of the Fermi distribution around the Fermi energy with increasing temperature would increase the chances of an electron finding an empty energy level in a neighboring microparticle to tunnel to.

Herman and Rhodin (4) take another approach by suggesting that tunneling is more probable through the substrate surface between the microparticles rather than across the vacuum gap separating them.

They assume that the surface of the glass substrate is covered by empty electron traps. The density of these traps must be high enough so that when the film is evaporated every microparticle formed on the substrate will cover at least one trap. When this occurs there will be a flow of electrons from the microparticles into the empty traps beneath them until an equilibrium is reached, forming a junction or interface between the glass and metal similar to a p-n junction in a transistor. The number of traps filled will depend on the position of the Fermi level relative to the distribution of traps in the energy gap of the substrate. Only those traps under the microparticles have any possibility of being filled. In Figure 2 is shown a simplified energy band diagram of the surface of the substrate

beneath a discontinuous film.

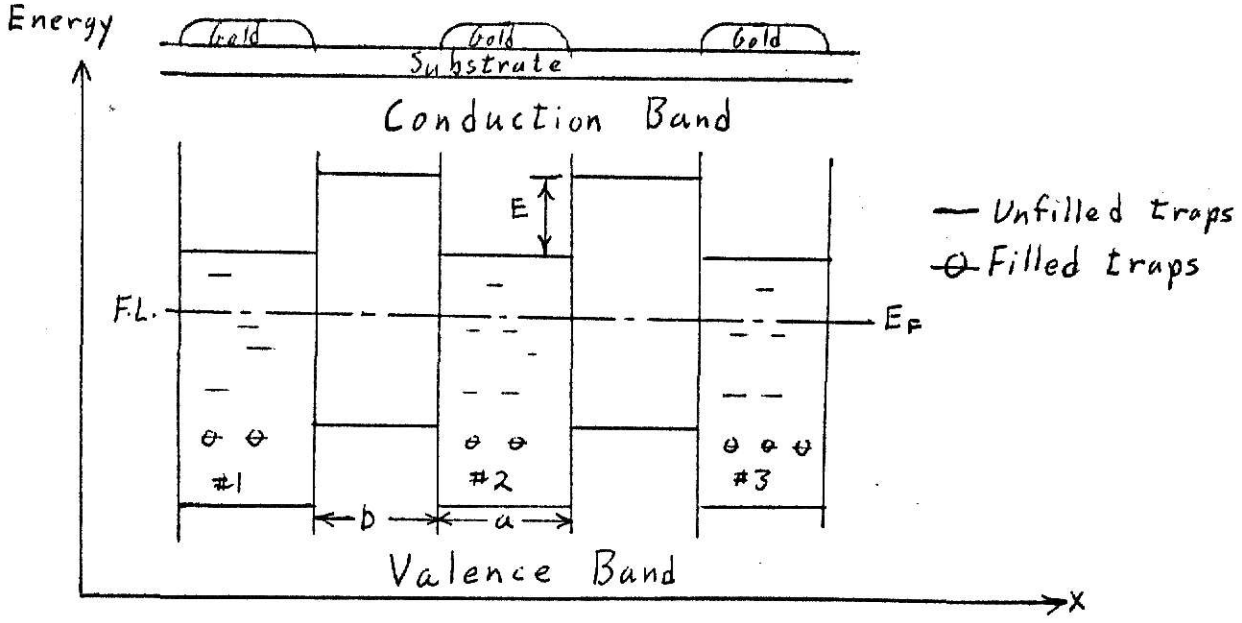


Fig. 2 Energy band diagram of the substrate.

At absolute zero each of the "a" regions in the substrate can be considered electrostatically neutral, but because of the image forces between the electrons in the filled traps and the overlaying metal microparticle the filled trap might not be at the same energy level as the unfilled traps. Because of this energy inequality an activation energy in the form of phonon absorption or emission would be needed in order for tunneling to occur between filled and unfilled traps in the surface regions under the microparticle.

To arrive at an expression for electrical conductivity Herman and Rhodin used the same procedure as did Neugebauer and Webb (2) except for some modifications. According to Boltzman's statistics, the number of charge carriers for $\epsilon > kT$, where ϵ is the activation energy is

$$n = Ne^{-\epsilon/kT} \qquad (12)$$

where N is the total number of filled traps which is dependent on the size of the microparticle, a; the depth of the surface trap region, δ ; the surface trap density, n' and the number of traps filled by electrons from the metal. Therefore, Eq. (12) can be written as

$$n = \left(\frac{n'}{a^2\delta}\right) e^{-\epsilon/kT} \tag{13}$$

At any temperature above absolute zero there will be an equilibrium number of filled traps above the Fermi level in the surface region beneath the microparticles. With the application of an electric field across the film shown in Fig. 2 the energy levels of the traps beneath microparticle 1 will be raised to E + eV relative to the traps under microparticle 2 and the energy of the traps under microparticle 3 will be lowered to E-ev. Using the added assumption that the cross-sectional area of the surface participating in the conduction is $\sim a\delta$, Herman and Rhodin modify Eq.(11) to read

$$\sigma \propto \left[D e^2 n' b(a+b)/a \right] e^{-\epsilon/kT} \tag{14}$$

Equation (14) predicts a linear relationship between voltage and current for a discontinuous film at a constant temperature.

If the values for the average cross-sectional area of a microparticle and the distance separating the microparticles in a typical discontinuous film (100 Å and 40 Å, respectively) were substituted into Simmon's (5) expression for tunneling current through a rectangular barrier of high 1 eV, the theoretical resistance of a discontinuous film would be on the order of $10^{20}\Omega$ per square. In reality, however, the resistivity is on the order of $10^{10}\Omega$ per square which would indicate a barrier thickness of 20 Å rather than 40 Å. This calculation by Milgram and Lu (6) prompted them to suggest

that conduction is by way of electron tunneling between trapping sites located in the substrate between the microparticles rather than directly through the substrate from one microparticle to another. These trapping sites could be defects in the glass or isolated metal atoms on the substrate. The existence of isolated metal atoms is suggested by the study of electrical resistance-strain characteristics of very thin films done by Parker and Krinsky (6). They assumed that the resistance of the thin discontinuous film is inversely proportional to the tunneling probability of electrons through the potential barrier separating the microparticles. This tunneling probability is given by

$$P \propto e^{-\mu X} \tag{15}$$

where $\mu = 2\pi (8m)^{1/2} \phi / h$, m = mass of electron, ϕ = work function of the metal, h = Planck's constant, and X = characteristic width of potential barrier. It was found for discontinuous films of Pt, Ni, and Pb that the product $\mu X \sim 10$ Å implying that $X \sim 5$ Å and for Au, $\mu X \sim 100$ Å implying $X \sim 50$ Å. The actual separation distance between microparticles in all the films was on the order of 50 Å, which implies the existance of isolated metal atoms on the substrate. These isolated metal atoms aid in the conduction process in all films except Au, which because of the high mobility of gold atoms on glass, tends to form discontinuous films where all of the gold goes into the microparticles.

Milgram and Lu (3) suggest the existence of two conduction currents in discontinuous films. These currents are parallel to each other and are represented by the expression

$$I = AV + BV^{h} \tag{16}$$

where A and B are functions of temperature, V is the voltage across the film and n is an exponent equal to or greater than 2 depending on the temperature of the film.

The first term in the above expression is due to the tunneling of thermally created charges via the trapping sites through the substrate between the microparticles. The number of these charges is independent of the applied field but does vary as $e^{-\epsilon/kT}$, where ϵ is the activation energy which depends on the concentration and energy distribution of the trapping sites in the substrate. If only one trapping level is considered the current due to the thermally created charges can be written as

$$I \propto Ve^{-\epsilon/kT} \tag{17}$$

which is similar to results of Herman and Rhodin (4).

The second term in the equation is due to the tunneling of charges that have been injected into the trapping sites by the electric field. The space charge Q of these charges is given by Q = CV, where C is the capacitance and V is the voltage difference between two microparticles. If this introduction of the space charge into the substrate does not appreciably alter the Fermi level and if all the charges can move in the insulator by tunneling via the trapping sites to the next microparticle, the space-charge-limited current I is given by

$$I = Q/t = CV/t \tag{18}$$

where t is the time required for tunneling to take place between two trapping sites. Since the tunneling probability P is a linear function the applied voltage

$$P \propto V, \tag{19}$$

one can write the transition time as

$$t = 1/P = 1/V \tag{20}$$

from which the space-charge-limited current becomes

$$I_s \propto V^2 \tag{21}$$

Combining the two currents one obtains the total current

$$I = AV + BV^2 \tag{22}$$

which is identical to Eq. (16) for the case where n is equal to two. This equation seems to be valid for temperatures down to 77^0 K. For lower temperatures the value of n increases because the assumption that the space charge Q forced into the substrate by the applied field does not alter the Fermi level is no longer valid. Most of the trapping sites below the Fermi level will be occupied; therefore, the injected charges can only occupy trapping sites above the Fermi level thereby raising it. According to Rose (7), the value for n at very low temperatures is

$$n = T_c/T + 1 \tag{23}$$

where T_c is a critical temperature that is dependent on the trap distribution in the substrate.

EXPERIMENTAL PROCEDURE

Data was collected on film samples of two different dimensions in order to study the effects that a relatively high and low applied electric field has over the conduction characteristics of gold discontinuous films. These samples are designated type A and type B, respectively. Type A samples contain films that are 0.965 mm long and 17.78 mm wide, and the films in type B samples are 3.155 mm long and 4 mm wide. The samples, consisting of electrodes, discontinuous films, and a silicon monoxide protective layer, were vapor-deposited on glass substrates in three evacuations of a Ultek high vacuum system equipped with a 400 liter per second ion pump and a Boost-Vac supplementary pumping unit. During the evaporations the pressure in the system was kept below 10^{-6} Torr. After fabrication electrical measurements were taken on the films.

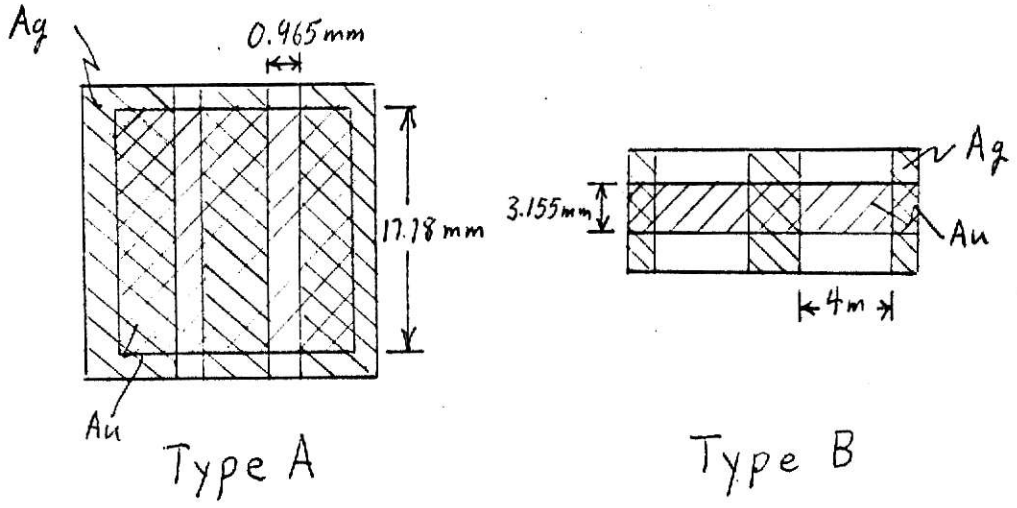


Fig. 3 Diagram of sample type A and B showing the discontinuous gold film acorss the three silver electrodes

The film samples were deposited on Corning 7059 glass slides. 7059 glass is ideal for this purpose because of its high volume resistivity. In

the interest of conserving this expensive glass two film samples were deposited on each substrate.

The glass substrates were cleaned before being used by subjecting them to the following cleaning procedure. After a preliminary cleaning with lens tissue, the glass substrates were put individually into small glass containers (test tubes) to prevent scratching and dust contamination. Then enough Acid Dichromate cleaning solution was added to each container to cover the substrate. After an overnight soaking, the cleaning solution was dumped out and the substrates were rinsed ten times with distilled water and then dried under a heat lamp. After drying the substrates they were removed from their respective containers.

In the first evacuation of the vacuum system, silver was evaporated to deposit electrodes on the substrates. The substrates were mounted on a rack facing a resistively heated source containing silver. The source consisted of two tantalum pan boats spot welded together back to back to form an enclosed container with a small hole drilled in one side. The source was mounted vertically between two copper bars with the side with the hole facing the substrates. The two copper bars were, in turn, connected to a high current power supply. In front of each substrate was placed, crosswise, a mask of two parallel strips of metal the width of which depended on the length of discontinuous film desired for the sample. When the silver was evaporated the masks shielded only that portion of the substrate directly beneath the two parallel strips thus forming three electrodes as shown in figure 3.

The gold discontinuous films were deposited in the second evacuation of the vacuum system. Substrates with silver electrodes were mounted

behind twelve rectangular holes equally spaced around the periphery of a flat aluminum disk. In front of each substrate was placed a mask to restrict the depositation of gold to a strip of desired width running lengthwise along the substrate across the three electrodes. The disk, which was capable of being turned from outside the vacuum system, was mounted on a horizontal axle behind a round piece of aluminum sheeting. This piece of sheeting was slightly larger in diameter than the wheel and had a wedge shaped piece cut out of it so as to allow the substrate to be exposed to the source one at a time as the wheel was turned. The source used was a tungsten wire basket in which 99.99% pure gold wire was inserted. The basket was connected to buses that were again connected to a high current power supply.

The procedure followed in making the discontinuous film was to first melt the gold wire and allow it to coat the basket uniformly while none of the substrates in the wheel were exposed. This created a line source from which gold could be evaporated to deposit a uniform discontinuous film across the substrate. Since a minute amount of gold was needed to make a film the current through the tungsten basket was shut off as soon as the gold started to vaporize.

Finally, a third evacuation of the vacuum system was required to evaporate the silicon monoxide protective layer over the gold films. While still in the substrate wheel, each film sample was exposed to a silicon monoxide source for a period of ten minutes. The source, which was purchased from R. D. Mathis Co., prevented direct exposure of the bulk source material to the substrate, thus eliminating any chance of splitting and streaming, which causes pinholes.

For current measurements the silver electrodes on the substrates were painted over with an inorganic silver micropaint (S C P 12) from Micro-Circuit Company to insure good electrical contact with the spring clips providing the electrical potential across the film. These clips held the substrate firmly on top of a thick, flat piece of glass that acted as a heat sink that helped to stabilize the temperature of the film. On the bottom side of the heat sink was a thick film of michrome which functioned as a heater. The heater was connected across the output of a Variac. The heater-substrate holder arrangement was placed in a shallow styrofoam dewar positioned in a heavy metal container which provided shielding for the film from stray electrical fields.

All electrical connections from the clips on the substrate holder to the outside world were made through three BNC plugs mounted on the bottom of the metal container. The center electrode on the substrate was connected to the positive terminal of a Hewlett-Packard 300V-100 ma constant current-constant voltage power supply. One of the other electrodes, depending on which film sample was to be measured, was connected to the negative terminal of the power supply through a Keithley G10 C R Electrometer. Both the negative terminal and the metal container were grounded to the power supply. The electrometer measured the current through the film and a Keithley 153 Micro-Ammeter measured the voltage output of the power supply. For the current measurements as a function of applied voltage the power supply was set to provide selected constant voltage across the film that was independent of the current.

The current vs. temperature data taken was obtained by feeding the output voltage of the electrometer to the Y-axis input of a Moseley Model

2D-2 X-Y recorder. A copper-constantum thermocouple that had one junction fastened to the substrate and the other junction immersed in ice water was connected to the x-axis of the recorder to give an indication of the temperature of the film. Liquid nitrogen was then poured into the dewar to cool the substrate down to -195°C. Then, as the temperature of the film was increased slowly from liquid nitrogen temperature to 0°C by increasing the current through the substrate heater, the recorder plotted a curve of the current through the film as a function of the emf output of the thermocouple.

DATA AND RESULTS

Data were gathered on three type A samples and one type B sample. Two of the type A samples were on the same substrate and the remaining two shared substrates with samples that turned out to be non-conducting. The latter two samples were used to obtain data of the effects of radiation damage in the glass substrate might have on the conduction of the discontinuous film.

In this particular case radiation damage was produced in the glass substrate of sample numbers 1 and 4 (a type A and type B sample, respectively) by exposing the substrates to an incident x-ray flux from a platinum target tube operating at 43 kvp and 20 ma. Irradiation gave the substrates a dark brownish tint.

The resistance of the films at seven different output voltages of the power supply ranging from 300 volts to 2 volts was calculated by substituting into Ohm's law the voltage output of the power supply as indicated by the Keithley 153 Micro-Ammeter and the current reading of the Keithley 610 electrometer. The resistance of the current sensing resistor in the electrometer (internal impedance) was subtracted from the calculated resistance since it is in series with the film. The electric field across the film was determined by dividing the applied voltage by the length of the film.

An examination of Plates I and II reveals that radiation damage to the substrates does affect the conduction of the gold films but in different ways. Plate I shows that damage seems to lower the resistance of the film although there is a poor correlation between the decrease in resistance to the time of exposure of the substrate to the x-ray flux except for the

fact that the resistance seems to decrease after each subsequent exposure. The resistance of the gold film in a type A sample seems to increase after each exposure as shown in Plate II. Again, in Plate II, there is a poor correlation between the time of exposure and the change in resistance. Except for the fact that the resistance of both films increases with decreasing applied electric field no sound conclusions can be drawn from these plates.

Plates III and V illustrate how the current through samples 2 and 3 varies non-linearly with the applied voltage which indicates the existence of a V^n term in the expression for current where $n \neq 1$. As it turns out, a V^2 term is needed to explain this non-linear behavior. The expression

$$I = AV + BV^2$$

fit the form V-I curves shown in Plates IV and VI where A and B are temperature dependent coefficients. Again, the electric field dependents of the resistance of these films is displayed in Plates IV and VI where it can be seen that the resistance generally decreases with increasing electric field.

After collecting the previous discussed data, the resistance of film samples 1 and 4 along with sample 3 (a type A sample) was measured as a function of temperature with the output of the power supply set at 100 volts. Using the curves drawn by the X-Y recorder the resistance of each film was calculated for each 0.25 millivolt interval along the X-axis. The results are shown on Plate VII where the thermocouple output was converted to reciprocal temperature of the film.

The three curves shown in Plate VII agree favorably with similar curves for a gold discontinuous film shown in Figure 12 of Herman and

Rhodin paper (4) in that the resistance of the films shows a sudden increase in the neighborhood of 200° K. According to Herman and Rhodin this behavior can be explained by the apparent temperature dependence of the filled trap density term n in Equation (17). Above 200° K the three curves are essentially straight lines which suggest that resistance depends exponentially on temperature as suggested by Neugebauer and Webb (2). It must be remembered that samples 1 and 4 have been exposed to an x-ray flux for a total time of thirty minutes thus showing that radiation damage to the substrate does not appreciably change the shape of the curves when compared with the curve of sample 3 whose substrate is free of damage. The current as a function of temperature curves for the three samples was irreversible, that is, when the films were warmed up to 0°C from liquid nitrogen temperatures they stop conducting at any temperature. This phenomenon cannot be explained by the fact that the size and distribution of gold microparticles vary with the temperature of the substrate as suggested by Herman and Rhodin because the silicon monoxide layer would prevent this. Perhaps the silicon monoxide layer could not stand up to the thermal shock and changes developed in it when the sample was warmed up from liquid nitrogen temperatures.

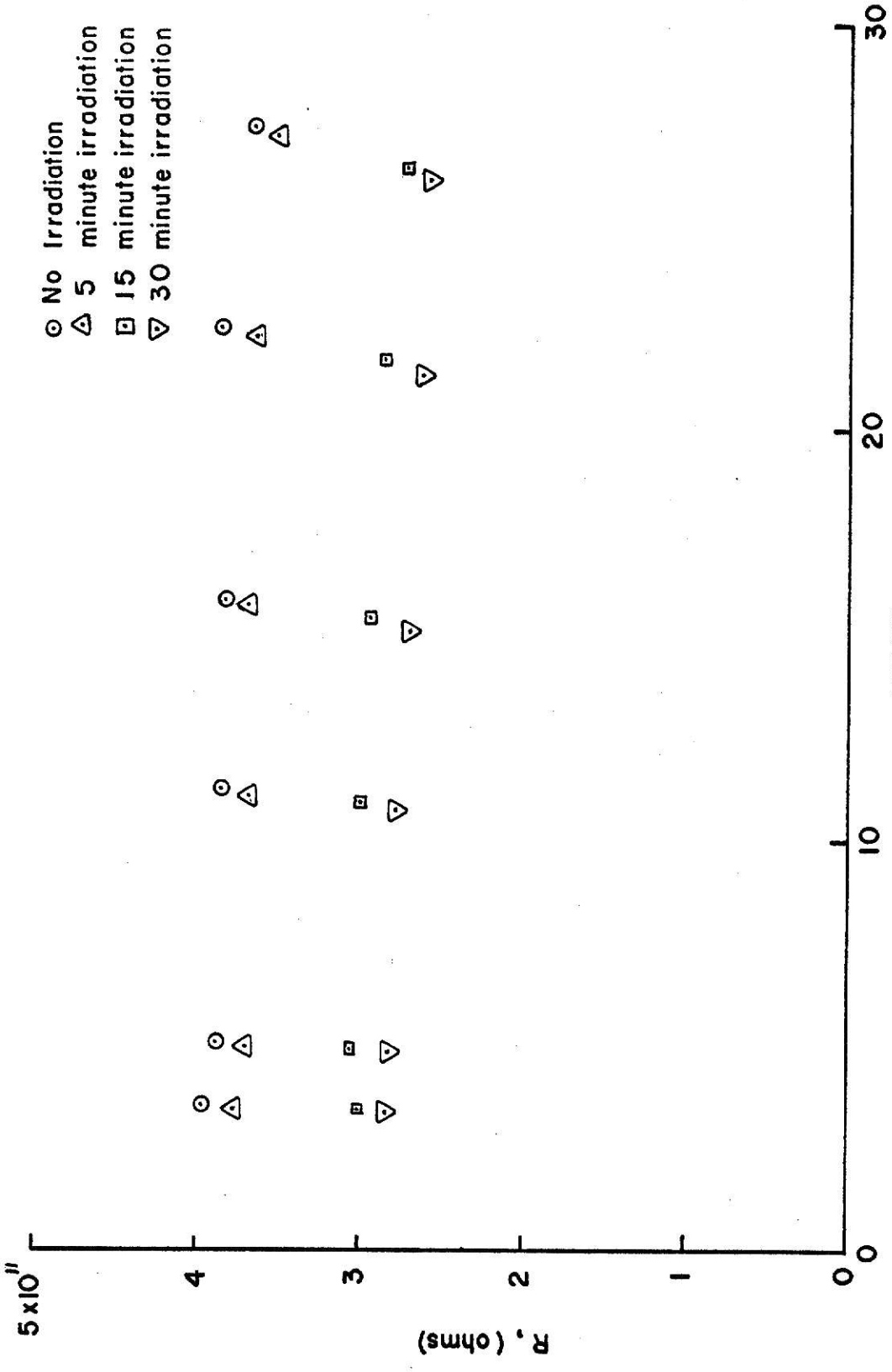
CONCLUSION

The introduction of radiation damage into the substrate seems to produce a slight change in the resistance of the gold discontinuous films that were looked at. After an exposure of 30 minutes to the x-ray flux the damage to the glass seems to reach a saturation point because an additional exposure time of 30 minutes did not change the resistance of the films. Perhaps this saturation density is still too small compared to the density of the natural structural defects in the glass to influence the conduction of the film much. On the other hand, most of the trap electrons may be associated with isolated gold atoms on the surface of the substrate instead of with the structural defects in the substrate. A way to clear up to this point would be to use an alkali-halide crystal that is relatively free of structural defects for a substrate and see what effect the density of F-centers has on the conduction of a discontinuous film. Another approach could be to introduce isolated atoms on the surface of the substrate of a discontinuous film after the initial electrical measurements were made and see what effect this had on conduction.

It was observed in samples 2 and 3 that the conductivity is dependent on the electric field even at low fields as shown in Plates IV and VI. This dependence seems to be greater at 77° K than at 300° K. These results are contrary to the results displayed by Neugebauer and Webb (2) which shows the independence of the conductivity of discontinuous gold films on electric fields up to 400 volts/cm at five different temperatures from 77° K to 297° K. Since this deviation from Ohm's law is proportional to the square of the applied voltage across the film the last of the three theories enunciated in this thesis seems to explain the conduction in gold discontinuous films best.

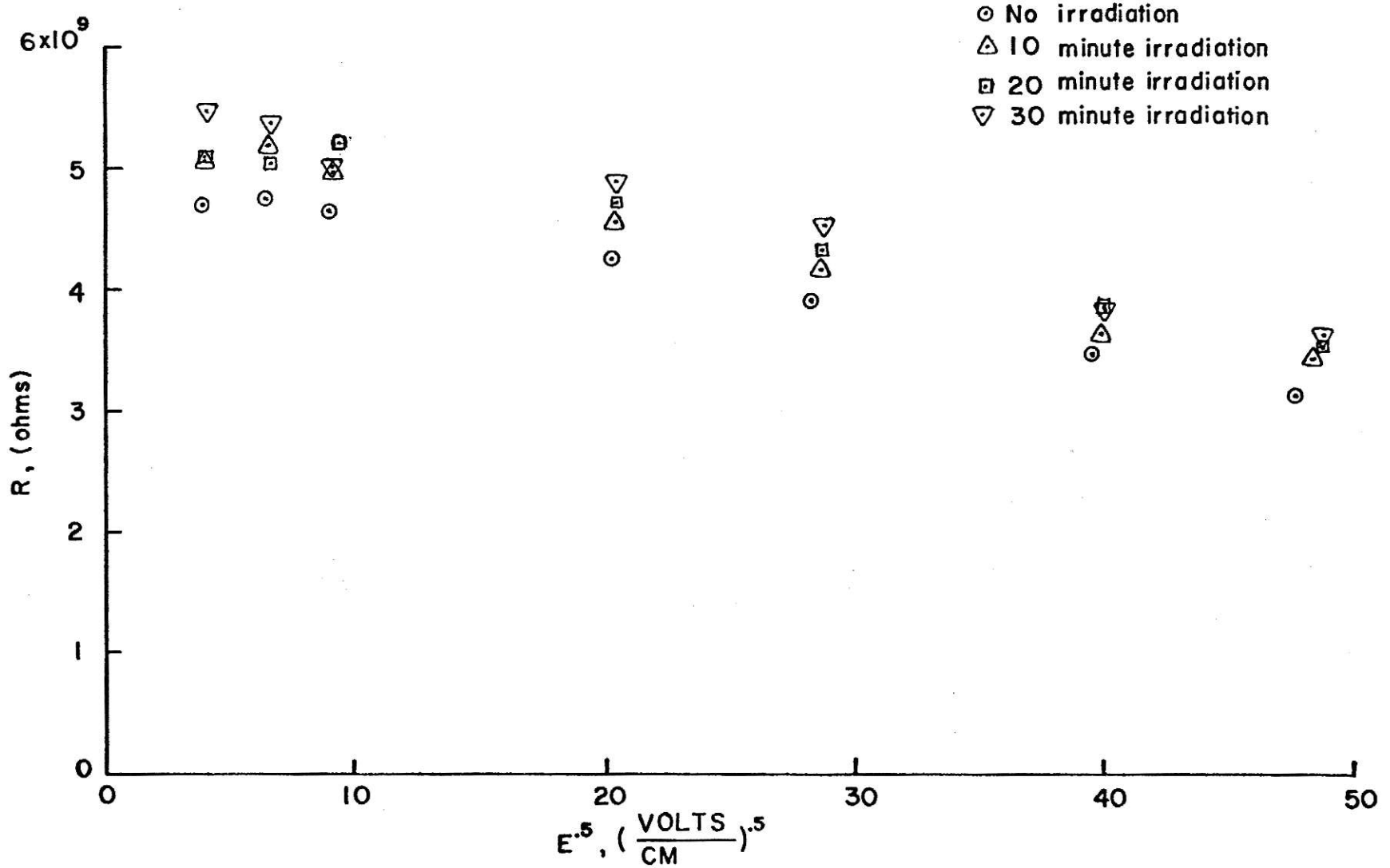
EXPLANATION OF PLATE I

Resistance of the type B sample as a function of the square root of the electric field.


⊙ No Irradiation
△ 5 minute irradiation
□ 15 minute irradiation
▽ 30 minute irradiation
5 x 10^11
4
3
2
1
0
R, (ohms)
0
10
20
30
E^.5, (VOLTS/CM)^.5

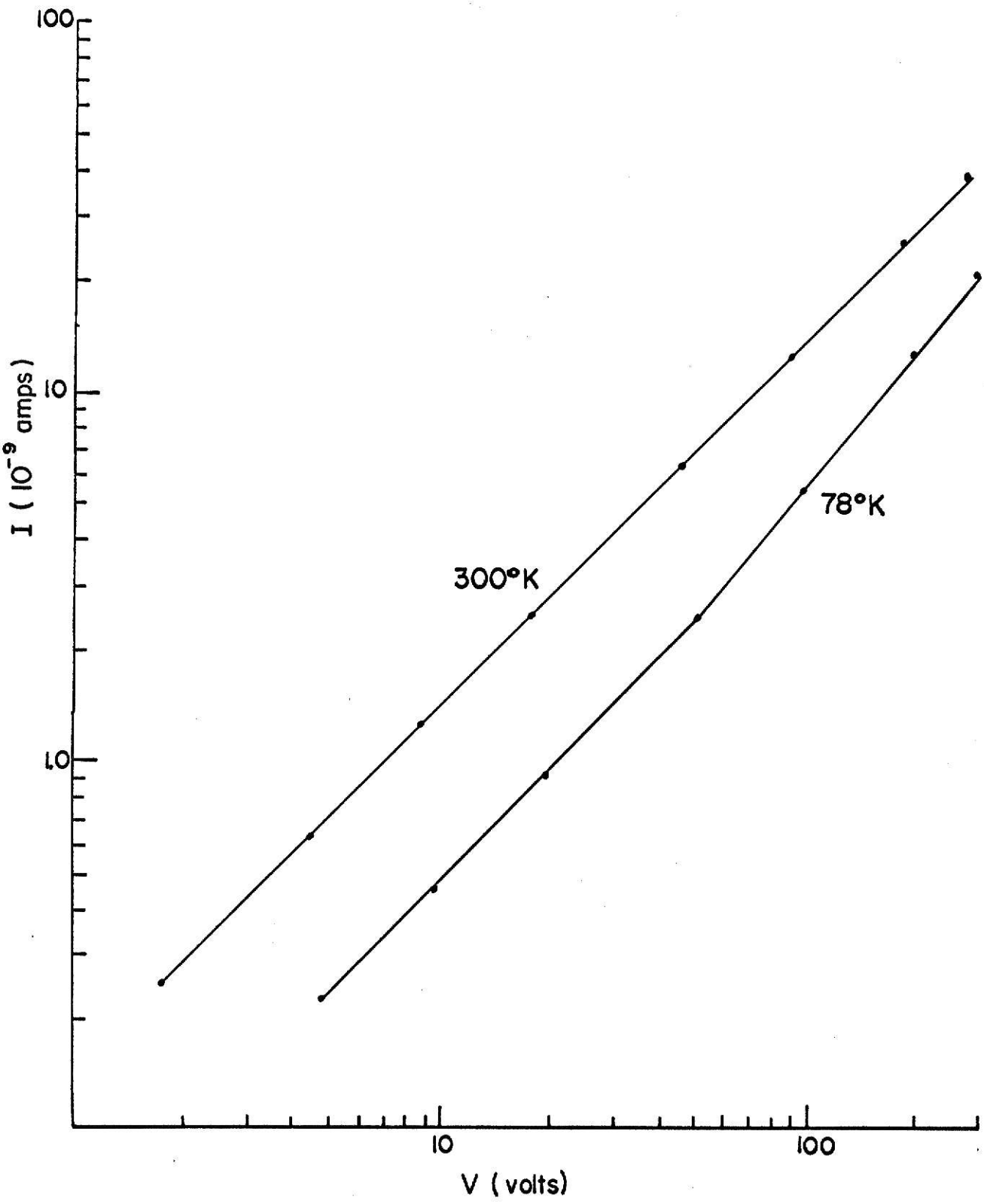
EXPLANATION OF PLATE II

Resistance of the type A sample as a function of the square root of the electric field.


⊙ No irradiation
△ 10 minute irradiation
⊡ 20 minute irradiation
▽ 30 minute irradiation
6x10^9
5
4
3
2
1
0
R, (ohms)
0
10
20
30
40
50
E^.5, (VOLTS/CM)^.5

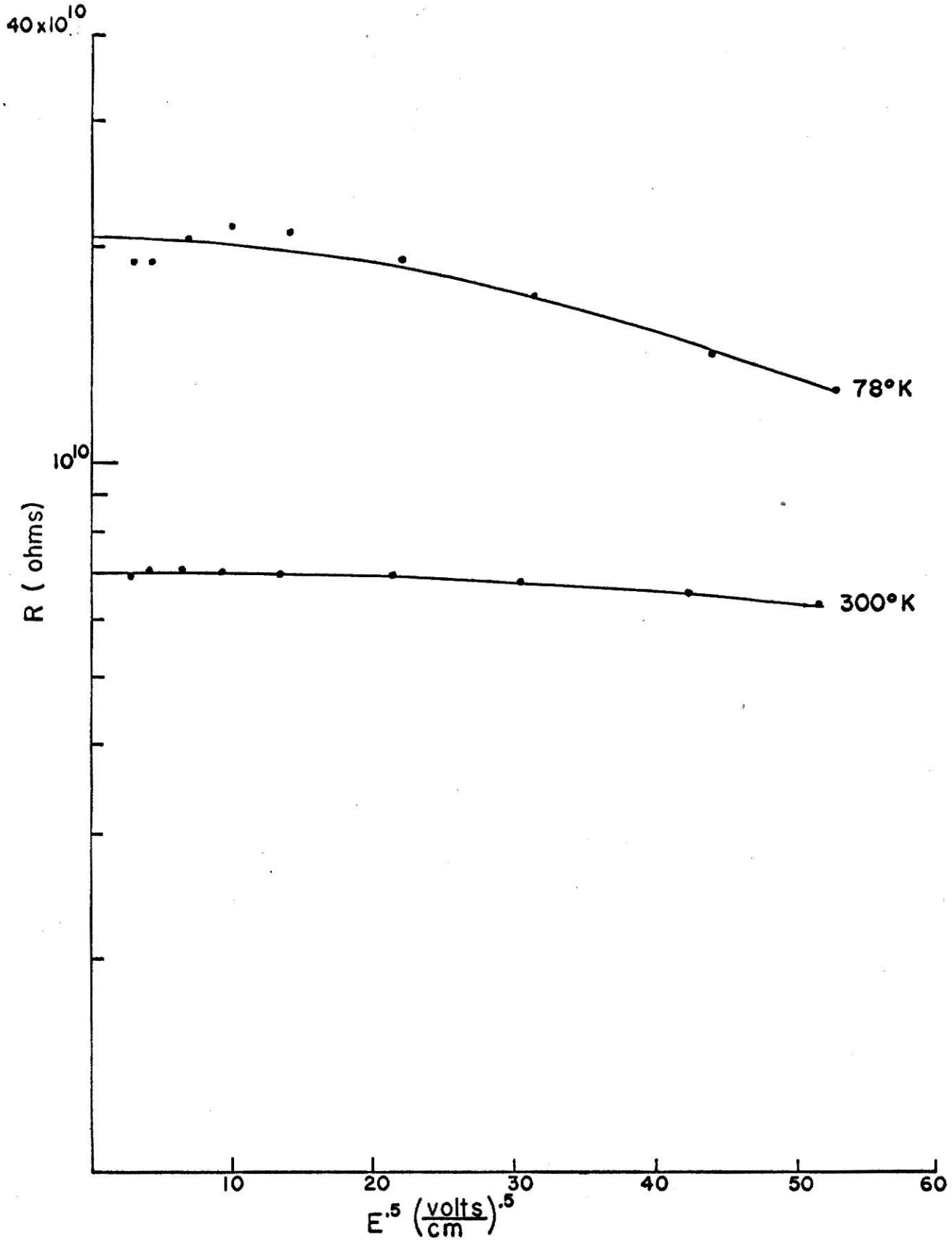
EXPLANATION OF PLATE III

Current as a function of voltage curves for sample 2 at 77° K and 300° K.


100
10
1.0
I (10⁻⁹ amps)
300°K
78°K
10
100
V (volts)

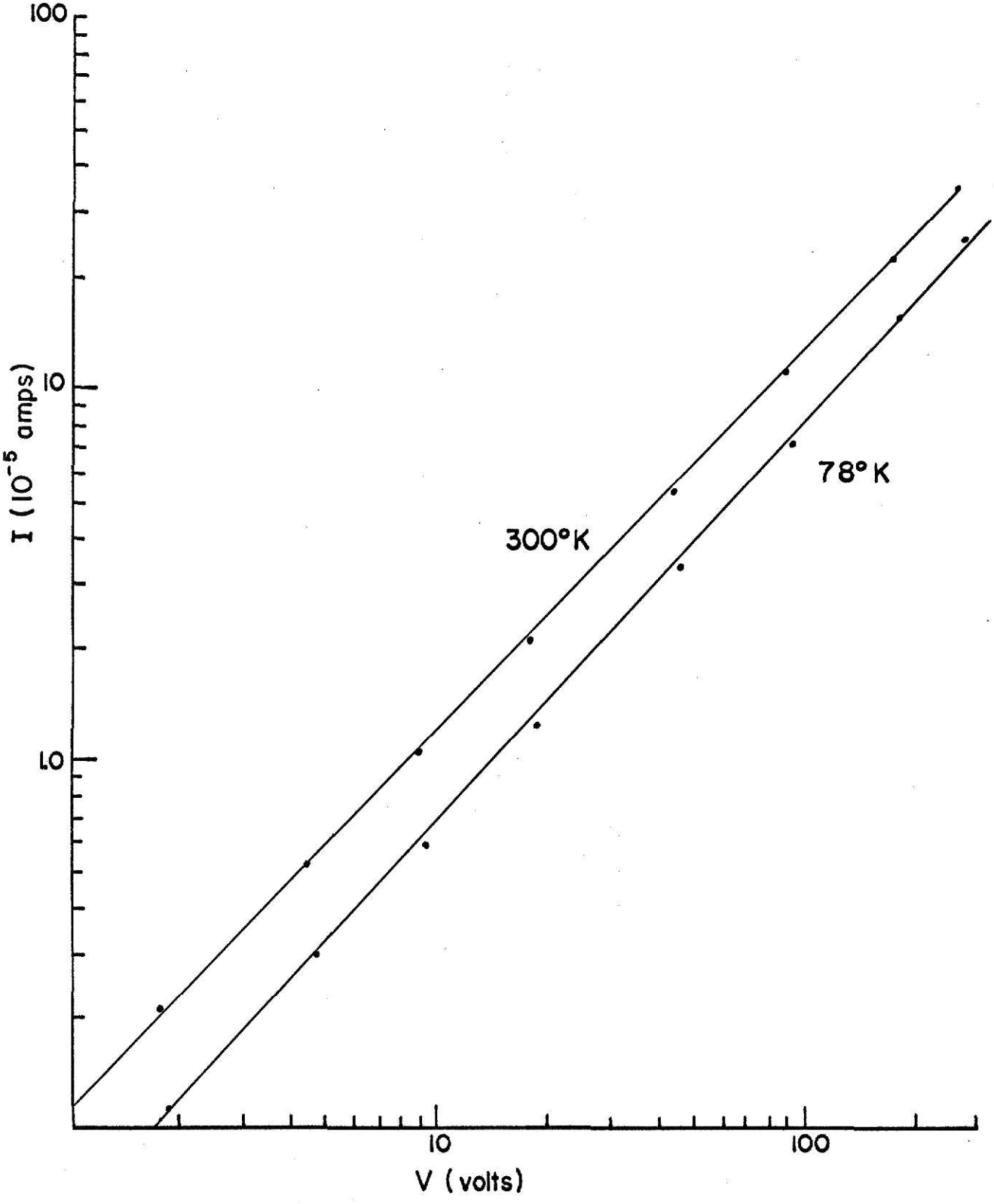
EXPLANATION OF PLATE IV

Resistance of sample 2 as a function of the square root of the electric field at 77° K and 300° K. The equation for the solid curves is $R = \frac{1}{A + BL(E1/2)2}$ where $A = 1.41 \times 10^{-10} \frac{amp}{volt}$, $B = 6.68 \times 10^{-14} \frac{amp}{volt^2}$ for $T = 300°$ K, $A = 4.81 \times 10^{-11} \frac{amp}{volt}$, $B = 1.12 \times 10^{-13} \frac{amp}{volt^2}$ for $T = 78°$ K and $L = 0.0965$ cm, the sample length.


40 x 10^10
10^10
R (ohms)
78°K
300°K
10
20
30
40
50
60
E^.5 (volts/cm)^.5

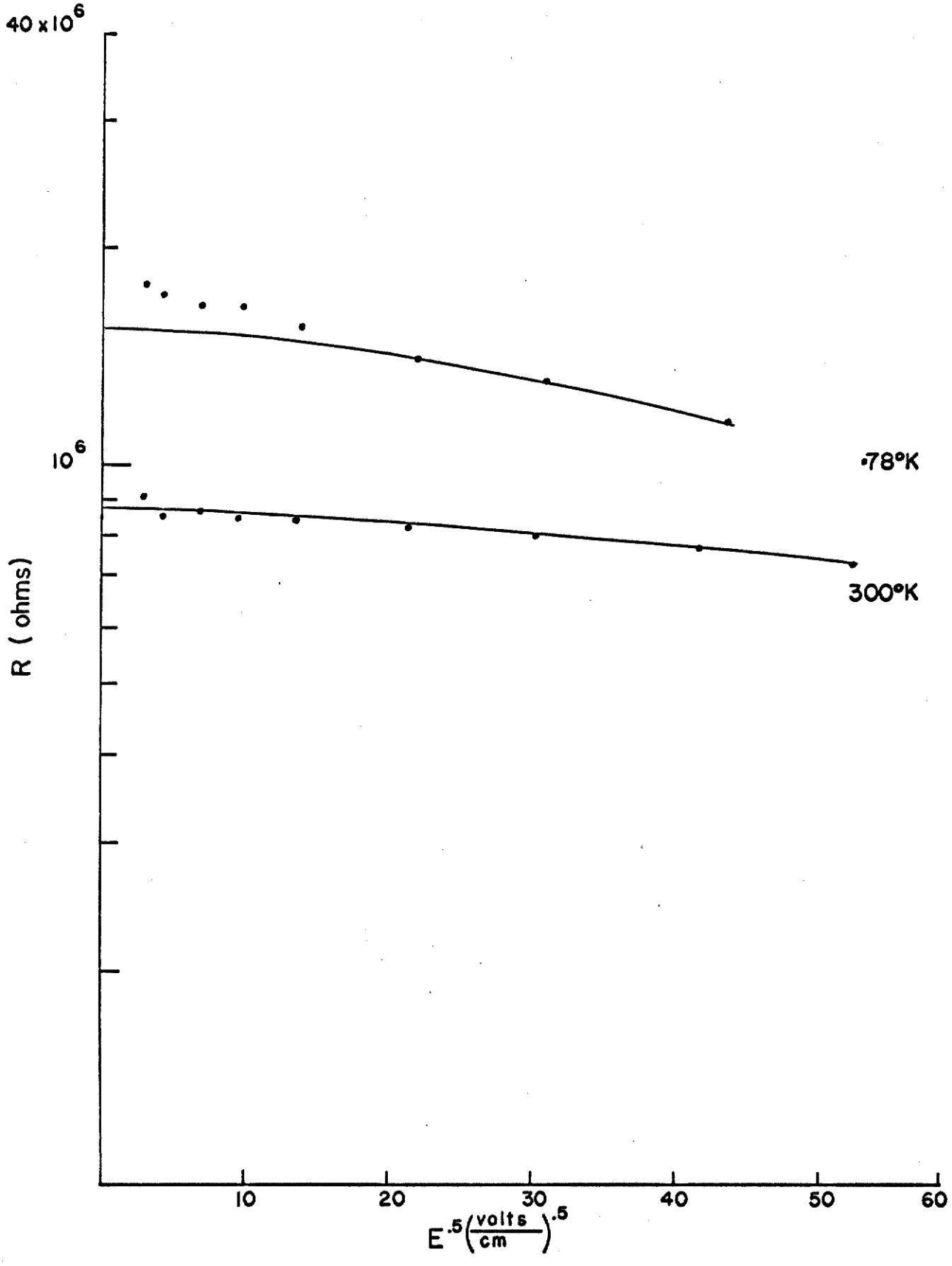
EXPLANATION OF PLATE V

Current as a function of voltage curves for sample 3 at 77° K and 300° K.


100
10
1.0
I (10^{-5} amps)
300°K
78°K
10
100
V (volts)

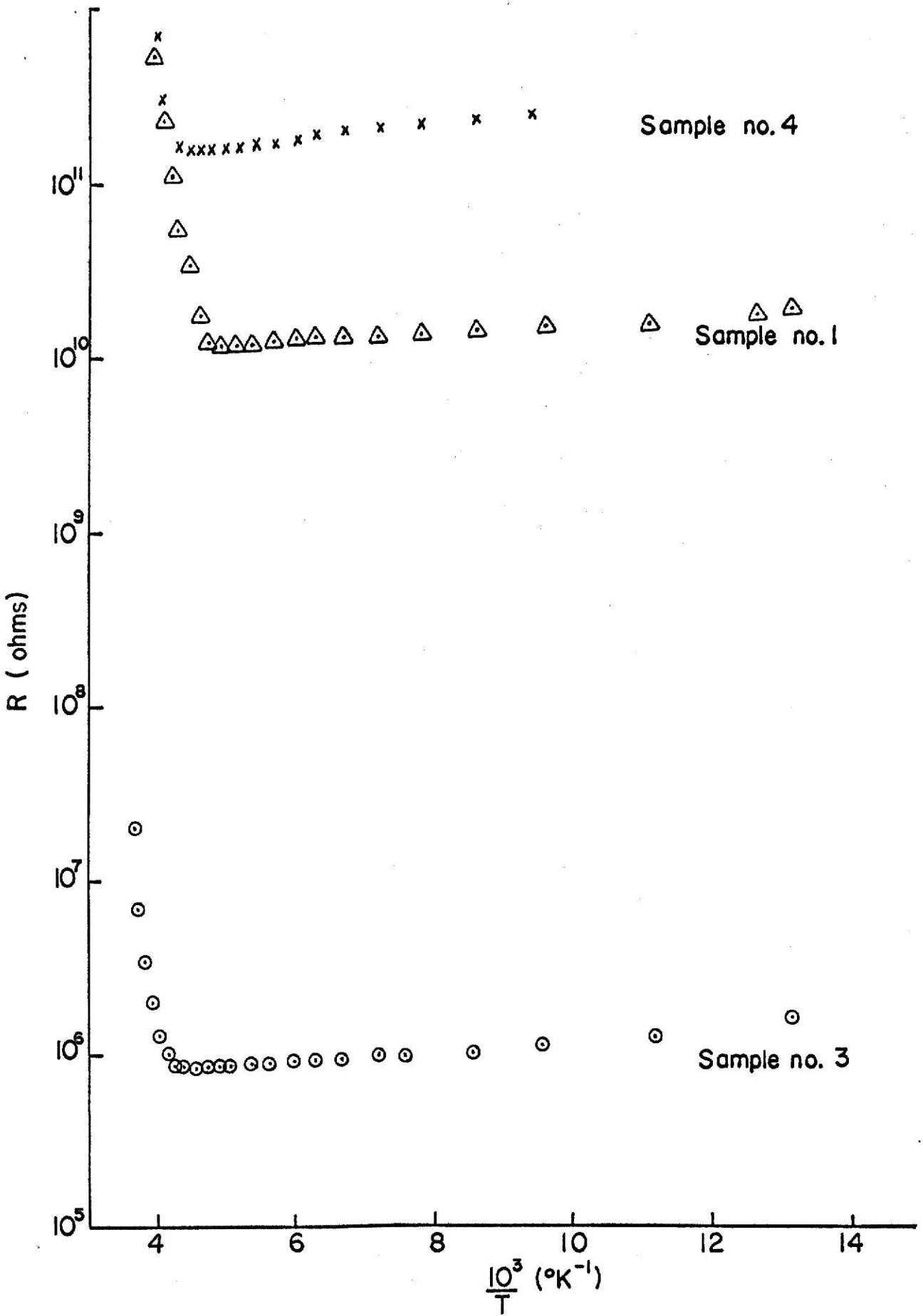
EXPLANATION OF PLATE VI

Resistance of sample 3 as a function of the square root of the electric field at 77° K and 300° K. The equation for the solid curves is $R = \frac{1}{A + BL(E1/2)2}$ where $A = 1.16 \times 10^{-6} \frac{amp}{volt}$, $B = 7.71 \times 10^{-10} \frac{amp}{volt^2}$ for $T = 300°$ K, $A = 6.44 \times 10^{-7} \frac{amp}{volt}$, $B = 1.06 \times 10^{-9} \frac{amp}{volt^2}$ for $T = 78°$ K and $L = 0.0965$ cm, the sample length.


40 x 10^6
10^6
R (ohms)
78°K
300°K
10
20
30
40
50
60
E^.5 (volts/cm)^.5

EXPLANATION OF PLATE VII

Resistance of samples 1, 3, and 4 as a function of reciprocal temperature, $^{o}K^{-1}$. The activation energy, ϵ, for samples 1, 3, and 4 is 2.2×10^{-3}eV, 1.6×10^{-3}eV and 3.1×10^{-3}eV, respectively.


Sample no. 4
Sample no. 1
Sample no. 3
R (ohms)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
4
6
8
10
12
14
$\frac{10^3}{T}$ ($^\circ K^{-1}$)

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ELECTRON TUNNELING BETWEEN MICROPARTICLES IN THIN DISCONTINUOUS GOLD FILMS

by

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AN ABSTRACT OF A MASTER'S THESIS

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The electrical conduction mechanism in thin, discontinuous gold films evaporated onto glass substrates and covered with a layer of silicon monoxide was investigated. These films consist of a planar array of small, isolated microparticles of gold. The current through the films was measured as a function of the applied voltage across the films at room temperature and liquid-nitrogen temperature, and as a function of the temperature of the films with a fixed applied voltage. The I-V curves thus obtained showed a slight deviation from Ohm's law for moderate electric fields (greater than 500 V/cm) for films at room temperature. A larger deviation was observed for films at liquid-nitrogen temperature. The I-V curves showed a negative temperature coefficient of resistance (TCR) in the temperature range 78 to 160°K and a positive TCR from 160 to 273°K, even though all films initially exhibited a negative TCR at room temperature. The coated substrates were irradiated with x-rays from a platinum target until the glass was visibly darkened. Small changes in the conduction were observed.