CONFERENCE ON SOLAR ENERGY: THE SCIENTIFIC BASIS.

AT THE

UNIVERSITY OF ARIZONA, TUCSON.

1955 OCTOBER 31 AND NOVEMBER 1,

MONDAY AND TUESDAY.

SILICON p-n JUNCTION SOLAR ENERGY CONVERTER.

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SECTION C Business Administration Building ROOM 110

DAY Tuesday HOUR 9:30 a.m.

Introduction

Our previous speakers have described theories of p-n junction solar energy converters and have given us information as to which semiconductors should be used for these devices. In this paper we shall consider an ideal model and from this show that silicon is a suitable semiconductor for a solar energy converter. After showing that silicon solar energy converters are desirable, we will change our model to conform to actual physical conditions which include series and shunt resistances with the p-n junction. This model indicates that the shunt resistance will not cause the device to lose appreciable efficiency whereas the series resistance must certainly be made as small as possible to keep the efficiency of this device up to some decent value. This series resistance can be attributed to two sources in the diffused junction type of device; one, the thin layer of converted material on the exposed surface of the device and two, the contacts to the n and p surfaces of the semiconductor. The latter series resistance has been reduced to extremely low values and will not be included in our discussion. The series resistance of the thin surface must be compromised with the geometry of the device. Theory will be given of this compromise and of the thermal variations of these devices. In order to show that the assumed models and theories are good first approximations, measurements of actual solar energy converters will be given. At present the best units are near 11% efficient which is just about the maximum value to be expected from simple calculations.

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General Ideal Theory

The problem of the photoelectric power converter may best be defined by considering the case of an ideal p-n junction in parallel with a constant current source (Figure 1). The constant current source results from the excitation of an excess over the thermal density of electrons into the conduction band and the diffusion and drift of these carriers across the barrier.

The I-V characteristic of such a device is given as

$$I = I_o (e^{qV/kT} - 1) - I_L \tag{1}$$

where I_o = reverse saturation current of ideal junction; q = charge of electron, k = Boltzmann's constant, T = absolute temperature, and I_L = strength of constant current source. I's will be used throughout this paper for currents and J's for current densities.

A plot of Eq. (1) is given in Figure 2 for selected values of the parameters. It is seen that the curve passes through the fourth quadrant and therefore power can be extracted from the device. By operating at the proper point, it is possible to extract close to 80% of the product $I_{sc} x V_{oc}$ where I_{sc} is the short circuit current and V_{oc} is the open circuit voltage of the device.

Let us calculate the maximum power that can be obtained from a solar energy converter exclusive of losses by reflection, recombination, and series and shunt resistances. In bright sunlight at sea level, if every photon falling on a unit created one hole-electron pair that caused current to flow across the junction, there would be a short-circuit current of 0.080 ampere per square centimeter of effective device area. However, the long wavelength limit for the creation of hole-electron pairs by photons depends on the energy gap of the semiconductor involved and this reduces the magnitude of the highest possible short-circuit current to 0.044 ampere/cm^2 in silicon and 0.068 ampere/cm^2 in germanium. Further reduction of these values occurs due to reflection losses. Even with "nonreflective" coatings the maximum short-circuit currents will be near 0.035 ampere/cm^2 in silicon and 0.055 ampere/cm^2 in germanium. One might think that by choosing semiconductors with lower energy gaps, one would obtain larger short-circuit currents and thus higher efficiencies. However, as will be shown in the next paragraph, decreasing the energy gap reduces the open-circuit voltage at a much faster rate than the short-circuit current increases.

The open-circuit voltage V_{oc} is given by

$$V_{oc} = kT/q \ln(I_L/I_o + 1) \tag{2}$$

with the 1 being negligible compared with I_L/I_o. Therefore, V_{oc} can be maximized by minimizing J_o. J_o is approximately given by

$$J_o = qp_n(D_p/t_p)^{1/2} + qn_p(D_n/t_n)^{1/2} \tag{3}$$

where p_n = equilibrium density of holes in the n-region; n_p = equilibrium density of electrons in the p-region; D_p, t_p = diffusion constant and lifetime of holes in n-region; and D_n, t_n = diffusion constant and lifetime of electrons in p-region. This approximation does not take into consideration any surface effects. Consider a heavily doped p-region in contact with a moderately doped n-region, a favorable condition for low I_o using the diffusion technique. Then

$$J_o \simeq qp_n (D_p/t_p)^{1/2} \tag{3a}$$

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and using the relationships

$$p_n = \frac{n_i^2}{n_n} = \frac{2.23 \times 10^{31} T^3 e^{-Eg/kT}}{n_n} \qquad (4)$$

and

$$n_n = 1/\rho_n \, q\mu_n \qquad (5)$$

where n_i = equilibrium density of electrons in intrinsic semiconductor, n_n = equilibrium density of electrons in n-region, ρ_n = resistivity of n-region, μ_n = mobility of electrons in n-region, and E_g = energy gap of semiconductor (volts), the open-circuit voltage can be expressed at 300°K as

$$V_{oc} = 0.026 \ln J_L \left[\frac{0.062 \, e^{39 \, Eq}}{\rho_n \, \mu_n} (t_p/D_p)^{1/2} \right] \qquad (6)$$

It is seen from Eq. (6) that in order to obtain a large V_{oc} one should use a semiconductor with a large energy gap, low resistivity consistent with the diffusion process, material with low mobility and high lifetime. Assuming a life-time of ten microseconds, a resistivity of one-tenth ohm centimeters, a mobility variation of $\mu_n E_g^{2.5}$ = constant, and a diffusion constant variation of $D_p E_g^{2.5}$ = constant, one can calculate the maximum power density as a function of the energy gap. The last two assumptions are not important in that almost any other assumption would give results with less than a few percent difference from the results given in Figure 3. It is seen that for optimum power with respect to the solar spectrum the energy gap in the semiconductor should lie between 1.0 and 1.6 electron volts. Thus silicon with a room temperature energy gap of 1.08 electron volts is ideally suitable as a material for solar energy converters. It is interesting to note that similar devices made from germanium would have about half the conversion efficiency of silicon devices. Since the solar radiant power density is 108 milliwatts per square centimeter at sea level on a bright clear day with the sun at the zenith and the maximum power density that can be obtained from a silicon unit is 23.5 milliwatts per square centimeter, the maximum possible efficiency for a silicon energy converter would be 21.7 percent. However, such an efficiency is unobtainable since no actual device is ideal.

Heuristic Model of Silicon Solar Energy Converter

As has been mentioned in the last section, the maximum I_{sc} in silicon solar energy converters even with "nonreflective" coatings is about 35 milliamperes/cm². This fact immediately reduces the maximum efficiency to 17.2% or 18.6 milliwatts/cm². However, these figures are based on anticipated values of various parameters; that is, improvement in the quality of the present silicon. The best values at present using the diffusion technique of introducing boron into n-type silicon are given in Table I. Using these values, the maximum expected power density P_A is

$$P_A = 0.8 \, J_{sc} V_{oc} = 0.8 \times 0.030 \times 0.58 = 0.0139 \text{ watt/cm}^2$$

or the maximum expected efficiency is 12.9%.

Devices of 12.9% efficiency have not been made and reasons for this fact must be given. Up to the present discussion only ideal junctions have been considered. Now let us consider a practical unit (Figure 4). It may have some shunt resistance

R_{sh} and certainly has some series resistance R_s due to the body material and the contact to the body. It can readily be shown that a model containing a R_s and R_{sh}, the I - V characteristic is given by

$$\ln\left[\frac{I+I_L}{I_o} - \frac{V-IR_s}{I_oR_{sh}} + 1\right] = \frac{q}{kT}\,(V-IR_s) \qquad (7)$$

Plots of this equation with all combinations of $R_s = 0.5$ and $R_{sh} = \infty$, 100 ohms are given in Figure 5 with the same parameters as given in Figure 2. It can be seen that a shunt resistance even as low as 100 ohms does not appreciably change the power output of a unit whereas a series resistance of only 5 ohms reduces the available power to less than 30% of the optimum power with $R_s = 0$. Since the R_{sh} does not affect our results, let us neglect it in future calculations. Figure 6 shows the theoretical I - V characteristics of units having R_s = 0, 1, 2, 3.5, 5, 10, and 20 ohms. It is seen that the maximum power depends very strongly on R_s. The relative maximum available power is plotted in Figure 7 as a function of R_s and shows graphically how extremely important it is to reduce the series resistance to as low a value as possible. Figure 8 shows the result of reducing R_s from 6.1 ohms to 2.7 ohms by improving the contact of an early unit that was about 7 cm^2 in area. This decrease in R_s allowed one to obtain from the unit at optimum load 2.2 times as much power after the improvement compared to that obtained before the improvement.

Now that it has been shown that the series resistance is a controlling parameter in reducing the available power from a silicon solar energy converter, let us consider a possible design of a unit and see how the series resistance must be compromised with other controlling parameters.

Consider Figure 9 which shows a possible configuration for a solar energy converter. Radiation is incident on the top surface. Contacts are made to the n island and p ring on the bottom surface. The geometrical parameters are the length L, width W, thickness H, and the depth of the p-layer t. The length and width of the unit are limited by the size of crystal from which the unit is cut. At the present time L is limited to about 6 cm. and W to 1.5 cm. The thickness of the wafer H should be made small such that the resistance in the n-type region of the device is a minimum. However, this parameter is not critical since it is easy to keep the resistance of this part below 1/4 ohm with thicknesses between 0.1 and 0.5 cm. Therefore in the interest of conservation of material, it is desirable to make $H \simeq 0.1$ cm. A more critical dimension is the thickness of the p-layer t. Practically all the electron-hole pairs produced by sunlight are created within 10^{-4} cm of the surface. Thus two conflicting demands are made on t; thick t to reduce the loss of minority carriers by recombination before diffusing to the junction. It can be shown that the power is related to the geometric parameters by

$$P = -\frac{kT}{q}\; I \ln\left[\frac{I+0.03\;\; WL\,\exp(-10^3t)}{10^{-10}\,WL} + 1\right] \quad -I^2\,\frac{Wp}{4tL} \qquad (8)$$

The first term represents the actual power developed and the second term represents the power lost in the p-layer. Equation (8) indicates that one should make L as large as possible and W small. Let L=5 cm as this is a convenient limit for this parameter and W=1 cm as anything smaller will make the fabrication unnecessarily difficult. Since the surface resistivity of boron diffused silicon is about 10^{-3} ohm-cm, let o be 2×10^{-3} ohm-cm as an average resistivity of the ρ-type layer. Then (8) can be rewritten as

$$P = -\frac{kT}{q}\, I \ln\left[2 \times 10^9\, I + 3\text{x}10^8\, \exp(-10^3t)\right] \; -10^{-4}\,\frac{I^2}{t} \qquad (9)$$

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Equation (9) has been maximized with respect to I for various values of t and plotted in Figure 10. The upper curve gives the maximum value of the power for the first term in the above expression and the lower curve represents the maximum value for the entire expression. It is observed that the maximum power occurs for our chosen geometry with $t = 2\text{x}10^{-4}$ cm and that the maximum is quite broad. For this unit (5 cm^2) there is an efficiency of over 8% and a p-layer resistance of 0.5 ohm. Controlled experiments have been carried out at the Bell Telephone Laboratories where the junction depth was the only experimental variable. These devices were measured for several of their characteristics including efficiencies. These are plotted in Figure 11 and show good agreement with theoretical predictions.

The temperature dependence of the operating characteristics is always of interest in the description of semiconductor devices. Since the short circuit current depends only on the light current intensity, it will have no temperature dependence (except for minor corrections due to lifetime and series resistance changes). The most important temperature effect is through the change in open circuit voltage. It can be shown that the temperature variation of the open circuit voltage can be expressed in silicon by

$$dV_{oc}/dT = -0.00288 \text{ volt}/^{o}\text{C}. \qquad (10)$$

Since the output power of the device varies linearly with V_{oc}, the power decreases with temperature at a rate greater than 1/2% per degree centigrade. Measurements of the V_{oc} as a function of temperature on a typical unit are given in Figure 12 in which the straight line is the theoretical curve.

There are two other sets of measurements that have interesting consequences. The first of these has to do with the response of these devices as a function of the intensity of solar radiation. The I - V characteristics of a converter as a function of the light intensity are given in Figure 13. This unit has a series resistance of 1.8 ohms. It has been observed on this and on other units that the maximum available power under different intensities of illumination occurs at a constant voltage for a particular converter. In the case of the unit whose characteristics are illustrated in Figure 13, this voltage is 0.30 volt or 2/3 the open circuit voltage. As a consequence of this fact, the ideal load for a solar converter would be one that required a constant voltage; e.g., a storage battery.

The second set of measurements has to do with coupling these devices to get higher voltages and/or currents. Such experiments have been carried out and it has been found that these devices can be put in series or in parallel without any appreciable loss of efficiency. As an example, Figure 14 shows the current voltage characteristic of a group of nine units in series. The efficiency of the entire assembly is 8% while the efficiencies of the individual units varied from 7% to 9%.

Conclusions

The fact that the experimental results are in agreement with the design theory for silicon solar converters leads us to believe that one should be able to produce units for conversion of incident solar radiant energy into electrical energy with efficiencies as high as 10% with slight modifications of present techniques. A few individual cells have been made with such efficiencies.

Theoretical predictions and experimental confirmations indicate that the most important factor in the design of a solar energy converter is the series resistance of the device. Experimentally, units have been made with the series resistance being less than one ohm.

Some other measurements and applications of these devices will be discussed by our chairman at a later session during the week.

TABLE I

Item	Best Value	Limiting Factor
$J_{sc} = J_L$	30 ma/cm^2	Reflection
t_p	10^{-7} sec	Diffusion Technique
ρ	0.1 ohm-cm	Surface Solubility of B in Si is about 10^{18} cm^{-3}
D_p	10 cm^2/sec	Consistency with high t_p and ρ
μ_n	700 cm^2/volt-sec	Consistency with high t_p and ρ

LEGENDS FOR FIGURES

Fig. 1	Ideal model p-n junction power converter
Fig. 2	Ideal I - V characteristic of solar energy converter
Fig. 3	Maximum converted power density in bright sunlight as a function of enery gap of semiconductor
Fig. 4	Heuristic model of p-n junction power converter
Fig. 5	Theoretical I-V characteristic for various converters including series and shunt resistances
Fig. 6	Theoretical I-V characteristic for various converters with different series resistances
Fig. 7	Relative maximum available power as a function of the series resistance
Fig. 8	Experimental I-V characteristic of a converter before and after improving contact
Fig. 9	A geometry of a solar energy converter
Fig. 10	Maximum available power as a function of active p-layer thickness
Fig. 11	Experimental values of efficiencies versus thickness of p-layer
Fig. 12	Open circuit voltage as a function of temperature
Fig. 13	Family of experimental I-V characteristics of a solar energy converter for various light intensities
Fig. 14	I-V characteristic of a series connection of nine solar energy converters in bright sunlight

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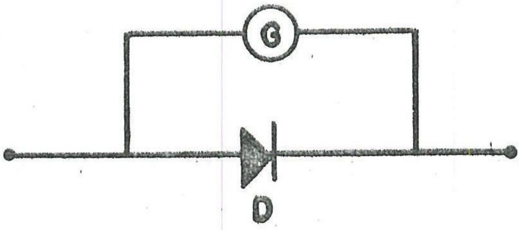

FIG. 1

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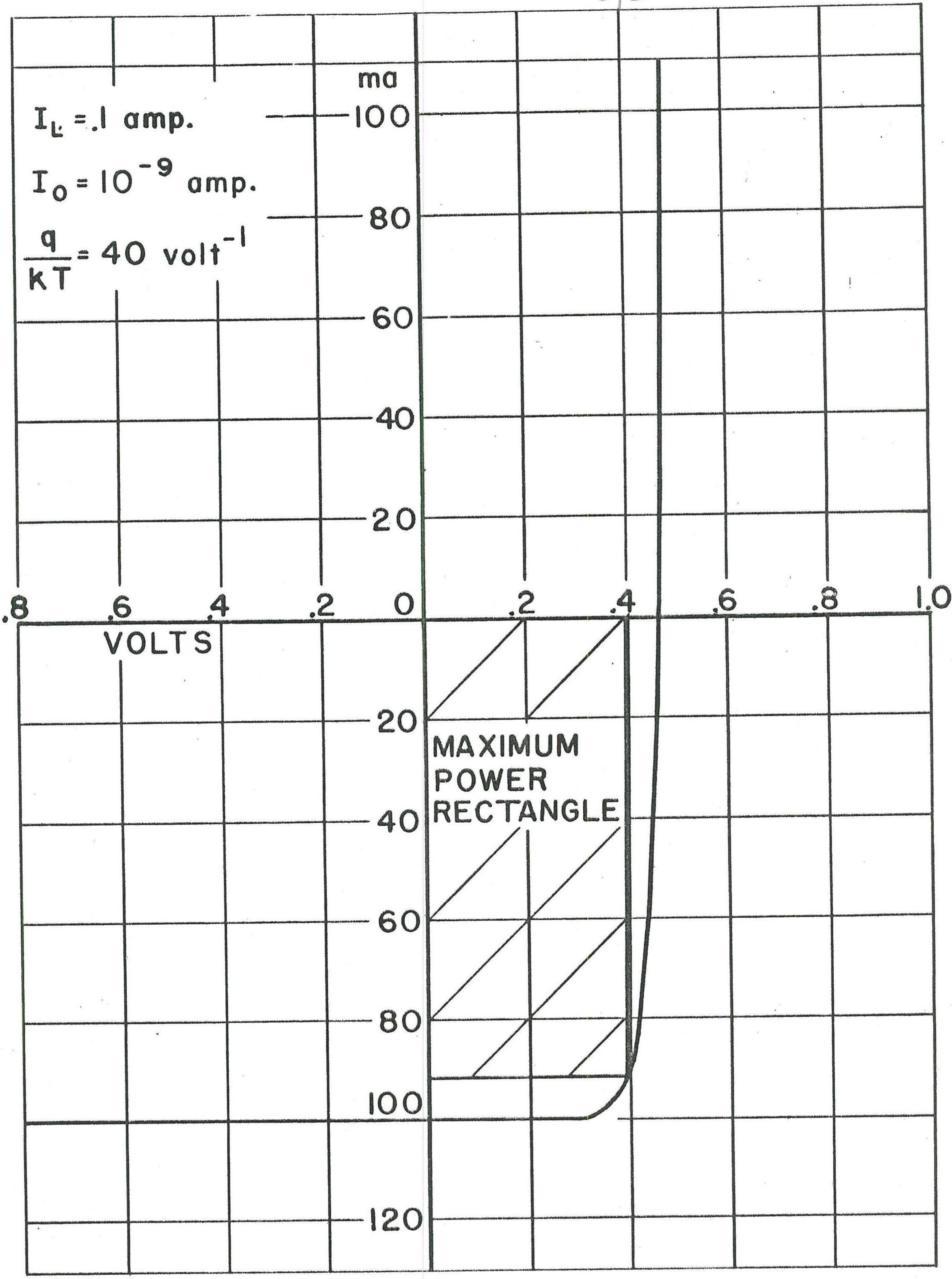

FIG. 2

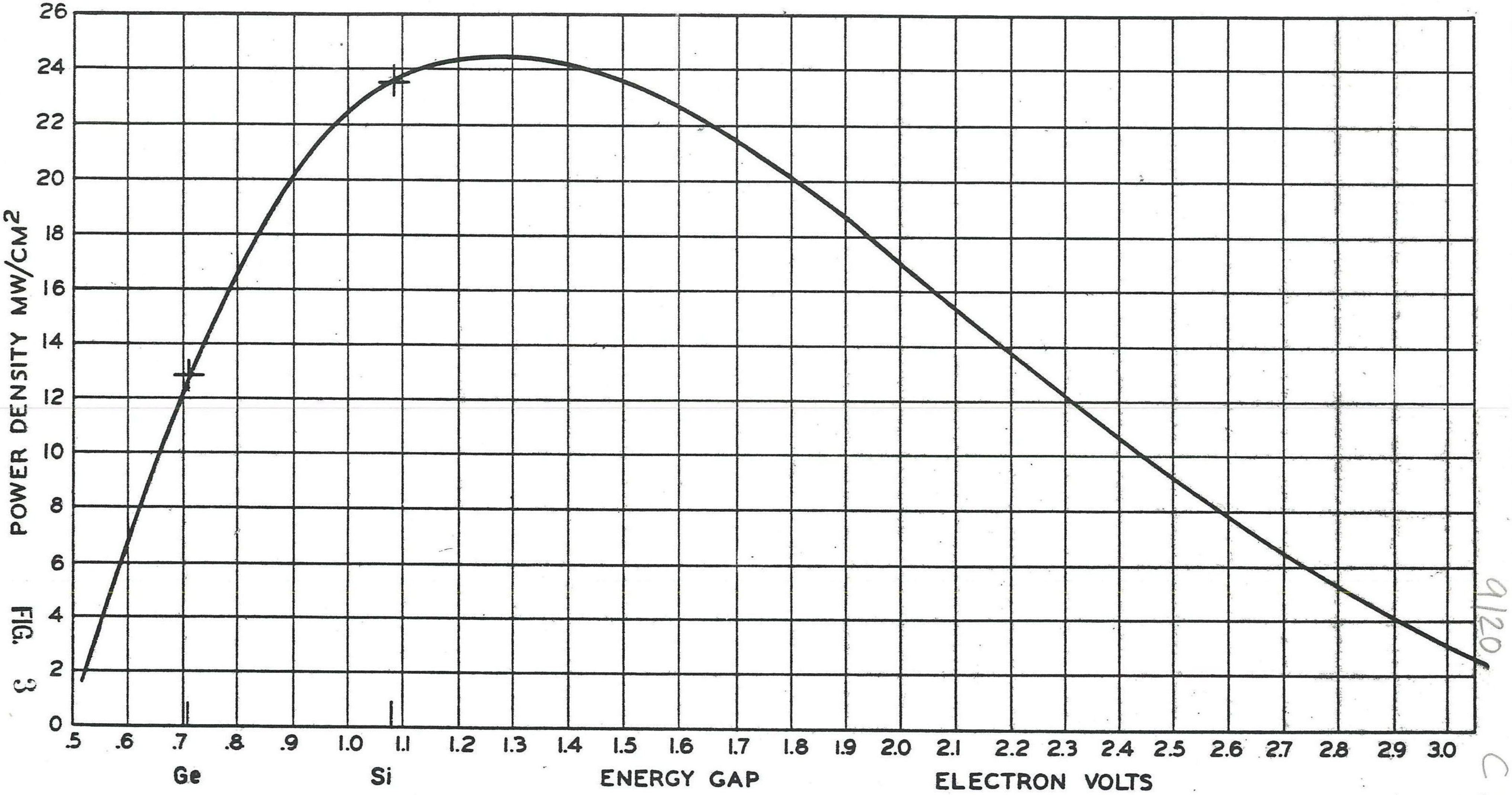

FIG. 3

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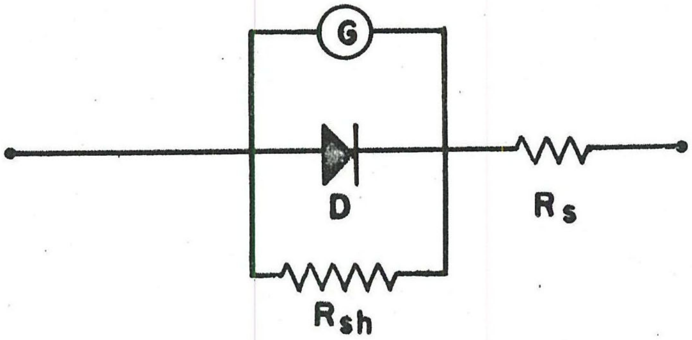

FIG. 4

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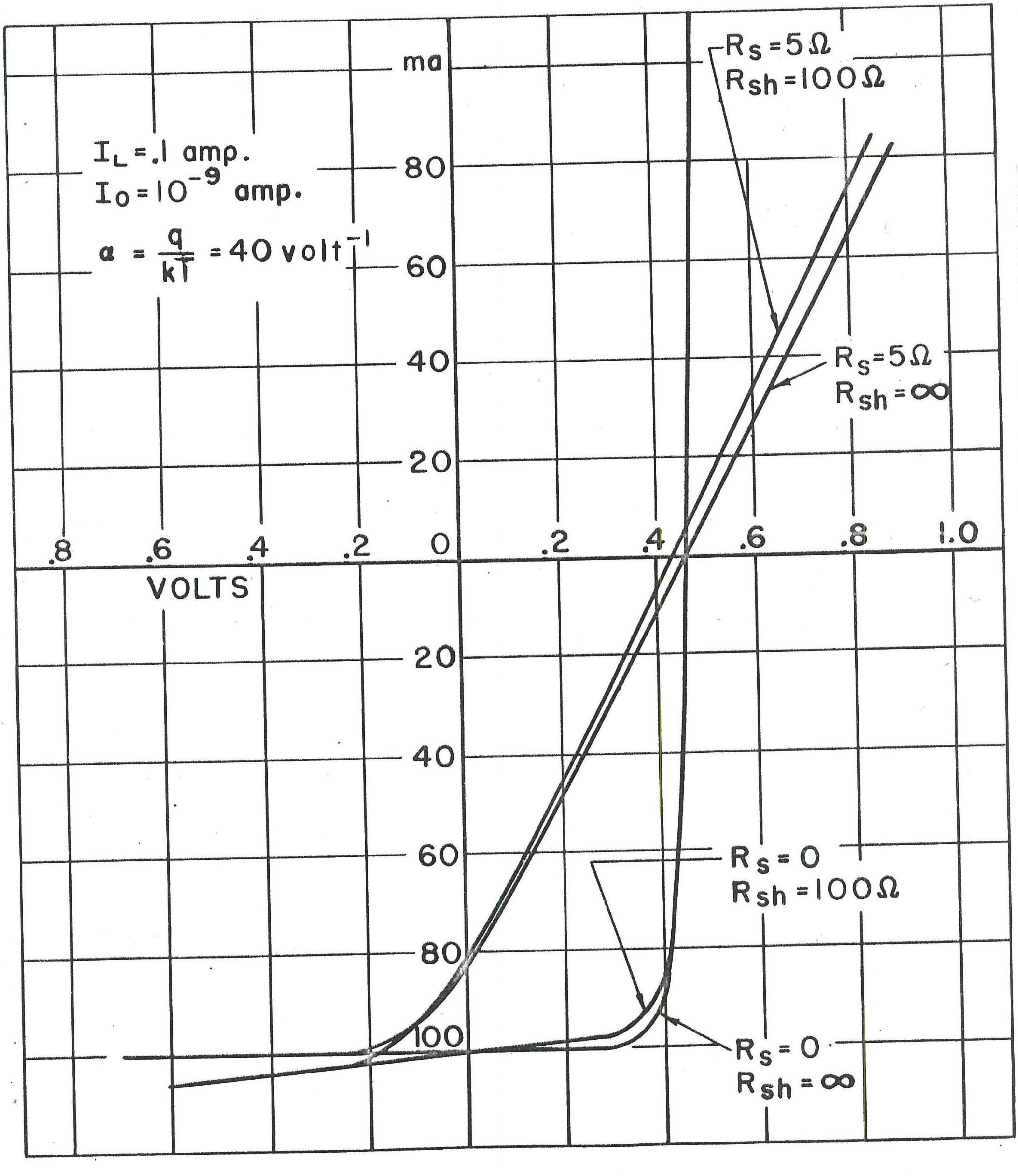

FIG. 5

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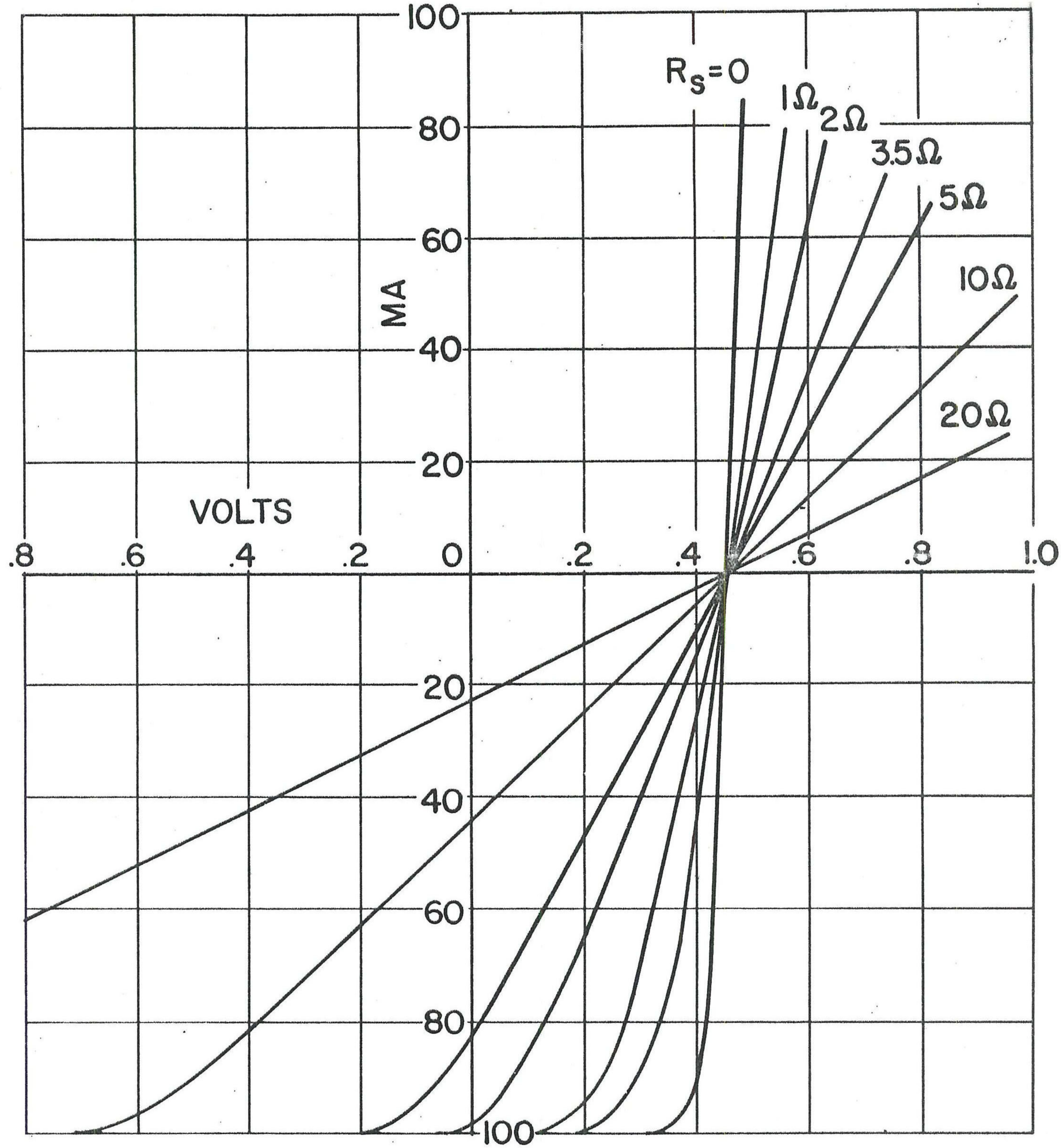
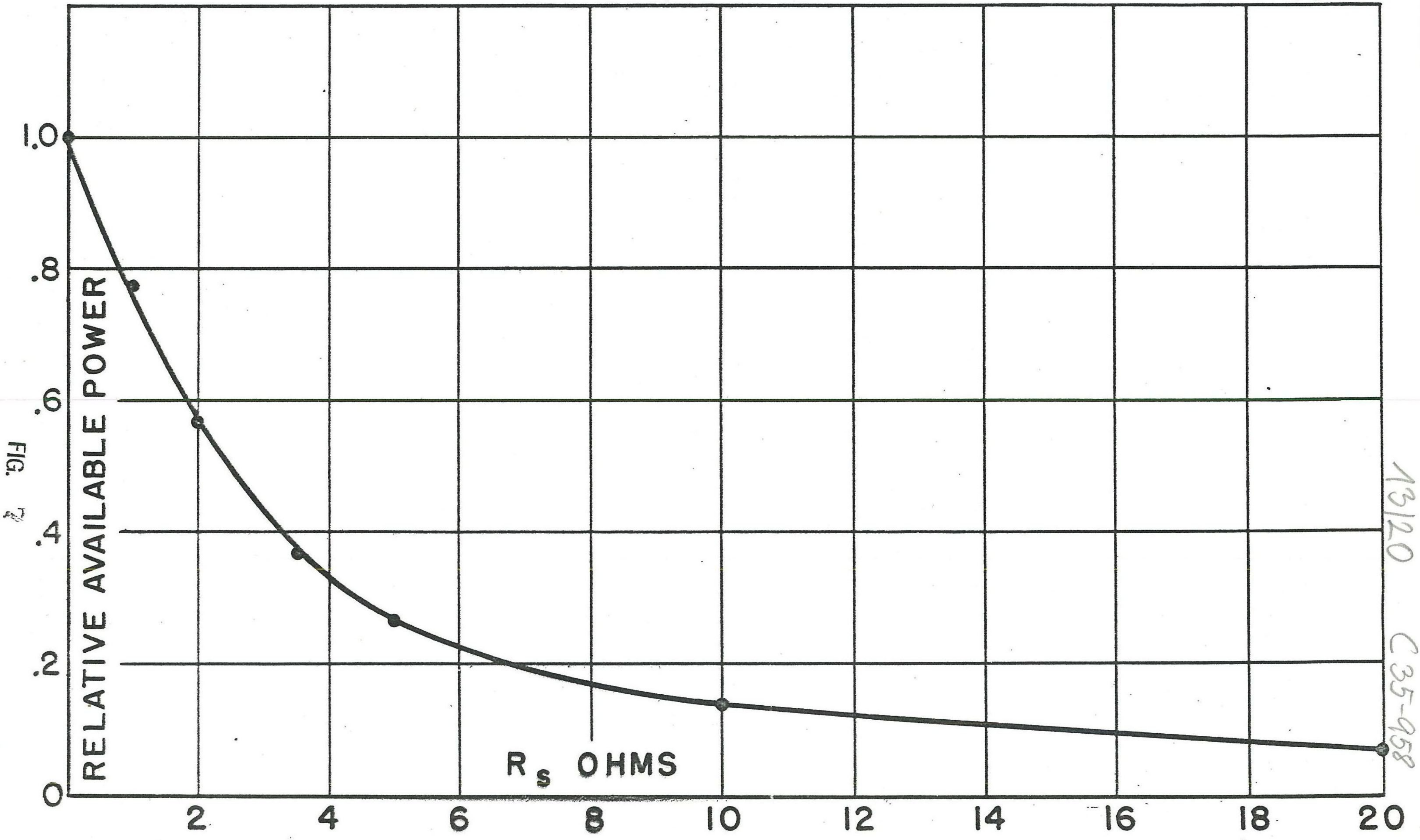


FIG. 6

FIG. 7



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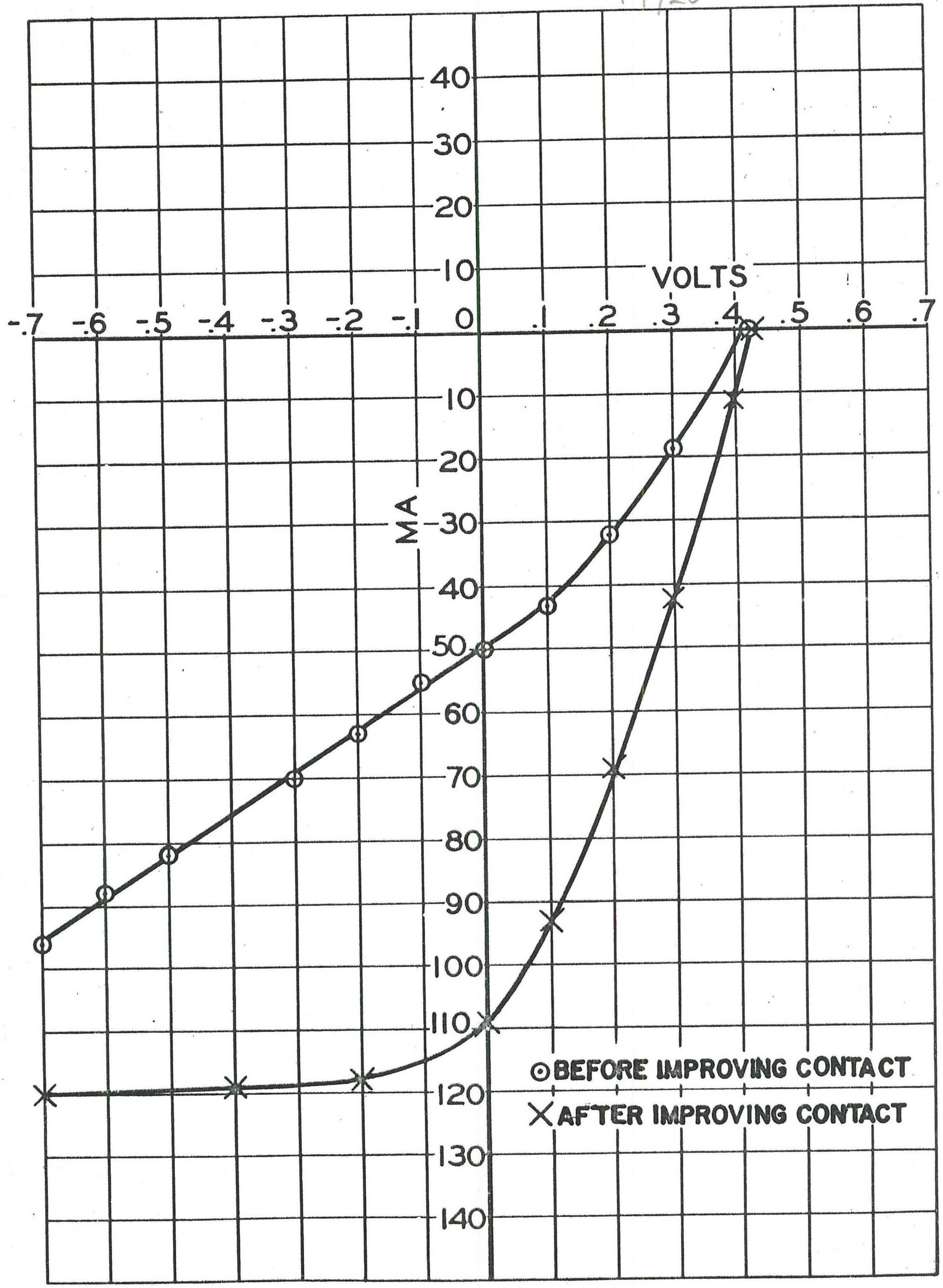
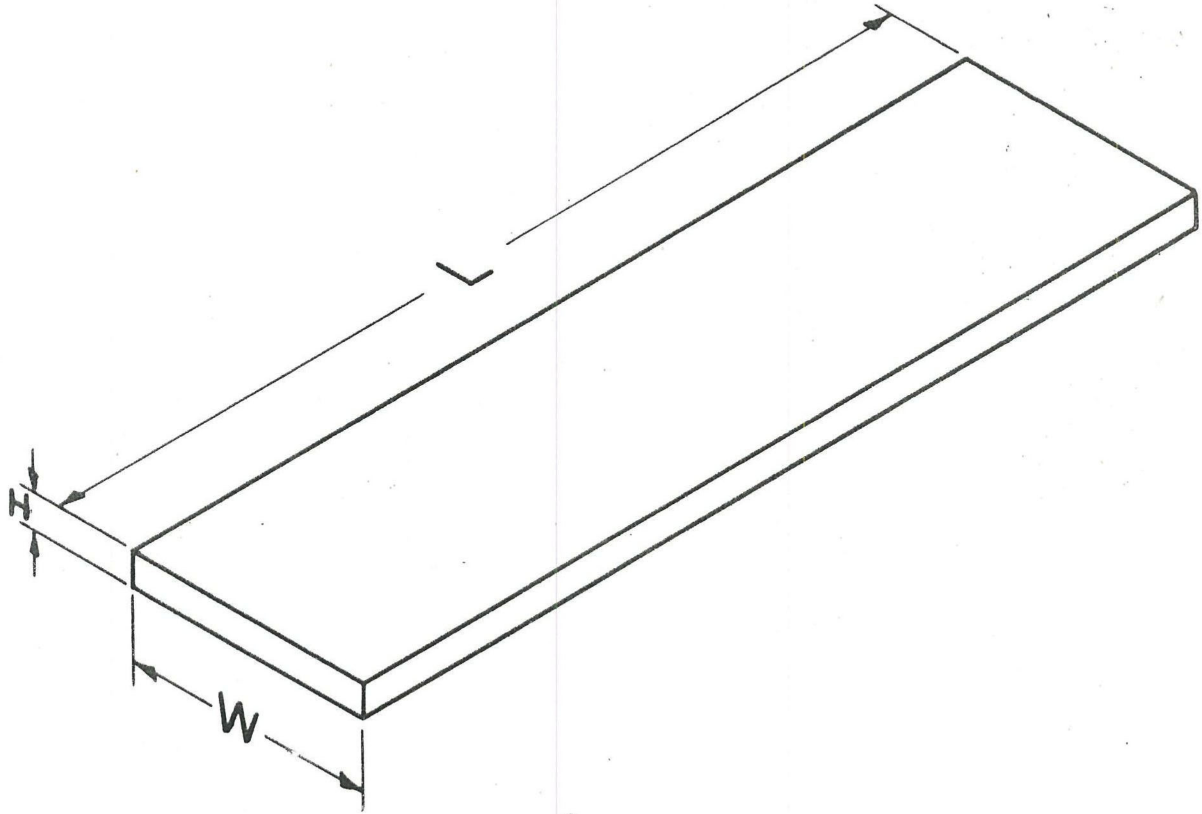
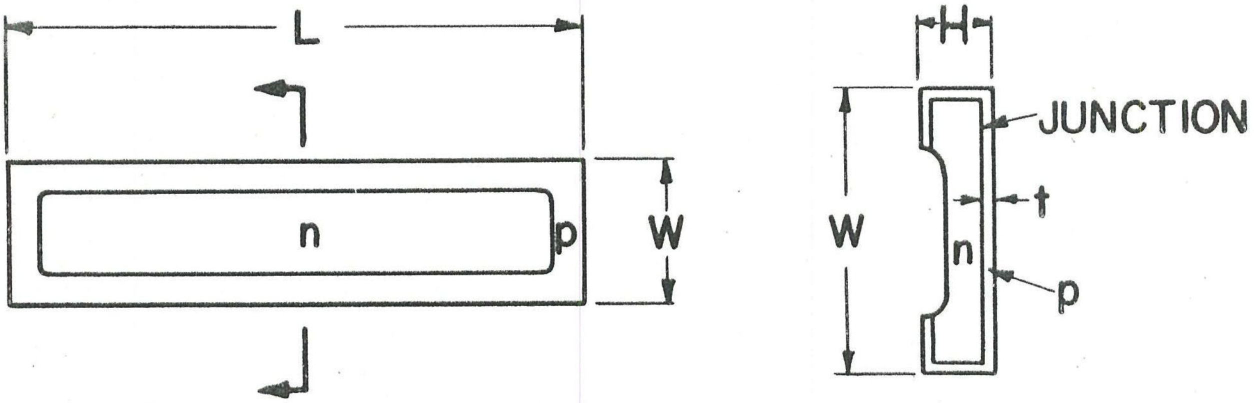


FIG. 8



A
TOP VIEW
ALL EXPOSED AREAS p-TYPE



B
BOTTOM VIEW

C
CROSS-SECTIONAL VIEW
SHOWING POSITION OF
JUNCTION

FIG. 9

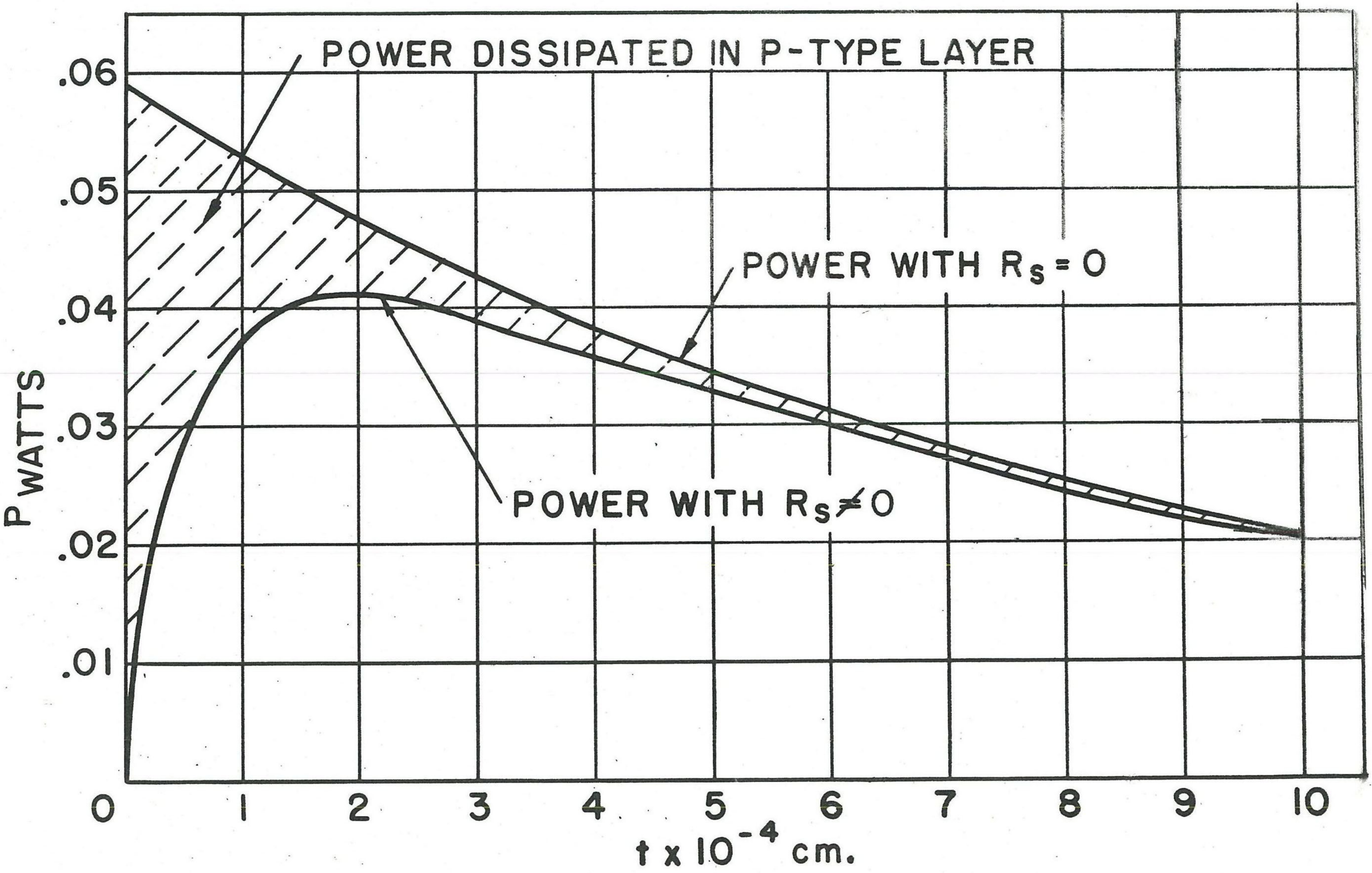

POWER DISSIPATED IN P-TYPE LAYER
POWER WITH $R_S = 0$
POWER WITH $R_S \neq 0$
P WATTS
.06
.05
.04
.03
.02
.01
0
1
2
3
4
5
6
7
8
9
10
t x 10^{-4} cm.

FIG. 10

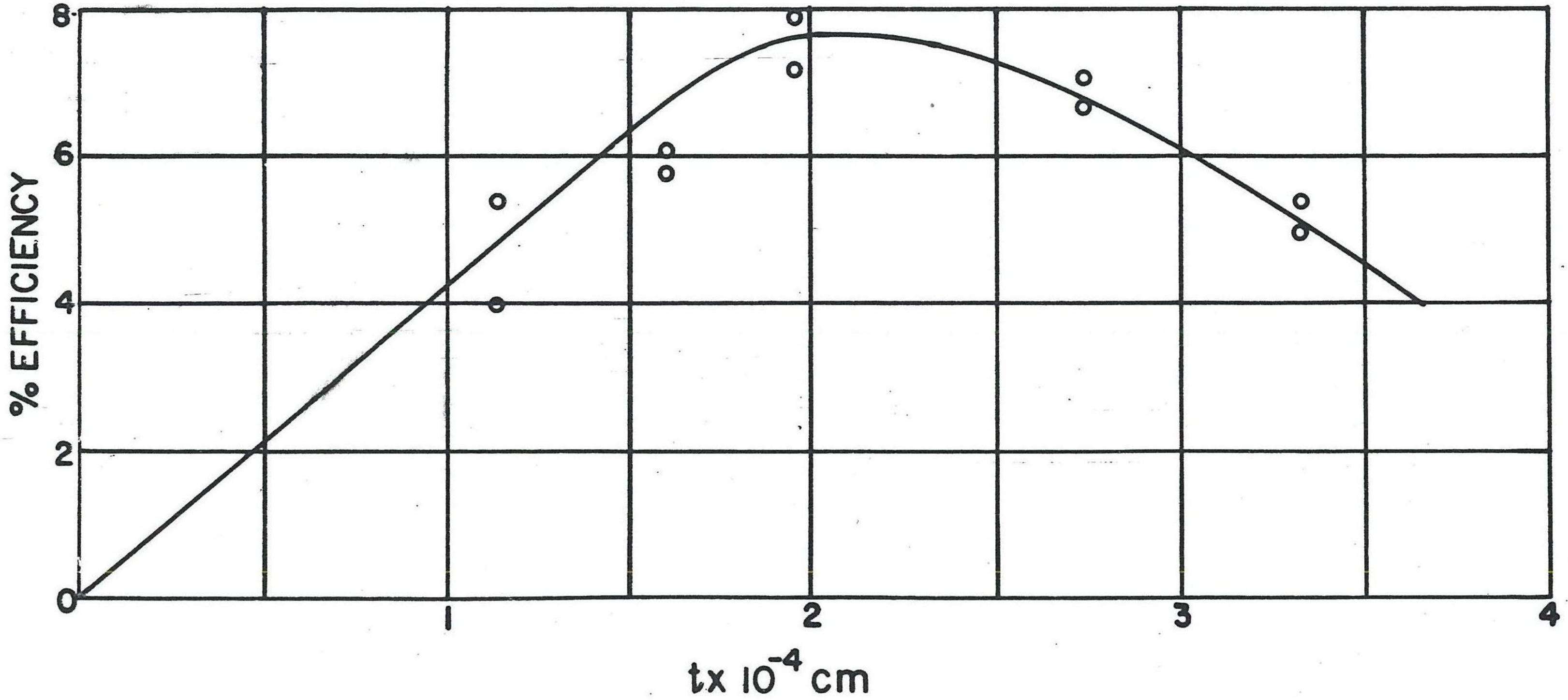
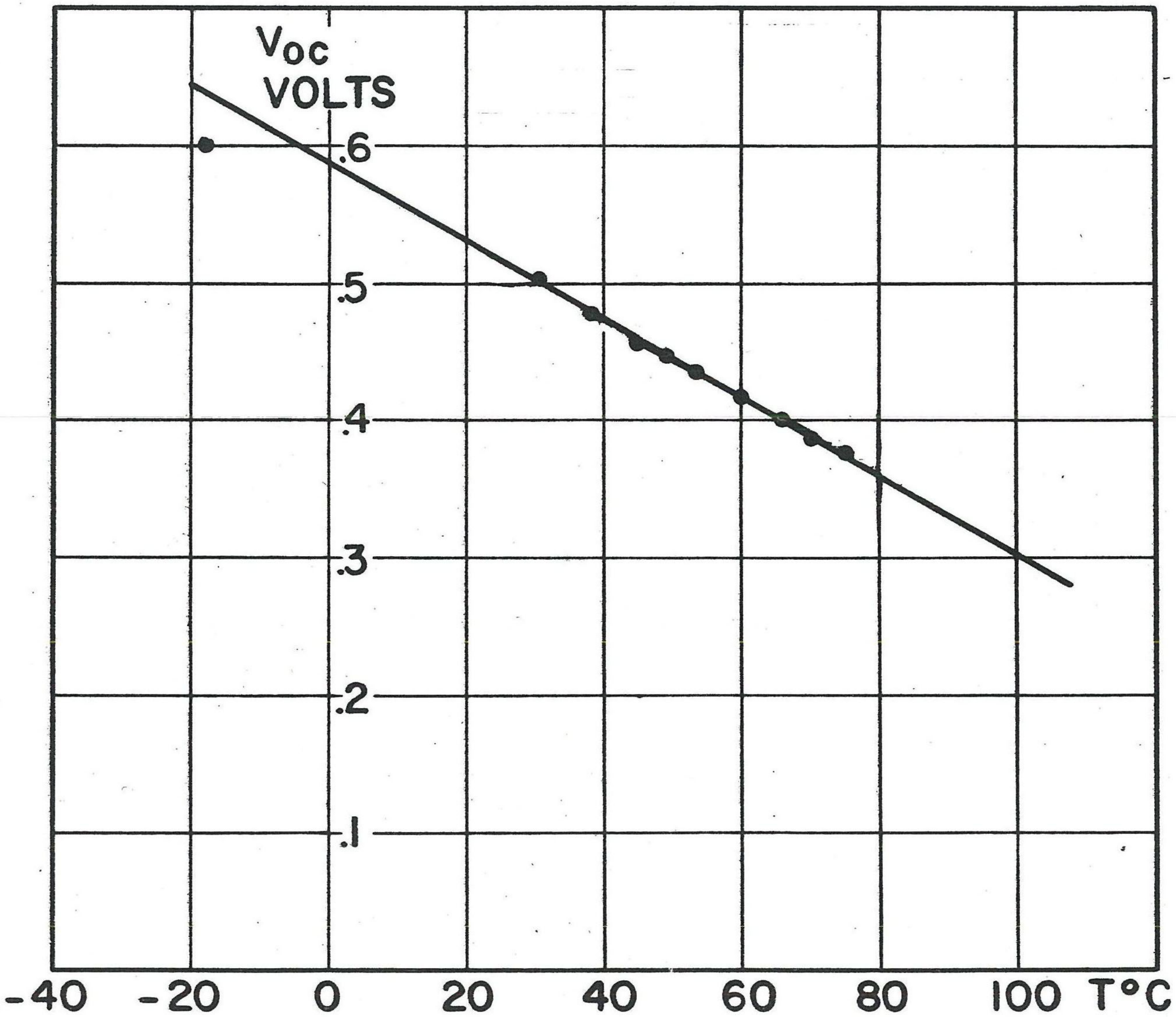


FIG. 11

FIG. 12



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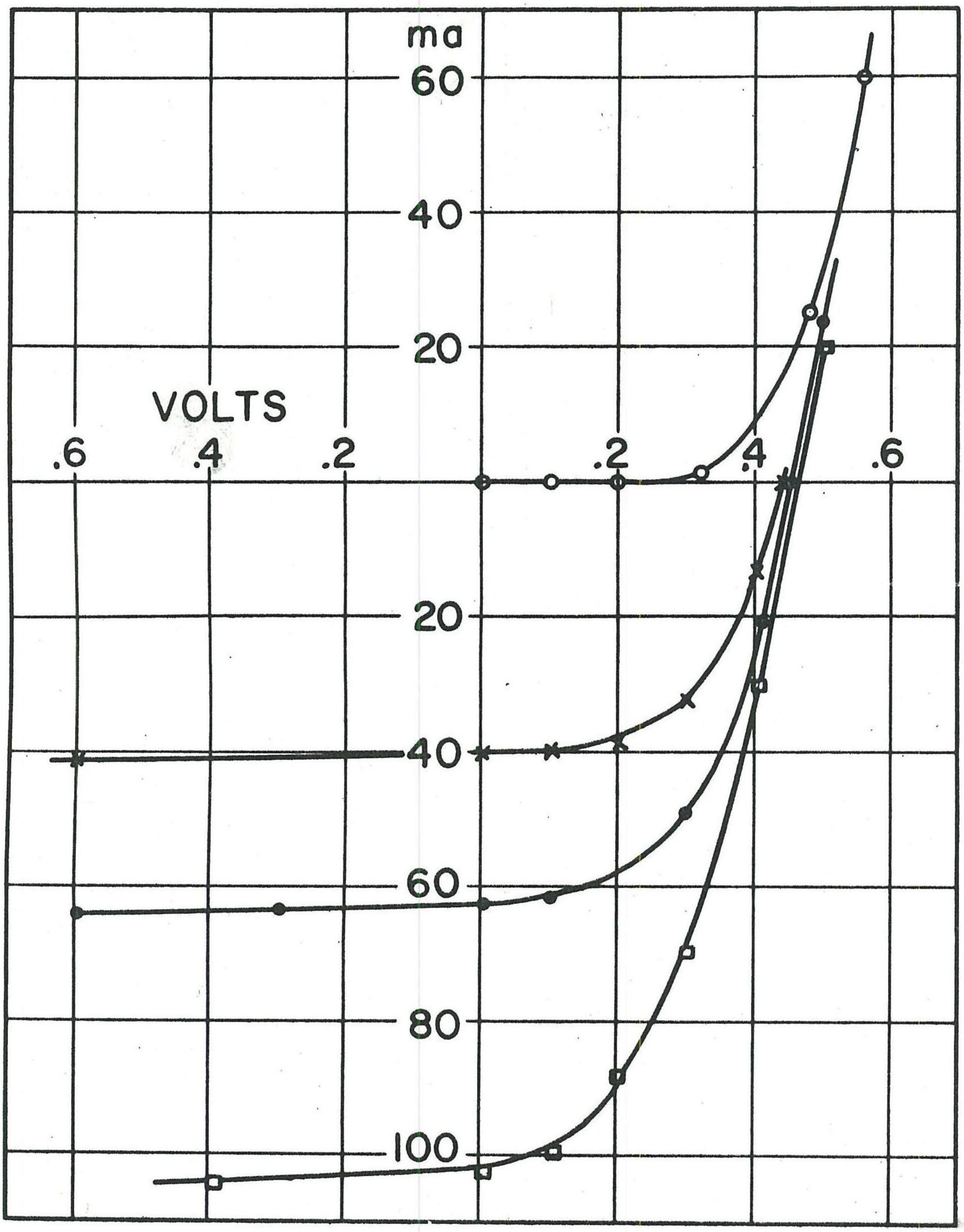

FIG. 13

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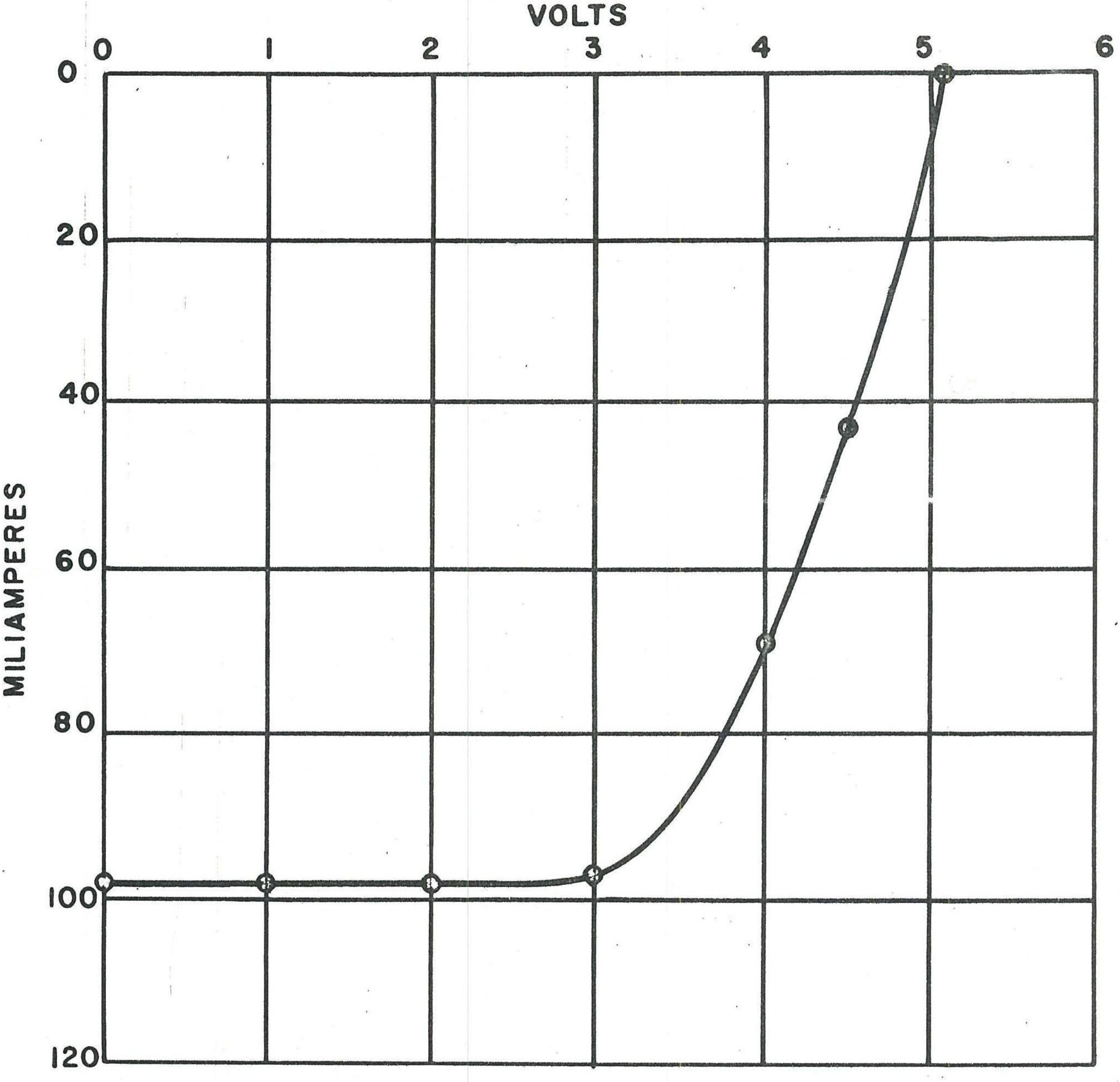

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