

THERMIONIC INJECTION AND SPACE-CHARGE-LIMITED CURRENT IN REACH-THROUGH p^+np^+ STRUCTURES

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Abstract—The current transport mechanisms of reach-through p^+np^+ and its related structures have been studied. It has been established that when the applied voltages is slightly greater than the reach-through voltage, at which the n layer is completely depleted, the current increases exponentially with voltage by thermionic injection mechanism. The current-voltage relationship is given by

$$J = A^* T^2 \exp \left[- \frac{q(V_{FB} - V)}{4kTV_{FB}} \right]$$

where A^* is the effective Richardson constant, T the temperature, V the applied voltage, and V_{FB} the flat-band voltage defined as $qN_D L^2 / 2\epsilon_s$ where N_D and L are the ionized impurity density and the length of the n layer respectively.

When the injected carrier density rises to a value comparable to the impurity density the space-charge-limited (SCL) effect causes the current to vary less rapidly with the applied voltage. The SCL effect is derived based on an accurate expression of the velocity-field relation, i. e., $v_s / (1 + E_s / E)$, where v_s is the scattering-limited velocity and E_s is the critical field given by the ratio of v_s to the low-field mobility. In the high current limit we obtain the linear current-voltage expression

$$J \simeq qN_D v_s (V / V_{FB}).$$

Experimental structures are made from epitaxial n on p^+ silicon substrate with an epitaxial layer thickness of $8.5 \mu\text{m}$ and doping concentration of $5 \times 10^{14} \text{ cm}^{-3}$. The second p^+ layer of about $1 \mu\text{m}$ is formed by diffusion. Good agreement have been obtained between the experimental results and theoretical predictions.

I. INTRODUCTION

In the present study, we shall analyze the current transport mechanisms in p^+np^+ structures when the applied field is high enough to "reach through" the thin

n -layer (Fig. 1). The voltage at which total depletion occurs is called the "reach-through voltage," V_{RT} , and is supposed to be substantially lower than the avalanche breakdown voltage of the reverse-biased p^+n junction.

For moderate currents, the limiting factor is found to be thermionic injection of carrier over the p^+n forward-biased junction. When the injected carrier density becomes comparable to the background ionized impurity density, the space charge of the moving carriers additionally limits the current. We shall divide the operation of a p^+np^+ structure into three regions.

- (1) *The low current region.* When the applied voltage is lower than the reach-through voltage, V_{RT} , the current is due to generation-recombination and surface leakage effects, and is practically indistinguishable from the leakage current of the reverse-biased p^+n junction.
- (2) *The thermionic injection region.* When the voltage is increased beyond the reach-through voltage, carriers are injected thermionically from the forward-biased p^+n junction. The current increases exponentially over several decades, and at any given current the voltage decreases as the temperature increases.
- (3) *The space-charge-limited region.* When the injected carrier density is comparable to or higher than the background ionized impurity density in the drift region, the space charge of injected carriers will tend to oppose further lowering of the barrier at the forward-biased junction. This is the so-called space-charge-limited effect. The current-voltage relation is then nearly independent of temperature.

We shall first describe the thermionic injection theory of the p^+np^+ reach-through structure in Section II. Section III considers the space-charge-limited effect where an accurate field-velocity relation is used. In Section IV we shall compare the theoretical predictions with the experimental results. A brief summary is given in Section V.

II. THERMIONIC INJECTION REGION

(1) Reach-Through and Flat-Band Voltages

A one-dimensional p^+np^+ structure is shown in Fig. 1(a), where the p^+ layers are heavily doped and the Fermi level approximately coincides with the edge of the valence band. Abrupt doping variation is assumed between the np^+ junctions as shown in Fig. 1(b).

When a voltage is applied across the p^+np^+ structure, one of the junctions is forward-biased and the other reverse biased. For simplicity, the depletion regions in the heavily doped p^+ layers are neglected, and only those depletion regions in the n layer are considered as shown in Fig. 1(c). The expressions for the depletion width are

$$W_1 = \sqrt{\frac{2\epsilon_s}{qN_D}(V_{bi} - V_1)} \quad (1)$$

$$W_2 = \sqrt{\frac{2\epsilon_s}{qN_D}(V_{bi} + V_2)} \quad (2)$$

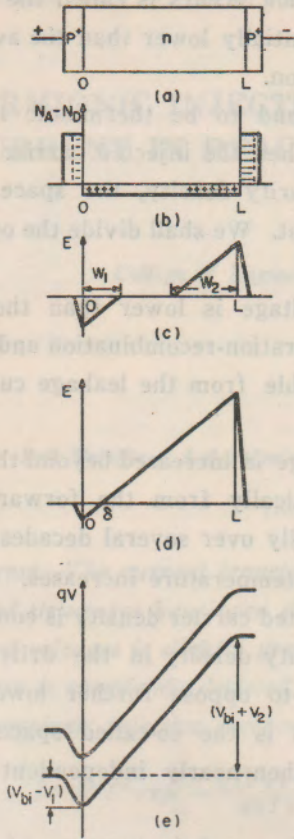


Fig. 1.

- (a) Schematic diagram of a p^+np^+ structure.
- (b) Charge distribution at equilibrium.
- (c) Electric field distribution before reach-through.
- (d) Electric field distribution after reach-through. δ is the reach-through point.
- (e) Potential profile after reach-through. V_{bi} is the built-in potential.

$$V_{bi} - V_1 = \frac{(V_{FB} - V)^2}{4V_{FB}} \tag{5}$$

The reach-through point δ as shown in Fig. 1(d) is given by

$$\frac{\delta}{L} = \frac{V_{FB} - V}{2V_{FB}} \tag{6}$$

(2) *I-V Characteristics for $V < V_{RT}$*

When the applied voltage is smaller than the reach-through voltage, the current is small, being limited by the reverse-biased junction. It is given approximately by the sum of the diffusion and the generation-recombination currents.

$$J \approx \frac{qD_p n_i^2}{[L - (W_1 + W_2)]N_D} (e^{\beta V_1} - 1) + \frac{qD_n n_i^2}{L_n N_A} + \frac{q n_i^2}{\tau_n} (W_1 + W_2) \tag{7}$$

where the first two terms on the right-hand side are the diffusion components in

where W_1 and W_2 are the depletion widths in the n layer for the forward- and reverse-biased junctions respectively, N_D is the ionized impurity density in the n layer, and V_{bi} is the built-in voltage which is assumed to be the same on both sides.

From Fig. 1(d), the reach-through voltage can be obtained from the condition $W_1 + W_2 = L$ which is the length of the n region:

$$V_{RT} = \frac{qN_D}{2\epsilon_s} L^2 - \sqrt{\frac{2qN_D}{\epsilon_s} (V_{bi} - V_1)} \tag{3}$$

It has been shown¹ that under negligible mobile space-charge effects, the first term on the right-hand side of Eq. (3) corresponds to the voltage at which the energy band is flat (or the electric field is zero) at the forward-biased junction. We can therefore define the flat-band voltage V_{FB} as

$$V_{FB} \equiv \frac{qN_D}{2\epsilon_s} L^2 \tag{4}$$

When the applied voltage is between the values of V_{RT} and V_{FB} (i.e., $V_{RT} < V < V_{FB}$), the relation between the applied voltage and the forward-biased barrier height, $V_{bi} - V_1$, is

the neutral region, the last one is the generation current in the depletion region, τ_n is the effective lifetime², n_i is the intrinsic carrier density, D_p is the diffusion constant of the holes in the n layer, and V_1 is the voltage drop at the forward-biased junction.

(3) *I-V Characteristics for $V > V_{RT}$*

After reach-through, mobile carriers are injected into the drift region by the thermionic emission process over the forward-biased junction. The injected current flowing toward the reverse-biased high-field junction can be expressed as

$$J_{p^+ \rightarrow n} = pq\bar{v}_x \tag{8}$$

where \bar{v}_x is the average velocity of the injected holes and p is the hole density injected from the p^+ layer to the n layer at the forward-biased junction. Since we have assumed that the p^+ layer is degenerate with its Fermi level coincident with the valence band edge, then

$$p \sim N_p = 2 \left(\frac{2\pi m_p^* kT}{h^2} \right)^{3/2} \tag{9}$$

where N_p is the effective density of states in the valence band.

The current density $J_{p^+ \rightarrow n}$ can be explicitly expressed as

$$\begin{aligned} J_{p^+ \rightarrow n} &= qN_p \left(\frac{m_p^*}{2\pi kT} \right)^{3/2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{v_{0x}}^{\infty} \frac{v_x dv_x dv_y dv_z}{1 + \exp\left[\frac{m_p^* (v_x^2 + v_y^2 + v_z^2)}{2kT} \right]} \\ &= \frac{4\pi q m_p^* K^2}{h^3} T^2 \sum_{r=1}^{\infty} \frac{(-1)^{r+1}}{r^2} e^{-\frac{rq(V_{bi}-V_1)}{kT}} \end{aligned} \tag{10}$$

where the velocity v_{0x} is the minimum velocity required in the x direction to surmount the barrier and is given by the relation

$$\frac{1}{2} m_p^* v_{0x}^2 = q(V_{bi} - V_1). \tag{11}$$

When $(V_{bi} - V_1) \gg kT/q$ Eq. (10) is reduced to the well-known thermionic emission expressions:

$$\begin{aligned} J_{p^+ \rightarrow n} &= \left(\frac{4\pi q m_p^* k^2}{h^3} \right) T^2 \exp\left[-\frac{q(V_{bi} - V_1)}{kT} \right] \\ &\equiv A^* T^2 \exp\left[-\frac{q(V_{bi} - V_1)}{kT} \right] \end{aligned} \tag{12}$$

where A^* is the effective Richardson constant.

Combination of Eqs. (5) and (12) yields the I-V relation for $V_{RT} < V < V_{FB}$

$$J_{p^+ \rightarrow n} = A^* T^2 \exp\left[-\frac{q(V_{FB} - V)^2}{4kT V_{FB}} \right]. \tag{13}$$

The conductance expression can also be derived from Eq. (13):

$$\frac{dJ}{dV} = \left[\frac{qA^*T}{2kV_{FB}} \right] (V_{FB} - V) \exp\left[-\frac{q(V_{FB} - V)^2}{4kT V_{FB}} \right]. \tag{14}$$

Since for a given value of $(V_{FB} - V)$, the numerical value in the first square bracket

is much higher than that of a metal-semiconductor-metal structure,¹ so the conductance of the p^+np^+ structure can be considerably higher.

A theoretical I-V plot of Eq. (13) for a typical silicon p^+np^+ structure is shown in Fig. 2 where the ionized doping in the n layer is $4.7 \times 10^{14} \text{ cm}^{-3}$ and the length (L) is $2.6 \mu\text{m}$. We note the rapid exponential increase of current with voltage. At higher current levels, however, we have to consider the space charge effect of the moving carriers.

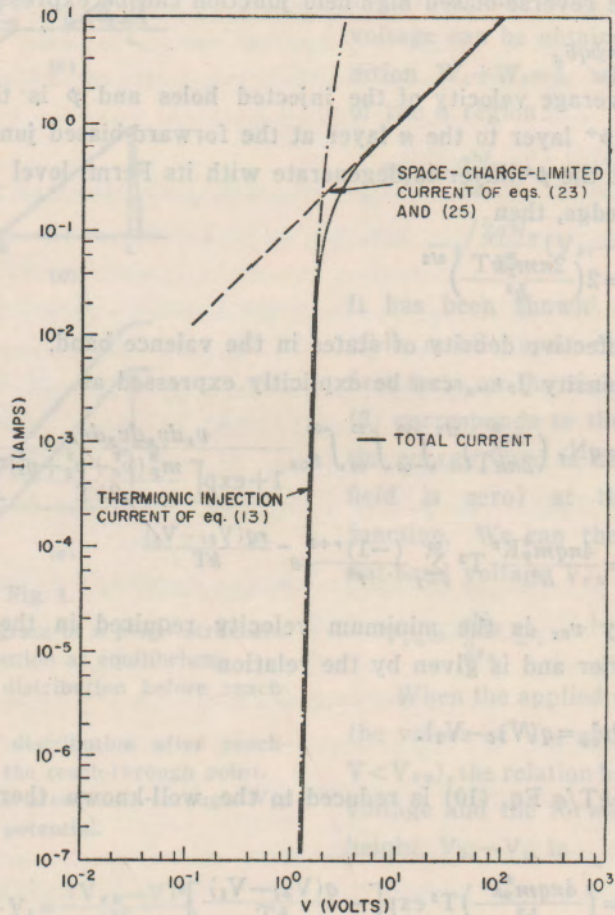


Fig. 2. Theoretical I-V characteristic obtained from Eqs. (13), (23) and (25) with the constants. $W(s)=L=2.65 \times 10^{-4} \text{ cm}$, $E_s = 3 \times 10^4 \text{ V/cm}$, $\rho=7.56 \times 10^{-5} \text{ coul}\cdot\text{cm}^{-3}$, $v_s=10^7 \text{ cm/sec}$.

III. SPACE-CHARGE-LIMITED REGION

When the current is sufficiently high such that the injected carrier density is comparable to the background ionized impurity density, the mobile carriers will influence the field distribution in the drift region.^{3,4} This is the space-charge-limited effect. The Poisson equation for the n layer (neglecting both diffusion and spread of velocity in the injected carriers) can be written as:

$$\frac{dE}{dx} = \frac{\rho}{\epsilon_s} + \frac{J}{\epsilon_s v(E)} \tag{15}$$

where ρ is the charge density of the ionized impurities in the n layer, v is the velocity of mobile holes and is a function of the electric field in the drift region, and J is the injected current density.

We shall solve the above equation using an accurate expression of v - E relation (for silicon) given as⁵

$$v(E) = \frac{v_s}{1 + \left(\frac{E}{E_s}\right)} \tag{16}$$

where v_s is the scattering-limited velocity, E is the electric field in the n layer, and E_s is the critical field given by the ratio of v_s to the low-field mobility.

We shall introduce a variable "s" defined as:^{3,4}

$$s = \int_0^x \frac{dx}{E}; \quad ds = \frac{dx}{E}. \tag{17}$$

By combining Eqs. (15), (16) and (17), we obtain

$$ds = \frac{dE}{\alpha(1 + \beta E)} \tag{18}$$

where

$$\alpha = \frac{JE_s}{e_s v_s} \tag{19}$$

and

$$\beta = \frac{\rho v_s + J}{JE_s} \tag{20}$$

Integrating (18) and adjusting the integration constant, so that $s=0$ when $E=0$, we obtain

$$E = \frac{1}{\alpha\beta} (e^{\alpha\beta s} - 1) \tag{21}$$

with the relation

$$\frac{dV}{ds} = -E^2. \tag{22}$$

By choosing the integration constant to satisfy the condition $s=0$ when $V=0$, we get

$$V = \frac{1}{\alpha^2\beta^2} \left(\frac{1}{2\alpha\beta} e^{2\alpha\beta s} - \frac{2}{\alpha\beta} e^{\alpha\beta s} + \frac{3}{2\alpha\beta} + s \right). \tag{23}$$

The total thickness W of the n layer can be obtained by integrating the following equation

$$W(s) = \int_0^s E \, ds. \tag{24}$$

We obtain

$$W(s) = \frac{1}{\alpha\beta} \left(\frac{1}{\alpha\beta} e^{\alpha\beta s} - \frac{1}{\alpha\beta} - s \right). \tag{25}$$

For a given width of the drift region and a given ionized doping density ρ , we can use Eqs. (23) and (25) to obtain the I-V relation. A typical example is shown in Fig. 2 with doping and length given previously. The scattering-limited velocity (v_s) is 10^7 cm/sec and the critical field (E_s) is 3×10^4 V/cm for holes in silicon at room temperature.

We note that the space-charge-limited effect causes the current to depart considerably from the exponential increase. At high current levels, the current tends to vary linearly with the applied voltage. The limiting case can be derived from Eq. (15) by assuming that $v(E) = v_s$ over the entire n region and that the second term on the right-hand side is much larger than the first term. We then have

$$\frac{dE}{dx} = \frac{J}{\epsilon_s v_s}. \quad (26)$$

Integrating twice (with boundary conditions $E=0, V=0$ at $x=0$) yields

$$J = \frac{2\epsilon_s v_s}{L^2} V = qN_D v_s (V/V_{FB}). \quad (27)$$

By combining Eqs. (13), (23), and (27), the total current can be obtained as indicated in Fig. 2.

IV. EXPERIMENTAL PROCEDURE AND RESULTS

In order to show that the mechanism of the current flow in a p^+np^+ and its complementary structures is due to thermionic injection when the n layer is totally depleted, we have fabricated two kinds of devices, one is the p^+np^+ structure, and the other is the Mnp^+ structure, where M stands for a metal contact.

(1) Device Fabrication

The semiconductor substrate for the structures was a p -type, single-crystal silicon wafer, $\langle 111 \rangle$ oriented, with a resistivity of 0.001–0.002 ohm-cm. The epitaxial n -type layer was $8.5 \pm 0.5 \mu\text{m}$ thick with a 9 ohm-cm resistivity. The substrate was polished to a final thickness of $20 \pm 1 \mu\text{m}$. Half of the wafer was Boron-diffused to form the p^+np^+ structure. The thickness of the diffused p^+ layer was about $1 \mu\text{m}$. For the metal- n - p^+ structure, a layer of Pt, 300 Å thick, was sputtered onto the other half of the wafer and sintered at 700°C to form a PtSi metal-semiconductor contact.

The wafer was mounted on a ceramic disc. Using Apeizon wax and a $3 \mu\text{m}$ layer of Au was plated onto the top side. A standard photolithographic method was used to define circular patterns and the unprotected top gold layer was removed by iodide etch yielding circular arrays of gold dots on the wafer with an area of $3.14 \times 10^{-4} \text{ cm}^2$. The devices were separated by etching. After cleaning they were mounted onto a "V"-type package.

(2) I-V Measurement

The current-voltage results were measured with dc voltage source for current below 1 mA; and for higher currents pulse measurement was used to avoid heating effects.

Figure 3 shows the experimental and theoretical results of I-V characteristics for a p^+np^+ structure at three temperatures.

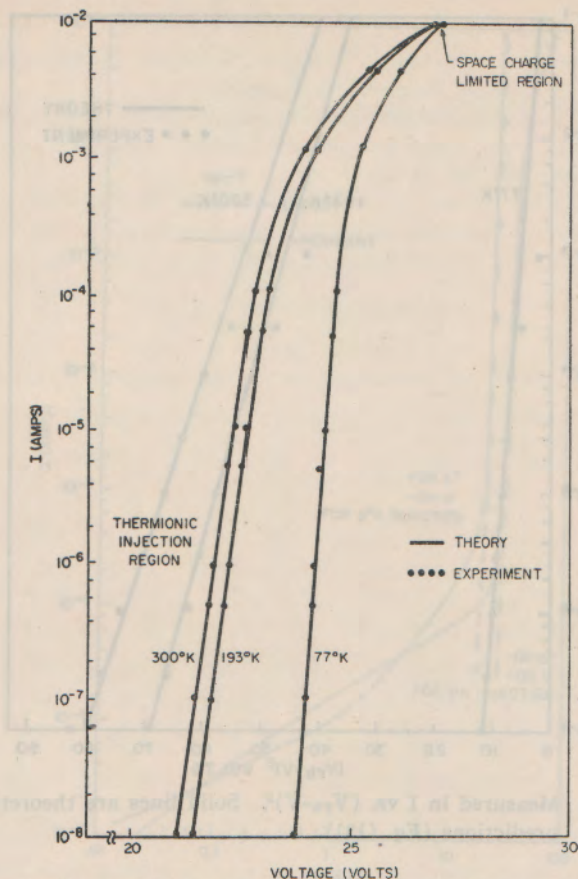


Fig. 3. Measured I-V characteristics of a p^+np^+ structure at three temperatures.

The flat-band voltage V_{FB} as defined in Eq. (4) is 30.1 V at 300°K and 193°K, and is 26.25 V at 77°K. The difference in V_{FB} is due to 10% deionization at 77°K. We note that (1) the measured current increases rapidly in the thermionic injection region and (2) the current varies approximately linearly with voltage in the SCL region. The theoretical curves are obtained using the method outlined in Fig. 2. Both the overall results and the temperature dependence of the I-V characteristics are in good agreement.

To study in more detail about the thermionic injection region, Fig. 4 shows $\ln I$ versus $(V_{FB}-V)^2$. The linear dependence over a wide temperature range is in good agreement with Eq. (13). In addition the slopes are found to be consistent with the theoretical value of $(q/4kT V_{FB})$. From the intercepts at $V_{FB}-V=0$, one can obtain the effective Richardson constant, A_p^* . The value of A_p^* which is obtained from the plots, is (75 ± 10) amp/cm²/°K² in agreement with that of metal-semiconductor-metal structures.¹

Figure 5 shows the difference in I-V characteristics for thermionic injection from the p^+n junction and from the metal- n contact. These two curves were measured on the same Mnp^+ device with opposite applied bias polarities. The main difference is that for injection from the forward-biased p^+n junction the factor

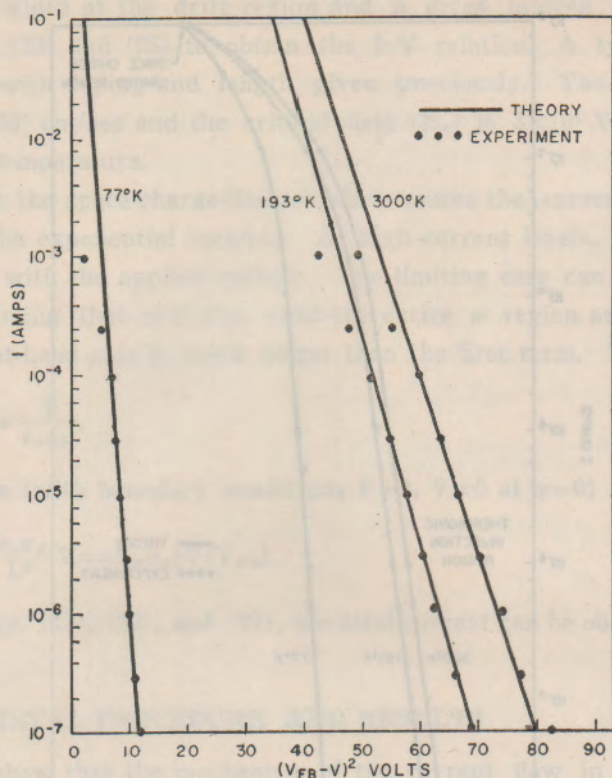


Fig. 4. Measured $\ln I$ vs. $(V_{FB}-V)^2$. Solid lines are theoretical predictions (Eq. (13)).

$e^{-q\varphi_{p2}/kT}$ is absent, where φ_{p2} is the fixed hole barrier height at the metal-semiconductor boundary and is equal to 0.2 V for the PtSi-Si contact.¹ Hence at 300°K for a given applied voltage the current for p^+n injection is expected to be about 3000 times larger than that for Mn injection. And conversely, for a given current the conductance for p^+n injection can be considerably larger (Eq. (14)). The experimental results as shown in Fig. 5 indeed confirm the predictions.

V. SUMMARY

The I-V characteristics of reach-through p^+np^+ and Mnp^+ structures have been studied. Good agreements have been obtained between theoretical predictions and experimental measurements.

It is shown that when the applied voltage is slightly higher than the reach-through voltage, the current is due to the thermionic injection process. The expression of the thermionic injection current for the p^+np^+ structure does not contain the factor $e^{-q\varphi_{p2}/kT}$. This means that the saturation current will be higher than that of Schottky type structures.

At high injection levels where the space-charge-limited effect occurs, the use of an accurate $v-E$ relation in Poisson's equation gives a linear relationship between current and voltage which is in better agreement with the experimental results than using constant mobility⁴ or $v \sim \sqrt{V}$.³

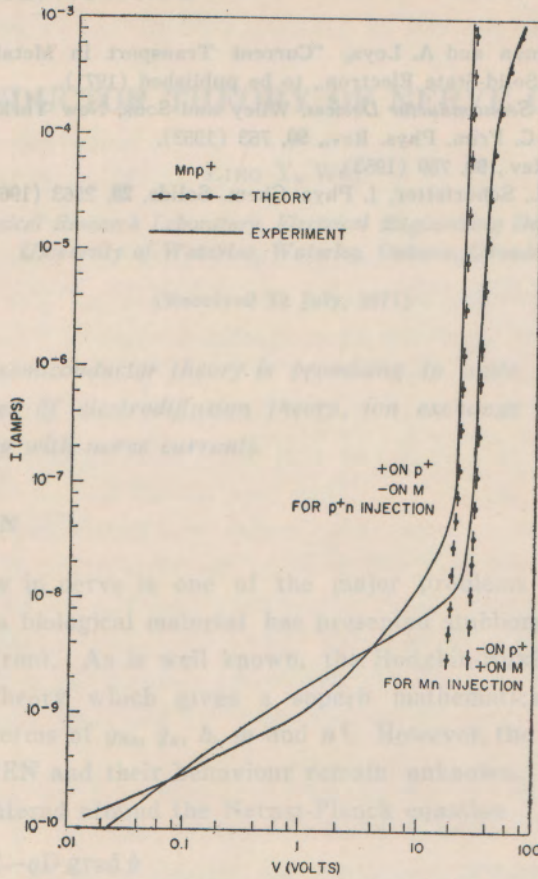


Fig. 5. Measured I-V characteristics of an Mnp^+ structure at opposite bias polarities.

From the above considerations we conclude that the p^+np^+ structure has two regions in series: (1) the injection region, i.e., the forward-biased junction where thermionic injection occurs, and (2) the drift region, i.e., the depleted n layer where injected holes can drift through. When the current density is small, the injection region dominates the transport process and the current varies as $A^*T^2 \exp[-q(V_{FB} - V)/4kTV_{FB}]$, where A^* is the effective Richardson constant and V_{FB} is the flat-band voltage. When the current density is comparable or larger than qN_Dv_s , where N_D is the ionized impurity density and v_s is the scattering-limited velocity, then space charge in the drift region dominates, and the current varies approximately as $qN_Dv_s(V/V_{FB})$.

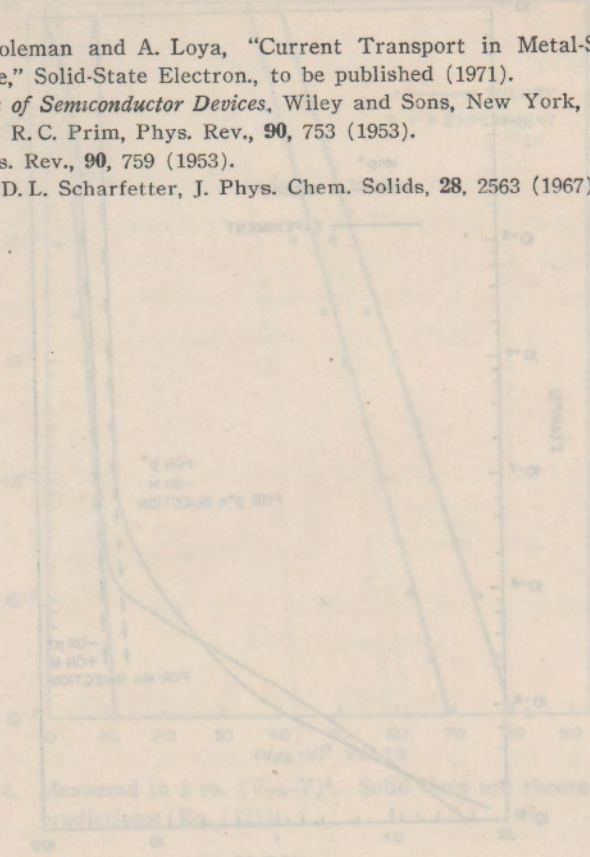
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Fig. 4. Plot of $\ln(I/I_0) - (V/V_0) - (V/V_0)^2$ vs. V/V_0 for various values of V_0 .



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