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Influence of dislocations on dark current of multicrystalline silicon N⁺ P junction

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Résumé. — Une analyse détaillée des composantes du courant d'obscurité en polarisation directe dans des jonctions N⁺ P au silicium multicristallin est proposée. Elle tient compte des dislocations qui traversent la jonction et sa région de charge d'espace. Un modèle a été établi, attribuant une conductibilité aux dislocations. Le courant traversant ces défauts varierait comme $\exp(qV/2 kT)$, et serait le courant dominant aux faibles tensions de polarisation ($V < 300$ mV). Toutefois pour des tensions supérieures à 300 mV, ce courant peut être comparable au courant de diffusion provenant des régions neutres de la jonction, lorsque la densité des dislocations est supérieure à 10^5 cm⁻². Les prévisions du modèle sont en bon accord avec les résultats expérimentaux.

Abstract. — A detailed characterization of the dark current in large grained polycrystalline silicon cells is given. This current is greatly influenced by the presence of dislocations. A new model for the shunt current transmitted by these defects is given. It is found that this current is proportional to $\exp(qV/2 kT)$. The comparison between the three essential components of the dark current (diffusion, recombination and shunt component) indicates that the shunt component is the dominant one at low applied voltage ($V < 300$ mV). Even at higher voltage ($V > 300$ mV) the shunt component is comparable to the diffusion one when the dislocation density is greater than 10^5 cm⁻². The computed results are in agreement with experimental ones.

1. Introduction.

The dark current in ideal N⁺ P junction produces two essential components. One represents the diffusion current within emitter and base regions while the second component represents the recombination of carriers within the space charge region (SCR). The existence of dislocation lines which cross the P-N junctions introduces additional dark current components. Both recombination of carriers at dislocations (the effect that is normally emphasized) and shunting due to a carrier motion along dislocation could increase the dark reverse current of P-N junction.

The shunting effect of dislocations was investigated by many authors [1, 2]. One of the works in this field is the one-dimensional model of Ranjith and Morrison [3]. These authors found that room-temperature data on mechanically damaged Metal-Insulator-Semiconductors (MIS) solar cells are best interpreted in terms of conduction of captured carriers along dislocations.

In the present paper we have developed a new model for the dark current supported by the conduction through dislocations. This current is found to be proportional to $\exp(qV/2 kT)$ like the conventional recombination current, however the preexponential factor is depending on parameters related to dislocations, especially the density and the radius of the dislocation pipe. All other dark current components are analysed and compared together.

2. Model.

A N^+P junction with a very thin emitter and a thick P-type base, made by conventional phosphorus diffusion in columnar large grained polycrystalline silicon was considered.

We assumed that :

- (i) the grains contained a regular array of homogeneously recombining dislocations that were perpendicular to the junction area ;
- (ii) the diameter of the dislocation core with its associated space-charge region was much smaller than the distance between two dislocations ;
- (iii) the contribution of the emitter was negligible ;
- (iv) pure ohmic contacts were applied to the back surface.

The preceding assumptions simplify obviously the computations. However they are acceptable in thin (200 μm) multicrystalline silicon wafers cut of cast ingots elaborated by directionnal solidification. In these samples, a large part of dislocation line cross the entire wafer perpendicularly to the junction (assumption (i)).

The mean dislocation density present in these wafers is sufficiently low (below 10^6 cm^{-2}) in order that assumption (ii) is verified. And finally, the process involved for the cells manufacturing lead to a highly doped and very thin ($\cong 0.3 \mu\text{m}$) emitter and a pure ohmic back contact (assumptions (iii) and (iv)).

2.1 RECOMBINATION CURRENT DUE TO DISLOCATIONS WITHIN THE SCR. — The presence of dislocation in the SCR introduces a component of an electric field directed towards the dislocation axis. This component which arises from the charge in the dislocation core results in a two-dimensional boundary value problem. The solution of this problem would describe the two-dimensional flow of holes and electrons to the dislocations where they are recombined. Following the theory previously proposed by Fossum and Lindholm [4], the net rate of recombination per unit length of dislocation could be given by :

$$U_s = \frac{1}{2} (s_p s_n)^{1/2} n_1 \exp \frac{E_{fn} - E_{fp}}{2 kT} \quad (1)$$

The recombination current at a dislocation within the SCR is :

$$I_{\text{dis}}^{\text{rec}} = \frac{q}{2} (s_p s_n)^{1/2} n_1 W \exp \frac{qV}{2 kT} . \quad (2)$$

For a dislocation density N_{dis} , the component of dark current density which represents the recombination of carriers at dislocations within SCR could be expressed by :

$$I_{\text{dis}}^{\text{rec}} = \frac{q}{2} (s_p s_n)^{1/2} n_1 W N_{\text{dis}} \exp \frac{qV}{2 kT} . \quad (3)$$

2.2 DIFFUSION CURRENT DUE TO DISLOCATIONS WITHIN QUASI-NEUTRAL BASE. — This component of the dark current is due to the recombination of carriers at dislocations within the quasi neutral base (the diffusion component). We have already discussed this component in details [5, 6]. A closed expression for this component was obtained which was written as :

$$J_{\text{dis}}^{\text{dif}} = J_{\text{od}} \left(\exp \left(\frac{qV}{kT} \right) - 1 \right) \tag{4}$$

with

$$J_{\text{od}} = qD_n \frac{n_i^2}{N_a} \sum_{m,n} \frac{4}{nma^4} \sin^2(ma) \sin(na) \times \left[\frac{\sin(na)}{nmL_2} - \sum_k \frac{4 \sin(ka)}{\gamma(ka + 1/2 \sin(2ka))} \left[\frac{\sin(n+k)a}{n+k} + \frac{\sin(n-k)a}{n-k} \right] \right] \tag{5}$$

where : $k = (p + 1/2) \pi$, $p = 0, 1, 2, \dots$, $1/L_1^2 = 1/L_n^2 + k^2$, $1/L_2^2 = n^2 + m^2 + 1/L_n^2$, L_n is the diffusion length in the defect free region, $m, n = (s + 1/2) \pi/a$, $s = 0, 1, 2, \dots$, $\gamma = 1/L_1 + 1/L_2$, and a is the half distance between two dislocations.

2.3 SHUNT CURRENT PROVIDED BY DISLOCATIONS. — Figure 1 shows an isolated dislocation traversing the junction. The part of dislocation lies within the junction SCR represents a shunt resistance which connects the N and P sides. We are interested in the calculation of this resistance. Under quasi equilibrium with a sufficient excitation condition the electron and hole densities at dislocation are given by [4].

$$n = \left(\frac{s_p}{s_n} \right)^{0.5} n_i \exp \left(\frac{(E_{fn} - E_{fp})}{2kT} \right) \tag{6}$$

$$p = \left(\frac{s_n}{s_p} \right)^{0.5} n_i \exp \left(\frac{(E_{fn} - E_{fp})}{2kT} \right) \tag{7}$$

where E_{fn} and E_{fp} are quasi electron and hole fermi levels ; s_n and s_p are electron and hole recombination velocities expressed by :

$$s_n = v_{\text{th}}^n \sigma_n Q_t, \quad s_p = v_{\text{th}}^p \sigma_p Q_t$$

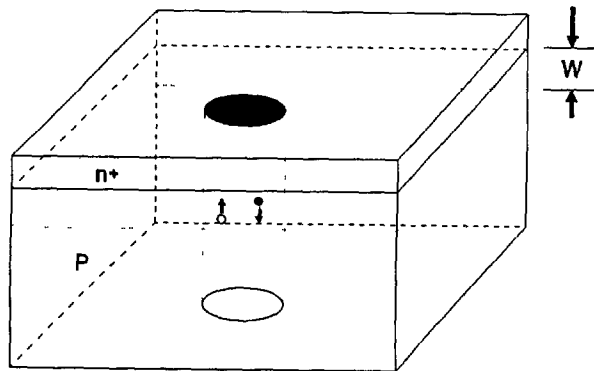


Fig. 1. — An isolated dislocation crossing the junction.

where v_{ih}^n and v_{ih}^p are the hole and electron thermal velocities, σ_p and σ_n are the hole and electron capture cross section and Q_1 is the dislocation trapping states per unit length. At the part of dislocation which lies within the SCR, the electron and hole densities are given by :

$$n = \left(\frac{s_p}{s_n} \right)^{0.5} n_i \exp \left(\frac{qV}{2kT} \right) \quad (8)$$

$$p = \left(\frac{s_n}{s_p} \right)^{0.5} n_i \exp \left(\frac{qV}{2kT} \right) \quad (9)$$

where V is the voltage drop on the SCR ($qV = E_{tn} - E_{tp}$). This dislocation path represents a shunt resistance between the n and p sides, given by :

$$R_{dis} = \frac{W}{\pi r^2} \cdot \frac{1}{q(n\mu_n + p\mu_p)} \quad (10)$$

Where W is the SCR width, r is the radius of the dislocation pipe ($r \cong 0.15 \mu\text{m}$ [1]), and μ_n , μ_p are electron and hole mobilities. Substituting for n , p from equations (8, 9) into equation (10) we get :

$$R_{dis} = \frac{W}{\pi r^2} \cdot \frac{1}{qn_i \mu} \cdot \exp \frac{-qV}{2kT} \quad (11)$$

where $\mu = \mu_n (s_p/s_n)^{0.5} + \mu_p (s_n/s_p)^{0.5}$.

The dark current transmitted by conduction through dislocation I_{dis}^{sh} (shunt component) could be written as :

$$I_{dis}^{sh} = \int_0^V \frac{dV}{R_{dis}(V)} AN_{dis} \quad (12)$$

where N_{dis} is the dislocation density and A is the cross section area of the junction.

The shunt component of the dark current density can be obtained from equations (11) and (12) as follows :

$$J_{dis}^{sh} = \frac{2kTn_i \mu \pi r^2}{W} N_{dis} \left(\exp \left(\frac{qV}{2kT} \right) - 1 \right) . \quad (13)$$

Equation (13) indicates that the shunt component of the dark current has the same exponential dependence on voltage like the conventional recombination component but the preexponential factor is proportionnal to N_{dis} and depends of dislocation pipe radius r .

This result is in agreement with that of Zolper and Barnett [1] who have suggested that dislocations in gallium arsenide solar cells introduce a parallel diode, in the equivalent electrical circuit of the perfect cells. In this supplementary diode the forward current I depends on the applied voltage V like $\exp(qV/nkT)$ with a preexponential factor I_{OD} related to the dislocation density.

3. Experimental.

Samples $2 \times 3 \text{ cm}^2$ in size were cut from solar cells made with P-type large grained cast polycrystalline silicon (Polix-Photowatt or Silso-Wacker). These materials contain a large density of extended crystallographic defects, principally dislocations.

Arrays of N^+P mesa diodes (3 mm in diameter) were realized by means of standard

photolithographic technique. They allowed to measure I-V characteristics in dark, thanks to a computer assisted set-up. Experimental details were given in [5].

After the different measurements, the diodes were chemically etched in order to reveal the dislocation etch pits and to determine the average dislocation density.

4. Results and discussion.

4.1 COMPUTED RESULTS. — In the following calculations we have assumed that

$$\sigma_n = \sigma_p = 10^{-14} \text{ cm}^2, \quad v_{th}^n = v_{th}^p = 10^7 \text{ cm s}^{-1}, \quad Q_t = 10^6 \text{ cm}^{-1}, \quad N_a = 10^{16} \text{ cm}^{-3},$$

and selecting for L_n, D_n the values of 90 μm and 20 $\text{cm}^2 \text{s}^{-1}$ respectively (these values are in a good average of the largest values measured in commercially available polycrystalline materials like Silso or Polix).

The variations of the dark current diffusion component with the dislocation density is shown in figure 2. From this figure we observe a pronounced increase in J_{od} with N_{dis} especially when N_{dis} is greater than 10^5 cm^{-2}

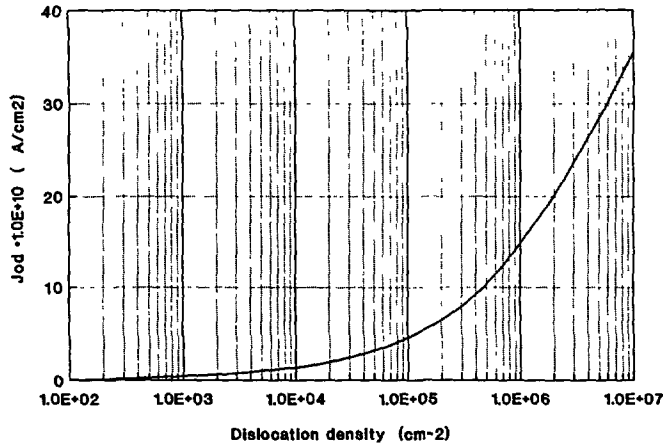
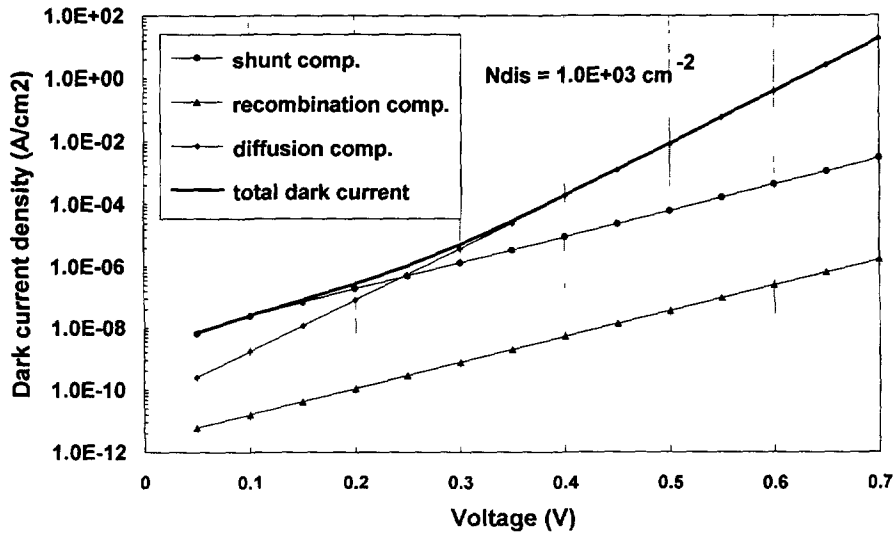


Fig. 2. — Computed diffusion component of dark current versus dislocation density.

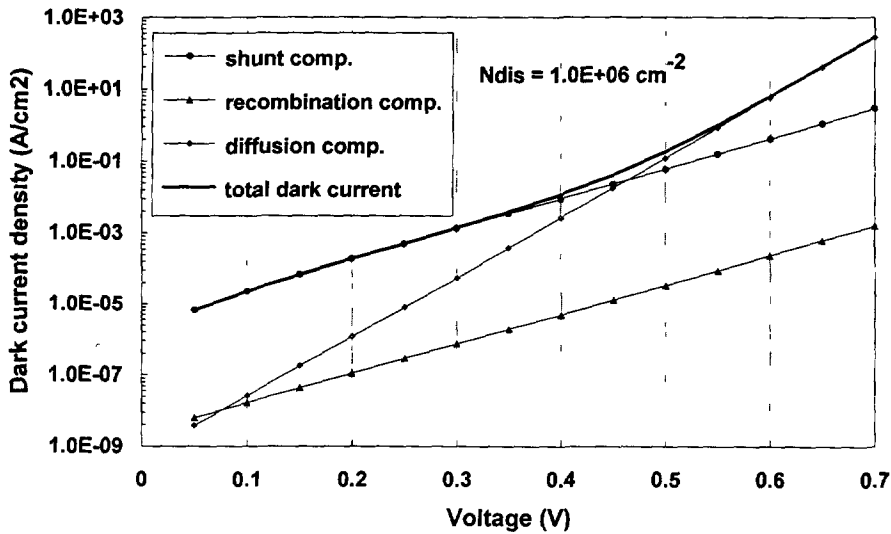
The logarithmic plots of the dark current components as a function of the applied voltage are given in figures 3a and 3b for $N_{dis} = 10^3$ and 10^6 cm^{-2} respectively. These figures show three main effects :

- (i) the recombination current at dislocations is always negligible whatever are the dislocation density and the value of the applied voltage ;
- (ii) the shunt component is dominant at low voltage ($V \leq 200 \text{ mV}$ for $N_{dis} = 10^3 \text{ cm}^{-2}$ and $V \leq 350 \text{ mV}$ for $N_{dis} = 10^6 \text{ cm}^{-2}$);
- (iii) the diffusion component is the dominant one when $V \geq 300 \text{ mV}$ and $N_{dis} = 10^6 \text{ cm}^{-2}$

Thanks to this study of individual effect of each component, we have plotted in the figure 4 the total dark I-V characteristics for different dislocation densities ($N_{dis} = 10^3 \text{ cm}^{-2}, 10^4 \text{ cm}^{-2}, 10^5 \text{ cm}^{-2}$ and 10^6 cm^{-2}). In these curves, if $V < 300 \text{ mV}$, the influence of dislocations appears clearly and the current seems to be dominated by the conductivity of these



a)



b)

Fig. 3. — Computed dark current component *versus* applied voltage. (a) $N_{dis} = 10^3 \text{ cm}^{-2}$. (b) $N_{dis} = 10^6 \text{ cm}^{-2}$

defects. If the applied voltage is higher than 400 mV, the diffusion component becomes dominant but the value of saturation current (i.e. the value of J extrapolated at $V = 0$) is influenced by the dislocation density.

We can also observe that the value of the voltage when the diffusion component becomes dominant is not constant but increases from nearly 300 mV at $N_{dis} = 10^3 \text{ cm}^{-2}$ to values higher than 400 mV at $N_{dis} = 10^6 \text{ cm}^{-2}$

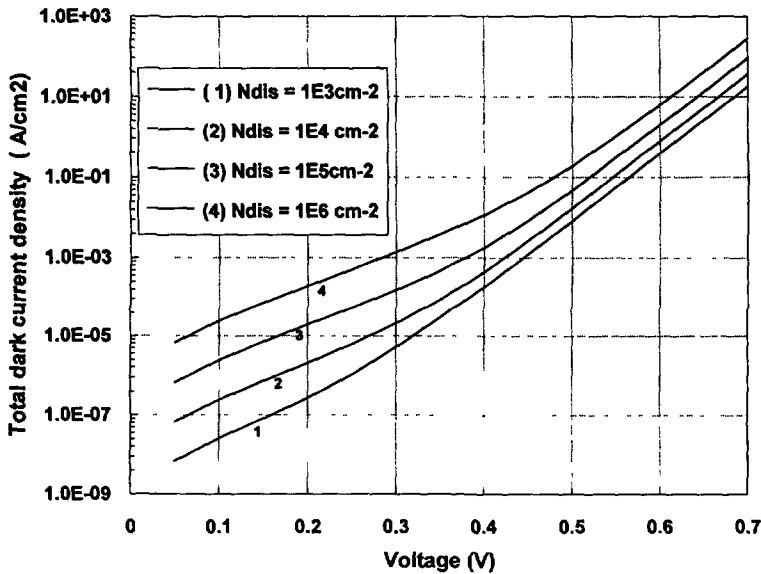


Fig. 4. — Computed total dark I-V curves for different dislocation densities.

4.2 EXPERIMENTAL RESULTS. — The experimental dark I-V characteristics of four mesa diodes containing different densities of dislocations is shown in figure 5. An enhancement in dark current is observed as the density of defects, mainly dislocations, increases. This enhancement is more pronounced at low applied voltages which is in a qualitative agreement with our theoretical model.

The assumption of the existence of a conductivity by the dislocation cores was already proposed and verified experimentally by Ossypian [7] and Pohoryles [8]. This conductivity could be due to the electrons of the dangling bonds of the atoms linked to the dislocation core, the energy levels of which form a one-dimensional band of levels in the forbidden gap. The width of this band depends on the amount of overlapping of the wave functions along the dislocation line.

In addition the presence of impurity clouds (metals, oxygen) around the dislocation cores can also introduce additional energy levels in the gap which can increase the energy level density available for this kind of conductivity.

5. Conclusion.

We have developed a model which evaluates the influence of dislocations on the dark current of N^+P junctions. This dark current is composed of three essential components : diffusion, recombination and shunt component. The shunt component is found to be the dominant one at low applied voltage. The fact that shunt component of dark current due to dislocations varie exponentially (not linearly) with the applied voltage is a new result, in silicon pn junctions.

The general expression of forward dark current for a dislocated diode could be expressed by :

$$I = I_{01} \exp \left(\left(\frac{qV}{kT} \right) - 1 \right) + I_{02} \exp \left(\left(\frac{qV}{2kT} \right) - 1 \right)$$

like that obtained for a defect-free diode, however that does not mean that the two cases are

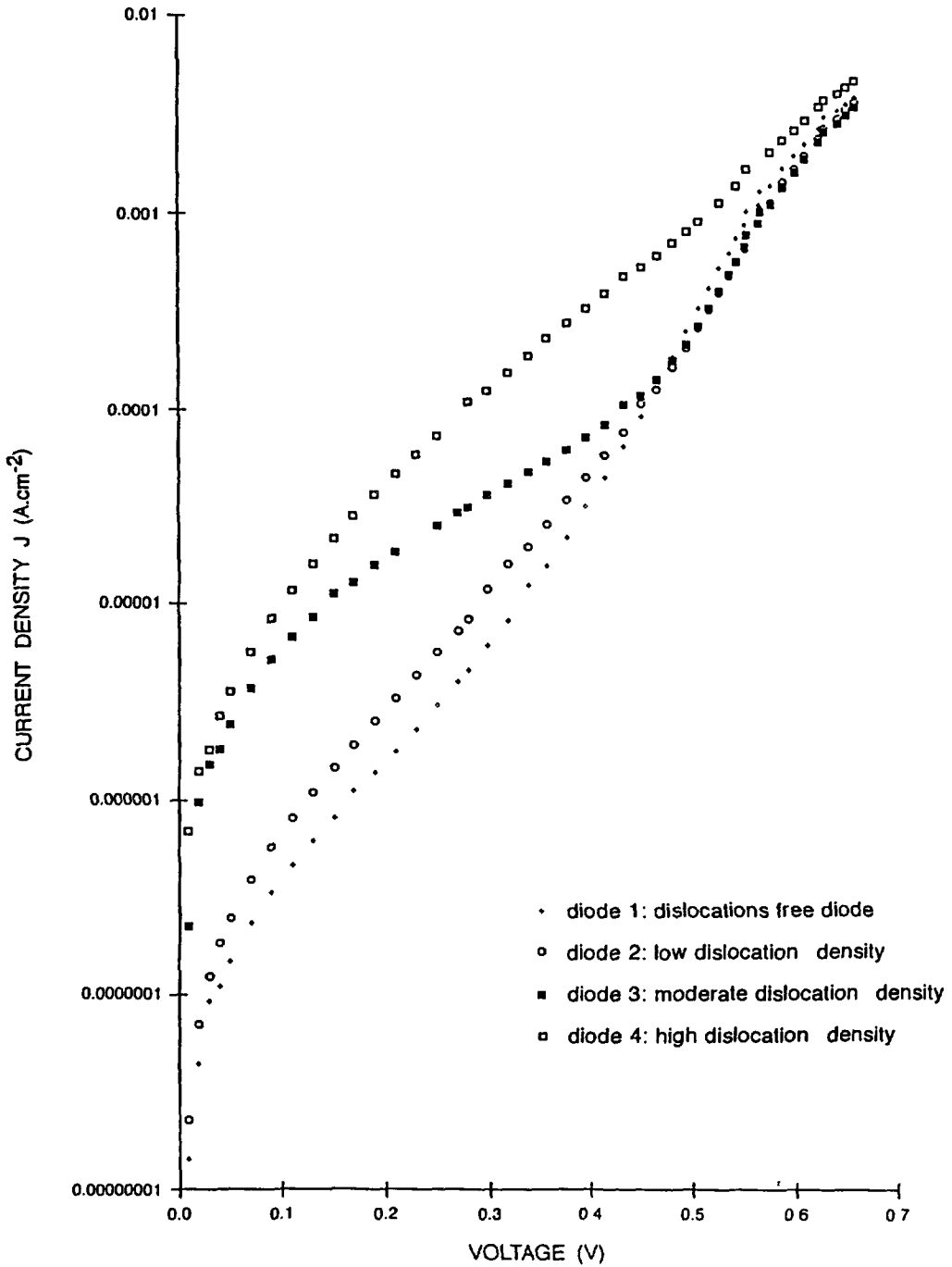


Fig. 5. — Typical experimental dark I-V characteristics of diodes containing different dislocation densities.

similar. Indeed the preexponential factors I_{01} , I_{02} for a dislocated diode are completely different from those of a dislocation-free diode. Especially, the preexponential factor I_{02} is proportional to the dislocation density N_{dis} .

The experimental measurements are in a qualitative agreement with the theoretical calculations.

The model suggests that if a passivation process of dislocations is necessary to reduce the dark current due to recombinations, it is not sufficient to eliminate the shunt effect, especially when the dislocations (or other extended defects like stacking faults) cross the junction.

The present model can be also applied to other polycrystalline semiconductor materials having the same features.

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