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Space-charge-limited conduction for the determination of the midgap density of states in amorphous silicon: Theory and experiment

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The density of states (DOS) in amorphous silicon is a key parameter in assessing the performances of photocells made of this material. The principle of the determination of the DOS by the study of the space-charge-limited current (SCLC) had first been given by den Boer in an approximate but very physical model. We have found that a precise determination of the DOS in amorphous silicon by this method requires special precautions, both theoretical and experimental: it is only after elimination of most of the pollution by the electrodes and walls of the chamber that we have found that the "scaling law" is valid with good precision, and only for films thicker than $d=1.5$ μm; in the usual experimental conditions (current density <1 A/cm^2), the situation is intermediate between the low-injection condition (Ohm's law) and the high-injection condition, so that the asymptotic solutions given by the "regional approximation," as used by previous authors, are not valid. By comparing the experimental curves with the exact solutions obtained by numerical integration of the SCLC equations, we have determined the DOS in amorphous silicon films with an estimated uncertainty of 15%. The application of the method to a series of films produced by capacitive glow discharge shows the following: (a) the DOS at the Fermi level is very sensitive to the quality of the pumping system (pollution by air, H_2O, pumping oil), the best value obtained in our films being 5×10^{15} cm^{-3}eV^{-1}; (b) for films produced in identical conditions, there is a well-defined minimum of the DOS at a preparation temperature $T_s=260\,^\circ$C, which explains why most of the best photocells are prepared at this temperature; (c) the DOS in the first 2000—4000 Å of the films is larger by a factor of 3—10 than that in the rest of the film. This has a direct implication for the fabrication of photocells which have a thickness only 2—3 times this perturbed region. The cause of this effect, whether it is an intrinsic surface effect or external effect, corrected by self-cleaning after a few minutes of plasma, remains to be determined.

I. INTRODUCTION

The density of states (DOS) in amorphous silicon is a key parameter for determining the semiconducting properties of this material. To measure this quantity, different methods have been used with all their advantages and their limitations. The pioneering work of Spear and LeComber,[1] based on the measurement of field effect, was the first to show that hydrogenated amorphous silicon was characterized by a low DOS in the gap. This method, however, measures the properties of the material very close to the surface[2,3] and is very sensitive to the possible presence of surface states: The results of field-effect measurements are expected to give only an upper limit of the DOS at the Fermi level. The results given by different groups[1,4,5] range from a few 10^{16} to 10^{17} cm^{-3}eV^{-1}.

Another type of determination of the distribution of DOS is based on the study of dynamic trapping of carriers by localized states. This includes the frequency- and temperature-dependence study of the capacitance of Schottky diodes.[6,7] The method of deep-level transient spectroscopy (DLTS), currently used for crystalline semiconductors, has also been applied to the study of lightly doped amorphous silicon[8,9] with results quite different from those obtained by other methods.[10] The interpretation of these methods is complicated by the existence of a very wide range of trapping times[11] which can, in some cases, be of the order of several hours at room temperature.

Recently, den Boer[12] has shown that the study of space-charge-limited current (SCLC) in the n^+nn^+ structure provides a reliable method for the study of the DOS in amorphous silicon. In principle, the measured values are characteristic of the bulk of the material. Besides, it is a steady-state method and should not be perturbed by uncontrolled trapping dynamics of the carriers.

In the present study, we have used this method for the determination of the DOS in a series of samples prepared by decomposition of silane in a capacitance glow-discharge reactor described previously.[13] The standard conditions of preparation were followed: The pressure was 20 mTorr of pure SiH_4, with a flow rate of 1 l/h and power density of 0.2 W/cm^2. We have solved exactly the equations of current injection in a n^+nn^+ structure, and the comparison with the experimental results provides a direct determination of the DOS of the material, without any other adjustable parameter.

II. SPACE-CHARGE-LIMITED CURRENT: THE SCALING LAW

The problem of current injection into solids has been extensively studied by Lampert and co-workers.[14,15] A geometry presenting the considerable simplification of a single type of carrier in one dimension is that of the n^+nn^+ sandwich, which is the structure studied in the present work. Except at very low current densities, a large number of electrons are injected in the central n region (which can be slightly doped or naturally n type) and the problem is that of the transport by SCLC.[12]

For such a sandwich the characteristic equations are

$$J=e\mu n(x)F(x)=\text{const}\ , \tag{1}$$

$$\frac{\epsilon\epsilon_0}{e}\frac{dF(x)}{dx}=n(x)-n_0+N_t(x)\ . \tag{2}$$

The first equation is the usual drift-current equation, with J the current density, e the electronic charge, μ and $n(x)$ the free-electron drift mobility and density, and $F(x)$ the electric field at the transverse position x, the origin being taken at the interface between the n^+ and the central region. Equation (2) is the Poisson-Boltzmann equation taking into account the space-charge effects due to the injected and trapped carriers. ϵ and ϵ_0 are the dielectric constant and the vacuum permittivity, $n(x)-n_0$ is the density of excess delocalized carriers, and $N_t(x)$ is the total density of trapped charges which is determined in each case by Fermi-Dirac statistics based on the assumption of the existence of well-defined quasi-Fermi-level. In Eq. (1) we neglect the diffusion currents which can be shown to be very small in general.[16]

A direct consequence of these equations is the "scaling law," valid only for *homogeneous* samples.[14] For a series of films, different only by their thickness L, the $J(V)$ curve must satisfy at a given temperature the general law

$$J/L=f(V/L^2)\ . \tag{3}$$

In the early stage of this work, we have found that this scaling law is poorly verified for films of amorphous silicon. The same discrepancy has been found by Mackenzie *et al.*[17] with spread in currents as large as 1 order of magnitude.

For a quantitative comparison between the experimental results and the theoretical predictions, we felt it necessary to investigate systematically the origin of this poor fit of the scaling law and possibly correct it.

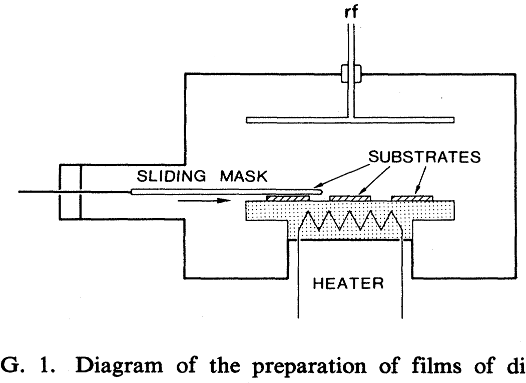

FIG. 1. Diagram of the preparation of films of different thickness during the same run. The sliding mask covers the substrates in succession after variable deposition times.

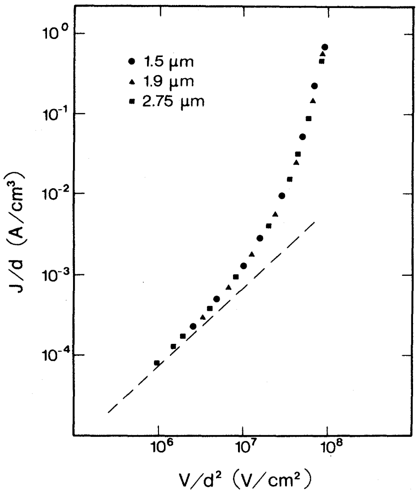

FIG. 2. Plot of J/d as a function of V/d^2 to test the scaling law for three films of different thickness d. The samples were prepared in the same run, as shown in Fig. 1.

(1) We found that the thin samples (1 μm or less) are on the average more conducting than the thicker samples. Since the intrinsic deposition follows the highly doped n^+ deposition, this effect can be explained by the residual phosphine gas remaining in the chamber or adsorbed on the walls. And indeed this effect could be decreased by stopping the plasma after the first n^+ deposition and pumping for about half an hour, until a vacuum of 10^{-6} Torr was reached. To decrease the adsorption, the whole system was maintained at 100 °C during the pumping.

(2) One origin of the nonreproducibility is certainly the pollution due to the layers deposited on the walls of the chamber and on the rf electrodes and partially etched by the plasma. In particular, the properties of the deposited films depended on the whole history of the chamber. In the absence of a multichamber system[18] a considerable improvement in the fluctuations was obtained by starting each run with a "clean" chamber, where all traces of previous depositions were removed from the walls and rf electrodes by a hot concentrated sodium hydroxide bath.

(3) As remarked by Mackenzie *et al.*,[17] it is extremely difficult to obtain a perfect reproducibility of deposition conditions for the intrinsic material from one run to the other. To avoid this difficulty, we have deposited the series of samples of different thicknesses in the *same run* by masking the substrate with a sliding mask during the deposition (Fig. 1).

With all these precautions, the improvement was dramatic, at least for the films of 1.4 μm or thicker (Fig. 2), where the scaling law is verified to better than 15% in currents, even in the strong-injection regime. In spite of these experimental precautions, the discrepancy still remains for thin samples (less than 1.4 μm). This is believed to be a real physical effect and will be discussed in Sec. IV.

III. THE "EXACT" SOLUTION OF THE SCLC PROBLEM

In general, the SCLC equations (1) and (2) cannot be solved analytically and different approximations have been used to obtain physically acceptable solutions. In particular the widely applicable "regional approximation" has been described in detail by Lampert *et al.*[14] However, this approximation does not provide a good fit to the experimental results and the limitations of the approximation will be discussed in Sec. V.

In this article, we present an exact numerical resolution of the equations which provides an unambiguous comparison with experiment, giving a reliable determination of the density of states. In the absence of a precise knowledge of the distribution of states in the gap of amorphous silicon, we shall use the convenient analytical form

$$g(E)=N_g \exp[-(E_c-E)/kT_g] , \tag{4}$$

where N_g and T_g are parameters characterizing the electron-trap distribution and E_c is the energy of the conduction-band edge. Of course, this distribution is arbitrary and is only justified *a posteriori* by the fact that the solution is quite insensitive to the exact form of the distribution. We have tried other shapes $g(E)$ of the DOS, but for the same $g(E_F)$ and as long as there is a fast increase of the DOS when one gets nearer the band edge, the calculated results are essentially the same (see next section). For the form given by Eq. (4), the "steepness" of the distribution can be characterized by the parameter

$$l=T_g/T , \tag{5}$$

where T is the actual temperature of the sample. For a variation of about 10^3 of the DOS from the center of the gap to the conduction-band edge,[1] the value of l at room temperature is expected to be approximately $l=5$. In fact, the experimental fit gives values ranging from $l=4$ to $l=9$. The final solutions will be discussed in terms of the two parameters $g(E_F)$ and l.

With this distribution, in the limit of $l \gg 1$, we can use the low-temperature approximation ($T \ll T_g$) and the density of trapped electrons is easily calculated

$$\begin{aligned} N_t(x) &= \int_{E_F}^{E_F+\Delta} g(E)dE \\ &= g(E_F)kTl\{\exp[\Delta(x)/kTl]-1\} , \end{aligned} \tag{6}$$

where $E_F+\Delta(x)$ is the position of the quasi-Fermi-level at x. From the definition of $\Delta(x)$, we have

$$n(x)/n_0=\exp[\Delta(x)/kT] , \tag{7}$$

so that Eq. (6) can be written

$$N_t(x)=g(E_F)kTl\{[n(x)/n_0]^{1/l}-1\} . \tag{8}$$

For practically attainable injections ($J<1$ A/cm^2) the number of surplus free carriers $n-n_0$ is smaller than the trapped charges N_t so that we can neglect the former in Eq. (2).

It is convenient to rewrite the SCLC equations in terms of dimensionless variables

$$\begin{aligned} v &= V/V_c , \\ f(x) &= \frac{F(x)}{V_c/L} , \\ j &= \frac{J}{en_0\mu V_c/L} , \end{aligned} \tag{9}$$

with

$$V_c=(e/\epsilon\epsilon_0)g(E_F)kTlL^2 . \tag{10}$$

We shall see below that V_c has a typical value of a few volts. With these variables, Eqs. (1) and (2) become

$$j=\frac{n(x)}{n_0}f(x) , \tag{11}$$

$$\frac{df(x)}{dx/L}=\left[\frac{n(x)}{n_0}\right]^{1/l}-1 . \tag{12}$$

The voltage V across the sample is given by

$$V=\int_0^L F(x)dx \tag{13}$$

or in terms of the variables (9)

$$v=\int_0^L f(x)dx/L . \tag{14}$$

The resolution of this set of equations, with the boundary condition

$$F(0)=f(0)=0 \tag{15}$$

will give, for each value of l, a universal curve $j(v)$ to be compared with experiment. It is convenient to use as an integrating variable[14,15]

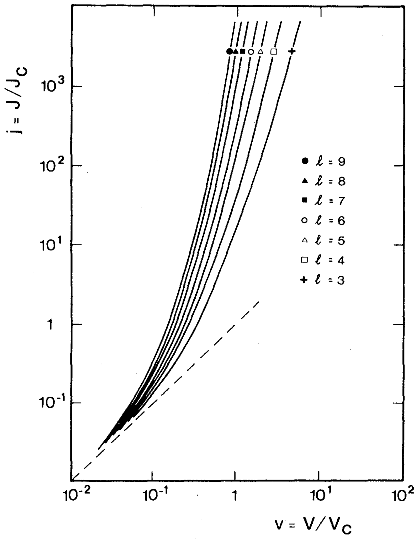

FIG. 3. Numerical solutions for the SCLC equations in reduced coordinates $v=V/V_c$ and $j=J/J_c$ [Eq. (9)]. The DOS has been taken with the form $g(E)\simeq\exp(E/lkT)$ [Eqs. (4) and (5)] and the SCLC curves for different values of l are shown in the figure. The dashed line is the extrapolated Ohm's law, valid in the limit of very small currents.

$$u(x)=n_0/n(x)\ . \tag{16}$$

With this variable, Eqs. (11) and (12) can be written

$$j\frac{du}{dx/L}=u^{-1/l}-1\ , \tag{17}$$

and Eq. (14) becomes

$$v=j\int_0^{u(L)}\frac{u\,du}{L\,du/dx}\ . \tag{18}$$

Thus, the $j(v)$ curve is given explicitly in a parametric representation[15]

$$\begin{aligned} j(u_L)&=\left[\int_0^{u_L}\frac{du}{u^{-1/l}-1}\right]^{-1}\ ,\\ v(u_L)&=j^2(u_L)\int_0^{u_L}\frac{u\,du}{u^{-1/l}-1}\ , \end{aligned} \tag{19}$$

where the running parameter is $u_L=u(L)=n_0/n(L)$. From the definition, $u<u_L<1$, and $1/u_L$ is a measure of the surplus injected electrons remaining at the collecting electrode ($x=L$) of the film. The integrals in Eqs. (19) have been performed numerically and the resulting $j(v)$ curves for different values of l ranging from $l=3$ to $l=9$ have been plotted in Fig. 3. As expected, in the limit of $v \ll 1$ ($V \ll V_c$) we obtain Ohm's law, which in our notations is simply written $j=v$.

IV. COMPARISON WITH EXPERIMENT

The fit between the calculated curve and the experimental $J(V)$ curve is excellent for a wide range of voltage and current values, as can be seen in Fig. 4. Of course, this perfect fit is not a crucial proof of the validity of the model. It simply indicates that *if* our starting hypothesis [boundary condition $F(0)=0$, constant mobility μ, well-defined quasi-Fermi-level across the sample, transverse homogeneity of the film] are valid, the present calculation gives a value of $g(E_F)$ that can be considered as reliable and precise.

In principle, the fit with the experimental points is obtained with two adjustable parameters, V_c and l. In fact, the shape of the curve is very insensitive to the value of l and the adjustment to the measured curve depends almost exclusively on a single parameter, the value of the DOS at the Fermi level $g(E_F)$.

This is illustrated in Fig. 5 where the calculated values of Fig. 3 have been plotted as a series of curves having the *same* $g(E_F)$ and different values l of the exponential distribution of states [Eq. (4)]. This is obtained by a plot of J/J_0 vs V/V_0, where $J_0=J_c/l$ and $V_0=V_c/l$ are current and voltage scales independent of l. Indeed from Eq. (10), we have

$$V_0=V_c/l=\frac{e}{\epsilon\epsilon_0}g(E_F)kTL^2\ . \tag{10'}$$

V_0 depends only on the density of states at the Fermi level, all the other quantities in this equation being known. In particular it is interesting to note that quantities like the number of carriers at equilibrium n_0 and the mobility μ, which are difficult to estimate, do not enter in its value. Thus the fit between theory and experiment yields a precise and unambiguous value of $g(E_F)$ with an error estimated to be in most cases less than ±15%. On the other hand, as can be seen in Fig. 5, the sensitivity of the calculated curves to the value of l is very weak, so that the

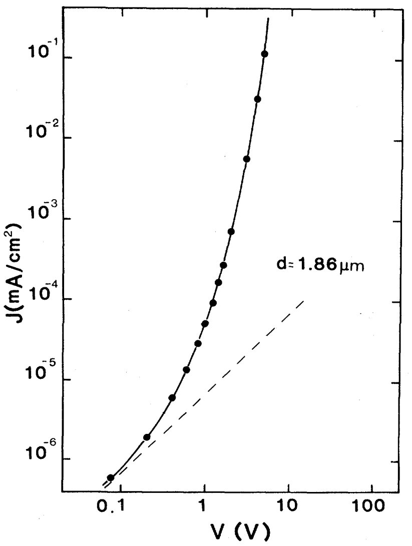

FIG. 4. Comparison between the calculated $J(V)$ curve and the measured values (solid circles). The fit is obtained with a single adjustable parameter (the DOS at the Fermi level) which is, for this particular sample, $g(E_F)=5.8\times10^{15}$ cm^{-3}eV^{-1}. The dashed line is the extrapolation of the Ohmic region.

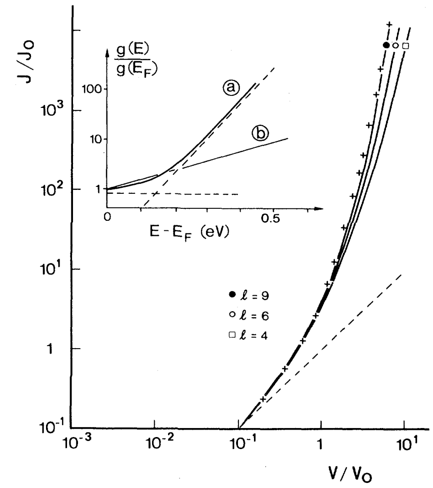

FIG. 5. Plot of three of the curves of Fig. 3 reduced to the same DOS at the Fermi level $g(E_F)$: The voltage scale V_0 is proportional to $g(E_F)$ [Eq. (10′)] and the l dependence is found to be very weak. The crosses represent the SCLC curve calculated with the density of states shown in the inset [curve a; Eq. (4′)]. It is almost indentical with the curve calculated for an exponential DOS (curve b) with an l value of $l=9$ and having the same $g(E_F)$. It shows that the SCLC curve is very insensitive to the exact form $g(E)$ of the DOS in the gap.

method is not suitable for the determination of the *distribution* of the states in the gap. To illustrate this point, we have calculated numerically, with the same method as described in Sec. III, the $J(V)$ curve for a more general form of the DOS

$$g(E) = g_1(E) + g_0 \tag{4'}$$

where $g_1(E)$ has the exponential shape of Eq. (4) and g_0 is constant. This is shown as the crosses in Fig. 5 which have been calculated for $g_1(E)$ having an l value of 2.5 and the constant part being $g_0 = 10 g_1(E_F)$ as indicated in the inset. The curve thus obtained is almost indistinguishable from the curve calculated for a purely exponential DOS having the same $g(E_F)$ and an l value of $l=9$.

It is thus quite clear that the important parameter in the solution of the SCLC equations is the DOS at the Fermi level $g(E_F)$ and not the exact form of the distribution. This has already been seen experimentally by Mackenzie *et al.*[17] who have shown, by the temperature dependence of the SCLC, that the levels controlling the SCLC are situated close to the Fermi level. The physical reason that we can give for this result is that the electric field is larger in regions where the number of injected electrons is smaller [see Eq. (1)] so that the voltage drop is dominated by the regions where the quasi-Fermi-level is nearer the equilibrium value.

The values of the DOS obtained by this method have been found to depend critically upon some of the deposition parameters. In particular, the details of the pumping system seem to play an important role and the work to evaluate this effect is in progress and will be reported later. As an illustration of the method, we have measured the DOS of a series of samples with variable deposition temperatures T_d, the other parameters being the same. We obtain (Fig. 6) a well-defined minimum for a value of $T_d \simeq 260\,^\circ\mathrm{C}$, with a density of states $g(E_F) = 5\times10^{15}$ $\mathrm{cm}^{-3}\,\mathrm{eV}^{-1}$. This is consistent with the empirical result that most of the best photocells are prepared at this temperature.

Another interesting effect is shown in Fig. 7. For the same conditions of preparation the DOS increases when the thickness of the films decreases below $L = 1.3$–1.5 μm. This explains why the scaling law is obeyed only for the thick samples with $L > 1.4$ μm. The question of the cause of this effect is still unresolved. It could be an intrinsic surface effect, for example due to the strains in the material that are relaxed only for the thicker samples. But it could also be an external pollution effect corrected by self-cleaning after a few minutes of plasma exposure. The deposition in a separate chamber system[18] which is under construction in our laboratory should help clarify the cause of this effect.

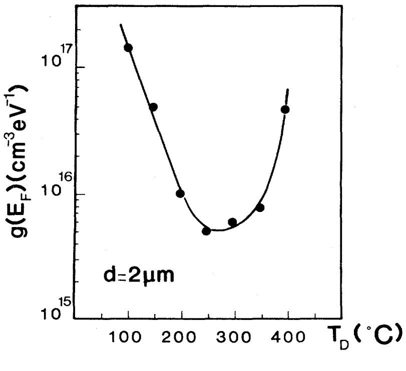

FIG. 6. Density of states at the Fermi level $g(E_F)$ as a function of the deposition temperature T_D.

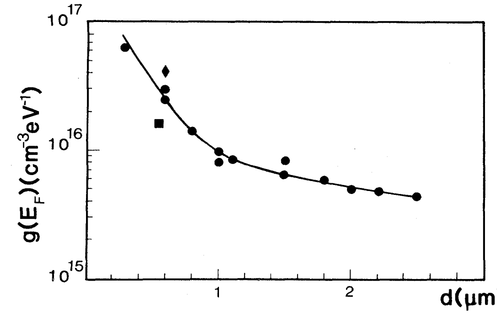

FIG. 7. Density of states at the Fermi level $g(E_F)$ for a series of samples of different thickness d deposited at 250 °C (●). ■, value deduced from Ref. 12 ($T_D = 300\,^\circ\mathrm{C}$); ◆, value deduced from Ref. 17 ($T_D = 300\,^\circ\mathrm{C}$).

V. DISCUSSION OF THE "REGIONAL" AND OTHER APPROXIMATIONS

In the absence of a numerical resolution of Eqs. (11), (12), and (14), the only available published result was that of the "regional approximation" as discussed in detail by Lampert and Mark,[14] and these were partially used by previous authors[12,17,19] for comparison with experiment. The result of this approximation, transposed in our notations [Eq. (9)] are

$$\begin{aligned} v &= j\left[1 - j\frac{l^2}{(l+1)(2l+1)}\right] \quad \text{for } v < \frac{(l+1)^2}{l(2l+1)}\,, \\ v &= \frac{l+1}{2l+1}\left[\frac{l+1}{l}\right]^{l/l+1} j^{1/l+1} \quad \text{for } v > \frac{(l+1)^2}{l(2l+1)}\,. \end{aligned} \tag{20}$$

The corresponding curve, for $l=6$, is plotted in Fig. 8 along with the exact solution for comparison. As can be seen, the curve obtained by this method shows a much sharper transition around the critical voltage V_c than the exact numerical solution. The solutions obtained by the regional approximation are in fact asymptotic solutions valid in the two limits $V \gg V_c$ and $V \ll V_c$. In the transition region ($V \simeq V_c$) obtained by the matching of the two asymptotic solutions, the approximation is rather poor as can be seen in Fig. 8. Unfortunately, the experimental limitations restrict the comparison to conditions close to this transition region. For example, the application of more than 10 V across a $L = 1$ μm film (100 kV/cm) is dangerously close to the destruction of the sample. Now for typical conditions [$\epsilon = 12$, $g(E_F) = 10^{16}$ cm^{-3} eV^{-1}, $l=6$, $L = 1$ μm], $V_c = 2.35$ V so that the applied voltage

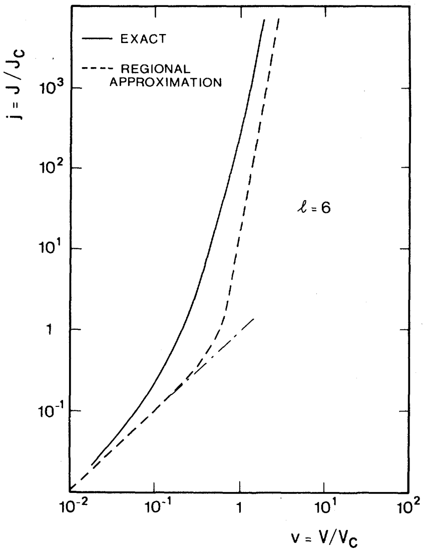

FIG. 8. Comparison between the solutions of the SCLC equations obtained by the "regional approximation" of Lampert and Mark (Ref. 14) (dashed curve) and the exact calculation [Eq. (19)] for $l=6$.

cannot be much larger than the critical voltage V_c. We have plotted in Fig. 9 the ratio of the approximate solution to the exact one for the case $l=6$. It is apparent that, for the available experimental region of SCLC, the approximate solution is off by 1 or 2 orders of magnitude, which prevents a valid quantitative comparison with experiment. In particular, it is not practically possible to reach the very high injection limit which, according to Eqs. (20) should give the power law $j \sim v^{l+1}$. On a limited range, the high-injection part of the experimental curve becomes close to a straight line on a log-log plot, but the comparison with the numerical calculation shows that the assymptotic value [Eqs. (20)] has not been reached and that the experimental power coefficient is less than the limiting theoretical value $l+1$.

The limitation, due to experimental conditions, to injection levels that are not very high suggests the use of another approximation which has been found[12,20] to give a good fit with experiment in the transition region. This approximation, which gives an exponential variation in the $J(V)$ curve can be justified theoretically, with a slight modification, by comparison with the exact solutions of the preceding section. If the displacement Δ of the quasi-Fermi-level is sufficiently small so that $\Delta \ll kT_g$, then the distribution of states can be considered as constant: $g(E)=g(E_F)$. This is obtained in the limit of $l \gg 1$ and $V \ll V_c$. The case of a constant density of states has also been solved in the regional approximation limit by Lampert and Mark,[20] and the result is a $J(V)$ function having the form

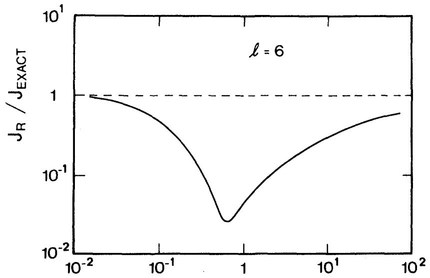

FIG. 9. Ratio of the solution of the SCLC equations obtained by the regional approximation (Ref. 14) to the exact solution for $l=6$. For most of the transition region ($V \simeq V_c$) the approximate solution is off by more than 1 order of magnitude.

$$J \sim V \exp(V/V_E) \tag{21}$$

with

$$V_E = \frac{1}{2}\frac{e}{\epsilon\epsilon_0} g(E_F) kTL^2 \, . \tag{22}$$

This is the asymptotic form for $V \gg V_E$. We remark that, by comparison with Eq. (10),

$$V_E = V_c/2l \tag{23}$$

so that Eq. (21) is valid for injection levels of about 1 order of magnitude less than the form of Eq. (20) valid only in the limit $V \gg V_c$.

The same exponential form of the $J(V)$ curve has been found by den Boer,[12] who was the first to apply the SCLC method for the determination of the DOS in amorphous silicon films. He has used an extremely simplified model which nevertheless contains most of the physical features of the problem.

In den Boer's formulation, all the quantities varying along x are replaced by "average" quantities. For example, the injection of carriers (electrons) is described by a single quasi-Fermi-level displaced by Δ from the equilibrium Fermi level. The average carrier and trapped charge densities n and N_t are thus given by

$$n = n_0 \exp(\Delta/kT) \, , \tag{24}$$

$$N_t = g\Delta \, , \tag{25}$$

where g is the density of states at the Fermi level. Equations (1) and (2) now take the simplified form

$$J \simeq en\mu V/L \, , \tag{26}$$

$$\frac{\epsilon\epsilon_0}{e}\frac{dF}{dx} \simeq N_t \, . \tag{27}$$

From the simplified Poisson equation (27), we calculate the voltage across the sample

$$V = \int_0^L F\,dx = \frac{eN_tL^2}{\epsilon\epsilon_0 2} \, . \tag{28}$$

In the original work,[12] a finite variation of voltage is applied to the sample resulting in a variation of the current density. From these measured quantities, one can deduce the variation of the quasi-Fermi-level [Eqs. (24) and (26)] and then the value of the density of states g [Eqs. (25) and (28)].

It is perhaps more illuminating to calculate directly,

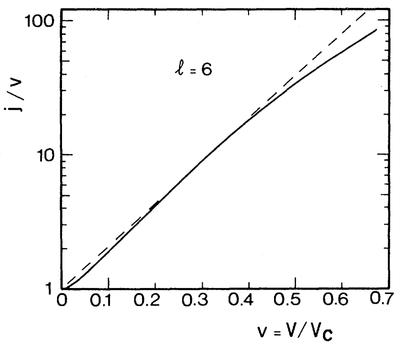

FIG. 10. Semilogarithmic plot of the reduced conductivity j/v as a function of $v=V/V_c$ for $l=6$. For $V<0.4V_c$, the curve is well approximated by the function $j/v \sim \exp(\alpha 2lv)$ with $\alpha=0.61$ (dashed line).

from this model, the predicted $J(V)$ curve in the case of a constant value of the DOS. By elimination of Δ and N_t between Eqs. (24) to (28), one obtains exactly the same form of the $J(V)$ curve as given by Eq. (21)

$$J=\frac{\sigma}{L}V\exp(V/V_E)\,, \tag{29}$$

where the quantity $\sigma=en_0\mu$ is simply the Ohmic conductivity of the material.

This exponential form of the $J(V)$ curve gives in general a fairly good fit with experiment in the transition region. Of course, this is not evidence for a uniform density of traps,[19] but simply indicates that the form given by Eq. (29) is a good approximation for medium injection levels. This is illustrated in Fig. 10 where $\log_{10}j/v$ as a function of v has been plotted for the case $l=6$. We see that for $v<0.4$ the numerically calculated curve is very close to a straight line. However, the slope of this line is not the one given by Eq. (21) or (29). In fact the correct approximation valid to within 20% for $v<0.4V_c$ is given by

$$J=\frac{\sigma}{L}V\exp(\alpha V/V_E)\,, \tag{30}$$

where the correcting factor α can be numerically computed and varies very little from 0.52 to 0.66 in the range $l=3$ to $l=9$. The determination of the DOS by the exponential from [Eq. (29)] which has been used explicitly[19] or implicitly by the step-by-step method[12,17] is essentially valid, except for a correcting factor of the order of $\alpha \simeq 0.6$. However, this form of the $J(V)$ curve is valid only for low injection levels and cannot be used for large displacement of the quasi-Fermi-level in order to study the *distribution* of the DOS in the gap, as has been tempted with the step-by-step method.

VI. CONCLUSION

The study of the space-charge-limited current in a n^+nn^+ sandwich configuration, provided certain experimental and theoretical precautions are being taken, provides a convenient method for the determination of the density of localized states in the gap of hydrogenated amorphous silicon.

(a) It is representative of the true bulk density, free from the perturbations dues to surface states.

(b) It is a steady-state method, so the influence of a wide range of trapping times is minimized.

However, for a correct comparison between theory and experiment, it is necessary to solve the SCLC equations numerically. Fortunately this can be done with a limited number of parameters because the results are very insensitive to the exact distribution of the states in the gap. The method is therefore well adapted for a precise determination of the DOS at the Fermi level, $g(E_F)$, but provides little or no information on the distribution $g(E)$ of states in the whole gap of a given sample.

We have applied the method to a series of samples satisfying the scaling law and have found a well-defined minimum of the DOS at a preparation temperature of $T_d=260\,^\circ\mathrm{C}$, with the best value obtained in our reactor being $g(E_F)=5\times10^{15}\ \mathrm{cm^{-3}\,eV^{-1}}$.

In a preliminary study, we have found that the DOS is very sensitive to the quality of the pumping system and work is in progress for the determination of the polluting agent (air, H_2O, pumping oil).

We have also found that the DOS in the first 2000—4000 Å of the films is larger by a factor 3 to 10 than the rest of the film. This has a direct implication for the fabrication of photocells which have a thickness only 2 to 3 times this perturbed region. The cause of this effect, whether it is an intrinsic surface effect or external pollution corrected by self-cleaning after a few minutes of plasma exposure, remains to be determined.

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