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Most conducting organic materials have a background p-type doping varying in the range $10^{15}-10^{17}\,\mathrm{cm}^{-3}$. We report results of a theoretical and experimental study of carrier transport in p-doped organic Schottky diodes. The theory given in this article shows that in a doped organic material with ohmic contacts the current is ohmic at low voltages. If the ohmic contact at the cathode is replaced by an Al Schottky contact the current varies exponentially with the applied voltage V. The current changes to space charge limited current (SCLC) at high voltages. The voltage at which the change takes place depends on the doping concentrations. In the SCLC regime the current varies according to the well-known V^2 law if there are no traps and the mobility is independent of the electric field. If either trapping or effect of field on mobility is important, the current varies as V^m, where $m>2$. We have investigated experimentally the $I-V$ characteristics of Schottky diodes fabricated using the PPV-based oligomer 2,5-di-n-octyloxy-1,4-bis (4′, 4″-bis-styryl) styrylbenzene (Ooct-OPV5) blended with polystyrene (PS) and the PPV-based polymer poly(2-methoxy-5-(3,7-dimethyloctyloxy)-p-phenylene vinylene) (OC_1C_{10}). As predicted by the theory, Al/Ooct-OPV5:PS/ITO (indium tin oxide) and Al/OC_1C_{10}/ITO Schottky diodes do show that the current varies exponentially with V at low voltages and as SCLC according to the V^m law (with $m=3$) at high voltages. The V^3 variation of the current in the SCLC regime can be due to trapping or field dependent mobility. It is not possible to distinguish unambiguously between the two mechanisms using the experimental results. The voltage at which transition from the Shockley current to SCLC takes place can be used to determine the background doping concentration. The p-type background doping concentration in the Ooct-OPV5 is found to be $\sim 10^{17}\,\mathrm{cm}^{-3}$. From the temperature variation of the hole current at low voltages, a value $0.53\pm0.1\,\mathrm{eV}$ is determined for the Schottky barrier height at the Al/Ooct-OPV5:PS contact. When image barrier lowering for $10^{17}\,\mathrm{cm}^{-3}$ doping is taken into account, this value of the barrier height is in good agreement with the difference in the Al work function and highest occupied molecular orbital of the organic material. Finally we suggest that if the background doping concentration can be eliminated, the SCLC and light emission in the light-emitting diodes should occur at lower voltages. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1352677]

I. INTRODUCTION

Transport properties of conducting organic materials are of great topical interest.[1–12] We have made theoretical and experimental investigations of the current–voltage characteristics of Al/Ooct-OPV5:PS/ITO (indium tin oxide) and Al/OC_1C_{10}/ITO Schottky diodes in the voltage range 0–15 V. These organic materials have a background p-type doping concentration in the range $10^{15}-10^{17}\,\mathrm{cm}^{-3}$. A complete transport theory of the doped organic material Schottky diodes should include: (1) the effect of background doping, (2) the effect of Al Schottky contact,[13] (3) the effect of

trapping,[7–9,11,12,14] and (4) the effect of electric field on mobility.[8,9,11,12] It is difficult to obtain analytical solutions taking into account all four effects. In Sec. II we first consider the effect of background doping alone. The contacts are assumed to be ohmic and the effects of trapping and field dependence of mobility are neglected. The results obtained with these simplifications are then extended to the organic diode with ITO contact (which is ohmic[11]) at one end and Al Schottky contact at the other end. Finally we include the effects of trapping and field dependent mobility as discussed in Refs. 7–9, 11, 12 and 14. In Sec. III the observed current–voltage characteristics of Al/Ooct-OPV5:PS/ITO and Al/OC_1C_{10}/ITO Schottky diodes are interpreted using the results of the theory. A summary of important results is given in Sec. IV.

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II. THEORY

A. Effect of background doping

If the organic material has no free carrier density due to doping or due to intrinsic thermal ionization, the theory of space charge limited current (SCLC) applies and the current density J is given by the V^2 law:[2–5,13,14]

$$J = \frac{9}{8} \varepsilon \varepsilon_0 \mu \frac{V^2}{L^3}. \tag{1}$$

Here V is the applied voltage, μ is the mobility of the carriers, ε is the dielectric constant of the insulator, L is the thickness of the sample, and $\varepsilon_0 = 8.85 \times 10^{-14}$ C/V cm is the permittivity of the free space.[13]

We now consider the effect of background p-type doping on the carrier transport. In the Al/Ooct-OPV5:PS/ITO and Al/OC$_1$C$_{10}$/ITO Schottky diodes the current is mainly carried by holes. When holes are injected in the p-type bulk of the diode, the total hole density $N(x)$ (at the point x measured from the ITO contact) in the diode consists of two parts: (1) the density of the existing holes n_0 induced by the background acceptors and (2) the density $[N(x) - n_0]$ of the injected holes. The total density of the holes determines the current. The space charge is determined by the distribution of injected holes only as the charge of the existing n_0 holes is compensated by the ionized fixed dopant ions. Therefore the Poisson's and the continuity equations can be written as[14]

$$\frac{\varepsilon \varepsilon_0}{q} \frac{dF(x)}{dx} = N(x) - n_0, \tag{2}$$

$$J = q \mu N(x) F(x). \tag{3}$$

Here $F(x)$ is the electric field at x. Diffusion is neglected in Eq. (3).[14,15] Equations (2) and (3) are identical to those used earlier for modeling the carrier transport in an insulator with thermal carriers.[14] Following Ref. 14 we define the following dimensionless quantities:

$$u = \frac{n_0}{N(x)} = \frac{q n_0 \mu F(x)}{J}, \tag{4}$$

$$w = \frac{q^2 n_0^2 \mu x}{\varepsilon \varepsilon_0 J}, \tag{5}$$

and

$$v = \frac{q^3 n_0^3 \mu^2 V(x)}{\varepsilon \varepsilon_0 J^2}. \tag{6}$$

Here u is the reduced field and $1/u$ is the reduced carrier density, w is the reduced distance, and v is the value of the reduced voltage $V(x)$. The derivative of w with respect to u can be expressed as[14]

$$\frac{dw}{du} = \frac{u}{(1-u)}. \tag{7}$$

Using the boundary condition that the ITO contact at $x=0$ is ohmic [i.e., $N(0)$ is large and $u(0)$ is practically zero], the solution of the above equation is[14]

$$w = -u - \ln(1-u). \tag{8}$$

Integrating the electric field over the distance w yields the expression for the reduced voltage v,

$$v = -\frac{1}{2} u^2 - u - \ln(1-u). \tag{9}$$

The expressions for dimensionless current J_R and voltage V_R can be written as

$$J_R = \frac{\varepsilon \varepsilon_0}{q^2 n_0^2 \mu L} = \frac{1}{w_a}, \tag{10}$$

$$V_R = \frac{\varepsilon \varepsilon_0 V}{q n_0 L^2} = \frac{v_a}{w_a^2}, \tag{11}$$

where w_a, v_a, and u_a are the values of w, v, and u, respectively for $x = L$. For more details of mathematical treatment the reader is referred to Ref. 14.

We have calculated the distribution of the carriers, $1/u$, and electric field u in the doped organic materials using Eq. (8). We have also calculated these quantities for the undoped samples in which the SCLC V^2 law is applicable. For the case corresponding to V^2 law, the relation between field strength with distance or carrier density with distance can be expressed as a single equation in reduced units:[14]

$$w = \frac{u^2}{2}. \tag{12}$$

We consider a sample of Al/Ooct-OPV5:PS/ITO with $L = 130 \times 10^{-7}$ cm. We have made the calculations of $1/u$ and u for a background doping concentration of $n_0 = 10^{15}$ cm^{-3}. The values used for the other parameters are $\mu = 10^{-6}$ cm^2/V s, $\varepsilon = 3$, and $\varepsilon_0 = 8.85 \times 10^{-14}$ C/V cm.[16] The calculated reduced carrier density $1/u$ and reduced electric field u are plotted as a function of $wJ (= x \mu q^2 n_0^2 / \varepsilon \varepsilon_0)$ in Figs. 1(a) and 1(b). The effect of increasing the applied voltage is simulated by increasing the current J. Curves 1(U) and 1(D) are for the small current density $J = 0.1$ A/cm^2, and curves 2(U) and 2(D) are for the large current density $J = 100$ A/cm^2. Curves 1(U) and 2(U) are calculated using Eq. (12) applicable to the undoped organic materials and the current is space charge limited. Curves 1(D) and 2(D) are calculated using Eq. (8) based on the theory applicable to the doped organic materials. For $J = 0.1$ A/cm^2, curve 1(D) approaches unity [i.e., $1/u = N(x)/n_0 \approx 1$] for wJ more than 0.2. We have made calculations for several values of J smaller than 0.1 A/cm^2. With decreasing J, curve 1(D) approaches unity for smaller values of wJ. This shows that at small currents (i.e., small applied voltages) the carrier density $N(x)$ is equal to the doping density n_0 over most of the sample thickness. The injected holes remain confined near the ITO contact. Since in this case the carrier density is constant at n_0 everywhere, there is practically no space charge and it is expected that Ohm's law will be obeyed. On the other hand, the carrier density in the undoped sample, curve 1(U) (corresponding to V^2 law) decreases continuously with the decrease of voltage. The behavior of the carrier density at high currents, and therefore at high voltages is quite different. At $J = 100$ A/cm^2, the curves 2(U) and 2(D) have come very close and overlap almost exactly. This happens because at
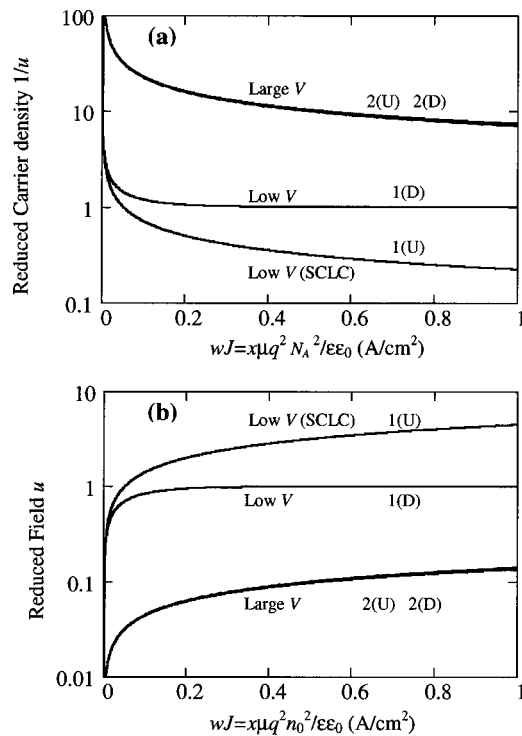
FIG. 1. (a) Plots of reduced carrier density $1/u = N(x)/n_0$ versus reduced distance wJ [see Eqs. (5) and (8)]. Curves (U) are the plots made using Eq. (12) and curves (D) are calculated using Eq. (8) of the present theory. Curves 1 are for $J = 0.1 \, \text{A/cm}^2$ and curves 2 are for $J = 100 \, \text{A/cm}^2$. (b) Reduced electric field $u = qn_0\mu F(x)/J$ vs wJ. Symbols on the curves have the same significance as in (a).
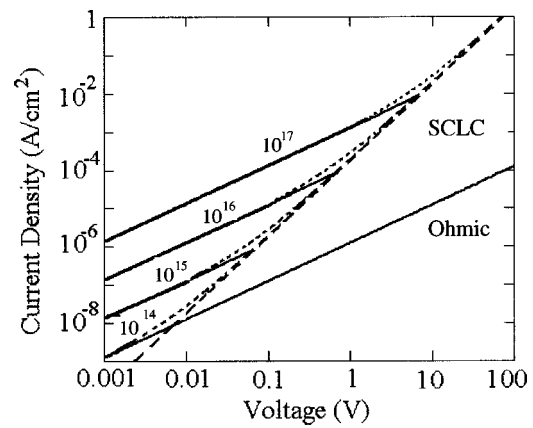

FIG. 2. Calculated current vs voltage curves for a conducting organic material containing different background doping concentrations. The doping concentrations (in units of cm^{-3}) are given on the curves. Solid straight lines are the plots of Ohm's law and the long dashed line is the plot of SCLC V^2 law [calculated using Eq. (1)].

high voltages, the injected carriers spread into regions farther from the ITO contact and the injected carrier density becomes considerably larger than the doping induced carrier density in most of the volume of the sample. Now the existing doping induced carriers can be neglected. The behaviors of the doped and undoped samples now become practically identical. One would therefore expect that the current would obey the SCLC V^2 law at high voltages in the doped organic material also.

These conclusions are consistent with the calculated values of electric field shown in Fig. 1(b). At low applied voltages, the field in the doped samples becomes constant over practically the whole length of the sample. Constant field indicates that there is no space charge and the conductor is ohmic. In the case of SCLC in the undoped material [curve 1(U)] the field increases as $\sqrt{x}$ characteristic of the SCLC V^2 law.[14,15] At high voltages and high currents the electric fields are equal in both samples and keep increasing as $\sqrt{x}$ in both cases. This implies that SCLC should now be observed in the doped organic material also.

For obtaining a direct relation between current and voltage, elimination of u between Eqs. (8) and (9) is required. Unfortunately, it is not possible to do so analytically.[14] However, current density versus voltage curves can be calculated numerically using these two equations. The $J-V$ characteristics calculated in this manner are shown in Fig. 2. The values of the four doping concentrations n_0 used in the calculations are shown in the figure. The long solid straight line is the plot of Ohm's law for $n_0 = 10^{14} \, \text{cm}^{-3}$. For each doping

concentration the plot consists of a straight line portion at low voltages (shown by the solid straight lines), a curved portion shown by short dashes, and a high voltage straight line portion shown by the long dashes. The long dashed straight line is a plot of the V^2 law given by Eq. (1). The low voltage solid straight-line plots are identical with the Ohm's law plots for each doping concentration. As the voltage increases the short dash curves deviate from the Ohm's law straight lines and bend upwards. As the voltage increases further the short dashed curved plots merge with the long dashed V^2 law line. Thus at low voltages the current is ohmic and at high voltages the current follows the universal V^2 law for all samples, a result already predicted by the behavior of the carrier and field distributions shown in Fig. 1.

Transition from the Ohm's law to SCLC takes place at a point at which the Ohm's law solid straight lines and the long-dashed straight line (corresponding to V^2 law) meet. Therefore an expression for the voltage V_{tr} at which the transition occurs can be derived by equating the ohmic current and the SCLC:

$$V_{tr} = \frac{8qn_0L^2}{9\varepsilon\varepsilon_0}. \tag{13}$$

This equation provides a method for determining the background doping concentration. The transition voltage V_{tr} can be determined experimentally and the background doping concentration n_0 can be calculated.

B. Effect of Al Schottky contact

The theory given in Sec. II A is applicable to a doped organic layer with ohmic contacts at both ends. The experiments have been performed with ITO ohmic contact[11] at one end and Al Schottky contacts at the other end. We now extend our theory to the sample with Schottky contacts at the exit end of the sample. The band diagram for the Al/Ooct-OPV5:PS/ITO Schottky diodes is shown in Fig. 3. It appears from the values of the ITO work function and the Ooct-OPV5 highest occupied molecular orbital (HOMO) level shown in Fig. 3 that the ITO contact should be rectify-
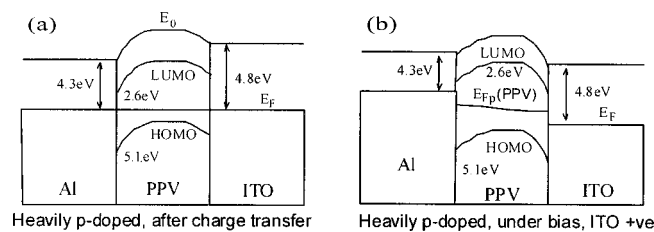
FIG. 3. Schematic band diagram of Al/Ooct-OPV5:PS/ITO Schottky diodes. (a) In thermal equilibrium and (b) under applying bias (ITO+ve). The barrier at the ITO contact shown in the figure is not observed experimentally. The ITO contact behaves as an ohmic contact.

ing. However, the barrier at this contact is reduced presumably due to interaction with oxygen. The ITO contact always behaves like an ohmic contact.[2,4,5,9,11,17] It is also seen from Fig. 3 that the Al/organic contact is a Schottky contact. When a voltage is applied with ITO as a positive electrode, the Al contact is forward biased for the holes. At low voltages (when the bulk of the sample behaves as the ohmic conductor discussed in Sec. II A) the whole structure behaves like an ordinary Schottky diode discussed by Sze.[13] The current is now limited by the Al Schottky contact. The current in a Schottky diode is determined either by thermionic emission, by diffusion of carriers, or by a combination of these two mechanisms. In all cases the current density is given by the following equation:

$$J = J_s \left[\exp\left(\frac{qV}{nkT} \right) - 1 \right]. \tag{14}$$

In the case of thermionic emission the saturation current J_s contains a factor T^2. If the current is diffusion limited J_s varies as $1/T$. However it is difficult to distinguish between the two mechanisms using the experimental data.

C. Effect of trapping and field dependent mobility

As the voltage increases, the barrier for the flow of holes (see Fig. 3) from the organic material into Al decreases. At sufficiently high voltages, flat band condition is approached asymptotically, i.e., the barrier at the Al contact tends to become zero. The current is now dominated practically completely by the bulk of the organic layer. We have already seen that at high voltages the current in the bulk of the sample is determined by the space charge created by the injected carriers. Thus as the voltage increases from low to high voltages, the contact limited mechanism of the current flow changes to the bulk limited mechanism. We expect the V^2 law to be valid at high voltages (as discussed in Sec. II B) if trapping is not important and if the mobility is independent of field. We now consider the modification of the V^2 law when trapping and dependence of mobility on the field are taken into account.

The effects of trapping and field dependent mobility on the $J-V$ curves have been discussed by several authors.[2,5,7–11,14] Most workers have assumed an exponential distribution of traps. The exponential distribution N_t of the traps is given by

$$N_t(E) = \frac{N_{\text{total}}}{kT_t} \exp(-E/kT_t), \tag{15}$$

where N_V is the density of states, T_t is the characteristic temperature of the distribution, and E is the energy. For this distribution of traps the current density J is given by[14]

$$J = q\mu N_V \left(\frac{\varepsilon \varepsilon_0}{qN_t} \right)^r \left(\frac{r}{r+1} \right)^r \left(\frac{2r+1}{r+1} \right)^{r+1} \left(\frac{V^{r+1}}{L^{2r+1}} \right), \tag{16}$$

$$r = \frac{T_t}{T}. \tag{17}$$

Here N_V is the effective density of states in the valence band. These equations give the $J = kV^m$ power law, where k is a constant and the value of the exponent m depends on the characteristic temperature T_t.

The effect of field dependent mobility has also been discussed by several authors, the most extensive discussion is given in Refs. 8, 11 and 18. Most authors have used the following equation for the mobility:[8]

$$\mu = \mu_0 \exp(\beta \sqrt{E}). \tag{18}$$

Variations of this equation are discussed in Ref. 11. It is shown in Ref. 11 that both SCLC with traps and field dependent mobility can give rise to the equation $J = kV^m$. However, experimental currents measured at different temperatures could not be described with one value of m.[11] At a given temperature and in a small voltage range, the V^m law with constant m was verified experimentally.

To summarize the theory given in this section (i.e., Sec. II), we have shown that a doped organic layer with ohmic contacts at both ends shows ohmic conduction at low voltages and a constant mobility and trap free V^2 SCLC law at high voltages. We then extended these results to a device with an ITO ohmic contact at the injecting end and an Al Schottky contact at the exit end. ITO contact injects holes when positive voltage is applied to it. The Al Schottky contact is forward biased for the holes and presents a voltage dependent barrier to the flow of holes from the organic material to Al. This gives rise to Schockley like current at low voltages. In the SCLC regime at high voltages the V^2 law changes to V^m when trapping and/or field dependent mobility are considered.

III. EXPERIMENTS

A. Experimental procedure

We have fabricated an oligomer Schottky diode with an active layer thickness of 130 nm. A 5-ring *n*-octyloxy-substituted oligomer [*p*-phenylene vinylene] (Ooct-OPV5) [full name: 2,5-di-*n*-octyloxy-1,4-bis (4′, 4″-bis-styryl) styrylbenzene][19] was used for the active layer. The device fabrication started from an ITO-coated glass substrate. ITO patterns were defined by using a photolithographical process. The cleaning steps involved ultrasonic acetone bath, boiling isopropylalcohol (IPA), and oxygen plasma treatment. The oligomer was spin-cast from a chloroform solution. Polystyrene (PS) is added to the solution; it acts as a mechanical support and allows larger thicknesses to be fabricated. At the
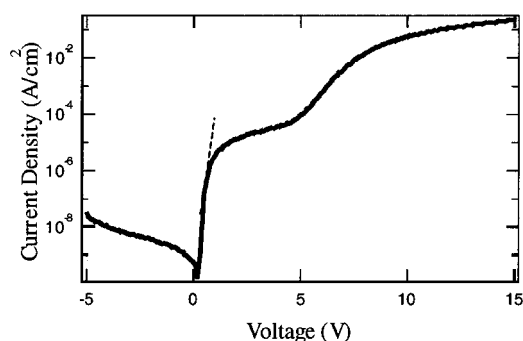
FIG. 4. Measured current density vs voltage of the Al/Ooct-OPV5:PS/ITO Schottky diode. The dashed straight line shows the fit of $\exp(qV/2kT)$ to the observed current at low voltages.
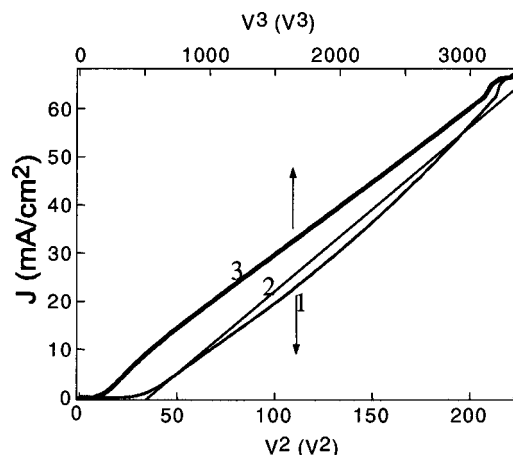

FIG. 5. Plots of current density J vs voltage of the Al/Ooct-OPV5:PS/ITO Schottky diode. Curve 1 is a plot of observed J vs V^2, straight line 2 is the plot of the V^2 law, and curve 3 is a plot of observed J vs V^3.

top, first an Al layer was deposited through a shadow mask by vacuum evaporation. A Ti/W layer was deposited on the Al layer. The topmost layer was an Au layer. The Au and the Ti/W layers protect the Al layer from oxidation. In this way a structure with an active device area of approximately 2 mm^2 was obtained. All processing steps were carried out in clean-room conditions. The $J-V$ characteristics were measured using a HP 4145B-semiconductor parameter analyzer. The measurement unit contained a thermochuck, which made it possible to vary the sample temperature between 12 and 200 °C.

Using the same method we have also prepared Al/OC$_1$C$_{10}$/ITO diodes. OC$_1$C$_{10}$ is a PPV-based polymer and it stands for poly(2-methoxy-5-(3,7-dimethyloctyloxy)-*p*-phenylene vinylene).[20] The thickness of the organic layer was 195 nm. Preliminary results obtained with these diodes are also discussed. The diodes were unstable at high temperatures. Therefore high temperature measurements could not be made with these diodes.

B. Results

The measured current density in the Al/Ooct-OPV5:PS/ITO diode as a function of voltage is shown in Fig. 4. Positive voltage in this figure implies that the ITO contact is positive and the Al contact is negative. It is seen that the current increases with the voltage more rapidly for positive voltage. A rectification ratio of about 4×10^3 can be seen at 2 V. As predicted in Sec. II B the observed current between 0 and 1 V fits closely with the Shockley like equation, Eq. (14) (the dashed straight line is the plot of this equation). The ideality factor n is 2. At V more than 2 V, the current starts bending downwards, presumably due to series resistance.

As the voltage increases to more than 5 V, current starts increasing again but not as rapidly as required by Eq. (14). We suggest that this is the beginning of the SCLC regime as predicted in Secs. II A and II C (see also Fig. 2). The current should vary as V^2 if the SCLC regime is trap free and mobility is field independent. If either trapping or effect of field on the mobility is important, we expect a V^m law for the current (as discussed in Sec. II C). To check the validity of this suggestion we have plotted the observed J as a function of V^2 and V^3 in Fig. 5. The observed current J is shown as a function of V^2 by curve 1. The straight line 2 is a plot of the

V^2 law, Eq. (1). The curves 1 and 2 show that the V^2 law characteristic of SCLC is valid only as a rough approximation. The slope of the straight line gives a mobility value of 1.8×10^{-6} cm^2/V s for the holes in the sample. A closer examination of curve 1 shows that the experimental plot is somewhat curved and not exactly a straight line. The curvature suggests that the current increases faster than V^2. We also plot the observed current J as a function of V^3 (curve 3) in Fig. 5. The V^3 law fits better with the experimental results.

Using the effect of trapping discussed in Sec. II C, a V^3 law is obtained at room temperature if the characteristic temperature $T_t = 600$ K is used in Eq. (17). We mentioned in Sec. II C that a V^m law is also obtained if the effect of field on the mobility is taken into account. In Ref. 11 the measured value of m at room temperature varied between about 3 and 8 depending on the organic material used. From these results, it is clear that our V^3 law can also be explained by assuming that the mobility is field dependent. Both trapping and field dependent mobility give qualitatively the same result, current varying with V as V^m where m is more than 2. Very detailed work in Ref. 11 shows that it is difficult to
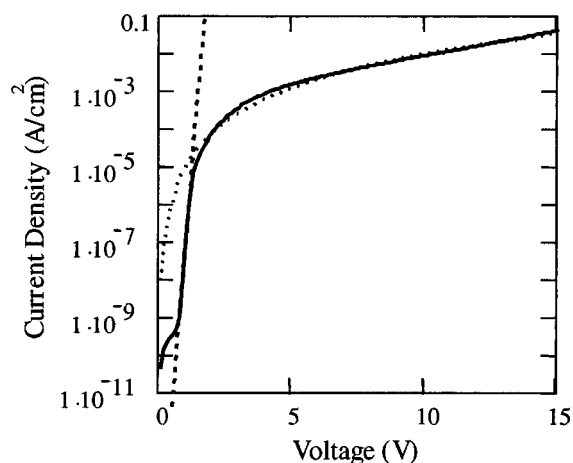

FIG. 6. Measured current density vs voltage in the Al/OC$_1$C$_{10}$/ITO Schottky diode shown by the solid line. The dashed straight line represents the fit $J \sim \exp(qV/2kT)$ and the dashed curved line is the fit of V^3 law.
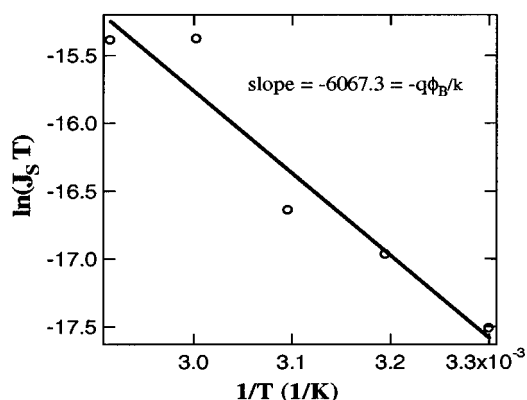
FIG. 7. Experimental plot of $\ln(J_S T)$ vs $1/T$ for the Al/Ooct-OPV5:PS/ITO Schottky diode.

distinguish between the two effects (trapping and field dependent mobility) at the present time.

The transition from the Schottky regime to the SCLC regime occurs at ~6 V. Using Eq. (13) we determine a value of 10^{17} cm^{-3} for the background concentration in the PPV-based oligomer. We will see later that this value of background doping is consistent with the measured effective barrier height at the Al Schottky contact.

We have repeated these measurements on the Al/OC$_1$C$_{10}$/ITO diodes. The $I-V$ characteristics are shown in Fig. 6. The dashed straight line is again the fit of Eq. (14) with $n=2$ and the dashed curve is the fit of the SCLC V^3 law. These results show that the initial Shockley like current at low voltages is obtained with this diode also. Results presented in Ref. 5 support our model that the Shockley like current is due to the forward biased Al Schottky contact. In Ref. 5 a gold contact instead of Al was used in the hole only device, the structure of the diode was ITO/PPV/Au. The current was space charge limited down to 0.1 V, Shockley like current was not observed.

A closer examination of the curves in Fig. 1 of Ref. 18 also shows that their data for single layer diodes at low voltages do not agree with their calculated values of SCLC. These authors used [poly(2-methoxy-5-(2′-ethyl-hexyloxy)-1,4-phenylenevinylene] MEH-PPV devices and Al as the exit electrodes. In two diodes the ohmic injecting Pt and Au electrodes were used. Though we have not made any attempt to analyze their data in detail, the deviation from the calculated SCLC at low voltages in these two diodes could be due to the Schottky barrier at the Al contact and due to the background doping as discussed in Sec. II.

From high temperature dependent $J-V$ measurements, a value of the saturation current density J_S can be obtained for each temperature T. The observed $\ln(J_S T)$ versus $1/T$ plot for the Al/Ooct-OPV5:PS/ITO device is shown in Fig. 7. The plot is made on the assumption of diffusion theory of the current in a Schottky diode, which states that

$$\ln(J_s T^2) \propto -\frac{q\varphi_B}{kT}, \tag{19}$$

where φ_B is the barrier at the Al contact, and k is the Boltzmann constant. The slope of the straight line fitted to the

experimental data gives a barrier height of 0.53 ± 0.1 eV. It is somewhat lower than the difference of Al work function and hole valence band edge (0.8 eV) at the Al/Ooct-OPV5:PS Schottky contact. For a doping of 10^{17} cm^{-3} determined earlier, the image barrier lowering comes out to be 0.17 eV bringing the barrier down to 6.3 eV. Considering the large scatter of the data point in Fig. 7 (due to inherent errors in the measurements) the agreement of the calculated and experimental barrier heights is reasonable. The experimental value of φ_B is not sensitive to whether diffusion or thermionic theory is used.

IV. SUMMARY AND CONCLUSIONS

We have made experimental and theoretical investigations of the current voltage ($J-V$) characteristics of Al/Ooct-OPV5:PS/ITO and Al/OC$_1$C$_{10}$/ITO Schottky diodes in the voltage range 0–15 V. According to the theory of transport in doped organic materials discussed in Sec. II, at low voltages J is expected to obey the Shockley like equation $J \sim \exp(qV/nkT)$, with n as the ideality factor. At higher voltages space charge limited current (SCLC) should be observed. These predictions of the theory agree with our experimental observations. At low voltages the Shockley like current has been observed. At high voltages the observed current varies according to the V^m law (with $m=3$). The value of m more than 2 indicates either the trapping and/or the effect of field on mobility are important. A background doping of 10^{17} cm^{-3} is estimated in the Al/Ooct-OPV5:PS/ITO from the voltage at which transition from Shockley like current to SCLC takes place. From the temperature dependence of the current, a value of 0.53 ± 0.1 eV is derived for the Schottky barrier height at the Al contact. It is lower than the difference (0.8 eV) of the Al work function and the hole HOMO edge at the Al/Ooct-OPV5:PS contact. For 10^{17} cm^{-3} background doping the image barrier lowering changes the barrier from 0.8 to about 0.64 eV. Considering large inherent errors in the measurements, this value is in good agreement with the experimental value of 0.53 ± 0.1 eV.

The results of this work show that if the background doping concentration is eliminated, the SCLC should be observed at lower voltages. This will probably result in light emission also at lower voltages. It is hoped as the technology improves and purer conducting organic materials become available, the LEDs will work at lower voltages.

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[1] S. C. Jain, A. Mehra, J. Poortmans, and R. Mertens (to be published).
[2] W. Riess, in *Organic Electroluminescent Materials and Devices* (Gordan and Breach, New York, 1997), pp. 73–146.
[3] S. C. Jain, W. Geens, J. Poortmans, A. Mehra, J. Nijs, and R. Mertens, MRS Proc. **558**, 485 (1999).
[4] W. Geens, J. Poortmans, S. C. Jain, J. Nijs, R. Mertens, S. C. Veenstra, V.

V. Krasnikov, and G. Hadziioannou, Sol. Energy Mater. Sol. Cells **61**, 43 (2000).

[5] P. W. M. Blom, M. J. M. de Jong, and J. J. M. Vleggar, Appl. Phys. Lett. **68**, 3308 (1996).

[6] P. E. Burrows, Z. Shen, V. Bulovic, D. M. McCarty, S. R. Forrest, J. A. Cronin, and M. E. Thompson, J. Appl. Phys. **79**, 7991 (1996).

[7] A. J. Campbell, D. D. C. Bradley, and D. G. Lidzey, J. Appl. Phys. **82**, 6326 (1997).

[8] B. K. Crone, P. S. Davids, I. H. Campbell, and D. L. Smith, J. Appl. Phys. **84**, 833 (1998).

[9] S. Karg, M. Meier, and W. Riess, J. Appl. Phys. **82**, 1951 (1997).

[10] N. C. Greenham and R. H. Friend, Solid State Phys. **49**, 1 (1995).

[11] A. J. Campbell, M. S. Weaver, D. G. Lidzey, and D. D. Bradley, J. Appl. Phys. **84**, 6737 (1998).

[12] S. V. Rakhmanova and E. M. Conwell, Appl. Phys. Lett. **76**, 3822 (2000).

[13] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).

[14] M. A. Lampert and P. Mark, *Current Injection in Solids* (Academic, New York, 1970), pp. 47–50.

[15] N. F. Mott and R. W. Gurney, *Electronic Processes in Ionic Crystals* (Dover, New York, 1964), pp. 168–173.

[16] Values of hole mobility and dielectric constant for Ooct-OPV5:PS are not known with any certainty. The values used are taken from our earlier work (Ref. 4) and are approximate. The conclusions derived from the plots in Figs. 1 and 2 remain valid if different values of these parameters are used.

[17] J. S. Kim, M. Granstrom, R. H. Friend, N. Johansson, W. R. Salaneck, R. Daik, W. J. Feast, and F. Cacialli, J. Appl. Phys. **84**, 6859 (1998).

[18] B. K. Crone, I. H. Campbell, P. S. Davids, and D. L. Smith, J. Appl. Phys. **86**, 5767 (1999).

[19] R. E. Gill, A. Meetsma, and G. Hadziioannou, Adv. Mater. **8**, 212 (1996).

[20] L. Lutsen, P. Adriaensens, H. Becker, A. J. Van Breemen, D. Vanderzande, and J. Gelan, Macromolecules **32**, 6517 (1999).