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D.C. I–V characteristics and steady-state photoconductivity of Au/Pb_2CrO_5/SnO_2 sandwich-structure films under illumination in the visible region

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The room temperature d.c. current–voltage (I–V) characteristics of an Au/Pb_2CrO_5/SnO_2 sandwich-structure 1.39 μm thick film have been measured for d.c. voltages, $V_{d.c.}$, in the range $0.25\ V \leq V_{d.c.} \leq 5.0\ V$. These measurements were carried out under both dark and visible-light illumination conditions. For $V_{d.c.} < 2.5$ V, the I–V curves of the sample in both dark and light environments were found to be non-linear and conform to space-charge-limited (SCL) current governed by traps uniformly distributed in energy. At higher d.c. voltages, a nearly Mott–Gurney V^2 behaviour of the dark current has been observed, whereas the I–V behaviour of the illuminated specimen was a combination of an ohmic conduction and a V^2 dependence at low illumination levels and became highly ohmic at large light intensities. This behaviour can be understood in terms of a reduction in the SCL dark current in favour of a larger ohmic d.c. photocurrent as a result of neutralization of the majority-carrier space charge by the photogenerated minority carriers of the electron–hole pairs produced under the illumination with visible light of energy $\hbar\omega \cong E_G$($\sim$2.1–2.3 eV for the Pb_2CrO_5 material). The d.c. photocurrent, I_{phot}, at a fixed d.c. voltage, was found to follow a power-law dependence on light intensity, F, of the form $I_{phot} \propto F^{\gamma}$, with the exponent γ being dependent on the applied d.c. voltage. At the low-voltage side ($V_{d.c.} < 1.5$ V), $\gamma \sim 0.5$, a value usually obtained when the photoconductivity behaviour is governed by bimolecular recombination mechanisms. As the d.c. voltage is increased further, γ increases monotonically until it saturates at a value of about 0.9 for d.c. voltages beyond 3.5 V, where monomolecular recombination processes seem to be more operative with increasing d.c. voltage.

1. Introduction

Pb_2CrO_5 is described as a dielectric material with a wide band-gap energy, E_G, $\sim$2.1–2.3 eV and a monoclinic c2/m structure which has been fabricated in the form of ceramic discs and/or film devices under various controlled experimental conditions [1–11]. The highly insulating aspect of the Pb_2CrO_5 material, characterized by a too low dark current and a large room-temperature dark resistivity ($\rho_D = 10^{13}\ \Omega$cm), together with its high absorption coefficient (10^4–$10^5\ cm^{-1}$) and high-speed photoresponse in the visible region of the spectrum, would render this material to be a potential candidate, among others, for use in photoconductors and optoelectronic devices [7–14]. Pb_2CrO_5 film specimens of a bulk structure are more advantageous and informative than ceramic samples. An as-deposited and untreated Pb_2CrO_5 film exhibits an amorphous-state structure for low substrate temperatures; however, crystallization of the film specimen is enhanced by heat treatment. Appropriate bulk-like films of Pb_2CrO_5 were fabricated with the substrate temperature, T_s, being in the range 100–200 °C and annealing temperatures, T_a, between 400 and 500 °C [6].

Some measurements on a variety of photoconductive effects in Pb_2CrO_5 have been described [3–10]. A somewhat detailed study of the a.c. complex-impedance of Pb_2CrO_5 ceramic and film specimens illuminated with visible light has yielded rather interesting findings with regard to the photoconductive behaviour of this material [15, 16]. However, the d.c. current–voltage (I–V) characteristics of illuminated Pb_2CrO_5 were not extensively investigated and not much information about the actual electrical transport mechanisms and the operative photoconduction phenomena in this material were reported from these measurements [7–11].

In general, various conduction mechanisms may, all or in part, be responsible for the electrical transport phenomena in materials under an externally applied d.c. voltage. In practice, the I–V characteristics of a d.c. biased sample are usually utilized to explore the

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dominant conduction processes operative in this sample under a variety of experimental external agents such as temperature, doping, illumination, etc. Several established theoretical and phenomenological models have been put forward to interpret the observed d.c. current–voltage characteristics associated with these conduction mechanisms [17–28]. Linear I–V characteristics are usually expected in the voltage range over which the thermally (or optically) generated free-charge carriers in the appropriate energy band (electrons and/or holes) dominate the electrical conduction in the sample under investigation. Assuming that electrons are the one-carrier free charges responsible for conduction in a dielectric material with a thermal equilibrium concentration, n_0, and a field-independent drift mobility, μ_e, the ohmic behaviour is usually described by

$$J = en_0\mu_e(V/d) \quad (1)$$

where J is the current density, d is the spacing between the sample and electrodes. However, free electrons (and/or holes) injected from the electrode contacts upon the application of a d.c. voltage would form a space-charge distribution into the material bulk which will give rise to a non-linearity usually observed in the I–V characteristics of many dielectric specimens [23–28]. This is often called the space-charge-limited (SCL) current which is determined by the applied d.c. voltage and geometric considerations. In a real dielectric, the current is usually limited by such a space charge and the presence of charge-carrier traps which often capture, and thereby immobilize, most of these free injected carriers. Thus, a noticeable modification in the functional dependence of the current on the applied d.c. voltage, depending on the type and distribution nature of the traps, would be observed. When the one-carrier current flow is controlled by single-energy shallow traps of concentration, N_t, and energy, E_t, below the conduction band, the SCL current–voltage characteristics are described by the well-known shallow-trap V^2 law (or the Mott–Gurney square law) [23, 24]

$$J = (9/8)\theta\varepsilon_0\varepsilon_s\mu_e V^2/d^3 \quad (2a)$$

where ε_s is the static dielectric constant of the material and the factor $\theta \ll 1$ is defined as the ratio of the concentration of free-charge carriers, $n = n_0 + n_i$, to the concentration of the trapped-charge carriers, n_t, i.e.

$$\theta = n/n_t = (N_c/N_t)\exp[-(E_c - E_t)/k_B T] \quad (2b)$$

where k_B is the Boltzmann constant, n_i and n_0 are respectively, the concentrations of the injected and the initially present free carriers, and N_c is the effective density of states in the conduction band which is equal to $4.83 \times 10^{15}(m^*/m_0)T^{3/2}$ cm^{-3} where m_0 and m^* are the free- and effective-masses of the electron. In general, charge-carrier traps are not always present with discrete energies but are distributed over a range of energy levels, particularly in materials rich in defect centres. A case of interest is that when these traps are uniformly distributed in energy with a constant trap density per unit energy, N_n. In this case, the SCL current–voltage behaviour is represented by the relation [23–25]

$$J = 2en_0\mu_e[V/d]\exp[(2\varepsilon_0\varepsilon_s/eN_n k_B T d^2)V] \quad (3)$$

Illumination of a dielectric sample sustaining a SCL current flow often leads to an increase in this current when the space-charge trapped carriers are photoionized into the conduction energy-band of the material and the optical release rate of these carriers from traps is larger than the rate of thermal re-emission of free carriers by these traps [24]. For traps that are distributed in energy below the conduction band, the corresponding one-carrier SCL d.c. photocurrent varies in accordance with a solely V^2 law, in contrast with the current–voltage behaviour of the d.c. dark current associated with such a distribution of traps [24]. However, the photogeneration of free charge carriers from traps is normally accompanied with the fundamental band-to-band absorption of light having the appropriate energy such that $\hbar\omega \geq E_G$, which results in the creation of free electron–hole pairs in the material bulk. However, the situation is rather complicated when the solid dielectric carries a two-carrier SCL current, as the corresponding current–voltage characteristics are governed by both trapping and recombination mechanisms [24, 28]. Nevertheless, the photogenerated minority-charge carriers, until trapped, can respond to the non-uniform electrical forces produced by the majority-carrier space charge and thereby tend to neutralize that space charge. An ultimate effect of such illumination is to reduce the SCL dark current of the injected space charge in favour of a larger ohmic d.c. photocurrent.

On the other hand, the photoconductive behaviour in dielectric materials can be used to obtain information about the mechanism for the recombination of the excess free-charge carriers. One property of particular interest in this respect is the dependence of the d.c. photocurrent, I_{phot}, on the intensity, F, of the illumination. A variety of theoretical models and/or empirical formulae have been proposed to explain such a dependence and its relation with the recombination mechanisms, in which the trapping and recombination centres present in the material and their energy distribution play a major role [14, 21–25, 28–44]. In principle, the predictions and relationships obtained from these models are too involved; however, the variation of I_{phot} with light intensity is often expressed as a power-law dependence of the form

$$I_{\mathrm{phot}} \propto F^{\gamma} \quad (4)$$

where the exponent γ is generally dependent on the actual operative recombination/generation mechanism. In brief, one usually finds that in dielectric systems with discrete-energy traps the exponent, γ, equals either unity when monomolecular recombination mechanisms through recombination centres and traps are dominant, or $\gamma = 0.5$ if the recombination is controlled by bimolecular processes, in which a photocarrier recombines directly with another photocarrier. However, a rather continuous distribution of localized energy-states associated with the trapping and defect centres would give rise to a mixed mechanism of both monomolecular and bimolecular recombination processes with the value of the exponent γ lying in the range 0.5–1.0.

The purpose of the present work was to investigate the current–voltage (I–V) characteristics of an Au/Pb_2CrO_5/SnO_2 sandwich-structure film under various illumination levels in the visible region of the spectrum. The observed data are described in view of the above discussed theoretical models of the photoconductivity phenomena and electrical conduction mechanisms operating in this dielectric material. This leads to a better understanding of the performance and photoconduction behaviour of Pb_2CrO_5 when used in technological devices.

2. Experimental procedure

The Pb_2CrO_5 specimen investigated in this work was a 1.39 μm thick film evaporated on a transparent SnO_2 film which serves as one of the electrodes for the specimen. The SnO_2 layer was deposited on a Pyrex-glass substrate which was maintained at a temperature $T_s = 200\,^\circ C$ throughout the evaporation cycle. The film was heat treated at an annealing temperature $T_a = 460\,^\circ C$. Such a film has a bulk-like structure and is rich in micrograins [6]. The other electrical electrode was a 40 nm thick and 0.05 cm^2 cross-sectional gold stripe deposited on to the surface of the Pb_2CrO_5 film. Electrical leads were fine copper wires connected to both electrodes by silver paste. The d.c. current produced by the Pb_2CrO_5 device (the film plus the electrodes) was measured at room temperature as a function of d.c. voltages with the device being placed in the dark or illuminated with a visible light produced by a 650 W tungsten halogen lamp. It was found [3–10] that the maximum photoresponse of Pb_2CrO_5 in the visible region of the spectrum occurs at wavelengths in the range 530–600 nm, corresponding to an energy $E = 2.1$–2.3 eV, and no activated electrons can be excited from the valence band to the conduction band for photon energies less than 1.9 eV ($\lambda \geq 640$ nm). Furthermore, we have noticed that the heat effects of the radiation produced by the high-power lamp are indeed troublesome. Thus, in order to minimize such effects on the device and to achieve a band-to-band absorption of visible light by the Pb_2CrO_5 film, an appropriate heat-shield glass plate, in conjunction with a set of quartz lenses, were used to filter out the unnecessary radiation outside this range. The intensity of illumination was varied using neutral density filters and monitored by the use of a thermopile unit.

The d.c. current in the dark or at a steady light intensity has been measured using a Keithley 614 electrometer as a function of a d.c. voltage in the range 0.25–5.0 V, corresponding to electric fields $< 4 \times 10^4$ V cm^{-1}, which are below an electric field of instability ($> 10^5$ V cm^{-1}) seen in the current measurements carried out on the Pb_2CrO_5 film devices [9–11]. The accuracy and reproducibility (over long periods of time exceeding weeks) of the current measurements were high enough under the same illumination level and d.c. voltage. The uncertainty in the measured values of light intensity, the applied d.c. voltage, and the d.c. current, particularly the high pico-ampere current readings, were better than 5%.

3. Results and discussion

3.1. D.c. *I*–*V* characteristics

Fig. 1 shows the room-temperature d.c. dark current–voltage (I–V) characteristics of the Pb_2CrO_5 film device investigated in this work. It is noticed that the dark d.c. current, I_D, is extremely low, implying that the Pb_2CrO_5 is a dielectric material with a very large room-temperature dark resistivity, ρ_D, of the order of 10^{13} Ωcm. Furthermore, the dark current increases monotonically in a non-linear fashion with increasing d.c. voltage. Detailed analysis of the observed I_D–$V_{d.c.}$ data suggests that the dark current of the Pb_2CrO_5 film of this work is best represented over the entire d.c. voltage range used by an emperical relation of the form

$$I_D(\mathrm{nA}) = 0.04V + 0.025V^2 + 0.008V^3 \qquad (5)$$

The same I_D–$V_{d.c.}$ data were also analysed by the use of the above-mentioned physically meaningful I–V relationships, as well as several others [17–28] and we have found that the observed I_D–$V_{d.c.}$ data can be

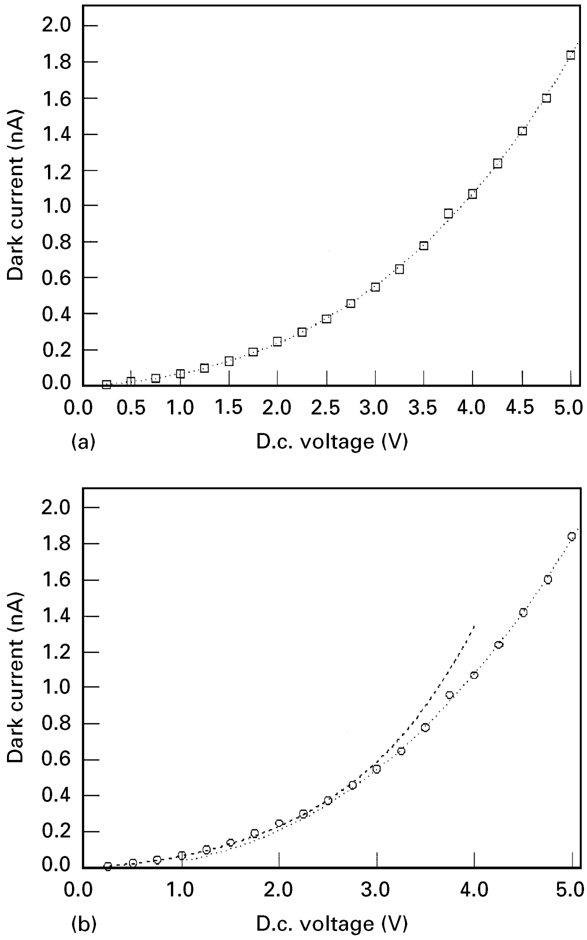


Figure 1 (a) The dark d.c. current–voltage (I_D–$V_{d.c.}$) characteristics of the Pb_2CrO_5 film at room temperature. (···) The best fit of the data to Equation 5 in the text. (b) the same I_D–$V_{d.c.}$ curve fitted to (– – –) Equation 6 and (···) Equation 7.

described by the relation

$$I_D = DV\exp(KV) \qquad (6)$$

for $0.25\ \text{V} \leq V_{\text{d.c.}} < 2.5\ \text{V}$, where D and K are adjustable parameters. The best fit to this relation yields $D = 4 \times 10^{-11}\ \text{AV}^{-1}$ and $K = 0.5\ \text{V}^{-1}$. This relation resembles that which describes the SCL current flow in a dielectric with uniformly distributed traps with the pre-factor $D = (2e\mu_e n_0)(S/d)$, where S is the effective cross-sectional area of the sample eletrode, and the parameter $K = (2\varepsilon_0\varepsilon_s)/(eN_n k_B T d^2)$. Using the above obtained values of D and K, values of $n_0 \sim 4 \times 10^9\ \text{cm}^{-3}$ and $N_n \sim 10^{16}\ \text{cm}^{-3}\ \text{eV}^{-1}$ have been estimated. In this voltage regime, Schottky-barrier effects (i.e. $J \propto \exp[\eta V]$) were not observed in the I_D–$V_{\text{d.c.}}$ characteristics of the Au/Pb_2CrO_5/SnO_2 sandwich-structure 1.39 μm thick film of this work. Toda *et al.* [11] observed a Schottky-barrier behaviour of the I_D–$V_{\text{d.c.}}$ curve of their Au/Pb_2CrO_5/Cr sandwich-structure 0.34 μm thick film in which the Au/Pb_2CrO_5 was a point contact (120 μm × 120 μm) and formed a Schottky barrier, whereas the Cr/Pb_2CrO_5 contact was quasi-ohmic. On the other hand, the high-voltage portion ($2.5\ \text{V} \leq V_{\text{d.c.}} \leq 5.0\ \text{V}$) of the I_D–$V_{\text{d.c.}}$ data was best fitted to a power-law dependence of the form

$$I_D(\text{nA}) = 0.04\, V^{2.3} \qquad (7)$$

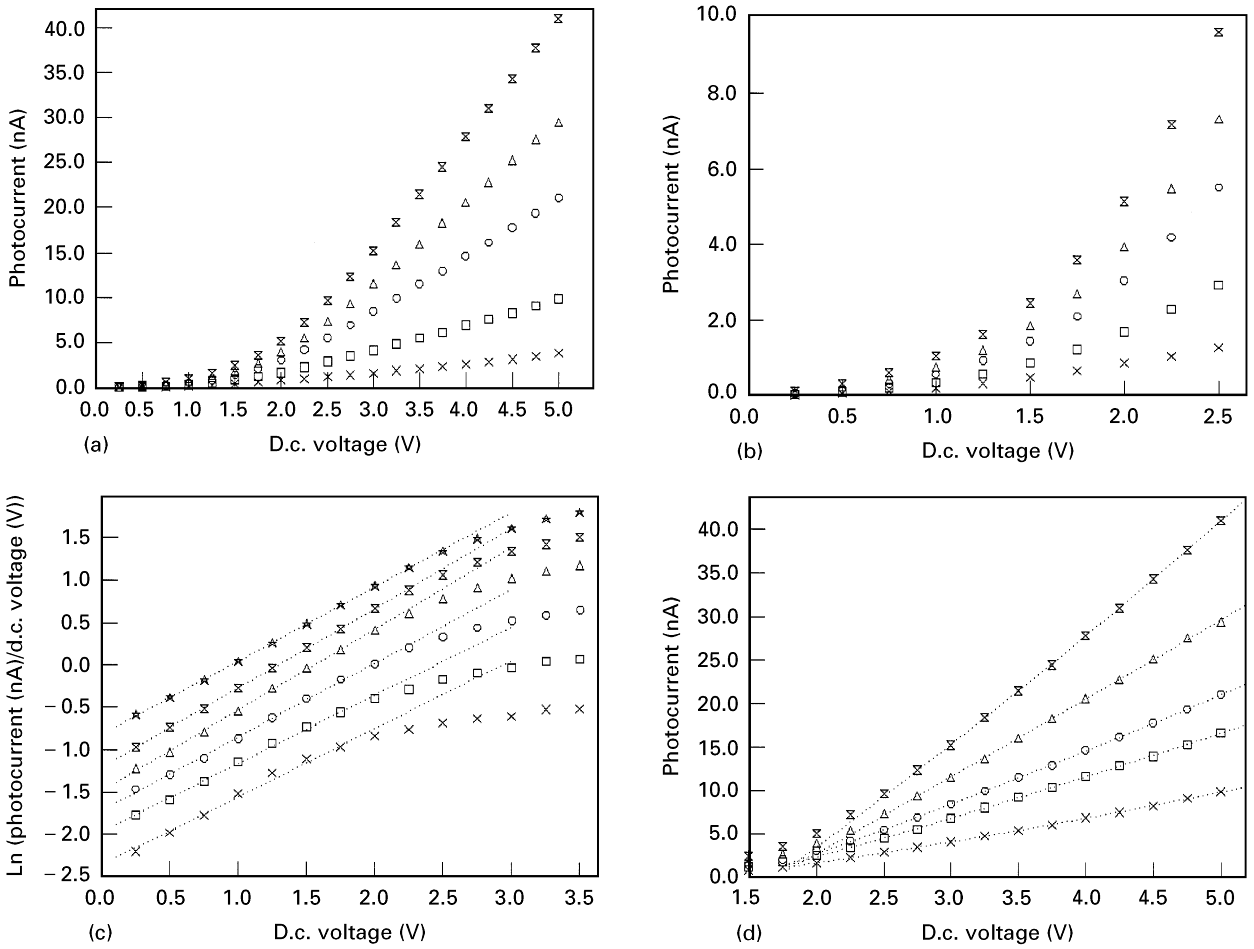
which can be presumed to represent a nearly Mott–Gurney V^2 behaviour. The results of the best fits to Equations 6 and 7 are shown in Fig. 1b. This sounds reasonable as Equation 5 is a good mathematical representation of these more physically meaningful relationships. Using the pre-factor of Equation 7, a value of the order of 10^{-4} was estimated for the factor θ which appears in Equation 2 indicating that a relatively large concentration of traps exist in the specimen and thus most of the injected free carriers can be trapped in the localized states of these traps. In conclusion, we have found that the low-voltage d.c. dark current of our Pb_2CrO_5 specimen is a SCL current being controlled by traps of uniform distribution, while the behaviour of the d.c. dark current seems to approach the Mott–Gurney V^2 type at high injection levels, where trap-filling by the injected free carriers is large. It is worth noting here that the bulk-like Pb_2CrO_5 films were found to be rich in micrograins [6] which probably serve as effective carrier traps and/or recombination centres; thus affecting the *I–V* characteristics and other physical properties of the specimen [29].

Illumination of our Pb_2CrO_5 film device with band-gap visible light was found to render the specimen rather conductive under any applied d.c. voltage in the range used. The d.c. photocurrent, I_{phot}, due to illumination was determined from the measured current, I_{meas}, at a fixed $V_{\text{d.c.}}$ and illumination level, as $I_{\text{phot}} = I_{\text{meas}} - I_D$. Fig. 2a demonstrates the variation of the d.c. photocurrent of the Pb_2CrO_5 film with the applied d.c. voltage at various illumination levels. It can be noticed that the I_{phot}–$V_{\text{d.c.}}$ curves are almost non-linear at the low-voltage side ($V_{\text{d.c.}} < 2.5\ \text{V}$) as seen in Fig. 2b. Furthermore, the d.c. photocurrent become more ohmic at higher d.c. voltages, progressively with increasing illumination level, in contrast with the behaviour of the d.c. dark current. Non-linear d.c. *I–V* characteristics of the illuminated Pb_2CrO_5 specimens of both ceramic and film forms, were also observed at low d.c. voltages and/or low-intensity illumination, whereas the same curves exhibit a linear *I–V* behaviour in the high-voltage regime, particularly at high illumination levels [3, 5, 8–10]. Furthermore, the d.c. *I–V* curves of a ceramic disc of Pb_2CrO_5 with identical planar gold electrodes, were found to be almost linear up to electric fields $< 10^3\ \text{V cm}^{-1}$ whether the sample is in the dark or illuminated with band-gap visible light [15].

The observed low-voltage ($V_{\text{d.c.}} < 2.5\ \text{V}$) I_{phot}–$V_{\text{d.c.}}$ data of the Pb_2CrO_5 device of this work seem to follow the *I–V* expression described in Equation 6 as demonstrated in Fig. 2c, suggesting that the d.c. photocurrent at these low d.c. injection levels is also governed by traps of uniform distribution under all the illumination levels used. The adjustable parameter, *D*, was found to be an increasing function of the light intensity, whereas the parameter *K* of the exponential term is almost equal to that found in the dark case and is slightly dependent on the illumination level, probably due to an increase in the dielectric constant of the Pb_2CrO_5 material with light intensity [15, 16]. The observed increase in the parameter D of Equation 6 with light intensity can be accounted for by an increase in the photogenerated free-charge carriers, *n*, in the material bulk. The value of *n* estimated from these results is nearly $5 \times 10^{10}\ \text{cm}^{-3}$ at the highest illumination level used, which is about an order of magnitude larger than the concentration of the thermal charge carriers, n_0. On the other hand, a solely V^2 dependence of the d.c. photocurrent cannot be ascribed to the observed I_{phot}–$V_{\text{d.c.}}$ data over the entire high-voltage region ($2.5\ \text{V} < V_{\text{d.c.}} \leq 5\ \text{V}$) but instead it was found that a combination of an ohmic behaviour and a V^2-dependence is rather representative of the observed results in this regime. In effect, the I_{phot}–$V_{\text{d.c.}}$ curves of this region can be described by a polynomial expression of the form

$$I_{\text{phot}} = A + BV + CV^2 \qquad (8)$$

where *A*, *B*, and *C* are adjustable intensity-dependent parameters. Typical curves with the best fits to this relation at various illumination levels are exhibited in Fig. 2d and e. At high injection levels, it is noticed that the *BV* term representing the ohmic behaviour appears to dominate the I_{phot}–$V_{\text{d.c.}}$ characteristics of the Pb_2CrO_5 film with increasing light intensity. At low illumination levels, however, both the V and V^2 dependences are significant in the high-voltage I_{phot}–$V_{\text{d.c.}}$ behaviour as contrasted with the nearly V^2 dependence being observed for the d.c. dark current in the same voltage region (see Fig. 1). These findings can be accounted for qualitatively if we presume, as already discussed, that illuminating the Pb_2CrO_5 specimen with the visible light will give rise to the fundamental band-to-band absorption and thus to the photogeneration of free electron–hole pairs in the bulk of the specimen. This would lead to a reduction in the effect



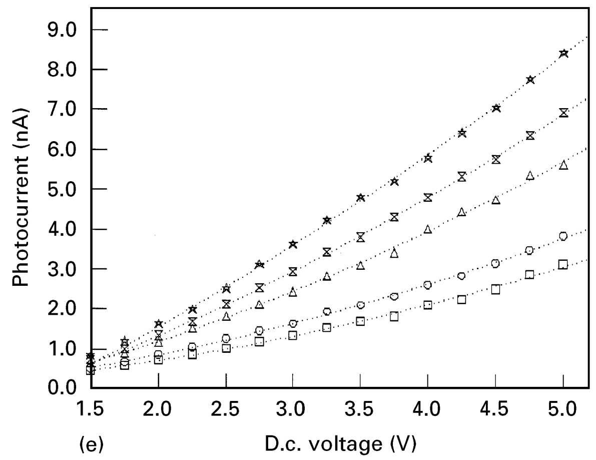


Figure 2 (a) The behaviour of the d.c. photocurrent, I_{phot}, of the Pb_2CrO_5 film with the applied d.c. voltage at various light intensities, F (Arb. units). (×) $F = 0.13$, (□) $F = 0.38$, (○) $F = 0.89$, (△) $F = 1.32$, (⧗) $F = 1.77$. (b) the low-voltage portions of these curves. (c) The I_{phot}–$V_{\text{d.c.}}$ data on an $\ln(I_{\text{phot}}/V_{\text{d.c.}})$ versus $V_{\text{d.c.}}$ plot at different illumination levels. (×) $F = 0.13$, (□) $F = 0.26$, (○) $F = 0.48$, (△) $F = 0.89$, (⧗) $F = 1.32$, (☆) $F = 1.77$. (···) Best fits of the data to Equation 6 at the low-voltage side. (d) The high-voltage portions of the I_{phot}–$V_{\text{d.c.}}$ curves fitted to Equation 8 at high light intensities: (×) $F = 0.38$, (□) $F = 0.68$, (○) $F = 0.89$, (△) $F = 1.32$, (⧗) $F = 1.77$. (e) The data at lower illumination levels: (□) $F = 0.1$, (○) $F = 0.13$, (△) $F = 0.19$, (⧗) $F = 0.26$, (☆) $F = 0.32$.

of the injected charge carriers on the SCL current due to neutralization of the majority-carrier space charge by the photogenerated minority-charge carriers. As a result, the ohmic behaviour of the d.c. photocurrent will show up at high illumination levels as observed. A similar trend can be noticed in the *I*–*V* curves reported for a ceramic disc of Pb_2CrO_5 with two coplanar gold electrodes of 59 nm thickness and a 50 μm electrode gap [3, 5].

3.2. Intensity dependence of the photocurrent

Fig. 3 exhibits the observed variation of the d.c. photocurrent produced by the Pb_2CrO_5 film of this work as a function of the light intensity, F, at different applied d.c. voltages. It has been noticed that the dependence of the photocurrent on light intensity is almost sublinear at low d.c. voltages but seems to approach a linear dependence at high d.c. voltages. Toda and co-workers [5, 8, 9] have reported that the d.c. photocurrent produced by Pb_2CrO_5 film devices and ceramic samples obeys Equation 4 with the exponent γ being dependent on the strength of the light intensity and the type of the electrode material. These authors found that $\gamma = 1$ at low light intensities and $\gamma = 0.5$ at higher illumination levels for the I_{phot}–F curves of a ceramic sample with coplanar gold electrodes [5]. In another ceramic (also with surface electrodes) they have reported that $\gamma = 0.77$ for Au/Pb_2CrO_5 contacts, while $\gamma = 0.49$ when aluminium electrodes were used [8]. In their film device with a coplanar array of electrodes of 3 μm spacing, the γ value was 0.73 at high d.c. voltages [9]. On the other hand, a value of $\gamma = 0.64$ was determined from the intensity dependence of the high-frequency resistance, R_b,

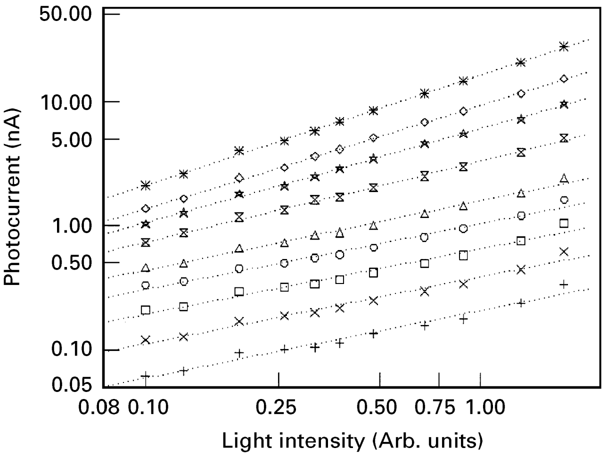


Figure 3 A log–log plot of the photocurrent-dependence of the Pb_2CrO_5 on light intensity at various d.c. voltages: (+) $V_{d.c.} = 0.5$, (×) $V_{d.c.} = 0.75$, (□) $V_{d.c.} = 1.0$, (○) $V_{d.c.} = 1.25$, (△) $V_{d.c.} = 1.5$, (⧖) $V_{d.c.} = 2.0$, (☆) $V_{d.c.} = 2.5$, (◇) $V_{d.c.} = 3.0$, (✳) $V_{d.c.} = 4.0$. The dotted lines are the best fits of the data to Equation 4 of the text.

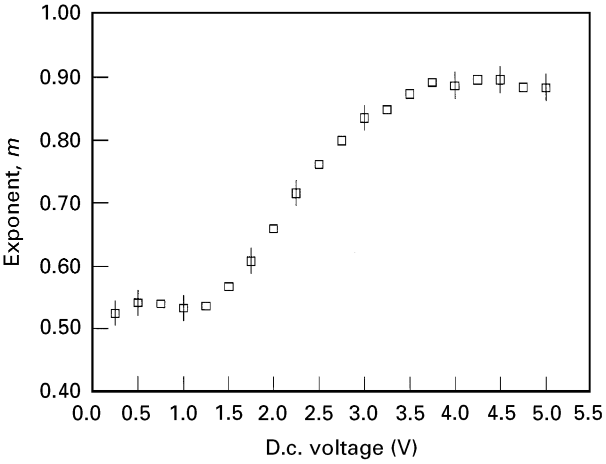


Figure 4 The variation of the exponent γ of Equation 4 of the text with the d.c. voltage. Error bars are shown on some selective points.

deduced from the observed a.c. complex impedance measurements on an $Au/Pb_2CrO_5/SnO_2$ film specimen [16].

The actual functional behaviour of the d.c. photocurrent produced by the Pb_2CrO_5 film investigated in this work on light intensity was found to follow a power-law dependence of the form given in Equation 4 with the exponent γ being a d.c. voltage-dependent parameter. Typical best-fitted I_{phot}–F curves to this power-law are also shown in Fig. 3. The observed I_{phot}–intensity data at different d.c. voltages show that the exponent γ varies with the applied d.c. voltage in a peculiar manner such that its value increases from ~ 0.5 at d.c. voltages less than 1.5 V to nearly 0.9 in the high-voltage regime ($V_{d.c.} > 3.5$ V) as seen in Fig. 4. A similar trend in the temperature-dependence of the exponent γ has been reported in the photoconductivity measurements on a-Si:H [30]. Fig. 4 exhibits a clear distinction between the $F^{0.5}$ dependence of the photocurrent and its $F^{0.9}$ behaviour through a monotonic transition-voltage region (1.5–3.5 V). The observed I_{phot}–$F^{0.5}$ behaviour can be accounted for if we presume that bimolecular recombination mechanisms, through which a photocarrier recombines directly with another photocarrier, are dominant at low d.c. voltages. On the other hand, the photocurrent–intensity behaviour seen at high d.c. injection levels may be discussed in terms of monomolecular recombination mechanisms through recombination centres and traps, which seem to become more operative with increasing d.c. voltage.

4. Conclusion

Measurements of the d.c. current produced by an $Au/Pb_2CrO_5/SnO_2$ film device were carried out as a function of d.c. voltages in the range 0.25–5.0 V at different intensities of illumination in the visible spectral region. For both the unilluminated and illuminated device of this work, the observed d.c. I–V characteristics show a clear non-linearity at low d.c. voltages ($V_{d.c.} < 2.5$ V) which has been interpreted in terms of an SCL current controlled by traps uniformly distributed in energy. A value of the density of these traps of the order of 10^{16} cm^{-3} eV^{-1} was estimated. At higher d.c. voltages, the I–V behaviour was found to be a mixture of ohmic conduction and V^2 dependence at low illumination levels, but appears to become largely ohmic at high light intensities, as contrasted with a nearly Mott–Gurney V^2 behaviour of the dark current at these d.c. voltages. This has been accounted for by an enhancement in the bulk-photogeneration of free electron–hole pairs with increasing light intensity which tend to wash out the SCL dark current in favour of a pronounced ohmic d.c. photocurrent.

The d.c. photocurrent, I_{phot}, at any fixed d.c. voltage used, increases with light intensity, F, as $I_{phot} \propto F^{\gamma}$ with the exponent γ being dependent on the applied d.c. voltage. A nearly $F^{0.5}$ dependence of the I_{phot} was found to be valid for $V_{d.c.} < 1.5$ V, which probably corresponds to bimolecular recombination processes. At d.c. voltages beyond 3.5 V, the d.c. photocurrent varies almost linearly with light intensity (as a $F^{0.9}$ law) and this can be discussed in terms of monomolecular recombination mechanisms which seem to be important at high injection levels. In the intermediate voltage region, 1.5 V $< V_{d.c.} <$ 3.5 V, the γ values show a monotonic increase with d.c. voltage between its extreme values, a behaviour that can be understood in terms of a mixed mechanism of bimolecular and monomolecular recombination processes.

Further d.c. and a.c. measurements on Pb_2CrO_5 specimens of different thickness and electrode material as a function of temperature and a broad range of illumination levels, would reveal more information about the actual dielectric properties and photoconduction phenomena in Pb_2CrO_5. This would give a better understanding of the performance and potentiality of the devices made of this insulating material when used in a variety of promising technological applications.

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References

1. T. NEGAS, *J. Am. Ceram. Soc.* **51** (1968) 716.
2. J. C. RUCKMAN, R. T. W. MORRISON, and R. H. BUCK, *J. Chem. Soc. Dalton Trans.* **426** (1972)
3. K. TODA and S. MORITA, *Appl. Phys.* **A33** (1984) 231.
4. *Idem*, *J. Appl. Phys.* **55** (1984) 210.
5. S. MORITA and K. TODA, *Appl. Phys.* **A36** (1985) 131.
6. K. TODA and S. MORITA, *J. Appl. Phys.* **57** (1985) 5325.
7. S. MORITA and K. TODA, *ibid.* **55** (1984) 2733.
8. K. TODA and S. YOSHIDA, *ibid.* **63** (1988) 1580.
9. *Idem*, *Appl. Phys.* **65** (1989) 857.
10. S. YOSHIDA and K. TODA, *Appl. Optics* **29** (1990) 1793.
11. K. TODA, S. YOSHIDA and H. IKENAGA, *J. Mater. Sci. Lett.* **12** (1993) 478.
12. K. OZAWA, N. TAKAGI, K. HIRANAKA, S. YANAGISAWA and K. ASAMA, *Jpn J. Appl. Phys. Suppl.* **22-1** (1983) 457.
13. N. YUKAMI, M. IKEDA, Y. HARADA, M. NISITANI and T. NISHIKURA, *IEEE Trans. Electron Devices* **ED-33** (1986) 520.
14. R. SHUKLA, P. KHURANA and K. K. SRIVASTAVA, *Philos. Mag.* **B64** (1991) 389.
15. M. M. ABDUL-GADER, K. A. WISHAH, Y. A. MAHMUD, K. TODA and R. N. AHMAD-BITAR, *Appl. Phys.* **A49** (1989) 665.
16. M. M. ABDUL-GADER and K. A. WISHAH, *J. Mater. Sci.*, in preparation.
17. G. FRIGERIO and C. PARACCHINI, *Solid State Commun.* **55** (1985) 625.
18. S. S. SIMEONOV, E. I. KAFEDJIISKA and A. L. GUERASSIMOV, *Phys. Status Solidi* (*a*) **136** (1993) 393.
19. J. G. SIMMONS, in "Hand Book on Thin Film Technology" ch. 14, edited by L. I. Maissel and R. Glang (McGraw-Hill, New York, 1970).
20. S. M. SZE, "Physics of Semiconductor Devices" (Wiley, New York, 1981).
21. M. SHUR, "Physics of Semiconductor Devices" (Prentice-Hall, Englewood Cliffs, NJ, 1990).
22. N. F. MOTT and E. A. DAVIES, "Electronic Processes in Non-Crystalline Materials" (Clarendon, Oxford, 1979).
23. D. R. LAMB, "Electrical Conduction Mechanisms in Thin Insulating Films" (Methuen, London, 1967).
24. M. A. LAMPERT and P. MARK, "Current Injection in Solids" (Academic Press, New York, London, 1970).
25. D. CARLES, C. VAUTIER and C. VIGER, *Thin Solid Films* **17** (1973) 67.
26. S. ANTOHE, *Phys. Status Solidi* (*a*) **136** (1993) 401.
27. V. E. BARANYUK and V. P. MAKHNIL, *Sov. Phys. Semicond.* **25** (1991) 130.
28. A. G. MILNES, "Deep Impurities in Semiconductors" (Wiley, New York, 1973).
29. S. HAVA, *J. Appl. Phys.* **59** (1986) 4097.
30. S. OZDEMIR and O. OKTU, *J. Non-Cryst. Solids* **107** (1989) 289.
31. M. HACK, S. GUHA and M. SHUR, *Phys. Rev.* **B30** (1984) 6991.
32. R. H. BUBE, "Photoconductivity in solids" (Wiley, New York, 1960).
33. A. ROSE, "Photoconductivity and Related Processes" (Interscience, New York, 1963).
34. S. M. PYVKIN, "Photoelectric Effects in Semiconductors" (Consultants Bureau, New York, 1964).
35. P. GORLICH, "Photoconductivity in Solids" (Dover, New York, 1967).
36. J. MORT and D. M. PAI (eds), "Photoconductivity and Related Phenomena" (Elsevier, Amsterdam, New York, 1976).
37. C. KITTEL, "Introduction to Solid State Physics", 4th Edn (Wiley, Chichester, 1971).
38. D. CARLES, G. LEFRANCOIS and J. P. LARMAGNAC, *J. Phys. Lett.* (*Paris*) **45** (1984) L901.
39. J. GRENET, D. CARELS, G. LEFRANCOIS and J. P. LARMAGNAE, *J. Non-Cryst. Solids* **56** (1983) 285.
40. S. EL-HALAWANY, R. BACEWIZ, J. FILIPOWICZ and R. TRYKOZKO, *Phys. Status Solidi* **A84** (1984) K89.
41. Z. EL CHARRAS, B. BOURAHLA and C. VAUTIER, *J. Non-Cryst. Solids* **155** (1993) 171.
42. M. F. KOTKATA, M. FUSTOSS-WEGNER, L. TOTH, G. ZENTAI and S. A. NOUH, *Appl. Phys* (*J. Phys. D.*) **26** (1993) 456.
43. V. HALPERN, *J. Phys. C* **21** (1988) 2555.
44. M. GAILBERGER and H. BASSLER, *Phys. Rev.* **B44** (1991) 8643.

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