SPACE-CHARGE-LIMITED CURRENT AND THE EFFECT OF LIGHT IN CdS-SINGLE CRYSTALS

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Thin CdS-single crystals in darkness show current-voltage characteristics in agreement with Lampert's theory. Illumination with photons in the extrinsic energy-range appears to increase considerably the amount of injected charge that remains free in the conduction band.

Space-charge-limited currents are of great interest in the study of insulators, mainly in getting information about defect states in the forbidden band-gap, and find wide application in solid-state devices [1]. Thin planar slabs of CdS with dimensions of about $2\times3\times0.1$ mm^3 were provided with indium contacts on opposite faces by evaporation in vacuum at about 10^{-6} mm mercury pressure. Current leads were attached to the indium layers with a silver paste.

Fig. 1 shows the current-voltage (I-V) characteristic of sample 1.1 in darkness at room temperature. Three portions can be distinguished, as predicted by Lampert's theory for space-charge-limited current in an insulator with traps [1]. At low voltages Ohm's law is found. At $V \approx V_{TFL} \approx 10$ V a steep rise occurs due to the fact that traps are filled in this voltage region by injected carriers. The square-law behaviour observed at high voltages conforms to Child's law for space-charge-limited current in a trap-free insulator. The latter was first discussed by Mott and Gurney [2] and is given by

$$j = 9\epsilon\epsilon_0\mu V^2/8L^3 \tag{1}$$

where j is the current density, $\epsilon\epsilon_0$ the permittivity of the insulator, μ the carrier mobility and L the electrode spacing.

The thickness of the crystal as obtained from eq. (1), assuming one-carrier electron injection, using $\epsilon = 12$ and $\mu = 2\times10^{-2}\,\mathrm{m}^2\,(\mathrm{V\,sec})^{-1}$ [3] turns out to be 2.5×10^{-4} m, which differs only a factor of two with the estimated value. The density $\bar{n}$ of free electrons in the ohmic region is about $5\times10^4/\mathrm{m}^3$. The effective trap-density $(N_t - \bar{n}_t)$ under thermal-equilibrium conditions follows from V_{TFL} according to Lampert's theory [1]

$$V_{TFL} \approx \frac{eL^2}{2\epsilon\epsilon_0}(N_t - \bar{n}_t) \tag{2}$$

where e is the electron charge, N_t the total trap-density and $\bar{n}_t$ the density of occupied traps at $V = 0$. Thus a relative low value of $10^{17}/\mathrm{m}^3$ is found, indicating that most traps are already occupied at $V = 0$. This conclusion agrees with the absence of a "reduced square-law" for voltages below V_{TFL}. On the other hand the low value of V_{TFL} enabled measuring the I-V characteristic without damage due to heating or electrical breakdown effects. It should be mentioned that our result for CdS resembles that of Ruppel in ZnS [4].

In addition the dependence on the light-intensity is shown for sample 1.3. Curve U_0, obtained without illumination, shows a square-law region for voltages below 40 V. This result, obtained from a sample with specific resistivity in excess of 10^{10} Ωm, can be interpreted as space-charge-limited current with shallow trapping. Comparing the experimental data with eq. (1) a reduction factor $\theta \approx 10^{-7}$ is found. The steep rise in the current at $V \approx 60$ V can be accounted for by putting $N_t = 10^{19}/\mathrm{m}^3$ according to eq. (2). Since in this case Child's law for completely filled traps could not be verified without overheating, it is not sure that there was only one, discrete, trapping level. In the region below 40 V however, nearly all injected charge will be trapped at a single level E_t, so the reduction factor may be written as

$$\theta \approx \frac{N_c}{N_t}\exp(-E_t/kT) \tag{3}$$

with $N_c \approx 3\times10^{24}/\mathrm{m}^3$ being the effective density of states in the conduction band [3], k Boltzmann's

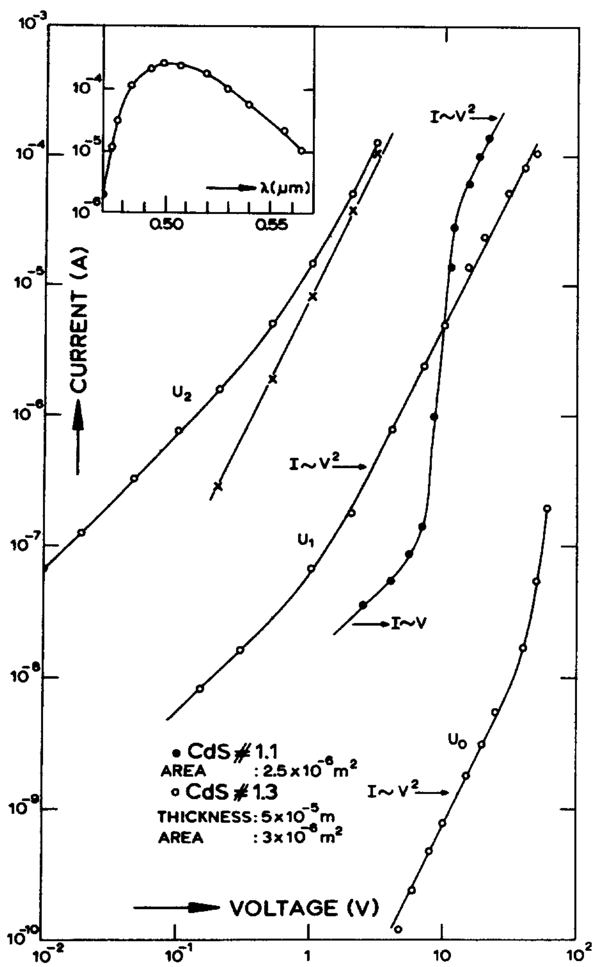

Fig. 1. • Current-voltage characteristic in darkness. Thickness as obtained from space-charge-limited current: 2.5×10^{-4} m. o Current-voltage characteristics in darkness (U_0), and with increasing amounts of integral light (U_1, U_2). Insert: space-charge-limited current-contribution as a function of wavelength at $V = 5.5$ V.

constant and T the temperature in $^{\circ}$K. From $\theta \approx 10^{-7}$, $N_t = 10^{19}/\mathrm{m}^3$ and eq. (3) it follows that $E_t = 0.7$ eV below the bottom of the conduction band.

Curves U_1 and U_2 were taken with increasing intensity U of illumination, incident on the transparant cathode-layer from an incandescent light source. Attenuating filters were used to obtain constant spectral distribution at different intensities. Considering the current as a superposition of an ohmic and a space-charge-limited current-part, the latter shown separately for curve U_2, we found that both parts increased as $U^{\frac{1}{2}}$ at fixed voltage.

As far as the space-charge-limited current-contribution is concerned, we may conclude that electrons are generated from trapping centers into the conduction band by photons with adequate energy, thus increasing θ. Photons with energy exceeding the band-gap energy however, are expected to induce preferably band-band transitions. So, the effect of increasing space-charge-limited current can only be expected from photons in the extrinsic energy range. On the other hand this long-wavelength light will increase the number of unoccupied centers in the forbidden gap at $V = 0$. The dependency of the space-charge-limited current-contribution on wavelength λ at constant photon density was measured with a tungsten ribbon light source and a Leiss single-monochromator. The result is given in the insert of the figure. A maximum was found at $\lambda \approx 5000$ Å, corresponding to an energy-value slightly greater than the bandgap energy 2.43 eV, usually obtained from photo-conductivity measurements in CdS. The decrease in current for lower values of λ is very clear.

The similar behaviour of the ohmic and square-law region under illumination is not quantitatively understood at the moment and will be further investigated. Since the evaporated contact layers cover only a part of the crystal surface it is possible that inhomogeneity of illumination causes ohmic and space-charge-limited current to flow in different parts of the crystal.

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