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DARK- AND PHOTOCONDUCTIVITY OF COMPENSATED a-Si:H

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Abstract.- In Li-diffused B-doped a-Si:H the dark conductivity can be changed from n- to p-type by annealing. Going from n- to p-type conduction, the photoconductivity changes by a factor of about 10$^6$ with a minimum close to compensation. The recombination kinetics is of second order in the n- and p-type range, and of first order around compensation. We conclude that the recombination lifetime is determined by charged centers near midgap which alter their charge state with the position of the Fermi level. As the p- and n-photoconductivities have different activation energies, the two kinds can be observed together when $E_F$ is near midgap: the photoconduction is n-type at low temperature and p-type at high temperature.

Introduction.- Photoconductivity has been shown to be a sensitive probe for the investigation of tail states and recombination centers in a-Si:H$^1$, $^2$, $^3$. It occurs, however, that the information contained in photoconductivity results is hard to separate. In addition, it is often not clear whether the photoconduction is of n or p character. - Here we attempt to unravel the situation by measuring the photoconductivity, $\sigma_p$, of a-Si:H for varying degrees of compensation, as a function of temperature. Moreover for each temperature and doping level the exponent $v$ of the intensity dependence $\sigma_p \propto q^v$ was measured ($q$ is the generation rate). By using Li-diffused B-doped films, the position of the equilibrium Fermi level $E_F$ could be shifted from n- to p-type in a single sample.

Experimental.- The compensated samples were obtained by B-doping a-Si:H films in the gas phase (3, 10, and 100 vppm $[B_2H_6]/[SiH_4]$) and, as described earlier$^4$, by overcompensating these films by in-diffusion of Li. Annealing brings the Fermi level gradually back to the original position, probably by out-diffusion of the Li. We used coplanar evaporated Al contacts with 1 mm distance.

The photoconductivity results were obtained using an expanded He-Ne laser beam as illumination source. Around the voltage used (15 V) the I-V-characteristics was linear, and the influence of contact photovoltages was negligible. We got similar results using light of small penetration depth ($\lambda = 440$ nm, $a^{-1} = 330$%). This indicates that the reported photoconductivity data are bulk properties.

Results.- The variation of the dark conductivity, $\sigma_D$, upon annealing is shown in Fig. 1. The dark conductivity at room temperature shows the usual V-like variation by a factor of more than 10$^7$, which indicates the change from n- to p-conduction. The data are plotted here vs. the activation energy of $\sigma_D$ as a rough measure for the position of the equilibrium Fermi level.
The pronounced change in $\sigma_D$ upon annealing is accompanied by a similar, though less pronounced, change in $\sigma_{ph}$ (Fig. 1). The more highly B-doped sample exhibits a generally smaller $\sigma_{ph}$ (curve 2), although the degree of initial B-doping does practically not influence the room-temperature dark conductivity. Around the dip of the photoconductivity, substantial changes in recombination kinetics occur (Fig. 2): From n-type towards compensation, the exponent $\nu$ rises from 0.5 to 1; at the same time the activation energy, $E_{ph}$, of $\sigma_{ph}$ drops from 0.1 eV to much smaller values (0.015 eV in this case). At compensation, both $\nu$ and $E_{ph}$ switch more or less suddenly (depending on temperature and on the initial B-doping) to the values characteristic for p-type photoconduction, $\nu=0.5$ and $E_{ph}=0.18$ eV. These changes are less pronounced in the case of more heavily B-doped samples (curve 2), where the exponent $\nu$ is equal to unity in a relatively broad range.

The temperature dependences of $\sigma_{ph}$ and $\nu$ are more clearly given in Fig. 3 for the two pure cases of n- and p-doping (right and left) and for an annealing state close to compensation (center). For both n- and p-photoconductance there is a trend towards lower $E_{ph}$, and higher $\nu$ at lower temperatures. The central diagram corresponds to a case where a distinct switching-over occurs from $\nu=1$ to 0.5 and from $E_{ph}$ near zero (low temperature) to 0.18 eV (high temperature).

By virtue of the different exponents for different temperatures (Fig. 3, center), the low-temperature part of $\sigma_{ph}$ vanishes faster upon reducing the illumination intensity than the high-temperature part, which then takes over and gradually changes the exponent from 1 to 0.5, as seen in Fig. 4b. One clearly sees that the photoconductivity with high $E_{ph}$ (0.18 eV) and $\nu=0.5$ extends to lower temperature at lower generation rate. The bending-over at high temperature is typical for the case when $\sigma_{ph}$ is comparable to $\sigma_D$, and is characterized by $\nu$ approaching unity. Corresponding changes can be observed when $g$ is varied, with $T$ as a parameter (Fig. 4a).

Model, discussion.- The simplest assumption to explain the dip in photoconductivity around compensation is clearly that both the n- or p-type photoconduction drop when the Fermi level is shifted from the conduction or valence band edges towards midgap. At the minimum, p- and n-photoconductivity contribute equally to the room-temperature photoconductivity. This decrease is explained...
Fig. 3: Temperature dependence of OD, $\sigma_{ph}$ and $v$ for three typical samples (details see text) with the influence of charged states originating from the overlap of the density-of-states tails near midgap. When $E_F$ is close to the conduction band (close to the valence band) practically all localized states in the pseudogap below $E_F$ (above $E_F$) are negatively (positively) charged. No positive (negative) centers with large capture cross sections for electrons (holes) are left. In the n-type case, neutral states with the density $P_R$ are generated, when these negative centers capture the photoexcited excess holes. The steady-state recombination equation therefore is

$$n = g - b \ P_R \ \gamma \ n \ \exp(-E_L/kT) = 0 \quad (1)$$

For this equation it was assumed that only the mobile fraction of the total number $n$ of electrons, $\gamma n \ \exp(-E_L/kT)$, can recombine$^5$. In this doping range (neglecting the equilibrium concentration $P_0$) $P_R$ is close to the total number $p$ of photoexcited holes which, for neutrality reasons, is equal to $n$. Assuming a trap-limited mobility $\mu = \mu_0 \ \exp(-E_L/kT)$, we obtain

$$\sigma_{ph} = e \ \mu_0 \ (g/b \gamma)^{1/2} \ \exp(-E_L/2kT) \quad (2)$$

and, thus, $v = 0.5$.

When $E_F$ recedes toward midgap, positive centers $P_R$ are created$^1$; these provide an effective recombination channel for electrons. If $P_R$ is large enough, it will be independent of the concentration of photoexcited holes and, therefore,

$$\sigma_{ph} = e \ \mu_0 \ g/b' \ P_R \ \gamma \quad (3)$$

In this case, the Boltzmann factors of $\mu$ and $n$ cancel, giving $E_{ph} = 0$ together with $v = 1$; the experimental $E_{ph}$ appears to approach this value (Fig. 2).

The intermediate cases $0.5 < v < 1$ can be explained with the aid of Rose's assumption of an exponential state distribution$^6$ (the tails of the bands or of defect levels). In that case, and with the present model, one finds that $E_{ph}$ and $v$ are connected by $E_{ph} = E_L (1 - v)$.

The switching-over of $v$ and $E_{ph}$ at compensation finds its natural explanation in the transition from one type of photoconduction to the other. By its relatively high $E_{ph}$, the hole photoconduction is suppressed relative to the electron photoconduction. The $p$ photoconductivity appears first at high temperature when its recombination kinetics is already of second order ($v = 0.5$); then the Fermi level lies in the lower part of the gap, and the recombination of electrons is dominated by the high concentration of positive recombination centers ($P_R'$ in eq. (3)). Therefore the recombination of electrons obeys first-order kinetics ($v = 1$). This situation is clearly shown in Fig. 3 (center) and Fig. 4.

We believe that the right and left parts of Fig. 3 do not represent mixed photoconduction but the pure n- and p-cases, respectively. Then, however, the in-
Fig. 4: Intensity dependence of $\sigma_{ph}$ with the temperature as parameter (a) and the temperature dependence of $\sigma_{ph}$ and $v$ for two typical light intensities (b). The decrease of $v$ towards lower temperature has to be explained differently than in the closely compensated case (center). We do this by again citing Rose's model of an exponential density of states. At lower temperature, the quasi Fermi levels $E_{Fn}$ and $E_{Fp}$ and the respective demarcation levels $E_{Dn}$ and $E_{Dp}$ are more widely separated than at high temperature. At low temperature, therefore, the concentration of recombination centers between $E_{Dn}$ and $E_{Dp}$ is larger than at high temperature. This leads to a gradual transition from the second-order case at high temperature towards a first-order case at low temperature. The decrease of $E_{ph}$ to lower temperature again follows as in eqs. (2) and (3).

Conclusion.- A consequence of the evaluation of eqs. (2) and (3) is that the relevant trap depths - entering both the mobility and the recombination probability - are twice as large as measured in a photoconductivity experiment, i.e. 0.2 eV for electrons and 0.36 eV for holes. These values are, however, not unreasonable since they agree with values directly measured by drift mobility experiments (0.19 eV and 0.35 eV, respectively). This large difference between the electron and hole trap depths makes it possible to observe (and distinguish) p- and n-type photoconduction at the same doping state of the sample. - The recombination properties can be described by the effect of overlapping tails, the nature of which cannot be specified from the present results alone. They could belong to the bands or to a distribution of defect states.

1. ANDERSON D.A., SPEAR W.E., Phil.Mag. 36 (1977) 695
4. BEYER W., FISCHER R., Appl.Phys.Lett. 31 (1977) 850
5. PUHS W., MILLEVILLE M., STUKE J., phys.stat.sol. (b) 89 (1978) 495
7. MOORE A.R., Appl.Phys.Lett. 31 (1977) 762