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DETERMINATION OF MIDGAP DENSITY OF STATES IN a-Si:H USING SPACE-CHARGE-LIMITED CURRENT MEASUREMENTS

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Abstract.—The density of states in glow discharge deposited amorphous silicon has been deduced from space-charge-limited (SCL) current measurements on samples with an n⁺-i-n⁺ sandwich configuration. The temperature and film-thickness dependence of the SCL current are found to be consistent with the theory of one-carrier steady-state SCL current flow. The resulting midgap density of states is $10^{16} - 10^{18}$ cm$^{-3}$ V$^{-1}$ln the energy region 0.75 to 0.6 eV below the conduction band edge. This figure is lower than that usually found by the field-effect technique ($\sim 10^{17}$ cm$^{-3}$ V$^{-1}$), probably due to the inclusion of interface states in field-effect measurements.

Introduction.—Much information on the quality and properties of hydrogenated amorphous silicon (a-Si:H) can be obtained from its distribution of localized states. The method most widely used to measure the density of states (DOS) in a-Si alloys is the field-effect technique [1,2]. This method does not distinguish between interface states at the semiconductor-insulator interface and bulk states and consequently provides an upper limit for the bulk DOS ($10^{17}$ cm$^{-3}$ V$^{-1}$ for a-Si:H). Deep level transient spectroscopy, on the other hand, is assumed to measure the true bulk DOS and application of this technique on a-Si:H has resulted in a midgap DOS below $10^{16}$ cm$^{-3}$ V$^{-1}$ [3].

Recently dark forward current-voltage measurements on a-Si:H Schottky diodes have been interpreted as giving evidence for space-charge-limited (SCL) current flow [4]. A quasi-exponential DOS was deduced from these experiments. The SCL current technique is a well-known method for determining trap distributions in high resistivity solids and has been applied to a large variety of materials [5].

We propose to use a sandwich structure with two ohmic contacts to measure SCL current flow. In this configuration the I-V-characteristic is not obscured by exponential behaviour for low voltages as in the case of Schottky diodes. Consequently the SCL current regime can be extended to lower voltages.

Theory.—Since undoped a-Si:H is slightly n-type and the contacts in an n⁺-i-n⁺ structure are blocking for holes, the SCL current is predominantly carried by electrons. Then, under the additional assumptions that quasi-equilibrium exists, that diffusion currents are negligible and that the ohmic contact is an infinite reservoir of electrons, the theory for one-carrier steady-state SCL current flow is applicable [5]. First we consider a quasi-exponential distribution of states:

$$N_t(E) = N_t \exp \left( \frac{E-E_c}{kT} \right) ,$$

where $N_t$ and $T_t$ are parameters characterizing the trap distribution and $E_c$ is the energy of the conduction band edge. For this distribution the current-density-voltage (j-V) characteristic is linear on a log-log-scale, i.e. j-V$^m$, with $m>2$.

$$N_t$$ and $T_t$ are deduced from the j-V-characteristic [5]:

$$j = N_c \omega_n \left( \frac{N_t}{N_t(l+1)} \right)^{1+1} \frac{1}{L^{2l+1}} ,$$

where $N_c$ is the effective density of states at the conduction band edge, $\omega_n$ is the...
free electron mobility, L is the sample thickness, $\varepsilon_s$ is the semiconductor permit-
tivity and $L = \frac{T}{T_s}$.

In general a straight-line fit to the log j-log V-characteristic is not possible.
The DOS can then be estimated by using the following analysis.
The concentration of filled electron traps in equilibrium is $n_{t,0}$. When a voltage is
applied the Fermi-level is raised from its equilibrium value $E_{F0}$ to $E_{Fn}$ due to space
charge injection from the ohmic contact. The concentration of filled electron traps
then becomes $n_t$. Assuming that the trap distribution $N_t(E)$ is continuous and only
slowly varying, $n_t - n_{t,0}$ can be approximated by

$$n_t - n_{t,0} \approx \int_{E_{F0}}^{E_{Fn}} N_t(E) \, dE.$$  \hfill (3)

To simplify the analysis we assume that the injected charge is uniformly distributed
across the film and that the electric field is constant and equal to $\frac{V}{L}$ throughout the
film.

These two assumptions are contradictory, but it can be shown [5] that this simplifi-
cation overestimates the DOS by not more than a factor of 2.
The injected charge $Q$ per unit area is then equal to $\frac{2\varepsilon_s V}{L}$.

Since the trap density is much larger than the free electron density most of the in-
jected charge is trapped, i.e.

$$eL \left( n_t - n_{t,0} \right) = \frac{2\varepsilon_s V}{L}. \hfill (4)$$

Taking two points $(j_1, V_1)$ and $(j_2, V_2)$ on the measured j-V-curve we calculate the
Fermi-level shift $\Delta E_F = E_{F2} - E_{F1}$ corresponding to a voltage change $\Delta V = V_2 - V_1$.

$\Delta E_F$ is deduced from the current-density equations

$$j_1 = n_1 e \mu n L, \hfill (5)$$

$$j_2 = n_2 e \mu n L,$$

where $n_1$ and $n_2$ are the free carrier densities at applied voltages $V_1$ and $V_2$,
respectively:

$$n_1 = N_c \exp \left( - \frac{E_c - E_{F1}}{kT} \right),$$ \hfill (6)

$$n_2 = N_c \exp \left( - \frac{E_c - E_{F2}}{kT} \right).$$

Then, from (5) and (6),

$$\Delta E_F = E_{F2} - E_{F1} = kT \ln \frac{N_2}{N_1} = kT \ln \frac{j_2}{j_1} V_2.$$ \hfill (7)

Using (3) and (4), we can write:

$$\frac{2\varepsilon_s \Delta V}{L} = eL \int_{E_{F1}}^{E_{F2}} N_t(E) \, dE.$$ \hfill (8)

The integral in (8) can be approximated by

$$\int_{E_{F1}}^{E_{F2}} N_t(E) \, dE \approx \tilde{N}_t \cdot \Delta E_F,$$ \hfill (9)

where $\tilde{N}_t$ is the average trap density between $E_{F1}$ and $E_{F2}$.

Then, from (8) and (9),

$$\tilde{N}_t \approx \frac{2\varepsilon_s \Delta V}{eL \Delta E_F}.$$ \hfill (10)
Experimental.- The films were grown in an rf glow discharge of silane at a substrate temperature of 300°C. For the ~50 nm thick n⁺ layer 1% phosphine was added to the silane. With these films solar cells with efficiencies exceeding 4% have been produced [6]. Quartz or glass plates with evaporated chromium stripes were used as substrates. As upper electrodes chromium-gold stripes were evaporated perpendicular to the lower electrodes, the overlapping area (1 mm² or 4 mm²) defining the device.

Results and discussion.- The current density was found to be independent of device area (1 mm² or 4 mm²), which eliminates edge effects. The applied electric field should not exceed ~5.10⁴ V/cm. At higher fields the free carrier density is not only increased by space-charge injection, but also by field ionization out of traps [7].

The temperature dependence of the j-V-curves is illustrated in Fig. 1 for a representative sample with an undoped layer thickness of 0.55 μm.

The trap density was calculated for the curves measured at T=251 K, 290 K and 375 K, using equations (7) and (10). The position of the Fermi-levels was calculated from (5) and (6), taking a value of 10²¹ (cm V sec)⁻¹ for the nNc product [8].

The resulting density of states is represented in Fig. 2. For energies between 0.75 and 0.6 eV below the conduction band edge the calculated Nₘ(E) is in the range 10¹⁶-4.10¹⁶ cm⁻² eV⁻¹, independent of the measuring temperature.

These results represent an upper limit and overestimate the DOS by not more than a factor of 2, as indicated in the figure.

![Fig. 1: j-V-curves at the indicated temperatures for a sample with undoped layer thickness L=0.55 μm.](image1)

![Fig. 2: Densities of states for three curves of Fig. 1 at T=251, 290 and 375 K. The calculations are based on equations (7) and (10).](image2)
The DOS has also been calculated by taking the best straight line fits for the log $j$-log $V$-curves at 251 K, 290 K and 375 K and using equation (2). The resulting exponential distributions are shown in Fig. 3 and are in reasonable agreement with the results of Fig. 2.

Equation (2) shows that the SCL current strongly depends on the undoped layer thickness $L$. As an additional check on the validity of the method, the DOS has been calculated for samples with different values of $L$. Fig. 4 shows the DOS calculated for samples with $L=0.55$, 1.1 and 2.45 μm, measured at $T=290$ K. The DOS is virtually independent of sample thickness.

In summary, a midgap density of localized states in a-Si:H of $\sim 10^{16}$ eV$^{-1}$cm$^{-3}$ has been deduced from SCL current measurements. The dependence of the SCL current on sample thickness and temperature is in reasonable agreement with theory. The calculated DOS is supposed to represent the true bulk DOS. Therefore, we argue that the SCL current technique provides a more reliable estimate of the bulk DOS in a-Si:H than the field-effect results in which interface states are likely to dominate.

**Fig. 3**: Densities of states calculated for three curves of Fig. 1 at $T=251$, 290 and 375 K. The calculations are based on equations (1) and (2).

**Fig. 4**: Densities of states calculated for three different samples with undoped layer thickness $L=0.55$, 1.1 and 2.45 μm. The measuring temperature was 290 K. Calculations are based on equations (7) and (10).

**References**