

## DETERMINATION OF THE DENSITY OF STATES IN AMORPHOUS SILICON FROM THERMOSTIMULATED CONDUCTIVITY MEASUREMENTS

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The density of states between the Fermi level and the conduction band in glow-discharge a-Si:H has been determined by measuring thermostimulated currents and photo-currents simultaneously. During the TSC measurements the sample is exposed to light pulses of low intensity. From the measurements both  $g(E)$  and the  $\mu\tau$  product can be calculated. Results are shown from samples grown at different glow-discharge powers. Minimum values of  $g(E)$  at 0.3 eV below  $E_c$  range from  $10^{16}$  to  $10^{17}$  eV<sup>-1</sup> cm<sup>-3</sup>.

### 1. INTRODUCTION

The increase in conductivity by carriers released from traps can be used to determine the density of gap states. If gap states are filled at a low temperature, the thermostimulated conductivity (TSC) during the heating of the sample is a measure for the distribution of traps in the gap. A thorough description of TSC measurements has been given by Simmons et al.<sup>1)</sup> To determine the number of released carriers from TSC, the  $\mu\tau$  product of the carriers has to be known. Zhu and Fritzsche<sup>2)</sup> showed how this product can be found from photoconductivity measurements. These measurements are rather extensive, since the  $\mu\tau$  product depends on the temperature as well as on the trapped carrier distribution in the bandgap. We suggest here a technique to combine thermostimulated and photo-induced current measurements.

Although both electrons and holes contribute to the TSC, we suppose that the influence of the hole transport in intrinsic amorphous silicon can be neglected. In that case, TSC yields the density of states in the bandgap between the conduction band and the Fermi level.

### 2. DESCRIPTION OF THE METHOD

#### 1.1. Principle

In our experiments we used samples with coplanar electrodes which were 0.50 mm apart. Before a TSC measurement, the samples are kept at a low temperature and exposed to light to fill the gap states. The intensity and the duration of the illumination may vary in a wide range to obtain, after a certain relaxation time, an occupation of trap states which is largely independent of the total photon flux. The energy range of filled traps is characterized by quasi-Fermi

levels which lie close to the mobility edges. By increasing the temperature at a constant rate of about 5 K/min, trapped electrons are released continuously until the quasi-Fermi levels reach the Fermi level.

To determine the number of released electrons from a measured TSC curve, Zhu and Fritzsche<sup>2)</sup> used steady state photocurrent measurements at various temperatures. In our method, low intensity light pulses are applied at regular time intervals during the measurement of a TSC curve. The duration of a light pulse is between 0.01 and 1 second. The induced current pulse, which is superimposed on the thermostimulated current, has a length of 30 s or less, depending on the sample properties. Tests have shown that these light pulses do not disturb the level of the TSC curve between the photocurrent pulses. If the number of the absorbed photons is known, the number of released carriers can be found rather easily by comparing the integrated thermostimulated current during a small time interval with the area of the photocurrent pulse.

Figure 1 shows schematically a part of a TSC curve and a photocurrent pulse. If we assume that the initial occupation function of the traps equals unity, the density of states follows from the number of released carriers within a small energy interval  $\Delta E$  scanned in a time interval  $\Delta t$ :

$$g(E)\Delta E = (N/v)(A_1/A_2). \quad (1)$$

Here  $N$  is the number of absorbed photons and  $v$  is the volume of the sample. The areas  $A_1$  and  $A_2$  are defined in figure 1.

From the photo-conductivity also a  $\mu\tau$  product can be found:

$$A_2 = \mu\tau eNV/l^2, \quad (2)$$

with  $l$  the distance between the electrodes and  $V$  the applied voltage. A definition of  $\mu$  and  $\tau$  is given in section 1.3.

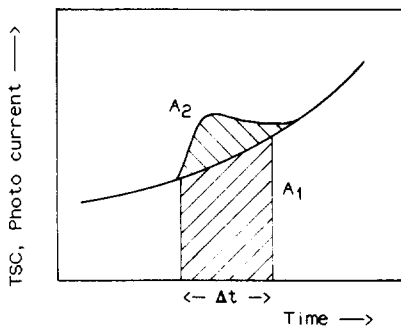


FIGURE 1  
TSC-curve with a photo-current peak of area  $A_2$ . The integrated TSC current in  $\Delta t$  is denoted by  $A_1$ .

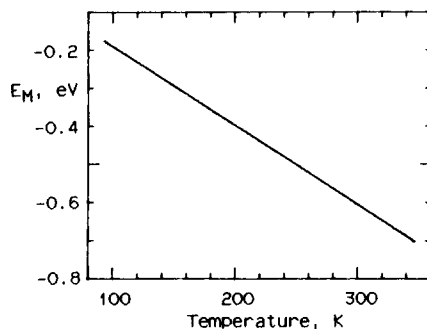


FIGURE 2  
Energy of maximum TSC,  $E_M$ , versus the temperature  $T$ . The starting temperature is 80 K and  $\beta$  is 5 K/min.

### 1.2. The energy of maximum TSC, $E_M$

Simmons et al.<sup>1)</sup> have shown that during a TSC experiment only trapped carriers are released from a small energy range around  $E_M$ , determined by a strongly peaked function  $P(E, T)$  with a width of  $2kT$ . The maximum of this function is found at the energy

$$E_M = -0.967 kT \ln(52\nu_e/\beta) + 0.017, \quad (3)$$

with  $\beta$  the heating rate in K/s and  $\nu_e$  an effective attempt to escape frequency expressed in  $s^{-1}$ . The numbers in (3) depend somewhat upon the starting temperature, which was 80 K in our experiments. With  $\partial E_M/\partial t = \beta \partial E_M/\partial T$  formula (1) yields:

$$g(E) = A_1 N / \{A_2 \Delta t \nu \beta k(0.967) \ln(52\nu_e/\beta)\}. \quad (4)$$

### 1.3. Attempt-to-escape frequency

To determine  $g(E)$ , the non-retrapping model of Simmons et al.<sup>1)</sup> was used, in which the release of carriers is described by an attempt-to-escape frequency  $\nu_0$ . The conductivity however is considered to be governed by a multiple trapping process. For that reason a correction factor has to be introduced to account for the mean number of retrapping events  $m$  before recombination. This yields the effective attempt-to-escape frequency  $\nu_e = \nu_0/m$ . The value of  $\nu_e$  is experimentally found by assuming that  $E_M = E_F$  at the temperature where the thermostimulated current becomes small compared to the dark conductivity. The activation energy of the dark conductivity at that temperature gives  $E_F$ .

The factor  $m$  can also be defined as the ratio of the recombination lifetime  $\tau$  and the mean lifetime in the conduction band between trapping,  $m = \tau/\tau_t$ . The mobility  $\mu$ , mentioned before, is the microscopic mobility.

Misra et al.<sup>3)</sup> made calculations for the TSC based on a multiple trapping model in which the ratio of the number of electrons in the conduction band and the number of electrons in the trap states is given by

$$n_c/n = \{N_c/g(E)\} \exp(-E/kT). \quad (5)$$

Their result yields the TSC as a function of  $g(E)$ ,  $\mu$ ,  $\tau$  and  $N_c$ . This  $N_c$  is the density of states in the lower part of the conduction band. They derived that

$$\nu_e(E) = N_c/\tau g(E) \quad (6)$$

must hold to bring the non-trapping model in agreement with their multiple trapping model. In our experiment we used a constant value for  $\nu_e$ , determined at  $E_F$ . This seems to be a reasonable approximation, moreover since  $g(E)$  in formula (4) is rather insensitive to changes in  $\nu_e$ . From the energy of the Fermi level, substituted for  $E_M$  in formula (3) we found  $\nu_e$  to be of the order of  $10^7/s$ .

## 2. EXPERIMENTS AND DISCUSSION

To illustrate the method, results are shown of measurements on four samples of intrinsic a-Si layers. The layers were deposited at four different glow-

discharge powers, 5, 10, 20 and 40 W. The growth rates amounted to 0.58, 0.86, 1.08 and 1.52 nm/s, respectively.

Figure 3 shows the density of states in the energy range of 0.15 to 0.65 eV below the conduction band as calculated from our TSC measurements with formula (4). The sample grown at 5 W has the lowest number of gap states. This may indicate that at a higher power more damage in the layer is caused by the ion bombardement from the glow-discharge. The samples are supposed to be of a rather good quality. An oxygen content of less than 0.1% was found from ERD measurements. In layers with more contamination a higher density of states was found.

Figure 4 shows the  $\mu\tau$  product of the same layers as a function of the temperature. As distinct from the results of Zhu and Fritzsche<sup>2)</sup>, our values of  $\mu\tau$  decrease continuously with lower temperature. We do not observe the increase in  $\mu\tau$  below 250 K which is associated with thermal quenching of photoconductivity.

We conclude that TSC measurement is a relatively easy way to determine the density of states, which is an important aspect of the quality of a-Si:H material. The method is limited to a part of the bandgap. Starting at lower temperatures, values closer to the conduction band can be found. The Fermi level can not be reached however within about 0.1 eV or several kT, which is the temperature resolution of the method.

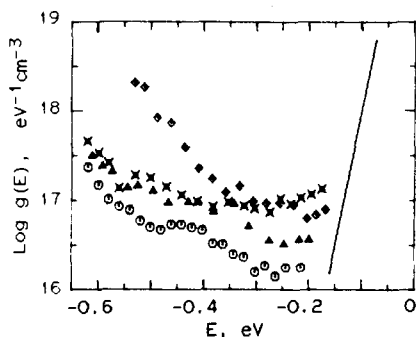


FIGURE 3

Density of states of four samples grown at different powers which are indicated in fig. 4. The straight line symbolizes the conduction band tail. In the figure  $E_C$  is 0 eV.

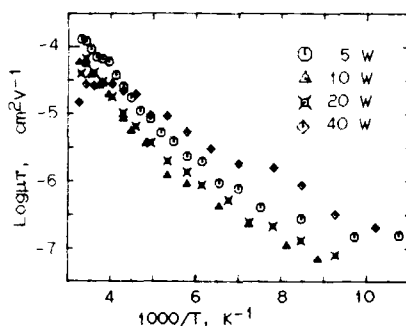


FIGURE 4

Product of microscopic mobility and recombination lifetime of four samples. The  $\mu\tau$  product concerns samples with partially filled traps up to quasi-Fermi levels.

#### REFERENCES

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