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L. Guimarães, R. Martins, A. Dias. PHOTORESPONSE TIME AND DENSITY OF LOCALIZED STATES IN THE MOBILITY GAP OF a-Si:H ALLOYS PREPARED BY R.F. GLOW DISCHARGE. Journal de Physique Colloques, 1981, 42 (C4), pp.C4-609-C4-612. 10.1051/jphyscol:19814133 . jpa-00220752

**HAL Id: jpa-00220752**

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Submitted on 4 Feb 2008

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# PHOTORESPONSE TIME AND DENSITY OF LOCALIZED STATES IN THE MOBILITY GAP OF a-Si:H ALLOYS PREPARED BY R.F. GLOW DISCHARGE

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**Abstract.**—Taking advantage of the well known Stevenson-Keys and Haynes-Shockley techniques we describe a way to achieve the photoresponse time and the density of localized states in the mobility gap of a-Si:H alloys produced by bias r.f. glow discharge. The effect of incident light upon samples under the action of d.c. bias plus an a.c. controlled pulse has been investigated. In the dark, the gate voltage is related with the surface charges through Poisson's equation. Under these conditions the differential capacitance ( $C_D$ ) is given by:

$$C_D = (\epsilon \epsilon_0 e^2 g_\alpha)^{1/2} \cdot F(\phi_s)$$

Where:  $\epsilon \epsilon_0$  is the dielectric constant;  $e$  is the electric charge;  $g_\alpha$  the density of localized states;  $F(\phi_s)$  is a function of the surface potential  $\phi_s$ . Which is determined after conductance and decay time measurements. The main effect of incident light is the increasing of the differential capacitance due to the decrease in the response time of minority carriers and/or the decrease of surface potential  $\phi_s$  due to space charge layer reduction. This is explained by the shift of the quasi-Fermi levels upwards (n-type material). The values of the density of localized states, minority carriers life time and the signal of charges have been calculated.

**Introduction.**—Recent work has shown that the density of localized states,  $g(E)$ , in a-Si:H films can be determined through the capacitance-voltage,  $C(V)$ , measurements as a function of the frequency (1,6). Such analysis have been performed in Schottky diodes assuming null temperature approximation. This paper describes a method for the determination of the density of localized states and the associated carrier's mobility. This is done from C-V measurements performed in metal-oxide-semiconductor structures and taking advantage of Shockley-Haynes (7) and Stevenson-Keys (8) experiments.

**Experimental Details.**—The a-Si:H films were produced by r.f. glow discharge (9) (3% Silane in Argon) deposited on a glass substract with gap Al electrodes. The Fermi level position extrapolated to  $T=0^\circ\text{K}$  was obtained from dark conductivity measurements. For C-V measurements, the films were coated with a thin layer of  $\text{Al}_2\text{O}_3$  placed under the active Al contact.

In order to know the pulse width to base the C-V measurements it is necessary to know the transit time,  $t_t$ , (ref.10) and the recombination lifetime,  $\tau_r$ , (ref.11). For C-V measurements under illumination, only a small area of the film near the electrode was illuminated. This was achieved by placing a pin hole array ( $\phi \approx 0.1\text{mm}$ ) over the films in a convenient position. Fig. 1 shows the experimental arrangement for C-V measurements in the dark or under illumination. The in-phase and out-of-phase currents are measured as a function of pulse amplitude, width and frequency, assuming that all induced charges are located at or near the oxide-semiconductor interface. Assuming also that the oxide layer is thin enough to be neglected (ref. 12) the induced charges can be represented by a Dirac pulse. We interpret the results using the usual two RC branches circuit (ref. 1-6) where the first branch is concerned with the

space charge region and the other with the bulk.

#### Description of the Model.-

The extension of the space charge region (for an accumulation or depletion layer), taking into account all charges in the interface and in the bulk is determined by solving the Poisson's equation, which gives, (12);

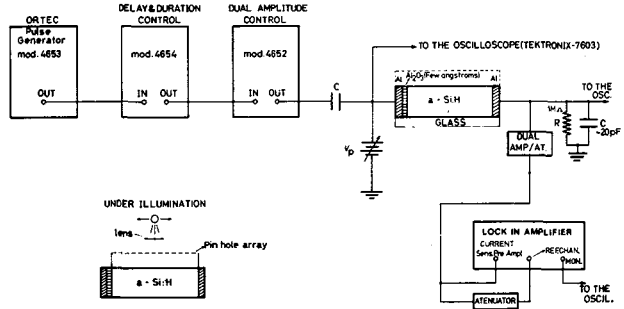


Fig. 1-Shows the set up used for the C-V measurements.

$$x_{\alpha} = \begin{cases} -L_o \cdot \ln \frac{(1 + e^{\Psi_s})^{1/2} - 1}{(1 + e^{\Psi_s})^{1/2} + 1} & \text{(accumulation or strong inversion layer-n type material)} \\ L_o \cdot (1 + \Psi_s)^{1/2} & \text{(weak inversion layer)} \end{cases} \quad (1)$$

where  $L_o^2 = \frac{\epsilon \epsilon_0}{2 \cdot e^2 \cdot g(E)}$ ;  $\epsilon \epsilon_0$  is the dielectric constant of the material;  $e$  the electron charge;  $g(E)$  the density of localized states in equilibrium with the interface states;  $\Psi_s = (e \cdot \phi_s / K \cdot T)$ ,  $\phi_s$  is the surface potential,  $K$  the Boltzman constant and  $T$  the absolute temperature.

Once known  $x_{\alpha}$ , the capacitance per unit area,  $C_D$ , associated with the induced space charge and the number of charges per unit area  $Q_D$  are:

$$C_D \approx (\epsilon \epsilon_0 / x_{\alpha}) \quad (2) \quad Q_D = C_D (1 + \Psi_s) (K \cdot T / e) \quad (3)$$

Now, taking into account the Gauss's theorem applied to the interface it obtains (12)

$$(e \cdot E_o \cdot \epsilon_0) / (K \cdot T \cdot C_D) \cdot (1 + \Psi_s) + (1 + e^{\Psi_s})^{1/2} / (1 + \Psi_s)^{1/2} \cdot \ln(((1 + e^{\Psi_s})^{1/2} - 1) / ((1 + e^{\Psi_s})^{1/2} + 1)) = 1 / (1 + \exp((E_c - E_F) / (K \cdot T) - \Psi_s)) \quad (4)$$

where  $\epsilon_0 \cdot E_o$  is equal to the total number of charges per unit area induced in the system. For differences of the order of  $K \cdot T$  between the energies  $E_s$  (surface states) and  $E_o$  (bulk) it is assumed that the induced space charge region vanishes. By solving eqn. 4 for  $(e \cdot \epsilon_0 \cdot E_o) / (K \cdot T \cdot C_D)$  as a function of  $\phi_s$ , it is possible to know the total amount of band bending once inferred the flat band position ( $\phi_s = 0$ ). Thus by knowing  $\phi_s$  and taking into account eqn. 2 it is possible to calculate  $g_{\alpha}(E)$ .

For the surface conductivity we have the expression (ref. 12):

$$\Delta \sigma_s = e \cdot \mu_s \cdot n_o \cdot L_o \cdot ((1 - e^{\Psi_s})^{1/2} + \ln((1 - (1 - e^{\Psi_s})^{1/2}) / (1 + (1 + e^{\Psi_s})^{1/2}))) \quad (5)$$

$$\mu_s = (\Delta \sigma_s) / (e \cdot n_o \cdot L_o \cdot ((1 - e^{\Psi_s})^{1/2} + \ln((1 - (1 - e^{\Psi_s})^{1/2}) / (1 + (1 + e^{\Psi_s})^{1/2}))) \quad (6)$$

Where  $e \cdot n_o$  is ascribed with the total number of induced charges, corresponding to the flat band condition and  $\mu_s$  is assumed to correspond to the mobility of the localized carriers.

**C-V Measurements and its Interpretation.-** For the determination of the C-V and G-V curves, the applied pulse is decomposed in a Fourier series and the induced charges represented by a combination of Dirac pulses. Thus, we have for the capacitance  $\langle C \rangle$ , and for the conductance  $\langle G \rangle$  the values (ref. 12):

$$\langle C \rangle = I_{90\phi} \cdot \sqrt{2} \cdot T / (4 \cdot V_M \cdot \sin(\pi \cdot d / T)) \quad (7)$$

$$\langle G \rangle = I_{0\phi} \cdot \sqrt{2} \cdot T / (V_M \cdot \sin(\pi \cdot d / T)) \quad (8)$$

where  $I_{0\phi}$  and  $I_{90\phi}$  are respectively the in-phase and out-of-phase currents measured by a lock-in-amplifier;  $T$  the signal's period;  $d$  the pulse width and  $V_M$  the peak vol

tage. From C-V and G-V curves (see Figs. 2-3) it is observed the existence of a minimum ascribed with the on set of the inversion layer and with the ability of the minority carriers to follow the a.c. signal (see ref. 13).

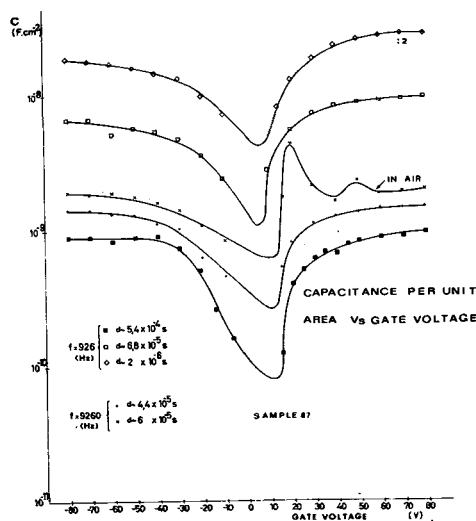


Fig. 2 - C-V curves at  $\neq$  frequencies

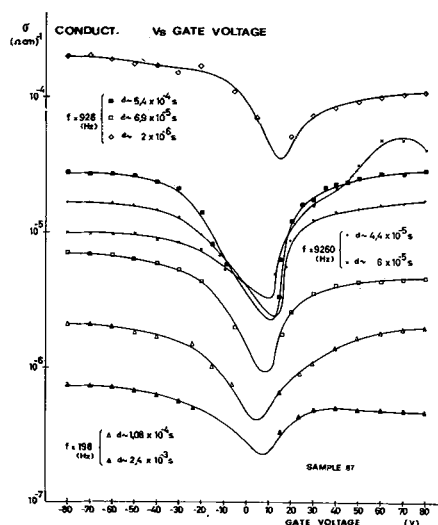


Fig. 3 - G-V curves at  $\neq$  frequencies

As the frequency is increased the value of the capacitance per unit area obtained as a function of the applied voltage decreases and it approaches the value of the geometrical capacitance, for pulses with the same width. The reason is that the frequency signal modulation becomes greater than the relaxation frequency ( $1/2\pi\tau\rho\epsilon\epsilon_0$ ) (ref. 3-6) and the frequency ascribed with the thermal release time  $\tau_i$  of the carriers from the states below  $E_c$ . Illuminating only the region near the Al active electrode the C-V measurements approaches the low frequency value when the intensity of illumination is raised. This is explained either by the decrease of  $\tau_i$ , or the generation of electron-hole pairs by photons which decreases the surface potential,  $\phi_s$ , and consequently  $x_\alpha$ , (ref. 13). It is also observed that the C-V values change as a function of pulse width. Such variation is related with different ways of interaction of the induced charges with the gap states. In order to interpret our results at low frequencies, we assume that: 1.-For pulse width  $> \tau_{rel}$  the applied signal can be approximated to a step function and the information concerned with the C-V curves corresponds to shallow states; 2.-For pulse width  $< \tau_t$ , the signal interact with deep states.

As the frequency is increased beyond the relaxation frequency, the information concerned with the pulse width is more and more connected with the surface states. Thus, assuming that the abrupt change in the  $C_D$  value is correlated with the Fermi level position we deduced the  $g(E)$  curves indicated in Fig. 4, with  $T = 0^\circ K$  (low curve) and  $T = \text{room temperature}$  (upper curve) for samples having values of  $(E_c - E_F)_0$  between .65 and .47 eV.

Taking into account that  $\Delta\sigma$  is related with  $\langle G \rangle$  (ref. 12) we obtain for  $\mu_s$  the values presented in Fig. 5. We also observed that the extension of the space charge region,  $x_\alpha$ , varies from  $2 \times 10^{-5}$  cm (at low frequencies) up to  $2 \times 10^{-2}$  cm.

**Conclusions.**— Our results show that it is possible to infer the density of localized states over a wide range of energies, either using different pulse width correlated with different applied voltages, or using samples differently doped. The main results are: 1- The density of localized states is similar to that obtained from field effect measurements. Nevertheless the density of localized states presents a flat region near the bottom of conduction band and the top of valence band, instead of a

well defined maximum: 2- Null temperature approximation gives density of localized states about one order of magnitude lower then those obtained using  $T \neq 0\text{K}$  (from  $\approx 4 \times 10^{16}$  to  $\approx 10^{17} (\text{eV})^{-1} \text{cm}^{-3}$ ): 3- The density of surface states varies between  $\approx 10^{12} - 10^{14} (\text{eV})^{-1} \text{cm}^{-2}$ : 4- The abrupt change observed in the mobility values confirms the existence of a mobility edge: 5- The transit time,  $t_t$ , varies between 100-600  $\mu\text{s}$ , while the recombination lifetime varies between 5 - 20  $\mu\text{s}$ .

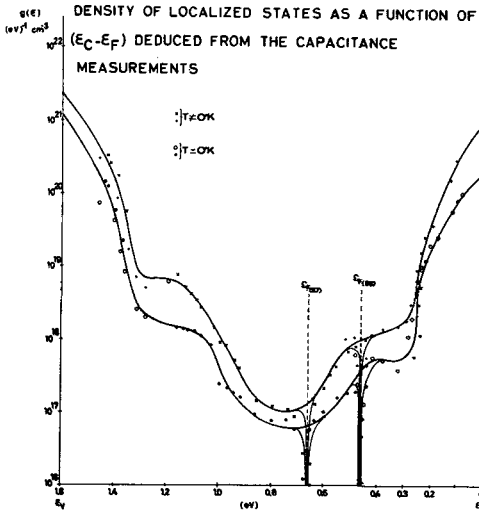


Fig. 4 -  $g(E)$  Vs  $(E_C - E_F)$  values

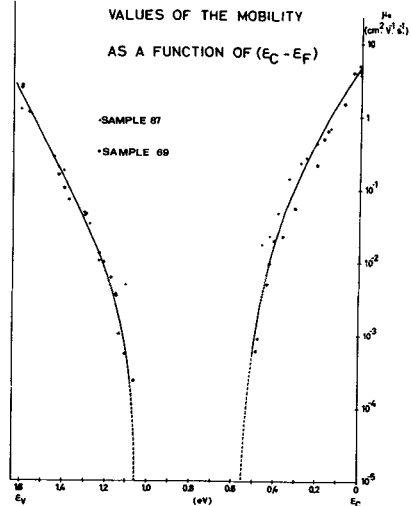


Fig. 5 -  $\mu_s$  Vs  $(E_C - E_F)$  values

Acknowledgements. - The authors would like to thank I.N.I.C., D.G.E., J.N.I.C.T. and U.N.L. by supporting this project.

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