INFLUENCE OF SURFACE STATES ON THE CHARGE TRANSFER ALONG THE DIELECTRIC-SEMICONDUCTOR INTERFACE

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ABSTRACT

Surface charge transfer analysis is made taking into account the interdependence of the concentration variation and in rate of generation-trapping of free carriers, as well as the field due to nonuniform trap filling during the transfer charge process. A method of determ ning small spectral surface state densities by means of CCD LSI is worked out. A simple and accurate method for determining small and very small integral surface state densities is proposed which determines, at room temperature, surface state densities over the range of 10^4- $10^{11}cm^{-2}$.

1. THE SURFACE CHARGE MOTION

The continuity equation for electrons, moving along the dielectric-semiconductor interface in an MIS-structure is (ref.1):

$$\frac{dQ_n}{dt} - \frac{d}{dx}\left[\mu_n Q_n E_x + D_n \frac{dQ_n}{dx}\right] = -\frac{dQ_t}{dt} \quad (1)$$

where Q_n is the surface density of free electrons and Q_t is the surface density of trapped electrons. The field E_x is due to a surface density gradient of free and trapped carriers and is given by:

$$E_x = \frac{e}{C_d}\frac{d}{dx}(Q_n + Q_t) \quad (2)$$

where C_d is the dielectric capacity per unit area.

Using Shockly-Read statistics one can show, that when the generation and trapping processes are at equilibrium the equation (1) becomes

$$\frac{d}{dt}\left[1+\frac{N_{ss}(\mathcal{E}_Q)\,T}{Q_n}\right]Q_n - \frac{d}{dx}\left\{\frac{e\mu_n}{C_d}Q_n\frac{dQ_n}{dx}+D_n\left[1+\eta\,\frac{e^2N_{ss}(\mathcal{E}_Q)}{C_d}\right]\frac{dQ_n}{dx}\right\}=0 \quad (3)$$

Eq.(3) is derived using the following relationships:

$$Q_t = \int_0^{\mathcal{E}_Q} N_{ss}(\mathcal{E})d\mathcal{E} \quad , \quad (4)$$

where $\mathcal{E}_Q$ is found from

$$Q_n = 1N_c\exp\left(\frac{\mathcal{E}_Q - \mathcal{E}_E}{T}\right) \quad (5)$$

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Here $N_{ss}(\mathcal{E})$ is the surface state density, l is the carrier localization length near the surface, N_c is the effective state density in the conduction band, $\mathcal{E}_g$ is the forbidden gap width. The energy is calculated from the valence band edge at the semiconductor surface. The η factor in (3) is:

$$\eta = 1 - \frac{d\ln l}{d\ln Q_n} \qquad (6)$$

and increases with Q_n from 1 to 2. The equilibrium condition for the generation and trapping processes is:

$$\frac{dQ_n}{dt} \ll Q_n \frac{\gamma_{\mathcal{E}_Q} Q_n}{l} \qquad (7)$$

where $\gamma_{\mathcal{E}_Q}$ is the trapping coefficient of electrons by a trap with energy $\mathcal{E}_Q$.

In the case of $e^2 N_{ss}(\mathcal{E}_Q) \gtrsim C_d$ the free charge carrier transport is affected by the trap field. At $C_d = 2\cdot 10^{-8}$F cm^{-2} this inequality holds good if $N_{ss}(\mathcal{E}_Q) \gtrsim 10^{11}$ cm^{-2}eV^{-1}. It is rather the reverse inequality that holds for CCD due to a small surface state density. Additionaly, if $Q_n < N_{ss}(\mathcal{E}_Q)T$, then it can be shown, that for long time intervals under the usual boundary conditions the Eq.(3) is solved as follows:

$$Q_n = N_{ss}(\mathcal{E}_Q)\, T\, \frac{L^2 - x^2}{2D_n t} \qquad (8)$$

where L is the electrode length in the direction of transfer. Substituting condition (7) into (8) we have

$$L^2 - x^2 \gg \frac{e\mu_n}{\gamma_{\mathcal{E}_Q}} \frac{l_d}{e^2 N_{ss}(\mathcal{E}_Q)} \qquad (9)$$

where l_d is Debye length. From this example it becomes obvious that the assumption of equilibrium between the two processes is true only for long enough electrodes.

From (8) and (5) it follows that variations in energy with time, $\mathcal{E}_Q$, are given by

$$\mathcal{E}_Q = \mathcal{E}_g - T \ln \frac{l_d N_c}{N_{ss}(\mathcal{E}_Q)T} \frac{2D_n t}{L^2 - x^2} \qquad (10)$$

If the interdependence of free carrier concentration variation and generation-trapping rate is neglected, as it was done in the study by Mohsen et al (ref.2), Eq.(10) assumes the form:

$$\mathcal{E}_Q = \mathcal{E}_g - T \ln \gamma_{\mathcal{E}_Q} N_c t \qquad (11)$$

It follows from the above-said that at $\mu_h = 200\ cm^2V^{-1}sec^{-1}$, $\gamma_{\mathcal{E}_Q} = 10^{-7} cm^{-3}sec^{-1}$, $N_{ss}(\mathcal{E}_Q) = 2 \cdot 10^{10} cm^{-2}eV^{-1}$ and $l_d = 10^{-5}$cm Eq.(11) is valid provided $L \leqslant 10\ \mu m$. In considering the process of charge transfer under prolonged electrodes one must rely on the Eq.(10). Comparison of (10) and (11) shows that attainment of equilibrium between the generation and trapping processes is described by a decrease in the effective coefficient of charge trapping away from that electrode edge at which the charge transfer takes place.

2. THE APPLICATION OF CHARGE-COUPLED DEVICES FOR DETERMINING THE SPECTRAL DISTRIBUTION OF SURFACE STATE DENSITY

Now we shall consider a method for determining the surface state characteristics using CCD. This method consists of the following: if voltage V_b is applied to CCD transfer electrodes for a relatively long time, then a stationary carrier distribution will be found at the semiconductor surface, at which distribution the surface states above the Fermi level are filled with holes and those below - with electrons (for n-type substrate). If a negative voltage is now applied to one of the electrodes and a hole charge of $Q_p^o \sim 10^{12} cm^{-2}$ density is injected under this electrode, practically all the traps in the gap will soon be filled with holes. If the transfer pulse cut-off time τ_c is more than the characteristic diffusion time (ref.3), all the free carriers will escape from under that electrode under the adjacent one. Besides the holes trapped by surface states with energy below $\mathcal{E}_\tau$ will have become free and accumulated under the adjacent electrode. $\mathcal{E}_\tau$ is found by equalizing the time of hole generation from this level to the cut-off time τ_c. According to (11) this equality takes the form:

$$\frac{1}{\tau_c} = \gamma(\mathcal{E}_\tau) N_v \exp(-\frac{\mathcal{E}_\tau}{T}) \qquad (12)$$

Thus, for the given supply conditions charge losses under one electrode are associated with the filling of traps in the range of energies $\mathcal{E}_\tau$ to $\mathcal{E}_F$. As the charge is passing along an electrode array the small losses are multiplied

and become readily measurable. Varying $\mathcal{E}_F$ (by varying V_b) and $\mathcal{E}_\tau$ (by varying τ_c and T) may be usefull in obtaining information about the surface state parameters. Indeed, if initially the semiconductor surface is in the state of depletion, it can be shown that the variation in charge transfer coefficient $\alpha = Q_p^m/Q_p^o$ as a function of V_b change is given by:

$$\frac{\Delta\alpha}{\Delta V_b} = -\frac{emN_{ss}(\mathcal{E}_F)}{Q_p^o\left[1 + \frac{e^2N_{ss}(\mathcal{E}_F)}{C_d}\right]} \qquad (13)$$

where m is the number of transfers. Similar relationships can be obtained for α variations with τ_c and T . Thus, the surface state density throughout the whole forbidden gap excepting regions located less than $\mathcal{E}_\tau$ away from the gap edges can be determined from measurements of $\alpha(V_b)$, $\alpha(\tau_c)$ and $\alpha(T)$. Additionally, the spectral distribution of minority carrier trapping cross-sections within a certain energy range can be determined by temperature measurements.

In Fig. 1 typical experimental $\alpha(V_b)$ plots for a range of τ_c at T= 300°K are shown for a sample prepared from thermally oxidized n-Si with ρ = 20 ohm·cm and (100) surface orientation. Fig. 2 shows the distribution of surface state density calculated from experimental values of $\alpha(V_b)$ for a range of τ_c and T, using (13).

3. THE PRINCIPLE OF DISCRETE CHARGE TRANSFER FOR DETERMINING OF VERY SMALL INTEGRAL SURFACE STATE DENSITIES

Elementary trapping events in multiple carrier transfer between the adjacent electrodes may be also summed up(ref.4). Let us consider a three-electrode structure to which voltage pulses are applied as illustrated in Fig. 3. The long pulse of negative voltage V_2 generates a potential well at the semiconductor surface under electrode 2 into which holes are injected due to microbreakdown under electrode 1. Multiple charge transfer is caused between electrodes 2 and 3 by applying the clocking voltage pulses with amplitude $V_3 \gtrsim 2V_2$ to electrode 3. The charge remaining after m transfers is injected into the substrate by the turnoff of voltage V_2 and is recorded at the resistance R. It should be noted that such measurement configuration is not the only one: charge

injection and recording may be carried out, for example, with using p-n junctions.

If the clocking voltage pulses have a constant component V_b, which causes majority carriers to be accumulated at the surface then once the clocking pulse is removed these carriers will recombine with trapped minority carriers. As a result, the traps will be empty and ready for the next trapping. The density, Q_p^m, of the carriers remaining under electrode 2 after the ending of a train of m pulses, will obviously be given by

$$Q_p^m = Q_p^o - mN_s \qquad (14)$$

where N_s is the integral density of surface states. Thus, by measuring Q_p^o and Q_p^m N_s is readily calculated. Taking into account the conditions of complete charge transfer (ref.3), it can be shown that using this method the minimum measurable surface state density, is given by

$$N_s^{min} \gg \frac{Q_p^o L^2}{D_p \tau_g} \qquad (15)$$

where τ_g is the dark current storage time. Thus, at $\tau_g \sim 10^2$ sec, $L \sim 10^{-3}$ cm, $D_p \sim 5$ cm^{-2}sec^{-1} and $Q_p^o \sim 10^{12}$ cm^{-2} the value of $N_s^{min} \sim 10^4$ cm^{-2}.

Fig. 4 shows typical experimental plots of losses versus the bias voltage, V_b, for different τ_c. The sharp reduction in loss with lowering V_b is associated with a slackening of the electron flow towards the surface, resulting in incomplete recombination of trapped holes. Curve 1 (Fig. 4) illustrates the increase in loss due to an incomplete free hole transfer ($\tau_c < L^2/D_p$). N_s was calculated using curve 4, for which the conditions of complete free carrier transfer were reliably satisfied. As the initial charge of $Q_p^o = 10^{12}$ cm^{-2} density is practically lost completely after 50-transfers, the surface state integral density calculated from (14) was $2 \cdot 10^{10}$ cm^{-2}.

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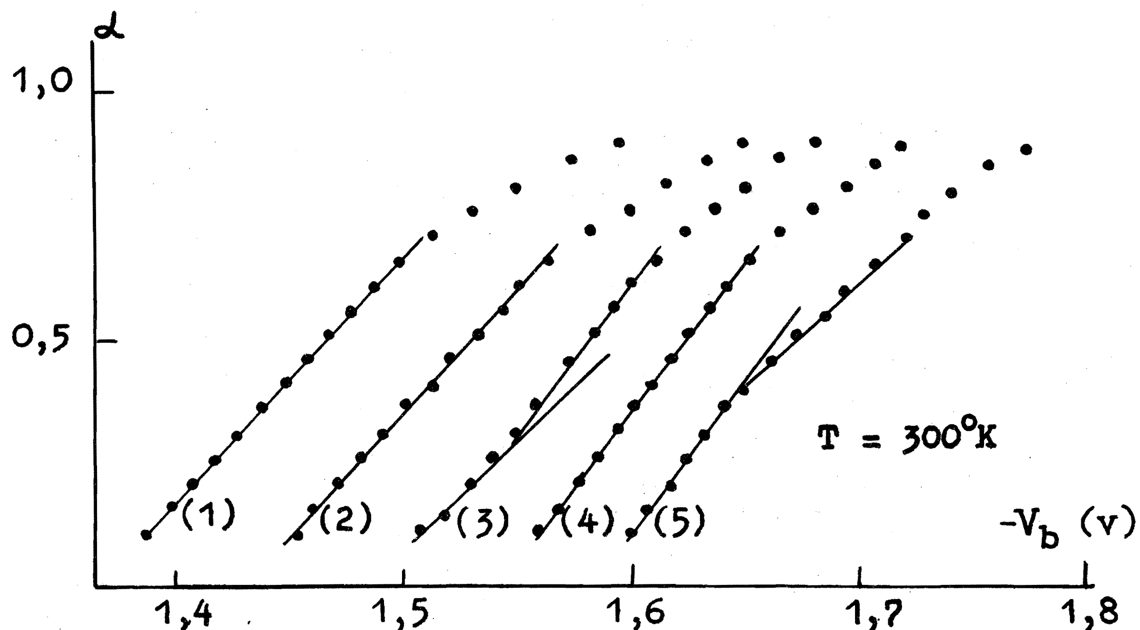

Fig. 1. Charge transfer coefficient vs. bias voltage for a range of τ_c values: (1) 20 μs; (2) 15μs; (3) 10 μs; (4) 5 μs; (5) 2,5 μs .

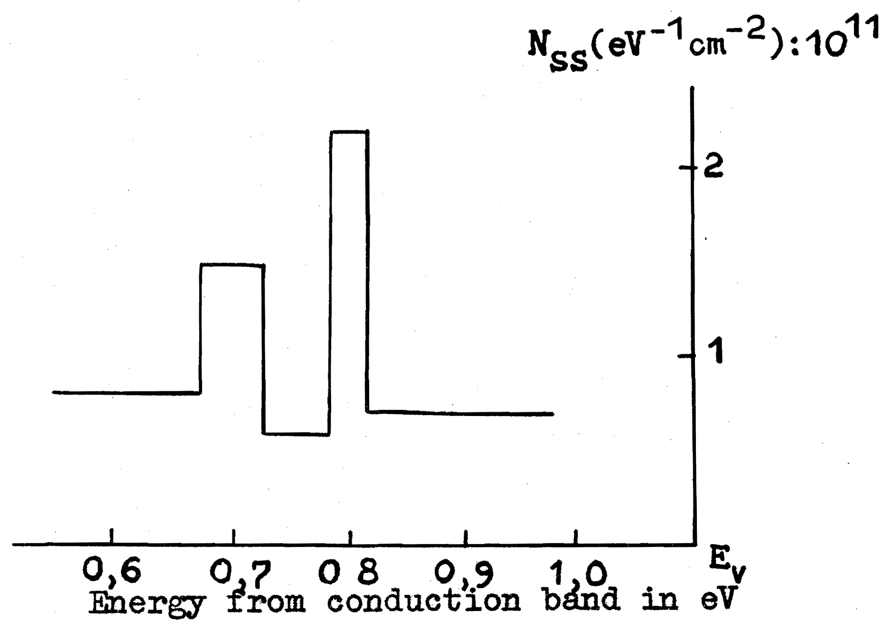

Fig. 2. Spectral density of surface states.

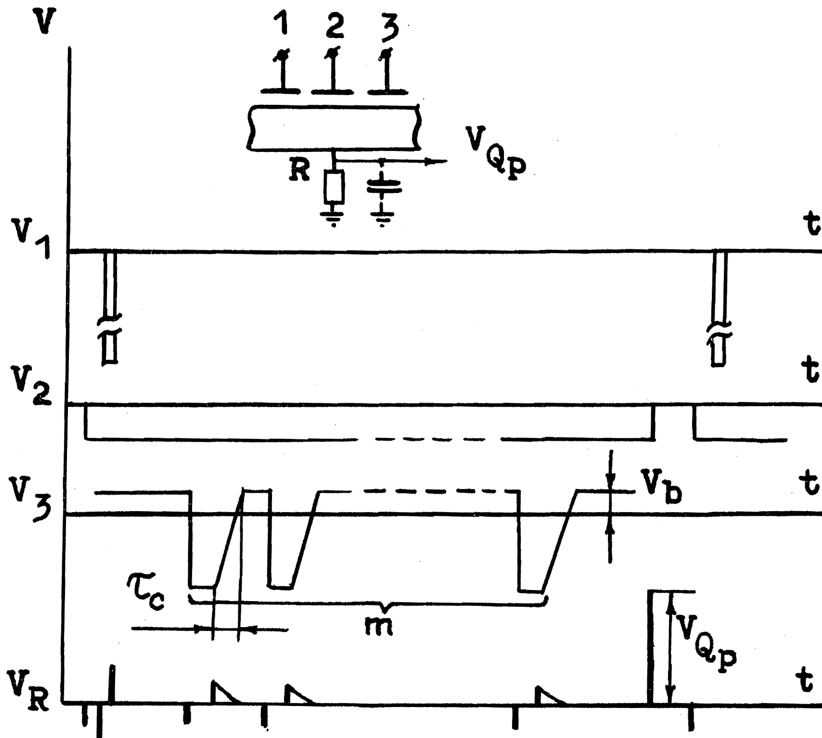

Fig. 3. Pulse diagram.

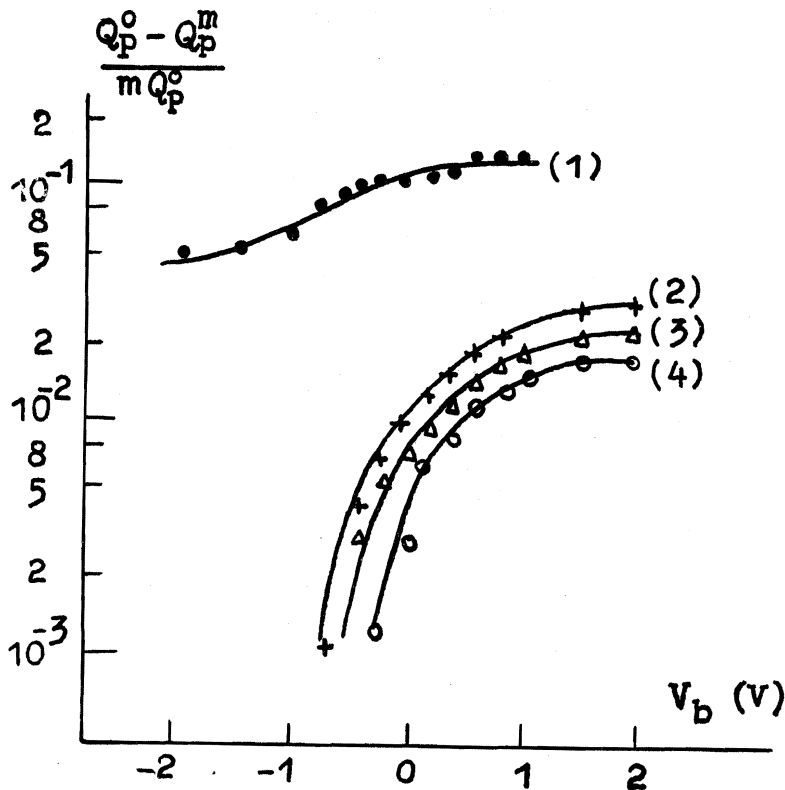

Fig. 4. Variation of charge losses with bias voltage for a range of τ_c : (1) 0,1 μs; (2) 2 μs; (3) 5 μs; (4) 20 μs .