New method of determining the density of states on the surface of a semiconductor

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A new method is proposed for measuring small integral densities of surface states on the boundary between a semiconductor and a dielectric. Estimates show that this method makes it possible to measure, at room temperatures, state densities down to 10^4 cm^{-2}, and at liquid nitrogen temperatures to 1–10 cm^{-2}. The results of the experimental verification of the method on structures with state densities on the order of 10^{10} cm^{-2} are presented.

Studies of surface properties are among the most important problems of modern semiconductor physics. Particularly timely in this connection is the question of precision measurements of the density N_s of the surface states (SS) of the carriers. The presently known methods do not make it possible to measure values of N_s lower than 10^9–10^{10} cm^{-2}.[1–3] Yet modern experiment techniques yield Si–SiO_2 structures with lower values of N_s on the interface.[4] This difficulty is connected in final analysis with the need for measuring the small charge of the surface state against the background of the large volume charge in the semiconductor.

The proposed method of determining the integral density of the SS is based on the effective increase of the number of the SS as a result of summation of multiple carrier capture by the surface states in a structure containing two closely located capacitors made up of metallic electrodes on the surface of a dielectric covering a semiconductor (Fig. 1).

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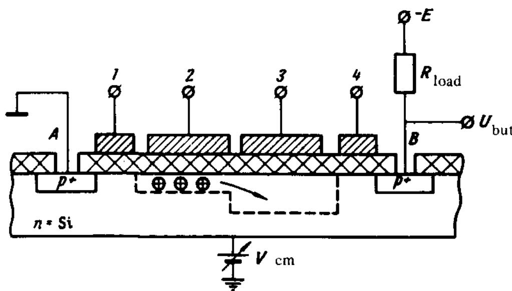

FIG. 1. Diagram of structure for the determination of the integral density of surface states.

Assume that minority carriers with charge equal to Q_0 (holes in the case of the structure of Fig. 1) are injected into the potential well produced in the semiconductor under the electrode 2 by applying a voltage of appropriate polarity. The injection can be realized either by local illumination or from a *p-n* junction *A*, after first applying to the electrode 1, which acts as a gate, a voltage that produces a surface channel for the minority carriers. A decrease of the voltage of electrode 2 and application of a voltage on electrode 3 causes the free carriers to flow from under the electrode 2 to under the electrode 3. As a result of capture of the carriers by the SS under the electrode 2, their charge under electrode 3 is decreased by an amount eN_sF, where F is the area of the electrode. If we apply to the substrate a sufficiently high voltage V_b, higher than that on the electrode 2, then the majority carriers will flow towards the surface and will be combined with the minority carriers captured by the SS. As a result the SS will become free of holes and ready for the next capture. The next transport of holes from electrode 3 to electrode 2 will double the losses. It is clear that the charge Q_m remaining after m transfers is $Q_0 - eN_sF_m$. Consequently, the density of states can be found from the formula

$$N_s = \frac{Q_0 - Q_m}{emF}. \qquad (1)$$

The value of Q_m can be measured by determining the current of the reverse-biased *p-n* junction *B*. To this end it is necessary, after the *m*th transfer, to apply to the electrode 4, which plays the role of a second gate, a voltage that produces a channel for the holes and enables them to flow from under the electrode 3 to the *p-n* junction *B*.

The described method calls for satisfaction of several conditions.

First, the distance between the electrodes must be small enough, so that no potential barrier preventing the flow of the minority carriers is produced in the gap between them.[5]

Second, it is necessary that the time interval τ between the start of the turning-off of the electrode voltage and the instant when the recombination begins exceed the characteristic time of flow of carriers from under one electrode to the other. Otherwise recombined carriers are not only those captured by the SS, but also the free ones. It is shown in[5] that this time is determined by the carrier diffusion. Thus, it is necessary to have

$$\tau >> \frac{L^2}{D}, \qquad (2)$$

where L is the width of the electrode and D is the coefficient of diffusion of the minority carriers along the surface.

Third, the time during which a noticeable decrease in the initial charge takes place, which is of the order of $m_{max}N_s\tau$, should be shorter than a time τ_g during which accumulation of minority carriers occurs as a result of their thermal generation. From expression (1) and condition (2) we then obtain the following limitation on the minimum SS density that can be measured by the proposed method,

$$N_s \approx \frac{Q_0}{em_{max}F} >> \frac{Q_0}{eF}\frac{L^2}{D\tau_g}. \qquad (3)$$

For the presently prepared Si—SiO_2 structures we have $\tau_g \sim 10^2$ sec at room temperature.[6] Thus, at $L \approx 10^{-3}$ cm, $D \approx 5$ cm^2/sec, and $Q_0/eF \sim 10^{12}$ cm^{-2} the minimum measured SS density is 10^4 cm^{-2}. At liquid-nitrogen temperatures, when τ_g reaches tens of hours, this quantity can be decreased by 3—4 orders of magnitude.

The described method was verified experimentally using the structure shown in Fig. 1, the gaps between the electrodes being 1—2 μ. Figure 2 shows plots of the losses per transfer against the substrate voltage V_b and the time τ. The sharp decrease of the losses with increasing V_b is due to the decrease of the flow of electrons to the surface, as a result of which not all the holes captured by the SS recombine. Curve *a* of Fig. 2 demonstrates the increase of the losses due to the incomplete transfer of the free holes (condition (2) is not satisfied). N_s was calculated from curve *d* of Fig. 2, *for which τ certainly satisfied the condition (2)*. Since the initial charge Q_0, amounting to $e10^{12}$ F, vanished practically completely after 50 transfers, the SS density calculated from (1) is equal to 2×10^{10} cm^{-2}, in agreement with the results of the ordinary measurements.

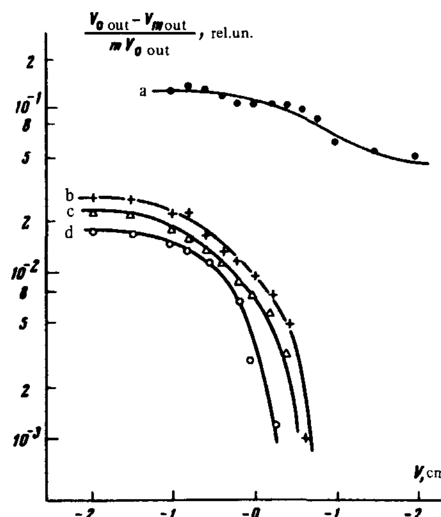

FIG. 2. Dependence of the charge loss per transfer on the substrate voltage for different values of the time (a—0.1 μsec, b—2 μsec, c—5 μsec, d—20 μsec).

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