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CHARGE CENTROID DETERMINATION IN FIELD-EFFECT EXPERIMENTS

S.D. Senturia, J. Rubinstein, S.J. Azoury and D. Adler

Department of Electrical Engineering and Computer Science, and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, U.S.A.

Abstract.- This paper presents a new method for making field-effect measurements in low-conductivity materials. The method complements conventional field effect methods by providing for the determination of the charge centroid of the field-induced charge.

Introduction.- In conventional field-effect measurements, contacts are applied to a sample, a bias is applied between the contacts, and a transverse electric field is applied to the sample through an insulator to achieve modulation of the sample conductance. Interpretation of the field effect requires knowledge both of the carrier mobility and the spatial distribution of the charges induced in the sample by the transverse field. This paper reports a new method of measurement that complements the conventional field effect by providing independent measurement of the centroid of field-induced charge. The method can be used both for static and dynamic measurements; this paper, however, is concerned only with static measurements.

The method is based on the charge-flow transistor (CFT), a device illustrated in Fig. 1. The CFT resembles a conventional metal-oxide-semiconductor field-effect transistor (MOSFET), except that a portion of the gate electrode is replaced by the sample material (1). Extensive experimental experience with CFT's both with polymeric and chalcogenide glass gate materials has shown that one can represent the channel of the CFT when operated in the linear region as consisting of two parts, the MOS region of total channel length $L-W$, for which the characteristics are identical to a standard MOSFET of corresponding dimensions, and the gap region of channel length W , for which the characteristics have the same algebraic form as the standard MOSFET, but with different values of threshold voltage and transconductance.

Specifically, with reference to the equivalent circuit of Fig. 2, the CFT can be modeled as two FET's in series, Q_{FET} which represents the metal-covered portion of the channel, and Q_{GAP} , which represents the sample-covered portion of the channel. If the gate-to-channel capacitance per unit area for Q_{FET} is denoted by $C_1 (= \epsilon_{OX}/t_{OX})$, and if the threshold voltage of Q_{FET} is denoted by V_T , then from standard MOSFET theory (2), the linear region V-I characteristic of Q_{FET} can be written as follows:

$$I_D = [Z\mu C_1 / (L-W)] (V_G - V_T) (1 - \eta) V_{DD} \tag{1}$$

where Z is the channel width, μ the carrier mobility, V_G the gate-to-source voltage, and where the parameter η describes how the drain-to-source voltage V_{DD} divides between the two transistors. The characteristic for Q_{GAP} has the same form as Eq. 1, but with parameters C_p replacing C_1 and V_p replacing V_T , and with appropriate channel dimensions and drain voltage. That is, for Q_{GAP} :

$$I_D = (Z\mu C_p / W) (V_G - V_p) \eta V_{DD} \tag{2}$$

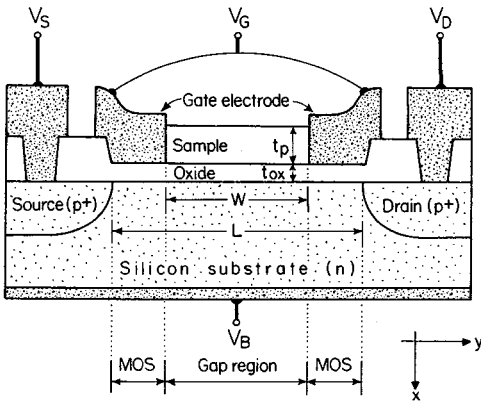


Fig. 1. CFT cross section

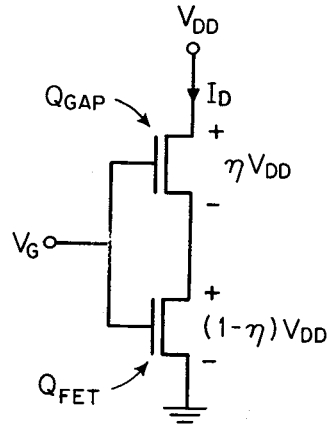


Fig. 2. CFT circuit model

Experimentally, η is determined by taking advantage of the fact that Q_{FET} and Q_{GAP} must always carry the same current I_D . One fabricates on the same substrate both a CFT and an identically dimensioned MOSFET with complete metal gate. The MOSFET serves to measure both V_T and μ , since the channel dimensions and oxide thickness are known. By measuring I_D vs. V_G for the CFT for a small value of V_{DD} (100 mV is typical), and by using the known values of V_G , V_T , μ , C_i , L , Z , and W , one can extract the value of η from Eq. 1, and can then recast Eq. 2 into the form

$$I_D/\eta = (Z\mu C_p/W)(V_G - V_p)V_{DD} \tag{3}$$

This equation for I_D/η vs V_G is linear, with an intercept at V_p and a slope from which the parameter C_p can be readily determined. Experimentally, it is always found that $C_p \leq C_i$, and $|V_p| \geq |V_T|$. Both results can be explained by examining the spatial distribution of the field-induced charge in the sample material, and can, in turn, be used actually to measure the centroid of the field-induced charge.

Because the threshold voltages V_T and V_p depend on a large number of process related variables such as surface-state densities, it turns out that the capacitance-per-unit-area parameter is the more reliable source of information on the charge centroid. The model for extracting the charge centroid from C_p is explained in the following section.

Model for C_p .— The sample material is assumed to be characterized by a screening length L_S determined by the density of localized states near the Fermi level, which is presumed to be at least weakly pinned near midgap. This screening length will show up in two places: If a Schottky barrier is formed at the metal-sample contact, the space charge associated with the Schottky barrier will extend into the sample a distance of several times L_S . Similarly, far from the sample contacts, and assuming that the sample thickness is greater than several screening lengths, the field-induced charge density in the sample will decay exponentially from a maximum at the sample-oxide interface toward zero at the upper surface of the sample with a characteristic length equal to L_S . Thus, for a sufficiently large gap width and a sufficiently thick sample, the distribution of field-induced charge in the sample is essentially uniform across the gap, and decays exponentially from the oxide toward the upper surface.

The structure consisting of the gap material, the gate oxide, and the semiconductor surface (which is presumed to be in strong inversion when the transistor is conducting) forms a capacitor with a capacitance-per-unit-area that is determined by the location of the charge centroid in the sample material. It is plausible that this capacitance-per-unit-area be identified as the parameter C_p . That is, if x_c is the distance of the charge centroid above the sample-oxide interface, and if ϵ_p is the sample permittivity, then for a sufficiently thick sample,

$$(1/C_p) = (1/C_i) + (x_c/\epsilon_p) \quad (4)$$

We have carried out a full two-dimensional numerical simulation of the quasi-static CFT characteristics, and have verified that this identification of C_p with the centroid is valid. Figure 3 shows the calculated ratio of C_p to C_i for two different oxide thicknesses, plotted as functions of t_p/L_S , where t_p is the sample thickness. It is seen that above a ratio of $t_p/L_S=2$, the C_p/C_i ratio is constant, and, although not shown explicitly in the figure, agrees with the result of Eq. 3. Below $t_p/L_S=2$, however, there is a sharp drop in C_p , indicating that the simple one-dimensional model for the field-induced charge breaks down. The actual centroid in this case becomes constant at half the sample thickness, whereas the centroid one would infer from an experimental value of C_p and the use of Eq. 3 would actually fall above the sample midpoint, and could even fall outside the sample. This fictitious result, in fact, provides a useful check on the validity of the model. If one finds a centroid from Eq. 3 above the midpoint of the sample, one can assume that the one dimensional model is invalid. This issue has been discussed more extensively elsewhere (3).

Experimental results.— We have carried out experiments on a five-component chalcogenide glass, $\text{Te}_{39}\text{As}_{36}\text{Ge}_7\text{Si}_{17}\text{P}_1$. The devices were p-channel enhancement mode, fabricated on (100) silicon n-type substrates doped $7\text{E}15 \text{ cm}^{-3}$. The overall channel dimensions were $254 \mu\text{m}$ wide and $50.8 \mu\text{m}$ long. Gap widths varied from 12.7 to $38.1 \mu\text{m}$. Four different gate oxide thicknesses were used in order to verify the dependence of C_p on oxide thickness. These were 950 , 1370 , 2040 , and 2230 \AA . Two different thicknesses of chalcogenide glass were used, 2100 \AA and 5200 \AA . In all, data were obtained from 28 devices with 2100 \AA glass and from 6 devices with 5200 \AA glass.

The values of C_p were extracted for each device as indicated in the Introduction. No significant variation either with gap width or glass thickness was observed. This is consistent with the assumption that the glass is more than two screening lengths thick and that the gap widths are much larger than the screening length. There was, however, a significant and systematic variation of C_p with oxide thickness. In order to verify that the variation was of the type predicted in Eq. 3, it is useful to recast that equation into the following form:

$$(C_i/C_p) - 1 = \epsilon_{\text{ox}} x_c / \epsilon_p t_{\text{ox}} \quad (5)$$

This form shows that a graph of $(C_i/C_p) - 1$ versus $1/t_{\text{ox}}$ should yield a straight line through the origin with a slope equal to $\epsilon_{\text{ox}} x_c / \epsilon_p$. Figure 4 shows the result of such a plot, with only the averages of the data for each oxide thickness shown for clarity. The slope of the solid line corresponds to a value of charge centroid scaled by the permittivity of $x_c/\epsilon_p = 119 \pm 4 \text{ \AA}$. Since the result is independent of glass film thickness, we conclude that the screening length must be less than half of 2100 \AA . The permittivity of a similar glass is reported to be 8.8 (4). Using this value, we estimate a centroid of 1047 \AA , which is just half the 2100-\AA film thickness, and much less than the 5200-\AA thickness, both cases being within the range of validity of the charge-centroid model.

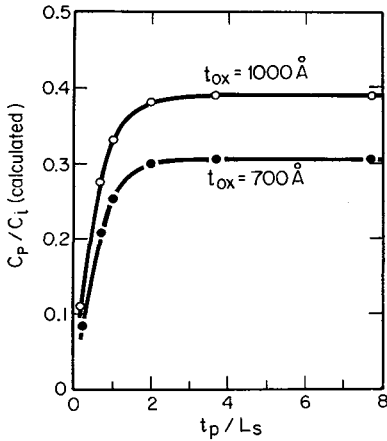


Fig. 3. Simulation results

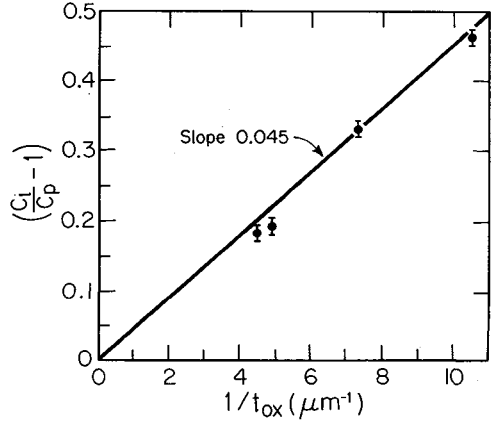


Fig. 4. Experimental results

Following the determination of the static centroid as described above, a qualitative experiment on the effect of light was performed. After measuring the C_p value in the dark, the devices were exposed to a microscope light for several minutes, and the device characteristics were then remeasured in the dark. We found that C_p increased by a few percent, corresponding to a small decrease in centroid. This result correlates well with the decay of the field effect noted by Frye and Adler (5).

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