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ABSTRACT

Magnetic field shifting of threshold voltage in silicon MOSFETs observed in 1968 by Kaplit and Zemel is explained on the basis of a new localization theory used previously in our analysis of the quantized Hall effect at low temperatures. Strong magnetic field H shifts the threshold voltage linearly with H towards higher voltages with the slope $dV_T/dH = \alpha d/\varepsilon$, where $\alpha = 1/137$ is the fine structure constant and d and ε are, respectively, the thickness and the permittivity of the oxide film. This agrees with the experimentally measured slope to better than 10%.

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In 1968 Kaplit and Zemel published an interesting paper [1] which in some sense may be regarded as a precursor of the recent quantum Hall effect (QHE) experiments [2-7], that attracted considerable theoretical attention [8-17]. Kaplit and Zemel [1] studied the gate capacitance of a metal - oxide - semiconductor - field - effect - transistor (MOSFET) structure in which 2-dimensional electron gas was induced at the {100} surface of p-type silicon, at temperatures $T = 1.3\,\mathrm{K}$ and strong magnetic fields H (up to 15 Tesla). Varying the gate voltage V_G (i.e., changing the average electron charge density σ in the inversion layer) at a fixed H, and probing the capacitance C with a small ac signal at 100 kHz, they observed an oscillatory behavior of the capacitance associated with Landau levels. At high $V_G > 0$, with the MOS structure being in strong inversion, Kaplit and Zemel observed notches (now called the plateaus) of nearly vanishing gate-to-channel capacitance, corresponding to the situation when an integer number of Landau levels was completely filled. Having positively identified the Landau level number for each notch, they resolved the spin and the valley splittings in the first Landau level and spin splitting in the second Landau level (for a review of theories discussing the origin of these splittings see [18]).

From our point of view, the most intriguing result of Kaplit and Zemel [1] is their observation of a significant shift in the threshold voltage of their MOSFET, induced by the applied magnetic field, see Fig. 1. For H above 4 Tesla the threshold voltage increases linearly with the magnetic field at the rate $dV_T/dH = 143\,\mathrm{mV/T}$. No reasonable explanation of this dramatic effect was given in ref. 1. As will be shown below, it is brought about by a peculiar metal - insulator transition which occurs in a 2-dimensional electron gas in strong magnetic fields and a random electrostatic potential. This phase transition of percolation nature has been discussed by us [17] in connection with the QHE at low temperatures.

Let us first briefly discuss the MOSFET capacitance in the absence of magnetic field. The typical dependence of the differential capacitance [19] on the gate voltage is shown in Fig. 2 by the solid line. At low V_G this capacitance is determined by the combined thicknesses of the oxide and the semiconductor depletion region weighted by the respective permittivities. At high V_G an inversion layer appears at the silicon/oxide interface, which screens further penetration of the electric field into the semiconductor. In this case the differential capacitance is determined by the oxide thickness only. Near and above the threshold the surface charge charge density σ in the inversion layer is given by [20] $\sigma \propto \exp[\beta(V_G - 4\pi\sigma d/\varepsilon)]$, where d and ε are, respectively, the oxide thickness and permittivity, and $\beta = e/kTn$ with n being an (approximately constant) ideality factor. The gate to channel capacitance per unit area, $\mathrm{d}\sigma/\mathrm{d}V_G$, is thus given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}V_G} = \frac{\varepsilon}{4\pi d}\,\frac{1}{1+\dfrac{\varepsilon kTn}{4\pi de\,\sigma}} \tag{1}$$

In strong inversion ($\sigma \gg \varepsilon kTn/4\pi de$) one has, obviously, $\mathrm{d}\sigma/\mathrm{d}V_G = \varepsilon/4\pi d$.

The nature of capacitance threshold in strong magnetic fields is quite different. Firstly, we note that it occurs when the MOSFET is already in the strong inversion limit. Therefore, the threshold is associated not with a screening effect but rather with the conductivity of the inversion layer. As discussed in [17], at low temperatures and strong magnetic fields the 2-dimensional electron gas in the presence of fluctuations of a fixed charge breaks in patches where the Landau levels have occupation numbers 0 and 1. (In the MOS structure the fluctuating fixed charge is both in the oxide and the depleted semiconductor layer.) Consider occupation of the lowest Landau level. Pictorially, it can be represented as a bi-colored map, in which filled regions are painted in black, and the remaining regions, empty of electrons, are painted in white. If the area of black regions constitutes less than 50% of the inversion layer, then these regions represent disjoint lakes disconnected from the source and drain contacts. In this situation the inversion layer does not respond to the high-frequency *ac* signal on the gate. This is analogous to the well-known high frequency *CV* characteristics of MOS capacitors with no source/drain contacts [19], except that the frequency cut-off here corresponds to the *RC* delay of hopping conduction rather than that of a generation current. On the other hand, when the total black area is over 50%, then it is globally connected and can be rapidly charged and discharged through the source. The percolation threshold for a 2-dimensional continuum (random coloring) problem corresponds to equal coverage by both colors [21].

Thus the transition occurs when the average density of charge σ in the inversion layer exceeds a critical value $\sigma_{cr} = \sigma_0/2$, where σ_0 is the density of states per unit area in one Landau level,

$$\sigma_0 = \frac{e^2 H}{hc} \quad . \tag{2}$$

The threshold voltage $V_T = V(\sigma_{cr})$ is, therefore, shifted by the magnetic field as follows:

$$\frac{\mathrm{d}V_T}{\mathrm{d}H} = \frac{\mathrm{d}V}{\mathrm{d}\sigma}\,\frac{\mathrm{d}\sigma_{cr}}{\mathrm{d}H} = \frac{e^2}{\hbar c}\,\frac{d}{\varepsilon} = \frac{d}{137\,\varepsilon} \tag{3}$$

The quoted value of d in [1] was approximately 2900 Å. This gives $\mathrm{d}V_T/\mathrm{d}H = 158\,\mathrm{mV/T}$ in good agreement with the experimental value 143 mV/T. This agreement lends support to our model of electron localization in strong magnetic fields used [17] for explanation of QHE experiments at very low temperatures.

At a finite temperature there must exist a critical magnetic field below which the localization does not occur even when $\sigma < \sigma_0/2$, since no localization, evidently, takes place in the MOSFET inversion layer at $H = 0$ and σ corresponding to strong inversion. According to the data of [1], in samples studied at 1.3 K the critical field was about 2 Tesla. As evident from Fig. 1, at "low" magnetic fields the threshold becomes independent of H. In this region V_T is determined by the usual screening effect. It should be interesting to study this question in more detail.

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FIGURE CAPTIONS

Fig. 1. Threshold voltage versus the applied magnetic field (from the data of ref. 1).

Fig. 2. Typical high-frequency capacitance-voltage characteristic of a MOSFET with source connected to the substrate; also shown the characteristic from ref. 1 at $H = 10\,\mathrm{T}$ (broken line).

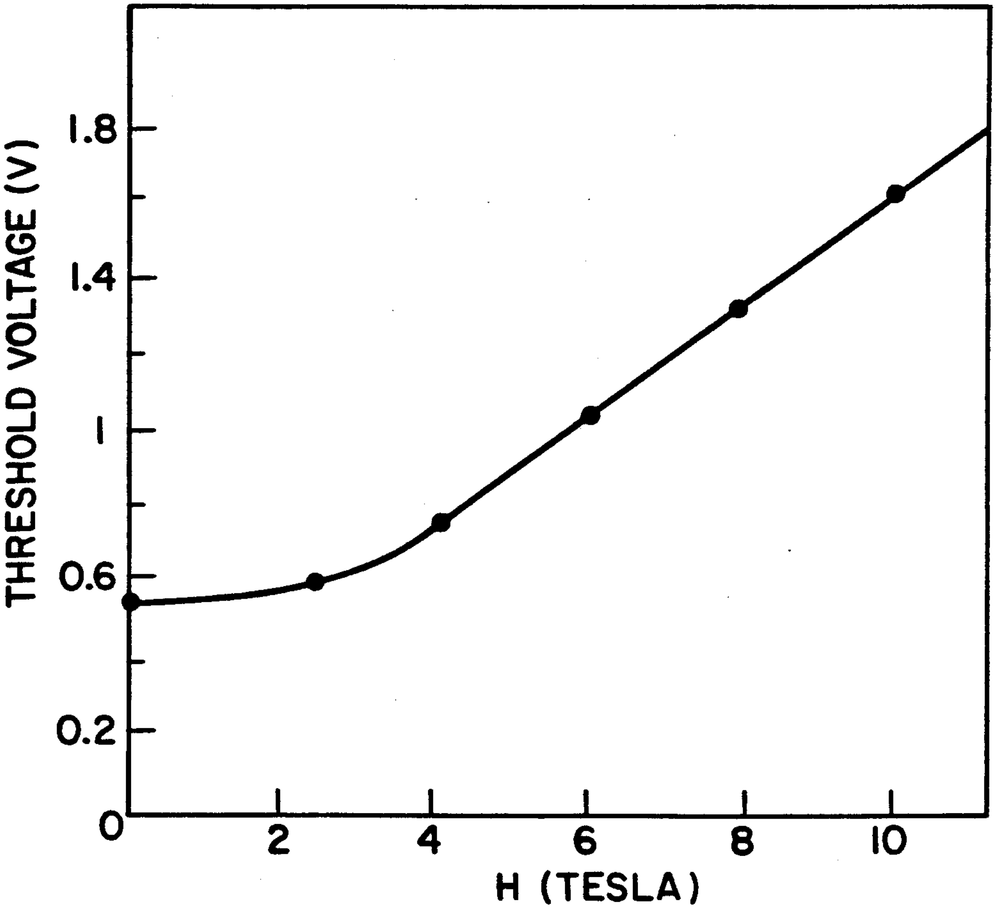

Fig. 1

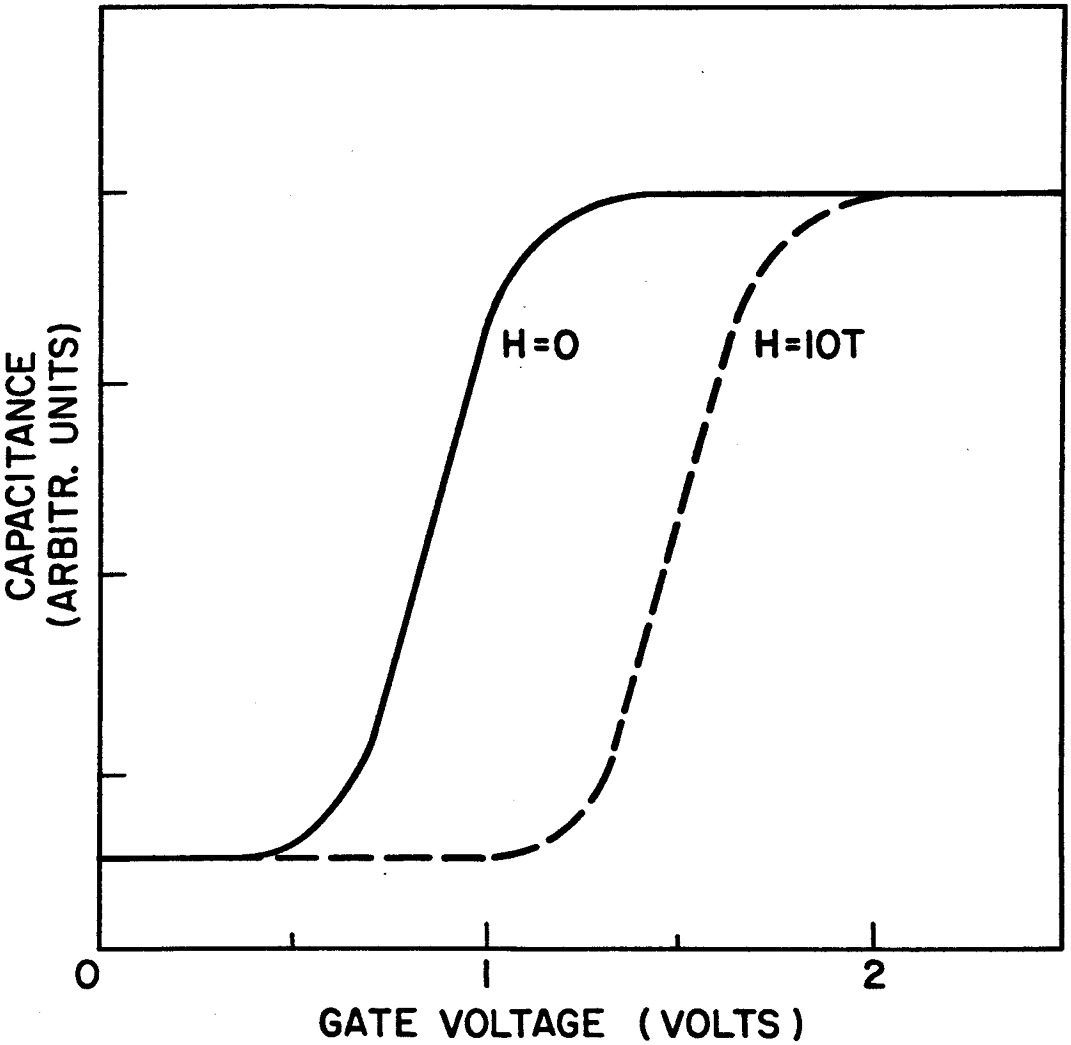

Fig. 2