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Electrical conduction in inversion layers modulated by a long-range potential

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Electrical properties of silicon inversion layers modulated by long-range potential are investigated experimentally and theoretically. The potential modulation has been induced by an electron beam scanning lines parallel and/or perpendicular to the current in a metal-oxide-semiconductor field-effect transistor (MOSFET) structure. We introduce threshold energies that result from the influence of the potential modulation on the conduction processes. Depending on the conduction regime, these thresholds account for carrier localization near the threshold or a mobility drop at higher energy. Using the field-effect technique, we are able to induce transition from a density-controlled conduction to a two-mobility-controlled conduction. A quantitative approach to previous mobility-edge and potential fluctuation models is proposed using MOSFET structures with controllable disorder as a physical tool.

I. INTRODUCTION

Electrical conduction in inversion layers has been for many years the subject of numerous experimental and theoretical investigations. The inversion layers provide a two-dimensional system in which the electron density may be directly varied over several orders of magnitude. Metal-oxide-semiconductor field-effect transistor (MOSFET) structures have provided an excellent system for investigating the Anderson transition,[1] the Mott minimum metallic conductivity, and variable-range hopping.[2] Potential inhomogeneities have been considered in percolation theories[3] and models of short-range and long-range disorders[4-7] as applied to inversion layers. Other authors[8,9] have proposed a model of electrical conduction in long-range disordered three-dimensional (3D) semiconductors, using the so-called potential fluctuation (PF) picture.

In this paper, we propose a new experimental approach to the long-range potential modulation in 2D semiconductors. A controllable potential modulation (PM) has been created in the channel using an *e*-beam irradiation along lines parallel or/and perpendicular to the drain-source current. The period of irrädiation has been large enough to avoid any resonant tunneling through the potential barriers. As a result, the electrical properties of the inversion have been strongly modified and allowed us to test the validity of some concepts introduced in the PF model. The main advantages of our method are the following:

(i) The shape of the electrostatic potential is easy to control both in its magnitude and range.

(ii) Percolative conduction is not involved.

(iii) Potential barriers are introduced, making our system similar to polycrystalline semiconductors.

(iv) Theoretical description of the PF model[10] is simplified, since in a 2D system the density of states is independent of energy.

(v) Scattering and screening mechanisms can be studied on the *same* sample by varying the gate voltage (i.e., the total carrier density).

The MOSFET silicon structures were irradiated through the gate oxide by a 20-keV electron beam with the dose 200 $\mu\mathrm{C\,cm^{-2}}$. The technological details have been described in Ref. 11. The *e* beam was scanned along lines parallel or perpendicular to the drain-source direction in L and T structures and a crossing *e*-beam irradiation was performed on LT structures. The periods of the scanning lines were $P=0.5$, 1, 5, and 10 μm, respectively. Consequently, a high density of interface states N_{it} was generated by the *e*-beam irradiation.[12] Assuming that all the states are charged, the gratinglike distributed defects induce a periodic modulation of the in-plane surface potential. The irradiation treatment results in a band bending at the Si/SiO$_2$ interface, leading to a shift of the transistor threshold voltage ΔV_T and a degradation of both effective and field-effect mobilities.[11]

It should be noted that the L and T structures were irradiated with the same dose, whereas the dose was twice for LT structures. The threshold voltages obey the inequality: $V_T(LT) > V_T(T) > V_T(L)$. The band bending at the Si/SiO$_2$ interface was the same in structures L and T. Thus the threshold voltage shift must be due to the longitudinal or transverse conductivity.[11,13,14] The Hall mobility in the LT structures was close to that in the T structures, indicating that the transverse barriers dominated the main scattering process.[13]

Figures 1 and 2 show the Hall carrier concentration and Hall mobility versus $1000/T$. The Arrhenius plots indicate the thermally activated behavior at low temperatures and low gate voltages. The minimum of n_{Hall} in the Arrhenius plot was more pronounced in the T and LT structures than in L structures, while the Hall mobility exhibited a strong thermally activated behavior in the T and LT structures.

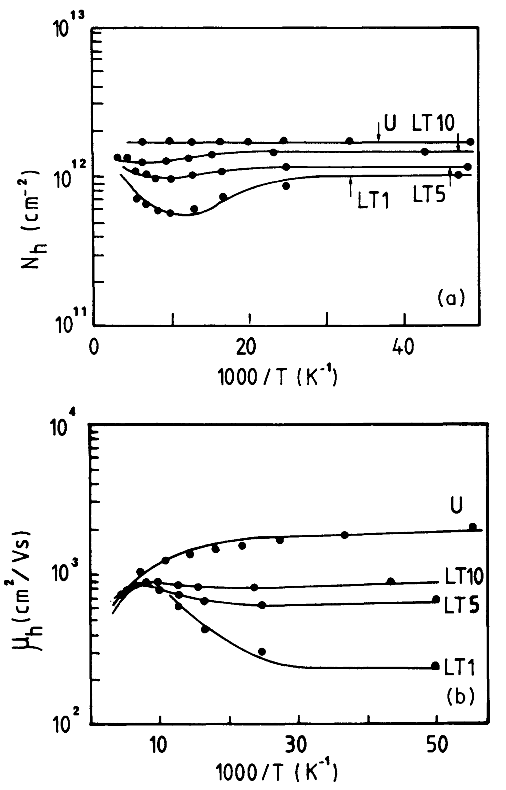

FIG. 1. Hall measurements in samples *LT*10, *LT*5, *LT*1 at $V_g=6$ V. (a) Carrier concentration, (b) Hall mobility. The dots correspond to experimental data. The solid lines correspond to theory (the fitting parameters are collected in Table I).

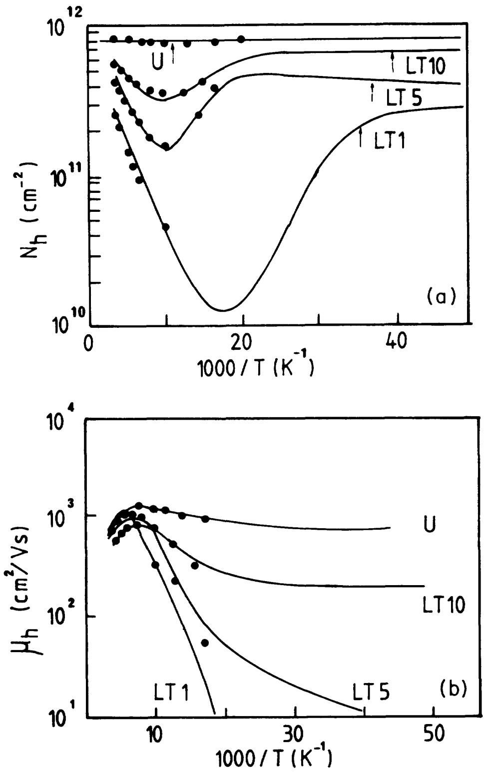

FIG. 2. Hall measurements in samples *LT*10, *LT*5, *LT*1 at $V_g=3$ V. (a) Carrier concentration, (b) Hall mobility. The dots correspond to experimental data. The solid lines correspond to theory (the fitting parameters are collected in Table I).

II. THEORETICAL APPROACH

We investigate two conduction regimes: the strong-inversion regime in which the barriers are low and/or narrow (i.e., not reflective), and the weak-inversion regime in which the barriers are high and wide such that localization due to nonpenetrable barriers occurs as in the PF model. In the following we will distinguish the two cases, focusing on both free-carrier density and scattering mechanisms (Hall mobility).

After the irradiation some carriers are trapped on the trapping centers $N_{\rm it}$ induced at the interface. We assume that this leads to a trapped carrier density calculated over an energy interval W above the subband edge E_0 in the unirradiated MOSFET. The remaining mobile carriers are separated into two categories: carriers n_2 with energy $E<E_{\rm th}$ having a low mobility μ_2 (since they are weakly localized) and carriers n_1 with energy $E>E_{\rm th}$ having a high mobility μ_1 (since they are free conducing). Moreover, the gratinglike irradiation leads to an additional potential modulation (barrier E_B).

Both the effective conductivity and the Hall effect depend on the PM profile and they are governed by two conduction mechanisms (mixed conduction).[15]

$$n_{\rm Hall}=\frac{(n_1\mu_1+n_2\mu_2)^2}{n_1\mu_1^2+n_2\mu_2^2}\ , \tag{1}$$

$$\mu_{\rm Hall}=\frac{n_1\mu_1^2+n_2\mu_2^2}{n_1\mu_1+n_2\mu_2}\ . \tag{2}$$

The carrier densities n_1 and n_2 are calculated using the unperturbed density of states $D(E)=D_0$. [$D_0=1.6\times10^{11}$ cm^{-2}/meV in electron inversion layers with $m^*=0.19m_0$ for a (100) silicon surface.]

According to our definition, W is the conduction threshold energy, whereas $E_{\rm th}$ is a two-mobility threshold energy. A part of the n_2 carriers can be localized in T and LT structures in the weak-inversion regime, in the same manner as in the PF model. This localization becomes larger when the gate voltage is lowered since both the barrier height E_B and the barrier thickness increase. A similar theoretical description has been previously applied to polycrystalline semiconductors in the frame of the PF model.[16]

The phonon- and impurity-scattering mechanisms and their temperature dependence have been studied in inversion layers as a function of the carrier density $n_{\rm inv}$.[17] To describe this temperature variation, we use the following expression[18,19] for carriers in density n_1:

$$\mu_1(T)=2\mu_0\left[\left[\frac{T}{T_0}\right]^{\alpha}+\left[\frac{T_0}{T}\right]^{\beta}\right]^{-1}, \tag{3}$$

where μ_0 is the maximum of the mobility measured a

$T=T_0$. The values of μ_0 and T_0 depend on V_g. The exponents α and β are related to the scattering mechanisms. The value of α is usually taken to be equal to 1.5 (phonon scattering in the high-temperature range), whereas β accounts for impurity, interface, and disorder scattering at low temperatures. In our samples it also accounts for the potential modulation which introduces additional scattering processes. In the weak-inversion regime, potential barriers are unscreened and the mobility μ_2 in L structures is lowered. The carriers n_2 conduct along the valleys and they are influenced by the lateral scattering, which leads to a decrease of their mobility. The actual temperature dependence of this scattering process is unknown, but it should be similar to the scattering by fixed charges Q_{it},[18] i.e., it should show a weak dependence on temperature. In contrast, in T structures the barrier scattering processes are similar to those present in barrier tunneling or thermoemission conduction.[20–22] Thus, their mobility is deduced from the conductivity of *all* the carriers n_2 averaged in the conduction band over the whole energy interval $E<E_{\text{th}}$ and it can be expressed as

$$\mu_2=\mu_{02}\exp(-E_B/kT)\ , \tag{4}$$

where E_B denotes the mean barrier height.

III. DISCUSSION AND CONCLUSION

Figures 1 and 2 show the comparison of the theory with experiment in the strong-inversion regime for samples *LT*10, *LT*5, and *LT*1, respectively. The value of W is deduced for each irradiated sample at low temperature from the ratio of its carrier concentration to that of the unirradiated MOSFET (sample *U*). Then, the threshold energy E_{th} which separates the two carrier populations is computed to account for the minimum observed in the Hall carrier concentration in the intermediate temperature range. The parameters μ_0, T_0, β (related to the mobility μ_1) and μ_{02}, E_B (related to the mobility μ_2) are determined to account for both the temperature dependence of the mobility and the value of the minimum of the carrier concentration. As a matter of example, parameters accounting for the behavior of the samples at gate voltages $V_g=6$ V and $V_g=3$ V are collected in Table I. The values of W and E_{th} are kept constant in the calculation for each structure, since it is assumed that all the interface trapping centers are charged and that the barrier height E_B is the same for all samples. The reason is that the structures differ only by the irradiation period P. In the weak-inversion regime, the Fermi energy E_F moves down crossing the band edge E_0. Consequently, the carrier concentration decreases by decreasing the temperature and in this conduction regime, conditions $N_{\text{inv}}=\text{const}$ and $V_g=\text{const}$ are not equivalent. Values of the parameters have not been calculated near the threshold voltage because of lack of the Hall data, but it is clear that the model predicts vanishing of both the minimum of n_{Hall} and the maximum of μ_{Hall} in the Arrhenius plots. Indeed, Table I shows that the values of the prefactor μ_{02} should decrease whereas the values of β and E_B should increase. In contrast, when $E_B\simeq 0$ (total screening of the barriers at high carrier concentration), the PM scattering is not predominant. The mobility μ_2 reduces to the preexponential term μ_{02}, which is always lower than μ_{01}. As mentioned above, E_B varies with V_g but E_{th} stays constant. At high V_g, the potential profile is nearly flat and the electrical behavior is similar to that of an uniformly irradiated structure. In that case, the anomalous minimum in the Hall carrier concentration needs to be interpreted again in the frame of the two-mobility model, the threshold E_{th} being the consequence of the irradiation. In contrast, the barrier potential E_B is the result of the gratinglike geometry only and it vanishes at high gate voltage due to the screening effect. Values of β deviate from the standard ones (unirradiated structure) when the gate voltage decreases. This fact indicates clearly that the influence of the PM scattering becomes predominant and Eq. (3) is not valid anymore. Thus, it can be concluded that transverse barriers lead to strong scattering, which perturbs both high- and low-energy carrier conduction in T and LT structures near threshold. The effective Hall mobility becomes thermally activated.[23] This behavior is analogous to that of polycrystalline semiconductors in which all the carriers in the band have their mobility controlled by the potential barriers at grain boundaries.

To qualify some assumptions introduced in the PF

TABLE I. The Hall carrier concentrations taken as reference in sample U were 1 E12 cm^{-2} at $V_g=6$ V and 8 E11 cm^{-2} at $V_g=3$ V, respectively. The conduction energy E_{th} is taken to be 28 meV for all the samples.

Sample	V_g (V)	W (meV)	μ_{01} (cm^2/V s)	T_0 (K)	β	μ_{02} (cm^2/V s)	E_b (meV)
U	6	0	1000	150	0		
U	3	0	1300	120	0.8		
*LT*10	6	1	1400	160	0	840	0
*LT*10	3	1	1500	110	0.5	200	0
*LT*5	6	3	1300	160	0	650	0
*LT*5	3	3	1250	120	2.5	150	5
*LT*1	6	4	1100	200	0	240	0
*LT*1	3	4	1000	150	4	5	10

model, we have proposed a quantitative approach to this description, applying it to the silicon inversion layer with a controlled electrostatic disorder. To induce large-scale potential modulation, a new gratinglike *e*-beam irradiation technique is used. The carrier concentration can be continuously increased so that the transition from a two-density conduction to a two-mobility conduction is induced in the same sample. The proposed model takes into account barrier effects which introduce additional scattering mechanisms similar to those present in polycrystalline semiconductors.

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