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INFLUENCE OF THE DOPING LEVEL AND THE TEMPERATURE ON ELECTRON MOBILITY IN THE *n* CHANNEL OF AN MOS FIELD-EFFECT TRANSISTOR

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Based on results of measurement and processing of volt-ampere characteristics as well as kinetic modeling of electron transfer by the Monte Carlo method, the influence of the doping level and the temperature on electron mobility in the n channel of a silicon MOS field-effect transistor operating in a linear regime is investigated.

As element dimensions of silicon integrated circuits are reduced, developers of new devices face a pressing need for accurate knowledge of the peculiarities of the influence of different factors on charge-carrier transfer in devices with effective channel lengths of the order of micrometers and less. We have investigated the influence of the doping level of the substrate and the temperature on electron mobility in the *n* channel of silicon MOS field-effect transistors (MOS-FET) operating in a linear regime. The mobility has been determined both by measurement and subsequent processing of volt-ampere characteristics (VAC) of test structures and by kinetic modeling of charge-carrier transfer in the MOS-FET channel.

It is known [1, 2] that with increase in the doping level of the MOS-FET substrate, the drain voltage at which the current in the channel is saturated decreases. It becomes much less than the effective gate voltage and near the drain region the inverse charge can decrease only insignificantly. In this case, the current takes a continuous path from the source to the drain in a rather wide range of the applied drain voltage and is saturated before shuttering of the channel. In such devices the electrical conductivity of the channel decreases and in order to maintain it at the specified level, it is necessary to increase the electron concentration in the channel, which is achieved by decreasing the threshold voltage by choosing a thinner gate oxide layer, provided that in the case of strong- inversion conditions the total electric field in the structure does not exceed the breakdown field [2]. Restrictions imposed on the change in the mobility of the inverse charge carriers and the threshold voltage can affect the volt-ampere characteristic and temperature stability of the device.

VAC measurements were made on transistors fabricated on a silicon substrate doped with boron with a dopant-atom concentration of $N_a = 7 \cdot 10^{21}$, 10^{23}, and $7 \cdot 10^{23}$ m^{-3} and a thickness of the gate oxide layer of 100, 200, and 300 nm, respectively. In order to prevent breakdown of the test structure the oxide thickness was increased for the highly doped substrate. The effective channel length L_{ch} was 3 μm, and the depth of occurrence of the source and drain regions was 0.8 μm. The gate electrode was made of aluminum.

Figure 1 shows dependences of the drain current on the gate voltage measured on the ohmic section of the VAC at different dopant concentrations [a) $N_a = 7 \cdot 10^{21}$ m^{-3}, b) $N_a = 7 \cdot 10^{23}$ m^{-3}] and temperatures. As is seen from the behavior of the curves, with increase in the doping level, the slope of the VAC curve relative to the abscissa axis (the V_g axis) increases, which is accompanied by an increase in the threshold voltage and disappearance of the thermostable point (the point of intersection of all the curves) in the investigated ranges of the gate voltage and the drain current [3].

The resistance in the ohmic section at drain voltages much lower than the effective gate voltage, with the substrate being grounded, can be determined by the relation [1]

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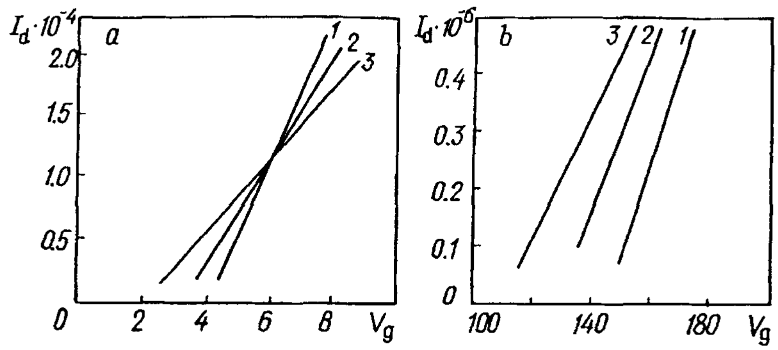


Fig. 1. Drain current versus gate voltage: 1, 2, 3) $T = -80, 25, 100°C$; a) $V_d = 0.4$ V, $W/L_{ch} = 10$; b) 0.1 and 4. I_d, A; V_g, V.

$$\frac{V_d}{I_d} = \frac{L_{ch}}{\mu C_0 W (V_g - V_{th})}. \quad (1)$$

After taking logarithms operation and differentiating with respect to the temperature T, we obtain [3]

$$\frac{1}{I_d}\frac{dI_d}{dT} = \frac{1}{\mu}\frac{d\mu}{dT} - \frac{1}{V_g - V_{th}}\frac{dV_{th}}{dT}. \quad (2)$$

It is obvious that the thermostable point on the VAC curve, at which the drain current and the gate voltage are constant for different crystal temperatures, is characterized by equality of the right-hand side of (2) to zero. Hence an expression can be derived to calculate the voltage difference $V_g - V_{th}$ at which MOS-FET thermostabilization occurs for a specified concentration of the doping impurity:

$$V_g - V_{th} = \mu \frac{dV_{th}/dT}{d\mu/dT}. \quad (3)$$

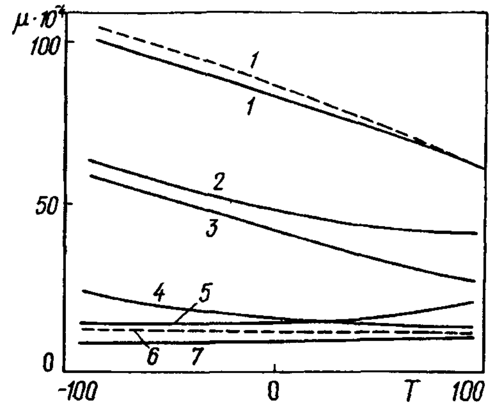
The electron mobility can be calculated by means of the familiar relation [1]

$$\mu = \frac{dI_d}{dV_g}\frac{C_0 W V_d}{L_{ch}}. \quad (4)$$

An analysis of the curves in Fig. 1 shows that, first, the difference $V_g - V_{th}$ increases with N_a, second, the derivative dV_{th}/dT is negative, and third, the mean electron mobility in the channel has a weaker temperature dependence in transistors with a higher doping level of the substrate.

In modeling electron transfer in the n channel of a silicon MOS-FET by the Monte Carlo method, we used the same algorithm as in [4, 5]. In so doing, we took into consideration that the charge carriers in the inversion layer of silicon form a quasi-two-dimensional electron gas due to quantization of their energy, and the transition of electrons from the quasi-two-dimensional ($Q2d$) to the three-dimensional ($3d$) state occurs as a result of their heating by the entraining drain field and their escape from a quantum well of the inversion layer. In the case of two-dimensional carriers, account was taken of such mechanisms of scattering as that by acoustic intravalley phonons, intersubband scattering, scattering by oxide charges, scattering by surface inhomogeneities, and electron-electron scattering; in the case of $3d$ electrons there are scattering by acoustic and optical intravalley phonons, scattering by dopant ions, intervalley scattering, electron-electron scattering, and impact ionization.

We calculated the electron mobility μ in the channel as a function of the channel length L_{ch}, dopant concentration N_a, and temperature T. Figure 2 shows curves $\mu(T)$ corresponding to the drain-transition region obtained by the Monte Carlo method (solid lines) and calculated from the experimental data given in Fig. 1 by formula (4) (dashed lines). As is seen, with increasing N_a, the behavior of the temperature dependence of the electron mobility changes. At low N_a values, μ decreases with increasing temperature, while at high values μ grows with T. Moreover, equality of the slope of the curves approximating the function $\mu(T)$ to zero occurs at concentrations $N_a \approx 7 \cdot 10^{23}$ m^{-3}. This behavior of the dependences can be explained by the following factors.



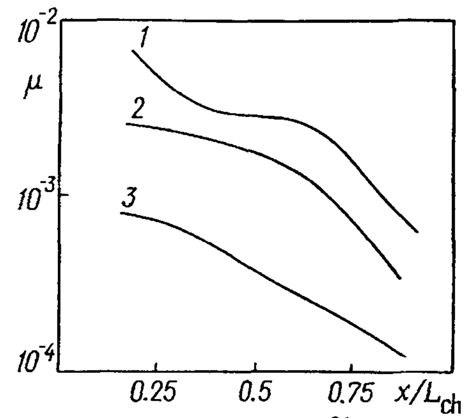


Fig. 2. Electron mobility in the channel versus temperature: 1) $N_a = 7 \cdot 10^{21}$ m^{-3}, $L_{ch} = 3$ μm; 2) 10^{23} and 1; 3) 10^{22} and 0.1; 4) 10^{23} and 0.1; 5) 10^{24} and 0.1; 6) 10^{23} and 3; 7) 10^{24} and 1. μ, $m^2/(V \cdot sec)$; T, °C.

Fig. 3. Electron mobility versus coordinate x along the channel: 1) $N_a = 10^{22}$ m^{-3}; 2) 10^{23}; 3) 10^{24}. L_{ch}, μm.

At very high dopant concentrations the mobility of electrons in the channel near the drain will depend to a large extent on scattering by dopant ions. To calculate the rate of such scattering (i.e., the scattering per unit time) for $3d$ electrons in this channel region, use was made of the Konwell–Weisskopf model [6], according to which the scattering rate decreases with decreasing energy of the charge carrier. Another important mechanism of electron scattering in the channel that determines their mobility is scattering by phonons. With increasing crystal temperature the intensity of scattering involving phonon ejection increases, thus leading to a decrease in the electron energy. Moreover, it is obvious that the relative contribution of phonon scattering to the total scattering intensity of charge carriers will decrease with increasing concentration N_a. Under these conditions with an increase in T as a result of the decrease in electron energy near the drain due to additional ejection of phonons and a decrease the intensity of scattering of such low-energy charge carriers by impurities their mobility will increase. However, at low concentrations N_a this is not observed, since the main contribution to the total scattering intensity is made by scattering by phonons, and therefore the mobility of the electrons will decrease with increasing temperature.

The good agreement between the curves calculated by the Monte Carlo method and those obtained experimentally using formula (4) points to the adequacy of the developed kinetic transfer model as well as to the correctness of the theoretical conclusions made based on the behavior of the mobility curves.

Figure 3 shows the mean electron mobility μ versus the coordinate x along the channel for three concentrations N_a. As is seen, near the drain the mobility considerably decreases due to heating up of the electrons. Here, a decrease in N_a leads to mobility enhancement, which is attributed to a decrease in the intensity of scattering by dopant ions.

Thus, the experimental data obtained and the calculations made by the Monte Carlo method show that with increasing dopant concentration in the n channel of a silicon MOS-FET the electron mobility and its thermal gradient decrease. The thermostable point can be displaced toward higher gate voltage values. The derivative $d\mu/dT$ at first decreases as well, but with increasing doping level it begins to increase, passing through a minimum in the concentration range $N_a = (5-7) \cdot 10^{23}$ m^{-3}. At a doping level of $N_a > (5-7) \cdot 10^{23}$ m^{-3} the electron mobility increases with the temperature.

NOTATION

N_a, dopant concentration; V_d, V_g, and V_{th}, drain, gate, and threshold voltage, respectively; I_d, drain current; μ, electron mobility; C_0, specific capacity of the oxide; W, channel width; L_{ch}, channel length; T, crystal temperature.

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