Consequences of negative differential electron mobility in insulated gate field effect transistors

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We study the consequences of negative differential electron mobility in insulated gate field effect transistors (FETs) using the field model. We show that, in contrast to the case of the monotonic velocity saturation model, the field distributions in a short-channel FET may be described by the gradual channel approximation even for high drain-to-source voltages. The current-voltage dependence of the short-channel FET should have a branch with a negative slope. The FET exhibits a negative differential resistance and may show convective or absolute instability, depending on the applied voltages. The fluctuation growth is governed by the diffusion law with a negative effective diffusion coefficient.

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INTRODUCTION

Since the electric fields in modern short-channel field effect transistors (FETs) may be very high, effects of electron velocity saturation are of importance. Studies implying monotonic saturation of the electron velocity with increasing electric field \cite{1}-\cite{4} have shown that in short-channel FETS the drain saturation current $j_{\text{sat}}$ and the drain-to-source voltage $U_{\text{sat}}$ at which the current saturation takes place are substantially smaller than the saturation current and voltage predicted by the constant electron mobility model. When the drain-to-source voltage $U_{D}$ is smaller than $U_{\text{sat}}$, the drain current increases with increasing $U_{D}$ and may be described by the gradual channel approximation \cite{4}. For $U_{D} > U_{\text{sat}}$ (in the current saturation region), the gradual channel approximation fails because of too sharp variation of the electric field along the channel. At this takes place, the drain current is supposed to be constant.

Recently, Dmitriev, Kachorovskii, Shur and Stroscio \cite{5} have shown that two-dimensional electron gas in silicon or germanium should exhibit a negative differential mobility caused by the electron runaway. Apparently, the above consideration implying monotonic electron velocity saturation is not sufficient to describe FETs, which may exhibit non-monotonic velocity-field dependence with negative differential electron mobility. This may be the case in Si or Ge MOSFETS or FET based on compound semiconductors, such as GaAs and InP.

In metal semiconductor FETs (MESFETS), the consequences of the negative differential mobility are similar to ones in bulk devices resulting in the Gunn effect \cite{6}. In particular, the stationary Gunn domain which may be described in a three-dimensional model plays an important role in MESFETS \cite{7}. In contrast, the consequences of the negative differential mobility should differ essentially in two-dimensional case such as metal-oxide semiconductor FETS (MOS-FETS), metal-insulator semiconductor FETS (MISFETS) and heterostructure FETS (HFETS).

Indeed, the distribution of electric field caused by a charged fluctuation is quite different in 2D layer and also depends on the induced charge in the conductive gate electrode. Due to this fact, the relaxation of a charged fluctuation is governed by the diffusion law \cite{8}, in contrast to conventional exponential law for three-dimensional Maxwellian relaxation. However, no analytical theory describing the consequences of the negative differential mobility in two-dimensional FET channel has yet been developed.

In this paper, we study the consequences of the negative differential electron mobility in the insulated gate FETS, such as MOSFETS, MISFETS and HFETS, using the field model and the gradual channel approximation. In these devices, the channel is isolated from the gate by an insulator (a wide band gap semiconductor in HFET). We shall not consider here MESFETS and junction FETS (JFETS) that have differing design and require other models.

We have found that the FET may exhibit convective or absolute instability, depending on the applied voltages. The growth of small electric fluctuations is governed by the diffusion law with a negative effective diffusion coefficient. We have also shown that, in contrast to results following from the monotonic velocity saturation model, the current-voltage dependence of the short-channel FET should have a branch described by the gradual channel approximation even at high drain-to-source voltages. This branch has a negative slope, i.e. the FET exhibits a negative differential resistance.

BASIC EQUATIONS

The surface electron concentration $n$ in the FET channel is determined by the conventional charge control model equation \cite{4}

$$ n = \frac{CU}{e} \cdot U = U_{\text{GC}}(x) - U_{T}, $$  \hspace{1cm} (1)
where $C$ is the surface gate capacitance, $U_{GC}(x)$ is the gate-to-channel voltage, $U_T$ is the threshold voltage. Eq.(1) is valid in the gradual channel approximation when the characteristic scale of variations of $U$ and $n$ is much greater than the gate-to-channel separation $d$.

In view of Eq.(1), the continuity equation may be written as

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}[V(E)U] = E = -\frac{dU}{dx}. \quad (2)$$

Here, $V(E)$ is the electron drift velocity which depends on the longitudinal electric field $E$ in accordance with the local field model. The $V(E)$ dependence in the FET channel may differ quantitatively from that in the bulk semiconductor but have a similar form with a negative slope for $E$ greater than the threshold field $E_t$ (see Fig.1,a). The dynamics of $E$ distribution is thus described by Eq.(2) with the use of Fig.1,a.

**STEADY STATES**

In a steady state, Eq.(2) becomes $U = j/CV$ where $j$ is the drain current per unit gate width. Differentiating this expression, we obtain

$$\frac{dE}{dx} = \frac{CE[V(E)]^2}{j\mu_d}, \quad \mu_d = \frac{dV(E)}{dE}, \quad (3)$$

where $\mu_d$ is the differential electron mobility. The boundary values of $E$, $U$ and $V$ at the source ($x = 0$): $E_0$, $U_0$ and $V_0$ are determined by the condition

$$V(E_0) = V_0 = \frac{j}{CU_0}, \quad U_0 = U_G - U_T, \quad (4)$$

where $U_G = U_{GC}(0)$ is the gate voltage, which is assumed to be fixed. Eqs.(3) and (4) allow one to calculate the $E$ distributions for certain $j$ if the $V(E)$ dependence is given in the form of an analytical approximation. One can however analyze their solutions qualitatively without calculations by simply looking at the $(dE/dx, E)$ diagram (see Fig.2,b) which results from Eq.(3) and Fig.1,a. It will be seen that $E$ increases along the channel when $E < E_t$ and drops when $E > E_t$. Note that, at $E \gg E_t$, $dE/dx$ increases with $E$ faster than $E$. Therefore, $E$ drops from infinity at a finite distance $x_m$. The general form of a solution of Eq.(3) is presented in Fig.2.

As it follows from Eqs.(3),(4), the characteristic scale of field variation $a$ is given by $a = (V_0/V_{ti})(U_0/E_{ti})$, where $V_{ti} = V(E_t)$ (in particular, $x_m$ is of the order of $a$). Assuming $U_0 \sim 1V$, $E_{ti} \sim 3$ kV/cm, $V_0 \sim V_t$, we have $a \sim 3\mu$m. Note that the gradual channel approximation used here is valid when $a \gg d$.

The actual field profile in the channel is represented by the section of the $E(x)$ curve (see Fig.2) which extends to the right from the point where $E = E_0$ for a distance of the channel length $L$. As it can be seen from Fig.1,a, if $V_s < V_0 < V_t$, two values of $E_0$ satisfy Eq.(4): $E_{01} < E_t$ and $E_{02} > E_t$. Then, two steady states determined by boundary fields $E_{01}$ and $E_{02}$ may exist in a FET with given drain current $j$: a positive state with $E < E_t, dE/dx > 0, \mu_d > 0$ and a negative state with $E > E_t, dE/dx < 0, \mu_d < 0$ (see inset in Fig.2). These two states differ in the value of the drain-to-source voltage $U_D = \int_0^L Edx$. It follows from Fig.1,a and Fig.2 that the negative state can exist if the channel length $L$ is short enough: $L < L_m$. The maximum length $L_m$ depends on $j$: $L_m \to 0$ when $V_0 = j/(CU_0) \to V_t$, and $L_m \to x_m \sim a$ when $V_0 \to V_s$.

The current voltage characteristics $j(U_D)$ following from this analysis are given in Fig.1,c. For short enough channel length $L < x_m$, the $j(U_D)$ dependence has two branches: I and II, corresponding to the above mentioned positive and negative states, respectively (curves 1 and 2). The type II branches existing for high drain-to-source voltages $U_D > E_tL$ show a negative differential resistance. In the voltage interval near $U_D \sim E_tL$, no steady states exist in the considered model. Actually, the current saturation regime similar to the one considered in
the monotonic velocity saturation model [3] should take place, which is not de-scribed by the gradual channel approximation. It is possible that states corresponding to the current saturation regime may also exist at higher $U_D$ in the region where branch II lies (see broken lines in Fig.1,c). Then the FET may presumably show branch II or the current saturation branch, depending on the circuit condition, applied voltages and the previous state of the FET. The question as to which of these branches should be observed requires three-dimensional computer simulations and is beyond the scope of this paper.

For very short channel lengths $d \ll L \ll a$, the $j(U_D)$ characteristic is close to the one determined by the $V(E)$ dependence since in the field in the channel is close to its boundary value $E_{01}$ or $E_{02}$ (curve 1, $j = C U_0 v(U_D/L)$). For $L > x_m$, branch II is absent and current saturation should occur at high $U_D$ (curve 3) as is the case in the conventional model.

STABILITY OF THE STEADY STATES

Let us consider the temporal behavior of small electric fluctuations in the channel. Adding small corrections $E'$ and $U'$ to the steady distributions of $E$ and $U$ described above, linearizing Eq.(2) and using Eq.(3), we obtain

$$\frac{\partial U'}{\partial t} + \frac{U'}{\tau} - D \frac{\partial^2 U'}{\partial x^2} + S \frac{\partial U'}{\partial x} = 0,$$

The parameters $\tau, D, S$ and $\mu_d$ vary with the characteristic scale $a$.

It can be shown that in the Fourier spectrum of fluctuations, only components with high $k$ are of importance: $a^{-1} \ll k \ll d^{-1}$. Then, they behave as $\exp(ikx - i\omega t)$ where $\omega$ varies slowly over the length $k^{-1}$. Putting this in Eq.(5) and noting that $\tau Dk^2 \gg 1$, we find: $\omega = kS - ik^2$. Note that this expression and Eq.(5) look like equations describing diffusion and drift processes, $D$ and $S$ being effective diffusion coefficient and drift velocity, slowly varying with coordinate $x$. Thus, fluctuations behave in accordance with the diffusion law. It can be seen that the negative states (branch II) are unstable since the effective diffusion coefficient $D = U \mu_d$ is negative. Then fluctuations grow with an increment $|D|^2 k^2$. The fast growing components with $k \sim d^{-1}$ are most essential because the gradual channel approximation is invalid for bigger $k$. The positive states are stable and fluctuations are damped out there since $D > 0$. As we have shown in [7], a similar diffusion relaxation with constant $D = \mu U_0$ takes place in the FET at $U_d = 0$, $\mu$ being the low field mobility.

The consequences of this convective instability depend on whether fluctuations have a chance to grow essentially during their non-uniform motion along the channel. Their growth is governed by $\exp(g), g \sim k^2 \int |D/S| dx, \int_0^L k \sim d^{-1}$. Under the condition $g < 1$, analogous to the well-known Kroemer criterion for the Gunn diode, the FET should presumably act as a stable amplifier, and at $g > 1$ as a generator. Note that, as it can be seen from Eqs.(3) and (5), the velocity $S$ becomes zero at a certain value $E > E_c$. If the field in the channel reaches this value, absolute instability occurs i.e. fluctuations grow without motion near the corresponding point $x$ in the channel. Detailed study of the instability criterion, requiring a numerical calculation, is beyond the scope of this paper.

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