Negative Differential Resistance and Thermal Effect
in Silicon MOS Field-Effect Transistors

Hiroyuki SAKAKI* and Takuo SUGANO
Department of Electronic Engineering,
University of Tokyo, Hongo, Tokyo, 113, Japan

I. Introduction

It was found by Katayama et al. that Si MOS transistors exhibit a negative
differential resistance (NDR) when measured by a pulse method at 4.2K. Later
Murayama et al proposed a semi-empirical model and attributed the NDR to a
scattering mechanism whose scattering rate increases with electron energy.

In the present work, this NDR effect is re-examined by measuring the
current-voltage characteristics on MOS transistors of various channel lengths L
and widths W with a refined pulse method. From the measured data, we shall show
that the NDR is ascribable to a thermal effect (temperature rise in the channel
due to Joule heating) rather than to an ad hoc scatterer of Murayama et al.

II. Experimental Method and Results

A square voltage pulse \( v(t) \) with the pulse width of 100 ns is applied to
the drain electrode of an FET, which is immersed in liquid helium, and the cur-
rent response \( i(t) \) is measured by a sampling oscilloscope. By sampling \( i(t) \) and
\( v(t) \) at some time \( t_s \) from the front edge of a square pulse, drain-current \( i(t_s) \)
versus drain-voltage \( v(t_s) \) characteristics are obtained. Typical results are
shown in Figs. 1 and 2 for the channel length of 10 \( \mu \)m and 100 \( \mu \)m, respectively.

(A) NDR of short-channel devices

It is shown in Fig. 1 that the NDR of
a short-channel FET is small and appears
when \( V_d \) exceeds 10V and when \( V_g \) is lower
than 40V (this corresponds to electron
concentration \( N_s \) of \( 10^{12}/\text{cm}^2 \)). These fea-
tures are found common to all the crystal
surface orientations studied, namely (111),
(110), and (100), and to the current-flow
directions. When samples of longer channel
are tested, the NDR becomes more marked.

This geometrical dependence and the in-
sensitivity to crystallographic orientation
suggest that the NDR is associated with the
thermal effect which depends on dimensions.

* Present Address, Institute of Industrial Science, University of Tokyo,
Roppongi, Tokyo, 106, Japan

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(B) NDR of long-channel devices  A long-channel FET \((L=100\mu m)\) exhibits a large NDR as shown in Fig. 2. Note that the electric field required for the onset of NDR is about \(2\times10^3 V/cm\) for \(L=100\mu m\) and is much lower than that for \(L=10 \mu m\). For \(t_s\) smaller than 70 ns, higher drain voltage is required to set on the NDR. In Fig. 3, the time dependence of \(I_d\) at \(V_g = 70V\) is shown for various values of \(V_d\). It is noteworthy that \(i(t)\) is composed of a high-current state and a low-current state. If the sampling point, which is indicated by a circle on each curve in Fig. 3, is in a high-current state, as in the case of curve (7), then the \(I_d-V_d\) characteristics in Fig. 2 exhibit a positive resistance. When the drain voltage is chosen higher than that of curve (7), then the sampling point falls on the transition region from the high- to the low-current state as in the case of curves (5) and (6). In such case, the NDR is observable in Fig. 2.

III. Discussions

By solving an equation of thermal conduction, it can be shown that the rise of temperature in the channel is typically of the order of \(10^6K\). In case the heat path in the real MOSFET is not as ideal as we assumed, it is probable to have a rise of several tens of degrees. In such case, the rise of \(T\) may lead to the decrease of electron velocities and consequently lowers the drain current.

For a device with \(L=10\mu m\), \(I_d\) is limited by the saturation velocity \(v_s\) of electrons for \(V_d > 10V\). In such case the rise in \(T\) can be shown to lead to an NDR because \(v_s^{-1}(3v_s/2T)\) is approximately \(-10^{-3}/0K\), as shown by Fang and Fowler.

For a long-channel FET, in which velocity saturation effect is negligible, the current is affected by the temperature rise through the temperature dependence of mobility. Most of the data described in II(B) can be explained by assuming \(\mu \) to be constant for low temperatures and to decrease with \(T\) for high temperatures.

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