INTERPRETATION OF EXPONENTIAL TYPE DRAIN CHARACTERISTICS OF THE STATIC INDUCTION TRANSISTOR

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The operation mechanism of a field effect transistor with triode-like characteristics, known as Static Induction Transistor SIT[1], has been the subject of recent publications[2-5]. For large drain currents the drain characteristics of this transistor have an almost linear character, which can be explained by effects of space charge[4, 5] or series resistance[1, 3]. For small currents the drain characteristics are of an almost exponential type. Two hypotheses for interpretation of this exponential type drain characteristics were given by Nishizawa[1, 2]. The first hypothesis is based on the assumption that the drain current is a thermoemission current injected from source to channel across a potential barrier and that the current-barrier height dependence is given by a standard thermionic emission relation similar to the Richardson equation. This hypothesis is questionable because the mean free path for electrons in silicon (60 Å[6]) is very small compared to the gate-source distance, which is of order of 1 μm. Thus the probability that electrons overcome the potential barrier without being scattered is much less than unity. The second hypothesis is based on a diffusion phenomenon.

An exact solution of the transport equations of the SIT can only be obtained by a two dimensional numerical method[5]. It is useful however to search for an approximate analytical solution which can indicate the influence of physical parameters on the characteristics of the device.

The current density in the centre of SIT channel is given by

$$J_n = q \cdot n(x) \cdot v(x) + q \cdot D_n \cdot \frac{dn(x)}{dx} \qquad (1)$$

where $v(x)$ is electron drift velocity in the electrical field.

Let us assume that the electron mobility is independent of the electrical field,

$$v(x) = \mu_n \cdot E(x) \qquad (2)$$

$$D_n = \mu_n \cdot kT/q. \qquad (3)$$

Substituting eqns (2) and (3) into (1) and multiplying both sides of eqn (1) by the factor $\exp[-qV(x)/kT]$ yields,

$$J_n \cdot \exp[-qV(x)/kT] = q \cdot D_n \cdot \frac{d}{dx}$$
$$\times \{n(x) \cdot \exp[-q \cdot V(x)/kT]\}. \qquad (4)$$

Integrating the above equation under the assumption that electron concentration in the channel is much smaller than the electron concentration in the source, the following equation for the current density in the centre of the channel as a function of potential distribution can be found,

$$J_n = -\frac{q \cdot D_n \cdot N_S}{\displaystyle\int_0^{x_0} \exp[-qV(x)/kT]\,dx} \qquad (5)$$

where N_S = electron concentration in source.

It can be concluded that the choice of the upper boundary of integration x_0 is not critical, because in the region between gate and drain the argument of the exponential function in (5) has a large negative value. It can be noticed also that, since in the region of integration between source and x_0 the electrical field is not very high, our earlier assumptions (2) and (3) are correct.

Generally the potential distribution can be obtained from Poisson's equation. For small current values the potential distribution in the channel of the SIT is not affected by electrical charge of electrons injected from the source. Additionally at drain voltages in the order of several volts or greater the boundary of channel depletion layer is fixed since the impurity concentration in the channel is very low. So, the potential can be calculated as a solution of a two dimensional electrostatic problem with disregard of the current flow. It can be seen from this simplified approach (Fig. 1) as well as from an exact solution[4] that the potential distribution in the region of potential barrier can be approximated by the square-law expression,

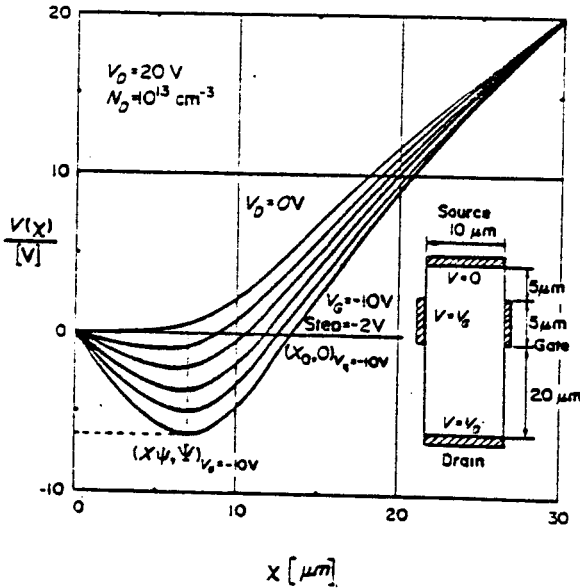$$V(x) = \frac{|\psi|}{x_0^2} \cdot x \cdot (x - 2x_0). \qquad (6)$$

Fig. 1. Potential distribution in the centre of SIT channel and transistor model used for calculations.

Here $|\psi|$ is the potential barrier height and $2x_\bullet$ is the effective barrier width. $|\psi|$ is approximately a linear function of the drain and gate voltages—V_D and V_G—due to the linearity of the Laplace operator in Poisson's equation,

$$|\psi| = |\eta \cdot V_G + \frac{1}{\mu} \cdot V_D + C| \qquad (7)$$

where $\eta = d|\psi|/d|V_G|$, μ is the amplification factor and C is a constant related to the ionized impurity charge.

Substituting eqn (6) into (5) leads to,

$$J_n = -\frac{q \cdot D_n \cdot N_S}{x_\bullet \cdot \mathrm{erf}\,(q|\psi|/kT)} \sqrt{\left(\frac{q \cdot |\psi|}{\pi \cdot kT}\right)} \exp\,(-q \cdot |\psi|/kT).$$

$$(8)$$

For small current level $|\psi| \gg V_T$ and eqn (8) can be simplified to the form

$$J_n = \frac{-q \cdot D_n \cdot N_S}{x_\bullet} \cdot \sqrt{\left(\frac{q \cdot \psi}{\pi V_T}\right)} \exp\,(-q \cdot \psi/kT). \quad (9)$$

It can be concluded that eqns (8) and (9) show an almost exponential character of SIT current as a function of V_D and V_G. The relation for the drain current in SIT is comparable with the second Nishizawa hypothesis but a parameter $l = x_\bullet \cdot \sqrt{(\pi \cdot kT/q \cdot |\psi|)}$ has to be taken in instead of L_n [1] or W_p [2]. Two dimensional numerical analysis is necessary in order to determine $x_\bullet$, $|\psi|$, η, μ.

In practice the shape of the transistor current slightly differs from an exponential relation. The same effect was observed by Morenza and Esteve[5]. An enlarged part of small current region of the drain characteristics of an 2SK78 transistor made by Yamaha is presented in Fig. 2. The current density J_n calculated according to eqn (5) as a function of V_D for the model from Fig. 1 is presented in Fig. 3. SIT characteristics differ from an exponential relation because:
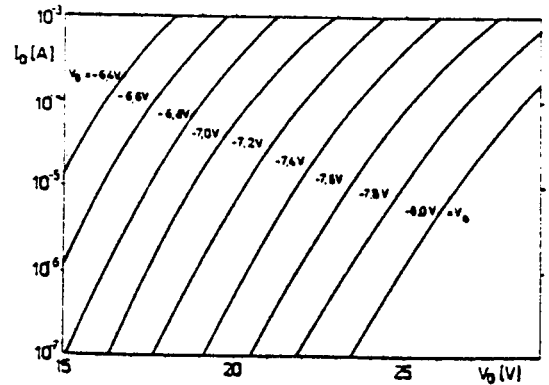

Fig. 2. Drain characteristics for small current region of 2SK78 transistor.

(a) The value of barrier height appears twice in eqn (9). It is due to the fact that the current value is functional dependent on the potential distribution near the potential barrier (see eqn (5)) and not a simple exponential function of $|\psi|$;

(b) The coefficient μ is a function of drain voltage;

(c) The distance $x_\bullet$ depends on drain voltage (see Fig. 1);

(d) Equation (5) holds for the current in the middle of the channel. In actual case, the major part of current flows in the middle of the channel, where the barrier height is the lowest, but with increasing transistor current part of this current flows on the channel side where the barrier height is larger. One can conclude that because of this current spreading effect the effective barrier height is slightly increasing with current.
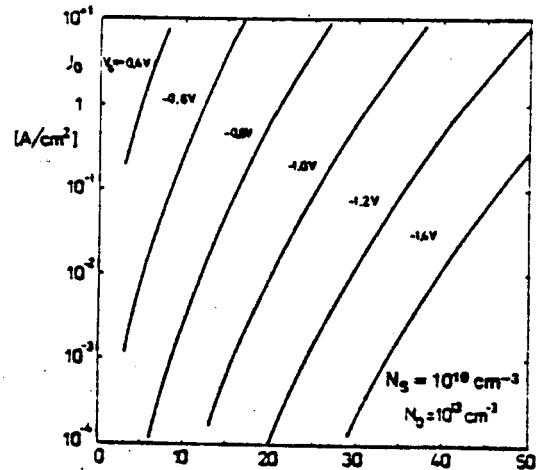

Fig. 3. J_D vs V_D calculated for a model presented at Fig. 1.

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