Computer-Aided Analysis of Surface-State Effects on Kink Phenomena in GaAs MESFETs

K. Horio and A. Wakabayashi

Faculty of Systems Engineering, Shibaura Institute of Technology
307 Fukasaku, Omiya 330-8570, JAPAN
E-mail:horio@sic.shibaura-it.ac.jp

Abstract — **Effects of surface states on kink phenomena in GaAs MESFETs are studied by two-dimensional (2-D) DC and transient simulation including impact ionization of carriers. The Spicer's unified defect model is adoped for a surface-state model. It is shown that a kink in the DC current-voltage characteristics could arise due to a space-charge effect originated from impact ionization of holes and the following hole capturing by the surface traps. Transient or dynamic simulation indicates that the trap-related kink phenomenon is a rather slow process.**

I. INTRODUCTION

To understand drain-to-source breakdown in GaAs MESFETs is important for realizing high-performance microwave power devices and ICs. In relation to this, an abnormal increase in output conductance with the drain voltage ("kink") is often observed at relatively low voltages. Because the kink in GaAs MESFETs was correlated to so-called a backgating effect [1], the kink was discussed in terms of impact ionization and substrate-related effects [2],[3]. The surface conditions should also affect the breakdown and the kink phenomena. However, few works have been reported on how the surface properties affect the kink phenomena in GaAs MESFETs.

So, in this work, we have made systematic 2-D simulation of GaAs MESFETs including surface states, and found that the kink could arise due to impact ionization and surface-state effects. In addition, we describe dynamic behavior of the kink phenomena in GaAs MESFETs, which has been scarcely reported in the literature.

II. PHYSICAL MODEL

Fig.1 shows device structure analyzed here. As a surface-state model, we adopt the Spicer's unified defect model [4], and assume that the surface states consist of a pair of deep donor and deep acceptor. As to their energy levels, we consider the following two cases based on experiments:

a) Sample 1: $E_{SD} = 0.925$ eV, $E_{SA} = 0.8$ eV [4],
b) Sample 2: $E_{SD} = 0.87$ eV, $E_{SA} = 0.7$ eV [5].

Here, E_{SD} is energy difference between the bottom of conduction band and the deep donor's energy level, and E_{SA} is energy difference between the deep acceptor's energy level and the top of valence band. The surface states are assumed to distribute uniformly within 5 Å from the surface and their densities (N_{SD}, N_{SA}) are typically set to 10^{13} cm^{-2} (2×10^{20} cm^{-3}). According to a previous work [6] where impact ionization is not included, the deep acceptor mainly determine the surface Fermi level, and it acts as an electron trap for Sample 1 and as a hole trap for Sample 2. To concentrate on surface-state effects, we mainly treat a perfectly insulating substrate here.

Basic equations to be solved are the Poisson's equation, continuity equations for electrons and holes, and rate equations for the deep levels. They are expressed as follows.

a) Poisson's equation

$$\nabla^2\psi = -\frac{q}{\varepsilon}(p - n + N_D - N_A + N_{SD}^+ - N_{SA}^-) \qquad (1)$$

b) Continuity equations for electrons and holes

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n + G - (R_{n,SD} + R_{n,SA}) \qquad (2)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot J_p + G - (R_{p,SD} + R_{p,SA}) \qquad (3)$$

where

$$R_{n,SD} = C_{n,SD}N_{SD}^+ n - e_{n,SD}(N_{SD} - N_{SD}^+) \qquad (4)$$

$$R_{n,SA} = C_{n,SA}(N_{SA} - N_{SA}^-)n - e_{n,SA}N_{SA}^- \qquad (5)$$

$$R_{p,SD} = C_{p,SD}(N_{SD} - N_{SD}^+)p - e_{p,SD}N_{SD}^+ \qquad (6)$$

$$R_{p,SA} = C_{p,SA}N_{SA}^- p - e_{p,SA}(N_{SA} - N_{SA}^-) \qquad (7)$$

c) Rate equations for the deep levels

$$\frac{\partial}{\partial t}(N_{SD} - N_{SD}^{+}) = R_{n,SD} - R_{p,SD} \tag{8}$$

$$\frac{\partial}{\partial t}N_{SA}^{-} = R_{n,SA} - R_{p,SA} \tag{9}$$

where N_{SD}^{+} and N_{SA}^{-} represent the ionized densities of surface deep donors and surface deep acceptors, respectively. C_n and C_p are the electron and hole capture coefficients of the deep levels, respectively, e_n and e_p are the electron and hole emission rates of the deep levels, respectively, and the subscript (SD, SA) represents the corresponding deep level. These capture coefficients and emission rates are given as functions of capture cross-sections and energy levels of the deep levels [7]. G represents the carrier generation rate by impact ionization, and is expressed as

$$G = (\alpha_n|J_n| + \alpha_p|J_p|)/q \tag{10}$$

where α_n and α_p are ionization rates for electrons and holes, respectively and given by [8]

$$\alpha_n = A_n \exp\{-(B_n/|E|)^{1.6}\} \tag{11}$$

$$\alpha_p = A_p \exp\{-(B_p/|E|)^{1.75}\} \tag{12}$$

where E is the electric field. $A_n = 2.994 \times 10^5$ cm^{-1}, $A_p = 2.215 \times 10^5$ cm^{-1}, $B_n = 6.848 \times 10^5$ V/cm, and $B_p = 6.570 \times 10^5$ V/cm [8].

The above basic equations are put into discrete forms and are solved numerically.

III. RESULTS AND DISCUSSIONS

A. I-V Characteristics

Fig.2 shows a comparison of calculated drain characteristics with and without impact ionization. Three cases without surface states and with different kinds of surface states (Sample 1 and Sample 2) are shown. In a case without surface states, an increase in the drain current due to impact ionization is seen around $V_D = 6$ V. This is originated from an increase in the gate current itself due to genarated holes. On the other hand, for the Sample 1 and Sample 2 cases, the drain currents increase due to impact ionization around $V_D = 5$ V and 11 V, respectively, but the gate currents are lower than the drain currents by over two or three orders of magnitude. Therefore, a space-charge effect originated from carrier capturing by surface traps seems to be a cause of the current rise or the kink in these cases.

Fig.3 shows potential profiles (at $V_D = 8$ V) for the Sample 1 case with impact ionization. The drain voltage is applied along the drain side of the gate, and hence electrons and holes are generated there. From Fig.4, we interprete that the deep acceptors (electron trap) capture electrons and the deep donors capture holes. But the increase in positive space-charges is larger, and hence the net negative charges at the surface decrease, resulting in the observed kink. Fig.5 shows a comparison of potential profiles (at $V_D = 11$ V) for the Sample 2 case with and without impact ionization. Without impact ionization, the drain voltage is applied along the interface between drain electrode and surface-state layer in this hole-trap case [6]. With impact ionization, generated holes at the drain edge are captured by deep acceptors, and hence the potentials become applied along the surface-state layer between gate and drain. Therefore, the onset voltage for current rise ($\sim$ 11 V) becomes higher in this case.

B. Transient Behavior

Next, we describe transient behavior including the kink region. Fig.6 shows drain current responses when the drain voltage steps abruptly from 0 to 8 V. Without surface states, the drain current reaches the steady-state value around 10^{-11} s, indicating that impact ionization itself is a fast phenomenon. On the other hand, for the Sample 1 case, the drain current remains a low value for some time and begins to increase slowly around 10^{-5} s (with impact ionization) or 10^{-2} s (without impact ionization). These slow transients are attributed to slow responses of the surface traps. As is understood from Fig.7, the increase in drain current starts due to electron emission from the deep acceptors (without impact ionization) or hole capturing by the deep donors (with impact ionization).

Finally, we describe current-voltage characteristics when the drain voltage is swept with different speeds. Fig.8 shows the drain characteristics for the Sample 1 case when the drain voltage is changed with sine waves. The parameter is the period. It is understood that the trap-related kink phenomenon is a rather slow process (and the characteristics are correlated to the transient behavior shown in Fig.6). This type of kink dynamics is also reported recently in an experimental work on InAlAs/InGaAs HEMTs [9].

IV. CONCLUSION

Our 2-D simulation has indicated that the kink in GaAs MESFETs could arise due to impact ionization and carrier capturing by the surface states. The onset voltage for current rise depends on the nature of surface states. It is also shown that the kink due to surface states is a rather slow process with long response time.

V. REFERENCES

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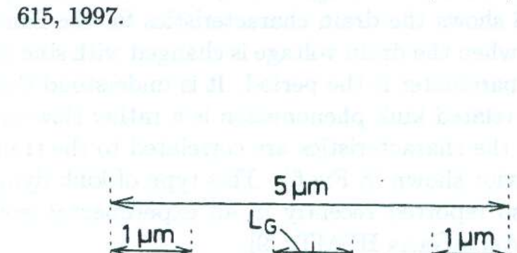

Figure 1: Device structure analyzed in this study.

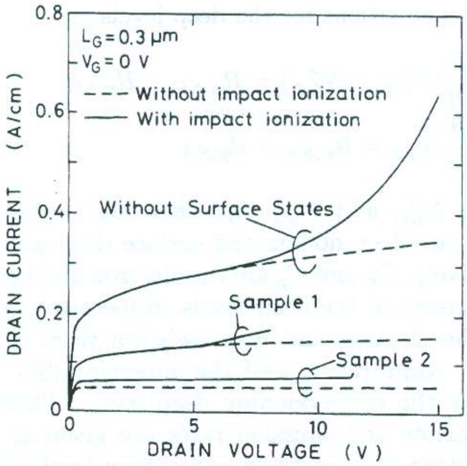

Figure 2: Calculated I_D - V_D curves with and without surface states.

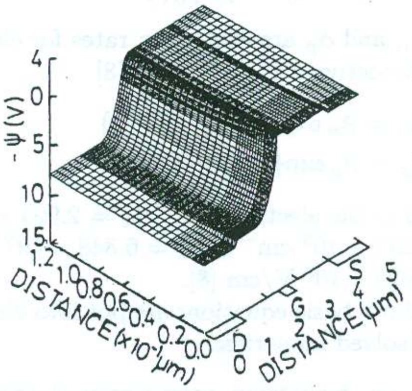

Figure 3: Potential profiles for the Sample 1 case (with impact ionization). $V_G = 0$ V and $V_D = 8$ V.

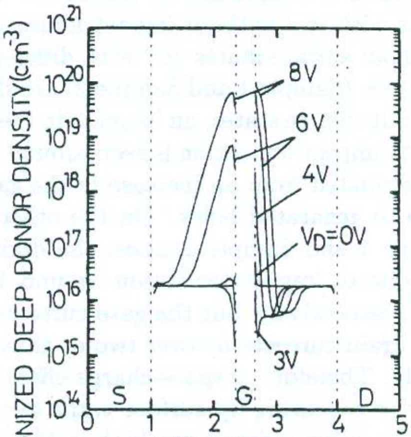

Figure 4: Ionized deep-donor density N_{SD}^{+} along the surface for the Sample 1 case (with impact ionization). $V_G = 0$ V.

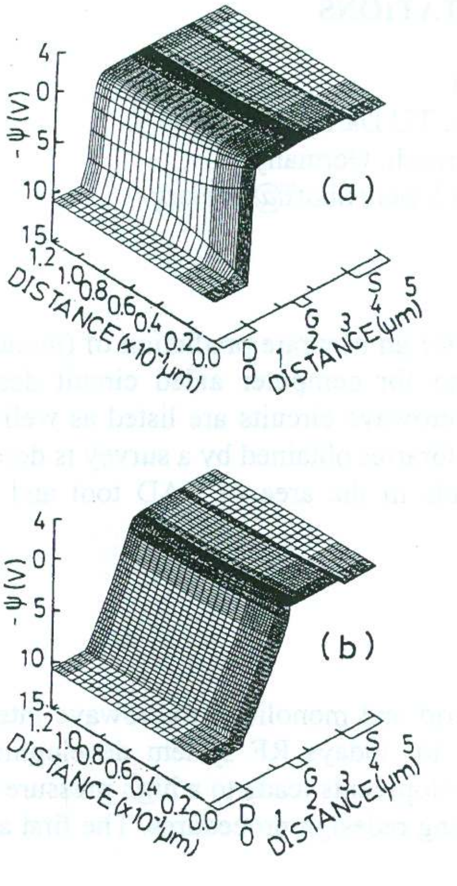

Figure 5: Potential profiles for the Sample 2 case. $V_G = 0$ V and $V_D = 11$ V. (a) without impact ionization, (b) with impact ionization.

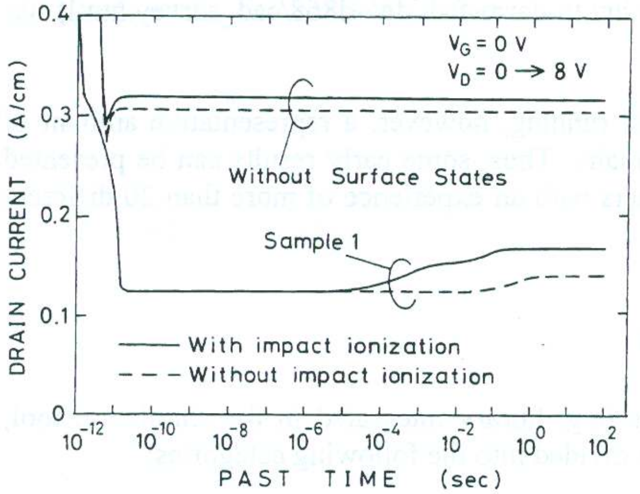

Figure 6: Responses of drain currents when V_D steps from 0 to 8 V. $V_G = 0$ V.

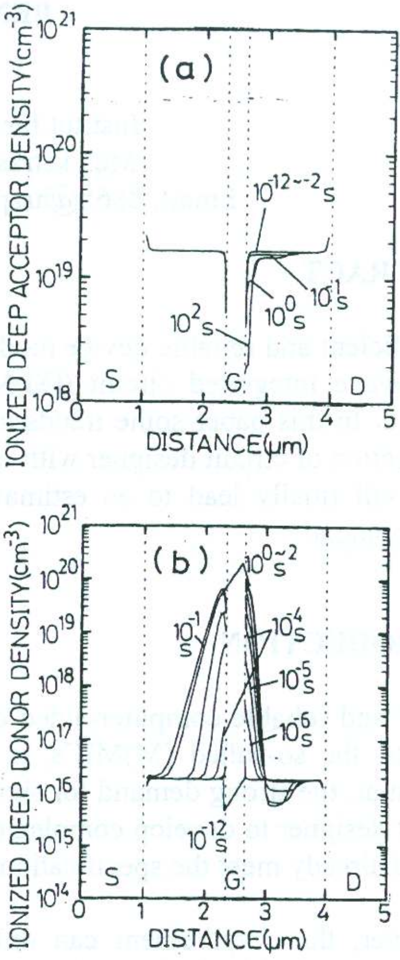

Figure 7: Ionized deep-level densities along the surface for the Sample 1 case, corresponding to Fig.6. (a) N_{SA}^- (without impact ionization), (b) N_{SD}^+ (with impact ionization).

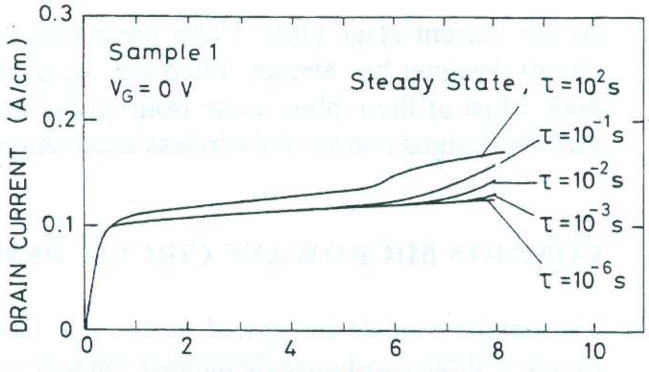

Figure 8: I_D - V_D curves for the Sample 1 case (with impact ionization) when V_D is changed with sine waves. τ is the period.