Two-Dimensional Simulation of Surface-State Effects on Breakdown Characteristics of Narrowly-Recessed-Gate GaAs MESFETs

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ABSTRACT

Effects of surface states on breakdown characteristics of narrowly-recessed-gate GaAs MESFETs are studied by two-dimensional simulation. Particularly, it is discussed how the characteristics depend on the surface-state densities and on the recess structure parameters. It is shown that the breakdown voltage could be raised when moderate densities of surface states are included. However, it is suggested that in a case with relatively high densities of surface states, the breakdown voltage could be drastically lowered by introducing a narrowly-recessed-gate structure.

Keywords: GaAs MESFET, surface state, breakdown characteristics, recessed-gate structure, 2D simulation

1 INTRODUCTION

Understanding high-voltage phenomena in GaAs MESFETs and HEMTs, such as drain-to-source breakdown, is very important for realizing high-performance microwave power devices and ICs, which are now receiving great interest particularly for mobile communication applications. To achieve high breakdown voltages, so-called a recessed-gate structure has been utilized [1], where the existence of surface depletion layer due to surface states is regarded as an origin of the high breakdown voltage. On the contrary, recently, the (narrowly) recessed-gate structure is used to reduce surface-state-related anomalies such as frequency-dependent transconductance and gate-lag [2]-[5]. So, in this work, to clarify recess effects and surface-state effects on the breakdown phenomena, we have made two-dimensional simulation of narrowly-recessed-gate GaAs MESFETs including surface states, and found that the breakdown voltage could be rather lowered in some cases by introducing the recess structure.

2 PHYSICAL MODEL

Fig.1 shows a modeled device structure analyzed here. The surface states are considered on the planes between source and gate and on the planes between gate and drain. As a surface-state model, we adopt Spicer's unified defect model [6], and assume that the surface states consist of a pair of a deep donor and a deep acceptor. As to their energy levels, the following case based on experiments is considered as in previous works [4],[7]: E_{SD} = 0.87 eV, E_{SA} = 0.7 eV [8],[9]. 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} (2x10^{20} cm^{-3}).

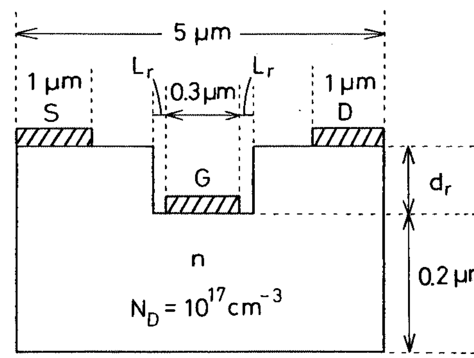

Fig.1 Modeled recessed-gate GaAs MESFET analyzed here.

Basic equations to be solved are Poisson's equation, continuity equations for electrons and holes and rate equations for the deep levels [4],[7]. They are expressed as follows.

1) Poisson's equation

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

2) Continuity equations for electrons and holes

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

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

where

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

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

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

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

3) 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 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. (Only) in the steady state, $R_{n,SD} = R_{p,SD}$ and $R_{n,SA} = R_{p,SA}$, and these carrier-loss rates can be expressed as normal recombination-rate form like

$$\frac{pn - n_i^2}{\tau_p (n + n_1) + \tau_n (p + p_1)}$$

where τ_n and τ_p are the electron and hole life times, respectively, n_1 and p_1 are the electron and hole densities when the Fermi level is equal to the deep-level energy. In Eqs.(2) and (3), G represents a carrier generation rate by impact ionization, and is expressed as

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

where α_n and α_p are ionization rates for electrons and holes, respectively, and are given by [10]

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

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

where E is the electric field. A_n = 2.994x10^5 cm^{-1}, A_p = 2.215x10^5 cm^{-1}, B_n = 6.848x10^5 V/cm and B_p = 6.570x10^5 V/cm [10].

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

3 BREAKDOWN CHARACTERISTICS

3.1 Surface-State Effects

Fig.2 shows calculated drain characteristics of a narrowly-recessed-gate GaAs MESFET without surface states, where the recess depth d_r is 0.1 μm and the distance between the gate and the recess edge L_r is 0.1 μm. The solid lines are calculated by considering impact ionization of carriers, and the dashed lines are calculated by neglecting it. The drain currents increase steeply around V_D = 7 V due to impact ionization. This is due to an increase in the gate current itself due to generated holes between the gate and drain region.

Fig.3 and Fig.4 show calculated drain characteristics of the same recessed-gate GaAs MESFET (as in Fig.2: d_r = 0.1 μm, L_r = 0.1 μm) with surface states, which densities are 10^{12} cm^{-2} and 10^{13} cm^{-2}, respectively. With relatively low surface-state densities of 10^{12} cm^{-2} or 2x10^{19} cm^{-3} (Fig.3), the characteristics show a slight kink around V_D = 3 V and a clear increase in drain currents (breakdown) beyond V_D = 10 V, which is higher than in Fig.2. The kink is attributed to a space-charge effect originated from (generated) hole capturing by surface states around the gate, the detail of which was described in [7]. On the other hand, with high surface-state densities of 10^{13} cm^{-2} or 2x10^{20} cm^{-3} (Fig.4), a steep increase in drain currents (breakdown) occurs at as low as V_D = 3 ~ 4 V. We will further discuss the last case below by describing the dependence of breakdown characteristics on the recess parameters (L_r, d_r).

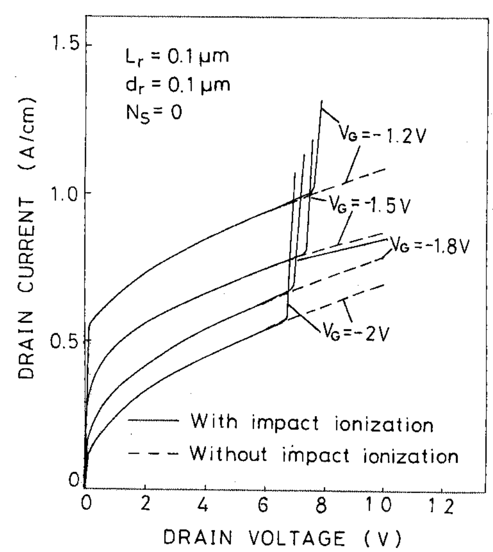

Fig.2 Calculated drain characteristics of a recessed-gate GaAs MESFET. Surface states are not included.

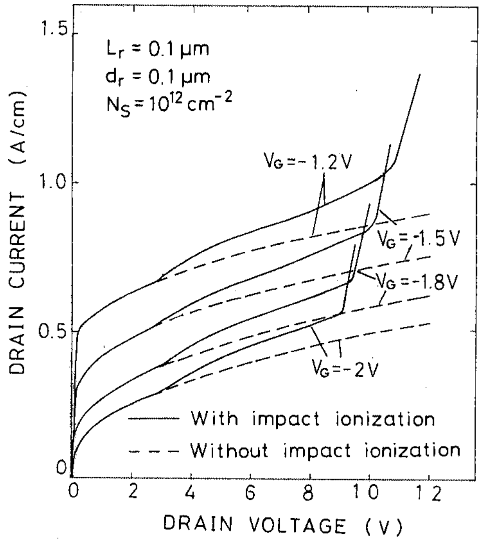

Fig.3 Calculated drain characteristics of a recessed-gate GaAs MESFET with low surface-state densities of 10^{12} cm^{-2}.

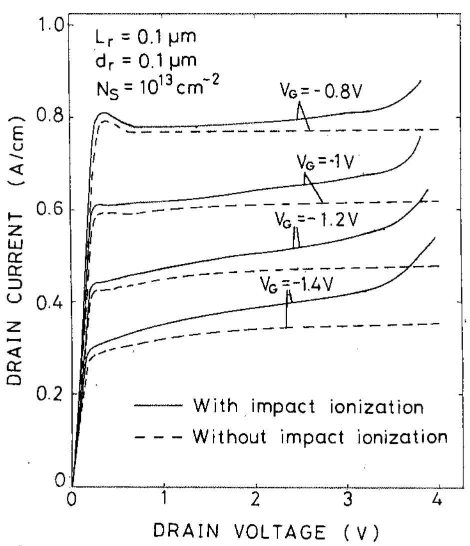

Fig.4 Calculated drain characteristics of a recessed-gate GaAs MESFET with high surface-state densities of 10^{13} cm^{-2}.

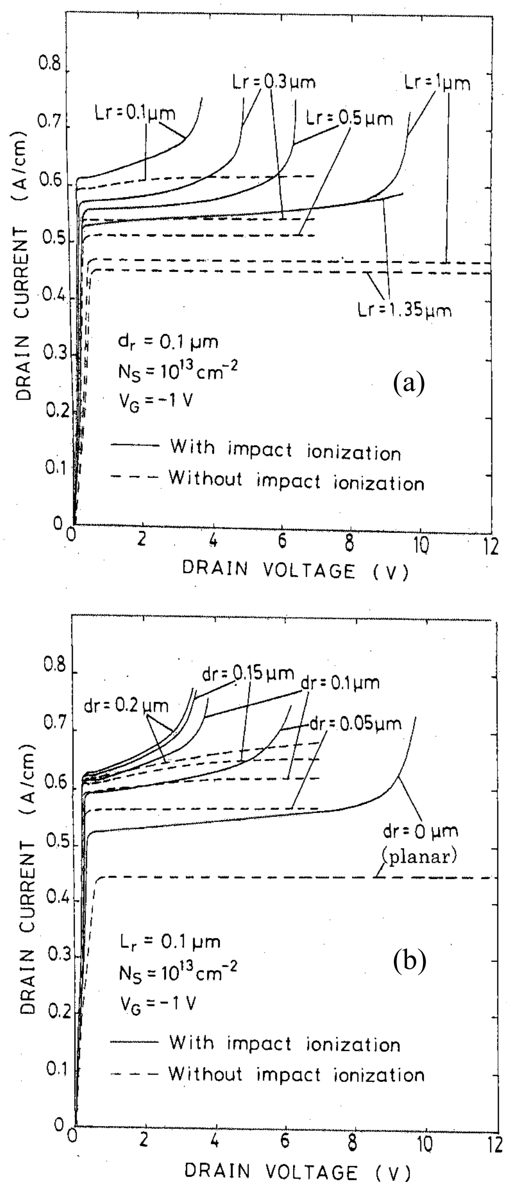

Fig.5 Calculated drain characteristics for the case of surface-state densities of 10^{13} cm^{-2}, as parameters of L_r ((a)) and d_r ((b)).

3.2 Recess-Structure Dependence

Fig.5 shows calculated drain characteristics of recessed-gate GaAs MESFETs (with surface-state densities of 10^{13} cm^{-2}) as parameters of the distance between the gate and the recess edge L_r ((a)) and the recess depth d_r ((b)). As L_r becomes longer, the steep increase in drain currents occurs at a higher drain voltage, that is, the breakdown voltage becomes higher, which can be naturally understood. On the other hand, we also see that as d_r becomes deeper, the breakdown voltage becomes lower than that for the planar structure (d_r = 0 μm), indicating that the breakdown voltage becomes low by introducing a recessed-gate structure. We will discuss below why this happens.

Fig.6 shows a comparison of potential profiles between (a) planar structure and (b) narrowly-recessed-gate structure (L_r = 0.1 μm, d_r = 0.1 μm). In the planar structure, the drain voltage is almost uniformly applied between the gate and the drain (1.35 μm). But in the recessed-gate structure, the voltage drop between the gate and the recess edge (0.1 μm) is quite large, which is a cause of the lower breakdown voltage (3 ~ 4 V).

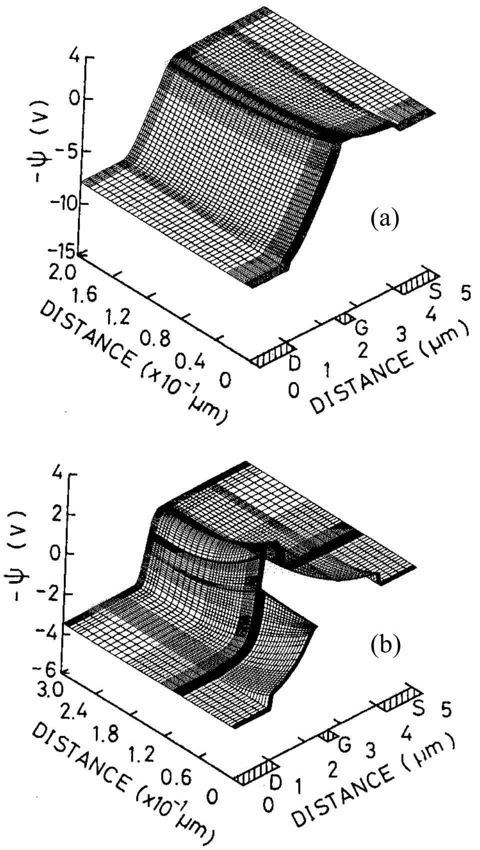

Fig.6 Comparison of potential profiles of GaAs MESFETs with surface-state densities of 10^{13} cm^{-2}. (a) planar structure (V_D = 8 V, V_G = - 1 V), (b) recessed-gate structure with L_r = 0.1μm and d_r = 0.1μm (V_D = 3.5 V, V_G = - 1 V).

4 CONCLUSION

Two-dimensional analysis of breakdown characteristics in narrowly-recessed-gate GaAs MESFETs has been performed considering surface-state effects. It has been shown that the breakdown voltage could be raised when moderate densities of surface states are included. However, it is suggested that in the case with relatively high densities of surface states, the breakdown voltage could be drastically lowered when introducing the narrowly-recessed-gate structure.

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