Tayloring the Breakdown Voltage in High Electron Mobility Transistor: Theoretical and Experimental Results

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In this paper the effect of a body contact to increase the breakdown voltage in GaAs based pseudomorphic HEMT has been theoretically investigated. The body contact is formed by a p-doped substrate connected to an ohmic back contact. By using a Monte Carlo simulation we show that the body contact reduces the density of holes generated by impact ionization and prevents holes from accumulating in the channel. 'The breakdown effect is quenched as the density of acceptors in the substrate increases. This extends the range of the usable drain voltages.

I. INTRODUCTION

Commercial and military applications require power amplifiers capable of delivering frequencies approaching the X-band. The relatively low breakdown voltage in GaAs and InP-based high mobility electron transistors limits the maximum output power levels at these frequencies. Several studies have been reported in order to extend the usable drain voltage. In a theoretical work David et al [l] have reported that the presence of the strained InGaAs increases the breakdown voltage. Recent experimental works by Brar et al [2] and Suemitsu et al [3,4] have shown that a p-doped buffer prevents holes generated by impact ionization from accumulating in the channel, resulting in higher breakdown voltage and kink suppression. It has been demonstrated that under near breakdown condition i) accumulation of holes generated by impact ionization takes place in the gate source channel region, and, in the lower layer and substrate; ii) holes injected into the substrate have the most dramatic effect on drain current I_D ; iii) accumulation of holes and the increase of I_D are correlated [5]. In this paper we present a Monte Carlo investigation of the effect of a body contact, namely to increase the breakdown voltage in pseudomorphic HEMTs.

II. SAMPLE DESCRIPTION AND CALCULATED RESULTS

A 2D self-consistent Monte Carlo code, accounting for 3 conduction valleys and 3 valence bands has been applied. The Poisson equation is solved by applying a multi-grid technique [6]. The impact ionization has been described by a modified Kane model [7].

The general-purpose weighted Monte Carlo procedure presented in [7] has been adopted to achieve a correct description of the physics of HEMT breakdown. We simulated a 250 nm double heterojunction pseudomorphic $Al_{0.22}GaAs/In_{0.15}GaAs/GaAs$ HEMT whose schematic cross section is sketched in Fig.1. The body contact is formed by an ohmic back contact which extend over the whole bottom of the device and a heavily p-type doped substrate with acceptor density N_A. The device is simulated at a temperature of 300 K. We have performed different simulations in order to analyse the impact of the body contact on the behaviour of carriers and the electrical drain current at breakdown conditions. Starting point is a reference simulation without body contact, i.e. a HEMT with an undoped GaAs doped p-type substrate $N_A=2\times10^{14}$ cm $^{-3}$ and without back contact. In a second step we have simulated the HEMT with body contact and heavily p-doped substrate. Figure. 2a shows the energy band edge profiles obtained for the structure without body contact compared to the structure with body contact. By increasing N_A in the substrate, the body contact raises the potential valley and consequently the Fermi level and conduction band. Hence the density of energetic electrons in the channel is reduced as it can be seen in Fig. 2b. The density of holes generated by impact ionization is also decreasing (see Fig. 2c).

Based on these results, the drain current has been simulated in various situations to see the effect of the body contact at breakdown condition V_{DS}= 10V and pinched channel V_{GS}=-0.4V. For all calculations presented in this Fig. 3, the impact ionization process has been initiated 50 ps after the beginning of the simulation. As reference, we have simulated the drain current without back contact. The device is driven directly into breakdown. By considering the body contact and increasing N_A, breakdown is avoided and the drain current reaches a new steady state. Indeed, the higher N_A is chosen the shorter is the transient time. It takes 50 ps with N_A=3x10^{18} cm^{-3} rather than 250 ps with N_A=1x10^{18} cm^{-3} to reach a steady state after initiating the impact ionization. The drain current is sharply reduced from 1100 to 500 mA/mm.

As it can be seen in Fig. 3 in the first 50 ps before the impact ionization the body contact induces a lower drain current with respect to the reference case. We have estimated that the gate bias corresponding to this current is -0.7 V. This gap can be justified by the evolution of the energy band edge showed in Fig. 2a. To verify this we have simulated the device without body contact for V_{DS}=10 V, V_{GS}=-0.7 V (long dashed line in Fig. 3). Its evolution confirms that the device is in breakdown condition.

Moreover the effect of the body contact on the dynamic evolution of holes generated by impact ionization in the high electric field region of the HEMT has been investigated. Figures 4 and 5 present the hole density at 100 ps and 200ps after initiating the impact ionization for the HEMT without and with body contact, respectively. Figure 5 shows that holes generated by impact ionization in the channel between the gate and the drain contact follow three paths as it has been demonstrated in [5]. The density of holes in the substrate is 3x10^{18} cm^{-3} because of N_A. Moreover the accumulation regions in the gate source channel and in the lower layer are not as large and important as those in Figure. 4. Thus the body contact reduces the extent the hole accumulation.

Figure. 6 presents the I/V characteristics of the HEMT with and without body contact obtained at room temperature for V_{GS}=-0.4 V. Without body contact the drain current shows a quick increase and goes directly to breakdown for V_{DS}>6V. By considering the body contact, the slope of the drain current decreases with increasing N_A .

In conclusion, a pseudomorphic HEMT with a body contact has been investigated by Monte Carlo method. We have shown that the body contact prevents holes from accumulating in the substrate, and dramatically improves the breakdown behaviour, and increases the range of usable voltages.

III. ACKNOWLEDGEMENTS

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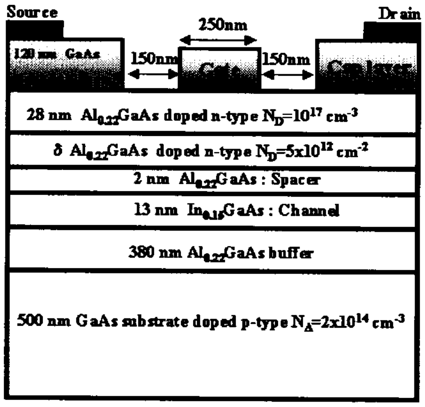

`FIG. 1. Schematic cross-section of the pseudomorphic HEMT.

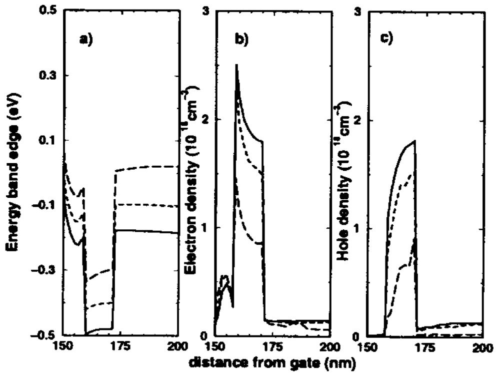

FIG. 2. Calculated a)energy band edge profile b)electron density c)hole density at V_{DS}=l0 V and V_{GS}=-0.4 V. Without body contact (continuous line). With body contact (dashed line, $N_A=2x10^{18}$ cm $^{-3}$, and long dashed, $N_A=3x10^{18}$ cm $^{-3}$)

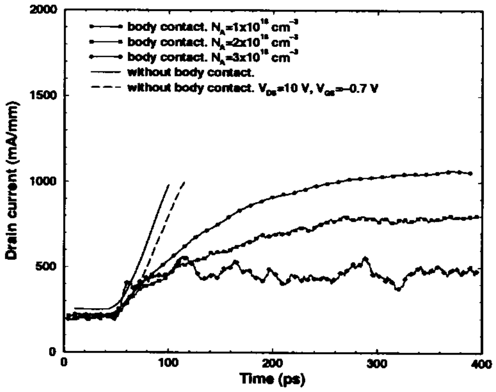

FIG. 3. Simulated dependence time of drain current for HEMT obtained at V_{DS}=l0 V, V_{GS}=-0.4 V. (except long dasheh line)

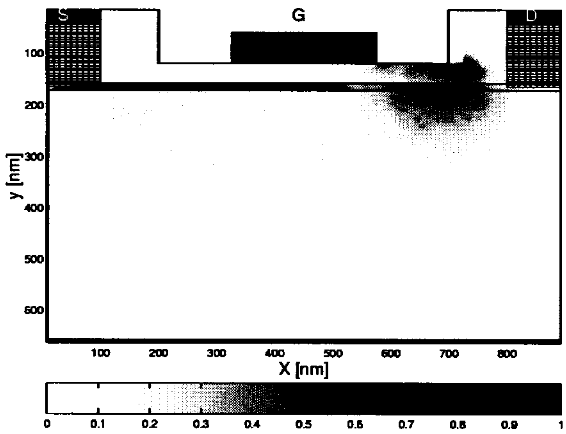

FIG. 4. Holes density at 100ps after switching-on the impact ionization in HEMT without body-contact. V_{DS}=l0 V, V_{GS}=-0.4 V. Scale in 10^{18} cm^{-3}

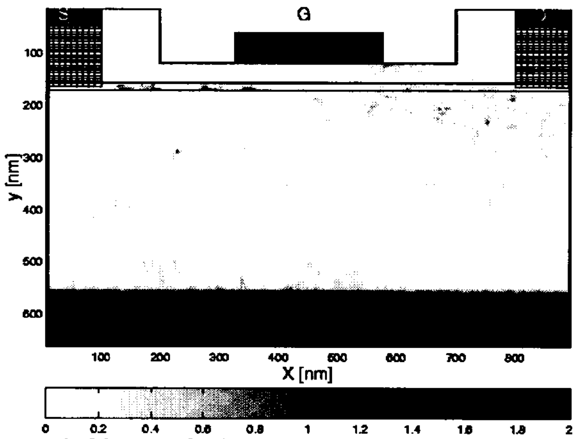

FIG. 5. Hole density 200 ps after switching on the impact ionization in HEMT with body-contact $N_A=3x10^{18}$ cm^{-3}. V_{DS}=l0 V, V_{GS}=-0.4 V. Scale in 10^{18} cm^{-3}

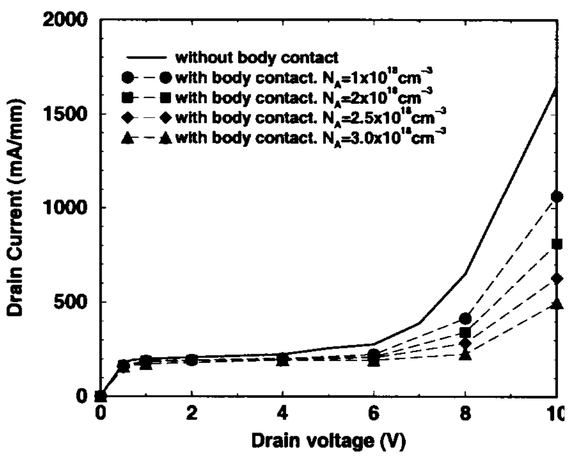

FIG. 6. Simulated HEMT characteristics for V_{GS} =-0.4 V.