Impact Ionization in GaAs MESFET's

KELVIN HUI, CHENMING HU, SENIOR MEMBER, IEEE, PETER GEORGE, AND PING K. KO

Abstract—**A method to measure impact ionization current in GaAs MESFET's is presented. The impact ionization current is then used to calculate the maximum electric field in the channel and the impact ionization coefficient. Data for the electron impact ionization coefficient in ⟨110⟩ GaAs are extended beyond previous studies by five orders of magnitude. Impact ionization is taken into account in a new gate current model.**

I. INTRODUCTION

THE understanding of impact ionization in GaAs MESFET's is important for both device degradation and breakdown studies. Since the number of electron–hole pairs generated by impact ionization is proportional to the product of the ionization coefficient and the carrier concentration, both mobile carriers and a strong electric field are required for impact ionization to occur. In MESFET's, impact ionization will occur at the field singularity at the drain edge of the gate where the electric field is highest [1], [2] or inside the high-field domain along the conduction channel where the electric field is high and current density highest. The site where impact ionization occurs first is bias and technology dependent. The effect of surface states in GaAs in suppressing the electric field at the field singularity point has been studied [3]. In general, the singularity at the drain edge of the gate determines the drain breakdown voltage when the MESFET channel is pinched off, whereas impact ionization along the channel current path is responsible for the weak impact ionization current with the channel open.

A knowledge of the electric field distribution along the conduction path is essential for the study of impact ionization. However, due to the negative differential mobility of electrons in GaAs at high electric fields, an accurate and analytic electric field model is still unavailable today. As the impact ionization coefficient is exponentially proportional to the negative inverse of the electric field, a small error in the estimation of the electric field will result in a large error in the calculation of the ionization rate. The limited experimental data on electron impact ionization rate, especially in the ⟨110⟩ direction in which most MESFET's are fabricated, has rendered both modeling and simulation of impact ionization difficult.

Accurate models for the channel electric field and impact ionization current (substrate current) have been developed for Si MOSFET's in recent years [4], [5]. The measurement of impact-ionization-generated substrate current has become the most convenient and effective means of characterizing hot-carrier phenomena in Si MOSFET's and has yielded the low-field impact ionization coefficient. In this paper we will examine the feasibility of extending these models to GaAs MESFET's.

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The authors are with the Electronics Research Laboratory and the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720.

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II. THEORY

The holes generated by impact ionization along the channel current path will follow the electric field lines and be collected at either the gate or source electrode. Two-dimensional (2-D) device simulations indicate that due to the proximity of the gate to the site of impact ionization, most of the holes are swept towards the gate by the electric field lines. This is true even for enhancement-mode MESFET's where the gate is biased positively. Hence, for simplicity, we shall assume the gate collection efficiency to be unity.

The weak (subbreakdown) impact ionization current I_{hole} in an n-MESFET is given by

$$I_{\text{hole}} = W \times \int_0^{L_g} \int_0^a q\alpha_n(E) n v_{\text{sat}}\, dx\, dy \tag{1}$$

where W is the gate width, L_g is the channel length, a is the channel depth, $\alpha_n(E)$ is the field-dependent impact ionization coefficient, n is the electron concentration, and v_{sat} is the saturation velocity. Since the ionization coefficient is exponentially proportional to the negative inverse of the electric field, it can be shown that most of the impact ionization occurs around the region with maximum electric field ($E_{\max}$). Thus (1) can be approximated [5] as

$$I_{\text{hole}} \approx \alpha_n(E_{\max}) \times I_{ds} \times l \tag{2}$$

where I_{ds} is the drain-to-source current and l is the characteristic length of the high-field region.

It has been shown analytically and through simulations that the peak electric field in the pinch-off region in Si MOSFET's can be expressed as

$$E_{\max} = \frac{(V_{ds} - V_{d\,\text{sat}})}{l} \tag{3}$$

when the drain-to-source voltage V_{ds} is greater than the saturation voltage $V_{d\,\text{sat}}$ by about 2 V [5]. The simple interpretation is that $V_d - V_{d\,\text{sat}}$ is the potential drop in the pinch-off region and l is the effective length of the pinch-off region. The effective length l is independent of bias voltages and channel length and depends only on the vertical (thickness) dimension of the transistor [5]. Fig. 1 shows the variation of

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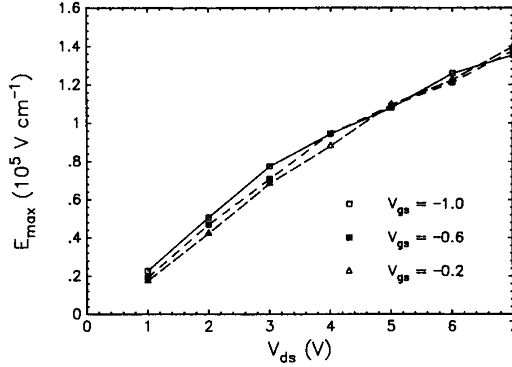

Fig. 1. Maximum channel electric field $E_{\max}$ versus the drain-source voltage V_{ds} obtained by 2-D simulation [6] of a 0.5-μm planar GaAs n-MESFET. The characteristic length l obtained from the reciprocal of the slope is approximately 0.36 μm. The intercepts on the abscissa correspond to the saturation voltages $V_{d\,\mathrm{sat}}$.

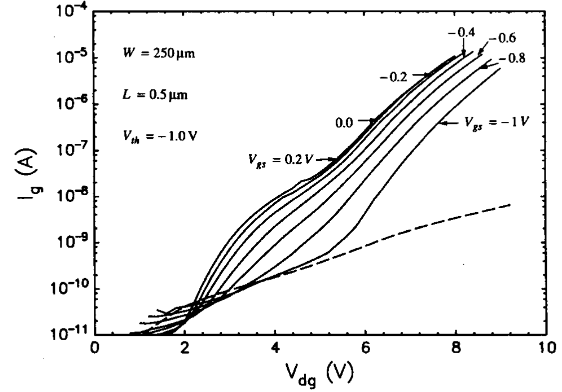

Fig. 2. Gate current I_g versus drain-to-gate voltage V_{dg} for different gate-to-source biases. V_{gs} varies from -1.0 to 0.2 V in steps of 0.2 V. The drain-to-gate Schottky leakage current with the source floating (dashed line) is included for comparison.

maximum channel electric field $E_{\max}$ versus V_{ds} obtained by 2-D simulation [6]. The MESFET is modeled with $L_g = 0.5$ μm, gate-source spacing $L_{gs} = 0.25$ μm, gate-drain spacing $L_{gd} = 0.5$ μm, and a channel-substrate junction at 0.25 μm. The Gaussian channel implant has a peak concentration of 2.5×10^{17} cm^{-3} at the surface and the uniform p-type substrate doping concentration is equal to 4×10^{15} cm^{-3}. $E_{\max}$ is seen to increase approximately linearly with V_{ds} in agreement with (3). The lines extrapolate to $E_{\max} = 0$, yielding $V_{d\,\mathrm{sat}} \approx 0.4$ V and $l \approx 0.36$ μm. For comparison, a typical value for l in Si MOSFET's is 0.25 μm.

The effective length l increases with the length of the lightly doped drain (LDD) region and the distance between the gate electrode and channel electrons (gate oxide thickness in Si MOSFET's). A larger l is to be expected for GaAs MESFET's since this distance, approximately equal to the channel thickness, is larger than that in Si MOSFET's even after correcting for the difference in material permittivities. The larger gate-drain spacing in GaAs MESFET's will also result in a larger l. The validity of (3) for GaAs MESFET's is not surprising considering the short transit time through the pinch-off region. This makes the analogy between GaAs MESFET's and Si MOSFET's even more obvious. The gate current I_g is given by

$$I_g(V_{gs}, V_{gd}) = I_{\mathrm{hole}}(I_{ds}, V_{ds}) + I_{\mathrm{Schottky}}(V_{gs}, V_{gd}) \quad (4)$$

where I_{Schottky} is the usual reverse Schottky-gate leakage current. The ratio of I_{hole} to I_{ds} is then obtained from (2) and (3) as

$$\frac{I_{\mathrm{hole}}}{I_{ds}} = \alpha_n \left(\frac{V_{ds} - V_{d\,\mathrm{sat}}}{l} \right) \times l. \quad (5)$$

III. Experimental Results and Discussions

The gate leakage current I_{Schottky} is conventionally obtained by adding the gate-drain and gate-source Schottky-diode reverse leakage currents obtained by two-terminal measurements. However, this method has its deficiencies. When the source is floating, the gate-source potential difference will be approximately equal to V_{gd}. This is much higher than the value in normal FET operation ($V_{gs} \approx 0$). Using this method, the sum of the gate-source and gate-drain diode leakage currents measured individually can be much larger than the actual gate leakage under normal bias. A more accurate value of gate-drain leakage current is obtained by biasing the MESFET in the pinch-off region and subtracting the gate-source leakage from the measured gate current. In pinch-off the drain current is very small and so is the contribution to gate current by impact ionization. The electric field distribution, on the other hand, will resemble that under normal FET bias. In our measurements we set V_{gs} to 1.4 times the threshold voltage.

Fig. 2 shows the gate current of a depletion-mode 250-μm $\times$ 0.5-μm ion-implanted recessed-gate GaAs MESFET measured at different gate and drain biases. The channel was formed by a 50-keV Si implant into a Cr-doped HB substrate, with dose $\phi = 10^{13}$ cm^{-2}. The nominal L_{gs} and L_{gd} values are 0.25 and 0.5 μm, respectively. The impact ionization current I_{hole} is obtained by subtracting I_{Schottky} from I_g according to (4). I_{hole} increases rapidly with V_{ds} and is often many orders of magnitude higher than I_{Schottky}. It is also a function of V_{gs} since it is dependent on I_{ds} (see (2)).

Fig. 3 shows the normal I_{ds} versus V_{ds} characteristics with superimposed constant I_{hole}/I_{ds} contours. According to (5), I_{hole}/I_{ds} is a unique function of $V_{ds} - V_{d\,\mathrm{sat}}$ since the characteristic length l is a constant. Thus these contours also represent constant $V_{ds} - V_{d\,\mathrm{sat}}$ contours. Indeed, the contours in Fig. 3 are found to be parallel to each other. When a contour is parallel shifted toward the origin, it gives a reasonable saturation voltage $V_{d\,\mathrm{sat}}$ contour. Experimental data shown in Fig. 4 demonstrate this behavior for different values of V_{gs}. Using (3) and (5), Fig. 4 can be replotted to yield a graph of ionization rate versus $1/E_{\max}$ as shown in Fig. 5. A value of 0.34 μm was chosen for the effective length l to translate $V_{ds} - V_{d\,\mathrm{sat}}$ into $E_{\max}$ according to (3) and make the α_n data match the impact ionization coefficient measured by Pearsall *et al.* [7] at high electric fields. This value of l is very close to the value of 0.36 μm obtained from Fig. 1.

Fig. 5 extends the α_n data range beyond what is available in the literature by five orders of magnitude. For electric fields

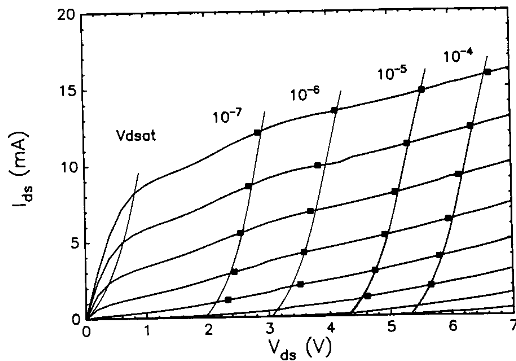

Fig. 3. Forward I_{ds} versus V_{ds} characteristics of a GaAs MESFET with superimposed constant I_{hole}/I_{ds} contours. The gate–source voltage ranges from −1.0 to 0.2 V in steps of 0.2 V. This ion-implanted 250-μm × 0.5-μm recessed-gate MESFET has a nominal V_t = −1.0 V.

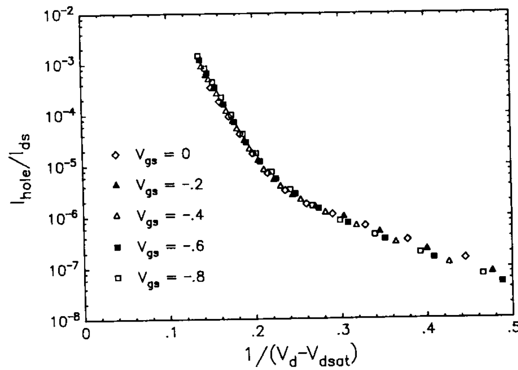

Fig. 4. I_{hole}/I_{ds} versus $1/(V_{ds} - V_{d\,sat})$ for different gate–source biases. The saturation voltages $V_{d\,sat}$ used for V_{gs} = 0, −0.2, −0.4, −0.6, and −0.8 V are 0.8, 0.6, 0.4, 0.2, and 0.1 V, respectively. The impact ionization current I_{hole} is obtained by subtracting the Schottky-gate leakage from the measured gate current (see (4)).

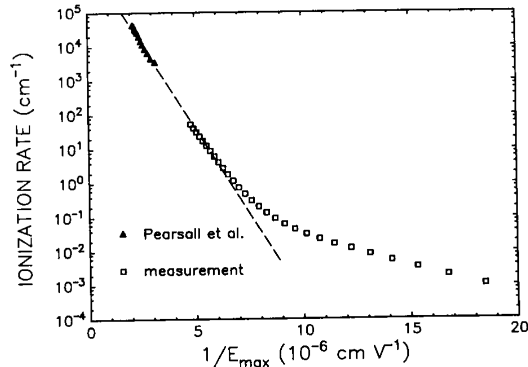

Fig. 5. Impact ionization coefficient in ⟨110⟩ GaAs plotted against the reciprocal of the electric field. The data from Pearsall *et al.* [7] are included for reference. The dashed line approximates the impact ionization coefficient at high electric fields (see (6)).

greater than approximately 1.5×10^5 V/cm, α_n can be fitted to the following equation:

$$\alpha_n = 4.0 \times 10^6 \times e^{-\frac{2.3 \times 10^6}{E}} \tag{6}$$

Below $\alpha_n = 0.1$ cm^{-1} and $E = 1.5 \times 10^5$ V/cm, α_n appears to decrease much less rapidly with decreasing E as if some energy-loss mechanism becomes less efficient at lower fields. More studies will be needed to verify and interpret this new observation.

IV. Conclusion

Two-dimensional device simulations show that the peak electric field along the channel current path in a GaAs MESFET increases linearly with V_{ds}, specifically $E_{max} = (V_{ds} - V_{d\,sat})/l$, where l is about 0.36 μm for a MESFET with 0.5-μm channel length. A technique was developed to measure the impact-ionization-generated hole current through gate current measurements. The electron impact ionization coefficient versus electric field was determined and found to match previously published data at high electric fields. We have also extended the $\alpha(E)$ data into the low-field regime by five orders of magnitude. Above 1.5×10^5 V/cm, α_n follows the $e^{1/E}$ relationship. Below 1.5×10^5 V/cm, α_n is less sensitive to E. That similar models apply to GaAs MESFET's and Si MOSFET's in the areas of channel field strength and impact ionization current should help further the understanding of hot-carrier phenomena in GaAs MESFET's.

Acknowledgment

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