Abstract

Two-dimensional computer simulations of charge collection phenomena in GaAs MESFETs have been performed for alpha and laser ionization. In both cases more charge is collected than is created by the ionizing event. The simulations indicate that a bipolar transport mechanism (t < 60 ps) and a channel modulation mechanism (t > 40 ps) are responsible for this enhanced charge collection.

I. INTRODUCTION

Previous studies examining single event charge collection in GaAs MESFETs have revealed enhanced charge collection, in which the drain charge collection can be as high as 8 times the amount of charge deposited in the device [1-4]. The understanding of these charge amplifying mechanisms requires correlation between experimental and simulation analysis. This work addresses the enhanced charge collection processes in buried p-layer GaAs MESFETs using a 2-dimensional carrier transport code.

Three mechanisms for enhanced charge collection in GaAs MESFETs have been suggested in the literature: (i) a backchannel turn on mechanism [4-7]; (ii) a bipolar source-drain, or bipolar gain mechanism [1-3]; and (iii) an ion shunt mechanism [8]. The "channel turn on" mechanism arises from reduction of the channel-substrate potential barrier's capability to confine electrons to the channel. The bipolar source-drain mechanism arises from a reduction of the source implant barrier, resulting in electron injection into the region between the source and drain, similar to the operation of a bipolar transistor. The ion-shunt effect [9,10] occurs when the ionization track intersects two regions of like carrier type with a potential difference between them, separated by a region of opposite carrier type. These mechanisms have been postulated to account for different experimental observations.

High speed measurements have been presented by McMorrow et al. [5,11,12] showing the dependence of the charge collection transients on gate and drain bias. Those results revealed the complex temporal signature that is associated with the drain charge-collection transients. The measured transients appear to consist of three dynamically distinct regions: an instrument limited decay (<50ps), followed by a relaxation with a time constant of approximately 150ps, and third, a slower decay of >1ns. That work also revealed a very sensitive dependence of the measured dynamics on the device bias conditions. In particular, it was observed that the amplitudes of the slower charge-collection contributions were significantly reduced as the gate was biased more negative. The slower components were most prevalent when the device was biased slightly above pinchoff, giving rise to the largest amount of collected charge. Those results suggest that the phenomena of enhanced charge collection in GaAs MESFETs, and their sensitivity to SEU, may be related to the slower mechanisms of the charge-collection process.

Researchers have investigated charge collection mechanisms via 2-Dimensional and 3-Dimensional modeling of the MESFET. Anderson et al. presented 2-D simulations on a depletion-MESFET device implanted into semi-insulating material [6]. The charge collection was attributed to a lowering of the substrate resistance and the opening of a current path around the gate depletion region. There was no attempt to compare results to experimental data. Moglestue et al. performed Monte Carlo calculations for alpha-particles incident on the MESFET. Those calculations illustrated the temporal evolution of an electron-hole plasma in the region of the ion strike, and a separation of electrons in space according to effective mass [13]. In Moglestue's simulation the drain-to-source voltage was zero with the gate biased negative. Therefore, because of the absence of a source-drain electric field, enhancement mechanisms due to transistor action are not expected between source and drain.

In this work we present a two-dimensional charge transport simulation of single event charge collection in an enhancement n-channel MESFET.

II. DEVICE SIMULATION

The charge transport modeling in this work is accomplished with a two-dimensional two-carrier transport code FETSIM [14]. FETSIM is a software product for time-domain simulation of GaAs MESFETS via a two dimensional electron temperature (ET) model. The ET model was first...
developed by Curtice and Yun [14]. The model includes the carrier heating effects of electron transport in GaAs. Electron transport coefficients are evaluated as a function of electron temperature at each point in the device. The electron temperature is a measure of the thermal energy of the electrons and is evaluated from the energy transport equation. Non-equilibrium effects, such as velocity overshoot resulting from the finite energy relaxation time occur naturally in this model. The time domain simulation of the photocurrent is based on Poisson's, charge continuity, and energy transport equations derived from the Boltzmann equation. The device simulation does not include bulk traps since the simulation time scale is much faster than that for trapping effects.

The device under analysis is a 50 μm wide enhancement mode MESFET (V_g = 0.1 V) fabricated in the Vitesse HGaAsII process (1.2 μm drawn/0.8 μm effective) which includes a buried p-layer, and is very similar to devices examined in previous work [2,3,5,7,11]. The cross section of the enhancement device modeled is shown in Figure 1. The simulation begins at t=0 by depositing electron-hole pairs in the ion or laser track. In what follows we present selected results for 3 MeV alpha particle excitation. Similar results were obtained for excitation by picosecond laser pulses. These will be presented in detail elsewhere.

Figures 4 through 7 illustrate the time evolution of the carrier transport in the MESFET. Figures 5 through 7 include current vectors to provide direction and magnitude of the respective electron and hole currents in the transistor (the length of the arrows are proportional to the current). The upper and lower amplitude limits were chosen in each figure to provide the best illustration of the charge enhancement mechanisms. Also, the amplitude scale factor varies from figure to figure, and can not be used for quantitative comparison. Figure 4 shows a potential plot 2 ps after the ionization event, which can be compared to the steady-state case of Figure 2. Figure 4 shows how the fields below the device are distorted by the introduction of the electron-hole plasma, and illustrates the reduction in the potential barriers that...
confine electrons to the channel and implants.

Figure 5 shows the electron and hole densities at 42 ps after the ion strike. At t=42 ps a significant fraction of the electron current occurs between the source and drain regions through the buried p-layer of the device. The current vectors illustrate how electrons are injected from the source through the buried p-layer into the semi-insulating substrate, and then up through the buried p-layer to the drain. The bipolar source-drain mechanisms that have been discussed previously [1-3] are consistent with this result. The lower portion of Figure 5 shows holes drifting from the initial track towards the more negative gate. The built-in fields of the Schottky gate junction provide a potential below ground. Also, at t = 42 ps, the accumulation of a positive hole density in the p-region below the channel of the device becomes evident.

By 68 ps after the ion strike (Figure 6) the source-drain current path through the buried p-layer has subsided, and the majority of electron current takes place in the channel of the device. The current at this point is controlled by the excess hole density that is present in the p-region below the channel. The dominant charge-collection mechanism at this point in the simulation is the back-channel turn-on mechanism [4-7], with the magnitude of the source-drain current is determined by the device bias conditions and the density of holes beneath the channel.

By 500 ps (Figure 7) the electron density and currents have recovered close to the steady-state conditions. However some source-drain current remains from the residual excess hole density beneath the channel (~10^{10} cm^{-2}/μm). Experimental results [15] reveal that this component decays on a timescale of 2-5 ns at room temperature, consistent with the hole lifetime.
The time evolution illustrated in these figures shows that the charge-collection process in MESFETs progresses through several stages. Following the initial charge deposition, the electron-hole plasma undergoes a rapid expansion with a very fast charge-collection process occurring in the first few picoseconds (not shown here). For times between 5 and 60 ps electrons are injected from the source implant into the p-layer (Figure 5), and through the substrate. Simultaneously, and persisting for the duration of the simulation, a positive hole density develops under the channel region backgating the channel (Figures 6 and 7).

Simulations also were performed for picosecond laser excitation at 620 nm to compare with recent experiments performed at this wavelength. The peak concentration of the carriers at the surface is 2.57 x 10^{17} electron-hole pairs/cm² (the illuminated area corresponds to most of the region between the gate and drain contacts). Total charge produced by the laser light is 2.25 fC/µm. The laser and ion cases differ in: i) the initial density of free carriers; ii) the initial lateral distribution of carriers; and iii) the penetration depth

![Electron Density](image1.png)

![Hole Density](image2.png)

Figure 7. Electron density (upper) and hole density (lower) at 500 ps after ion event. Contour lines correspond to decade increments in carrier density. The contour line for the lowest density in each case is 10^17 carriers/cm².

(620 nm light corresponds to a 1/e absorption depth of 0.21 µm in GaAs). Despite these differences, the laser simulation results are very similar to the ion results, revealing that the primary mechanisms of charge collection and, in particular, the mechanisms of charge enhancement, are fundamentally the same in the two cases. While there are significant differences at very short times, the computer simulations show that after approximately 10 ps the charge distributions and fields in the device are comparable. The differences are primarily quantitative rather than qualitative. For example, for equivalent amounts of charge deposited, the hole density in the p-region is larger for the ion case because the charge is deposited further into the device. This effect can be addressed by using a longer wavelength laser; such experiments are currently under investigation. In a future paper we will present detailed results on the laser simulations and experiments.

**IV. DISCUSSION**

Enhanced charge collection refers to charge collected at the drain contact that is not associated with the original deposition of charge. The deposited charge in the ion and laser simulations was 2.25 fC/µm. Enhancement was observed in both ion and laser simulations. The collected drain charge was 4.0 fC/µm and 5.5 fC/µm for the ion and laser examples respectively. The high value obtained for the laser is due to shorting of the gate-to-drain junction in the initial part of the simulation.

The computer simulation results presented here reveal two mechanisms for the transport of electrons from the source to the drain that are capable of giving rise to charge enhancement. The first involves the injection of electrons from the source into the substrate. This occurs because the excess hole density in the substrate (and p-region) forward biases the p-n junction of the source-implant to p-region and increases the electron current into the p-region. This is evident during the early part of the simulation (up to approx. 60 ps), and is related to the bipolar source-drain mechanisms that have been discussed in earlier literature [1,3,7].

The second charge enhancement mechanism is associated with channel modulation effects that can persist for several nanoseconds [16]. Following the ionizing event a positive hole density becomes confined in the p-region below the channel. The positive charge associated with this increased hole density backgates the channel, diminishing the controlling effect of the gate electrode. Consistent with experimental observations [11,12], this effect is most significant near pinch off when small changes in the channel conductance can give rise to large changes in collected charge. Because this effect is controlled by the holes, it persists as long as a positive hole density exists under the channel. This depends on the bias conditions, but can be on order of the hole lifetime (2 to 5 ns for p-type GaAs) and, consequently, the charge enhancement from this mechanism can be quite large. Both simulations and experiments reveal that this back-channel modulation effect becomes less significant as devices are biased more strongly off [12]. For devices biased near pinchoff, however, simulation and experimental results suggest that this is the major contributor to charge enhancement in the buried p-layer devices of this study.
The buried p-layer acts to shield electrons deposited (or injected) into the substrate from the active regions of the device. In agreement with experimental observations [7] and the results of Figure 5, it may be assumed that if the p-layer were not present charge collection from the bipolar source-drain mechanism may be more efficient. In addition, the simulations indicate that the lower potential in the p-region acts as a well to "trap" holes. This stabilization of holes contributes to the back-channel turn-on mechanism and, in this regard, the p-region may increase the total charge collected. These effects are under further investigation.

A primary limitation of 2-D computer simulations is the difficulty in drawing quantitative conclusions, such as the determination of an accurate value for the critical charge. The 2-D simulations, however, contain all of the underlying physics that is included in 3-D simulations, and thus provide considerable insight into the charge collection mechanisms with a significant reduction in computational requirements. In addition, the 2-D simulations exhibit good agreement with the qualitative trends in the experimental data [12], such as changes in bias conditions and the observation of charge enhancement. 3-Dimensional simulations provide an improved representation of the real device and, therefore, selected 3-D runs would be a useful complement to the 2-D results presented here.

V. CONCLUSIONS

The present work reveals that electrons can be transported from the source to the drain in an enhancement-mode MESFET by two mechanisms. The first is a bipolar type effect which injects charge into the bulk of the device and is collected at the drain due to the electric field. The second is a back channel turn-on mechanism which is associated with a positive hole density located beneath the channel and exists on a much longer time scale.

These results show that the electrons supplied by the source implant are responsible for charge collected at the drain in excess of any collected deposited charge. We note that the observation of enhanced charge collection in these simulations was obtained without including bulk trapping effects in the device model.

Additionally, the simulations affirm that both charge enhancement mechanisms can be observed with either alpha or laser excitation, in agreement with experimental observations.

VI. ACKNOWLEDGEMENTS

The authors would like to thank Upul Obeysekare and Chas Williams of the NRL Research Computation Division in assisting us with the AVS software to develop the figures and animation in this work. We also thank Ray Milano of Vitesse Semiconductor for providing devices.

VII. REFERENCES