High Voltage Microwave/MM-Wave Field-Effect Transistors

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ABSTRACT

Wide bandgap semiconductor devices potentially offer performance previously available only from microwave tubes. AlGaN/GaN HFET's have demonstrated RF output power density over 30 W/mm when biased at Vds=120v. Thse devices should produce useful performance well into the mm-wave region, and potentially as high as 100 GHz. However, these devices are currently limited by a variety of physical phenomena affecting RF performance, linearity, and device reliability. This presentation will focus upon the RF large-signal operation of these devices, with an emphasis upon the physical effects associated with various charge trapping, surface, and space-charge phenomena.

I. INTRODUCTION

The generation of high RF output power, on the order of 100's to 1000's of watts necessary for transmitters for radars and wireless communications systems, remains a difficult challenge for semiconductor devices. RF power devices fabricated from standard semiconductors such as Si and GaAs are limited in the RF output capability by the inherent breakdown voltage of the semiconductor material. Recently, the development of wide bandgap semiconductors, such as SiC and the AlGaN/GaN heterojunction, offers the potential to fabricate transistors with significantly improved RF output power compared to traditional devices. In particular, the development of mcrowave field-effect transistors fabricated from the AlGaN/GaN heterostructure offers the potential to fabricate FET's with significantly improved output power performance. The improved RF output power is possible due to high critical field for breakdown in the nitride-based semiconductors. AlGaN and GaN have breakdown fields greater than $E_c>10^6$ V/cm, which is significantly higher that comparable fields of slightly over $E_c>10^5$ V/cm in standard semiconductors such as Si and GaAs. The increase in critical field results in the ability to sustain a much increased bias voltage.

The AlGaN/GaN heterojunction yields a two-dimensional electron gas sheet charge density greater than $n_{ss}=10^{13}$ cm^{-2}. This is a factor of five larger than is obtained with the traditional AlGaAs/GaAs heterojunction, and over twice the sheet charge density obtained from the GaInAs/InP heterojunction. The high sheet charge density results in high dc and RF currents, and the product of high device current and high bias voltage results in the development of high RF output power. Field-Effect Transistors fabricated from the AlGaN/GaN heterostructure demonstrate the ability to produce RF output power on the order of 100's of watts, and these devices can be easily combined to fabricate kW level and higher transmitters.

The generation of high RF output power by microwave field-effect transistors requires that high bias voltage be applied. However, the drain bias that can be applied is limited in magnitude for FET's by electronic breakdown of the gate electrode. Standard power GaAs FET's are generally limited to drain bias voltages in the range of 8-12 v, which limits the RF voltage and RF output power that can be developed [1]. It has been shown that the use of field-plate technology suppresses gate breakdown and permits significantly higher drain bias voltages to be applied [2]. Field-plate power GaAs FET's biased with drain voltage of 35 v have produced RF power density of 1.7 W/mm of gate periphery, and a 230 W amplifier when the FET was biased at Vds=24v [3]. Wide bandgap semiconductors such as those based upon the III-N materials system have much improved critical electric fields for breakdown compared to GaAs and HFET's fabricated from these materials can sustain significantly improved bias voltages, with Vds>40v before breakdown is observed. Field-plate technology is also being widely used with nitride-based HFET's [4] to permit even greater drain voltage to be applied, and a field-plate HFET when biased at a Vds=120v has produced over 30 W/mm RF power density at S-band [5], and over 5 W/mm at 30 GHz with a drain bias of Vds=30v [6].

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Although the use of field-plates permit high drain voltage to be applied operation of the device at high bias can produce physical effects that influence the performance of the device. In particular, the electric field in the conducting channel can obtain magnitude greater than the critical field for avalanche. Channel breakdown under RF operation can occur, and this can result in a previously unrecognized IMPATT-mode of operation in these devices.

II. CHANNEL ELECTRIC FIELD

It is well known that charge dipole domains form in the conducting channel of field-effect transistors. This domain supports the majority of the potential drop from the drain to source and produces a high electric field region under the gate edge in the conducting channel. In particular, in is known that the magnitude of the electric field at the edge of the gate electrode on the drain side can be very high, depending upon the magnitude of both the drain potential and the RF voltage. For high RF drive the peak of the RF voltage will add to the drain potential and a terminal voltage on the order of twice the dc bias can result. When the magnitude of the electric field at the gate edge exceeds the tunnel limit electrons tunnel form the gate electrode to the semiconductor creating a leakage current that is the primarily breakdown mechanism in field-effect transistors [7]. The electric field for a GaAs MESFET with a 0.6 μm gate length is shown in Fig. 1. The electric field is shown at the GaAs surface, at mid-channel, and at the channel/substrate interface.

The magnitude of the electric field within the conducting channel can also obtain high magnitude, as shown in Fig. 1. The electric field in the conducting channel can exceed the breakdown field for the semiconductor, which for GaAs is on the order of E_c~500 kV/cm. As the bias voltage is increased, either by an increase in the drain bias or by the application of a large-signal RF voltage, the magnitude of the electric field will increase and the device will experience breakdown, either at the gate edge, or in the conducting channel. Impact ionization in the conducting channel of short-gate FET's has previously been reported [8]. The use of field plates has been demonstrated to reduce the magnitude of the electric field at the gate edge, thereby suppressing the gate leakage and permitting high drain voltages and large RF voltage to be applied. However, the field-plate introduces a high electric field region within the conducting channel and located under the edge of the field plate, as shown in Fig. 2. The field plate does not increase the threshold for breakdown in the conducting channel. The field-plate moves the high electric field region away from the gate edge, but moves it into the conducting channel region between the gate and drain where it can facilitate channel breakdown, as shown in Fig. 2 for an AlGaN/GaN HFET.

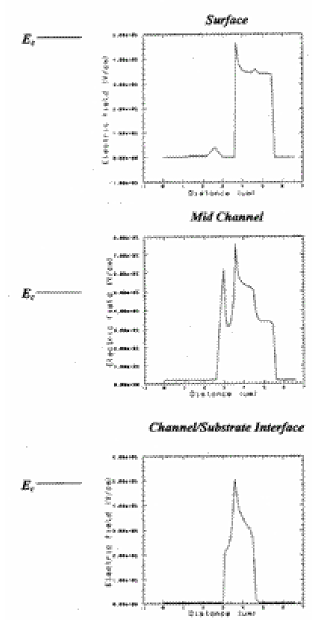

Fig. 1. Electric Field in the Conducting Channel of a GaAs MESFET for Vds=9v. Breakdown Field is Shown for Reference.

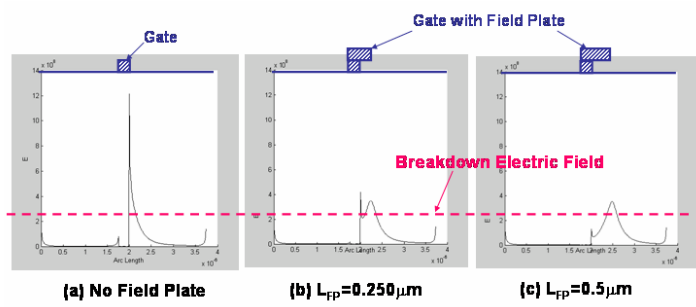

Fig. 2 Electric Field in the Channel Between the Gate and Drain of an AlGaN/GaN HFET with Vds=100v for Various Field-Plate Lengths

III. IMPATT OPERATING MODE

When driven with large-signal RF voltages the magnitude of the electric field in the high field domain will oscillate in magnitude as shown in Fig. 3. During the high voltage portion of the RF cycle the total dc and RF fields can increase until the critical field for avalanche ionization is exceeded. When this occurs a pulse of charge, consisting of electrons and holes, is generated in the conducting channel as illustrated in Fig. 4. The holes have very low mobility and move slowly towards the source where they recombine with free electrons, thereby reducing the electron density in the source region of the channel. The reduction in electron density in the gate-source region contributes to an increase in source resistance, which increases as a function of RF drive [9]. This phenomenon contributes to the 'RF knee walkout' effect often observed in practical devices.

The application of the high drain bias creates a depletion region that extends from under the gate into the region between the gate and drain. Simulations reveal that under high drain voltage the depletion region exists in AlGaN/GaN HFET's, even under forward gate bias open channel conditions [9]. The combination of the electron-hole charge pulse generation during the high voltage portion of the RF cycle, and the existence of the channel depletion region create the necessary conditions for IMPATT operation.

The electrons generated during the breakdown pulse are injected into the depletion region, where they drift at saturated velocity towards the drain. The drifting electrons induce an RF current in the external circuit that is more than 90^{o} out of phase with the RF voltage, thereby creating an IMPATT mode of operation. A current controlled instability (i.e., the i-v characteristic is multi-valued in current which is generally termed 'S-type') that can be represented as a negative resistance with an inductive phase delay in the drain circuit is generated. The breakdown charge generation is synchronized with the RF signal and is, therefore, phase-locked. Once initiated, the dc current increases and the RF signal is amplified by the negative resistance. An electron transit-time delay that affects frequency response is introduced. This effect is sometimes referred to an 'gate lag', or 'dispersion'.

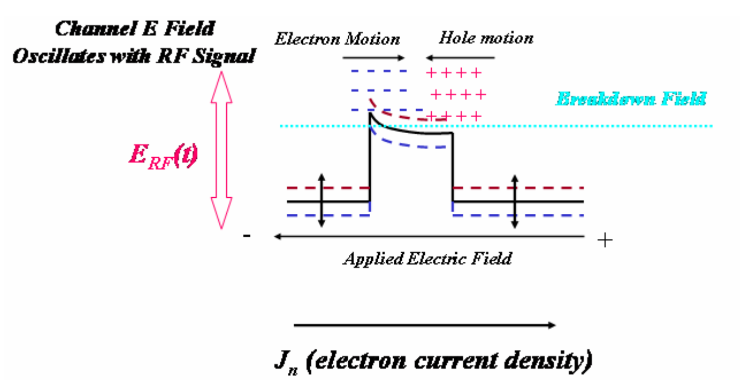

Fig. 3. Electric Field in the Conducting Channel Oscillating with RF Drive

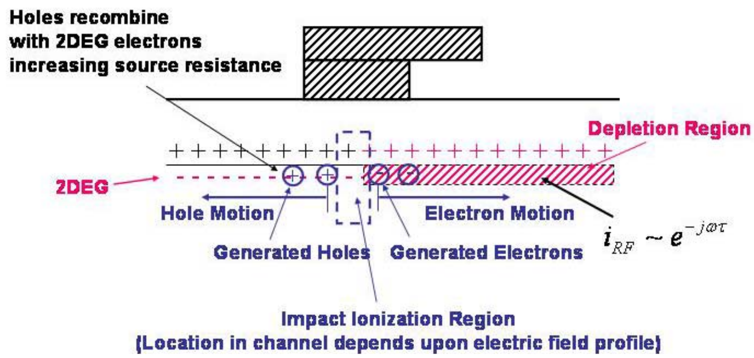

Fig. 4. Electron-Hole Generation in the Conducting Channel Under RF Drive in an AlGaN/GaN HFET

The negative resistance can be observed in the S22 for the device, which can exceed unity when the IMPATT mode conditions are satisfied.

IV. Conclusion

AlGaN/GaN HFET's demonstrate potential for fabrication of improved RF output power devices. These devices should find application as microwave amplifiers for radars and communications systems. However, current devices are affected by physical effects that limit RF performance. One effect is an IMPATT mode of operation that can be excited under high RF voltage conditions. The electric field that exists in the conducting channel can approach or exceed the conditions for avalanche breakdown with increasing drain bias and/or large-signal RF voltage. Under large-signal RF voltage during the high voltage portion of the RF cycle a pulse of electron-hole pairs is generated. The electrons are injected into the depletion region in the gate-drain region of the conducting channel, where they drift at saturated velocity towards the drain contact. This induces a current in the external circuit that is more than 90^{o} of phase with the RF voltage. An IMPATT mode of operation is generated that increases the bias current and increases the RF output power of the device. The mode is observed as an S22 with magnitude greater than unity and can be modeled as a negative drain resistance. The IMPATT mode increases the dc current and amplifies the RF signal, thereby increasing the RF output power of the device.

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