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TITLE: Impact Ionization in High Performance A1GaN/GaN HEMTs

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TITLE: Proceedings IEEE Lester Eastman Conference on High Performance Devices at University of Delaware, Newark, Delaware, August 6, 7, and 8. 2002

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Impact Ionization in High Performance AlGaN/GaN HEMTs

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Abstract

We report compelling evidence of impact ionization in high-performance AlGaN/GaN HEMTs. Relevant to the present paper, these devices also show excellent low-leakage DC properties that contain signatures of impact ionization in the output and sub-threshold characteristics. Temperature and bias dependent data are presented to support the identification of impact ionization in the devices.

I. Introduction

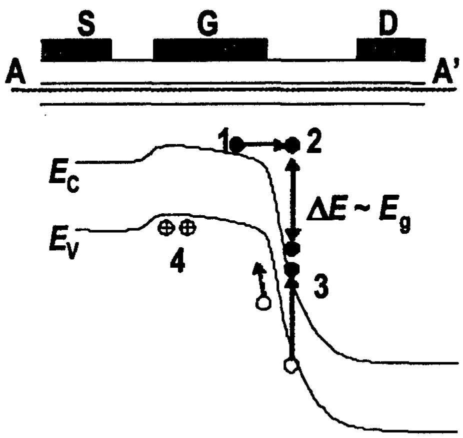
Gallium Nitride HEMTs are the focus of intense research and development for the realization of power amplifiers with high gain and record levels of power delivery. Very high power densities > 10W/mm have been published.[1] Assisted by significant momentum in Nitride-based optical devices, the materials growth and process techniques for electronic devices have been steadily improving. Such improvements would allow the observation of fundamental phenomenon reported in more-mature semiconductor materials. In the present paper, we report on a relatively well-known field-effect transistor phenomenon commonly referred to as the "kink effect," observed for the first time in GaN/AlGaN HEMTs. The "kink effect" simply describes an increase in the drain conductance of the device under open-channel operation at drain biases nominally greater than the bandgap of the channel. The effect is initiated by impact ionization of hot electrons in the drain-to-gate region of the device and proceeds with the accumulation of the impact-generated holes at the source-end of the channel. The impact-generated holes forward-bias the source-to-channel energy barrier thereby causing an increase in the drain conductance. The feedback process is well studied and documented in other materials, but the detailed mechanisms remain a subject of investigation.[2,3,4]

II. Growth and Process Details

The epitaxial materials were an $Al_{0.3}GaN_{0.7}$/GaN π-HEMT structure obtained from RF Nitro and grown at Cornell University. The device layers consisted of a conventional GaN/AlGaN HEMT single heterostructure on a 2" semi-insulating SiC substrate. The top AlGaN barrier was nominally

0-7803-7478/02/$17.00

30% Al with a thickness of 25nm. The charge was supplied to the channel from the surface through so-called piezoelectric-doping.[5] The transistors were fabricated at RSC in the baseline High Power Amplifier process using implant isolation, Ti/Al/Ti/Au Ohmic contacts, and a 0.25 μm electron-beam Pt/Au T-gate. The Ohmic contact resistance was in the range 0.5-0.8 Ω-mm. Measured DC device parameters show an I_{dss} of 1.2 A/mm, and a G_m of 230 mS/mm. The threshold voltage varied systematically across the wafer from -4 to –9 V. Small-signal RF measurements show extrapolated f_T of 70GHz and f_{max} of 90 GHz. On-wafer large-signal measurements at X-band gave power densities as high as 6 Watts/mm on 100 μm devices, at modest drain voltages of 20-25 V. Measurements on 800 μm wide devices showed that power density was maintained above the 3 W/mm level for the same drain bias. The devices had a power density of 3.3 W/mm and a maximum output power of 2.63 Watts. This output power was achieved while maintaining a high gain of 9.2 dB, and a PAE of 44.3%.



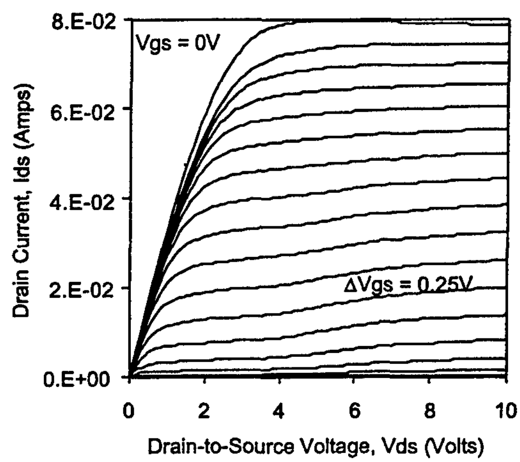


Figure 1 a) Schematic of the energy band diagram along the channel (A-A') showing electrons in the channel at 1 picking up energy from the drain voltage between 1 and 2. Impact ionization at 3 generates an electron hole pair. The impact-generated hole moves back towards the source along the channel to 4. At 4 the hole represents a positive charge that lowers the potential barrier, which increases the drain current. The holes at 4 are also collected by the negatively charged gate and contribute to the gate current. b) Output characteristics of a GaN/AlGaN HEMT with an 80 μm gate width The "kink" in the output characteristics is a direct result of the feedback mechanism described in Fig. 1a. Note the "kink" in the drain current occurs for drain biases greater than the bandgap of the GaN channel.

III. Experimental and results

Impact ionization in the channel affects device operation in many ways. The basic mechanism relevant to the present paper is described in Fig. 1a. In Fig. 1a electrons in the channel at 1 enter the high-field drift region between the gate and drain and pick up energy equal to the bandgap of the GaN channel at 2. These hot electrons undergo impact ionization, producing two conduction band electrons and a hole in the valence band. The electrons are simply collected by the drain and by themselves do not account for the large increase in the drain conductance.[3] The holes at 3 are attracted to the source and the gate, and in some cases may be trapped in the barriers. The positive charge contributed by the holes that accumulate at 4 lower the barrier between the source and the channel and increases the drain conductance.

The room-temperature output characteristics of the GaN/AlGaN HEMT are shown in Fig. 1b. The increased output conductance or "kink" is evident at drain biases above 4V. The effect is more readily observed in a plot of the same output characteristics on a semi-log plot as shown in Fig. 2a. Measurement of the device at lower temperatures enhances the "kink" as shown in Fig. 2b for –50C. The enhancement of the output conductance at lower temperatures is consistent with the "kink" being associated with impact ionization: As the device temperature is reduced the electron mean-free-path increases and the impact ionization rate increases.

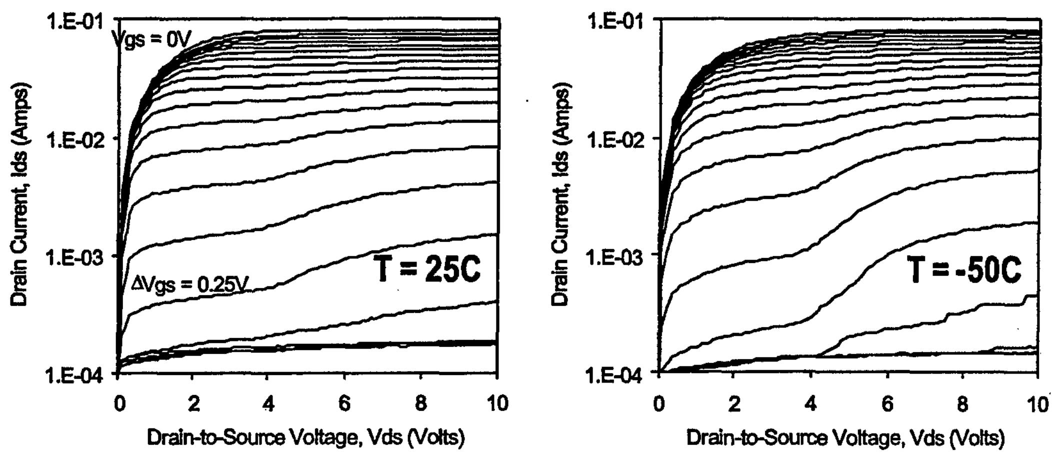
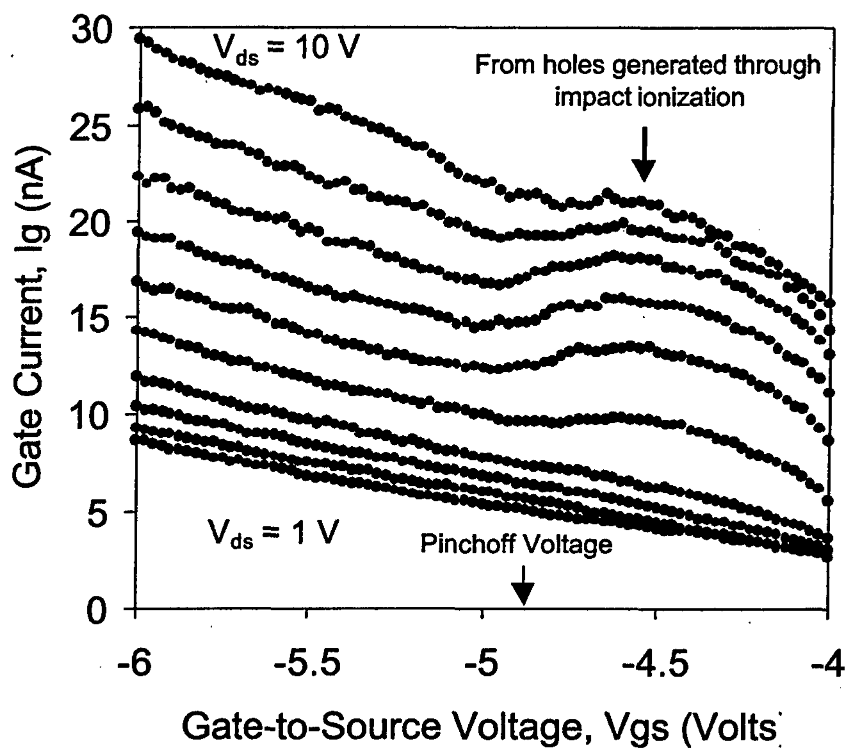


Figure 2 a) Output characteristics of an 80 μm wide AlGaN/GaN HEMT at room temperature. The logarithmic scale is chosen to highlight the increase in the output conductance at lower drain currents. V_{gs} is stepped from 0 to –5V. b) Output characteristics of the device from Fig. 1 at –50C. The impact ionization rates increase at lower temperatures and the enhancement in the output conductance is more pronounced.

The most important aspect of the devices described in the present paper is their low gate-leakage characteristics. Devices with low gate leakage allow us to probe the generation of holes with impact ionization directly, through an excess gate leakage. As described in Fig. 1a the holes that are generated are also attracted to the negatively charged gate. These holes, if collected by the gate, will provide an excess gate leakage current over and above the nominal gate leakage observed in the device. The excess gate leakage has the following unique dependencies on the applied bias: 1. The drain voltage has to be above the threshold for impact ionization (~ 4V from Fig. 2); 2. The excess gate current will increase as the gate-to-drain voltage is increased; and 3. The excess gate current will decrease as the device nears pinch-off and the drain current in the channel is turned off. Such an unambiguous signature of impact ionization is found in the gate current for these devices.

The gate currents at –25C in these AlGaN/GaN HEMTs are plotted in Fig. 3 and clearly show an excess leakage that has the requisite functional dependence on drain current and drain voltage. We add that while the increase in the output conductance was seen on all our devices, the enhanced gate leakage in Fig. 3 was not as easily observed in all our devices and in all parts of the wafer. The device had to have a combination of high quality material allowing electrons to gain energy for impact ionization *and* low gate leakage to observe the signature of the impact-generated holes. In fact, the temperature of the device had to be lowered to –25 C to be able to observe the excess



current.

Additional measurements of gate leakage as a function of temperature, not shown here, seem to indicate that impact ionization continues to play a role in the sub-threshold region of device operation. Such measurements will be useful to monitor the quality of the GaN materials and may ultimately provide important information about breakdown and physics of failure of GaN/AlGaN

Figure 3. Gate current vs. gate voltage for various drain biases (from 1 to 10 V in 1V steps) at –25C. The "bump" in the gate current is a clear signature of impact ionization generated holes that are collected by the gate electrode and is only observed for drain voltages commensurate with the increase in the output conductance in figures 1 and 2. For a given drain voltage, the gate current increases above the ordinary leakage as the gate-to-drain voltage increases. As the device pinches-off at -5V, the drain current decreases and the number of holes generated by the impact ionization also decrease causing the excess gate leakage to decrease.

HEMTs.

IV. Conclusions

The DC characteristics of our low-leakage high-performance GaN/AlGaN HEMTs show compelling evidence of impact ionization of hot electrons in the GaN channel. The impact ionization process generates holes that increase both the output conductance and the gate leakage in these devices with a nominal bias threshold associated with the bandgap of the GaN channel. Lowering the temperature enhances these signatures due to an increase in the impact ionization rate of the hot electrons. The voltage and current dependence of the gate leakage arising from the impact-generated holes is shown to be consistent with our claim.

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