Letter

Hot-electron induced defect generation in AlGaN/GaN high electron mobility transistors

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Hot-carrier effects in gated AlGaN/GaN based high electron mobility transistors are studied by microwave noise temperature spectroscopy. Electron temperature profiles are measured and correlated to defect generation in the AlGaN/GaN channel interface. It is found that new defects are created at the AlGaN/GaN interface due to hot-electrons which are fairly well confined to the channel under the gated part.

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1. Introduction

The high LO phonon energy (~92 meV) and large inter-valley separation (~2 eV) in nitride semiconductors ensure significant generation of hot-electrons during normal operation of AlGaN/GaN based High Electron Mobility Transistors (HEMTs). Furthermore, a smaller LO phonon emission lifetime compared to LO phonon decay lifetime ensures substantial build-up of the lattice temperature due to the strong electron–phonon coupling. In essence this creates a formidable combination of non-equilibrium phonons which are energetic but highly localized due to their low group velocity and hot-electrons which are mobile and energetic. These electrons have enough energy to degrade device performance temporally and permanently [1]. Fig. 2 shows how these electrons negatively impact the device performance by interaction with various parts of the device structure like the barrier, buffer or the gate stack. Many experimental studies have demonstrated the existence of these hot-electrons in AlGaN/GaN channels or GaN buffer materials [2–4]. Electron temperature profiles have been measured directly in un-gated AlGaN/GaN channels by microwave noise temperature spectroscopy [5]. Other groups have measured electron temperature profiles using photoluminescence spectra [6]. Very few experimental studies exist on gated AlGaN/GaN HEMTs. Furthermore, realistic bias conditions have not been probed. This work demonstrates the use of microwave noise spectroscopy to measure electron temperature profiles in a fully processed advanced GaN HEMT. This is used to understand electrically stressed GaN HEMTs which underwent high channel electric field stress and resulted in permanent defect generation at the AlGaN/GaN interface. Low frequency noise is used as a defect spectroscopic tool to confirm microscopic defect generation and their spatial location in the device.

2. Experimental details

The devices under study are gated Al0.25Ga0.75N barrier based GaN transistors grown on a silicon (111) substrate by MOCVD. Schottky gate and source/drain ohmic contacts are made of Ni/Au and Ti/Al/Ti/Au metal stack respectively formed by rapid thermal annealing. They also have a source connected field-plate and a SiN passivation layer. The devices were fully packaged preventing any ambient light related instability to affect the measurements. Fig. 1 shows the critical dimensions of the device. The microwave device noise temperature is measured via Gasquet’s circulator method [8] modified for a FET structure by the authors [9]. The measurements were not performed under pulsed condition thereby allowing the lattice temperature to reach steady state at each bias. The gate terminal was AC-open circuited with the help of a tuner to minimize the impact of both induced gate noise and GaN HEMTs.
thermal noise associated with gate resistance on the channel noise. It was found that at high drain biases the drain noise mainly stemmed from the channel electrons since the transconductance of the device was relatively constant while the measured device noise temperature increased with bias. The setup to measure low frequency noise is detailed in a prior work[7]. The devices were subjected to two different stress regimes where electric fields in the channel were kept constant but the number of carriers were varied by changing the gate voltage. $V_{DS} = 20$ V and $I_{DS} = 230$ mA stress is a hot-carrier and self-heating stress. This is a fairly harsh stress and the duration of the stress is 5 min. The second stress is applied at $V_{DS} = 30$ V and $I_{DS} = 1$ mA for 60 min and generates hot electrons without much self-heating.

3. Results and discussion

It was found that the hot-carrier and self-heating stress led to a permanent increase of low frequency channel noise characteristics. By measuring the normalized drain noise dependence on drain current it was found that the defect generation primarily occurred in the gated part of the channel[10]. It is discussed in more detail later. This indicates that hot-electrons along with self-heating are responsible for this effect. The other stress at low $I_{DS} \sim 1$ mA was primarily hot-carriers and quite benign to the device. Only transient effects like threshold voltage increase and recovery were observed during and after stress. Low frequency channel noise confirmed that no degradation occurred in the channel. To gain further insight into this hot-carrier and self-heating induced failure mechanism noise temperature measurements were performed. In a previous paper[9] the authors measured noise temperatures as a function of both drain and gate bias. It was demonstrated that noise temperature is well correlated to the channel electric field and not to the self-heating in the device. In this work the authors analyze this data to correlate device noise temperatures to an effective electron temperature in the channel.

In a FET biased in the linear region, the channel electric field is uniform in the direction of the electron flow. Once the device goes into saturation the electric fields are no longer uniform due to pinch-off effects. A further increase of the drain voltage mainly drops across a very narrow region of the channel near the drain end and there the electric fields become two dimensional due to a space charge region. For the linear region the electron temperature is equal to the noise temperature. In a previous work it was observed that electron temperatures monotonically increase at drain biases in the saturation region as well[9]. It is generally argued that the pinched-off region of the channel does not contribute much to the measured channel noise since carriers are mostly traveling at the saturation velocity and they do not produce velocity fluctuations[11]. Thus, the measured noise is mainly stemming from the linear part of the channel where electric fields are still uniform. From the DC $I_D-V_D$ characteristics of the device it was found that significant channel length modulation occurs after saturation. An empirical parameter ($z$) is often used to model the channel length reduction due to drain bias. A value of 0.7 was extracted by extrapolating the output conductance in saturation for different gate biases. The effective channel length then becomes a function of drain bias

$$L_{eff} = \frac{L_G}{1 + zV_{DS}}$$

Here, $L_G$ is the gate length and $V_{DS}$ is the drain voltage above saturation. Using a simple MOSFET model the effective electric field in the linear part of the channel is given by

$$E_{CH} \approx \frac{V_{GS} - V_T}{2L_{eff}}$$

Fig. 3 shows the plot of noise temperature as a function of channel electric field for three different gate biases. Some interesting features can be read from the data. Even though large electric fields exist in the channel, the electron temperatures are not too high.

Fig. 2. Conduction band diagram along the gate to channel direction for a gate voltage higher than the threshold voltage. Equivalent electron temperatures in the channel are plotted and two regions of high (15,000–25,000 K) and low energy (0–6000 K) electrons are shown. The effects of high and low energy electrons on DC and low frequency noise characteristics are delineated.
This could be due to thermal quenching of the hot-electrons since measurements were performed at steady state without any application of pulsed techniques. This gives enough time for the hot-electrons to lose their energy to the lattice. This trend is also verified by two other factors. First, for low electric fields (<10 kV) the electron temperatures are similar to as measured by other groups [5,6]. Second, for higher electric fields the larger the gate bias value, the lesser is the electron temperature. At higher gate biases, more electrons exist in the channel for the same channel electric field. This leads to larger self-heating and higher thermal quenching of hot-electrons. Another interesting part is the physical location of these hot-electrons in the channel. Due to channel length reduction most of the hot-electrons are confined under the gated part of the channel. Two dimensional simulations of GaN HEMTs operating in the saturation region have shown that a space charge zone forms in the pinched-off part of the channel [12]. The electrons under this part are not confined to the quantum-well and move far away from the channel and deeper into the buffer region [13]. Electric fields in that part are very high and most of the electrons are highly energetic populating more the upper valleys like $L-M$ or $T_2$. These electrons generate the so-called hot-spots in the device but since they are farther away from the channel they won’t affect the AlGaN/GaN interface much and thus, the low frequency channel noise.

Fig. 4 shows the conduction band diagram along the gate to channel region simulated by the 1D Poisson–Schrodinger solver NEXTNANO [14]. The equivalent electron temperature of the 2DEG is plotted in the channel. The measured electron temperatures fall within the low energy part of the channel between 0 and 3000 K. These electrons are fairly well confined along the AlGaN/GaN interface and have significant energies to generate new defects at the interface. Due to built-in electric field in the AlGaN barrier the threshold voltage of the device is more sensitive to the charge distribution near the gate metal rather than the channel interface. No change of threshold voltage or the gate leakage current was observed confirming that the electrons were restricted in the channel.

4. Conclusion

In summary, electron temperatures in the channel were extracted for a biased GaN HEMT as a function of channel electric field for different gate biases. It was shown that hot-electrons are generated in the gated part of the channel and are well confined to the AlGaN/GaN interface. The high energy of these electrons generates new defects at the AlGaN/GaN interface which is confirmed by channel low frequency noise measurements.

References


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