Hot-Phonon Effect on the Reliability of GaN-Based Heterostructure Field-Effect Transistors

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INTRODUCTION

GaN-based high electron mobility transistors (HEMTs) are among the most promising devices for high power radio frequency (RF)/microwave (MW) and switching applications owing to their high breakdown voltage, high electron density, and high electron saturation velocity.[1,2] In fact, GaN HEMTs are currently employed in RF/MW high power amplifiers, low-noise amplifiers (LNA), and RF switching modules in radar and electronic warfare (EW) systems.[3]However, reliability is still an issue to be addressed since GaN-based technology has not reached its maturity yet. Hence, addressing physical mechanism behind relatively poor reliability of GaN-based crystal structure is imperative along with the empirical analyses of conventional reliability data collected from device tests such as accelerated life tests.
The Joule heating is considered as main culprit that accelerates degradation of power devices. The mechanism simply relies on that energy of the electrons increase due to the high electric field and dissipate it through electron–phonon scattering. Since hot electrons do not cool down through the interaction with acoustic phonons, emission of optical phonons dominates the phonon population at elevated power levels. Therefore, emitted optical phonons accumulate, and hot-phonon effects become significant in the GaN crystal structure especially around the channel.

Optical phonon-associated heat cannot reach the heat sink efficiently due to their low group velocity unless they converted to acoustic phonons. Therefore, the main avenue for device heat dissipation includes emission of longitudinal optical (LO) phonons by hot electrons, decay of the LO phonons into longitudinal acoustic (LA) phonons, and diffusion of the excess LA phonons into the remote heat sink. Moreover, the hot-electron and hot-phonon temperatures were shown to be approximately equal meaning that they constitute an almost isolated hot subsystem formed in the channel, and the bottleneck for the dissipation was caused by slow decay of hot phonons into LA phonons. The concept of this power dissipation bottleneck is highly important for power HEMT operation.

Hot-phonon lifetime quantifies this type of mechanism, which is throughly visited for III-V systems such as GaAs and GaN both at low and high electron densities. At high electron densities as in GaN two-dimensional electron gas (2DEG), another phenomenom manifests itself which is called plasmon assisted decay of hot phonons. As bulk density of electrons approaches near 10^{19} cm^{-3} the plasma frequency and optical phonon frequency crosses over and phonon lifetime exhibits the lowest value. This finding drives the hypothesis such that if phonon-plasmon coupling leads to lower phonon life-time, then devices should perform better around some certain resonant 2DEG density since the joule heat dissipation to the heat sink is more efficient by intrinsic device design.[4-13]

In this paper we selected a particular InAlN/GaN-based HFET structure as a test bed since two-dimensional electron gas (2DEG) densities reach up to $3x10^{13}$ cm^{-2}.[14-16] This presumably allow to monitor aforementioned resonant 2DEG density value at which the heat removal expected to be maximum.

EXPERIMENTAL

The InAlN/AlN/GaN structure was grown on a c-sapphire substrate in a metalorganic chemical vapor deposition system.[16] The HEMT structure consisted of a 250 nm AlN initiation layer grown at ∼1030 °C, 3 μm of undoped GaN deposited at ∼1000 °C, a 1 nm AlN spacer layer grown at 1000 °C, a 20 nm $In_{0.15}Al_{0.85}N$ barrier layer grown at 800°C, and a 2 nm GaN cap layer grown at 900°C. The Ti/Al/Ni/Au Ohmic contacts for the HEMT devices were fabricated and mesa isolation was performed in a SAMCO inductively coupled plasma etcher based on Cl chemistry. Finally, the standard liftoff procedure was used to form the gate electrodes of Pt/Au (thickness 30/50 nm, length/width 2/90 μm).

Three different techniques were utilized to study the effect of degradation regarding the hot-phonon effect as follows: DC current-voltage (I-V) characteristics, current-transient measurements and low-frequency phase noise (LFPN) measurements. The current transient and standard DC I-V characteristics were monitored using a Keithley 4200 parameter analyzer. LFPN measurements conducted using an Agilent phase noise setup for which the detailed description can be found elsewhere.[17]

RESULTS

Devices were selected among nearly identical devices from the same wafer, based on their current densities, transfer properties, and leakage currents measured using the standard DC characterization methods. The maximum dispersion in the current density of the selected devices was about 0.06 A/mm, which corresponds to a 5% variation. The threshold voltage was about -6.8 V. The maximum 2DEG density of $2.3\text{x}10^{13}$ cm^{-2} was obtained from the Hall effect measurement; the minimum density was assumed to be zero at the pinch-off condition in biased HFETs. These two values and I_D vs. V_{GS} plots were used to estimate the 2DEG density as function of gate bias. All devices were subjected to a 7 h DC stress at V_{DS}=20 V at different gate voltages.

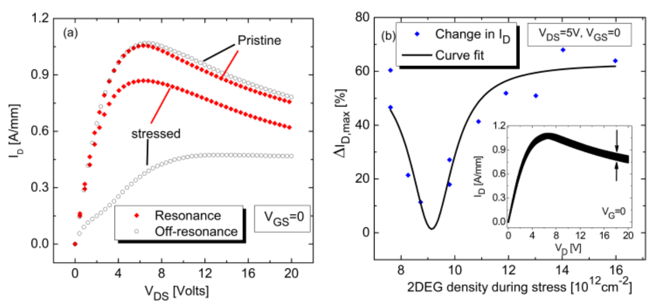

Fig. 1 (a) A representative I_D vs. V_{DS} graph measured at zero gate bias for two HFETs before and after the stress at V_{DS} = 20 V when the gate was biased to the hot phonon–plasmon resonance (closed diamonds) and at the off-resonance (open circles). The percentage of drain current degradation can be estimated from the ratio of the current after the stress (lower curve) with the value before the stress (corresponding upper curve). (b) Change in drain current ΔID due to the stress at VDS = 20 V vs. the 2DEG density during the stress and the Lorentzian fit; the minimum degradation occurs at a sheet density of ~$9.2\text{x}10^{12}$ cm^{-2} corresponding to a drain current density of 0.55 A/mm. (Inset) Drain current vs. drain-source voltage for the devices used. A dispersion of five percent was observed among the maximum drain current values of the selected devices.

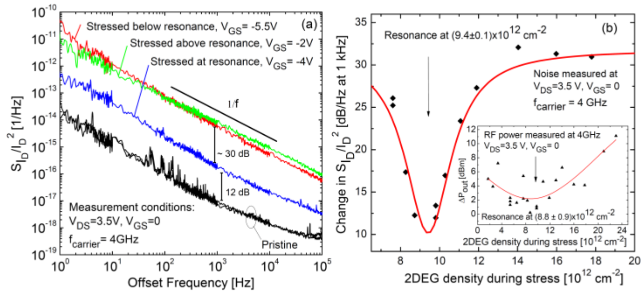

Fig. 2 (a) Normalized noise data (SID/ID^2 vs. offset frequency) for resonant and off-resonant 2DEG densities under stress. The power spectral density (PSD) shows no peak of a single generation–recombination source for both pristine and stressed devices. (b) Increase in the noise measured at zero gate bias after 7 hr electrical stress at 20V drain bias as a function of channel 2DEG density during stress controlled by the gate bias. The clear resonance is observed at a 2DEG density around $9.4\text{x}10^{12}$ cm^{-2} (fitting line) corresponding to the minimum degradation. The current density during stress was measured as 0.55 A/mm for the bias conditions at resonance. The inset shows the reduction in the RF output power (ΔP_{out}) at 4GHz after stres with the fit guiding the eye to see the trend. Output power was directly measured by feeding the device output into the spectrum analyzer. The arrows mark the resonant 2DEG density.

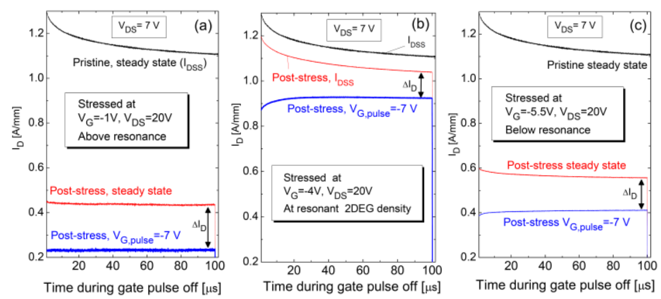

Fig. 3 (a) Drain current transient of a device stressed at off-resonant conditions for which the 2DEG density is higher than the resonant 2DEG density value. There is a remarkable permanent degradation about 60 %. Post-stress pulsed measurements exhibited almost total loss of the drain current (80 %). $\Delta I_D = I_{DSS} - I_{Pulsed}$ = 0.43-0.23= 0.20 A/mm.(b) Transient current data for the device stressed at resonant 2DEG conditions yielded much less degradation results (6 %) and the trapping effect is lower with the devices stressed at off-resonant conditions (ΔI_D=0.12A/mm). (c) Device stressed at off-resonant conditions where the 2DEG density is lower than the resonant 2DEG density exhibited high degradation (50 %). ΔI_D=0.15A/mm.

CONCLUSIONS

Low-frequency phase noise measurements, DC current vs. voltage results, and current transient measurements on InAlN/AlN/GaN HFETs show that device degradation is lower at the resonant 2DEG density of $9.4\text{x}10^{12}$ cm^{-2} compared with those degraded at off-resonant conditions. This 2DEG density value is also consistent with the resonances observed in experiments on small signal RF measurements. The results are consistent with the phenomenon of hot-phonon build-up and ultrafast decay due to the phonon–plasmon coupling at the resonant 2DEG density.

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ACRONYMS

HEMT: High Electron Mobility Transistor
RF: Radio Frequency
MW: Microwave
LNA: Low Noise Amplifier
2DEG: Two-dimensional Electron Gas
LFPN: Low-frequency Phase Noise