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Degradation in InAlN/AlN/GaN heterostructure field-effect transistors as monitored by low-frequency noise measurements: Hot phonon effects

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Low-frequency noise technique was applied to analyze performance of nearly lattice-matched InAlN/AlN/GaN heterostructure field-effect transistors and their degradation caused by electrical stress. Nearly identical devices from the same wafer have undergone a 7 h DC electrical stress at a fixed DC drain bias of $V_{DS} = 20$ V and different gate biases. We noted up to 32 dB/Hz higher low-frequency noise for stressed devices over the entire frequency range of 1 Hz-100 kHz. The measurements showed the minimum degradation at a gate-controlled two-dimensional electron gas density of 9.4×10^{12} cm^{-2}. This result is in good agreement with the reported stress effect on drain-current degradation and current-gain-cutoff-frequency measurements and consistent with the ultrafast decay of hot-phonons due to the phonon–plasmon coupling. © *2011 American Institute of Physics*. [doi:10.1063/1.3624702]

GaN-based heterostructure field-effect transistors (HFETs) continue to promise potential for high power radio frequency (RF) and switching applications owing to their high drain breakdown voltage, high electron density, and high electron saturation velocity,[1] Particularly, InAlN/GaN-based HFET structures reached two-dimensional electron gas (2DEG) densities up to 3×10^{13} cm^{-2} (Refs. 2–4). However, higher current density leads to more heat generated in the GaN channel unless care is taken to enhance heat dissipation. The main avenue for 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.[5,6] Since the LO-phonon emission by hot electrons is faster than the decay rate of these phonons to acoustic phonons, the non-equilibrium population of LO phonons builds up (referred to as hot phonons).[7] Moreover, the hot-electron and hot-phonon temperatures were shown to be approximately equal meaning that the hot electrons and hot phonons were constituents of 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.[8] The bottleneck is often quantified in terms of hot-phonon lifetime. The concept of this power dissipation bottleneck is crucially important for power HFET operation.[9]

Studies conducted on bulk GaN (Refs. 10 and 11) and GaN 2DEG channel[8,12–14] showed that the hot-phonon lifetime depends on the electron density. For example, time-resolved Raman spectroscopy exhibited almost an order of magnitude drop in the hot-phonon lifetime when the bulk density of electrons increased from 10^{16} to 10^{19} cm^{-3}.[10] This monotonous decrease in lifetime was explained by a plasmon–LO-phonon coupling model.[11] Moreover, in 2DEG channels, the shortest value of the lifetime was attained at the electron density for which the plasma and LO-phonon frequencies approached each other, i.e., the resonance condition. A resonant 2DEG density of $\sim 6.5 \times 10^{12}$ cm^{-2} has been observed at low fields.[6] The resonance was also observed in current-gain-cutoff-frequency measurements carried out on the InAlN/AlN/GaN HFETs, and the highest drift velocity corresponded to a 2DEG density of 9.3×10^{12} cm^{-2} at high fields.[15]

The build-up of hot phonons at high fields increases lattice vibrations and may possibly contribute to device degradation through additional defect generation due to the already defective GaN, aided by its pyroelectric and piezoelectric crystal structure.[16,17] Likelihood of defect generation by enhanced lattice vibrations can be further supported by strong confinement of the hot phonons to a relatively narrow portion of the momentum and real spaces in an HFET channel.[8] It then follows that the effect of hot phonons on defect generation can be minimized at the resonant 2DEG density which causes a rapid decay of hot-phonons. This has motivated the attempts to analyze degradation of performance of nearly lattice-matched InAlN/AlN/GaN HFETs caused by electrical stress as an indirect verification of the role of hot phonons. The impact of hot-phonon lifetime in current degradation of InAlN/AlN/GaN HFET was reported earlier by applying high-field electrical stress.[18] The lowest degradation of the drain current was obtained at the resonant 2DEG density of approximately 1×10^{13} cm^{-2} near to the value of 9.3×10^{12} cm^{-2}, which was obtained from the shortest signal delay time in a similar HFET at the same bias.[15]

It is highly beneficial to expand the study using more sensitive measurement techniques such as low-frequency noise, which is particularly useful to address the mobility and trap-related fluctuations in an HFET channel and its vicinity.[19,20] This may pave the way to answer the question: How and where does the trap generation occur in the HFET structures? In this report, our goal is use the low-frequency phase-noise technique to monitor and verify the effect of the high-field electrical stress and its close relation to the hot-phonon lifetime as a function of the applied gate bias and, therefore, the effective electron density in the channel.

The InAlN/AlN/GaN structure was grown on a sapphire substrate in a metalorganic chemical vapor deposition

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system.[18] The 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 HFET devices were fabricated and mesa isolation was etched 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).

The HFETs were selected for testing 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 2.3×10^{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) shows the change in the drain current, ΔI_D, measured at $V_{DS} = 5$ V and $V_{GS} = 0$ V, after the electrical stress at $V_{DS} = 20$ V and different gate bias. Consistent with the earlier report,[15] the minimum degradation takes place when the gate voltage during the stress has corresponded to the resonant 2DEG density of 9.2×10^{12} cm^{-2}. The change is below 20% at the resonance, whereas the change above 60% is observed in the samples stressed at zero gate bias when the 2DEG density during the stress has been far away from the resonance. It should be noted specifically that at lower electron densities (lower than the resonant 2DEG density), the degradation is worse in spite of lower drain current.

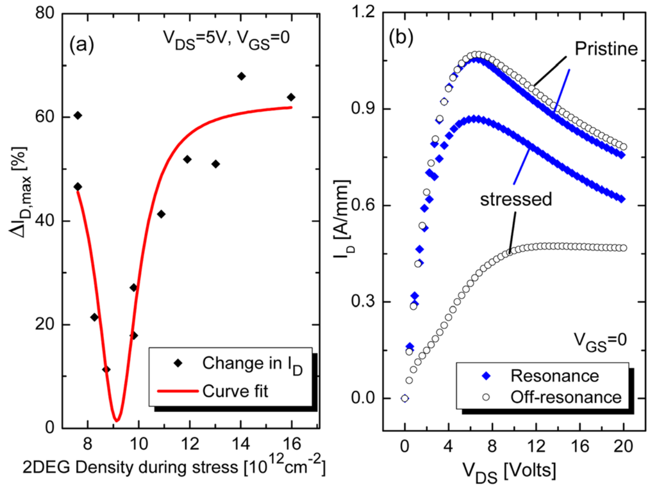

FIG. 1. (Color online) (a) Change in drain current ΔI_D due to the stress at $V_{DS} = 20$ V vs. the 2DEG density during the stress and the Lorentzian fit; the minimum degradation occurs at a sheet density of ~9.2×10^{12} cm^{-2} corresponding to a drain current density of 0.55 A/mm. (b) A representative 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).

Two representative HFETs have been stressed at resonant and off-resonant 2DEG density conditions (Fig. 1(b)). The off-resonant stress causes some gate-lag (open circles) in addition to the severe drain-current drop compared with the devices stressed at resonant 2DEG density condition (closed diamonds). We suggest the following account for these observations: The hot-phonon build-up under the off-resonant bias conditions causes both the drain–gate access region degradation and trap generation in the barrier and buffer due to the thermally isolated subsystem of hot electrons and hot-phonons.

We also monitored low-frequency phase noise for each device relative to a 4 GHz carrier signal using an Agilent 5505 test set. More details on this particular technique can be found in Refs. 19–21. After noting the least amount of degradation to be corresponding to the resonant 2DEG density, we obtained the change in the noise values from the data acquired in parallel with the DC measurements. Fig. 2 shows the representative noise data in the normalized power spectral density (PSD) units. The noise spectra exhibit no peak due to generation–recombination noise associated with a single trap. The pristine devices exhibited almost identical noise spectral densities. The stress condition corresponding to the resonant 2DEG density ($V_{GS} = -4$ V) yielded a 12 dB increase in the noise power, whereas the completely off-resonant stress conditions ($V_{GS} = -2$ V and $V_{GS} = -5.5$ V) exhibited an increase of about 30 dB.

The change in normalized PSD at 1 kHz as a function of the 2DEG density (under stress) is estimated for different gate biases (Fig. 3). The trend in the normalized noise data strongly correlates with that of the ΔI_D data [(Fig. 1(a)]. A sharp resonance is resolved at a sheet density around 9.4×10^{12} cm^{-2} (fitting line). This value is consistent with the values of 9.2×10^{12} cm^{-2} and 9.3×10^{12} cm^{-2} obtained from Fig. 1(a) and current-gain-cutoff-frequency measurements at high fields,[15] respectively. The reduction in the RF power output (ΔP_{out}) at 4 GHz carrier frequency plotted as a function of the 2DEG density during the stress is shown in the inset (Fig. 3). The results support the noise data: the devices stressed at a given gate bias demonstrate the minimum power loss at the

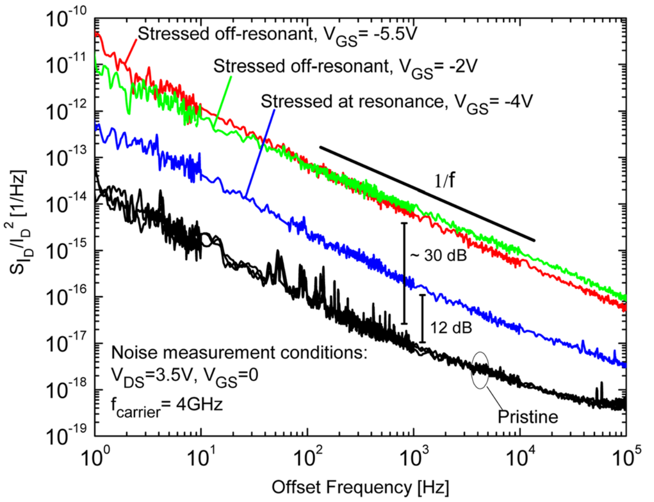

FIG. 2. (Color online) The normalized noise data (S_{ID}/I_D^2 vs. offset frequency) for resonant and off-resonant 2DEG densities under stress. The PSD shows no peak of a single generation–recombination source for both pristine and stressed devices.

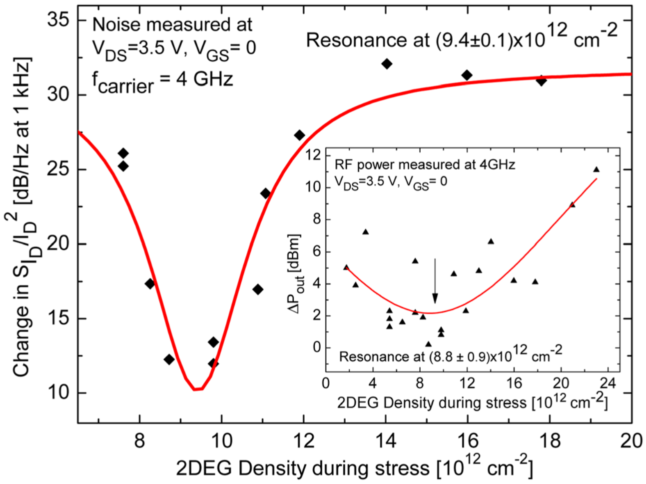

FIG. 3. (Color online) Increase in the noise measured at zero gate bias after 7 h electrical stress at 20 V drain bias as a function of channel 2DEG density during stress controlled by the gate bias. The clear resonance is observed at a 2DEG density around 9.4×10^{12} cm^{-2} (fitting line) corresponding 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 4 GHz after stress 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 arrow marks the resonant 2DEG density.

same optimal 2DEG density. As expected, these high-field values are slightly larger compared to the low-field resonant 2DEG density ($\sim 6.5 \times 10^{12}$ cm^{-2}) obtained for 2DEG channels from density dependence of the hot-phonon lifetime estimated from the microwave noise.[12–14] The reason for this difference was explained in Ref. 18—hot-electrons spread over a larger volume in a GaN channel, and a higher 2DEG density is required to reach the resonance.

Indeed, the low-frequency noise technique turns out to be a very sensitive diagnostic tool for both mobility and number fluctuations in the channel of a device and offers valuable information on trap activity and for its analysis.[19,22] The devices exhibit dramatically higher normalized PSD values in the range from 12 dB/Hz to 32 dB/Hz after being subjected to the stress at $V_{GS} = -4$ V and $V_{GS} = -2$ V, respectively. On the left-hand side of the resonance, the noise increases up to 28 dB/Hz at $V_{GS} = -5.5$ V. Compared to the stress at the resonant conditions, the HFETs stressed at completely off-resonant 2DEG densities exhibit up to 16–20 dB higher noise values for the left-hand and the right-hand sides of the resonance, respectively. These results combined with the data in Fig. 1(b) suggest that either number or mobility fluctuations or both contribute to the degradation. At the resonant 2DEG density condition, the degradation of the GaN channel quality and mild deep-trap generation in the buffer layer can be responsible for the higher noise and stronger drain-current drop.[23] However, under the off-resonance conditions, up to 20 dB more degradation as observed from the PSDs was caused by carrier number fluctuation as a result of trap generation in the barrier and buffer layers as well as the amplified mobility-fluctuations due to the damage in GaN-channel. In this context, the current transient (gate-lag) measurements[24] were also performed on pristine and highly degraded devices at 430 K for up to 5 ms pulse durations. Drain current is almost totally lost in degraded HFETs as opposed to a very small drop for pristine devices and no recovery observed for both indicating that generation of deep traps in GaN buffer. In addition, a permanent loss in the drain current caused by stress implies that the channel degradation is likely. Further measurements and analyses are warranted to shed additional light on this matter such as photoionization of possible deep traps in buffer layer[25] and change in channel resistance due to degradation.

In conclusion, low-frequency noise measurements on InAlN/AlN/GaN HFETs show that degradation due to high-field stress is 16–20 dB/Hz lower at a resonant 2DEG density of 9.4×10^{12} cm^{-2} compared with those degraded at off-resonant conditions. This 2DEG density value is consistent with the resonances observed in experiments on the current-gain-cutoff frequency and the effect of electrical stress on the drain current. The relatively small stress-induced increase in noise at the resonance is attributed to the mild damage of the channel, whereas at off-resonant conditions, the additional noise is believed to be caused by the generation of barrier traps and damage to the channel itself. 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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