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Degradation in InAlN/GaN-based heterostructure field effect transistors: Role of hot phonons

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We report on high electric field stress measurements at room temperature on InAlN/AlN/GaN heterostructure field effect transistor structures. The degradation rate as a function of the average electron density in the GaN channel (as determined by gated Hall bar measurements for the particular gate biases used), has a minimum for electron densities around 1×10^{13} cm^{-2}, and tends to follow the hot phonon lifetime dependence on electron density. The observations are consistent with the buildup of hot longitudinal optical phonons and their ultrafast decay at about the same electron density in the GaN channel. In part because they have negligible group velocity, the build up of these hot phonons causes local heating, unless they decay rapidly to longitudinal acoustic phonons, and this is likely to cause defect generation which is expected to be aggravated by existing defects. These findings call for modified approaches in modeling device degradation. © *2009 American Institute of Physics.* [doi:10.1063/1.3271183]

InAlN/GaN heterostructure field effect transistors (HFETs) offer some benefits over AlGaN/GaN HFETs for high frequency/high power applications, and are as such the subject of intense research.[1–5] The reason for the drive to InAlN is twofold. First, InAlN can be grown lattice matched to GaN which is important since the strain present in AlGaN-based HFETs could be eliminated, which bodes well for the long term reliability of the devices.[6–10] Second, the large difference in spontaneous polarization between GaN and lattice matched InAlN leads to a high density two-dimensional electron gas (2DEG), above 2.5×10^{13} cm^{-2}, which translates into higher current densities and therefore potentially higher power as compared to typical AlGaN-based HFETs.[1] Although touted as a blessing, when one considers the high electron densities that have been achieved in InAlN-based devices,[5,11] it becomes even more imperative to consider the dissipation of the heat from the GaN channel. The power dissipation from hot electrons to the thermal bath[12,13] is illustrated in Fig. 1. High fields, present in a GaN channel of a HFET, give rise to nonequilibrium (hot) electrons which tend to lose their heat mainly through interaction with nonequilibrium LO phonons (hot phonons) because of strong electron-phonon coupling in this highly ionic material. In less ionic semiconductors with reduced electron phonon coupling, hot electrons are able to lose energy directly to longitudinal acoustic (LA) phonons. Having been generated in the GaN channel, the LO phonons with very low group velocity tend to remain localized in the channel, and their energy cannot be dissipated or removed unless they are converted to some other phonon modes with higher group velocities, such as LA phonons.[12,14] This conversion of LO mode heat into LA mode heat can be treated in terms of the LO phonon lifetime, associated with the decay of the hot phonons into e.g., transverse optical and (mobile) longitudinal acoustic modes

through the route LO→TO+LA proposed some time ago.[13] Presently, the exact route of LO phonon decay is not clearly understood but there is compelling evidence for it being through plasmon-phonon interaction.[15,16] When the lifetime of these hot phonons is long enough, a buildup of hot phonons occurs, in turn causing additional scattering,[17] and degrading device performance.[18] Additionally, it can be surmised that the buildup of hot phonons is likely to be intimately related to reliability in GaN-based HFET devices since large quantities of hot phonons will likely lead to generation of new defects, particularly in a piezoelectric and pyroelectric material such as GaN which is defective to begin with. To understand why the hot phonons would generate defects, consider that the hot phonons have been determined to occupy a relatively narrow portion of the momentum space in the channel of a HFET.[14] In this regard, the generation of locally large atomic vibrations and the subsequent
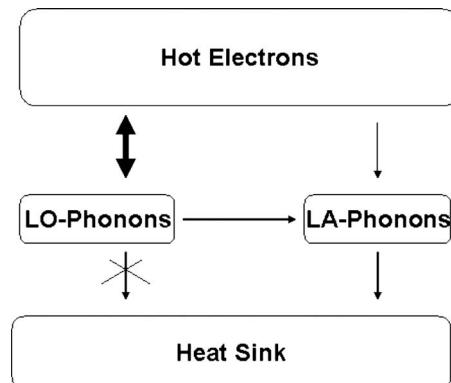
FIG. 1. Schematic demonstration of heat dissipation in a GaN channel. Hot electrons primarily lose their energy through interaction with LO phonons because of large electron phonon coupling in this material. LO phonons in turn decay into LA modes before the heat is removed from the device through the heat sink. The decay of LO mode heat to LA mode heat represents a bottleneck for the overall heat dissipation.

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new crystal defects is likely, particularly in the presence of defects caused by heteroepitaxy on foreign substrates.[19]

Recent measurements of hot phonon lifetimes (τ_{ph}) in InAlN-based structures have provided evidence for the optimal 2DEG density[15,16] as determined by observing a minimum in the phonon lifetime, τ_{ph}, apparently due to the onset of phonon-plasmon coupling which tends to enhance LO phonon decay.[15,20] This provides an impetus for us to seek a correlation between the hot phonon effect and the reliability of the HFET devices. In this work, we subject InAlN/AlN/GaN HFET devices to high field electrical stress under various gate biases for a fixed drain bias and find an essential correlation between two dependences on the 2DEG density: that of the degradation rate and that of the hot phonon lifetime. This work represents a study of degradation in different conditions of "on-state" high power biasing, where electric fields are high and hot electron or hot phonon effects are expected to play a role in device degradation. Previous degradation studies utilizing dc stresses at room temperature tend to focus on a single on-state bias condition where hot carriers are expected to participate in degradation.[9,10,21–24] The results are then often compared to the degradation realized under off-state conditions (high fields and low current), under on-state low power conditions (low fields and high current), or to devices subjected to different processes (i.e., to determine the effect of passivation, surface treatment, use of field plates, etc.). Our observations, utilizing biases in which hot electrons are expected to play a dominant role, are consistent with the proposition that hot phonons constitute an efficient degradation mechanism in these heterostructures and that the control of their lifetimes can be used to tailor the degradation rate.

The lattice matched InAlN/AlN/GaN HFET structures were grown on sapphire substrates in a low-pressure custom-designed organometallic vapor phase epitaxy system using trimethylgallium, trimethylaluminum, trimethylindium, and ammonia as the Ga, Al, In, and N sources, respectively.[5] The structure consisted of a 250 nm AlN initiation layer grown at $\sim$1030 °C, 3 μm of undoped GaN deposited at $\sim$1000 °C, a 1 nm AlN spacer layer grown at 1000 °C, a 20 nm In$_{0.15}$Al$_{0.85}$N barrier layer grown at 800 °C, and a 2 nm GaN cap layer grown at 900 °C. HFET devices and a gated Hall bar were fabricated using Ti/Al/Ni/Au Ohmic contacts followed by etched mesa isolation in a SAMCO inductively coupled plasma etcher in a Cl-based chemistry. Finally, the standard liftoff procedure was used to form gate electrodes of Pt/Au (thickness 30/50 nm, length/width 2/90 μm). The devices were not passivated.

As mentioned above, the bottleneck to overall heat dissipation is the conversion of hot LO modes into the mobile LA modes, and this conversion can be treated in terms of a hot phonon lifetime. This lifetime is known to depend on the 2DEG density. In our experiment, we controlled the electron density with the gate voltage and used gated Hall effect measurements for an estimation of the 2DEG density. Armed with this knowledge, we subjected the HFET devices to high field stress (V_D=20 V) in the dark at room temperature. We stressed the devices for periods of time up to 20 h, and observed the maximum drain current, peak transconductance, and channel access resistances every hour or half hour in order to quantify the device degradation. Simultaneously, we measured the gate leakage current during the stress and ob-
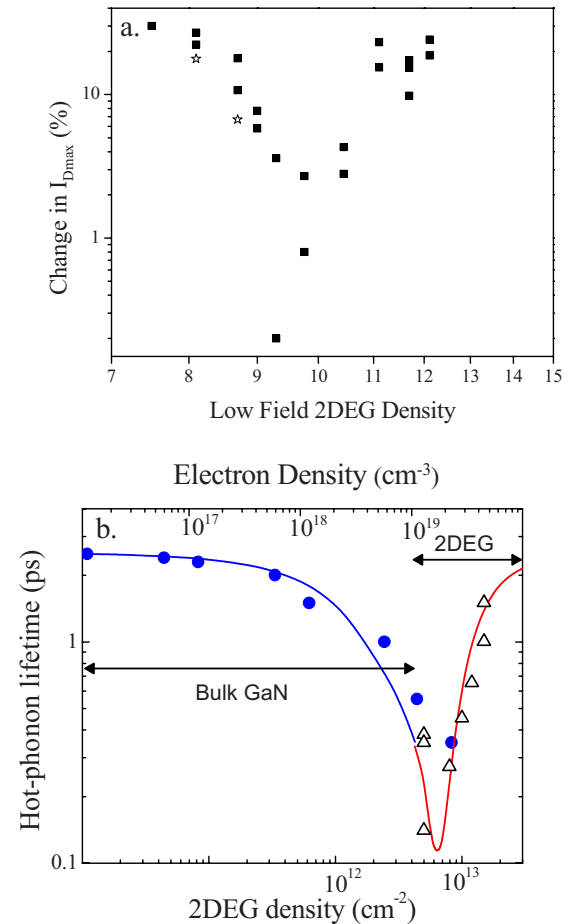

FIG. 2. (Color online) (a.) Change in maximum drain current after subjecting devices to high field electrical stress. The change is given for devices which have passed 1500 mA h/mm of charge. The electron density is controlled by the gate bias. The stars represent devices that were stressed at a reduced drain voltage so that the devices were subjected to V_{DG}=24 V, which is the same as that employed for the devices stressed with 2DEG density $\sim$10.5$\times$10^{12} cm^{-2}. (b.) Measured hot phonon lifetimes vs electron density for GaN 3D (solid circles) and GaN 2DEGs (open triangles) at low fields. The existence of a minimum around 6.5$\times$10^{12} cm^{-2} is attributed to the phonon-plasmon resonance, from Ref. 16.

served the level of degradation, at a fixed electron density, as a function of the total charge passed through the drain and the gate electrodes. In this vein, we can fairly compare degradation of the devices subjected to low, moderate, and high current.

For all devices subjected to high field stress we observed a general trend of a reduction of maximum drain current and peak transconductance, as well as an increase in channel access resistances as stress proceeded. These observations are consistent with other reports in which devices were subjected to high fields and subsequent hot electron effects.[21–24] Figure 2(a) shows the change in the maximum drain current for the HFET devices subjected to high field electrical stress (V_D=20 V) at gate voltages from −3 to −7 V after a charge of 1500 mA h/mm has passed through the drain. We use the change in the maximum drain current as the parameter of interest as it is the most prominent feature of the degradation. Stars show the same albeit for devices wherein the drain voltage was reduced so that the drain-gate bias (V_{DG}=24 V) is maintained in order to exclude possible degradation due to high V_{DG} for devices subjected to high negative gate bias, corresponding to electron densities below 9
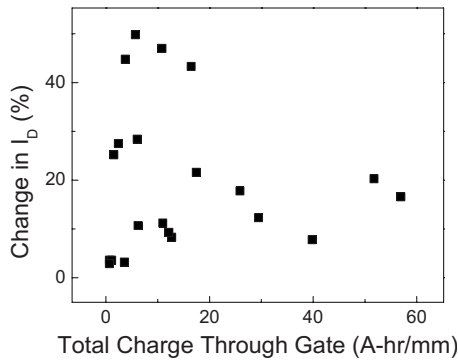
FIG. 3. The total change in drain current for all devices in this study vs the total charge passed through the gate. The lack of any discernable dependence of degradation on the gate leakage indicates that the primary degradation mechanism is not related to the gate leakage.

$\times 10^{12}$ cm^{-3}. Clearly, the degradation rate exhibits a minimum at electron densities around 10^{13} cm^{-2}. This dependence on the 2DEG density [Fig. 2(a)] is strikingly similar to the dependence of the LO phonon lifetime on the 2DEG density [Fig. 2(b)]. The figure shows that the degradation rate decreases to a minimum, then increases again as a function of the average channel sheet density. This is despite the fact that at lower sheet densities, the devices are being subjected to lower power densities (and therefore channel temperatures)[25] and additionally devices subjected to comparable lateral fields still tend to degrade at higher rates. As such, we propose that the buildup of hot phonons plays a considerable role in the device degradation.

If the degradation were attributable to the buildup of hot phonons, the least degradation would be expected at the 2DEG density around 6.5×10^{12} cm^{-2} where the shortest lifetime τ_{ph} is expected [Fig. 2(b)]. Our stress measurements show the weakest degradation for slightly higher electron densities. This can be understood in the following way. Hot electrons tend to occupy a larger volume in real space when they gain energy from the electric field. Therefore, the "bulk" density of electrons decreases as the field applied to the channel increases. As a result, a higher 2DEG density is needed to reach the phonon-plasmon resonance, and the minimum LO phonon lifetime is achieved at the 2DEG density exceeding the optimum value measured at low fields [6.5×10^{12} cm^{-2}, as in Fig. 2(b)]. Experimental evidence for such a phenomenon was recently reported in Ref. 16. Measurements on gateless devices with low field 2DEG densities greater than 6.5×10^{12} cm^{-2} as a function of applied power showed that the hot phonon lifetime first decreases to a minimum, then begins to increase again as the power increases, showing that the 2DEG density needs be higher than the low field optimal 2DEG density (6.5×10^{12} cm^{-2}) in order achieve phonon-plasmon resonance at a high field.[16]

As a final endeavor in attributing the buildup of hot phonons as the primary degradation mechanism rather than some gate leakage related mechanism, we quantified the degradation for all the devices in this study as a function of the total amount of charge which has leaked through the gate (Fig. 3). No systematic degradation with the gate leakage is found; some devices suffer high degradation with little gate leakage, some suffer little degradation with high gate leakage. The lack of the dependence on the gate leakage leads us inevitably to conclude that the gate leakage is not a major contributor to the degradation for these devices.

In conclusion, we subjected lattice matched InAlN/AlN/GaN HFET structures to electrical stress at high bias for extended periods of time. We found that the amount of degradation as a function of the 2DEG density in the channel appeared to follow the same trend known for the hot phonon lifetime as a function of 2DEG density. The least device degradation is observed for a 2DEG concentration which leads to a minimum in hot phonon lifetime, determined independently. Therefore, we propose that the buildup of hot phonons plays an essential role in the degradation of the HFET devices. Further efforts to suppress the degradation rate should consider the role played by hot phonons in device reliability, particularly in channels with low and high 2DEG densities. This also explicitly implies that hot phonon effects must be included in realistic degradation modeling efforts.

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