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Effect of hot phonon lifetime on electron velocity in InAlN/AlN/GaN heterostructure field effect transistors on bulk GaN substrates

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We report on electron velocities deduced from current gain cutoff frequency measurements on GaN heterostructure field effect transistors (HFETs) with InAlN barriers on Fe-doped semi-insulating bulk GaN substrates. The intrinsic transit time is a strong function of the applied gate bias, and a minimum intrinsic transit time occurs for gate biases corresponding to two-dimensional electron gas densities near $9.3\times10^{12}\ \text{cm}^{-2}$. This value correlates with the independently observed density giving the minimum longitudinal optical phonon lifetime. We expect the velocity, which is inversely proportional to the intrinsic transit time, to be limited by scattering with non equilibrium (hot) phonons at the high fields present in the HFET channel, and thus, we interpret the minimum intrinsic transit time in terms of the hot phonon decay. At the gate bias associated with the minimum transit time, we determined the average electron velocity for a 1.1 μm gate length device to be $1.75\pm0.1\times10^{7}\ \text{cm/sec}$. © *2010 American Institute of Physics*. [doi:10.1063/1.3358392]

Electron energy dissipation within the high field regime associated with a GaN heterostructure field effect transistor (HFET) channel is dominated by the electron interaction with optical phonons, mainly longitudinal optical (LO) phonons, due to the very strong Fröhlich interaction associated with the highly ionic GaN crystal.[1] However, as the LO phonons have very low group velocity, they tend to build up, causing the equilibrium values for the occupancy of the phonon states to be exceeded and subsequently forming a "hot phonon" cloud in the channel. The strong hot electron-hot phonon scattering both decreases electron velocities[2,3] and additionally keeps heat trapped in the channel[4,5] unless the hot phonons can decay into propagating (acoustic) modes and exit. Electron drift velocities in biased GaN two-dimensional electron gas (2DEG) channels are known to be limited by this hot phonon effect, as confirmed by realistic Monte Carlo simulations.[6,7] In the case wherein the electron velocity is limited by the hot phonon effect, the velocity can be expected to be improved only if the decay of hot phonons can be accelerated, or equivalently, the lifetime of the hot phonon can be reduced.

The hot phonon lifetime appears to be dependant on the power applied to and the electron density in GaN 2DEGs, and is understood in terms of the interaction between hot phonons and plasmons.[8,9] According to experiments at low fields, the hot phonon lifetime in a GaN 2DEG exhibits a minimum at a 2DEG density of $\sim6.5\times10^{12}\ \text{cm}^{-2}$.[10] This is understood as one considers that dispersion curves of the phonon (independent of electron density, n) and the plasmon ($\propto\sqrt{n}$) intersect at the LO phonon energy of 92 meV and near a bulk electron density of $\sim10^{19}\ \text{cm}^{-3}$. For 2DEG densities greater or less than this density, the hot phonon lifetime increases. Measurements of the hot phonon lifetime utilizing the microwave noise temperature technique[7] at low fields for a number of 2DEGs in GaN channels have been compiled and appear to support the phonon-plasmon resonance model,[8,10] as shown in Fig. 1, open squares. Furthermore, application of electric field to a 2DEG tends to heat up the electrons (relaxing the confinement), causing their bulk density to decrease and/or causing the plasmon frequency to decrease, thus making the optimal density (the density at which the hot phonon lifetime is minimum) accessible for higher density 2DEGs at high applied powers.[3] The implication is that the minimum lifetime can be reached at high applied powers for 2DEG densities higher than $\sim6.5\times10^{12}\ \text{cm}^{-2}$

Evidence for the power dependent hot phonon lifetime is illustrated in Fig. 1. For a device with a 2DEG density of $0.8\times10^{13}\ \text{cm}^{-2}$, the value of hot phonon lifetime tends to decrease to a minimum and subsequently begins increasing again as the power applied to the 2DEG is increased further and further, Fig. 1, closed squares. The solid lines are a fit using a simple resonance curve,[11]

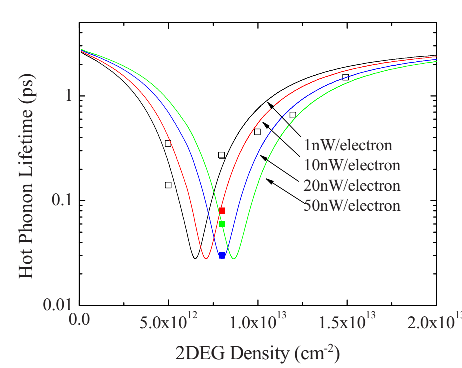

FIG. 1. (Color online) (Open squares) experimentally measured hot phonon lifetimes for various GaN-based 2DEGs measured by the microwave noise technique at low power and from intersubband absorption. Details of the layers can be found in Ref. 10. (Closed squares) experimentally measured lifetimes for a 2DEG with a fixed density of $0.8\times10^{12}\ \text{cm}^{-2}$ at various applied powers. The power dependant data can be found in Ref. 10. The solid lines are a fit using the simple resonance curve expressed in Eq. (1).

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$$\tau_{LO} = a\left\{1 + \frac{b}{(\sqrt{n} - \sqrt{n_{res}})^2 + c}\right\}^{-1}, \quad (1)$$

where n is the 2DEG density, n_{opt} is the "optimal" 2DEG density at the phonon-plasmon resonance, and a, b, c are fitting parameters which control the value of the lifetime far from resonance, the "sharpness" of the resonance curve, and the value of the minimum lifetime. The value of n_{opt} is shifted to higher electron densities as the applied power increases, to match the data reported in 10. We used values of n_{opt} of 6.5, 7.1, 8.0, and 8.65×10^{12} to generate the curves for applied powers of 1, 10, 20, and 50 nW/electron. Note that the value of the lifetime far from the resonance position is around 2.5 ps, which matches the experimental data at low densities.[12] The power applied to an average electron is estimated in the following way: when the power dissipated equals the power applied under steady state conditions, the applied power per electron is $P_e = VI/N_e$ where V and I represent the voltage drop across and current through the channel, respectively, and N_e is the number of electrons in the channel represented by the product of the surface area of the channel with the 2DEG density.

Other evidence of the phonon-plasmon model for hot phonon lifetime was presented in Ref. 13 wherein the control of the lifetime as a function of gate bias (controlling the 2DEG density) was inferred through the degradation of HFET structures. In this work, we present additional direct evidence of the optimal 2DEG density in terms of device performance by deducing the electron velocity from the transistor unity gain cutoff frequency. We measure the electron velocity as a function of bias conditions and find that the optimal 2DEG density in terms of a maximum electron velocity can be obtained for 2DEG densities near 9.3×10^{12} cm^{-2}, where the velocity is $\sim1.75\times10^{7}$ cm/sec for a 1.1 μm gate length. Our estimates, which are inclusive of the power dependence of hot phonon lifetime are consistent with the established phonon-plasmon model. As such, we interpret the maximum in electron velocity in terms of a minimum in hot phonon lifetime.

Several development approaches in InAlN-based structures have resulted in very respectable performance lately in terms of dc,[14,15] rf,[16] and electron velocities,[17] and such approaches were utilized for this study. InAlN/AlN/GaN HFET structures were grown on c-plane semi-insulating GaN:Fe substrates (with a bulk resistivity of $\sim10^{9}$ Ω cm)[18,19] by MOCVD. Growth and fabrication details can be found in Ref. 16. The devices were not passivated. Schottky diodes, incorporated into the HFET masks, were fabricated alongside the HFET devices in order to determine the 2DEG density in the regions directly adjacent to the devices under test. High resolution x-ray diffraction was used to confirm the barrier layer thickness and composition.

On-wafer microwave measurements from 2 to 20 GHz were carried out using an HP8510B vector network analyzer. The S-parameters were collected under many dc bias conditions and subsequently were used to compute the small signal current gain, H_{21}. By collecting small signal current gain cutoff frequencies at various bias conditions, we were able to perform Moll's transit time analysis[20] as is often employed.[16,21–23]

Capacitance-voltage (C-V) measurements on the Schottky diodes were conducted in order to estimate the

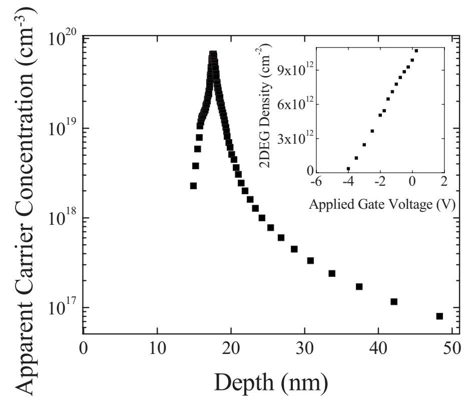

FIG. 2. Electron density vs depth profile deduced from CV- measurements of a Schottky diode and (inset) integrated electron density for various biases. The values represent the approximate 2DEG density.

2DEG density by using the typical expression of,

$$n = -2\left\{\varepsilon q A^2 \frac{d(1/C^2)}{dV}\right\}. \quad (2)$$

Here ε is the dielectric constant ($8.0^*\varepsilon_0$ for InAlN), q is the electron charge, and A is the area of the diode. The electron density as a function of the depletion depth, $\varepsilon A/C$, is plotted in Fig. 2. An estimate of the 2DEG density as a function of applied voltage can then be obtained by integrating the density vs. depth profile with respect to the applied voltage, as shown in the inset to Fig. 2. The 2DEG density changes linearly with the applied voltage, and the value at which the density approaches zero is close to −4 V, which is consistent with the transistor pinchoff voltage.

Using the results obtained for the 2DEG density versus the gate bias, the transit time analysis can be performed using the cutoff frequencies, which were measured at drain biases ranging from 12 to 16 V in 2 V steps and at gate biases ranging from 0.25 to −1.5 V in 0.25 V steps. The maximum cutoff frequency for the 1.1 μm gate length device was 14.2 GHz, associated with a bias condition of $V_D = 14$ V, $V_G = -0.5$ V. From the measured cutoff frequencies the intrinsic transit time was calculated as follows (explained in greater detail with figures in 16). First, the intrinsic transit time plus the time constant associated with the charging of the RC components of the HFET equivalent circuit ($\tau_{int} + \tau_{RC}$) is obtained by plotting the total transit time, $(2\pi f_T)^{-1}$, at constant gate bias versus the voltage drop across the channel (the applied voltage minus the voltage drop across the access resistances, which was measured under bias using the method presented in Ref. 24, $R_S + R_D = 24$ Ω) and extrapolating to the vertical axis. In this way, the contribution of the drain delay, τ_D, can be eliminated. Next, the intrinsic transit time plus the drain delay is determined by plotting the total transit time versus the inverse current density in the channel for a given drain bias. By extrapolating to the axis in this case, the time constant associated with RC components' charging can be eliminated. After determining $\tau_{int} + \tau_{RC}$ and $\tau_{int} + \tau_D$, we can calculate the intrinsic transit times at a given bias. The intrinsic transit time is plotted in Fig. 3 as a function of the 2DEG density determined from the CV measurements (Fig. 2, inset) for each of the drain biases used in the analysis. One can see that a clear minimum in the intrinsic transit time exists for 2DEG densities near 9.3×10^{12} cm^{-2} for each drain bias. The electron velocity corresponding to

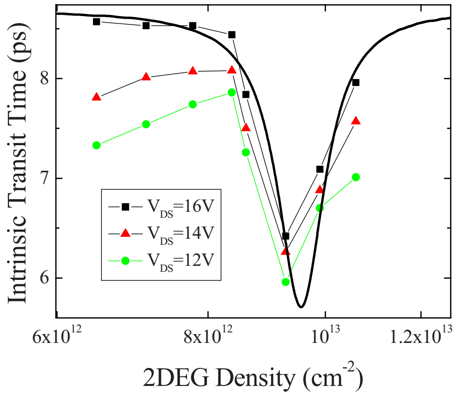

FIG. 3. (Color online) Intrinsic transit time as a function of the 2DEG density. The density corresponding to the minimum intrinsic transit time is consistent with that corresponding to the minimum hot phonon lifetime.

minimum transit time is estimated to be $v=(L_G/\tau_{\text{int}}) \sim 1.75 \pm 0.1 \times 10^7$ cm/sec. Also in the figure, we include a fitting after Eq. (1) (solid line); the best fit occurs using an optimal electron density of 9.5×10^{12} cm^{-2}.

The existence of a minimum in the intrinsic transit time, or a maximum in the electron velocity at a particular 2DEG density can be understood in terms of the hot phonon effect on the device performance discussed earlier. In the regime where the hot phonon effect is prominent, i.e., when electric field in the channel is high, we expect the velocity to increase as the lifetime decreases. As illustrated in Fig. 1, the hot phonon lifetime is a non-monotonic function and exhibits a minimum for a 2DEG density near 6.5×10^{12} cm^{-2} at low fields, which increases with application of power. We estimate the applied power to electron in our device (at the bias conditions at which the intrinsic transit time is minimum) to be $0.058(\text{A}) \times \{V_{\text{applied}} - [24(\Omega) \times 0.058(\text{A})]\}$ after correcting for the source and drain access resistances. Using this and the estimate of the number of electrons at the minimum (3 [μm]$\times$90 [μm]$\times 9.3 \times 10^{12}$ [electrons/cm^2]), we estimate the average power dissipated per electron to be ~25–35 nW/electron, for V_{DS} between 12 and 16V. Note that the difference in the powers applied when changing drain voltage from 12 to 16 only corresponds to an increase in power applied to the electrons of a factor of 1.25; therefore we do not expect to be able to resolve different positions of the velocity maximum (in terms of 2DEG density) for the drain biases shown in Fig. 3. From the power dependent data presented in Fig. 1, we would expect that a shift in the hot phonon lifetime curve resulting in a minimum lifetime occurring around 9.3×10^{12} cm^{-2} should correspond to an applied power of ~>50 nW/electron. Considering the simplicity of our approximations, and the fact that the actual electric field and subsequently the actual power applied is a function of the spatial position under the gate (in the region where hot phonon effects would tend to play the most important role, near the drain side of the gate, the actual electric field is quite large and the density of carriers reduced; the energy of these electrons would likely be higher than our estimate), this value of 2DEG density for a minimum hot phonon lifetime in our device of 9.3×10^{12} cm^{-2} is quite reasonable in our opinion. The reason for the decrease in intrinsic transit time at higher reverse gate biases for the lower drain bias conditions is not fully clear but could tentatively be attributed to a mitigation of the hot phonon effect for low density 2DEGs (Ref. 3) or simply to a reduction in the Joule heating of the sample under lower applied power.

In conclusion, we have demonstrated non-monotonically varying electron velocities in InAlN/AlN/GaN HFET structures (determined from an examination of the current gain cutoff frequency) which we associate with the non-monotonic change in independently determined hot phonon lifetime. In light of the deleterious effects of hot phonons on device performance and reliability, we propose that optimal performance can only be expected when the device is operating under bias conditions in which the 2DEG density associated with the given bias condition is congruent with the value associated with the shortest hot phonon lifetime.

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