Evidence of hot electrons generated from an AlN/GaN high electron mobility transistor

Suvranta K. Tripathy, Guibao Xu, Xiaodong Mu, and Yujie J. Ding[a)]
Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, Pennsylvania 18015, USA

Kejia Wang, Yu Cao, and Debdeep Jena
Department of Electrical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, USA

Jacob B. Khurgin
Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, Maryland 21218, USA

(Received 29 August 2007; accepted 12 December 2007; published online 11 January 2008)

We have observed that the temperature of the electrons drifting under a relatively high electric field in an AlN/GaN-based high-electron-mobility transistor is significantly higher than the lattice temperature (i.e., the hot electrons are generated). These hot electrons are produced through the Fröhlich interaction between the drifting electrons and long-lived longitudinal-optical phonons. By fitting electric field versus electron temperature deduced from the measurements of photoluminescence spectra to a theoretical model, we have deduced the longitudinal-optical-phonon emission time for each electron is to be on the order of 100 fs. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2830834]

High-electron-mobility transistors (HEMT's) based on AlGaN/GaN heterostructures have potentials of handling high microwave powers and operating within wide bandwidths.[1,2] However, the accumulation of the longitudinal-optical (LO) phonons emitted by the electrons drifting in a HEMT may cause the device characteristics to deteriorate. Such an accumulation is due to the fact that LO-phonon emission time for an electron is an order of magnitude shorter than the decay time for the LO-phonons. Indeed, using time-resolved backward Raman scattering spectroscopy, the electron-LO-phonon emission time was previously determined to be (50 ± 10) fs,[3] which is close to the theoretical estimate of 10 fs.[4] Another approach to deduce the LO-phonon emission time for an electron is to balance the LO-phonon scattering loss per electron[5,6] and the relaxation rate of the excess energy of the electron system in time domain. Using such a method the LO-phonon emission time was determined to be 0.2 ps.[4] Under a DC electric field, the power loss per electron through its collision with the LO-phonon is approximately equal to the power gain per electron drifting under a DC electric field. Therefore, the LO-phonon emission time was also deduced for an *n*-GaN metal-semiconductor field effect transistor.[7] It is worth noting that most of the previous investigations[3,4,7] were focused on the bulk-GaN structures. On the other hand, the decay time for the LO-phonons in bulk GaN was measured to be 3 ps at room temperature.[8] Therefore, due to the Fröhlich interaction between the long-lived LO-phonons and the electrons, the electron temperature is expected to be higher than the lattice temperature, i.e., the generation of hot electrons. Hot electrons and hot phonons in an AlGaN/GaN channel were investigated using microwave noise technique.[9]

In this letter, we investigate the hot electrons generated in a biased AlN/GaN HEMT using photoluminescence experiment. We show that the hot electrons are produced as a result of the Fröhlich interaction between the long-lived LO-phonons and the electrons drifting in the HEMT and also determine the LO-phonon emission time.

An AlN/GaN-based HEMT, grown by molecular beam epitaxy, consists of a 4 nm AlN layer, a 200 nm unintentionally doped GaN layer, a semi-insulating GaN layer, and a GaN-on-sapphire template layer (from top to bottom). A patterned metallic film was evaporated onto the AlN layer. By wire bonding the selected metal stripes onto bias pads, HEMT devices with different separations between the source and drain can be investigated in turn. For this work, the distance between the source and drain was 30 μm and there is no gate present. Due to the spontaneous and strain-induced piezoelectric polarizations,[2] a two-dimensional electron gas with a high electron density was confined within the GaN layer in the proximity of the GaN/AlN interface. At room temperature, the sheet electron concentration and the electron mobility were measured to be 2.5×10^{13} cm^{-2} and 1200 cm^2/V s, respectively.

Photoluminescence (PL) spectra emitted by the HEMT were measured when the device was pumped by a 3 ps pulsed coherent radiation at the wavelength of 208 nm. Such a pump beam was the output of quadrupling the frequency of the laser pulses at a central wavelength of 832 nm using two β-BaB_2O_4 crystals. The maximum output power of the pump beam was measured to be 3.0 mW. During our experiment, however, the average power of the pump beam focused on the samples surface was fixed to 1.0 mW. At such a pump power, the effect of the pump-induced HEMT heating was negligible. The PL intensity was collected at room temperature for different voltages between the source and drain in the range of 0–30 V. The collected PL signal was sent through a double monochromator and then detected by a photomultiplier tube. A lock-in amplifier was used to reduce the noise of our measurements.

[a)]Electronic mail: yud2@lehigh.edu.

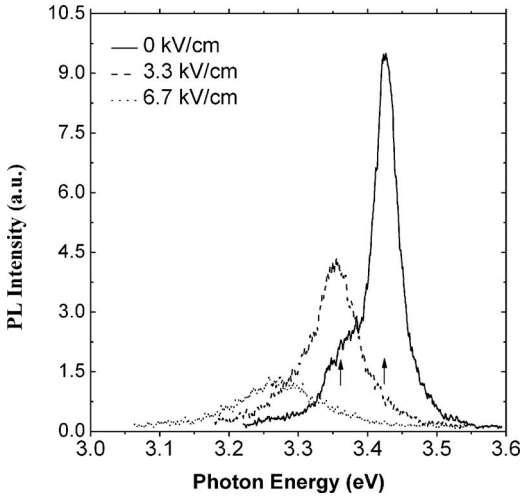

FIG. 1. Photoluminescence spectra measured on an AlN/GaN-based HEMT structure at an excitation wavelength of 208 nm for three different DC electric fields. Arrows mark two transition peaks under the zero electric field.

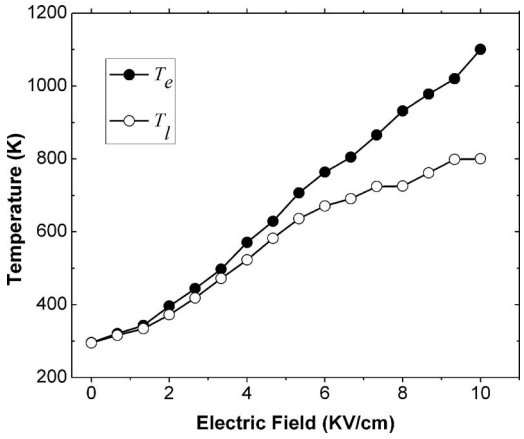

FIG. 2. Electron temperature (filled dots) and lattice temperature (open circles) under different electric fields, deduced from PL spectra (see Fig. 1).

Figure 1 shows the typical PL spectra taken at room temperature. At the zero bias between the source and drain of the HEMT, the PL spectrum is primarily dominated by recombination between electrons and holes in the GaN/AlN channel at 3.425 eV (362 nm).[10] A shoulder at 3.362 eV can be attributed to recombination of excitons in the GaN/AlN channel. With increasing the bias (the corresponding electric field given by the ratio of the bias and the distance between the source and drain), the PL spectrum became more and more broadened while the emission peak was significantly redshifted. The redshift of the dominant PL emission peak was caused by joule heating of the device due to the applied bias voltage through the HEMT (the current can be as high as 85 mA at 30 V). When the electric field was increased, the photogenerated electrons and heavy holes drifted toward the opposite directions. Consequently, the recombination rate between these electrons and heavy holes was subsequently reduced. According to Ref. 11, the bandgap of bulk GaN as a function of temperature is given by

$$E_g(T_l) = E_g(0) - 9.09 \times 10^{-4} T_l^2/(830 + T_l), \tag{1}$$

where $E_g(0)$ is the bandgap of GaN at 0 K and T_l is the lattice temperature. According to Ref. 12, we fitted the low-energy side of each PL spectrum by using $I_{\mathrm{PL}} \propto \sqrt{E - E_g}$ and, therefore, obtained the bandgap (E_g) at each bias. Substituting the resulting bandgap at the zero bias into Eq. (1), we obtained $E_g(0) \approx 3.468$ eV. This value is 42 meV lower than the accepted value of 3.510 eV.[11] Such a difference may be caused by bandgap renormalization due to the high-density electrons present in the AlN/GaN channel. Indeed, in our sample the sheet density of electrons was measured to be 2.5×10^{13} cm^{-2}, which is sufficiently high for causing the effective bandgap to shrink by 42 meV.[13] For the rest of the biases applied to the HEMT, we then used Eq. (1) to determine the corresponding lattice temperatures (see Fig. 2). The obtained lattice temperatures are in a good agreement with the photoluminescence measurements at high temperatures.[14]

Since the effective mass for electrons is much smaller than that for the heavy holes, photogenerated electrons gain much higher kinetic energies than the heavy holes. Consequently, these electrons not only drift under the DC electric field but also emit and absorb LO-phonons through the Fröhlich interaction. Besides the interaction between electrons and LO-phonons, the collision between electrons brings the electrons to an equilibrium at the electron temperature (T_e). The electron temperature for the nondegenerate electrons can be determined by fitting each PL intensity spectrum on the high-energy side using the following dependence:[6,12]

$$I_{\mathrm{PL}} \propto e^{-(E-E_g)/kT_e}. \tag{2}$$

For the PL spectrum measured by us at each bias, we have determined the corresponding value of T_e (see Fig. 2). It is worth noting that the hot-electron temperatures obtained by us are in the same order of magnitude as that determined previously.[9] According to Fig. 2, the electron temperature is quite close to the lattice temperature for the DC electric field less than 5 kV/cm. Above such a value, however, the electron temperature is significantly higher than the lattice temperature (see Fig. 2). This is due to the fact that as the electric field is increased the kinetic energies of the electrons are increased. These more energetic electrons then emit and absorb more LO-phonons. Since the LO-phonon emission time for an electron is much shorter than the decay time of the LO-phonons, the LO-phonons become accumulated in time, which results in the increase of the phonon temperature. Consequently, the electron temperature is also increased.

Under our experimental condition the scattering of the electrons by acoustic phonons is negligible. Therefore, we assume that the dominant mechanism for the energy loss of the electrons at room temperature is the scattering of the electrons by LO-phonons. Under such a case, the power loss per nondegenerate electron is given by[5]

$$P(T_e)_{\mathrm{LO}} = \frac{\hbar\omega_{\mathrm{LO}}}{\tau_{e\text{-ph}}}\left[\frac{e^{(x_0 - x_e)} - 1}{e^{(x_0)} - 1}\right] \times \left[\frac{(x_e/2)^{1/2} e^{x_e/2} K_0(x_e/2)}{\sqrt{\pi/2}}\right] \tag{3}$$

where $\hbar\omega_{\mathrm{LO}} = 91.8$ meV is the LO-phonon energy for GaN, $\tau_{e\text{-ph}}$ is the LO-phonon emission time for an electron, $x_e = \hbar\omega_{\mathrm{LO}}/k_B T_e$, and $x_0 = \hbar\omega_{\mathrm{LO}}/k_B T_l$ with k_B the Boltzmann constant and K_0 is the modified Bessel function of zero order. Under the steady state, the power loss given by Eq. (3) should be approximately equal to the power gain for an electron from the DC electric field. As a result, one can obtain an expression for the DC electric field applied to the HEMT,

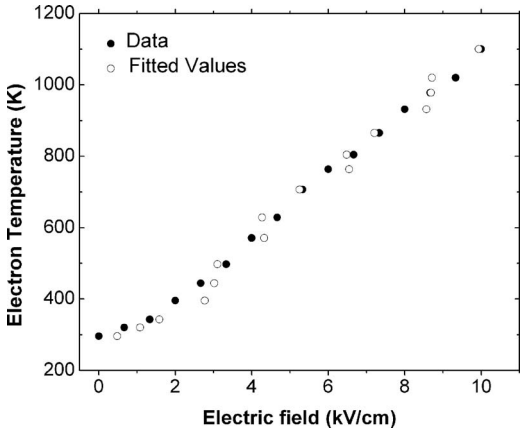

FIG. 3. Electron temperature vs electric field: data (filled dots)—deduced from the PL spectra (see Fig. 1); fitted values (open circles)—after fitting data using Eq. (4).

$$E_{\mathrm{DC}} = \sqrt{P(T_e)_{\mathrm{LO}}/(e\mu_e)}, \tag{4}$$

where e is the charge of an electron and μ_e is the mobility of the electrons.

According to Eq. (4), the DC electric field is as a function of $\tau_{e\text{-ph}}$ whereby T_e and T_l can be replaced by the values deduced from the PL spectra (see Fig. 2). Such a function was then used by us to achieve a nonlinear-least-square fit to the values of the electric fields calculated by the bias applied to the HEMT divided by 30 μm (see Fig. 3). As a result, the LO-phonon emission time for an electron was obtained to be on the order of 100 fs. This value lies between those determined based on time-resolved backward Raman scattering spectroscopy (i.e., 50 ± 10 fs) (Ref. 3) and using a similar approach under the zero electric field (0.2 ps) (Ref. 4) for the bulk GaN. Our value of the LO-phonon emission time is much higher than the theoretical value of 10 fs. Such a discrepancy may be caused by the screening of electron-phonon interaction due to the presence of the high-density electrons in a two-dimensional HEMT.[15] The rate of the energy dissipation for the hot electrons is reduced by the reabsorption of the hot phonons,[16] which may increase the emission time of the LO-phonons.

In conclusion, we have investigated hot-electron effects in an AlN/GaN-based HEMT structure. Through the measurements of PL spectra at different DC electric fields, we have observed that the electron temperature can be significantly above the lattice temperature. Such hot electrons are generated as a result of the Fröhlich interaction between the electrons drifting under a DC electric field and long-lived longitudinal-optical phonons. By assuming that the power loss and gain balance out, we have deduced the LO-phonon emission time for each electron to be on the order of 100 fs. This value is within the same order of magnitude as those determined previously for the bulk GaN.

We are indebted to M. Rosker for valuable discussions. This work has been supported by U.S. AFOSR.

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