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Hot-Phonon Decided Carrier Velocity in AlInN/GaN Based Two-Dimensional Channels

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Nanosecond-pulsed measurements of hot-electron transport were performed for a nominally undoped two-dimensional channel confined in a slightly strained $Al_{0.8}In_{0.2}N$/AlN/GaN and nearly lattice matched $Al_{0.84}In_{0.16}N$/AlN/GaN heterostructures at room temperature. No current saturation is reached because we minimized the effect of the Joule heating. The electron drift velocity is deduced under assumption of uniform electric field and field-independent electron density. The estimated drift velocity $\approx 1.5 \times 10^7$ cm/s at 140 kV/cm bodes well with the value of hot-phonon lifetime exceeding 0.1 ps.

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1. Introduction

$Al_{1-x}In_xN$ alloys are very promising materials for applications in high power electronic and optoelectronic devices [1]. Device structures based on AlInN/GaN heterojunctions and superlattices, such as high electron mobility transistors (HEMTs) [2, 3], laser structures [4] and intersubband photodetectors [5] have previously been reported. In the absence of intentional doping, a two-dimensional electron gas (2DEG) (with a typical density in excess of 2.5×10^{13} cm^{-2}) can be formed in GaN at the hetero-interface due to spontaneous and piezoelectric polarization [6]. The insertion of a thin AlN interlayer between the AlInN and GaN layers helps to reduce the remote alloy scattering and achieve high electron mobility [7].

Recently, electron drift velocity has been measured for AlInN/AlN/GaN HEMT [8] and ungated [9, 10] channels. The intrinsic electron velocity of the HEMT with a gate length of 1 μm was estimated as $\approx 1 \times 10^7$ cm/s [8], while for the same In composition ($x = 0.15$) containing the ungated 2DEG channel $\approx 1.6 \times 10^7$ cm/s at 65 kV/cm [10]. High fields, present in a GaN channel during transport measurements, give rise to nonequilibrium (hot) electrons which tend to lose their energy (heat) mainly through interaction with nonequilibrium LO phonons (hot phonons) [11, 12]. The decay of the latter is often quantified as hot-phonon lifetime [13]. The lifetime is understood in terms of the interaction between hot phonons and plasmons [14]. According to microwave noise experiments, the hot phonon lifetime in a GaN 2DEG exhibits a minimum at a certain 2DEG density [15]. This is called LO-phonon–plasmon resonance and is understood as one considers that dispersion curves of the phonon and the plasmon intersect at the LO phonon energy of 92 meV. For the AlInN/AlN/GaN channels, at a fixed 2DEG density, the lifetime decreases as the supplied power increases [16, 17]. The decrease ensures high values of electron drift velocity (3.2×10^7 cm/s at 180 kV/cm) measured for the same sample [9]. After the resonance is reached, the lifetime starts increasing with the supplied power [15]. This should affect the electron drift velocity since at a given 2DEG density, the velocity is lower if the lifetime is longer at a fixed bias [12, 18]. The main aim of this letter is to report on high-field electron transport experiments for the AlInN/AlN/GaN under conditions of well-controlled channel temperature. The results will be interpreted in terms of hot-phonon effect on electron drift velocity.

2. Samples

The $Al_{1-x}In_xN$/AlN/GaN structures were grown in a vertical low-pressure metal-organic chemical vapor deposition (MOCVD) system [7] at Virginia Commonwealth University (VCU). First, an initiation layer of AlN (250 nm) was grown on 2 inch (0001) sapphire substrate at 1300 K at a chamber pressure of 30 Torr, followed by 4 μm thick undoped GaN buffer layer deposited at 1270 K at 200 Torr. Next, an optimized AlN spacer layer was grown at 1270 K with a thickness of 1 nm, which was determined from X-ray diffraction (XRD) data from a superlattice calibration structure grown under identical conditions. Next, the temperature was ramped down and the carrier gas switched from H_2 to N_2 for 19 nm of slightly compressively strained $Al_{0.8}In_{0.2}N$ or for 20 nm of nearly lattice matched $Al_{0.84}In_{0.16}N$. Finally, the temperature was ramped up to 1170 K for the deposition of a 2 nm thick GaN cap layer. Transmission line measurement patterns were defined on the samples and stacks of Ti/Al/Ni/Au were then deposited by evaporation. Coplanar ohmic Ti/Al/Ni/Au electrodes were annealed at 1070 K.

The 2DEG channel was located in the GaN layer close to the interface. A degenerate 2DEG, $n_{2D} = 8\times10^{12}$ cm^{-2} for $Al_{0.8}In_{0.2}N$/AlN/GaN, was induced by the spontaneous and piezoelectric polarization and was

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estimated from capacitance–voltage measurements. The samples had a channel length $L = 5$ μm and an electrode width $w = 260$ μm. Another $Al_{0.84}In_{0.16}N/AlN/GaN$ structures had $L = 3$, 5, 6.75, 8.75, 11.5, 16 μm. The contact resistance R_c was estimated from the dependence of the sample resistance on the channel length measured at low electric fields: $R_c = 3$ Ω for $Al_{0.8}In_{0.2}N/AlN/GaN$ and $R_c = 4.6$ Ω for $Al_{0.84}In_{0.16}N/AlN/GaN$. No asymmetry of the current was observed in the investigated range of applied voltages (the asymmetry often results from the voltage-dependent contact resistances).

The low-field mobility for $Al_{0.8}In_{0.2}N/AlN/GaN$ was $\mu_0 = 1581$ cm^2/(V s) at room temperature as determined from the measured low-field resistance R and n_{2D}. Here $\mu_0 = L/(Rwen_{2D})$, where e is electron charge. It is worth noting that the Hall mobility was lower, i.e. $\mu_{Hall} = 1330$ cm^2/(V s).

3. Experimental results and discussion

Hot-electron experiments were carried out using a nanosecond-pulsed current–voltage technique [9, 19]. The sample was placed into microstrip line holder that was connected in series into the break of transmission line. For $Al_{0.84}In_{0.16}N/AlN/GaN$ structures applied electric pulses up to 100 kV/cm ranged from 300 ps to 15 ns in order to resolve channel self-heating effect on current I. It was found that for the 15 ns duration pulses the effect of the Joule heat was negligible within the measured field E range (see Fig. 1). Here $E = (V - IR_c)/L$, and V is the applied voltage. The optimum channel length was also considered. The current–field dependence on the channel length L was weak: the values of current were scattered within 5% for the $L = 3$–11.5 μm samples (Fig. 2). The current only of the 16 μm samples differs by 20% at 100 kV/cm. From this we conclude that the electric field across the channel was homogeneous enough. Samples with a length not greater than 16 μm survived 2 ns pulses of the electric field $E < 120$ kV/cm. At higher fields, soft damage took place from time to time. The damage of the samples was estimated according to the change of the zero-field resistance measured before and after the high-field experiments. No tendency for the current to saturate is observed. The current slowly increases without any signature of impact ionization or any other threshold-type processes that can possibly cause a notable change in the 2DEG density.

When the 2DEG density is independent of the bias and the electric field is uniform, the electron drift velocity v_{dr} can be estimated from the measured current–field characteristic and the low-field mobility μ_0. The current I_O in the ohmic range ($E < 2$ kV/cm) is expressed as $I_O = C\mu_0 E$, and the normalized variable I/C, equivalent to the drift velocity $v_{dr} = \mu(E)E$, is plotted in Fig. 3 for the $Al_{0.8}In_{0.2}N/AlN/GaN$ channel (open squares) together with the $\mu_0 E$ data (solid line). The highest electron drift velocity $\approx 1.5 \times 10^7$ cm/s (open squares) is reached at 140 kV/cm. The experimental results for the investigated 2DEG channel (Fig. 3,

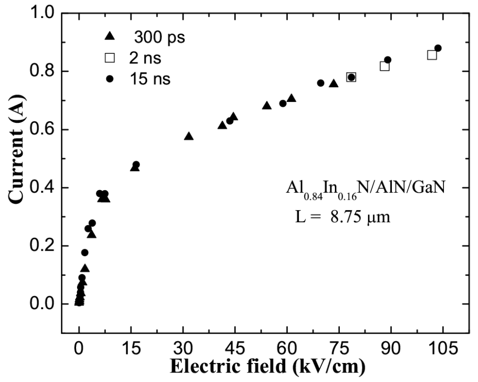

Fig. 1. Dependence of current on electric field for $Al_{0.84}In_{0.16}N/AlN/GaN$ channel at room temperature. Voltage pulse duration is 300 ps (triangles), 2 ns (open squares), 15 ns (bullets); $L = 8.75$ μm.

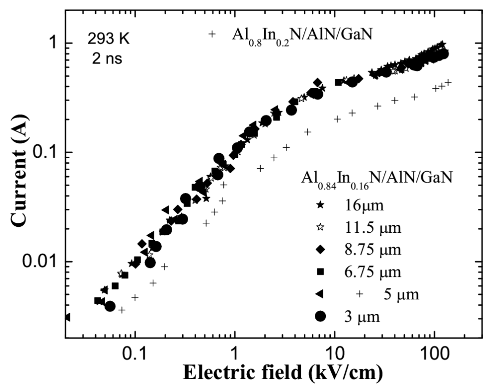

Fig. 2. Dependence of current on the electric field for $Al_{0.84}In_{0.16}N/AlN/GaN$ and $Al_{0.8}In_{0.2}N/AlN/GaN$ channel at room temperature. Channel length is $L =$ 3 μm (bullets), 5 μm (triangles, crosses), 6.75 μm (squares), 8.75 μm (diamonds), 11.5 μm (open stars) and 16 μm (closed stars). Voltage pulse duration is 2 ns.

open squares) are compared with those for nearly lattice matched $Al_{0.82}In_{0.18}N/AlN/GaN$ (stars) [9]. A reasonably good agreement of the stars and the squares is obtained at fields below 15 kV/cm.

The electron interaction with hot phonons is the dominant energy relaxation mechanism in GaN 2DEG channels at moderate-high electric fields [16, 18], but this is not always true for the momentum scattering. The electron drift velocity is determined by the combined action of many scattering mechanisms such as impurity, alloy, strain non-uniformity, just to mention a few in addition to the hot-phonon scattering. Supposing that the hot phonons limit the electron transport, the drift velocity depends on the hot-phonon lifetime [18]: at a given 2DEG density, the velocity is higher if the lifetime is shorter. At $E > 70$ kV/cm, the drift velocity for $Al_{0.82}In_{0.18}N/AlN/GaN$ 2DEG (Fig. 3, stars) channel is higher than the simulated one (open squares) [20] when the simulation takes into account hot-phonons life-

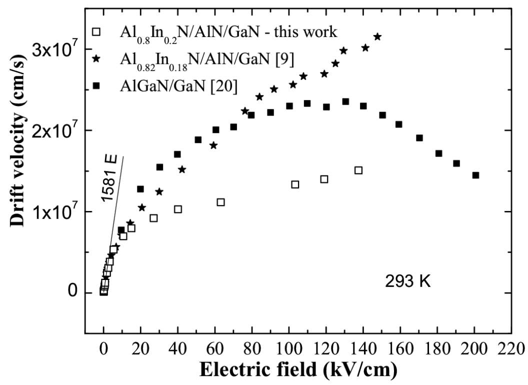

Fig. 3. Dependence on electric field of the estimated electron drift velocity for the $Al_{0.8}In_{0.2}N$/AlN/GaN channel at room temperature (open squares). The duration of voltage pulses is 2 ns, $L = 5$ μm. Line is $\mu_0 E$. Monte Carlo simulation for AlGaN/GaN calculated with hot-phonons taken into account (closed squares) [20]. Experimental data for $Al_{0.82}In_{0.18}N$/AlN/GaN (stars) [9].

time of $\tau_{ph} = 0.3$ ps. The obtained high values of the velocity (stars) suggest that the hot-phonon lifetime is shorter than 0.3 ps. Indeed, the measurement leads to the differential lifetime of 65 fs at ≈ 70 kV/cm [17]. The hot-phonon lifetime of $\tau_{ph} = 0.1$ ps for $Al_{0.8}In_{0.2}N$/AlN/GaN is equal to that of nearly lattice matched structure at 40 kV/cm and tends to increase with the field [15]. This supports an idea that the measured drift velocity is lower for $Al_{0.8}In_{0.2}N$/AlN/GaN. However, the difference in the electric field value from which the drift velocities take apart (Fig. 2, stars and open squares) is 15 kV/cm (not 40 kV/cm) because not only one scattering mechanism might be present. Lattice strain related friction can be one of them [10].

4. Conclusions

The dependence of current on voltage has been measured for a slightly strained $Al_{0.8}In_{0.2}N$/AlN/GaN and nearly lattice matched $Al_{0.84}In_{0.16}N$/AlN/GaN 2DEG channel under controlled self-heating. No current saturation has been obtained in the investigated field range below 140 kV/cm when the self-heating effect is avoided. The results are interpreted in terms of the dominant scattering of hot electrons by hot-phonons. The highest estimated hot-electron drift velocity $\approx 1.5 \times 10^7$ cm/s correlates with hot-phonon lifetime exceeding 0.1 ps.

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