Room-Temperature Ballistic Transport in III-Nitride Heterostructures


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Room-temperature ballistic transport in III-Nitride heterostructures

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Room-temperature (RT) ballistic transport of electrons is experimentally observed and theoretically investigated in III-Nitrides. This has been largely investigated at low temperatures in low band-gap III-V materials due to their high electron mobilities. However, their application to RT ballistic devices is limited by the low optical phonon energies, close to KT at 300 K. In addition, the short electron mean-free-path at RT requires nanoscale devices for which surface effects are a limitation in these materials. We explore the unique properties of wide-band-gap III-Nitride semiconductors to demonstrate RT ballistic devices. A theoretical model is proposed to corroborate experimentally their optical phonon energy of 92 meV, which is ∼ 4x-larger than in other III-V semiconductors. This allows RT ballistic devices operating at larger voltages and currents. An additional model is described to determine experimentally a characteristic dimension for ballistic transport of 188 nm. Another remarkable property is their short carrier depletion at device sidewalls, down to 13 nm, which allows top-down nanofabrication of very narrow ballistic devices. These results open a wealth of new systems and basic transport studies possible at RT.

Ballistic transport has attracted huge interest of the research community since electrons can propagate through the semiconductor without random scattering from lattice defects, impurities and phonons. This regime was referred to as electron optics[1] and occurs when electrons travel a distance shorter than their mean free path $L_m$, defined as the average distance travelled between consecutive scatterers.

Semiconductors presenting very high electron mobility have been used as means to investigate ballistic and other transport phenomena. Most of these studies were undertaken at low temperatures where $L_m$ can be quite large, on the order of a few microns[2]. Moreover, low temperature operation was required due to the very low optical phonon energies, close to KT at 300 K, of semiconductors such as Arsenides and Antimonides. In addition, the conductance is quantized at low temperatures, fundamentally similar to the quantized Hall effect[3], where only a small number of transverse quantum channels are occupied. These effects have been explored and demonstrated in a number of different devices based on quantum interference[4, 5], quantized conductance in a point contact[6, 7], electron focusing[8], negative bend resistance[9, 10], quenched and negative Hall effects[11], and lateral hot ballistic electron[12].

While these devices were demonstrated under low temperature, ballistic transport at RT would open a pathway for many practical applications[13–16], offering a new design space for high frequency devices with quicker switching responses and lower dissipation losses than conventional devices. At RT however, $L_m$ is largely reduced, below 100 nm in some III-V semiconductors. This requires much smaller device dimensions, where surface effects can be a limiting factor[17]. The large depletion of carriers near etched sidewalls of the device, typically over 100 nm due to

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the relatively small carrier concentrations, poses severe limitations for top-down fabrication in several materials such as GaAs-AlGaAs and InSb-AlInSb[18, 19].

Another important consideration for RT ballistic devices is the energy at which optical phonons are emitted by electrons. Ballistic transport is largely degraded above such energy, when electrons are strongly scattered by the crystal lattice through the emission of optical phonons. This limits the use of many materials as ballistic devices operating at RT due to their low optical phonon energy, close to KT, such as 25 meV in InSb/AlInSb[19], 33 meV in InGaAs/InP[20], 27 meV in InAs [17] and 19 meV in Si/SiGe[21].

In this work, we demonstrate for the first time that the high electron mobility in wide band-gap materials, such as in III-Nitrides, coupled to their very high optical phonon energies (∼4x-larger than in other III-V semiconductors) allows the observation of ballistic transport at RT. Ballistic devices have been largely investigated in low-band gap III-V materials where their reduced effective mass results in higher mobilities. Here, we show that the high optical phonon energy of wide band-gap III-Nitrides (∼ 92 meV) allows ballistic transport of electrons with much larger energy even at RT. A pronounced ballistic transport at RT was demonstrated in III-Nitride heterostructures using top-down nanofabrication, which is enabled due to the very short depletion of carriers at etched sidewalls. This is a remarkable property of III-Nitrides allowing electronic conduction in top-down nanoscale devices, not found in semiconductors such as Arsenides or Antimonides, where the depletion of carriers at etched sidewalls extends over hundreds of nanometers. Using state-of-the-art nanofabrication technology, we demonstrate high-quality nanoscale ballistic filters with dimensions down to 33 nm, much shorter than the mean free path of electrons at RT. In combination to experimental results, theoretical models were proposed to determine the optical phonon energy from the current density and the characteristic ballistic length from the bend resistance in these devices. The former offers a robust method to assess experimentally the optical phonon energy independently on the device geometry and clears some misconceptions found in previous works. The latter offers a more direct quantification of the dimensions for ballistic transport than the theoretical $L_m$. This first demonstration of high-energy electrons under ballistic transport at RT combined to the unique suitability of III-Nitrides for top-down nanofabrication opens new opportunities for advanced semiconductor devices presenting higher frequencies and lower power dissipation operating at RT.

The electronic transport was investigated by fabricating nanoscale crosses with dimensions close to $L_m$ (Figure 1) combined with temperature-dependent measurements. The principle of operation of the device is the following:

![Diagram](image-url)
Under diffusive regime, electrons flow from leads 1 to 2, following the electric field created in the cross by the applied voltage $V_{21}$ (blue dotted arrow in Figure 1a). This induces a potential $V_{34}$, between leads 3 and 4, of the same sign as the applied $V_{21}$. This is equivalent to the voltage drop at a small resistance $R_{\text{cross}}$ present at the center of the cross, which can be written as $V_{34}^{\text{drift}} = R_{\text{cross}} I_2$.

When the cross width $w$ is reduced below $L_m$, a large number of electrons is injected ballistically into the opposite lead 3 (red dotted arrow in Figure 1a) since there are much fewer scattering events to change their momentum along the electric field. This induces a negative potential in lead 3 relative to lead 4, thus a $V_{34}$ of opposite sign relative to $V_{21}$. This is equivalent to a negative bend resistance $R_b$ at the center of the cross - a signature of ballistic transport - creating a negative potential $V_{34}^{\text{ballistic}} = R_b I_2$. Thus, this cross geometry offers a way to decouple ballistic from drift transport, operating as a filter for ballistic electrons.

The devices investigated in this work were fabricated on In$_{0.17}$Al$_{0.83}$N/GaN on SiC substrate. The epitaxial structure was composed of InAlN (7.3 nm)/ AlN (1 nm)/ GaN (10 nm)/ InGaN (3.3 nm)/ GaN (1.8 μm), where the In-GaN layer acts as a back-barrier to improve confinement of electrons in the two-dimensional electron gas (2DEG). Nanoscale crosses with length of 1 μm and widths of 315 nm, 205 nm, 94 nm, 59 nm and 33 nm (these were measured dimensions after fabrication) were first defined by electron-beam lithography on hydrogen silsesquioxane 2% (HSQ) (Figures 1b-c). This served as a hard mask for Cl$_2$-based etch of the surrounding material (200 nm-deep) to isolate different devices. The dimensions of the crosses were chosen based on the estimated $L_m$, calculated from the Fermi velocity of electrons using the semi-classical expression $L_m = v_F \tau = \sqrt{2 \pi n \hbar \mu}/q$. The electron concentration $n$ and mobility $\mu$ in the 2DEG were determined from temperature-dependent Hall measurements as $n = 1.51 \times 10^{13}$ (1.24x10$^{13}$) cm$^{-2}$ and $\mu = 3476$ (1285) cm$^2$/Vs, and the estimated $L_m$ was 223 nm (75 nm) at 4 K (300 K). A Ti (200 Å)/Al (1000 Å)/Ni (250 Å)/Au (500 Å) metal stack was deposited over large mesa structures (60 μm-wide) connected to the four nanoscale leads and annealed at 845°C to form ohmic contacts.

The contact resistance $R_c$ and sidewall depletion width $w_{\text{dep}}$ were determined from the linear dependence of the two-terminal resistance versus the ratio of length $L$ over the effective width $w_{\text{eff}} = w - w_{\text{dep}}$ using the following model

$$R = R_c + R_{\text{sh}} L/(w - w_{\text{dep}})$$

(1)

where $R_{\text{sh}}$ is the equivalent sheet resistance in the cross and $w_{\text{dep}}$ is the depletion width formed at both etched sidewalls which effectively shrinks the nominal cross width $w$. This model is plotted in dashed lines in Figure 1d, at both 300 K and 4 K, which resulted in $R_c$ of 3747 Ω at 300 K and 1522 Ω at 4 K ($R_c$ is similar for all devices and includes contact and other parasitic resistances). The voltage drop in the nanoscale cross was determined after removing the voltage drop in $R_c$ as $V_{\text{wire}} = V_{21} - R_c I_2$. Equation (1) was also used to determine $w_{\text{dep}}$, resulting in values between 19 nm and 26 nm obtained from the linear dependence of $1/(R - R_c)$ versus $w$. The shorter $w_{\text{dep}}$ compared to other material systems [18, 19] is due to the larger carrier concentration in the 2DEG in III-Nitride heterostructures which allows the top-down nanofabrication of much narrower devices. In this case, the narrowest cross (33 nm-wide) was depleted of carriers at all temperatures, impeding its electrical characterization.

Ballistic transport was probed in two ways: (1) By lowering the temperature which increases $L_m$; (2) By reducing the cross width below $L_m$. The transport was measured by applying voltage independently in two adjacent orthogonal leads 1 and 2, in a push-pull configuration with $V_2 = -V_1$, and by measuring the induced voltage in leads 4 and 3.
with $I_3 = I_4 = 0$. The samples were measured in a micro-manipulated cryogenic probe station from Lake Shore, at temperatures varying from 300 K to 4 K cooled with liquid Helium.

![Graph showing induced voltage $V_{34}$ versus applied voltage $V_{wire}$ for 1 $\mu$m-long crosses on InAlN/GaN heterostructure.](image)

**FIG. 2.** Induced voltage $V_{34}$ versus applied voltage $V_{wire}$ for 1 $\mu$m-long crosses on InAlN/GaN heterostructure. (a) Room temperature measurement showing a change from drift (positive slope) to ballistic transport (negative slope) as the cross width is reduced. (b) Measurement at 4 K indicating much more pronounced ballistic transport.

Figures 2 shows the measurement of $V_{34}$ versus $V_{wire}$. At RT, the transport was determined by drift in the wide crosses, which is indicated by the linear positive slope of $V_{34}$ with respect to $V_{wire}$ for the 315 nm-, 205 nm- and 94 nm-wide crosses (Figure 2a). A clear transition from drift to ballistic transport is observed in the 59 nm-wide cross, indicated by the negative slope of $V_{34}$. This is an important observation of ballistic transport at RT for the 59 nm-wide cross (Figure 2a), which is in agreement with $L_m$ of 75 nm at RT. When the temperature was lowered to 4 K, $L_m$ increased from 75 nm to 223 nm, and a pronounced ballistic transport was observed for the 94 nm- and 59 nm-wide crosses by the negative slope of $V_{34}$ versus $V_{wire}$, corresponding to a negative bend resistance (Figure 2b). Despite its smaller dimension than $L_m$, the 205 nm-wide cross only showed a very mild negative slope of $V_{34}$. More representative than $L_m$ is the characteristic ballistic length $L_b$ which is defined and experimentally determined later in this paper.

The negative bend resistance is observed for $V_{wire} < V_{knee}$ (Figure 2b), after which electrons have enough energy to emit optical phonons which changes both their energy and momentum (schematic in Figure 2c), reducing the effective mean free path of electrons due to electron-phonon scattering and undermining their ballistic transport. The energy $qV_{knee}$ is often attributed in the literature directly to the energy of optical phonons [20, 21] as $\hbar\omega_{op} \approx qV_{knee}$.

However, in the present case, the observed $V_{knee} \sim 126$ mV was much larger than the expected 92 mV of III-Nitrides. In addition, similar measurements performed in longer crosses with 5 $\mu$m fabricated in the same material resulted in a much less pronounced ballistic effect as well as in a much larger $V_{knee}$, close to 500 mV (see Supplementary Information). These results show that $V_{knee}$ extracted from such measurements cannot be directly assigned to $\hbar\omega_{op}$, since the energy of electrons crossing the center portion of the crosses, where the transport is probed, is smaller than the energy $qV_{knee}$ applied at the leads (electrons scatter and lose part of their energy during their propagation to the center of the crosses).

The current density $J_2 = I_2/w$ is a more consistent variable to look at these effects since it is not dependent on the cross geometry. Unlike $V_{knee}$, the current density $J_2$ corresponding to the transition between diffusive and ballistic regimes in the plot of $V_{34}$ versus $J_2$ (Figure 3), was similar for 1 $\mu$m- and 5 $\mu$m-long crosses (see Supplementary Information), which motivated us to propose an alternative method to extract $\hbar\omega_{op}$ directly from $J_2$. $J_2$ in a 2DEG can be written as the product of the density of states, group velocity $\hbar k/m^*$ (where $m^*$ is the effective mass of
electrons in GaN) and occupation probability function \( f_k(k) \) integrated over all states in k-space as

\[
J_2 = \frac{2q}{4\pi^2} \int k f_k(k) dk = qn_s \frac{\hbar k_0}{m^*}
\]  

where \( k_0 \) corresponds to the geometrical centroid of the occupied area in k-space[24]. In this approach, the geometrical centroid \( k_0 \) incorporates the averaged effect of non-uniformities of the potential distribution in the nanocrosses[25], present especially at their corners.

At large enough applied bias, ultra-fast optical phonon emission in GaN fixes the difference of quasi-Fermi levels[24] as \( E_r - E_l = \hbar \omega_{\text{op}} \), where an electron at the right-going state \( E_r \) is scattered to the lowest available left-going state \( E_l \) in the band structure (Figure 3c). At this moment, the current \( I_2 \) starts slowly to saturate and the slope of \( V_{34} \) changes sharply at \( V_{\text{knee}} \), as observed in Figure 3d. The optical phonon energy can be written as the difference in electron energy at \( E_r \) and \( E_l \) as:

\[
\hbar \omega_{\text{op}} = E_r - E_l = \frac{\hbar^2 (k_F + k_0^*)^2}{2m^*} - \frac{\hbar^2 (k_F - k_0^*)^2}{2m^*}
\]  

where \( k_F \) is the Fermi wavevector given by \( k_F = \sqrt{2\pi n} \) and \( n \) is the carrier density in the 2DEG. The geometrical centroid \( k_0^* \), at which optical phonon emission starts happening, can be determined from the current density \( J_2^* \), at which current starts saturating, using Equation (2):

\[
k_0^* = J_2^* m^*/\hbar n_s
\]
Thus, \( \hbar \omega_{\text{op}} \) can be calculated from \( J_2^* \) using Equations (3) and (4). In the measurement from Figure 3b, \( J_2^* = 2.86 \) A/cm, which corresponds precisely to the current density where \( V_{\text{knee}} = 126 \) mV. This results in \( \hbar \omega_{\text{op}} \) of 95.1 meV which is very close to the optical phonon energy of III-Nitrides.

The induced voltage was also modelled as a function of the current density as \( V_{34} = V_{34}^{\text{drift}} + V_{34}^{\text{ballistic}} \). The drift component was written as \( V_{34}^{\text{drift}} = \rho_{\text{cross}} J_2 \), where \( \rho_{\text{cross}} = R_{\text{cross}} w \), and the ballistic component \( V_{34}^{\text{ballistic}} = w R_b J_2 \), thus:

\[
V_{34} = w (R_{\text{cross}} + R_b) J_2 \tag{5}
\]

A great deal of information can be obtained by modelling the bend resistance \( R_b \), which is proportional to the transmission probability of a ballistic electron to the opposite lead[18]. An expression for \( R_b \) can be written using Büttiker-Landauer’s approach[26] as \( R_b = R_t (T_S - T_F)/ [4 T_S (T_S + T_F)] \), where \( R_t = \pi \hbar / (2 e^2 k_F w) \) is the two-terminal resistance of a quantum wire of width \( w \). \( T_S \) and \( T_F \) are the transmission probability of electrons going forward and sideways respectively. These probabilities are very sensitive to the amount of scattering at the center of the cross. Under diffusive transport, electrons are scattered randomly in all direction, hence \( T_S = T_F \approx 1/4 \), thus \( R_b \approx 0 \) and \( V_{34} = V_{34}^{\text{drift}} \). Under ballistic transport, the forward-going transmission probability is increased by the ballistic probability as \( T_F = 1/4 + T_b \). The bend resistance can then be simplified[27] as \( R_b = -2 R_t T_b \), which is negative as first predicted by M. Büttiker[22]. The term \( T_b \) can be written as[18, 28, 29] \( T_b = \int_{-\theta_c}^{\theta_c} f_0(\theta) d\theta \exp(-w/L_b) \) where here a ballistic length \( L_b \) is introduced, which represents a characteristic dimension under which electron transport is ballistic (similarly to the mean free path). The angular distribution of electrons injected forward is given by the function \( f_0(\theta) \) which can be approximated[15] by \( \cos(\theta)/2 \), where \( \theta_c = \arctan(1/2) \) corresponds to the range of angles for which electrons can be transmitted to the forward lead (inset of Figure 4). After integration, \( T_b = 0.45 \exp(-w/L_b) \). Thus,

\[
R_b = -0.9 \exp(-w/L_b) \frac{\hbar}{2 e^2 k_F w_{\text{eff}}} \pi \tag{6}
\]

where the effective width \( w_{\text{eff}} = w - w_{\text{dep}} \) accounts for the sidewall depletion.

At 300 K, for crosses much larger than \( L_b \), \( R_b \approx 0 \) thus, from Equation (5), \( V_{34} \) has a positive slope equal to \( \rho_{\text{cross}} \cdot \) For the 315 nm-wide cross at 300 K, \( \rho_{\text{cross}} = 2.4 \) m\(\Omega\)cm (\( R_{\text{cross}} = 76.2 \Omega \)) (Figure 3a). When the cross width is reduced below \( L_b \), still at 300 K, the fraction of ballistic electrons increases as \( \exp(-w/L_b) \) but \( V_{34}^{\text{drift}} \) remains the same since the normalized \( \rho_{\text{cross}} \) is nearly constant, leading to a negative slope of \( V_{34} \) versus \( J_2 \) (Figure 3a). On the other hand, when the temperature is lowered, both ballistic and drift terms change. The mobility of electrons increases, which reduces \( \rho_{\text{cross}} \). In addition, \( L_b \) increases which increases the fraction of ballistic electrons going to the lead 3, thus \( |R_b| \gg R_{\text{cross}} \) yielding a much more apparent ballistic effect at low temperatures (Figure 3b) and \( V_{34} \sim V_{34}^{\text{ballistic}} \) (Equation (5)).

Equation (6) offers a direct way to determine experimentally the characteristic ballistic length \( L_b \) which was extracted from the slope of the experimental \( w_{\text{eff}} |R_b| \) versus \( w \) in logarithmic scale (Figure 4a), resulting in \( L_b \) of 143 nm for InAlN/GaN at 4 K. This model is only valid for \( |R_b| \gg R_{\text{cross}} \), thus not applicable for the 315 nm-wide crosses.

To check their consistency, these models were applied to another III-Nitride heterostructure, consisting of
FIG. 4. Experimental determination of the characteristic ballistic length for both heterostructures. a. Logarithmic scale plot of $w_{\text{eff}}|R_b|$ versus $w$ for both InAlN/GaN and AlGaN/GaN heterostructures at 4 K. The characteristic ballistic length $L_b$ was extracted from the slope of these curves. b. Bend resistance $R_b$ versus effective cross width $w_{\text{eff}} = w - w_{\text{dep}}$ (squares for AlGaN/GaN and triangles for InAlN/GaN), along with the theoretical curves (solid lines). (Inset) Schematic of the ballistic transmission of electrons to the opposite lead in these crosses.

Al$_{0.25}$Ga$_{0.75}$N (25 nm)/ AlN (8 nm)/GaN on Silicon substrate which presented larger $\mu$ and $L_m$. The 2DEG formed at the heterostructure interface presented $n = 1.10 \times 10^{13}$ cm$^{-2}$, $\mu = 5151$ cm$^2$/Vs at 4 K and an estimated $L_m$ of 281 nm. A similar transition from drift to ballistic transport was observed, where for completeness, the full temperature-dependent measurement at 300 K, 150 K, 77 K, 50 K and 4 K is shown in the Supplementary Information. For this structure, $J_2^2 = 2.40$ A/cm (see Supplementary Information), resulting in $h\omega_{\text{op}} = 93$ meV, which is again in agreement with $h\omega_{\text{op}}$ of III-Nitrides despite the different heterostructure, electron mobility and carrier density. $L_b$ extracted from the slope of $w_{\text{eff}}|R_b|$ versus $w$ was equal to 188 nm for AlGaN/GaN (Figure 4a). The larger $L_b$ in AlGaN/GaN compared to InAlN/GaN is due to its higher electron mobility, thus larger $L_m$. In both cases, the measured $L_b$ was shorter than the estimated $L_m$ which is likely due to extra scattering mechanisms that reduce the electron mobility[25], such as at etched sidewalls, and are not taken into account in the model based on the Fermi velocity. Hence, $L_b$ can be used to measure experimentally the effect of scattering mechanisms that cannot be estimated with $L_m$.

The theoretical $R_b$ from Equation (6) was plotted after determining $L_b$ and agreed well with the experimental values of bend resistance for both materials, as shown in Figure 4b. This model corroborates the ballistic nature of the transport measured in these structures and offers an analytical expression of $R_b$ which can be used in the design of future ballistic devices.

In conclusion, high-quality nanoscale ballistic filters, with dimensions down to 33 nm, were used to demonstrate for the first time ballistic electronic devices operating at room temperature (RT) in III-Nitride semiconductors. These nanoscale devices presenting dimensions much shorter than the mean free path of electrons at RT were fabricated using state-of-the-art top-down nanofabrication technology, which was possible due to the very short depletion of carriers at etched sidewalls. This is a remarkable property of III-Nitrides allowing electronic conduction in very narrow devices, which is not found in other semiconductors such as Arsenides or Antimonides. More importantly, this work highlights that high electron mobility in wide band-gap materials, such as in III-Nitrides, coupled to their very high optical phonon energies - $\sim 4x$-larger than in other III-V semiconductors - allows ballistic transport at RT of electrons with higher energy than in other III-V semiconductors.
Complementing our experimental results, we proposed a theoretical model to determine the optical phonon energy from the current density across the device, which was applied to both InAlN/GaN and AlGaN/GaN heterostructures. The results were in very good agreement with the $h\nu_{\text{op}} = 92$ meV in III-Nitrides, revealing a much more consistent method than assigning the optical phonon energy directly to $qV_{\text{knee}}$, as often found in the literature. In addition, a model of the bend resistance was described and used to determine the characteristic ballistic length $L_b$. This method offered an experimental quantification of the dimensions for ballistic transport. The measured $L_b$ of 143 nm for InAlN/GaN and 188 nm for AlGaN/GaN heterostructures were shorter than the estimated $L_m$ revealing the presence of extra scattering mechanisms, such as at etched sidewalls, that were not taken into account in the semi-classical model based on the Fermi velocity.

This work opens a wealth of new systems and basic transport studies possible at RT in wide band-gap semiconductors, and offers new opportunities for advanced semiconductor devices operating at higher frequencies and lower power dissipation operating at RT.

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