Flux quantization signatures in InAs-InAlAs core-shell nanowires

Gregory W. Holloway, Daryoush Shiri, Chris M. Haapamaki, Grant Watson, Ray R. LaPierre, and Jonathan Baugh

1Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
2Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
3Waterloo Institute for Nanotechnology, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
4Department of Chemistry, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
5Department of Engineering Physics, Centre for Emerging Device Technologies, McMaster University, Hamilton, Ontario L8S 4L7, Canada

(Dated: May 27, 2013)

We study axial-field magnetoconductance in InAs core-shell nanowire field-effect transistors, finding oscillatory behaviour at low temperatures when the device is in accumulation mode. The primary oscillations have the periodicity of the flux quantum $\Phi_0$ corresponding to an effective radius close to the InAs core radius. The magnetoconductance as a function of gate voltage matches well to theory based on coherent electronic states in a cylindrical shell near the surface, i.e., a two-dimensional electron gas. This implies an electronic phase coherence length $\gtrsim$ 163 nm at a temperature of 3.8 K. It is remarkable that such coherent quantum effects can be observed in the diffusive transport regime, with a device length (1.2 $\mu$m) much greater than the elastic scattering length. These results suggest a high degree of crystalline order at the InAs-InAlAs interface, a key necessity for utilizing core-shell nanowires in coherent quantum device experiments.

PACS numbers: 73.22.-f, 73.63.Nm, 75.47.-m, 81.05.Ea

Introduction—Semiconductor nanowires are increasingly utilized in exploring fundamental quantum transport physics in low dimensions and realizing devices useful for nanoscale sensing [1, 2] and quantum information processing [3–7]. A well-known challenge with nanowires is that charge carriers will always be within nanometers of the surface, often leading to transport and optical properties exquisitely sensitive to surface states, crystalline imperfections and other defects [8–10]. Introducing a wider bandgap epitaxial shell [11–13] is a promising way to suppress these effects and potentially achieve an interface quality similar to that of planar two-dimensional electron gas (2DEG) heterostructures. Here we report magnetoconductance (MC) measurements on InAs-In$_{0.8}$Al$_{0.2}$As core-shell nanowires that show clear signatures of phase coherent electronic states around the circumference of the InAs core. The energy landscape of these states can strongly influence transport when the conduction is dominated by a surface accumulation 2DEG and the phase coherence length is at least comparable to the nanowire core circumference. Evidence for such states was seen previously in InN nanowires and attributed to the high crystalline quality of the surface [14]; however, these signatures have thus far been absent in InAs nanowires [15]. Our experimental results show a dominant MC oscillation with the periodicity of the flux quantum, $\Phi_0$, and match the gate voltage dependence predicted by a simple theoretical model. Further, we see evidence of higher harmonics at some gate voltages that may suggest a phase coherence length $> 500$ nm at $T = 3.8$ K. We attribute these effects to a high degree of crystalline order at the InAs-InAlAs interface, in agreement with previous work that found higher mobilities in core-shell nanowires [16, 17]. This complements other important structural improvements, such as eliminating stacking faults [18–20], as an important step towards optimizing III-V nanowires for experiments in the coherent quantum regime.

Methods—InAs nanowire cores were first grown axially by the Au-assisted vapour-liquid-solid mechanism on a GaAs (111)B substrate at a growth temperature of 420 °C [21] in a gas source molecular beam epitaxy system. A second growth step utilized Al to facilitate the radial growth of an In$_{0.8}$Al$_{0.2}$As shell [17, 22]. The core diameters were typically in the diameter range 60 ± 20 nm, and the shell thickness is independent of core diameter [22], estimated as 12 ± 3 nm by superposing high-angle annular dark field images with energy dispersive x-ray spectroscopy line-scans. Field effect transistor (FET) devices were realized by mechanically depositing the core-shell nanowires onto a 300 nm thick layer of SiO$_2$ on degenerately doped Si. Using a scanning electron microscope (SEM) we select untapered nanowires with a total diameter of 95 ± 10 nm (core diameter ~ 70 ± 10 nm). The contact areas were prepared by first etching in a citric acid:H$_2$O$_2$ (15:1) solution to remove the InAlAs shell, followed by an ammonium polysulfide etch and passivation to prevent oxide regrowth. Ni/Au (40 nm/40 nm) contacts were then evaporated, preceded by a short Ar$^+$-ion cleaning. The devices were annealed in vacuum at 150 °C for 10 minutes to promote Ni diffusion into the contact area [23]. This procedure typically yields a two-terminal resistance in the range of 10 - 100 kΩ at room temperature for a $L \approx 1 \mu$m FET channel length in the device on-state, consistent with a contact resistance small compared to the channel resistance [23]. The presence of
ferromagnetic Ni adds a small complication to our analysis of MC; however, we find no measurable hysteresis in our data, consistent with a very small coercive field, and the saturation flux due to the Ni contacts is readily taken into account in our comparison of experiment and theory. Transport measurements were made in vacuo in a pumped liquid helium cryostat, with a sample base temperature of 3.8 K and an in-plane applied magnetic field up to 2 T. A low-noise current preamplifier was used to measure the DC current-voltage (I-V) characteristics. The nanowire axis was aligned with the in-plane magnetic field direction to within ± 10 degrees. MC was measured by sweeping the applied magnetic field at a rate of 1.3 mT/s and sweeping the gate over a 1 V range at 0.125 V/s, while continuously sampling the device conductance under a source-drain bias of 10 mV.

Model and results—A surface accumulation layer of electrons, due to Fermi level pinning and the low bandgap of InAs, is well known in the literature for InAs surfaces [24, 25]. A cylindrical 2DEG can form at the InAs surface, in this case, at the core-shell interface (see Figure 1). Note that it is unlikely that strain adds to the surface confinement potential since the compressive hydrostatic strain resulting from the InAlAs shell will slightly raise the energy of the Γ valley [11]. At large positive gate voltages, the device operates in accumulation mode where the 2DEG should be most pronounced, continuous around the nanowire circumference and responsible for a large fraction of the device conductance [26]. The movement of electrons in such a 2DEG can be decomposed into a longitudinal component along the axis of the nanowire (z) and a circular component characterized by angular momentum quantum numbers (see Figure 1b). In the simplest picture, ignoring Zeeman and spin-orbit effects, the energy eigenvalues can be written as [14, 27]:

$$E_l = \frac{\hbar^2 k_z^2}{2m^*} + \frac{\hbar^2}{2m^* r_{\text{eff}}^2} \left( l - \frac{\Phi}{\Phi_0} \right)^2$$  \hspace{1cm} (1)$$

where $k_z$ is the electron wave number along the nanowire axis and $m^*$ is effective mass of electron in InAs, 0.023$m_0$ ignoring strain effects ($m_0$ is the rest mass of the electron), $l$ is the angular momentum quantum number for circular motion and $\Phi$ is the magnetic flux. $\Phi_0 = h/e$ is the quantum of magnetic flux, where $h$ and $e$ are Planck's constant and the electronic charge, respectively. For a given axial magnetic field $B_z$ and effective radius $r_{\text{eff}}$, the magnetic flux is given as $\Phi = \pi B_z r_{\text{eff}}^2$.

Figure 1c shows the energy eigenvalues of Equation (1) versus normalized magnetic flux ($\Phi/\Phi_0$). For clarity only a few angular momentum quantum numbers are shown. Periodicity of the MC versus magnetic field
arises due to the periodic crossing of these states with the Fermi level, as was observed for MC oscillations in InN nanowires [14]. Crucially, this effect can persist even in the diffusive transport regime if the phase coherence length is comparable to the nanowire circumference. Examples of the MC we observe are shown in Figure 2. Oscillations are seen in the high-conductance regime (device on-state), whereas no clear oscillation is present in the low conductance state near device pinchoff. Qualitatively similar behaviour was observed in several devices, and we focus on one device for the remainder of the paper. Plotted in Figure 2b is the normalized conductance $\frac{G - \langle G \rangle}{G_0}$, where $G$ is conductance, $\langle G \rangle$ and $G_0$ are the average conductance and $B_z = 0$ conductance at a given gate voltage, respectively. From Figure 2b it is evident that the phase of the MC oscillation is dependent on the gate voltage, i.e., on the Fermi level in the nanowire. The normalized MC as a function of applied magnetic field and gate voltage is shown in Figure 3a. Note the raw data contains only 29 points along the $V_g$ axis but has been smoothed in this figure to reduce both pixelation and random telegraph noise. Figure 3a reveals the presence of complex structure in the normalized conductance, with diagonal features indicating oscillations versus both magnetic field and gate voltage. No measurable magnetic hysteresis due to the Ni contacts is observed (see Supplementary Material), consistent with a small coercive field $H_c \approx 7$ mT and a saturation field of similar magnitude, as observed in comparable films [29]. We calculated the stray field at saturation for our device geometry, finding a maximum parallel field in the nanowire of 0.11 T adjacent to the contact that drops off rapidly and is 0.01 T at the centre of the channel (Supplementary Material). This stray field is therefore effectively constant for our measurements, and the main effect is a field gradient $\sim 0.1$ T along the nanowire. Also note Figure 3a represents data taken from two separate cooldowns of the device over a range of 7.1-8.0 V and 7.5 - 8.5 V respectively. The two data sets agree well with each other in the overlapping region, and have thus been stitched together at 7.5 V. In general, measurements made during different cooldowns often have small relative shifts in gate voltage with respect to each other due to changes in the electrostatic potential, as a different arrangement of static charge is induced in the gate dielectric during each cooldown.

**Theory compared to experiment** — In order to gain insight into the underlying mechanism of the MC oscillations, we calculate the conductance for the 2DEG channels in the InAs core of the core-shell FET. The calculation is based on the quantized circular states discussed above and the Landauer-Büttiker formula for conductance in the linear response regime, given by [30]:

$$G = \frac{2e^2}{h} \int_0^\infty T(E) \left( -\frac{\partial f(E)}{\partial E} \right) dE$$  \ (2)

where $f(E)$ represents the Fermi-Dirac distribution function and $T(E)$ is the transmission coefficient. For a given magnetic field (constant $\Phi$) and values of $l = 0, \pm 1, \pm 2$, etc, $T(E)$ is the number of subbands with energy lower than $E$. Hence, $T(E)$ resembles a staircase in which the height and width of the stairs depend on $\Phi/\Phi_0$. As we discuss below, the transport in our $L = 1.2$ $\mu$m device is diffusive, with an elastic scattering length $l_e \approx 30$ nm. Nonetheless, the essential physics of the MC oscillations can be captured by calculating Equation (2) in the ballistic regime and relating it to the actual device via the statistical conductance in the diffusive regime [31] $G_{\text{diff}} = 2Ne^2l_e/(hL)$, which is equivalent to the ballistic conductance for $N$ spin degenerate channels scaled by the factor $l_e/L$. The accumulation mode device resistance $R = 58$ kΩ (Figure 2a) yields $Nl_e = 267$ nm by setting $G_{\text{diff}} = R^{-1}$. For $N \approx 9$, as we find below, this implies $l_e \approx 30$ nm.

In order to connect the evaluation of Equation (2) with experiment, the range of Fermi energies $E_F$ must be chosen to be consistent with the experimental data. We will assume that the device conductivity is dominated by the contribution of the 2DEG in a subsurface shell with outer radius similar to the nanowire core radius, $r = 35 \pm 5$ nm estimated from SEM measurement. Electrons are confined to this shell by a triangular well at the interface, shown schematically in Figure 1a. We assume there is only one radial bound state in the well. The circular modes then correspond to the
eigenvalues in Equation (1), and $N$ of the states below $E_F$ contribute to conductance. $N(E_F)$ can be evaluated using Equation (1): setting $k_z = 0$ and $\Phi = 0$, $N(E_F) = 2l + 1 = 2\sqrt{2m^*E_Fr_{\text{eff}}/\hbar} + 1$. The results below will indicate that it is only possible to match the experimental data in Figure 3a to simulation in a Fermi level range $27 - 54$ meV. For $E_F = 40$ meV, we obtain $N = 9$ corresponding to a highest occupied state with $l = 4$ and Fermi wavelength $\lambda_F = 40$ nm.

We next derive an expression for the electron density $n$ appropriate to a quasi-1D problem with multiple subbands, using a 1D density of states and summing over the circular modes (see Appendix). The electron density is given by:

$$n = \frac{\sqrt{2m^*kT}}{\hbar A} \sum_i F_{-1/2} \left( \frac{E_F - E_i}{kT} \right)$$

where $F_{-1/2}$ is the Fermi-Dirac integral of type $-1/2$. Since $E_F - E_i \gg kT$ for nearly all the states below $E_F$ at $T = 3.8$ K, the Fermi-Dirac integral is approximated as $F_{-1/2}(g) \approx 2\sqrt{g}$ [32]. Numerical evaluation of Equation (3) at $\Phi = 0$ shows that $n \approx E_F \times 4.1 \times 10^{18}$ cm$^{-3}$ eV$^{-1}$, i.e. $n$ is a nearly linear function of $E_F$. Here we take the cross-sectional area $A = \pi(35 nm)^2$ to calculate the average electron density over the whole nanowire volume. To relate $E_F$ and $V_g$, the electron density is also estimated from a capacitive model $n = C_g(V_g - V_t)$, where $C_g$ is the gate capacitance and $V_t$ is the pinchoff threshold voltage. $C_g \approx 51$ aF is calculated from a metallic cylinder over a plane model, taking into account that the nanowire is not embedded in the SiO$_2$ dielectric [33]. The possible range of $E_F$ to match the data is tightly constrained by this condition that $\Delta E_F$ and $\Delta V_g$ must be consistent with the geometric capacitance $C_g$. Comparing Figure 3a and 3b yields $\Delta E_F/\Delta V_g = 0.019$ eV/V, which is consistent with $C_g$ to within 25%. No higher or lower ranges of $E_F$ can both produce a qualitative match to the experimental data and satisfy this condition. From the peak field-effect mobility $\mu \approx 2.8 \times 10^3$ cm$^2$/Vs at $T = 20$ K, a Drude elastic scattering length $l_e = \hbar k_F\mu/e \sim 30$ nm is obtained, consistent with the estimate from $N_{t_e}$ above. At $E_F = 40$ meV, $k_F = \sqrt{2\pi n_{2D}}$ gives a 2D electron density $n_{2D} = 3.1 \times 10^{11}$ cm$^{-2}$.

The simulation in Figure 3b was carried out by evaluating Equation (2) over a range of magnetic field $B_z = 0 - 2$ T and Fermi energy $E_F = 0 - 0.1$ eV, and finding the precise range of $E_F$ that best matches the experimental data in Figure 3a, consistent with $C_g$ as noted above. We neglect the $\sim 0.1$ T field gradient due to Ni contacts since it is small compared to the $\sim 1.5$ T period of MC oscillations, and should only slightly distort the waveforms without affecting the measured period (see Supplementary Material). To account for a finite thickness of the 2DEG quantum well and disorder effects, we averaged the MC curves over a range of radii. The range $26.2 \pm 4.2$ nm was found to give the best match to the data. While this appears to capture the physics in our experiment well enough, a more rigorous treatment would include the radial term in the Hamiltonian as in ref. [27], leading to a modified version of our Equation 1. The radial averaging tends to smooth the oscillations, which are square-wave like for a single radius at very low temperature. This procedure may roughly account for disorder in the electrostatic potential, and the small magnetic flux gradient due to the Ni contacts. The amplitudes of the experimental MC oscillations are $\delta G_{\text{diff}} \sim (2e^2/h)(l_e/L)$, so that the normalized MC signals from experiment and simulation are comparable, $\delta \tilde{G}_{\text{diff}} \sim \delta \tilde{G}$. It is remarkable that the MC oscillations are observable in this device, despite being well into the diffusive transport regime. This indicates that the phase coherence length is at least comparable to the effective circumference of the 2DEG, $l_\phi \geq 2\pi r_{\text{eff}} \approx 163$ nm. We observe the amplitudes $\delta G_{\text{diff}}$ of the experimental MC oscillations to decay exponentially with temperature (Supplementary Material), as expected for a phase coherent effect.

The good agreement between the experimental and simulated data in Figure 3 is further confirmed by taking the Fourier transform of the data with respect to the
magnetic field, shown in Figure 4. The black line superimposed over Figures 4a (experiment) and 4b (simulation) traces out the frequency $f$ of the fundamental Fourier component in the simulated data. The modulation of $f$ with respect to Fermi level arises because the predicted MC oscillations are non-sinusoidal, and the widths of high (or low) conductance regions change depending on the Fermi level. The experimental data is seen to follow a similar overall trend. The average fundamental frequencies are 0.59 T$^{-1}$ and 0.61 T$^{-1}$ for the simulation and experiment, respectively. These correspond to effective radii $r_{\text{eff}}$ of 27.9 nm and 28.3 nm, respectively.

Higher harmonic components are difficult to reliably extract from the Fourier transform data, since the MC data only extends to 2 T. Instead we analyzed the raw MC curves by fitting with a fundamental frequency plus higher harmonics. Two examples are shown in Figure 4(c,d). The data in Figure 4c is fit well with nearly equal amplitude contributions from $f$, $2f$ and $3f$ signals where $f = 0.5$ T$^{-1}$, corresponding to $r_{\text{eff}} = 26$ nm. The data in Figure 4d has only $f$ and $2f$ components, with the second harmonic at half the amplitude of the first. The MC signals at many other gate voltages are strongly dominated by the first harmonic only, i.e. higher harmonics do not appear at all gate voltages. Higher harmonics do result from the model based on Equation (1), since the MC at a single radius value has the character of a square-wave, and thus includes higher frequency components. However, even in the single radius case, the intensity ratio of the second harmonic to the fundamental is much smaller than what we observe in Figure 4(c,d). Averaging over radii suppresses the higher harmonics quite efficiently, so it is unlikely that the harmonics observed experimentally are due to this property of the model. Another possibility explaining the second harmonic is the Al'tsshuler-Aronov-Spivak (AAS) type oscillation [34, 35], an analogue of the Aharonov-Bohm effect in the presence of weak localization that survives in diffusive regime. The second harmonics in Figure 4(c,d) are consistent with AAS oscillations since the conductance first increases upon applying magnetic flux. However, for some MC curves the second harmonic fits are shifted in phase (Supplementary Material), which is not consistent with AAS oscillations. The higher harmonics could be due to circular paths of higher winding number [27], which would suggest the phase coherence length could be as large as $3 \times 163$ nm = 489 nm. Prior studies have demonstrated phase coherence lengths on the order of a few hundred nm in InAs nanowires at low temperatures [15, 36].

We have not included the spin-orbit or Zeeman interactions in the theoretical modelling. The role of these interactions has been extensively studied for quasi-1D cylindrical nanowires [27, 37]. Their main effects are to mix angular momentum states and split the degenerate energy eigenvalues non-uniformly, leading to aperiodicity of the MC oscillations. For the relatively low magnetic fields in this work, i.e. $|B| \leq 2$ T, the energy band splittings can be ignored in a coarse first-order approximation.

Conclusion—In conclusion, we have observed MC oscillations in core-shell InAs nanowires periodic in $\Phi_0$ and consistent with conduction via a surface 2DEG. The dependence of these oscillations on gate voltage agrees well with a simple model of transport through phase coherent circular states. This implies a phase coherence length $l_p \geq 163$ nm at 3.8 K associated with the surface layer, suggesting a high quality InAs-InAlAs interface. That we observe these MC oscillations despite a device length much greater than the elastic scattering length is remarkable. Future MC and tunnelling studies on shorter channel devices in the quasi-ballistic regime are expected to provide detailed information about the electronic states in such core-shell nanowires.

APPENDIX

Equation (3) follows from writing the electron carrier density as a function of the radial coordinates $(r, \theta)$:

$$ n(r, \theta) = \sum_i |\Psi_i(r, \theta)|^2 \int_{E_i}^{\infty} g(E - E_i) f(E) dE \quad (4) $$

where $\Psi_i$ and $E_i$ are the $i^{th}$ wavefunction and energy of the circular modes, respectively, $g(E) = \frac{L}{\pi \hbar} \sqrt{\frac{2\pi m^*}{E}}$ is the 1D density of states (with spin degeneracy) and $f(E)$ is the Fermi-Dirac distribution. Integrating over the cross-sectional area $dA$ and dividing by volume $AL$ gives the average electron density

$$ n = \frac{1}{AL} \sum_i \int_{E_i}^{\infty} g(E - E_i) f(E) dE \quad (5) $$

$$ = \frac{\sqrt{2\pi m^*}}{\hbar \pi A} \sum_i \int_{E_i}^{\infty} \frac{(E - E_i)^{-1/2} dE}{1 + e^{(E - E_F)/kT}} \quad (6) $$

Making a change of variables $x = \frac{E - E_F}{kT}$ we obtain

$$ n = \frac{\sqrt{2\pi m^* kT}}{\hbar \pi A} \sum_i \int_0^{\infty} \frac{x^{-1/2} dx}{1 + e^{-(E_F - E_i)/kT}} \quad (7) $$

The integral is the Fermi-Dirac integral $F_{-1/2}((E_F - E_i)/kT)$.

Acknowledgements—We would like to acknowledge the Canadian Centre for Electron Microscopy, the Centre for Emerging Device Technologies, and the Quantum NanoFab facility for technical support. Shahram Tavakoli provided assistance with MBE and Roberto Romero provided technical assistance. We thank B.
Reulet and M. Khoshnegar for helpful discussions. This work was supported by NSERC, the Ontario Ministry for Research and Innovation and the Canada Foundation for Innovation. G. W. H. and K. W. acknowledge WIN Fellowships.

[1] J. Du, D. Liang, P. A. Xuan, and X. P. Gao, Nano Lett., 9, 4348 (2009).
[2] J. Salfi, I. G. Savelyev, M. Blumin, S. V. Nair, and H. E. Ruda, Nat. Nanotechnol., 5, 737 (2010).
[3] C. Flindt, A. S. Strelsen, and K. Flensberg, J. Phys.: Conf. Ser., 61, 302 (2007).
[4] M. D. Schroer, K. D. Petersson, M. Jung, and J. R. Petta, Phys. Rev. Lett., 107, 176811 (2011).
[5] S. Nadj-Perge, S. M. Frolov, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Nature, 468, 1084 (2010).
[6] P. D. Sau, R. M. Lutchyn, S. Tewari, and S. Das Sarma, Phys. Rev. Lett., 104, 066802 (2010).
[7] V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Science, 336, 1003 (2012).
[8] S. A. Dayeh, C. Soci, P. K. L. Yu, E. T. Yu, and D. Wang, Journal of Vacuum Science and Technology B, 25, 1432 (2007).
[9] Q. Hang, F. Wang, P. D. Carpenter, D. Zemlyanov, O. Zakharov, E. A. Stach, W. E. Buhro, and D. B. James, Nano Lett., 8, 49 (2008).
[10] M. H. Sun, H. J. Joyce, Q. Gao, H. H. Tan, C. Jagadish, and C. Z. Ning, Nano Lett., 12, 3378 (2012).
[11] M. E. Pistol and C. E. Pryor, Phys. Rev. B, 78, 115319 (2008).
[12] E. M. Gallo, G. Chen, M. Currie, T. McGuckin, P. Prete, N. Lovergine, B. Nabet, and J. E. Spanier, Appl. Phys. Lett., 98, 241113 (2011).
[13] C. Haapamaki, J. Baugh, and R. LaPierre, J. Cryst. Growth, 345, 11 (2012).
[14] T. Richter, C. Blömers, H. Lüth, R. Calarco, M. Indlekofer, M. Marso, and T. Schäpers, Nano Lett., 8, 2834 (2008).
[15] C. Blömers, M. I. Lepsa, M. Luysberg, D. Grützmacher, H. Lüth, and T. Schäpers, Nano Lett., 11, 3550 (2011).
[16] J. W. W. van Tilburg, R. E. Algra, W. G. G. Immink, M. Verheijen, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Semicond. Sci. Technol., 25, 024011 (2010).
[17] G. W. Holloway, Y. Song, C. M. Haapamaki, R. R. LaPierre, and J. Baugh, Appl. Phys. Lett., 102, 043115 (2013).
[18] H. Shtrikman, R. Popovitz-Biro, A. Kretinin, and M. Heiblum, Nano Lett., 9, 215 (2009).
[19] H. J. Joyce, J. Wong-Leung, Q. Gao, H. H. Tan, and C. Jagadish, Nano Lett., 10, 908 (2012).
[20] K. A. Dick, C. Thelander, L. Samuelson, and P. Caroff, Nano Lett., 10, 3494 (2010).
[21] M. C. Plante and R. R. LaPierre, J. Appl. Phys., 105, 114304 (2009).
[22] C. M. Haapamaki, J. Baugh, and R. R. LaPierre, J. Appl. Phys., 112, 124305 (2012).
[23] Y.-L. Chueh, A. C. Ford, J. C. Ho, Z. A. Jacobsen, Z. Fan, C.-Y. Chen, L.-J. Chou, and A. Javey, Nano Lett., 8, 4528 (2008).
[24] M. Noguchi, K. Hirakawa, and T. Ikoma, Phys. Rev. Lett., 66, 2243 (1991).
[25] L. O. Olsson, C. B. M. Andersson, M. C. Häkansson, J. Kanski, L. Iver, and U. O. Karlsson, Phys. Rev. Lett., 76, 3626 (1996).
[26] C. Blömers, T. Grap, M. I. Lepsa, J. Moers, S. Trelkenkamp, D. Grützmacher, H. Lüth, and T. Schäpers, Appl. Phys. Lett., 101, 152106 (2012).
[27] Y. Tserkovnyak and B. I. Halperin, Phys. Rev. B, 74, 245327 (2006).
[28] G. Holloway, Y. Song, C. M. Haapamaki, R. R. LaPierre, and J. Baugh, J. Appl. Phys., 113, 024511 (2013).
[29] S. Haque, A. Matsuo, Y. Yamamoto, and H. Hori, Physica B: Condensed Matter, 325, 259 (2003), ISBN 0921-4526.
[30] D. K. Ferry and S. M. Goodnick, Transport in nanostructures, Cambridge Stud. Semicond. Phys. Micro Electr. Eng. (Cambridge Univ. Press, Cambridge, 1997).
[31] O. N. Dorokhov, Solid State Commun., 51, 381 (1984).
[32] W. J. Cody and H. C. Thacher, Mathematics of Computation, 21, 30 (1967).
[33] O. Wunnicke, Appl. Phys. Lett., 89, 083102 (2006).
[34] B. L. Al’tshuler, A. G. Aronov, and B. Z. Spivak, JETP Lett., 33, 94 (1981).
[35] A. Bachtold, C. Strunk, J.-P. Salvetat, J.-M. Bonard, B. L. Al’tshuler, A. G. Aronov, and B. Z. Spivak, JETP Lett., 33, 94 (1981).
[36] X. Zhou, S. A. Dayeh, D. Aplin, D. Wang, and E. T. Yu, Appl. Phys. Lett., 89, 053113 (2006).
[37] S. Q. Jin, J. Waugh, S. Matsura, S. Faniel, H. Z. Wu, and T. Koga, Physics Procedia, 3, 1321 (2010).