Phase-coherent transport in InN nanowires of various sizes

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We investigate phase-coherent transport in InN nanowires of various diameters and lengths. The nanowires were grown by means of plasma-assisted molecular beam epitaxy. Information on the phase-coherent transport is gained by analyzing the characteristic fluctuation pattern in the magneto-conductance. For a magnetic field oriented parallel to the wire axis we found that the correlation field mainly depends on the wire cross section, while the fluctuation amplitude is governed by the wire length. In contrast, if the magnetic field is oriented perpendicularly, for wires longer than approximately 200 nm the correlation field is limited by the phase coherence length. Further insight into the orientation dependence of the correlation field is gained by measuring the conductance fluctuations at various tilt angles of the magnetic field.

Semiconductor nanowires fabricated by a bottom-up approach have emerged as very interesting systems not only for the design of future nanoscale device structures but also to address fundamental questions connected to strongly confined systems. Regarding the latter, quantum dot structures, single electron pumps, or superconducting interference devices have been realized. Many of the structures cited above were fabricated by employing III-V semiconductors, e.g. InAs or InP. Apart from these more established materials, InN is particularly interesting for nanowire growth because of its low energy band gap and its high surface conductivity.

At low temperatures the transport properties of nanostructures are affected by electron interference effects, i.e. weak localization, the Aharonov–Bohm effect, or universal conductance fluctuations. The relevant length parameter in this transport regime is the phase coherence length \( \phi \), that is the length over which phase-coherent transport is maintained. In order to obtain information on \( \phi \), the analysis of conductance fluctuations is a very powerful method. In fact, in InAs nanowires pronounced fluctuations in the conductance have been observed and analyzed, recently.

Here, we report on a detailed study of the conductance fluctuations \( \delta G \) measured in InN nanowires of various sizes. Information on the phase-coherent transport is gained by analyzing the average fluctuation amplitude and the correlation field \( B_c \). Special attention is drawn to the magnetic field orientation with respect to the wire axis, since this allowed us to change the relevant probe area for the detection of phase-coherent transport.

The InN nanowires investigated here were grown without catalyst on a Si (111) substrate by plasma-assisted MBE. The measured wires had a diameter \( d \) ranging from 42 nm to 130 nm. The typical wire length was 1 \( \mu \)m. From photoluminescence measurements an overall electron concentration of about \( 5 \times 10^{18} \text{ cm}^{-3} \) was determined.

For the samples used in the transport measurements, first, contact pads and adjustment markers were defined on a SiO\(_2\)-covered Si (100) wafer. Subsequently, the InN nanowires were placed on the patterned substrate and contacted individually by Ti/Au electrodes. Four wires labeled as A, B, C, and D will be discussed in detail, below. Their parameters are summarized in Table I. In order to improve the statistics, additional wires which are not specifically labeled, were included in part of the following analysis. A micrograph of a typical contacted wire is depicted in Fig. 1 (inset).

The transport measurements were performed in a magnetic field range from 0 to 10 T at a temperature of 0.6 K. In order to vary the angle between the wire axis and the magnetic field \( B \), the samples were mounted in a rotating sample holder. The rotation axis was oriented perpendicularly to the magnetic field and to the wire axis. The magnetoresistance was measured by using a lock-in technique with an ac bias current of 30 nA.

The fluctuation pattern for nanowires with different dimensions are depicted in Fig. 1A. Here, the normalized conductance fluctuations \( \delta G \) for wires A to C comprising successively increasing diameters are plotted.
Obviously, for wire A, which has the smallest diameter, of the measurements shown in Fig. 1 are listed in Table I. Therefore, for these wires it can be concluded that the phase coherence length \( L \) is smaller than the wire length \( L \), which is physically unreasonable. We attribute the discrepancy to the different geometrical situation, i.e., for the latter a confined two-dimensional electron gas with a perpendicularly oriented magnetic field was considered, while in our case the field is oriented parallel to the wire axis. In addition, an inhomogeneous carrier distribution within the cross section, e.g., due to a carrier accumulation at the surface can also result in a disagreement between experiment and theoretical model. As can be seen in Fig. 2(a) (inset), \( F(\Delta B) \) also shows negative values at larger \( \Delta B \). This behavior can be attributed to the limited number of modes in the wires, as it was observed previously for small size semiconductor structures. However, as discussed by Jalabert et al. at small fields \( F(\Delta B) \) and thus \( B_c \) being calculated fully quantum mechanically correspond well to the semiclassical approximation.

In order to elucidate the dependence of \( B_c \) on the wire diameter in more detail, a larger number of wires was measured. As can be seen in Fig. 2(a), \( B_c \) systematically decreases with \( d \). Leaving out wire D which has the largest diameter, the decrease of \( B_c \) is well described by a \( 1/d^2 \)-dependence. As mentioned above, for short wires \((L \approx 200 \text{ nm})\) we found that phase coherence is maintained over the complete length. This length corresponds to a circumference of a wire with a diameter of about 64 nm. Except of wire D, \( d \) is in the order of that value, so that one can expect that phase coherence is maintained within the complete cross section. For the parameter \( \alpha \) we found a value of 0.24, which is by a factor of 4 smaller than the theoretically expected value of 0.95. Choosing \( \alpha = 0.95 \) would result in lower bound values of \( B_c \) being larger than all corresponding experimental values, which is physically unreasonable. We attribute the discrepancy to the different geometrical situation, i.e., for the latter a confined two-dimensional electron gas with a perpendicularly oriented magnetic field was considered, while in our case the field is oriented parallel to the wire axis. In addition, an inhomogeneous carrier distribution within the cross section, e.g., due to a carrier accumulation at the surface can also result in a disagreement between experiment and theoretical model. As can be seen in Fig. 2(a) (inset), the data point of the wire with the largest diameter of 130 nm, i.e., wire D, is found above the calculated curve. This indicates that presumably for this sample, \( A_\phi \) is slightly smaller than the wire cross section.

Next, we will focus on measurements of \( \delta G \) with a magnetic field oriented perpendicular to the wire axis. As a typical example, \( \delta G \) of wire C is shown in Fig. 1(b). Here, a correlation field of 0.17 T was extracted, which is smaller than the value of corresponding measurements with \( B \) parallel to the wire axis (c.f. Fig. 1(a) and Table I). The smaller value of \( B_c \) can be attributed to the eff-
FIG. 2: (a) Correlation field $B_c$ as a function of the wire diameter $d$. As illustrated in the schematics the magnetic field $B$ was oriented axially. The solid lines corresponds to the calculated correlation field. The inset shows $F(\Delta B)/F(0)$ for wire C. (b) $B_c$ as a function of the maximum area $A = Ld$ (see schematics) of the wire. The magnetic field is oriented perpendicular to the wire axis. The solid lines represents the calculated lower boundary correlation fields assuming $\alpha = 0.95$ and 0.24, respectively.

In Fig. 2(b) the $B_c$ values of various wires are plotted as a function of the maximum area $A_{\text{max}} = Ld$ penetrated by the magnetic field. As a reference, the calculated curve using Eq. (1) and assuming $A_\phi = A_{\text{max}}$ are also plotted. It can be seen that the $B_c$ values of two wires with small areas, including wire A, match to the theoretically expected ones if one takes $\alpha = 0.95$, as given byBeenakker and van Houten. This corresponds to the case of phase-coherent transport across the complete wire, as it was, in case of wire A, already concluded from the rms$(G)$ analysis. For all other wires the $B_c$ values are above the theoretically expected curve, corresponding to the case $A_\phi < A_{\text{max}}$. At this point, one might argue that for $B$ oriented along the wire axis a better agreement is found for $\alpha = 0.24$. However, as can be seen in Fig. 2(b), if one assumes $\alpha = 0.24$ all experimental values are above the calculated curve, i.e. $A_\phi < A_{\text{max}}$. This does not agree with the observation that for short wires rms$(G)$ is in the order of $e^2/h$. We attribute the difference between the appropriate $\alpha$ values for different field orientations to the different character of the relevant area penetrated by the magnetic flux, e.g. due to carrier accumulation at the surface.

Beside $B_c$ we also analyzed the fluctuation amplitude for five different wires with $B$ oriented perpendicular to the wire axis. Only wires with comparable diameters of $(75 \pm 5)$ nm were chosen, here. It can be seen in Fig. 3 that rms$(G)$ tends to decrease with increasing wire length $L$. From the previous discussion of $B_c$ it was concluded that for long wires, as it is the case here, $l_\phi < L$. In this regime rms$(G)$ is expected to depend on $L$ as,

$$\text{rms}(G) = \beta \frac{e^2}{\hbar} \left( \frac{l_\phi}{T} \right)^{3/2},$$

with $\beta$ in the order of one. The above expression is valid as long as the thermal diffusion length $l_T = \sqrt{D/k_BT}$, is larger than $l_\phi$. Here, $D$ is the diffusion constant. From our transport data we estimated $l_T \approx 600$ nm at $T = 0.6$ K. As can be seen in Fig. 3, the available experimental data points roughly follow the trend of the calculated curve using Eq. (2) and assuming $l_\phi = 430$ nm and $\beta = 1$. For the limit $l_\phi < L$, a correlation field according to $B_c = 0.95\Phi_0/dl_\phi$ is expected. As confirmed in Fig. 2(b), most experimental values of $B_c$ are close to the calculated one.

If one compares the rms$(G)$ values for wires with $d \approx 75$ nm and $B$ oriented axially (not shown here) with the corresponding values for $B$ oriented perpendicularly, one finds, that both are in the same range. Thus it can be concluded that the fluctuation amplitude does not significantly depend on the magnetic field orientation. This is in contrast to the correlation field, where one finds a systematic dependence on the orientation of $B$.

In order to discuss the latter aspect in more detail the correlation field was studied for various tilt angles $\theta$ of the magnetic field. Figure 4 shows $B_c$ of sample D if $\theta$ is
increased from 0° to 90°. The inset in Fig. 4 illustrates how θ is defined. Obviously, $B_c$ decreases with increasing tilt angle θ. As explained above, the value of $B_c$ is a measure of the maximum area normal to $B$, which is enclosed phase-coherently by the electron waves in the wire [see Fig. 2 (schematics)]. As long as $\theta \leq \arctan(L/d)$, this maximum area is given by $A(\theta) = \pi d^2/4 \cos \theta$. The expected $\theta$-dependence of the correlation field is then given by $B_c(\theta)=B_c(0) \cos(\theta)$, with $B_c(0)$ the correlation field at $\theta = 0$. As can be seen in Fig. 3, the calculated correlation field $B_c$, corresponding to fully phase-coherent transport, decreases much faster with increasing $\theta$ than the experimentally determined values. The experimental situation is better described by a linear decrease. As it was discussed above, at $\theta = 0$ one can assume that the area enclosed phase-coherently is equal to $A(0)$. However, if the tilt angle is increased the maximum wire cross section $A(\theta)$ presumably becomes larger than $A_0$, resulting in a much smaller decrease of $B_c$ than theoretically expected for fully phase-coherent transport. In addition, as pointed out above, the different tilt angles result in an angle-dependent parameter $\alpha$. This is supported by the measurements of $B_c$ for $B$ parallel and perpendicular to the wire axis, where different values for $\alpha$ were determined, respectively.

In conclusion, the conductance fluctuations of InN nanowires with various lengths and diameters were investigated. We found that for an axially oriented magnetic field the correlation field $B_c$ and thus the area where phase-coherent transport is maintained is limited by the wire cross section perpendicular to $B$. In contrast, $\text{rms}(G)$ decreases with the wire length, since this quantity also depends on the propagation of the electron waves along the wire axis. If the magnetic field is oriented perpendicularly we found that for long wires $B_c$ is limited by $l_\phi$ rather than by the length $L$. Our investigations demonstrate that phase-coherent transport can be maintained in InN nanowires, which is an important prerequisite for the design of quantum device structures based on this material system.

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