Temperature-dependence of the phase-coherence length in InN nanowires

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We report on low-temperature magnetotransport measurements on InN nanowires, grown by plasma-assisted molecular beam epitaxy. The characteristic fluctuation pattern observed in the conductance was employed to obtain information on phase-coherent transport. By analyzing the root-mean-square and the correlation field of the conductance fluctuations at various temperatures the phase-coherence length was determined.

Semiconductor nanowires are versatile building blocks for the design of future electronic devices. They include, e.g., nano-sized transistors, resonant tunneling devices, or quantum dot based devices, to name just a few. Among the many possible materials suitable for semiconductor nanowires, InN is particularly interesting because of its low energy band gap and its high surface conductivity.

At low temperatures electron interference effects often play a prominent role in the transport characteristics of nanostructures. Typical phenomena observed in this regime are weak localization, the Aharonov–Bohm effect, or universal conductance fluctuations. The characteristic length connected to these effects is the phase-coherence length $l_\phi$, i.e., the length over which phase-coherent transport is maintained. The length $l_\phi$ is an important parameter for the design of device structures based on electron interference.

The analysis of conductance fluctuations is one of the possible methods, in order to obtain information on $l_\phi$ in semiconductor nanostructures. Due to the small dimensions of semiconductor nanowires, often only a limited number of scattering centers are involved in the transport. In this case, pronounced fluctuations in the conductance can be expected, e.g., when the magnet field is varied. This was indeed observed by Hansen et al. for InAs nanowires.

In this letter we will exploit the characteristic fluctuation pattern in the magnetoresistance of InN nanowires, in order to obtain information on the phase-coherent transport. By analyzing the root-mean-square and the correlation field of the fluctuation pattern, the temperature dependence of $l_\phi$ will be determined.

Two InN nanowires of different thickness, prepared by plasma-assisted MBE, were investigated in this study. The wires were grown on a Si (111) substrate at a temperature of 475°C under N-rich conditions. For the growth of the first sample (wire A) a beam equivalent pressure for In of $3.0 \times 10^{-8}$ mbar was chosen, while for the second sample (wire B) $7.0 \times 10^{-8}$ mbar was adjusted. As illustrated in Fig. 1a, using this scheme growth of InN nanowires with a length of approximately 1 µm was achieved. From photoluminescence measurements a typical overall electron concentration of $5 \times 10^{18}$ cm$^{-3}$ was estimated.

For the transport measurements of the InN wires, contact pads and adjustment markers were defined on a SiO$_2$-covered Si (110) wafer. The InN nanowires were dispersed on the patterned substrate, by separating them first from their host substrate in an acetone solution. Subsequently, a droplet of acetone containing the detached InN nanowires was put on the patterned substrate wafer. In the final step, the wires were contacted individually using Ti/Au electrodes defined by electron beam lithography. Wire A had a diameter of $d = 67$ nm with contact pads separated by $L = 410$ nm, while wire B had a diameter of $130$ nm with contacts separated by $530$ nm. An scanning electron micrograph of wire B is shown in Fig. 1.

The measurements were performed in a He-3 cryostat at temperatures between 0.6 and 25 K. The cryostat was equipped with a 10 T magnet. The magnetic field was oriented perpendicular to the axis of the wires. The magnetoresistance was measured by using a lock-in technique with an ac bias current of 30 nA.

The fluctuation pattern in the total magnetoresistance of wire A at various temperatures is shown in Fig. 2a. The measurements were performed in a magnetic field...
range from $-1.5$ T to 10.0 T. It can be seen clearly that the fluctuation amplitude decreases substantially if the temperature is increased. Furthermore, one finds that although the amplitude is damped with increasing temperature, the pattern itself is reproduced. As can be seen in Fig. 2a), due to the two-terminal measurement, the fluctuation pattern is symmetric with respect to the magnetic field $B$.

Before we proceed to discuss the temperature dependence of $B_c$, we focus on the analysis of the temperature-dependence of the conductance fluctuations. The magnitude of $\delta G$ can be quantified by the root-mean-square of the conductance fluctuations $\text{rms}(G)$, which is defined by $\sqrt{\langle \delta G^2 \rangle}$. Here, $\langle \ldots \rangle$ represents the average over the magnetic field. In Fig. 3a) the $\text{rms}(G)$ of wire A is plotted as a function of temperature. Two regimes are revealed: At temperatures below about 1.5 K, $\text{rms}(G)$ tends to saturate, whereas at temperature above 1.5 K a decrease of $\text{rms}(G)$ proportional $T^{-0.4}$ is observed. A similar decrease proportional to $T^{-0.4}$ was found for wire B above $\approx 2$ K, while below 2 K a slightly steeper decrease was observed compared to wire A.

In order to analyze the electron interference phenomena in detail, first, the fluctuations in the magnetoresistance were converted to the corresponding conductance fluctuations $\sqrt{\text{conductance fluctuations}}$. After subtracting the contact resistance, the contribution by subtracting the slowly varying parabolic background amplitude is in the order of $R_t$.

We will now focus on the analysis of the temperature-dependence of the conductance fluctuations. The magnitude of $\delta G$ can be quantified by the root-mean-square of the conductance fluctuations $\text{rms}(G)$, which is defined by $\sqrt{\langle \delta G^2 \rangle}$. Here, $\langle \ldots \rangle$ represents the average over the magnetic field. In Fig. 3a) the $\text{rms}(G)$ of wire A is plotted as a function of temperature. Two regimes are revealed: At temperatures below about 1.5 K, $\text{rms}(G)$ tends to saturate, whereas at temperature above 1.5 K a decrease of $\text{rms}(G)$ proportional $T^{-0.4}$ is observed. A similar decrease proportional to $T^{-0.4}$ was found for wire B above $\approx 2$ K, while below 2 K a slightly steeper decrease was observed compared to wire A.
lated values of $l_\phi$ saturate at about the wire length $L$, indicating that phase coherence is maintained over the complete length. Above 1.5 K, $l_\phi$ decreases with increasing temperature following a dependence proportional to $T^{-0.19}$. Using the same procedure as described above, $l_\phi$ was determined from $B_c$ for wire B, as well. As can be seen in Fig. 4 b), $l_\phi$ monotonously decreases with temperature following a dependence proportional to $T^{-0.22}$ in the whole temperature range. Consequently, one can state that for this wire $l_\phi$ is always smaller than $L$ in the temperature range considered here. For both wires the temperature dependence of $l_\phi$ is slightly smaller than the theoretically expected dependence proportional to $T^{-1/3}$.

Using the interpolation formula derived by Beenakker and van Houten: 

$$\text{rms}(G) = \alpha \frac{e^2}{h} \left( \frac{l_\phi}{L} \right)^{3/2} \left[ 1 + \frac{9}{2\pi} \left( \frac{l_\phi}{l_T} \right) \right]^{-1/2}, \quad (1)$$

the temperature dependence of $\text{rms}(G)$ was estimated. The formula is valid for $l_\phi \approx l_T < L$. Ideally, the constant $\alpha$ has a value of $\sqrt{6}$. The calculated values for wire A and B using Eq. (1) are shown in Fig. 4. One finds that at $T > 1$ K the experimental values of $\text{rms}(G)$ vs. $T$ fit very well to the theoretical curves. The values of $\alpha$ with 0.38 and 1.32 for wire A and B, respectively, deviate to some extent from the theoretically expected value. This can be attributed to uncertainties in the determination of $R_c$ affecting the amplitude of $\text{rms}(G)$. For comparison, the $\text{rms}(G) \propto (l_\phi/L)^{3/2}$ curves, representing the case of neglected thermal averaging, are also shown in Fig. 4. One finds that in this case the decrease of $\text{rms}(G)$ is too small. The fact that thermal smearing has to be considered is also supported by comparing $l_T$ to $l_\phi$ (cf. Fig. 4). Here, one finds that $l_0$ and $l_T$ are in the same order of magnitude. At lower temperatures ($T < 1$ K) the smaller slope of $\text{rms}(G)$ can be explained by the reduced effect on $l_T$ and to the fact that $l_\phi$ exceeds or approaches $L$.

In summary, the phase coherence length $l_\phi$ of InN nanowires was determined by analyzing the characteristic conductance fluctuation pattern. For the shorter wire it is found that at low temperatures $l_\phi$ exceeds the wire length $L$, while at temperatures above 1.5 K $l_\phi < L$ and continuously decreases with increasing $T$. In contrast for the longer wire (sample B) $l_\phi$ was smaller than $L$ in the complete temperature range. Our investigations demonstrate, for short InN nanowires phase coherent transport can be maintained along the complete length.
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