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Effect of wire length on quantum coherence in InGaAs wires

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Quantum phase coherence lengths were experimentally measured in nanolithographic wires to investigate the effects of wire length on quantum decoherence, which can be limited by mechanisms such as coupling to an external classical environment. The work demonstrates that device geometry and coupling to the environment have to be taken into account in quantum coherence, of relevance in quantum technologies using electronic nanostructures. The low-temperature measurements of the quantum phase coherence lengths use quantum transport, specifically antilocalization, on wires fabricated from an InGaAs/InAlAs heterostructure. It is observed that longer wire lengths result in longer quantum phase coherence lengths, tending to an asymptotic value in long wires. The results are understood from the observation that longer wires average out the quantum decoherence introduced at the end sections by coupling to the external environment. The experimental results are quantitatively compatible with a model expressing reduced backscattered amplitude due to quantum interference at the wire ends.

PACS numbers: cfr Physics Subject Headings

I. INTRODUCTION

The study of quantum coherence of charge carriers in the solid-state has attracted increasing attention for the insights it provides into the fundamental properties of quantum systems and into quantum measurement theory, and for the importance it carries for the field of quantum information processing. Solid-state systems that are larger than the atomic scale but still of a spatial extent along which quantum coherence is maintained, constitute a ready platform to study mechanisms limiting quantum coherence of electrons. Such solid-state quantum systems find distinctive use as nanoelectronic devices, and hence quantum electronic transport approaches, as used in this work, are in this application intrinsically suited to study quantum coherence. In particular, the spatial extent along which quantum coherence is maintained in mesoscopic conducting wire geometries is of relevance today due to the interest in hybrid semiconductor-superconductor nanowires for the study of solid-state Majorana quasiparticles, where the Majorana states are localized at the ends of a wire, along the length of which quantum coherence of the Majorana states must be preserved. The carrier quantum phase coherence length \( L_\phi \) is defined as an average length scale over which quantum coherence is maintained, and thus beyond which the relative quantum phases of the carrier states are randomized. In mesoscopic electronic systems several decoherence mechanisms limit \( L_\phi \). Among these are inelastic or quasi-elastic scattering mechanisms such as electron-phonon and electron-electron scattering. Decoherence can also result from energy level broadening beyond the Thouless energy, thermally or due to excitation voltages or currents, causing averaging over independent and incoherent channels. At low temperature \( T \), many decoherence mechanisms dependent on energy exchange are suppressed, and \( L_\phi \) reaches values sufficiently long to study electronic transport phenomena relying on quantum interference in nanoscale and mesoscopic devices. Yet geometrical effects also play a role, e.g. via environmental coupling decoherence originating from the fact that measurement of a quantum system necessitates coupling to the external environment, taken as a classical system. Environmental coupling decoherence can be regarded as the effect of dynamical degrees of freedom disregarded in the definition of the original Hamiltonian describing the quantum state, and added in retrospect to more completely define the state. The present work demonstrates the general importance of device geometry -particularly wire length- and of environmental coupling decoherence in studying and using quantum-coherence phenomena, among others in the characterization of new quantum states of matter realized in nanoscale systems. Previous studies relating to the dependence of quantum decoherence on device geometry and size have been performed in quantum wires, quantum rings, quantum ring arrays or cylinders, and quantum dots.

In this work parallel arrays of wires of various lengths were fabricated on an InGaAs/InAlAs heterostructure. The heterostructure is essentially free of any magnetic impurities, and is thus a good host for studying intrinsic decoherence mechanisms. Each wire array consists of 20 parallel quasi-one-dimensional (Q1D) wires of
II. MATERIAL AND SAMPLE PROPERTIES

Hall bar mesas were defined on the InGaAs/InAlAs heterostructure by photolithography and wet etching, and subsequently arrays of 20 parallel Q1D wires were defined on the mesas by electron-beam lithography and wet etching (Fig. 1. a). Wire lengths were \( L = 11.0 \, \mu m \). Etched trenches (darker regions) form insulating barriers for the 2DES, thus delineating the conducting wires. The lithographic wire width is 0.70 \( \mu m \) for all wires. (b) \( R_{XX} \) (black) and \( R_{XY} \) (red) at 0.38 K on a Hall bar fabricated on the InGaAs/InAlAs heterostructure, with the heterostructure layer sequence depicted in the inset.

![Image](image-url)
layer, a 7 nm In0.52Al0.48As spacer, the 10 nm wide In0.53Ga0.47As electron quantum well (QW), a 17 nm In0.52Al0.48As spacer, and a 2 nm undoped InP cap layer. Electrons are provided to the QW by 6 nm Si-doped In0.52Al0.48As, and the two-dimensional electron system (2DES) is hosted in QW with areal carrier density $N_s = 1.58 \times 10^{16} \text{ m}^{-2}$ as determined on the Hall bar at $T = 0.38 \text{ K}$ from both $R_{xy}$ and Shubnikov-de Haas oscillations (Fig. 1. b). The unpatterned 2DES’ sheet resistance is obtained as $R_{\text{2D}} = \frac{1}{N_s e^2 D_{2D}}=287 \Omega/\Box$, with mobility $\mu_{2D} = 1.38 \text{ m}^2/(\text{Vs})$. In the range $0.38 \text{ K} \leq T \leq 10.0 \text{ K}$ of the measurements both $\mu_{2D}$ and $N_s$ do not vary significantly. Other parameters depending on $\mu_{2D}$ and $N_s$ are evaluated accounting for nonparabolicity in the InGaAs conduction band, with a ratio of $\Gamma$-point effective mass $m^*$ to free-electron mass of 0.0353 and a low $T$ band gap of $E_g = 813 \text{ meV}$.

In the unpatterned 2DES we have the elastic scattering time $\tau_{2D} = 0.81 \text{ ps}$, the mean-free-path $\ell_{2D} = 0.59 \text{ nm}$, the Fermi energy $E_F = 80.4 \text{ meV}$, $\lambda_F = 19.9 \text{ nm}$ ($\ll W$), and the diffusion constant $D_{2D} = 0.11 \text{ m}^2/\text{s}$. $D_{2D}$ is calculated using the 2D degenerate expression $D = \frac{1}{2} v_F \ell_{2D}$, where $v_F$ is the Fermi velocity derived from $N_s$. Situating the In0.52Al0.48As doping layer below the In0.53Ga0.47As QW results in asymmetry in the QW confinement potential for the 2DES and in a substantial SOI, yet also depresses $\mu_{2D}$ compared with other In0.53Ga0.47As/In0.52Al0.48As heterostructures. Measurements occurred in a $^3$He cryostat using four-contact low-frequency lock-in techniques under constant current $I = 20 \text{ nA}$, sufficiently low to avoid heating the 2DES. For each array of parallel wires, the measured magnetoresistance $R_m(B)$ includes a magnetoresistance $R(B)$ of each of the 20 identical wires in the array and a series magnetoresistance of the unpatterned 2DES regions. Hence $R_m(B) = \frac{R(B)}{20} + \frac{L_{2D} R_{\text{2D}}(B)}{W_{2D}}$, where $L_{2D}$ and $W_{2D}$ are the dimensions of the unpatterned regions known from pattern design, and the unpatterned sheet magnetoresistance $R_{\text{2D}}(B)$ is measured on the Hall bar. $R(B)$ is then obtained as $R(B) = 20 (R_m(B) - \frac{L_{2D} R_{\text{2D}}(B)}{W_{2D}})$, and $R(B)$ yields the wire magnetococonductance $G(B) = 1/R(B)$ required for WAL analysis. As an example, Fig. 2 shows $\Delta G(B) = G(B) - G(B = 0)$ for the $6.0 \mu \text{m}$ wires at $T$ from 0.38 K to 10.0 K. The sharp negative magnetococonductance for $B < 12 \text{ mT}$ followed by a positive magnetococonductance is characteristic of WAL.

The following discussion introduces the WAL analysis appropriate for QI wires. The quantum correction to the 2D conductivity $\sigma_{2D} = (L/W)G$ is proportional the length over which a wave packet retains coherence. In the absence of SOI for a system of width $W$ at $B = 0$ the quantum correction per spin channel $\delta\sigma_{2D}$ is expressed as:

$$\delta\sigma_{2D} = -\frac{1}{2} \frac{e^2}{\pi \hbar} \frac{L_\phi}{W}. \tag{1}$$

Under applied $B$, the Aharonov-Bohm phases for time-reversed paths differ in sign, and hence time-reversal symmetry breaking due to the accumulation of Aharonov-Bohm phases will reduce the effective coherence length. An effective time-reversal symmetry breaking length known as the magnetic length $L_B$ is introduced, which forms a limit for the effective coherence length $1/\sqrt{L_{\phi}^{-2} + L_B^{-2}}$. The effect of $L_B$ is to delay accumulation of a magnetic flux and its associated Aharonov-Bohm phase to higher $B$ in a narrow wire, and hence to spread out the magnetoresistance features over higher $B$. The Aharonov-Bohm phase weakens the constructive interference of time-reversed paths and leads to the negative magnetoresistance characteristic of weak-localization. Under SOI however, the effective vector potential due to SOI also introduces spin-dependent Aharonov-Casher phase shifts, leading to spin decoherence (properly dephasing) with a characteristic length scale $L_{\phi}$. The pairing of time-reversed trajectories (Cooperons) then leads to singlet and triplet contributions to the quantum correction $\delta\sigma_{2D}$. Under SOI $L_{\phi}$ is thus replaced by a combination of length scales categorized as singlet and triplet length scales. The singlet length scale $L_{0,0}$ is expressed as:

$$L_{0,0} = \left(L_{\phi}^{-2} + L_B^{-2}\right)^{-\frac{1}{2}} \tag{2}$$

The singlet $L_{0,0}$ does not contain $L_{so}$ and is not sensitive to spin decoherence under SOI since the corresponding total spin adds to zero. $L_{\phi}$ and $L_B$ limit $L_{0,0}$. The triplet length scales $L_{1,m}$ ($m = \pm 1, 0$) are expressed as:

$$\begin{align*}
L_{1,m} &= \left(L_{\phi}^{-2} + L_B^{-2}\right)^{-\frac{1}{2}} \cdot \frac{2m + 1}{2} \\
L_{0,0} &= \left(L_{\phi}^{-2} + L_B^{-2}\right)^{-\frac{1}{2}}
\end{align*}$$

FIG. 2: Magnetococonductance $\Delta G(B)$ vs $B$ for the wires with $L = 6.0 \mu m$ parametrized in $T$. 

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\end{align*}$$
TABLE I: Lengths and lithographic widths of the wires, quantum phase coherence lengths at $T = 0.38$ K, and exponent $p$ of the $T$-dependence of the quantum decoherence rate for $T$ varying from 1.0 K to 10.0 K.

<table>
<thead>
<tr>
<th>Wires</th>
<th>$L=11.0$ µm</th>
<th>$L=6.0$ µm</th>
<th>$L=4.0$ µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_0$ (µm)</td>
<td>$W_{1th}=0.70$ µm</td>
<td>$W_{1th}=0.70$ µm</td>
<td>$W_{1th}=0.70$ µm</td>
</tr>
<tr>
<td>$\tau_0^{-1} \sim T^p$</td>
<td>1.42</td>
<td>1.27</td>
<td>1.04</td>
</tr>
<tr>
<td>$p=0.690 \pm 0.030$</td>
<td>$p=0.679 \pm 0.056$</td>
<td>$p=0.716 \pm 0.052$</td>
<td></td>
</tr>
</tbody>
</table>

$$L_{1,\pm 1} = \left( L_{\phi}^{-2} + L_{so}^{-2} + L_B^{-2} \right)^{-\frac{1}{2}}$$

$$L_{1,0} = \left( L_{\phi}^{-2} + 2L_{so}^{-2} + L_B^{-2} \right)^{-\frac{1}{2}}$$

(3)

The difference between $L_{1,\pm 1}$ and $L_{1,0}$ lies in anisotropic spin decoherence in 2D systems, and does not exist in 3D systems. The triplet contributions to $\delta \sigma_{2D}$ will be negative (leading to positive magnetoconductance) while the singlet contribution will be positive and will reverse weak-localization to WAL (negative magnetoconductance at low $B$). In wide, laterally unconstrained 2D systems, $L_B = l_m = \sqrt{\hbar/eB}$. When the 2DES is narrowed to a Q1D wire with $W \leq l_m$ the accumulation of Aharonov-Bohm phases is impeded (equivalently, the wave function boundary conditions are modified). If also the mean-free-path $\gtrsim 0.6 W$, ballistic magnetic flux cancellation has to be considered due to self-crossing of time-reversed trajectories in narrow wires. Considered together, for low $B$, $L_B$ is then modified to $^{19,21,29,48,53}$:

$$L_B = l_m \sqrt{\frac{C_1 l_m^2 \ell_{1D}}{W^2}}$$

(4)

Here $C_1 = 4.75$ for specular boundary scattering and $C_1 = 2\pi$ for diffusive boundary scattering $^{19,21,53}$, while $\ell_{1D}$ is the mean-free-path in the Q1D wire. From Eq. (1), the quantum correction $\delta \sigma_{2D}$ is finally expressed as:

$$\delta \sigma_{2D} = -\frac{1}{2} \frac{e^2}{\pi \hbar W} (\sum_{m=0,\pm 1} L_{1,m} - L_{0,0})$$

(5)

The measured conductance correction $\delta G(B) = G(B) - G_0$, is related to $\delta \sigma_{2D}$ by $\delta G(B) = (W/L) \delta \sigma_{2D}$, with $G_0$ the classical conductance of the wire ($G_0 \neq G(0)$ due to the effects of $L_0$ and $L_{so}$). The dependence of $\delta G(B)$ on $B$ thus reduces to a combination of length ratios $^{19,21,47,48,51}$:

$$\delta G(B) = -\frac{1}{2} \frac{e^2}{\pi \hbar L} \left( L_{1,+1} + L_{1,-1} + L_{1,0} - L_{0,0} \right)$$

(6)

The experimental data can be directly compared to fits to Eq. (6) since $\Delta G(B) = G(B) - G(0) = \delta G(B) - \delta G(0)$.

With the presence of an electronic depletion layer in InGaAs structures, a smooth potential is formed at the wire edges, and we expect boundary scattering to be specular. Hence $C_1 = 4.75$ is used $^{21,53,54}$. Values for $L_0$, $L_{so}$ and $\ell_{1D}$ (entering in Eq. (4)) are used as fitting parameters to fit the experimental data for $\Delta G(B)$ to Eq. (6). It is to be noted that similarly to previous work $^{21}$, we expect $\ell_{1D} < \ell_{2D}$, a drop in electron mean-free-path in the wire compared to the unpatterned 2DES (in Ref. $^{21}$ equivalently expressed via a drop in $D$). The WAL analysis depends on $\ell_{1D}$ and on $W$, neither of which are known a priori. While $\ell_{1D}$ is obtained as a fitting parameter, $W$ can be calculated as follows. A first estimate $W_0$ is obtained by assuming the sheet resistance in the wires $R_{\square 1D}$ equals $R_{\square 2D}$, and using $R_B = \frac{L}{W} R_{\square 2D}$ at $T=0.38$ K. By a least squares fitting over the 3 wire sets, we obtain $W_0 = 0.34$ µm. By using the known wire resistance $R = \frac{\hbar}{e^2} \sqrt{\frac{2}{N_s W_{\ell_{1D}}}}$ and assuming constant $N_s$, we obtain $W \rightarrow \ell_{1D} W_0$. By consistent fitting over the 3 wire sets, we arrive at $\ell_{1D} = 0.50$ µm and $W = 0.41$ µm, common to the 3 wire sets.

III. DATA ANALYSIS AND RESULTS

Fig. 3 depicts examples of fits of Eq. (6) to $\Delta G(B)$ for the Q1D wires with $L = 11.0$ µm, 6.0 µm and 4.0 µm. It is apparent that the model captures the experiments well. The fluctuations in magnetoconductance are due to universal conductance fluctuations surviving the averaging process, aggravated by the subtraction of the series resistance of unpatterned areas and the calculation of the magnetoconductance correction $\Delta G(B)$. Since the characteristic magnetoresistance due to WAL occurs predominantly at lower $B$, the fitting is not affected by the fluctuations.

In Fig. 4 the extracted $L_0$ is plotted vs $T$, parametrized in $L$. Prior to discussing the dependence of $L_0$ on $L$ and $T$, we briefly discuss Fig. 5 where extracted fitting values of $L_{so}$ are plotted vs $T$, parametrized in $L$. Values for $L_{so}$ vary from ~ 0.4 µm to 0.2 µm over the ranges of $L$ and $T$, short lengths compatible with expectations for a 2DES with substantial SOI. A systematic dependence of $L_{so}$ on $L$ cannot readily be concluded, although it is tentatively observed that $L_{so}$ increases with increasing...
L. A weak decrease of $L_{\phi}$ with increasing $T$ is noted for $L = 4.0 \mu m$ and $L = 11.0 \mu m$. The weak decrease with increasing $T$ was previously observed$^{16,20,21}$ and hitherto not fully explained.

Fig. 4 shows that $L_{\phi}$ decreases with increasing $T$, in agreement with other work, both theoretical and experimental$^{4,5,19,20,55,56}$. At lower $T < 1$ K a saturation of $L_{\phi}$ appears, also previously observed and discussed$^{5,19,20,57-61}$. While the origin of the saturation is under debate, several causes can be ruled out in our experiments. Magnetic impurities possibly present in metal samples are typically absent in semiconductor heterostructures grown by molecular-beam epitaxy$^{12,33}$. To rule out thermal causes due to sample current, we measured the wire magnetoresistance at $T = 0.38$ K with $10$ nA $\leq I \leq 100$ nA. The magnetoresistance remained identical for $10$ nA $\leq I \leq 50$ nA, and at $100$ nA showed a smaller WAL amplitude, implying that for $I \leq 50$ nA electron heating can be neglected.

Present results were all measured at $I = 20$ nA. Further, $T$ in the measurement system is calibrated using a Dingle analysis of Shubnikov-de Haas oscillations in a high-mobility 2DES in GaAs/AlGaAs. The analysis of Shubnikov-de Haas oscillations can also largely rule out non-equilibrium electrical noise$^{62}$ (e.g., injected into the sample via the wiring and the measurement system) as a dominant source of decoherence in the range of $T$ of the experiments. Indeed what is measured via Shubnikov-de Haas oscillations$^{63,64}$ is the broadening of quantum levels, specifically Landau levels, due to either thermal effects or electrical noise by an amount $\sim \hbar/\tau_{\phi}$. Electrical noise would likely limit the visibility of Shubnikov-de Haas oscillations as well as the visibility of WAL, because in both cases quantum levels would be broadened by the electrical noise by $\sim \hbar/\tau_{\phi}$. Since the value of the effective $T$ indicated by Shubnikov-de

FIG. 3: (a) Magnetoconductance $\Delta G(B)$ vs $B$ for wire with $L = 11.0 \mu m$ at $T = 2.89$ K (data in black, fitting of Eq. (6) in red). (b) Magnetoconductance $\Delta G(B)$ vs $B$ for wire with $L = 6.0 \mu m$ at $T = 0.38$ K (data in black, fitting of Eq. (6) in red). (c) Magnetoconductance $\Delta G(B)$ vs $B$ for wire with $L = 4.0 \mu m$ at $T = 2.04$ K (data in black, fitting of Eq. (6) in red).

FIG. 4: Phase coherence lengths, $L_{\phi}$ vs $T$ extracted from $\Delta G(B)$ using 1D WAL analysis for the Q1D wire sets with $L = 4.0 \mu m$, $6.0 \mu m$ and $11.0 \mu m$. Solid lines for $T > 1$ K represent fits to $L_{\phi} \sim T^{-\frac{p}{2}}$ with values for $p$ as listed in Table I.

FIG. 5: Spin coherence lengths due to spin-orbit interaction, $L_{so}$ vs $T$ extracted from $\Delta G(B)$ using 1D WAL analysis for the Q1D wire sets with $L = 4.0 \mu m$, $6.0 \mu m$ and $11.0 \mu m$. Lines are guides to the eye.
Haas analysis is a measure of the level broadening. Shubnikov-de Haas analysis would register a lowering of $\tau_\phi$ due to electrical noise as a discrepancy between the measured $T$ and the effective $T$ experienced by the 2DES in a sample. The saturation of $L_\phi$ is not the focus of the present work and won’t be discussed hereunder.

A drop in $L_\phi$ with increasing $T$ for all samples is present in Fig. 4 for $T > 1$ K. Analysis shows that for $T > 1$ K, the results fit $L_\phi \sim T^{-p/2}$ with $p/2 \approx 0.34 \pm 0.02$, leading to a decoherence rate $\tau_\phi^{-1} \sim T^p$ with $p \approx 0.69 \pm 0.03$. Values for $p$ are listed in Table I. The dependence on $T$ of $\tau_\phi^{-1}$ can have several causes. Electron-phonon scattering leads to a decoherence rate $\tau_{ep}^{-1} \sim T^q$ with $q$ experimentally determined as $2.4^{5,20}$. Electron-electron scattering$^{4,5,20,31}$ with large energy transfer leads to a decoherence rate $\tau_{ee}^{-1} \sim T^2$ in 1D and 2D, while quasi-elastic Nyquist scattering leads to a decoherence rate $\tau_{N}^{-1} \sim T^{2/3}$ in 1D$^{20,61}$ and $\tau_{N}^{-1} \sim T$ in 2D$^{4,31,42,65}$. Averaging of transport phenomena over incoherent channels, expressed as broadening of energy levels beyond the Thouless energy, leads to a decoherence rate $\tau_{\phi}^{-1} \sim T^{1/2}$, and can result from thermal effects or excitation by applied voltages or currents$^6$. For the Q1D wires by fitting $L_\phi \sim T^{-p/2}$, we obtain $p \approx 0.69, 0.68$ and 0.72 respectively (Table I), consistent with Nyquist scattering in 1D with $\tau_{N}^{-1} \sim T^{2/3}$. An analysis of $L_\phi$ on the unpatterned 2DES in the Hall bar (not shown) shows $L_\phi \sim T^{-p/2}$ with $p \approx 1.04$, consistent with a 2D Nyquist decoherence rate $\tau_{N}^{-1} \sim T$. According to discussion above and results in Fig. 4, we can conclude that quasi-elastic Nyquist scattering plays a role in limiting $L_\phi$ in our samples.

The dependence of $L_\phi$ on both $L$ and on $T$ in Fig. 4 point to the importance of geometrical effects, expressed in environmental coupling decoherence. In general, the observations illustrate the sensitivity of quantum coherence in nanoscale structures to interactions with wide neighboring regions. Environmental coupling decoherence can be quantified using a dwell time $\tau_d$, via a total decoherence rate given by $\tau_\phi^{-1} = \tau_{\phi0}^{-1} + \tau_d^{-1}$. The term $1/\tau_d$ quantifies an escape rate out of the quantum system, associated with environmental coupling, and hence denotes the environmental decoherence rate. The term $1/\tau_{\phi0}$ equals the decoherence rate for an isolated system where $\tau_d \rightarrow \infty$. The dwell time has been invoked for decoherence in lateral quantum dots$^{12,33}$, while experiments show that the wider the aperture connecting the quantum dots to the environment, the shorter is $\tau_d$ due to shorter $\tau_d$.$^{13}$ In the present wires it is possible that the limit imposed on $\tau_d$ by $\tau_d$ is responsible for the saturation of $L_\phi$ at low $T$, where other decoherence mechanisms play a lesser role.

The effect of environmental decoherence (and equivalently of $\tau_d$) on the effectively measured $L_\phi$ in a wire of length $L$ can be quantified using expressions derived for the backscattered amplitude of a diffusing electron due to quantum interference$^{18,39,40}$. This approach bears a close similarity to the concept of escape rate, in that an electron diffusing from the wire into the wide 2D connecting regions at the endpoints of the wire, thereby escaping the quantum system, has a reduced probability of returning to its starting point and contributing to the quantum interference correction to conductance. Assuming perfect contacts between the wire and the wide 2D connecting regions at the endpoint, such that the backscattering amplitude for an electron diffusing into the environment is zero, one obtains$^{19,39}$:

$$L_\phi = L_{\phi0}\left(\frac{L}{L_{\phi0}}\right) \left(\frac{L_{\phi0}}{L}\right)$$  \hspace{1cm} (7)$$

Here $L_\phi$ denotes the effectively measured coherence length in a wire of length $L$, and $L_{\phi0}$ denotes the coherence length in a wire with $L \rightarrow \infty$ for which interaction with the environment can be neglected. As depicted in

![Figure 6: Phase coherence lengths $L_\phi$ vs $L$ at $T = 0.38$ K. Black dots are data, the red line represents the fit to Eq. (7) with $L_{\phi0} = 1.73 \mu$m.](image)
Fig. 6, Eq. (7) can remarkably well reproduce the dependence of \( L_{\phi} \) on \( L \) for the values of \( L \) in this work. The fit to the data yields \( L_{\phi,\infty} = 1.73 \text{ pm} \) (\( T = 0.38 \text{ K} \)). Since Nyquist scattering due to quasi-elastic electron-electron interactions dominates decoherence for \( T \gtrsim 1.5 \text{ K} \), it is expected that a value close to \( L_{\phi,\infty} = 1.73 \text{ pm} \) will result from the expression for Nyquist scattering evaluated for \( T = 1.5 \text{ K} \), at the onset of saturation of \( L_{\phi} \). For Q1D wires, \( L_{\phi} \) limited by Nyquist scattering is theoretically described by\(^{19,26,29}\),

\[
L_{\phi} = \sqrt[3]{2 \left( \frac{\hbar^2 D_{1D} g(E_F) W}{k_B T} \right)}^{1/3} \tag{8}
\]

illustrating the characteristic dependence \( L_{\phi} \sim T^{-1/3} \). Here \( g(E_F) \) represents the 2D density of states at \( E_F \), \( D_{1D} \approx (\ell_{1D}/\ell_{2D}) D_{2D} \) represents the diffusion constant in the wires, and \( k_B \) is Boltzmann’s constant. A nonparabolic band approximation\(^{43,44}\) predicts \( g(E_F) = \frac{m^*}{\pi \hbar^2} (1 + 2E_F/E_g) \). Evaluation of Eq. (8) for \( T = 1.5 \text{ K} \) then yields \( L_{\phi} = 1.95 \text{ pm} \), indeed close to the value \( L_{\phi,\infty} = 1.73 \text{ pm} \) derived from the measurements and Eq. (7). The consistency between the data in Fig. 4 and Fig. 6, with Eq. (7) and Eq. (8) strengthens the interpretation presented for the dependence of \( L_{\phi} \) on \( L \) and \( T \).

IV. CONCLUSIONS

In conclusion, quantum phase coherence lengths \( L_{\phi} \) as function of wire length \( L \) were obtained via a 1D WAL analysis, with ballistic transport corrections, for wires fabricated on a 2DES in a InGaAs/InAlAs heterostructure. It is observed that the measured \( L_{\phi} \) increases with increasing \( L \), effectively explained by the quantum decoherence effect introduced at the wire endpoints by environmental coupling. The decoherence effect of the coupling between the wire and the wide 2D connecting regions at the endpoints can be quantified by an expression for reduced coherent backscattering at the endpoints. The dependence of \( L_{\phi} \) on \( T \) is consistent with the effects of quasi-elastic Nyquist scattering in the 1D regime. The work underlines the influence of sample geometry and interactions with external neighboring regions on quantum decoherence in nanostructures, with particular emphasis on decoherence in nanowires with relevance to the study of new quantum states of matter, and with relevance in quantum technologies.

V. ACKNOWLEDGMENTS

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