Influence of environment and geometry on measured quantum coherence in InGaAs mesoscopic wires and stadia

Jean J Heremans¹, Yuantao Xie¹ and Clément Le Priol²
¹Virginia Tech, Department of Physics, Blacksburg, Virginia 24061, USA
²Ecole Polytechnique, Department of Physics, 91128 Palaiseau, France
E-mail: heremans@vt.edu

Abstract. Lithographically fabricated mesoscopic wires and stadia, coupled to a decohering classical environment by two side-wires, were studied using low-temperature quantum transport to obtain quantum phase coherence lengths. Longer phase coherence lengths were observed in longer wires, an effect due to environmental coupling decoherence being mitigated by averaging over longer wire lengths. In stadia the dominant decoherence mechanism appears as device-device, here stadium-wire, coupling decoherence rather than environmental coupling decoherence. Consistency between the experimental results and a decoherence mechanism due to stadium-wire coupling is found in the relation between lower decoherence rate and relative geometrical similarity between the stadia and their connecting wires.

1. Introduction

Investigations in quantum coherence promise insight in applications of quantum technologies, and help elucidate the boundary between classical and quantum systems. Quantum coherence can be characterized by a quantum phase coherence length \( L_\phi \), the length scale over which carriers’ wave functions maintain their phase coherence. \( L_\phi \) can be reduced by decoherence mechanisms, such as electron-phonon and electron-electron scattering \([1, 2]\), and by decoherence mechanisms introduced during measurements, such as level broadening, and by decoherence via interaction with a wider classical environment \([3–5]\). The latter will be studied in this work. Another decoherence effect, \textit{device-device} coupling decoherence due to connections between different geometrical parts of devices, is barely investigated, and will be studied here as well. Devices were fabricated on an In\(_{0.53}\)Ga\(_{0.47}\)As/In\(_{0.52}\)Al\(_{0.48}\)As heterostructure by electron-beam lithography. Sample dimensions and geometries are listed in Table 1, with examples shown in Fig. 1. The quantum well in the heterostructure contains a two-dimensional electron system (2DES), with mobility \( \mu_{2D} = 1.49 \text{ m}^2/(\text{V} \cdot \text{s}) \) and areal carrier density \( N_s = 2.02 \times 10^{16} \text{ m}^{-2} \), at a temperature \( T = 0.38 \text{ K} \). The electron Fermi wavelength \( \lambda_F = 17.6 \text{ nm} \). The electron mean-free-path \( \ell_e = 0.77 \mu\text{m} \) was derived from \( N_s \) and \( \mu_{2D} \) using a \( \Gamma \)-point effective mass \( 0.0353m_e(m_e, \text{ free electron mass}) \) and a low \( T \) band gap 813 meV. Samples were measured in a \(^3\)He cryostat, with \( T \) varying from 0.38 K to 5.0 K. The transport properties of the heterostructure do not appreciably change over this temperature range. Quantum interference effects visible in quantum transport, weak-antilocalization (WAL) \([6–11]\) and universal conductance fluctuations (UCFs) \([12–14]\), are used to extract values for \( L_\phi \) from measured device conductance \( G \) as function of magnetic field \( B \) applied normally to the 2DES.
Table 1: Type and characteristic dimensions of the wire samples (wire length $L$) and of stadia samples (width $W$ and length $L$ of the side-wires), referring to geometries in Fig. 1. Values listed for $L_{\phi}$ are measured at $T = 0.38$ K.

| Sample | A | B | C | D | E | F | G | H |
|--------|---|---|---|---|---|---|---|---|
| Geometry | wire | wire | wire | wire | stadium | stadium | stadium | stadium |
| $W$ (µm) | 0.75 | 0.75 | 0.75 | 0.75 | 1.4 | 1.0 | 1.0 | 0.6 |
| $L$ (µm) | 11 | 6 | 4 | 2 | 1.0 | 1.0 | 3.0 | 1.0 |
| $W/L$ (µm) | 1.4 | 1.0 | 0.33 | 0.6 |
| $L_{\phi}$ (µm) | 5.10 | 4.87 | 4.65 | 4.13 | 2.17 | 2.06 | 1.91 | 1.81 |

Figure 1: Micrographs of two example sample geometries. Left panel: two U-shape trenches delineate a wire, in this example with length $L = 11$ µm (the lithographic width of all wires is 0.75 µm). Right panel: an example stadium sample with side-wires with $W = 1$ µm and $L = 1$ µm. The inner diameter of 4 µm is constant for all stadia. The lighter regions denote etched trenches, which form barriers for the electrons.

2. Models of WAL and UCFs

Quantum corrections to the magnetoconductance $G(B)$ of the wires and stadia contain both WAL and UCF signatures. An example of measured $G(B)$ vs $B$ is depicted in Fig. 2 for stadium sample F. Data analysis choices to extract values for $L_{\phi}$ were made dependent on the relative amplitudes of WAL and UCFs. In the wires, UCFs are relatively weaker, while in the stadia analysis of WAL is hindered by strong UCFs. Thus $L_{\phi}$ in wires and stadia were extracted by analysis of WAL and UCFs respectively. Concerning the 1D WAL analysis, under spin-orbit interaction (SOI), singlet and triplet states are formed in pairing of time-reversed trajectories. The quantum correction to conductance $\delta G(B)$ due to each state is proportional to a corresponding effective coherence length. The sum of corrections for all four states is the WAL correction expressed as [6, 7, 15, 16]

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

in which $L_{0,0} = \left( L_{\phi}^{-2} + L_{B}^{-2} \right)^{-\frac{1}{2}}$ is the effective length for the singlet state, and $L_{1,\pm 1} = \left( L_{\phi}^{-2} + L_{so}^{-2} + L_{B}^{-2} \right)^{-\frac{1}{2}}$ and $L_{1,0} = \left( L_{\phi}^{-2} + 2L_{so}^{-2} + L_{B}^{-2} \right)^{-\frac{1}{2}}$ are effective lengths for the triplet states, with $L_{so}$ the characteristic length of spin decoherence due to SOI [15]. For narrow wires with $\ell_e \gtrsim 0.6 W$, the magnetic length $L_B$ is expressed as $L_B = l_m \sqrt{C_1 l_m^2 e / W^3}$ at low $B$ [17], with $l_m = \sqrt{\hbar / e B}$, and $C_1 = 4.75$ for specular boundary scattering [6, 7, 18], valid in this work due to the existence of side depletion layers.

Concerning UCF analysis, the correlation function shows discernible quantum coherence effects, and can be used to extract $L_{\phi}$. The correlation function is defined as,
Figure 2: Magnetoconductance data $G(B)$ vs $B$ for stadium sample F, for various $T$. The amplitude of the UCFs decreases with increasing $T$, as expected. While the WAL signature is visible over a very small range of $B$, UCFs were used in the stadia samples to obtain $L_\phi$.

![Magnetoconductance data](image)

Figure 3: $L_\phi$ plotted vs $T^{-1/3}$ for the wire samples. Dashed lines are guidelines rather than fitting curves, illustrating the presence of 1D Nyquist scattering limiting $L_\phi$ for $T > 1$ K. For $T > 1$ K, $L_\phi \sim T^{-1/3}$, while $L_\phi$ approaches saturation values at lower $T$. $L_\phi$ increases with increasing wire length $L$.

![L vs T^{-1/3}](image)

\[
\frac{\delta G(B)\delta G(B + \Delta B)}{(G(B) - \langle G(B) \rangle)(G(B + \Delta B) - \langle G(B) \rangle)} = \langle G(B) \rangle^2 \frac{1}{b} \Psi\left(\frac{1}{2} + \frac{1}{b}\right) 
\]

in which the angled brackets denote an average over a range of $B$. We define $B_\phi = h/(4eL_\phi^2)$, the $B$ under which one flux quantum $h/e$ threads the area $8\pi L_\phi^2$. If $B >> B_\phi$, we have an expression allowing determination of $L_\phi$:

\[
\frac{\delta G(B)\delta G(B + \Delta B)}{\delta G(B)} = \frac{1}{b} \Psi\left(\frac{1}{2} + \frac{1}{b}\right) 
\]

in which $b = \Delta B/2B_\phi$, and $\Psi(x)$ is the digamma function.

3. Experimental Results & Discussion

Extracted values for $L_\phi$ in wires are plotted in Fig. 3. The dependence of $L_\phi$ on $T$ is clear. $L_\phi$ decreases with increasing $T$, in agreement with previous work [2, 6, 12, 14, 19]. $L_\phi$ for $T > 1$ K follows $L_\phi \sim T^{-p}$, with $p \approx 0.34 \pm 0.02$. This result is consistent with quasi-elastic Nyquist electron-electron scattering in a 1D wire [14, 20]. For the stadia however the $T$-dependence of $L_\phi$ is weak ($p \approx 0.07$, not pictured), implying that a dominant decoherence mechanism for the stadia can be found in $T$-independent processes.

The results in Fig. 3 show that for wires $L_\phi$ increases with increasing of $L$ in the entire range of $T$ of the measurements. The reason lies in decoherence via interaction at the wire endpoints with the wider classical environment. Since this effect is averaged out in long wires, mitigating its effect on measured $L_\phi$, longer wires show longer $L_\phi$ as observed. $L_\phi$ measured in stadia samples at $T = 0.38$ K are listed in Table 1, where the dimension dependence cannot be explained solely by environmental coupling decoherence (which would predict that the wider the side wire is, the shorter $L_\phi$ is). Device-device, here stadium-wire, coupling decoherence is invoked to explain the results. Device-device coupling decoherence is induced by low wavefunction hybridization efficiency between different geometries. With the stadium-wire coupling...
decoherence rate noted as $\gamma_a$, the total decoherence rate can be expressed as

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_{\phi 0}} + \frac{1}{\tau_d} + 2\gamma_a \quad (4)$$

where the factor 2 is due to 2 connection points, and the second term denotes environmental interaction decoherence via the dwell time $\tau_d$ [1, 21]. The decoherence rate of stadium-wire coupling is dependent on geometrical similarity between inner circular stadia and the side-wires. High levels of internal coherence were observed between identical dots in quantum dot arrays [4, 22], implying a low dot-dot (identical in geometry) coupling decoherence rate. In the present work $\gamma_a$ can be large and even dominate over $1/\tau_d$ due to the difference in geometry between stadia and side-wires. $W$ and $L$ of side-wires are comparable to the 2 $\mu$m radius of the stadia and lower $W/L$ of the side-wires imply higher geometrical similarity with the stadia. In Table 1, for stadia E, F, G, H, $L_\phi$ decreases with decreasing $W/L$, except in the comparison between G and H (cfr below). A decrease in $W/L$, here caused either by narrower $W$ or longer $L$, lowers wavefunction hybridization efficiency and thus leads to shorter $L_\phi$. For stadium G, the side-wire with long $L = 3$ $\mu$m impacts the results, and environmental interaction decoherence obscures the effect of stadium-wire coupling decoherence.

4. Conclusions

The dependence of $L_\phi$ on mesoscopic device geometry is studied in this work. Decoherence by interaction with a classical environment is detected in wires, leading to a decreasing $L_\phi$ in shorter wires. For stadia, stadium-wire coupling decoherence dominates over environmental interaction decoherence effects, except for samples with longer side-wires. The work shows that values for $L_\phi$ in mesoscopic devices should be interpreted in the light of device geometry. The work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under award DOE DE-FG02-08ER46532.

References

[1] Hackens B, Faniel S, Gustin C, Wallart X, Bollaert S, Cappy A and Bayot V 2005 Phys. Rev. Lett. 94 146802
[2] Lin J J and Bird J P 2002 J. Phys.: Condens. Matter 14 R501
[3] Bird J P, Micolich A P, Linke H, Ferry D K, Akis R, Ochiai Y, Aoyagi Y and Sugano T 1988 J. Phys.: Condens. Matter 10 L55
[4] Elhassan M, Bird J P, Akis R, Ferry D K, Ida T and Ishibashi K 2005 J. Phys.: Condens. Matter 17 L351
[5] Bird J P, Micolich A P, Ferry D K, Akis R, Ochiai Y, Aoyagi Y and Sugano T 1998 Solid-State Electron. 42 1281
[6] Kallaher R L, Heremans J J, Goel N, Chung S J and Santos M B 2010 Phys. Rev. B 81 035335
[7] Kallaher R L, Heremans J J, Roy W V and Borghs G 2013 Phys. Rev. B 88 205407
[8] Iordanskii S V, Lyanda-Geller Y B and Pikus G E 1994 JETP Lett 60, 206(1994) Pis‘ma Zh. Eksp. Teor. Fiz 60 199
[9] Bergmann G 2010 Int. J. Mod. Phys. B 24 2015
[10] McPhail S, Yasin C E, Hamilton A R, Simmons M Y, Linfield E H, Pepper M and Ritchie D A 2004 Phys. Rev. B 70 245311
[11] Deo V, Zhang Y, Soghomonian V and Heremans J J 2015 Sci. Rep. 5 9487
[12] Hackens B, Delfosse F, Faniel S, Gustin C, Broutry H, Wallart X, Bollaert S, Cappy A and Bayot V 2002 Phys. Rev. B 66 241305(R)
[13] Ferry D K, Akis R A, Pivin D P, Bird J P and Holmberg N 1998 Phys. E 3 137
[14] Rudolph M and Heremans J J 2011 Phys. Rev. B 83 205410
[15] Heremans J J, Kallaher R L, Rudolph M, Santos M, Roy W V and Borghs G 2014 Proc. of SPIE 9167 91670D
[16] Zduniak A, Dyakonov M I and Knap W 1997 Phys. Rev. B 56 1996
[17] Ren S L, Heremans J J, Vijeyaragunathan S, Mishima T D and Santos M B 2015 J. Phys.: Condens. Matter 27 185801
[18] Beenakker C W J and van Houten H 1988 Phys. Rev. B 38 3232
[19] Bird J P, Ishibashi K, Ferry D K, Ochiai Y, Aoyagi Y and Sugano T 1995 Phys. Rev. B 51 18037
[20] Natelson D, Willett R L, West K W and Pfeiffer L N 2001 Phys. Rev. Lett. 86 1821
[21] Hackens B, Faniel S, Gustin C, Wallart X, Bollaert S, Cappy A and Bayot V 2006 Physica E 34 511
[22] Elhassan M, Bird J P, Shaitos A, Prasad C, Akis R, Ferry D K, Takagaki Y, Lin L H, Aoki N, Ochiai Y, Ishibashi K and Aoyagi Y 2001 Phys. Rev. B 64 085325