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# Spin and phase coherence in quasi-1D InSb wires under strong spin–orbit interaction

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ABSTRACT

We investigate the low temperature spin and phase coherence lengths in quasi-one dimensional wires fabricated from a high mobility InSb/InAlSb two dimensional electron system. Spin and phase coherence lengths as a function of wire width and temperature are obtained by fitting the magnetoconductance to an antilocalization theory modified to account for ballistic transport through the wires. Extracted spin coherence lengths are found to be inversely proportional to wire width and display a weak dependence on temperature. Results for the phase coherence length suggest that mechanisms originating in the two dimensional electron system are responsible for phase decoherence.



## 1. Introduction

Theoretical [1–3] and experimental [4] investigations have shown that spin decoherence can be suppressed in narrow wires fabricated from two-dimensional electron systems (2DES). These studies offer the possibility of controlling the spin coherence length $L_S$ through geometric design of devices. In this paper, we experimentally study $L_S$ and the phase coherence length $L_\phi$ in quasi-one dimensional (Q1D) wires fabricated from a high mobility InSb/InAlSb 2DES. Values for $L_S$ and $L_\phi$ at temperatures $T \leq 15$ K are obtained by analyzing the magnetoconductance in antilocalization (AL) theory [3,5,6]. Extensive experimental and theoretical research on AL phenomena in various semiconducting systems [4,6–8] demonstrate that AL is a valuable experimental tool for investigating spin and phase coherence.

## 2. Experiment

We fabricated four sets of narrow wires from a molecular-beam epitaxy grown $InSb/In_{0.85}Al_{0.15}Sb/InSb$ (quantum well)/$In_{0.85}A_{0.15}Sb/GaAs$ (0 0 1) (substrate) 2DES heterostructure (Fig. 1) using electron beam lithography and reactive ion etching. Electrons are provided to the 25 nm wide InSb quantum well by two Si $\delta-$doped layers which are located 40 nm above and 40 nm below the well. A third Si $\delta-$doped layer, 23 nm below the surface, compensates surface states [9]. AL measurements performed on the unpatterned InSb/InAlSb heterostructure indicate that the spin–orbit interactions (SOI) in the 2DES are characterized by the Rashba parameter $|\alpha| \approx 0.03$ eVÅ and the Dresselhaus coefficient $\gamma \approx 490$ eVÅ$^3$ [9]. Each set of wires contains 10 identical wires oriented in the $[1\,\bar{1}\,0]$ direction with length $L = 24\,\mu$m, the nominal design width $w_{litho}$ of the individual wires being the only difference between sets. Magnetotransport across the different wire sets ($0.475\,\mu m < w_{litho} < 0.875\,\mu m$) was measured for $0.4\,K < T < 15\,K$ in a perpendicularly applied magnetic field $B$. Data presented in this paper are scaled to conductance per wire, $G$.

Resistivity and Hall effect measurements performed on an unpatterned region of the sample indicate a carrier density $n_{2D} \approx 5.2 \times 10^{15}\,m^{-2}$ and a mobility $\mu_{2D} \approx 9.7\,m^2/Vs$ at low $T$. These values for carrier concentration and mobility also pertain to the narrow wires. Measurements of Shubnikov-de Haas oscillations up to 4 T at 0.4 K show, within $\sim 5\%$, a constant carrier density $n = n_{2D}$ as a function of $w_{litho}$. Therefore, for all wire sets we take $n = n_{2D}$ as determined via Hall measurements at each $T$. Fig. 1 displays the zero field conductance $G(0)$ as a function of $w_{litho}$ at $T \approx 34$ K where phase coherent effects, such as AL, are expected to be minimal. If the mobility $\mu$ and $n$ are not affected by the reduced dimensions in narrow wires, $G(0)$ should decrease linearly with the conducting width of the wire $w$ according to the relation—$G(0) = (w_{litho} - w_{dep})/L\rho_{2D} = (w/L\rho_{2D})$ [10,11]; where

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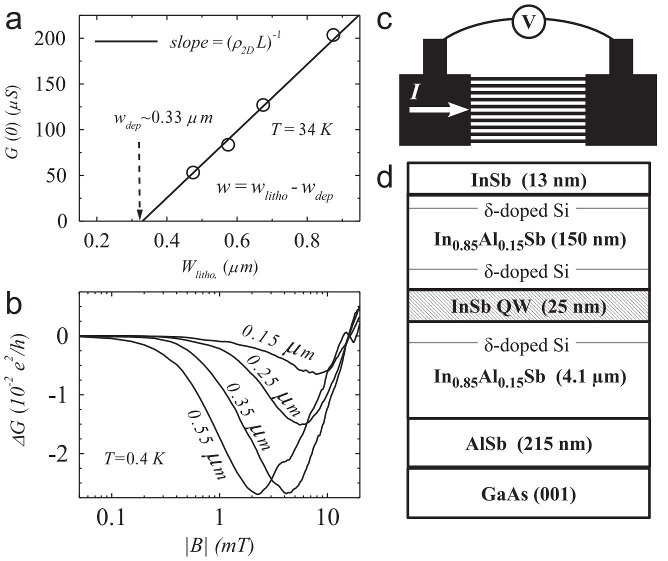


**Fig. 1.** (a) $G(B=0)$ as function of wire design width $w_{litho}$. (b) $\Delta G$ at 0.4 K for wires of width $w = 0.55\,\mu m$, $0.35\,\mu m$, $0.25\,\mu m$, and $0.15\,\mu m$. (c) Schematic illustration of measurement geometry. (d) Schematic of the InSb/InAlSb 2DES heterostructure. The $\delta$–doped layers are located at the following positions: 40 nm below, 40 nm above, and 140 nm above the quantum well (QW).

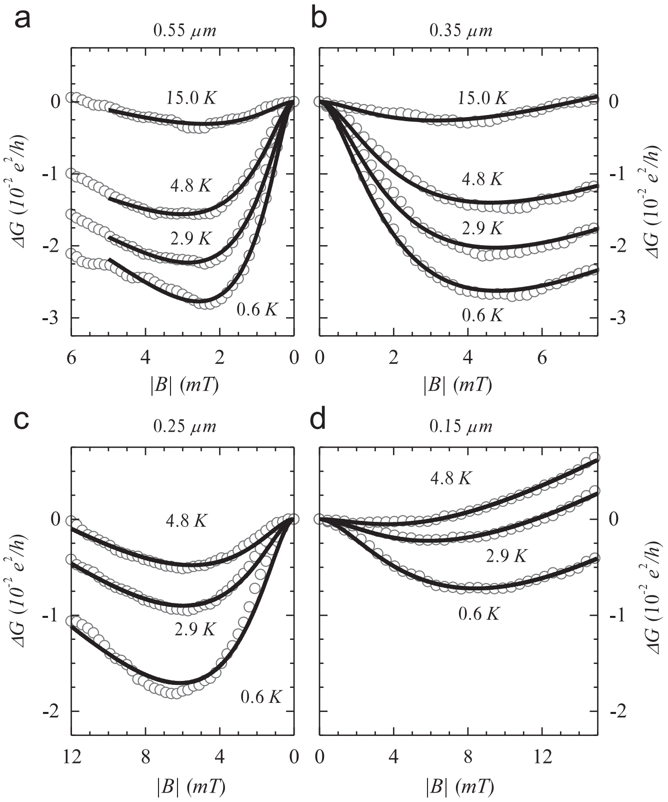


**Fig. 2.** Change in conductance $\Delta G$ as a function of magnitude of the applied magnetic field $|B|$ at various $T$ for wires of width $w =$ (a) $0.55\,\mu m$, (b) $0.35\,\mu m$, (c) $0.25\,\mu m$, and (d) $0.15\,\mu m$. Solid lines indicate fits to antilocalization theory.

$\rho_{2D} = (1/n_{2D}e\mu_{2D})$ is the resistivity of the parent 2DES and $w_{dep}$ is the average depletion width in the wires. From Fig. 1, we find that $G(0)$ is well described by a line of slope $1/L\rho_{2D}$. Therefore, we conclude that $\mu$ is not affected by the confined geometry of the narrow wires. The mean free path $l_e$ in the wires can hence be calculated, as $l_e = 3.3\,\mu m$. We also determine that scattering from the boundaries is specular, since diffusive boundary scattering leads to lower $\mu$ in narrow wires [10]. From the $G(0) = 0$ intercept we find $w_{dep} = 0.33\,\mu m$ allowing $w$ to be determined through $w = w_{litho} - w_{dep}$. It should be emphasized, however, that $w_{dep}$ may not be entirely electrical in nature, as it may also include effects from the fabrication process.

Examples of the low field magnetoconductance $\Delta G \equiv G(B) - G(B=0)$ are shown in Figs. 1 and 2. In order to account for Hall effect contributions to the data, the component antisymmetric in $B$ has been subtracted from the data by averaging $G(+B)$ and $G(-B)$ for each data set, and hence $\Delta G$ is plotted in terms of the magnitude of the applied field, $|B|$. The observed negative magnetoconductance around $B = 0$ which crosses over to positive magnetoconductance at higher $B$ is characteristic of AL. We note that the large broadening of $\Delta G$ as a function of decreasing $w$ depicted in Fig. 1 is a consequence of the flux cancelation effect [8,10]. Qualitatively, the magnitude of the negative magnetoconductance around $B = 0$ decreases with $w$. In analogy with the $L_\phi$ and $L_S$ dependence of AL in 2 dimensions [6], this indicates a lowering of the ratio $L_\phi/L_S$ as $w$ narrows.

## 3. Analysis of magnetoconductance

Under AL, the magnetic field dependence of $G$ in a narrow wire of length $L$ is described by [3,8,10,12]:

$$G(B) = G_0 - \frac{e^2}{hL}\left(\sum_{m=\pm 1,0} \tilde{L}_{1,m} - \tilde{L}_{0,0}\right). \tag{1}$$

$\tilde{L}_{1m}$ represents contributions corresponding to triplet modes which depend on $L_\phi$ and $L_S$, whereas the singlet contribution $\tilde{L}_{00}$ is only sensitive to $L_\phi$ [3,6,12]. For diffusive Q1D wires fabricated from a 2DES, Kettemann has determined the different contributions to be determined by [3]: $\tilde{L}_{s,m}^{-2} = L_\phi^{-2} + \nu_{s,m}L_S^{-2} + L_B^{-2}$; with $\nu_{1,\pm 1} = 0.5$, $\nu_{1,0} = 1$, $\nu_{0,0} = 0$.

Kettemann's model was developed for diffusive wires where $l_e < w$. We implement the following two modifications in order to account for *ballistic transport* in the wires presented here, where $l_e \gg w$. First, we use a magnetic length $L_B$ appropriate for ballistic Q1D wires [10]:

$$L_B = \sqrt{C_1 l_m^4 l_e w^{-3} + C_2 l_m^2 l_e^2 w^{-2}}, \tag{2}$$

where $l_m = \sqrt{\hbar/eB}$. For predominately specular (diffusive) boundary scattering, $C_1 = 4.75$ $(2\pi)$ and $C_2 = 2.4$ $(1.5)$ [10]. We also implement the ballistic wire correction first introduced by Beenakker [10] in regards to weak localization theory. The triplet and singlet contributions in the ballistic Q1D wires become [10]:

$$\tilde{L}_{s,m} = (L_\phi^{-2} + \nu_{s,m}L_S^{-2} + L_B^{-2})^{-1/2} - (L_\phi^{-2} + \nu_{s,m}L_S^{-2} + L_B^{-2} + 2l_e^{-2})^{-1/2}. \tag{3}$$

In order to extract both $L_S$ and $L_\phi$ the low $T$ magnetoconductance curves were fit to Eq. (1) using Eq. (3) to describe $\tilde{L}_{s,m}$ and adopting specular values for $C_1$ and $C_2$ when evaluating $L_B$ in Eq. (2). The resulting fits are shown along with the experimental data in Fig. 2. Fits are restricted to $T$ where AL is experimentally observed. Thus for $w = 0.15\,\mu m$ and $w = 0.25\,\mu m$, values for $L_S$ and $L_\phi$ are only reported in the range $0.4\,K < T < 5\,K$; whereas for $w = 0.35\,\mu m$ and $w = 0.55\,\mu m$ values for $L_S$ and $L_\phi$ are given for $0.4\,K < T < 15\,K$. The $w$ and $T$ dependence of the extracted $L_S$ and $L_\phi$ are presented below.

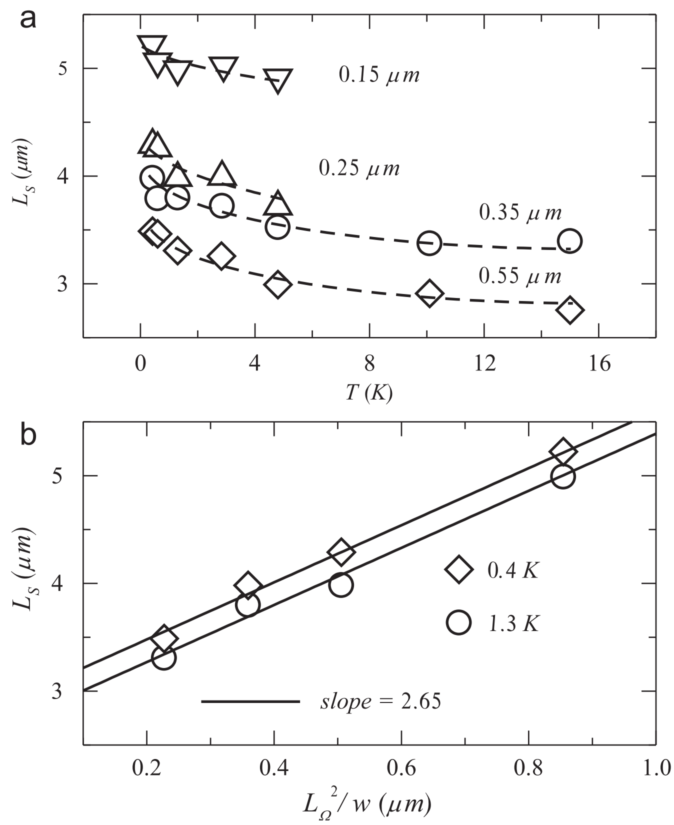


**Fig. 3.** (a) Extracted spin coherence length $L_S$ as function of $T$ for wires of width $w=0.55\,\mu$m, $0.35\,\mu$m, $0.25\,\mu$m, and $0.15\,\mu$m. Dashed lines are guides to the eye. (b) Dependence of $L_S$ on $w$ at 0.4 and 1.3 K.

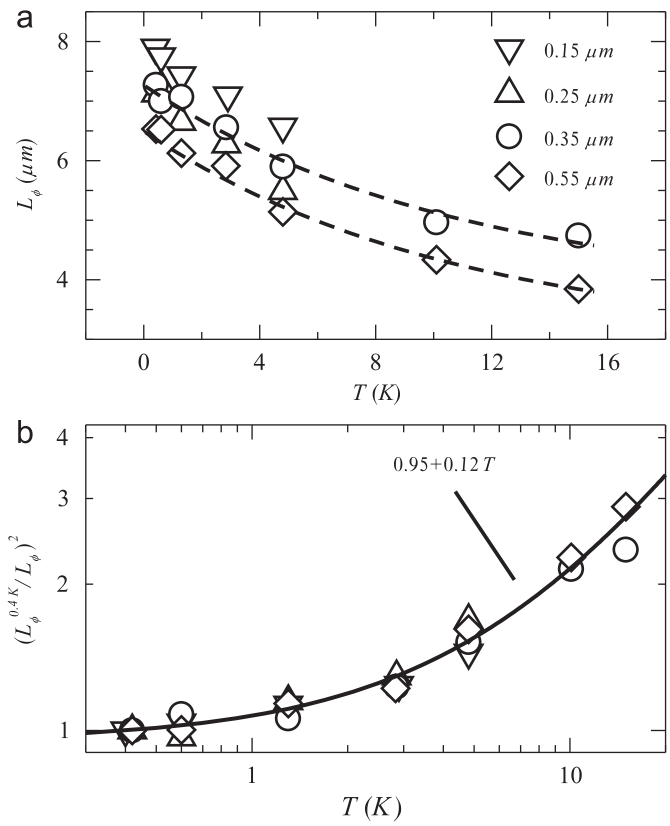


**Fig. 4.** (a) $T$ dependence of phase coherence length $L_\phi$ in wires with four different widths $w=0.55\,\mu$m, $0.35\,\mu$m, $0.25\,\mu$m, and $0.15\,\mu$m. Dashed lines are guides to the eye. (b) Logarithmic plot of the $T$ dependence of $L_\phi^{-2}$, normalized by its value at 0.4 K, for all $w$.

## 4. Results and discussion

### 4.1. Spin coherence time

Values of $L_S$ extracted from the fits to $\Delta G$ are found to be inversely proportional to $w$, with $\sim 3\,\mu\mathrm{m} < L_S < \sim 5\,\mu$m. We note that the large magnitude of $L_S$ is not indicative of exceptionally long spin coherence times, but is, rather, a consequence of the high electron $\mu$ in the 2DES. The large $\mu$ leads to a long $l_e = 3.3\,\mu$m, a large diffusion constant, and consequently significant $L_S$ in the wires. Taking into account both Rashba and Dresselhaus SOI [13], the spin precession length $L_\Omega \equiv v_F/\Omega \approx 0.35\,\mu$m is calculated from the Fermi velocity $v_F \approx 8.85\times 10^5$ m/s and average SOI induced spin precession frequency $\Omega \approx 2.5\times 10^{12}\,\mathrm{s}^{-1}$ in the 2DES. Fig. 3 shows the linear dependence of $L_S$ on $w^{-1}$ for $T=0.4$ and 1.3 K. Within experimental errors, we find $L_S \propto 2.65(L_\Omega^2/w)$ for $0.4\,\mathrm{K} < T < 5\,\mathrm{K}$, the range of $T$ where AL was observed for all $w$. For pure Rashba SOI in diffusive wires, Kettemann has predicted an $L_S \propto \sqrt{12}(L_\Omega^2/w)$ dependence [3]. Thus, we find agreement, within $\approx\sqrt{2}$, with this prediction, even in the presence of the strong cubic Dresselhaus SOI in InSb.

Extracted $L_S$ are found to gradually decrease as $T$ increases from 0.4 K, Fig. 3. Together with the observation that the enhancement of $L_S$ with $w$ is not affected by $T$, the similar $T$ dependence of $L_S$ for all $w$ indicate that a common mechanism limits $L_S$ and the spin coherence length in the 2DES, $L_S^{2D}$. Thus, the observed $T$ dependence of $L_S$ suggests a changing $L_S^{2D}$ with $T$. For 2DESs where $L_\Omega < l_e$ it is common to estimate the spin coherence time $\tau_s^{2D} \approx \tau_p$, where $\tau_p$ is the momentum scattering time [2,14]. In contrast to the motional narrowing regime ($L_\Omega > l_e$), this implies that increased scattering leads to shorter $L_S^{2D}$. Although no significant changes in $l_e$ are observed in this range of $T$, it has been shown that scattering mechanisms can have a much larger impact on spin relaxation as compared to momentum relaxation [15]. Increasing phonon and electron-electron scattering with $T$ offer mechanisms for decreasing $L_S^{2D}$ and $L_S$.

### 4.2. Phase coherence time

Extracted $L_\phi$ for the separate $w$ are displayed as a function of $T$ in Fig. 4. Qualitatively we find increasing $L_\phi$ with decreasing $w$. A similar $T$ dependence of $L_\phi$ for all $w$ is observed with $L_\phi$ gradually increasing as $T\to 0$. The logarithmic plot of $L_\phi^{-2}$ vs $T$, with $L_\phi$ normalized to its value at 0.4 K, shown in Fig. 4 highlights the similar $T$ dependence of $L_\phi$ in the different wires. After normalizing to $L_\phi(0.4\,\mathrm{K})$, we find that $L_\phi$ for different $w$ are all described by $(L_\phi(0.4\,\mathrm{K})/L_\phi)^2 = 0.95+0.12T \approx 1+0.12T$. Thus for all $w$, $L_\phi$ saturates to a constant value as $T\to 0$ and at higher $T$, $L_\phi^2 \propto T^{-1}$.

In studies of phase coherence, it is often found that the phase coherence time $\tau_\phi$, where $\tau_\phi \propto L_\phi^2$, approaches a constant value as $T\to 0$ [16]. Mechanisms proposed to explain the saturation of $\tau_\phi$ at low $T$ include magnetic scattering from trace amounts of magnetic impurities [16] and zero-point fluctuations of the electromagnetic environment [17]. At slightly higher $T$, $\tau_\phi$ is expected to follow a power law $\tau_\phi \propto T^{-\nu}$ with the exponent $\nu$ depending on the mechanism responsible for phase decoherence [16]. From Fig. 4, we find $\nu=1$ which is characteristic of the Nyquist dephasing mechanism in 2DESs. The experimental observations of an increasing $L_\phi$ with decreasing $w$ and a $T$ dependence typical of 2DESs may suggest that $L_\phi$ in the narrow wires is determined by phase decoherence mechanisms in the parent 2DES that they are in electrical contact with.

## 5. Conclusions

We have measured the low $T$ magnetotransport across narrow wires fabricated from a high mobility InSb/InAlSb 2DES. Both $n$ and $\mu$ are found to be independent of $w$ as scattering from the wire boundaries is predominately specular. The $w$ and $T$ dependence of $L_S$ and $L_\phi$ in the wires are examined by modeling $\Delta G$ with a modified low-dimensional AL theory. Even though there is strong cubic Dresselhaus SOI in the ballistic InSb wires, the observed $L_S \propto 2.65(L_\Omega^2/w)$ agrees within a factor $\approx\sqrt{2}$ with predictions for the enhancement of $L_S$ in diffusive wires under Rashba SOI. We find that the extracted $L_\phi$ increase with decreasing $w$ and display a $T$ dependence typical of phase decoherence via the Nyquist mechanism in two dimensions.

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