Saturation of Phase Coherence Length in GaAs/AlGaAs On-Facet Quantum Wires

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Phase coherence length ($L_\phi$) is one of the important scales in design of quantum intereference devices. The dominant mechanisms determining phase coherence length in each dimension are becoming clear. However, for GaAs/AlGaAs heterojunction wires\textsuperscript{1,2} (quasi-1-dimensional wires) at $T \leq 0.3K$ there is no clear definition of temperature exponent or $L_\phi$ saturation. The poorly defined $L_\phi$ saturation may indicate a temperature-independent scattering mechanism at very low temperatures. It is thus interesting to determine the mechanism which dominates $L_\phi$ in that temperature range.

In this work quasi-1-dimensional (Q1D) and 2-dimensional (2D) on-facet quantum wires are used. These on-facet wires have a unique structure and properties\textsuperscript{3}. In particular they have both high carrier concentration and high mobility, enabling them to have long $L_\phi$s. Further these wires are potentially damage free because the wire structure is formed by only one selective growth process\textsuperscript{4}. The Q1D sample used here has a 0.3-$\mu$m channel width, whose basic properties are $\mu \sim 3.4m^2/V.s$, $n_1 \sim 3.46 \times 10^{12} cm^{-2}$ and $L_e$ (mean free path) $\sim 0.7 \mu m$. Sample lengths are 1.7$\mu$m and 20$\mu$m. Conductance fluctuation is observed in the short sample. The 2D sample has a 0.8-$\mu$m channel width, $\mu \sim 1.3m^2/V.s$ and $n_2 \sim 5.8 \times 10^{11} cm^{-2}$.

Low temperature magnetoresistance measurement was performed down to 50 mK. Magnetoresistance of Q1D shows a positive part implying antilocalization effect below 0.1K (in Fig. 1). $L_\phi$ for the Q1D sample is directly determined by the amplitude of the conductance fluctuation using $(L_\phi/L)^{3/2} = \langle \delta g^2 \rangle^{1/2}/0.52(e^2/h)$. As shown in Fig. 2 temperature exponent of $L_\phi$ decreases loosely as temperature decreases, and $L_\phi$ almost saturates below about 0.4K. In addition, phase coherence length is determined with correlation field of conductance fluctuation $L_\phi = \alpha B_e (h/e)(1/w)$. Numerical constant $\alpha$ is uncertain, but a similar temperature dependence is obtained. For 2D wire, $L_\phi$ is determined by fitting with the 2D weak localization theory without spin-orbit scattering. $L_\phi$ saturation occurs as for the Q1D wire as shown in Fig.3, although positive magnetoresistance is not seen in this temperature range.

These saturation phenomena are thought to be derived from spin-orbit interaction, corresponding to positive magnetoresistance, because electron Joule heating was eliminated by using small ac current in the 10nA order and spin-flip scattering is not applied in these samples. In order to determine the spin-orbit scattering length, magnetoresistance data is fitted to the weak localization theory including spin-orbit interaction. For Q1D it is modified for the quasi-ballistic case, because $W < L_e$\textsuperscript{5}. Characteristic length with spin-orbit scattering $L_{so}$ (= $\sqrt{D\tau_{so}}$) which is about 2.8 $\mu$m ($\tau_{so}$ is 20 psec) and inelastic scattering length ($L_{in}$) are separated. The Q1D results are also shown in Fig.2. These two lengths converge, accompanying $L_\phi$ saturation. The temperature $T_{so}$ below which spin-orbit interaction is effective is defined as $h/\tau_{so}k_B$. In this case $T_{so}$ is calculated at 0.38K and it is consistent with the beginning temperature of $L_\phi$ saturation. For 2D case, $L_{so}$ is determined to be 2$\mu$m($\tau_{so}$=150 psec.). In this case $T_{so}$ is 0.05K, then loose saturation in $L_\phi$ is thought to be attributed to spin-orbit interaction as in the Q1D wire, although $\tau_{in}$ is 10 to 20 percent of $\tau_{so}$. Spin-orbit scattering appears at a very low temperature and affects the electron coherence.

Characteristic time with spin-orbit interaction is expressed as $\tau_{so} = \tau_0/(g-2)^2R^2k_F^2$\textsuperscript{6}, where $R$ is some length scale of a scattering center for electrons and $k_F$ is fermi wave number. The
g-factor used here is 0.52. R is estimated to be 3.7Å and 2Å when experimental values of Q1D and 2D, respectively, are applied. Comparing these values with the atomic radius of Ga or As (1.2Å) shows good agreement. Scattering centers of several angstroms size are effective in spin-orbit scattering. However, the image of R is not clearly defined. There may be defects, impurities, interface roughness or lattice relaxation.

In conclusion, we obtained temperature dependence of phase coherence length $L_\phi$ from magnetoresistance at very low temperatures. The saturation of $L_\phi$ is observed and at very low temperatures spin-orbit interaction is effective as the scattering mechanism whose characteristic time is temperature independent.

References


Fig.1 Magnetococonductance of Q1D wire. Below 0.1K a negative part appears.

Fig.2 Temperature dependence of characteristic lengths of Q1D wire. $L_\phi$ is directly determined by the amplitude of conductance fluctuation (denoting $L_\phi$(CFamp.)) $L_\phi$ saturates at about 0.4K where $L_{so}$ and $L_{in}$ are close. Blow 0.1K this method did not give proper length. The reason is not yet clear. $L_\phi$(CFcorr.) is determined by the correlation field of conductance fluctuation ($\alpha=1.2$).

Fig.3 Temperature dependence of characteristic lengths of 2D wire. $L_\phi$ is determined by fitting with weak localization theory. $L_{so}$ and $L_{in}$ are obtained by fitting with the theory including spin-orbit interaction. $L_\phi$ saturates as for Q1D.