Suppression of Quantum Decoherence in an Aharonov-Bohm Ring

Hisashi AIKAWA*, Kensuke KOBAYASHI, Shingo KATSUMOTO, and Yasuhiro IYE

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Chiba 277-8581, Japan.

(Received August 19, 2002)

KEYWORDS: mesoscopic system, ballistic transport, Aharonov-Bohm effect, phase coherence, Landauer-Büttiker formula

1. Introduction

Quantum coherence is one of the most important topics in fundamental physics. In mesoscopic systems, decoherence has often been studied using Aharonov-Bohm (AB) interferometers, and in such a coherent transport, it is well known that probes of a sample play an essential role and transport property has been successfully described by the Landauer-Büttiker (LB) formalism.[1] Here we present evidence that the quantum coherence itself is also affected by the probe configuration.

2. Experiment

We prepared an AB ring with four probes and performed two different types of four-terminal measurements. Figures 1(a) and 1(b) illustrate the two probe configurations. In the "local" or conventional setup in Fig. 1(a), electric current I_{14} is applied through the sample and voltage difference across the ring V_{23} is measured. The other setup is referred as "nonlocal" setup and illustrated in Fig. 1(b). The measured AB ring

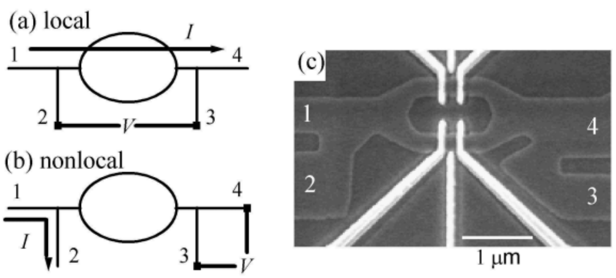

Fig. 1. (a) "Local" or conventional four-terminal setup ($I: 1 \to 4$, $V: 2 \to 3$) that gives resistance $R_{14,23}$. (b) "Nonlocal" setup ($I: 1 \to 2$, $V: 4 \to 3$) gives nonlocal resistance $R_{12,43}$. (c) Scanning electron micrograph of the AB ring with four leads. White regions are metallic gates, one was used to modulate the AB interference and the others were kept open during the study.

shown in Fig. 1(c) was fabricated on 2DEG (mobility $\mu = 90\ \mathrm{m^2/Vs}$, and carrier density $n = 3.8\times10^{15}\ \mathrm{m^{-2}}$) in the GaAs/AlGaAs heterostructure. The electron mean free path $\sim 8\ \mu$m is larger enough than the length of the arm of the ring $\sim 2\ \mu$m, meaning that our sample is in the quasi-ballistic regime. Two samples with the same geometry were measured between 30 mK and 4.2 K by using a dilution refrigerator and standard lock-in technique, yielding almost the same result.

* E-mail: astar@issp.u-tokyo.ac.jp

3. Result and Discussions

Figures 2(a) and 2(b) show typical AB oscillations for the local and the nonlocal setup, respectively. They are different mainly in two ways. One is the AB oscillation amplitude, which is about $20 \sim 70$ % of the total in the nonlocal setup, in contrast to at most a few percent in the local setup.

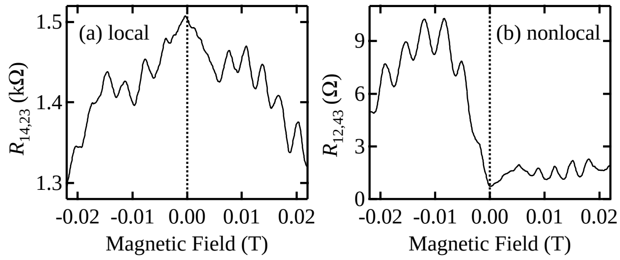

Fig. 2. Typical AB oscillations taken at the base temperature (30 mK) for (a) the local and (b) the nonlocal setup.

The other is the symmetry with respect to the magnetic field reversal. This can more clearly be seen as the difference of AB oscillation phase behavior in Fig. 3. The vertical axis is the gate voltage, which changes the electron density and hence the wave number of the traversing electrons, leading to the modulation of AB oscillation phase. In the local setup, the AB phase rigidity is maintained (Fig. 3(a)), while a continuous phase shift is realized in the nonlocal setup (Fig. 3(b)).

These two differences are well explained within the LB framework.[1] The LB formula gives four-terminal resistance as $R_{mn,kl} = (h/2e^2)(T_{km}T_{ln} - T_{kn}T_{lm})/D$, where $T_{ij}(\geq 0)$ is the transmission coefficient from the terminal i to j, and the denominator D is a quantity including all of the T_{ij}'s. From our sample geometry, it is legitimate to approximate that $T_{12} = T_{21} = T_{34} = T_{43} \equiv T_0$, $T_{14} = T_{41} = T_{23} = T_{32} \equiv T_1$, $T_{13} = T_{31} = T_{24} = T_{42} \equiv T_2$, and $T_0 \gg T_1, T_2$. Then the LB formula gives the local and the nonlocal resistances as

$$R_{14,23} \sim \frac{h}{4e^2}\frac{1}{T_1 + T_2}, \tag{1}$$

$$R_{12,43} \sim \frac{h}{4e^2}\frac{T_1 - T_2}{T_0^2}, \tag{2}$$

respectively. To take the decoherence into account,

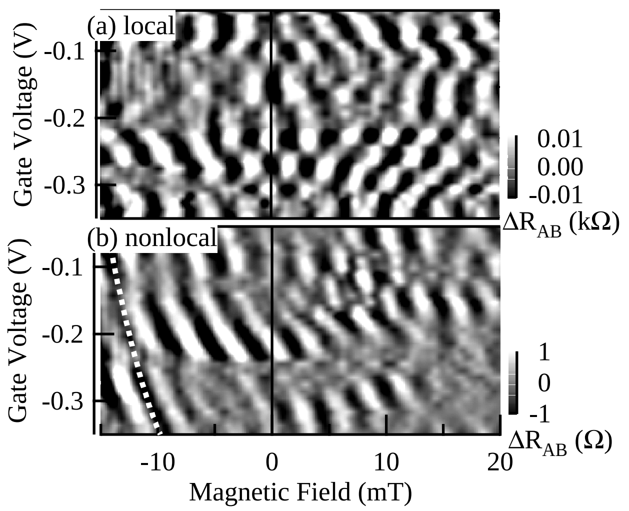

Fig. 3. Gray-scale plots of the AB oscillation components as a function of a gate voltage (or phase modulation) for (a) the local and (b) the nonlocal result. The dotted line in (b) represents the theoretically expected equiphase line assuming the linear correlation between the electron density and the gate voltage.[2)]

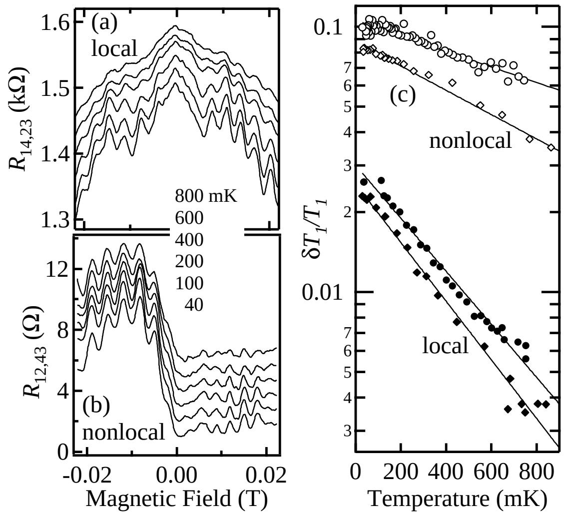

Fig. 4. The AB oscillations taken at various temperatures for (a) the local and (b) the nonlocal setups. Each trace is displayed with offset from the bottom (40 mK) to the top (800 mK). (c)Temperature dependence of the portion of the AB amplitude in the transmission coefficient $\delta T_1/T_1$ for the local (lower) and the nonlocal (upper) setup. The result for two different sample are displayed as circle and diamond.

we assume T_1 and T_2 are expressed as $T_i = \alpha_i + \delta T_i \cos(2\pi\phi/\phi_0 + \delta_i)$,[3)] where δT_i represents the AB amplitude, α_i the other part of the transmission, ϕ the magnetic flux threading the ring, and $\phi_0 \equiv h/e$ the flux quantum.

It is understood from eq. (2) that the non-oscillatory parts α_1 and α_2 cancel out in the nonlocal resistance, resulting in the large AB oscillation amplitude. In the local resistance, however, such an extraction cannot be realized. This qualitatively explains the observed difference of AB amplitude. Another deduction from this simplified LB formula is that the local resistance fulfills the relation $R_{14,23}(B) \sim R_{14,23}(-B)$ like the two-terminal resistance, which does not hold for the nonlocal resistance.

Now we will focus on its temperature dependence. A striking difference is that the AB amplitude is less sensitive to increasing temperature in the nonlocal setup (Fig. 4(b)) than in the local case (Fig. 4(a)). For quantitative comparison, we estimated the portion of the interference term δT_1 in the transmission coefficient through the ring T_1. Figure 4(c) displays $\delta T_1/T_1$ as a function of the temperature, which can be fitted to $\exp(-aT)$ with a as a fitting parameter. We obtained $a = 0.70$ and 1.0 K^{-1} for the nonlocal setup, while $a = 2.3$ and 2.5 K^{-1} for the local setup.

These are two important factors attenuating the AB amplitude with temperature. One is the thermal broadening of the electron wave, which is expressed as $\beta_i \propto \exp(-\tau_L/\tau_{\mathrm{th}})$ in the ballistic regime, where $\tau_L = L/v_{\mathrm{F}}$ (L: the length of the arm of the ring, and v_{F}: the Fermi velocity) and $\tau_{\mathrm{th}} = \hbar/k_{\mathrm{B}}T$. The other is the quantum decoherence, which affects the coherence as $\beta_i \propto \exp(-\tau_L/\tau_\phi(T))$. When only the thermal effect is considered, the coefficient a is expected to be $a \sim 1\ \mathrm{K}^{-1}$ for our sample, that is close to the observed value $a = 0.7 \sim 1.0\ \mathrm{K}^{-1}$ in the nonlocal setup. However, to account for the larger value in the local setup, quantum decoherence should be included in addition to the thermal effect.

We speculate that the key difference lies in the decoherence caused by charge fluctuation induced by the transport current. It is suggested that the current causes charge fluctuations around the AB ring, yielding electron coherence time $\tau_\phi \propto T^{-1}$,[4)] which is consistent with our result for the local setup. Such a mechanism, on the other hand, would be suppressed in the nonlocal measurement where no net current flows across the AB ring.

4. Conclusion

In summary, we have performed two ways of resistance measurements on a small AB ring and found that the quantum decoherence is suppressed in the nonlocal measurement. As a possible cause, we note the difference of current flow leads to the difference of charge fluctuation and decoherence.

Acknowledgements

We thank H. Ebisawa and H. Fukuyama for helpful discussion. This work is partly supported by a Grant-in-Aid for Scientific Research and by a Grant-in-Aid for COE Research ("Quantum Dot and Its Application") from the Ministry of Education, Culture, Sports, Science, and Technology.

1) M. Büttiker: Phys. Rev. Lett. **57** (1986) 1761.
2) A. Yacoby, U. Sivan, C. P. Umbach and J. M. Hong: Phys. Rev. Lett. **66** (1991) 1938.
3) M. Büttiker: IBM J. Res. Develop. **32** (1988) 317.
4) G. Seelig and M. Büttiker: Phys. Rev. B **64** (2001) 245313.