ELSEVIER

Microelectronic Engineering 63 (2002) 53–56

MICROELECTRONIC ENGINEERING

www.elsevier.com/locate/mee

Reduction of quantum decoherence in non-local resistance measurement

K. Kobayashi[a,*], H. Aikawa[a], S. Katsumoto[a,b], Y. Iye[a,b]

[a]*Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Chiba 277-8581, Japan*
[b]*CREST, Japan Science and Technology Corporation, Mejiro, Tokyo 171-0031, Japan*

Abstract

We have found that the coherence of electrons is better retained in a non-local resistance measurement compared to in the conventional four-terminal resistance setup which is pervasively used. The observed configuration-dependent decoherence poses an important question on pictures of the mechanism of quantum decoherence.

Keywords: Coherence; AB effect; Quantum transport

1. Introduction

Quantum decoherence of electrons in solids due to interaction with a huge number of degrees of freedom is one of the most fundamental issues in physics (for example, see Refs. [1] and [2]). It is also regarded as the most serious obstacle to the realization of quantum computers. Recently, the Aharonov–Bohm (AB) effect has been intensively studied from this viewpoint. It is well known that the probes of the sample under measurement are important in coherent transport and this can be taken into account through connection of *S*-matrices and the Landauer–Büttiker (LB) formula [3]. In single-electron phenomena, it has been frequently announced that the probes greatly affect the charging effect itself, while, in coherent transport, quantum coherence is usually believed to be unaffected by the probe configuration. As performed by Buks et al. [4], however, electric current flowing nearby an AB ring causes decoherence of electrons in the ring. In this respect, the above belief should be worth reconsidering.

2. Experiments

To investigate the effect of probe configuration on quantum decoherence, we fabricated an AB ring

*Corresponding author.

0167-9317/02/$ – see front matter
PII: S0167-9317(02)00636-6

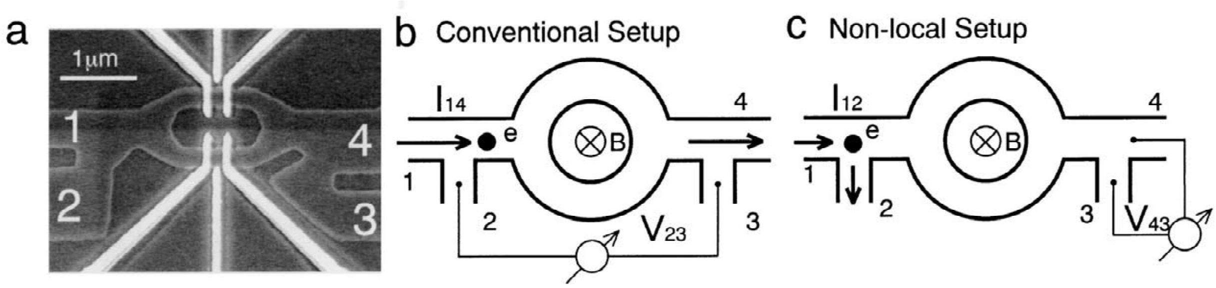

Fig. 1. (a) Scanning electron micrograph of the AB ring. The Au/Ti gates on top of the arms of the AB ring were kept open for the experiments discussed in this paper. (b) The conventional four-terminal setup (current: $1 \rightarrow 4$, voltage: $2 \rightarrow 3$). (c) The non-local four-terminal setup (current: $1 \rightarrow 2$, voltage: $4 \rightarrow 3$).

shown in Fig. 1a by wet-etching a two-dimensional electron gas system at an AlGaAs/GaAs heterostructure with a mobility of 9×10^5 cm^2/V s and a sheet carrier density of 3.8×10^{11} cm^{-2}. The electron mean free path (l_e) ~8 μm is larger enough than the length of one arm of the ring $L \sim 2$ μm, so that our sample is in the quasi-ballistic regime. Two samples (1 and 2) with the same geometry were measured between 30 mK and 4.2 K using a dilution refrigerator, yielding almost the same results. The probe configuration of the present devices allowed us to perform two distinct types of measurement. One is a 'conventional' four-terminal measurement: electric current I_{14} is applied between the terminals 1 and 4, and then the voltage V_{23} between 2 and 3 is measured as shown in Fig. 1b, giving the resistance $R_{14,23}$. The other setup shown in Fig. 1c is referred to as a 'non-local' setup henceforth, yielding the signal $R_{12,43}$ (current: $1 \rightarrow 2$, voltage: $4 \rightarrow 3$). The standard lock-in techniques were used with typically $I_{14} = 3$ nA and $I_{12} = 15$ nA for the conventional and non-local setup, respectively, which we have checked to be sufficiently small to be free from any heating effect.

3. Results and discussion

The upper part of Fig. 2a and b show the AB oscillations obtained at $T = 40$, 400, and 800 mK in the conventional setup and non-local setup, respectively. The oscillation period is 3.1±0.5 mT, which agrees with the one expected from the ring dimension. First, let us see the data at the lowest temperature. The lower part of Fig. 2a shows the AB component (ΔR_{AB}) extracted from $R_{14,23}$ through fast Fourier transform (FFT), whose amplitude is about 2% of the total resistance of the ring ~1 kΩ. As seen in the non-local resistance in Fig. 2b, however, the corresponding AB component $R_{12,43}$ relative to the total resistance ΔR_{AB} is quite enhanced that it averages up to 20–30% of the total signal. This AB amplitude is one of the largest among all the AB experiments ever known.

We show that the above is a unique property of the non-local measurement derived from the LB formula. According to the LB formula [3], $R_{14,23} = (h/2e^2)(T_{21}T_{34} - T_{24}T_{31})/D$ and $R_{12,43} = (h/2e^2)(T_{41}T_{32} - T_{42}T_{31})/D$, where T_{ij} (≥ 0) is a transmission coefficient from terminal i to j (i, $j = 1....4$, $i \neq j$) summed over the relevant conductive channels and the denominator D is a function including all the T_{ij} values. If we consider a most simplified case by assuming that $T_{12} = T_{21} = T_{34} = T_{43} = T_0$, $T_{14} = T_{41} = T_{23} = T_{32} = T_1$, $T_{13} = T_{31} = T_{24} = T_{42} = T_2$, and $T_0 >> T_1, T_2$, the LB formula

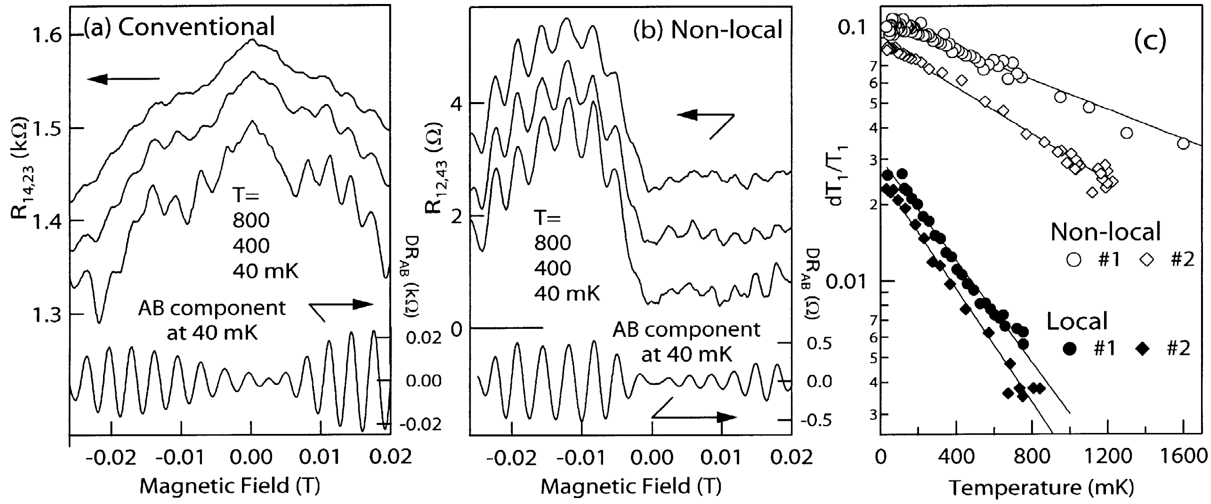

Fig. 2. (a) The conventional AB oscillation of the sample 1 taken at different temperatures. The data at $T = 400$ and 800 mK are incrementally shifted upward by 0.05 kΩ. (b) The counterpart of (a) for the non-local measurement. The data at 400 and 800 mK are incrementally shifted upward by 1 Ω. (c) Temperature dependence of the AB amplitude for the two types of measurement for samples 1 and 2. The solid lines are fitted to the exponential decay function of temperature.

gives $R_{14,23} \sim (h/4e^2)/(T_1 + T_2)$ and $R_{12,43} \sim (h/4e^2)(T_1 - T_2)/T_0^2$. When T_0 contributes little to the AB effect and $T_1 \sim T_2$, the AB amplitude can be expressed using the fluctuation of the transmission coefficients, as $\delta R_{14,23} \sim (1/\sqrt{2})(h/4e^2)|\delta T_1|/T_1^2$ and $\delta R_{12,43} \sim (1/\sqrt{2})(h/4e^2)|\delta T_1/T_0^2$ ($\delta T_1 \sim \delta T_2$ is also presumed). This expression means that the non-local AB ratio ($\delta R_{12,43}/R_{12,43}$) can be very large when $T_1 \sim T_2$, explaining the observed very large AB amplitude, while the conventional one ($\delta R_{14,23}/R_{14,23}$) remains of the order of $|\delta T_1|/T_1$. More intuitively, the non-local signal is geometrically very small in the absence of the magnetic flux and hence the AB effect prominently appears as a deviation from this small signal. The above argument is fully supported by numerical simulation with realistic combinations of T_{ij} values.

We have seen that the apparent difference in the AB amplitude between the two setups is interpreted within the LB framework. There is, however, another aspect which suggests a fundamental difference between the two configurations. In the upper panels of Fig. 2a and b, it is clear that the temperature dependence of the AB oscillation is qualitatively different between the two: the AB oscillation in the non-local setup is less dependent on temperature than that in the local one. In Fig. 2c, we plot the temperature dependence of $|\delta T_1|/T_1$ which is experimentally obtained from the raw resistance, the AB amplitude, and the transmission coefficients (T_0, T_1, and T_2) as a function of temperature according to the above simple model. Remarkably, the AB oscillation in the non-local setup survives at higher temperatures than that conventionally obtained. Furthermore, the data can be fitted to $\exp(-aT)$ with a as a fitting parameter. We obtained $a = 0.72$ and 1.0 K^{-1} for the two samples in the non-local configuration, while $a = 2.3$ and 2.5 K^{-1} for the conventional case.

There are two main factors that degrade the AB amplitude. One is the thermal broadening of the electron wave packets. The other is the decoherence which contributes as $\delta T_{ij} \propto \exp[-\tau_L/\tau_\phi(T)]$ where τ_ϕ is a phase coherence time and $\tau_L = L/v_f$ (v_f: Fermi velocity). Since these effects are presumed to be included commonly in all the transmission coefficients in the LB formula, the temperature dependence of the AB amplitude should be the same in both measurements as long as the same T_{ij} values are adopted. Because the thermal averaging in the ballistic regime is expected to occur in the time scale $\tau_{th} \sim \hbar/k_B T$, τ_ϕ^{-1} is replaced by $\tau_\phi^{-1} + \tau_{th}^{-1}$ and this τ_{th} would contribute to the AB degradation as $\exp(-bT)$ where $b \sim 1$ K^{-1}. Our observation, therefore, indicates that $\tau_\phi \propto T^{-1}$ with very different coefficients between the two setups.

We propose that the observed probe-dependent decoherence is due to the difference of the current path in the conventional and non-local setups. No net current flows across the ring in the non-local setup. This makes the AB ring effectively 'decoupled' from the environment such as the leads. Alternatively, the charge fluctuation around the ring is possibly suppressed in the non-local setup compared with in the conventional setup. Indeed, Seelig and Büttiker [5] predict that the charge fluctuations coupled with a nearby capacitor cause decoherence to the electrons traversing the AB ring such that $\tau_\phi \propto T^{-1}$, while this mechanism may be suppressed in our non-local setup.

Finally, we compare our results with recent studies on the decoherence in the ballistic AB ring measured in the conventional setup. Cassé et al. [6] explained the temperature dependence of the AB amplitude as due to thermal averaging. Hansen et al. [7], however, showed that thermal averaging alone cannot explain the AB degradation and $\tau_\phi \propto T^{-1}$, being consistent with our observations.

4. Conclusion

We have applied the conventional and non-local measurements to the AB ring. The analysis of the temperature dependence of the AB amplitudes based on the LB framework reveals that τ_ϕ *depends* on the probe configuration, contrary to what might be believed naively. Possible mechanisms for the observed suppression of decoherence in the non-local setup are proposed.

Acknowledgements

This work is supported by Grant-in-Aid for Scientific Research and by Grant-in-Aid for COE Research ('Quantum Dot and Its Application') from the Ministry of Education, Science, Sports, and Culture.

References

[1] P. Mohanty et al., Phys. Rev. Lett. 78 (1997) 3366.
[2] D.S. Golubev, A.D. Zaikin, Phys. Rev. Lett. 81 (1998) 1074;
D.S. Golubev, A.D. Zaikin, Phys. Rev. Lett. 82 (1999) 3191;
I.L. Aleiner, B.L. Altshuler, M.E. Gershenson, Phys. Rev. Lett. 82 (1999) 3190.
[3] M. Büttiker, Phys. Rev. Lett. 57 (1986) 1761.
[4] E. Buks et al., Nature 391 (1998) 871.
[5] G. Seelig, M. Büttiker, cond-mat/0106100.
[6] M. Cassé et al., Phys. Rev. B 62 (2000) 2624.
[7] A.E. Hansen et al., Phys. Rev. B 64 (2001) 45327.