Non-equilibrium dephasing in ballistic interferometers

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Abstract. It was recently reported that the interference visibility in electronic Mach-Zehnder interferometers behaves unexpectedly in the non-equilibrium regime. Here we report an experiment on non-equilibrium dephasing in two different kinds of electron interferometers. Our results indicate that there exist some universal factors in the dephasing phenomenon in ballistic systems.

1. Introduction
Electron interference in ballistic interferometers has been one of the central topics in mesoscopic physics since 1980’s. The Aharonov-Bohm (AB) effect is a typical example of the interference, and has been widely studied for many years. Recently, the AB effect was proposed to be used as a method to detect the electron entanglement in an electron Mach-Zehnder interferometer (EMZI) [1]. In the experiments to investigate coherence in an EMZI, however, there have been observed a few unexpected phenomena [2,3,4]. The main discovery was the “lobe structure”, which is a rapid decrease of the interference visibility with a phase reversal of the interference signal (AB oscillation) when the drain-source bias for the EMZI is varied. This has invoked researchers to reconsider decoherence of the quantum interference in non-equilibrium ballistic systems. Several theoretical attempts propose that Coulomb interactions are responsible for the lobe structure to emerge and imply that this can be observed in other ballistic interferometers besides EMZI’s [5,6]. However, experimental evidences to support this claim have been lacking.

Here, we report the measurement of the dephasing of the AB oscillation in non-equilibrium region in an AB ring (ABR). The drain-source bias dependence of the interference visibility shows a lobe-like structure whose energy scale is much larger than those observed at EMZI’s. The numerical analysis for the observed structures shows that the energy scale is strongly dependent on the sample size. We also discuss the relevance of the Gaussian phase averaging under high magnetic field [3].

2. Measurement setup and Sample
The AB ring sample was fabricated on a GaAs/AlGaAs two-dimensional electron gas 34 nm under the surface by the local oxidation technique using an atomic force microscope (AFM) (see Fig. 1a) [7,8].

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Measurements were performed by using standard lock-in technique with 5 μV excitation signal at 37 Hz around zero magnetic field (up to 50 mT) and in the integer quantum hall (IQH) regime (with the Landau level filling ~10). The schematic picture of the electron channels in each region is shown in Fig. 1b. The sample was placed in a dilution refrigerator with a base electron temperature of 125 mK [9].

3. Results and discussion

Figures 1c and 1d show the conductance of the AB ring obtained at zero-bias voltage as a function of the magnetic field around zero magnetic field and in the IQH regime, respectively. Clear AB oscillations are seen in both regimes. The corresponding diameter of the AB ring obtained from the period of the AB oscillation is 0.51 μm at weak magnetic field, and 0.56 μm under higher magnetic field. The difference reflects the formation of the edge channel along the outer side of the ring in the IQH regime, which makes the path of the interferometer longer.

In order to obtain the interference visibility, we calculated the difference between the conductance at a peak ($G_{\text{max}}$) and the one at a dip ($G_{\text{min}}$) of the zero bias AB oscillations (See Fig. 2a). The visibility ($v$) is defined by $v = (G_{\text{max}} - G_{\text{min}}) / (G_{\text{max}} + G_{\text{min}})$. Interestingly the bias dependence of the visibility shows a structure that looks similar to the well-known lobe structure observed in EMZI's (Fig. 2b). The oscillation phase is reversed around 300 μV with a decaying oscillation amplitude as the bias voltage increases. This observation is totally unexpected from the conventional single-particle picture, where the interference visibility is insensitive to the bias voltage [2]. We also succeeded in obtaining the lobe-like structure in the ABR in the IQHE regime, as well as in a Fabry-Pérot interferometer (FPI) (Fig. 3b. See Ref. [10] for more detail). Note that all our lobe structures have only one side lobe.

Interestingly, the energy scale to characterize these lobe structures is much larger than those observed at EMZI. To evaluate the energy scale quantitatively, the obtained structures are fitted by the following function [4].
This empirical function is a product of an oscillation term and a relaxation term, and it is dominated by two different energy scales, $\varepsilon_0$ for the dephasing and $\varepsilon_L$ for the phase reversal. Equation (1) is in a good agreement with the experimentally obtained visibility (upper panel of Fig. 2b and Figs 3a, 3b). Although the relation between the two energy scales is still unclear, we found that they are strongly dependent on the sample size [10].

Typically, the energy scales have the relation, $\varepsilon_L \sim a/L$, where $L$ is the arm length of the interferometer and the value $a$ is around 200 $\mu$eV$\mu$m.

It is interesting to compare our result with another type of fitting function proposed in Ref. [3],

$$v = v_0 \left[ 1 - \frac{(eV)^2}{\varepsilon_G^2} \right] \exp\left( -\frac{(eV)^2}{2\varepsilon_G^2} \right)$$

which is obtained based on the assumption of “Gaussian phase averaging”: the oscillation phase is distributed obeying the Gaussian distribution with the phase variance proportional to the bias voltage. This function is characterized by only one energy scale $\varepsilon_G$. In Ref [3], this function is applied to the lobe structures obtained in the IQHE regime, and it explains well the shape of the lobe structures. In the same way, we tried to apply the function to the lobe-like structures that we observed in the IQHE regime. These results are shown in the lower panels of Fig. 3. These lobe-like structures are explained well by Eq (2) as well as Eq (1). From the fitting, the value $\varepsilon_G$ is around 150 $\mu$eV in the AB ring and 100 $\mu$eV in the Fabry-Perot interferometer. Thus these results may be compatible with the Gaussian phase averaging as one of a universal and essential factor of the lobe structure under strong magnetic field.

On the other hand, at zero magnetic field, this fitting function does not yield a good agreement with the lobe-like structures (lower panel of Fig. 2b). There may be a mechanism for the dephasing at zero magnetic field which is different from that in the IQHE [10].

4. Conclusion

In conclusion, these results imply that the lobe structure can be universally observed in ballistic interferometers, and not only in EMZI. The energy scale of the lobe structure depends strongly on the arm length of the interferometer. This supports that the coulomb interaction between electrons in the interferometer arm are at the origin of the lobe structure. While the model based on Gaussian phase averaging might also be responsible for the lobe structure in the IQHE regime, it fails in explaining quantitatively the lobe structure at zero magnetic field.

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