Aharonov Bohm oscillation in a multi-domain ferromagnetic $Fe_{19}Ni_{81}$ ring

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Abstract

The magnetoresistance of a ferromagnetic $Fe_{19}Ni_{81}$ ring with 420 nm in inner diameter and 500 nm in outer diameter was measured at 4.2 K and 30 mK. When the magnetic field is applied to the ring, the magnetoresistance exhibits a periodic oscillation due to the Ahoronov Bohm effect in both a single domain configuration and a multi domain configuration. This indicates that the interference effect of a conduction electron in the submicron ferromagnet subsists even in the strong modulation of local magnetization.

Key words: nanomagnets ;coherence ;Aharonov Bohm effect

The coherent charge motion in submicron-sized ferromagnets has attracted interest due to the relevance to their transport properties at low temperatures. In submicron-sized ferromagnets, local spin modulation gives rise to the decoherence of conduction electron[1–3]. Such a decoherence is a candidate for the mechanism of the resistive changes by nucleation or annihilation of a domain wall[1], and was believed to critically suppress the quantum interference such as the Aharonov-Bohm (AB) oscillation[4] in ferromagnets. Recently, we found an AB oscillation in a ferromagnetic $Fe_{19}Ni_{81}$ submicron ring around the magnetic field of 3 T[5]. In such a magnetic field range, the magnetization of the $Fe_{19}Ni_{81}$ submicron ring is almost saturated and the domain walls disappear. This paper describes the AB oscillation in a multi domain ferromagnetic $Fe_{19}Ni_{81}$ ring. The result indicates that the interference effect in a submicron ferromagnet subsists even when the local magnetization is highly modulated.

The sample investigated in the present study consists of an $Fe_{19}Ni_{81}$ ring and wires attached to the ring edges. It was fabricated by the lift-off technique using electron beam lithography[5]. A scanning electron microscope image of the sample is shown in the inset in Fig. 1(a). The size of the sample is as follows: the outer diameter of the ring D_o=500 nm, the inner diameter of the ring D_i=420 nm, and the width of the wire w=40 nm. The thickness of the wire and ring is 20 nm. For resistance measurement, Cu electrodes were attached to the wires. The distance between the two voltage electrodes is 2.5 μm. The sample was mounted on a $^3He^4He$ dilution refrigerator. The temperature dependence of magnetoresistance was measured with using the conventional four probe method (25 Hz, 50 nA). The magnetic field was applied at an angle of 15° in a perpendicular direction to the substrate (see Fig. 1(a)). The sweep rate of the magnetic field was 2 Oe/sec.

Figure 1(a) shows the magnetoresistance at 4.2 K. The application sequence of the magnetic field is depicted by the arrows. While applying the magnetic field, the resistance gradually decreases and jumps at 0.7 T, and then almost saturates around B=3 T. The field dependence of the resistance is mainly caused by the anisotropic magnetoresistance effect (AMR)[6] typically observed in ferromagnets, indicating that the resistance jump at 0.7 T corresponds to a magnetization reversal. While decreasing the magnetic field from 4 T to 0, the resistance gradually increases without ex-

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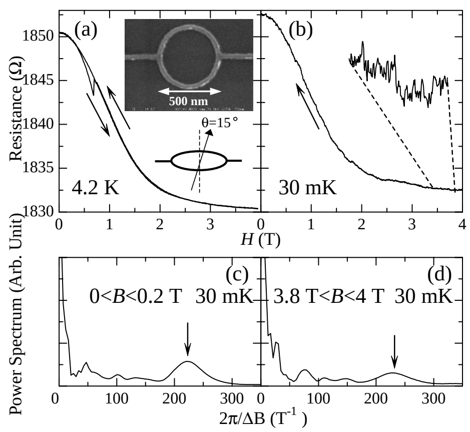

Fig. 1. (a,b) Magnetoresistance for a NiFe submicron-ring at 4.2 K and 30 mK (see text). The inset to (b) is a scanning electron microscope image of the sample. (c,d) Power spectra of $R_{30\mathrm{mK}}(B) - R_{4.2\mathrm{K}}(B)$ for 0< B <0.2 T and 3.8 T< B < 4 T at 30 mK. The arrows show the peak positions.

hibiting steep change. This indicates that the remnant magnetic state is a multi domain configuration. Such a configuration is also confirmed by a magnetic force microscopy.

Figure 1(b) shows the magnetoresistance at 30 mK. Before the measurement, the external magnetic field of B=4 T was applied, and then the resistance was measured with decreasing the magnetic field. It should be noted that fine structures of magnetoresistance including periodic oscillations were observed at 30 mK. As reported in a previous paper[5], the periodic oscillation is due to the AB oscillation.

The AB oscillation was observed in both the single domain and the multi domain configuration. In order to assess the oscillation in a quantitative manner, the AMR signal was removed from the magnetoresistance data at 30 mK ($R_{30\mathrm{mK}}(B)$) by subtracting those measured with decreasing the magnetic field at 4.2 K ($R_{4.2\mathrm{K}}(B)$). Figure 1 (c) and (d) show the power spectra deduced from $R_{30\mathrm{mK}}(B) - R_{4.2\mathrm{K}}(B)$ for 0<B<0.2 T and 3.8 T< B < 4 T, respectively. The increasing tail structure towards $2\pi/\Delta B$= 0 in the spectra corresponds to the UCF. The $R_{30\mathrm{mK}}(B) - R_{4.2\mathrm{K}}(B)$ for 0< B <0.2 T represents quantum transport properties in a multi domain configuration while that for 3.8 T<B<4 T represents properties in a single domain configuration. In both the magnetic field ranges, clear peak structures appear around $2\pi/\Delta B$=230 T^{-1}. The corresponding period of oscillation is ΔB ≈0.027 T, which is consistent with the expected period due to the AB oscillation, 0.020 T< ΔB < 0.029 T, given by the inner-diameter (D_i) and outer-diameter (D_o) of the ring. This indicates that the AB oscillation in ferromagnet subsists even in the multi domain configuration.

The amplitude of the AB oscillation observed in the multi domain configuration (0< B <0.2 T) is comparable to that in the single domain configuration (3.8 T< B <4 T). This indicates that the quantum decoherence due to the local spin modulation around the domain walls in $Fe_{19}Ni_{81}$ is negligible. There are two contradicting theories for the adiabaticity relevant to the coherent electron motion in the spin modulation. One is Stern's criterion[2] which requires $\omega_B \gg 1/\tau$, where ω_B and τ represent the spin precession frequency due to the effective internal magnetic field for conductive s-electrons (H_eff) and the elastic scattering time, respectively. In the present case, τ can be estimated to be of the order of 10^{-12} s from the residual resistivity. Such a small τ leads to unnaturally huge(≫10 kOe) H_eff within the Stern's criterion, indicating that the criterion cannot be responsible for the coherent charge dynamics in $Fe_{19}Ni_{81}$. On the other hand, Loss, Schoeller and Goldbart (LSG)[3] concluded that the adiabaticity is reached at a much weaker magnetic field, $\omega_B \gg 1/\tau(l/L)^2$, where L and l represent the typical extension of the domain walls and the mean free path, respectively. In the present case, l can be estimated to be of the order of 100 nm from the magnetic force microscopy (not shown here), which allows H_eff to be moderate (∼100 Oe). Recently, the LSG's criterion was examined numerically; Langen *et al.*[7] showed that a numerical simulation of the decoherence cannot fully be accounted for by the LSG's theory but is rather consistent with the Stern's theory. In the present experimental study, however, the Stern's criterion is apparently too pessimistic but less strict criterion, such as the LSG's criterion, should be considered.

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