Experimental Demonstration of a Persistent Current

By combining an epitaxial FePt nanopillar with perpendicular magnetic anisotropy and a non-magnetic nanoring, we will demonstrate an alternative method to generate a spin-polarised persistent current in a non-magnet. Even though such a spin-polarised persistent current has been proposed theoretically almost 20 years ago [1], there has been no experimental demonstration to date. This device would open up new horizon as a spin source for quantum computation.

Quantum phases of charged particles have been investigated in mesoscopic structures, and have revealed interference and oscillatory behavior induced by an external field application [2]. For instance, electrons travelling along semiconductor or normal metal rings threaded by a magnetic flux acquire a quantum dynamical phase, producing interference phenomenon such as the Aharonov-Bohm (AB) and Altshuler-Aronov-Spivak (AAS) effects. In addition, when the spin of electron rotates during its orbital motion along the ring-shaped path, the electron acquires an additional phase contribution known as the geometrical or Berry phase.

Recently, a geometrical phase has been predicted by studying electron transport under an inhomogeneous magnetic field. The geometrical phase can drive a persistent current. A pioneering experiment has been performed using spin-orbit scattering in a two-dimensional electron gas (2DEG) semiconductor, which also strongly couples spin and orbital motion and introduces a spin rotation. For metallic rings, it has been pointed out that electrons can sense the geometrical phase even when an effective exchange field is induced by ferromagnets. However, no results have been reported on the correlation between the geometrical phase and the presence of the ferromagnets. Interestingly, as opposed to a general belief that ferromagnets destroy quantum phase effects due to their complex dephasing mechanisms, an oscillatory behavior of resistance in a permalloy nanoring has been observed and an effect of ferromagnetic ordering in a GaMnAs semiconductor has been detected experimentally [3]. Such an AB oscillation in a ferromagnetic ring has been studied theoretically, suggesting that a dynamic phase can exist under the special condition when a ferromagnetic ring possesses perpendicular anisotropy. I have previously explored the effect of ferromagnets upon the electron quantum phase using a metallic nanoring, consisting of a trilayered FeNi/Cu/FeNi structure known as a current-in-plane (CIP) giant magnetoresistive (GMR) spin valve [4].

Previously we have fabricated FePt nanopillar encircled by a Au nanopillar. At 350 mK, significant hysteresis was observed in the magnetoresistance when the magnetisation of the pillar was measured [5]. The stray field from the pillar will act at a slight angle to the nanoring because the two objects do not lie in exactly the same plane. This will induce a persistent current in the ring. The simple 4-terminal configuration then allows the persistent current to be detected. The persistent current was observed via the hysteresis in the magnetoresistance when the magnetisation of the pillar was measured.

We have further improved a new nanofabrication method has been successfully developed to produce a quantum device on a MgO(001) substrate consisting of a 300-nm-inner-diameter non-magnetic nanoring and a 70-nm-diameter FePt nanopillar inside by using electron-beam lithography and Ar-ion milling. The nanoring is 100 nm wide with 15 nm Cr and 5 nm Au layers to improve the adhesion onto the MgO substrate. As shown in Fig. 1, the center nanopillar is designed to provide a non-uniform magnetic field in the nanoring at its remanent state after perpendicular saturation. Such a non-uniform field is theoretically expected to induce a persistent spin current in the nanoring [1]. The induced current is intended to be measured by four contacts fabricated near the nanoring.

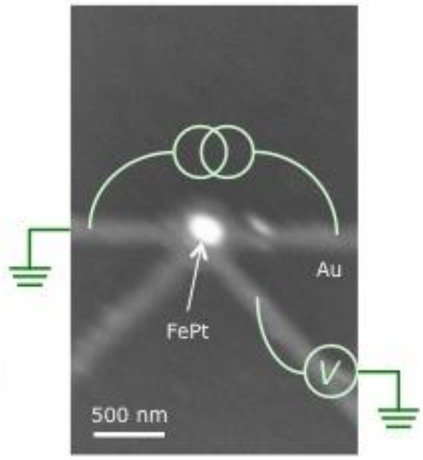

Fig. 1 SEM image of the device measured.

We introduced a constant current of 150 nA using three-terminal geometry to observe new quantum phenomena. The measurements were carried out at Prof. Kobayashi's group in Osaka University using their dilution refrigerator (Oxford

Instruments, MX Kelvinox400) at a temperature range between 25 mK and 5.0 K under magnetic fields within ±1 T. A combination of a lock-in amplifier (Stanford, SR830), low-noise pre-amplifier (NF, LI-75A) and a standard resistance (2 MΩ) was used to improve signal-to-noise ratios. We will first detect the observation of the AB signals to confirm the quality of the devices. Accordingly, we will focus on a persistent current induced in a non-magnetic nanoring under a non-uniform magnetic field application as predicted in Ref. [1].

Figure 2 shows magnetoresistance curves measured at 25 mK. A clear oscillation is observed at the period of 80~100 mT, which is larger than that estimated from the nanoring diameter (20~60 mT). This may be caused by the presence of multiple electron paths or universal conductance fluctuation within 100-nm-wide nanoring. Under the non-uniform magnetic fields generated by the FePt nano-pillar, the Berry phase is induced, resulting shifts in the AB oscillation. Such shits are sensitive to the directions of the non-uniform fields and are expected to be hysteretic. However, our measured magnetoresistance shows no hysteresis and indicate that the Berry phase is not detected at this stage.

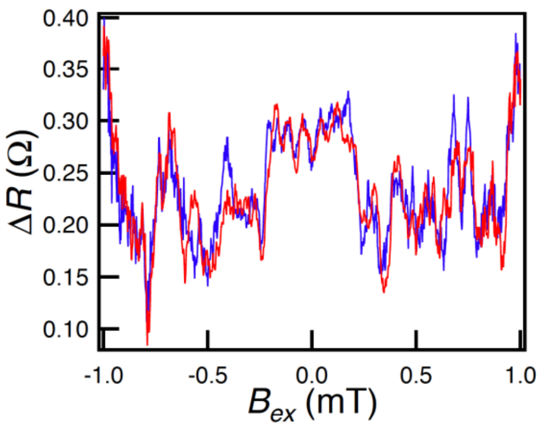

Fig. 2 Magnetoresistance measured at 25 mK with increasing (blue) and decreasing (red) an applied magnetic field.

Around zero field, symmetric increase in the magnetoresistance was observed with increasing field as a proof of weak anti-localisation. By fitting these data with the weak anti-localisation theory [6], we estimated the phase relaxation and spin-orbit coupling lengths. The phase relaxation length was found to be 480 nm at 500 mK and to be reduced to 410 nm with increasing temperature up to 5 K as expected. These values are two orders of magnitude smaller than previously reported value (12 μm) in a 60-nm-thick Au film measured at 300 mK [7]. Such reduction may be induced by scattering at the Cr/Ag interfaces. The spin-orbit coupling length, on the other hand, was found to be 240 nm at 500 mK almost independent of temperature.

In summary, we have successfully fabricated a quantum device consisting of a ferromagnetic nanopillar enclosed by a non-magnetic nanoring. As the first step towards the demonstration of a spin-polarised persistent current, we observed AB oscillation and weak anti-localisation in the nanoring below 5 K. Unfortunately we could not measure the AB oscillation induced by the Berry phase. We will improve our devices by (i) removing the Cr seed layer in the nanoring, (ii) replacing Au with Ag to increase the spin diffusion length, (iii) narrowing the width of the nanoring and (iv) minimising the nanofabrication damage onto the nanopillar.

References

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