Experimental Demonstration of Spin Geometric Phase: Radius Dependence of Time-Reversal Aharonov-Casher Oscillations

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A geometric phase of electron spin is studied in arrays of InAlAs/InGaAs two-dimensional electron gas rings. By increasing the radius of the rings, the time-reversal symmetric Aharonov-Casher oscillations of the electrical resistance are shifted towards weaker spin-orbit interaction regions with their shortened period. We conclude that the shift is due to a modulation of the spin geometric phase, the maximum modulation of which is approximately 1.5 rad. We further show that the Aharonov-Casher oscillations in various radius arrays collapse onto a universal curve if the radius and the strength of Rashba spin-orbit interaction are taken into account. The result is interpreted as the observation of the effective spin-dependent flux through a ring.

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Manipulation of electron spin in solid state devices is important for spintronics. A promising way to control spin is through the electric field [1]. So far, electrical manipulation of spin has been observed in a semiconductor two-dimensional electron gas (2DEG) [2,3] and topological insulator [4]. The physical origin of these observations is a gate control of Rashba-type spin-orbit interaction (SOI) [5], which gives rise to the effective magnetic field $\mathbf{B}_R$ perpendicular to both the propagation direction of the electron waves and the electric field induced by an asymmetric quantum well. In the presence of SOI, i.e., the Rashba field $\mathbf{B}_R$, the time evolution leads to the precession of spins. Since the direction of the precession depends on a propagation path, a phase contribution from the spin precession is called a dynamical phase. In this sense, the spin-manipulation experiments have mainly demonstrated a control of the dynamical phase of spin through SOI.

In general, the spin-interference effect induced by the electric field is referred to as the Aharonov-Casher (AC) effect [6,7], which is the electromagnetic dual of the Aharonov-Bohm (AB) effect [8]. Previous theoretical works have revealed that the AC phase consists of not only the dynamical phase, but also a geometric phase of electron spin [9,10]. A geometric phase is now commonly used in various fields of physics, and has been a topic of intense theoretical and experimental research since the pioneering work of Berry [11]. In particular, the spin geometric phase is related to topological spin currents [12] and is robust against the dephasing [13]; thus it is of great importance for future spintronics. So far, however, observation of the spin geometric phase has remained challenging. Although the split of Fourier spectra of the AB oscillations was discussed from the view point of the spin geometric phase [14,15], those experiments did not show its direct observation.

It has been theoretically shown [10,16–18] that spins traversing a one-dimensional Rashba ring subtend a solid angle $2\pi(1 - \cos\theta)$, which characterizes the spin geometric phase. The parameter θ denotes the tilt angle between a mean axis of the spin precession and the normal direction to the ring plane as depicted in Fig. 1, and is written as

$$\tan\theta = \frac{2m^*\alpha r}{\hbar^2}, \tag{1}$$

where m^* is the effective mass, α is the strength of Rashba SOI, and r is the radius of the ring. As one can see in Eq. (1), the spin geometric phase is affected by the radius and the strength of Rashba SOI. It is worth noting that if the spin precession is fast enough compared with propagation of the electron waves along the ring (adiabatic limit), the spin precession axis lies parallel to $\mathbf{B}_R$ ($\theta \to \pi/2$) [16]; this condition is realized with a large radius and strong

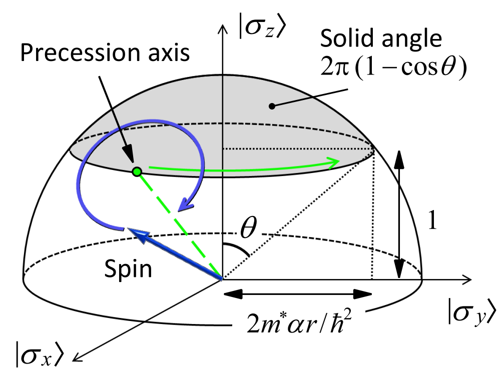

FIG. 1 (color online). Schematic image of the spin geometric phase. The axis label $|\sigma_i\rangle$ denotes the spinor along the i axis. A 2DEG ring subject to Rashba SOI is assumed to lie in the x-y plane; therefore, $\mathbf{B}_R$ points along the radial direction. The spin eigenstate is not aligned with $\mathbf{B}_R$ but with the precession axis, even in the absence of an external perpendicular field [16].

Rashba SOI. In this condition the spin geometric phase specifically corresponds to a Berry phase [11] of electron spin. By contrast, in the nonadiabatic condition, the spin precession axis cannot follow $\mathbf{B}_R$ and is no longer parallel to it ($\theta \neq \pi/2$). As a result, an Aharonov-Anandan phase [19] of spin arises.

In this Letter, we present the observation of the spin geometric phase in pure spin systems. Specifically, the radius dependence of the spin geometric phase in the time-reversal symmetric AC effect of the electrical resistance is discussed. In addition, a universal oscillatory behavior of the AC effect is demonstrated. The result corresponds to the observation of the effective spin-dependent flux, which has only been discussed theoretically [6,20].

An InAlAs/InGaAs structure was epitaxially grown on a (001) InP substrate by metal organic chemical vapor deposition. Ring arrays were fabricated by means of electron beam lithography and reactive-ion etching. One array consists of 40×40 rings with 0.608 μm of the radius, the other four arrays consist of 50×50 rings with the radius between 0.525 and 1.05 μm. A scanning electron micrograph of the 40×40 ring array is shown in the inset of Fig. 2. The ring arrays were covered with 200 nm of an Al_2O_3 insulator layer by atomic layer deposition and a Cr/Au top-gate electrode, in order to control the Rashba SOI strength α by the gate voltage V_g. All the measurements were performed at a temperature of 1.7 K.

In order to inspect the AC effect, interference from the orbital part of the wave function must be eliminated. Note that the gate voltage affects not only the Rashba SOI strength, but also the carrier density, i.e., the electron wavelength. The strategy in this Letter, which is in the same manner as previous studies [2,21], is to investigate the gate voltage dependence of the Al'tshuler-Aronov-Spivak (AAS) amplitude [22] at zero magnetic field ($B = 0$).

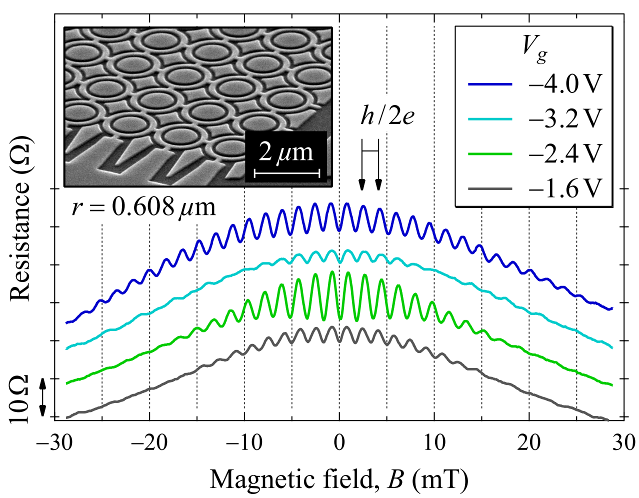

FIG. 2 (color online). Magnetoresistance curves of the 40×40 ring array ($r = 0.608$ μm for each ring) as a function of gate voltage. The curves are shifted vertically for clarity. Inset: Scanning electron micrograph of the 40×40 ring array. Other fabricated four arrays consist of 50×50 rings with the radius of 0.525, 0.681, 0.857, and 1.05 μm.

Figure 2 shows magnetoresistance curves measured using the 40×40 ring array for fixed gate voltages. It is well known that a perpendicular magnetic field to a ring induces the AB effect, which gives rise to resistance oscillations with a period of one flux quantum Φ_0 ($= h/e$). The period observed in Fig. 2, however, is $\Phi_0/2$. Also, it is confirmed that a higher magnetic field suppresses the amplitude of the resistance oscillations, whereas in the case of the AB effect, the oscillations should persist at relatively high magnetic fields. According to these facts, our measured magnetoresistance oscillations are attributed to the AAS effect [22], that is, the AB effect in the time-reversal paths. Since our fabricated arrays consist of a huge number of rings, the ensemble averaging allows one to observe the AAS effect instead of the AB effect [23]. It is notable that in the time-reversal paths, a phase contribution from the orbital part of the wave function is always constructive at zero magnetic field.

Figure 3(a) displays the filtered AAS oscillation from the magnetoresistance at the gate voltage of −2.4 V (see Fig. 2). The gate voltage dependence of the AAS oscillations is shown in Fig. 3(b). At zero magnetic field, a phase contribution from the orbital part of the wave function is invariable, therefore along the vertical axis, namely V_g axis, the spin part of the wave function plays an important role through Rashba SOI. Figure 3(c) shows the AAS amplitude plotted against the gate voltage at zero magnetic

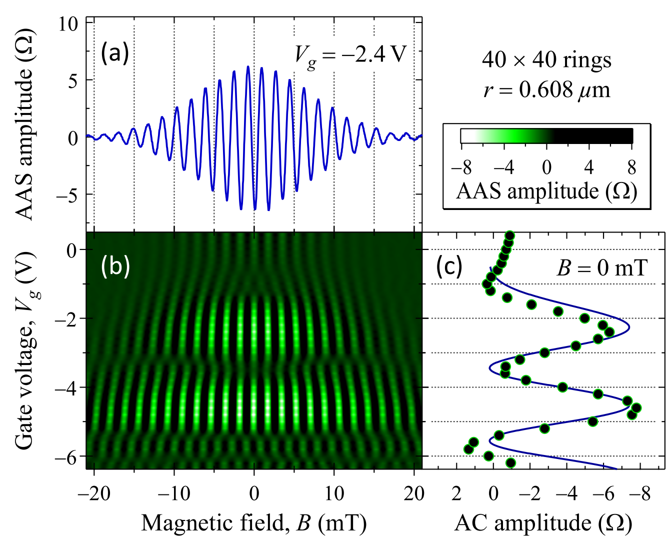

FIG. 3 (color online). (a) AAS oscillation of the 40×40 array ($r = 0.608$ μm rings) at $V_g = -2.4$ V. The horizontal axis represents the magnetic field. (b) Gate voltage dependence of the AAS oscillations. The color scale is shown in upper-right margin. (c) AAS amplitude at $B = 0$ as a function of gate voltage (time-reversal AC effect). The vertical axis represents the gate voltage. The solid line was calculated by using Eq. (2).

field. In Fig. 3(c), one can clearly see the phase switching by varying the gate voltage. This phase modulation is ascribed to the spin interference in the time-reversal paths, i.e., the time-reversal AC effect. Notice here Bergsten *et al.* [2] obtained similar results, but they had to average magnetoresistance curves at slightly different gate voltages because their sample consisted of 6×6 rings at the most. On the other hand in our samples, which consist of a huge number of rings, owing to the ensemble averaging the time-reversal AC effect is readily acquired.

The time-reversal AC effect has been obtained for the five ring arrays. By analyzing the Shubnikov–de Haas effect, a linear relation between the strength of Rashba SOI and the gate voltage has been acquired. Figure 4(a) displays the time-reversal AC oscillations as a function of Rashba SOI strength. The amplitude of the oscillations has been normalized for clarity. Solid lines are calculated time-reversal AC oscillations by using the equation derived by Frustaglia and Richter [16]:

$$\frac{\delta R_{\alpha\neq 0}}{\delta R_{\alpha=0}} = \cos\left[2\pi\sqrt{1+\left(\frac{2m^*\alpha r}{\hbar^2}\right)^2}\right], \quad (2)$$

where $\delta R_{\alpha\neq 0}$ and $\delta R_{\alpha=0}$ are resistance modulations due to the spin interference with and without Rashba SOI, respectively. By considering Eqs. (1) and (2) together, the time-reversal AC effect can also be expressed as the following forms [16].

$$\frac{\delta R_{\alpha\neq 0}}{\delta R_{\alpha=0}} = \cos\left[\frac{2\pi}{\cos\theta}\right] \quad (3)$$

$$= \cos\left[2\pi\frac{2m^*\alpha r}{\hbar^2}\sin\theta - 2\pi(1-\cos\theta)\right]. \quad (4)$$

The argument of Eq. (3) can be divided into two components as displayed in Eq. (4): one is the dynamical phase, $2\pi\frac{2m^*\alpha r}{\hbar^2}\sin\theta$, another is the spin geometric phase, $2\pi(1-\cos\theta)$.

To evaluate the spin geometric phase, a cosine function has been fitted to each AC oscillation. The total phase obtained by the fit was equated with the argument of the cosine of Eq. (3), namely $2\pi/\cos\theta$. Accordingly, $\cos\theta$ has been obtained as a function of Rashba SOI strength. Now the spin geometric phase, $2\pi(1-\cos\theta)$, can be inspected. The relation between the spin geometric phase and the radius for fixed Rashba SOI strengths ($\alpha = -1.4$, -1.7, and -2.0 peV m) is shown in Fig. 4(b). Solid lines are calculated results obtained by equating the argument of Eqs. (2) and (3). We found from both experimental and calculated results that the spin geometric phase tends to increase in larger radius samples. The difference of the spin geometric phase between the smallest ($r = 0.524$ μm) and the largest ($r = 1.05$ μm) ring arrays is approximately 1.5 rad for any fixed value of α. Arrows in Fig. 4(b) indicate the difference of the spin geometric phase between $\alpha = -1.4$ peV m and -2.0 peV m. For the smallest radius array the difference is 0.96 rad, whereas 0.75 rad for the largest one. This relation holds as well for calculated results, 0.84 rad for the smallest array and 0.74 rad for the largest one. Thus, the observed radius dependence of the spin geometric phase is consistent with calculation.

One might have concerns about the multichannel effect, which inevitably gives rise to a randomization of the AB interference [3,24]. In this study, by taking advantage of the time-reversal symmetric interference, we have ruled out the orbital interference and observed the clear AC oscillations, which only depend on the SOI strength [10]. Furthermore, the spin geometric phase is independent from

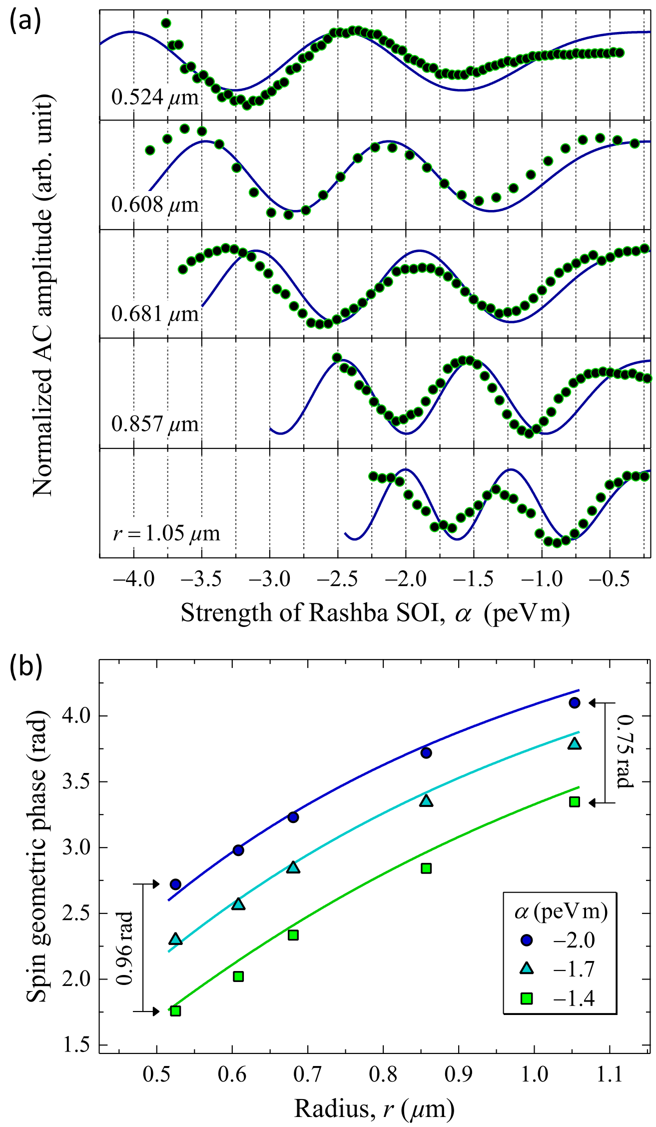

FIG. 4 (color online). (a) Normalized time-reversal AC oscillations of the electrical resistance plotted against the Rashba SOI strength ($B = 0$). According to the Shubnikov–de Haas analysis, the Rashba SOI strength α is proportional to the gate voltage. Solid lines are calculated results by using Eq. (2). (b) Spin geometric phase vs radius for fixed Rashba SOI strengths, together with calculated results (solid lines).

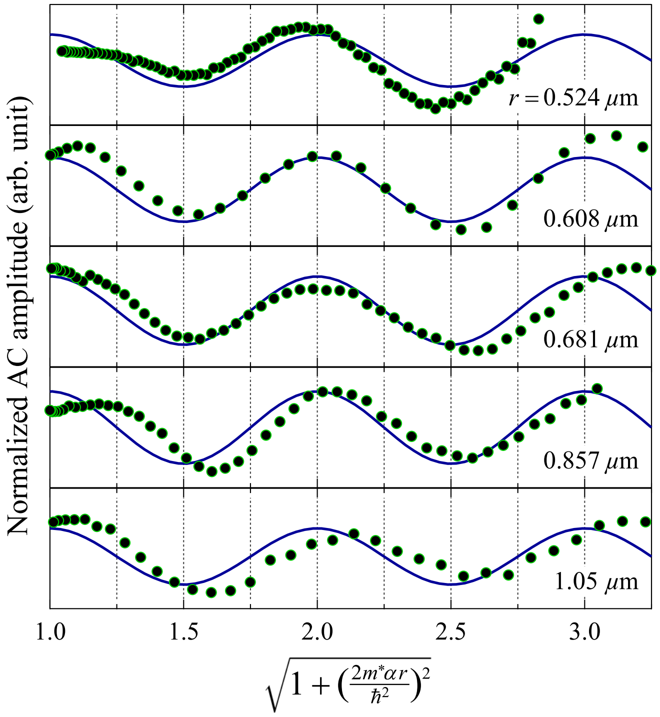

FIG. 5 (color online). Universal AC oscillations of the electrical resistance at zero magnetic field. The data are the same as those shown in Fig. 4(a) but plotted against different arguments. Solid lines represent the function in the right-hand side of Eq. (2).

the Fermi velocity and the number of channels by its definition. Hence, the multichannel effect can be neglected in our experiments.

Turning now to the effective spin-dependent flux of the AC effect. As is well known, the AB effect is intimately related to the magnetic flux through a ring. From the viewpoint of the electromagnetic duality between the AB and AC effects, the latter can be regarded as a conductance modulation by the effective spin-dependent flux [6,20]. To examine this duality, the time-reversal AC oscillations are replotted against $\sqrt{1 + (\frac{2m^*\alpha r}{\hbar^2})^2}$ in Fig. 5 [see Eq. (2)]. As one can see in Fig. 5, the AC oscillations universally occur for all the samples. Therefore, the term $\sqrt{1 + (\frac{2m^*\alpha r}{\hbar^2})^2}$ is an oscillation unit for the time-reversal AC effect. The electromagnetic correspondence of this term is a flux for the AAS effect, $\frac{\Phi}{\Phi_0/2}$, with Φ being the magnetic flux. Thus, the duality is explicitly written as

$$\frac{\Phi}{\Phi_0/2} \Longleftrightarrow \sqrt{1 + \left(\frac{2m^*\alpha r}{\hbar^2}\right)^2}. \quad (5)$$

Hence, the right-hand side of Eq. (5) can be regarded as the effective spin-dependent flux penetrating a ring.

In conclusion, by analyzing the radius dependence of the time-reversal AC effect of the electrical resistance, we have demonstrated that the largest modulation of the spin geometric phase reaches approximately 1.5 rad. Thus, we have succeeded in determining the spin geometric phase quantitatively. In addition, we have experimentally verified that the term $\sqrt{1 + (\frac{2m^*\alpha r}{\hbar^2})^2}$ is an oscillation unit for the time-reversal AC effect. These results indicate a new spin-phase degree of freedom and provide further understanding of the AC effect.

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