Experimental realization of a ballistic spin interferometer based on the Rashba effect using a nanolithographically defined square loop array

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The gate-controlled electron spin interference was observed in nanolithographically defined square loop (SL) arrays fabricated using In0.52Al0.48As/In0.53Ga0.47As/In0.52Al0.48As quantum wells. In this experiment, we demonstrate electron spin precession in quasi-one-dimensional channels that is caused by the Rashba effect. It turned out that the spin precession angle θ was gate-controllable by more than 0.75π for a sample with L = 1.5μm, where L is the side length of the SL. Large controllability of θ by the applied gate voltage as such is a necessary requirement for the realization of the spin FET device proposed by Datta and Das [Datta et al., Appl. Phys. Lett. 56, 665 (1990)] as well as for the manipulation of spin qubits using the Rashba effect.

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Exploitation of spin degree of freedom for the conduction carriers provides a key strategy for finding new functional devices in semiconductor spintronics [1–6]. A promising approach for manipulating spins in semiconductor nanostructures is the utilization of spin-orbit (SO) interactions. In this regard, lifting of the spin degeneracy in the conduction (or valence) band due to the structural inversion asymmetry is especially called the “Rashba effect” [7,8], the magnitude of which can be controlled by the applied gate voltages and/or specific design of the sample heterostructures [9,10].

Recently, we proposed a ballistic spin interferometer (SI) using a square loop (SL) geometry, where an electron spin rotates by an angle θ due to the Rashba effect as it travels along a side of the SL ballistically [11]. In a simple SI model, an incident electron wave to the SI (see Fig. 1 in Ref. [11]) is split by a “hypothetical” beam splitter into two partial waves, where each of these partial waves follows the SL path in the clockwise (CW) and counter-clockwise (CCW) directions, respectively. Then, they interfere with each other when they come back to the incident point (at the beam splitter). As a consequence, the incident electron would either scatter back on the incident path (called “path1”) or emerge on the other path (called “path2”). The backscattering probability to path1 (Pback) for the case that the incident electron is spin unpolarized is given by [11],

\[ P_{\text{back}} = \frac{1}{2} + \frac{1}{2} (\cos^4 \theta + 4 \cos^2 \theta \sin^2 \theta + \cos 2\theta) \cos \phi \equiv \frac{1}{2} + A(\theta) \cos \phi, \]  

(1)

where \( \phi \) is the quantum mechanical phase due to the vector potential responsible for the magnetic field \( \mathbf{B} \) piercing the SL (\( \phi = 2eBL^2/h \), \( L \) being the side length of the SL) and \( \theta \) is the spin precession angle when the electron propagates through each side of the SL due to the Rashba effect (\( \theta = 2\alpha m^*L/h^2 \), \( \alpha \) and \( m^* \) being the Rashba SO coupling constant and the electron effective mass, respectively). A plot of \( A(\theta) \) as a function of \( \theta \) is found in Ref. [11]. We note that \( A(\theta) \) corresponds to the amplitude of the Al’l’shnaker-Aronov-Spivak (AAS)-type oscillation of electric conductance experimentally [12]. Equation (1) predicts that the amplitude of the AAS oscillation should be modulated as a function of \( \theta \), which, in turn, can be controlled by the applied gate voltage \( V_g \) through the variation of the \( \alpha \) values.

In this Letter, we present the first experimental demonstration of the SI using nanolithographically defined SL arrays in epitaxially grown (001) In0.52Al0.48As/In0.53Ga0.47As/In0.52Al0.48As quantum wells (QW). Details of the sample preparation are following: we use the same MOCVD-grown epi-wafers of In0.52Al0.48As/In0.53Ga0.47As/In0.52Al0.48As QWs as those we used for the weak antilocalization (WAL) study previously (samples1–4 in Ref. [10]). We first exploit the electron beam lithography (EBL) and electron cyclotron resonance (ECR) plasma etching techniques to define an array of SLs in the area of 150×200 μm². We then use the photolithography and wet etching techniques to form a Hall bar mesa of the size of 125×250 μm² over the SL array regions. In this way, the area of the final SL array region in the Hall bar mesa...
However, these islands do not contribute to the electric conductivity, since they are not electrically connected one another. We sketch a SL path for the spin interference by the dotted white square in the inset of Fig. I(a), where electrons would be reflected when passing through the white square. The width $W$ of the SL path is also defined in Fig. I(a). We used $W = 0.5 \mu m$ throughout the present experiment. We can see that these SLs are electrically connected with the neighboring SLs. As a result, they contribute to the electric conductivity of the whole Hall bar.

Shown in Fig. 2 is the gate voltage ($V_g$) dependence of $\sigma_{2D}(B)$ for a SL array sample ($L = 1.5 \mu m$) that is fabricated using the sample2 epi-wafer in Ref. 10. Here, we clearly see the AAS oscillations, whose period ($\Delta B$) is given by $h/2eL^2$. We also note that as the value of $V_g$ is increased from 0.0 V, the peak feature in $\sigma_{2D}(B)$ at $B = 0$ becomes dip across $V_g = 0.3 \text{ V}$ [a dashed $\sigma_{2D}(B)$ curve]. Then, the dip feature becomes peak for $V_g > 0.9 \text{ V}$ [also indicated by another dashed $\sigma_{2D}(B)$ curve]. Finally the peak feature again becomes dip for $V_g > 3.1 \text{ V}$. Thus the amplitudes of the AAS oscillations at $B = 0$ oscillate as a function of $V_g$ as predicted in Eq. 10.

**FIG. 1:** (a) SEM micrographs of the nanolithographically defined square loop array ($L = 1.2 \mu m$). A two-dimensional electron gas exists in the relatively light regions. (b) Schematic diagram for the Hall bar sample used in the present experiment.

**FIG. 2:** Gate voltage dependence of the electric sheet conductivities $\sigma_{2D}$ as a function of the magnetic field $B$ for a square loop (SL) array sample ($L = 1.5 \mu m$) fabricated using the sample2 epi-wafer in Ref. 10. The plotted curves are shifted along $y$ axis for the ease of comparison. The magnitudes of $\sigma_{2D}$ at $B = 0$ range from $3.7 \times 10^{-4} \Omega^{-1}$ (for $V_g = 0.0 \text{ V}$) to $10.3 \times 10^{-4} \Omega^{-1}$ (for $V_g = 4.0 \text{ V}$). The range of $B$ ($\Delta B$) that corresponds to the magnetic flux half quanta piercing the SL ($\Delta B \times L^2 = h/2e$) is indicated by “$h/2e$” in the figure.
FIG. 3: Amplitudes of the experimental AAS oscillations at $B = 0$ measured for various SL array samples ($L = 1.5 - 1.8 \mu m$ using the sample 1–4) plotted as a function of the sheet carrier density $N_S$. $\theta$ values at the node positions (denoted as $\theta^*$ in the text) are also given. We plot $-\Delta \sigma(B = 0)$ instead of $\Delta \sigma(B = 0)$ to match the signs of the values with those for $A(\theta)$ given in Eq. 4.

Plotted in Fig. 3 are the amplitudes of the experimental AAS oscillation at $B = 0$ [denoted as $\Delta \sigma_{2D}(B = 0)$] as a function of $N_S$ for the SI devices fabricated using the sample 1–4 epi-wafers ($L = 1.7$ and $1.5 \mu m$ for samples 1 and 2, respectively, and $L = 1.8 \mu m$ for samples 3 and 4), where we employed the Fast Fourier Transform (FFT) and inverse FFT techniques to extract only the oscillatory part of $\sigma$ whose period corresponds to the magnetic flux half quanta $\hbar/2e$. We indeed see that $-\Delta \sigma(B = 0)$ oscillates with $N_S$, where we observe several nodes. Using the $\alpha$ vs. $N_S$ relations that are obtained from the WAL analysis of an unpatterned QW sample and the $k \cdot p$ model calculation using appropriate boundary conditions [10], $\theta$ values for sample 2 at these node positions (denoted as $\theta^*$ below), for example, are identified as (from left to right) $1.178\pi$, $0.822\pi$ and $0.4245\pi$ (see Fig. 2 in Ref. 11). We thus demonstrated that the spin precession angle $\theta$ is gate-controllable by more than $0.75\pi$ for a length of $1.5\mu m$. The $\theta^*$ values for the other SI devices using the other epi-wafers are also identified in Fig. 3. We can, then, calculate the $\alpha$ values at these node positions using the relation $\alpha = \theta^* \hbar^2/2m^*L$.

In Fig. 3 we plot the $\alpha$ values obtained in this way (denoted as $\alpha_{SI}$) for various SL array samples made of the sample1-4 epi-wafers as a function of $N_S$. Also plotted in Fig. 4 are (1) the $\alpha$ values obtained from the WAL analysis of the unpatterned (bare) Hall bars (denoted as $\alpha_{WAL}$) and (2) those obtained from the $k \cdot p$ model calculations (denoted as $\alpha_{k \cdot p}$) using the appropriate boundary conditions and assuming the presence of the background impurities [10]. We note that the unpatterned Hall bars for $\alpha_{WAL}$ are prepared on the same wafer pieces as those used for the SL array samples. We also note that in Ref. 11 we obtained $\alpha_{k \cdot p}$ values without assuming the background impurities and found quantitatively good agreement with $\alpha_{WAL}$ values. In the present work, we included the effect of the background impurities (mostly they are present in the In$_{0.52}$Al$_{0.48}$As buffer layer) in the model calculation of $\alpha_{k \cdot p}$ to better fit the experimental $\alpha_{WAL}$ and $\alpha_{SI}$ values. It turned out that the values of the background impurity densities obtained from these fittings are reasonably small (typically $1 \times 10^{16}$ cm$^{-3}$). The details of this analysis are discussed elsewhere [13].

In summary, we have demonstrated experimentally the electron spin interference phenomena based on the Rashba effect, which are predicted previously [11]. For this demonstration, we prepared nanolithographically defined square loop array structures in In$_{0.52}$Al$_{0.48}$As/In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As.
quantum wells using the electron beam lithography and ECR dry etching techniques and measured the low-field magnetoresistances of these samples (B \perp sample surface) at low temperatures (0.3 K). We observed the Al'tshuler-Aronov-Spivak (AAS) oscillations, whose magnitudes at B = 0 oscillated as a function of the gate voltage as the result of the spin interference. We also deduced the \( \alpha \) values (Rashba spin-orbit coupling constant) from the analysis of the spin interferometry experiments. We obtained quantitative agreements among (1) the \( \alpha \) values obtained from the spin interferometry experiments, (2) those obtained from the weak antilocalization analysis, and (3) those obtained from the \( k \cdot p \) model calculations.

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