Realization of Ballistic Spin Interferometer using a Square Loop Array

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We report an experimental realization of a spin interferometer using a nanolithographically defined square loop array on an epitaxially grown $In_{0.53}Ga_{0.47}As$ quantum well (QW). This sample has a gate electrode covering the entire Hall bar (Fig. 1), which makes it possible for us to control the carrier density N_S and the Rashba spin-orbit parameter α by the applied gate voltage. The electric conductivity σ across this sample was measured as a function of the magnetic field B at T = 0.3 K, where B was applied perpendicularly to the sample surface. We investigated the AAS (Al'tshuler, Aronov and Spivak) type oscillation of σ, i.e. the self-interference effect of the electronic partial wave functions that were related by the time reversal operation.[1]

A simple model for our spin interferometer is described in Fig. 2. An incident electron wave is split by the beam splitter into two partial waves. These partial waves follow the square path in the clockwise (CW) and counter-clockwise (CCW) directions, respectively. Then, they interfere with each other again when they come back to the incident point (at the beam splitter). As a consequence, the incident electron will either pass back (backscattered) to the incident path (path1) or emerge on the other path (path2). The backscattering probability to path1 P_{back} is given by,[2]

$$P_{\mathrm{back}} = \frac{1}{2} + \frac{1}{4}\left(\cos^4\theta + 4\cos\theta\sin^2\theta + \cos 2\theta\right)\cos\phi \equiv \frac{1}{2} + A(\theta)\cos\phi, \qquad (1)$$

where ϕ is the quantum mechanical phase due to the vector potential responsible for the magnetic field B inside the square loops and θ is the spin precession angle when the electron propagates through each side of the square loop (θ=$2\alpha m^* L/\hbar^2$, where L is the length of the side) due to the Rashba effect (Fig. 3). Equation (1) predicts that the amplitude of AAS oscillation oscillates with the gate voltage V_g.

Plotted in Fig. 4 is the amplitude of the experimental AAS oscillation (denoted as AMP) as a function of the gate voltage for the L=1.5 μm sample. We indeed see that AMP oscillates with the gate voltage V_g, where we can observe several nodes. Using the α values obtained from the weak antilocalization (WAL) analysis for an unpatterned QW sample,[3] θ values at these node positions are identified as (from left to right) 1.178π, 0.822π and 0.424π (see Figs. 3 and 4). We can then reversely estimate the α values at these nodes using these θ values and the relation θ=$2\alpha m^* L/\hbar^2$. In Fig. 5, we plot the α values obtained in this way for L=1.4, 1.5 and 1.8 μm samples as a function of N_S together with the α values for an unpatterned QW sample. We find a good agreement between the experimental α values obtained from both the WAL and spin interferometer analyses, and the theoretical α values obtained from the **k·p** calculation.

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References:

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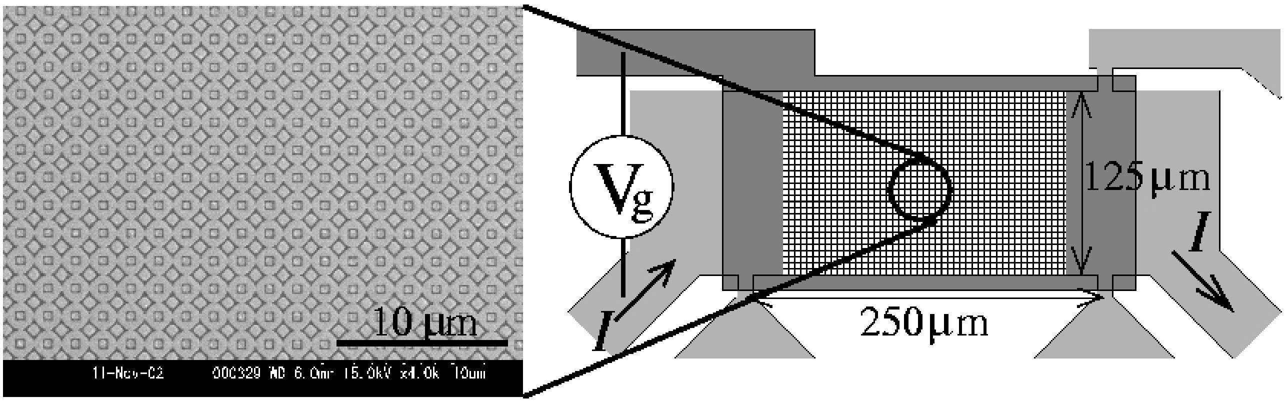

Figure 1: (Left) SEM micrograph of the nanolithographycally defined square loop array. A two-dimensional electron gas exists in the light region. (Right) schematic diagram for the Hall bar sample used in the present experiment.

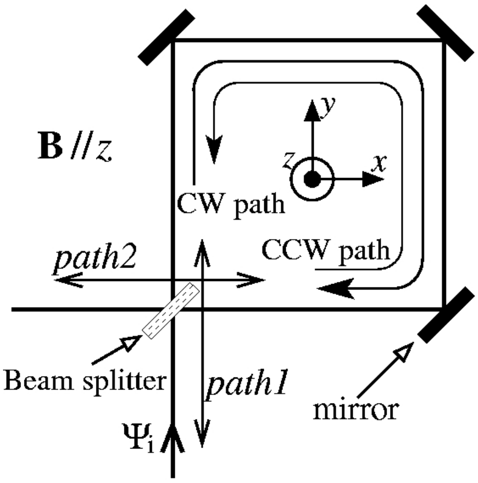

Figure 2: A simple model for the proposed spin interferometer. Ψ_i denotes the incident electron wave function.

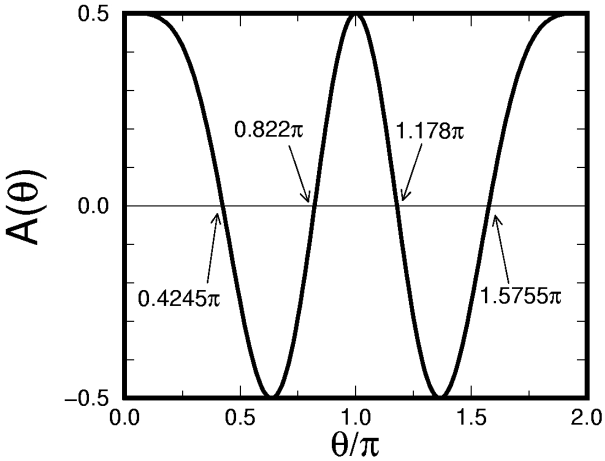

Figure 3: Calculated amplitude of the AAS oscillation as a function of the spin precession angle θ for the proposed spin interferometer.

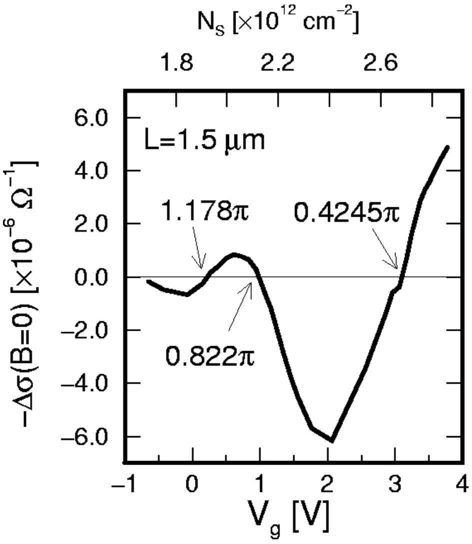

Figure 4: Amplitude of the experimental AAS oscillation measured for the L=1.5 µm loop array sample plotted as a function of the gate voltage V_g and the carrier density N_S. θ values for the nodes are also given.

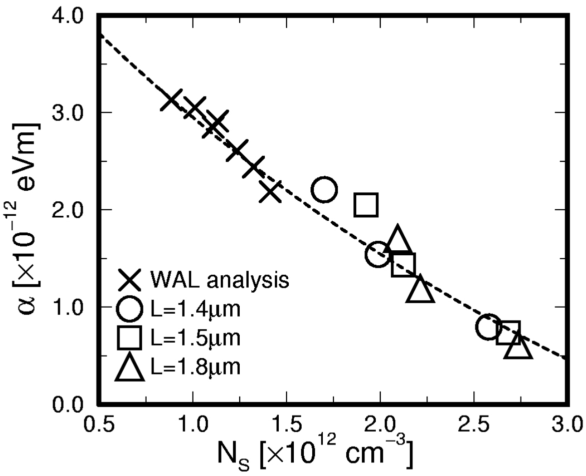

Figure 5: Rashba spin-orbit parameter α deduced from the weak antilocalization and present analyses (various symbols) together with the theoretical result using the background impurity density N_i=4×$10^{16}$$cm^{-3}$ (dashed curve).