Quantum Interference Effects in the Magnetopiezoresistance of InAs/AlGaSb Quasi-One-Dimensional Electron Systems

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We measured the low temperature magnetopiezoresistance of a quasi-one-dimensional electron system by fabricating an InAs/AlGaSb micromechanical cantilever. The magnetopiezoresistance curve showed aperiodic but reproducible oscillation, which was similar to the differential magnetoresistance curve obtained for the same device. A detailed comparison with model calculations strongly suggests that the quantum interference effects that cause the conductance fluctuations in the magnetoresistance are responsible for the peculiar behavior of the magnetopiezoresistance.

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The coupling of electronic and mechanical properties in micro- or nanomechanical beams and cantilevers has received increasing attention, not only for practical device applications [1] but also in terms of fundamental science, such as quantum Hall magnetometry [2,3], single spin sensing [4], and the detection of the quantized mechanical motion of nanoscale cantilevers [5]. Piezoresistive properties constitute one of the most significant examples of the coupling of two properties. They are particularly important regarding highly accurate displacement sensing under low temperature and high magnetic field conditions [6] and also for reducing the structure size to nanometer scale [7].

Piezoresistance (PR) is the change in resistance caused by induced strain and has larger values in semiconductors than in other materials [8]. This is because the strain modulates the energy band structure of semiconductors via the deformation potential and/or the piezoelectric field, leading to a large change in their carrier concentration and mobility [8]. PR has long been employed in practical detection systems [6,9], but until now their operation has been based on the PR as bulk properties.

The electron transport in low-dimensional semiconductor systems has been extensively studied over many years. One of the most significant features of these systems is the nonlinear response of device conductance as a function of externally applied parameters, such as gate voltage and/or magnetic field. The conductance generally exhibits a complicated dependence on the parameters due to quantum mechanical interference and/or resonance. This nonlinear response is also expected to have a significant effect on the PR of low-dimensional systems. The induced strain modifies the band structures, leading to a change in the quantized energy levels or the interference pattern. If the external parameters are chosen in such a way that the system conditions are changed abruptly from off resonant to on resonant, or positively interfered to negatively interfered, the conductance is also expected to be highly sensitive with respect to applied stress, where a large PR is obtained.

Recently, the use of freestanding beams and cantilevers that contain quantum low-dimensional systems have been theoretically and experimentally studied [3,10–14]. It has been confirmed that PR is enhanced by utilizing the nonlinear response of conductivity to the gate voltage [12,13], but there has been no clear evidence of quantum mechanical interference effects. In this Letter, we report on the PR of a diffusive InAs/$Al_{0.5}Ga_{0.5}Sb$ quasi-one-dimensional (Q1D) system as a function of magnetic field. We confirmed that the quantum interference caused the PR to oscillate aperiodically and that an adjustment of the magnetic field significantly enhanced the PR. This is the first report to demonstrate the large influence of quantum interference on the PR of low-dimensional electron systems.

The procedure we used for fabricating the devices has already been reported in detail [7]. The used InAs(15 nm thick)/$Al_{0.5}Ga_{0.5}Sb$(285 nm thick) heterostructure has the nearly temperature independent electron sheet concentration and mobility of 2.4×10^{12} cm^{-2} and 5000 cm^2/Vs, respectively. The bilayer film was then processed into a freestanding suspended structure by using a microfabrication technique [7]. A square cantilever pad 10 μm long and 14 μm wide is suspended by two 10 μm long and 4 μm wide supports, which lead a current from one AuGeNi Ohmic contact to the other through the cantilever pad [Fig. 1(a)]. Because the estimated electron elastic mean free path (l_e) of the 2D InAs channel is 0.13 μm, the processed structures are expected to behave as diffusive systems. In particular, the 4 μm wide supports, where strain concentrates when deflecting the cantilever, exhibit diffusive Q1D transport characteristics as shown later. The sample was mounted on a piezoelectric actuator and mechanically driven by applying alternating voltage in vacuum. The resonance frequency and the quality factor were $f_1 = 283.16$ kHz and $Q = 12\,000$, respectively, at 2.5 K. The drive frequency was then fixed at f_1, and the PR was measured as a function of a perpendicular magnetic field. We used a heterodyne detection technique to avoid the large capacitance cross talk. The device is biased by an alternate current with the frequency of $f_2 = 270.46$ kHz, which is slightly different from f_1, and the PR was detected by a lock-in amplifier at the difference frequency ($f_1 - f_2 = 12.7$ kHz).

Figure 1(b) shows the PR as a function of magnetic field, i.e., the magnetopiezoresistance (MPR) $R_{\rm piezo}$, which exhibited aperiodic oscillation as a function of magnetic field. The oscillation was not observed under off-resonance conditions, i.e., when the actuation frequency was slightly shifted to 283.36 kHz. This result confirms that the signal was measured at the piezomodulation frequency and that the mechanical vibration of the cantilever caused the oscillating signal. In addition, we could not observe the shift in the resonance frequency and confirm that the magnetization of 2D electron systems is not responsible for the magnetic field dependence [2,3].

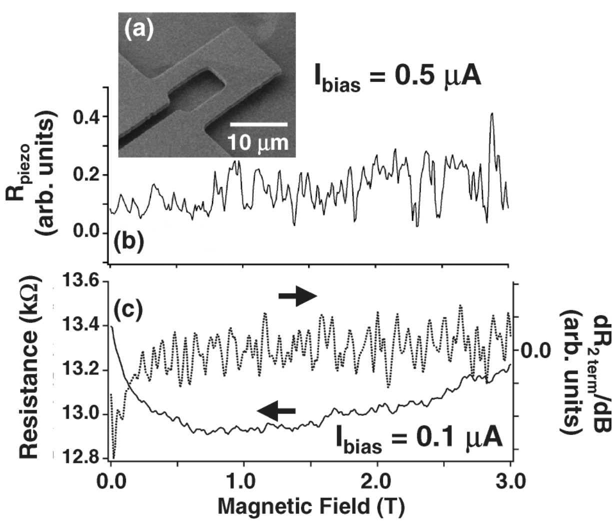

FIG. 1. (a) Fabricated InAs/AlGaSb piezoresistive cantilever. (b) Piezoresistance as a function of magnetic field measured at 2.5 K. Because the actuation amplitude was not directly measured at low temperature, the arbitrary unit was used for the vertical axis. (c) The two-terminal magnetoresistance of the same sample obtained after measuring (b). The dotted line ($dR_{2\,\rm term}/dB$) is the derivative with respect to the magnetic field.

This aperiodic oscillation was reproducibly obtained with repeated measurements but showed a different oscillation pattern when the sample was heated to 150 K and then cooled again to 2.5 K. This behavior of "magnetofingerprints" is similar to that observed in the magnetoresistance (MR) of Q1D systems, known as a universal conductance fluctuation [15–18], which is caused by the quantum interference.

We also measured the two-terminal MR of the same device. Figure 1(c) shows the MR ($R_{2\,\rm term}$) and the derivative with respect to the magnetic field ($dR_{2\,\rm term}/dB$). As the field increased, the MR first decreased for a low magnetic field ($B < 0.7$ T), but increased again at a higher field, while exhibiting slight aperiodic oscillation. These features can be interpreted as weak localization effects and conductance fluctuation, both of which are commonly observed in diffusive Q1D systems. As in the case of MPR, this aperiodic oscillation in the MR was reproducibly obtained with repeated measurements but showed a different oscillation pattern when the sample was once heated and then cooled again. The fluctuation amplitude $\Delta R \sim 50\ \Omega$ is much smaller than the universal value ($h/e^2 \sim 25.8$ kΩ) because the channel length $L \sim 20\ \mu$m and the width $W \sim 4\ \mu$m are much larger than the order of phase coherence length l_ϕ (for example $l_\phi \sim 0.5\ \mu$m in [18]). The roughly estimated suppression factor $l_\phi^2/L^{3/2}W^{1/2} \sim 10^{-3}$ is consistent with the resistance ratio: $\Delta R/(h/e^2) \sim 2 \times 10^{-3}$. The Fourier spectra of the MPR and $dR_{2\,\rm term}/dB$ curves are shown in Fig. 2. From the width of the Fourier spectra ($\Delta B^{-1} \sim 20$ T^{-1}), the magnetic scattering length l_c can be roughly estimated to be $\sqrt{\hbar \Delta B^{-1}/e} \sim 0.1\ \mu$m, which has the similar order with l_ϕ. These estimations indicate that the aperiodic oscillation can be caused by conductance fluctuation [16].

Conductance fluctuation is induced by quantum interference among many different conduction paths formed in the Q1D channels. First, we discuss the origin of MPR when only two conduction paths, A and B, form a closed interference loop in the cantilever support. This corresponds to an Aharonov-Bohm (AB) ring. The simplest approximation gives the electron phase difference $\Delta\phi$ between the two paths as

$$\Delta\phi \cong eSB/\hbar + \Delta l k_F - \phi_0, \tag{1}$$

where S is the area of the ring formed by paths A and B, Δl is the length difference between the two paths, and k_F is the Fermi wave number. The second term has gradual magnetic field dependence and is usually renormalized in the constant phase factor, ϕ_0, but explicitly written here because Δl and k_F can be modulated by the cantilever deflection. The resistance change ΔR induced by the interference is given by $\Delta R \sim \cos(\Delta\phi)$, which oscillates as a function of B with a periodicity of $2\pi\hbar/eS$, showing AB oscillation. When we deflect the cantilever, three parameters, S, Δl, and k_F, can be modified by the induced strain. The PR, $\delta\Delta R$, is then given by

$$\delta\Delta R \sim -\sin(eSB/\hbar + \Delta l k_F - \phi_0) \times (eB/\hbar \delta S + \Delta l \delta k_F + k_F \delta\Delta l). \quad (2)$$

Therefore, the PR also has the same periodicity of $2\pi\hbar/eS$ as a function of the magnetic field but with a 90°-shifted phase from the MR. In other words, R_{piezo} has a similar B dependence to $dR_{2\,\text{term}}/dB$.

When there are many interference loops, corresponding to conductance fluctuation in diffusive systems, the MPR curve becomes more complicated. What we were observing in the MPR is the incoherent superposition of periodic oscillations among different coherent segments because $L, W \gg l_\phi$. This situation makes the comparison of MPR with the $dR_{2\,\text{term}}/dB$ curve more complicated because the applied strain is different for different coherent segments in the 10 μm $\times$ 4 μm support parts. To undertake the comparison in a more quantitative way, we theoretically simulated R_{piezo} and $dR_{2\,\text{term}}/dB$ curves by using a tight-binding model [19].

To obtain a very simple and reasonable approximation, we assume that only the Fermi level is modulated by the induced strain. We calculated the two-terminal resistance of coherent 160×80 square lattices with randomly fluctuating lattice site energy. The lattice size was chosen so that it was large enough to satisfy the diffusive condition; i.e., the average conductivity is independent of the lattice size. The nearest neighbor hopping energy and the fluctuation in the site energy were then chosen in such a way that the effective electron mass and the total average two-terminal resistance, respectively, could be well reproduced. R_{piezo} was obtained by calculating the change in $R_{2\,\text{term}}$ induced by a small variation in the electron Fermi energy, and both were calculated for two 40 independent sets of random numbers, which we used to simulate the scattering potential fluctuation in different coherent segments. The calculated PR values of each segment were added together to calculate the total PR of the whole incoherent region after they had been multiplied by a weight factor corresponding to the nonuniform strain distribution along the deflected supports. We assumed that the induced strain is approximately uniform over a single coherent region, where the strain variation is estimated to be less than 10% and the inhomogeneous strain contribution can be neglected. The total MR was therefore obtained by simply adding together the calculated MR values of each coherent segment. We disregarded the contribution from the 10×14 μm cantilever pad and the contact resistance for simplicity. A sufficiently small modulation in the Fermi energy ($\delta E_F \sim 0.013$ meV) was chosen in order to maintain the linear response of the resistance change to the induced strain. Figure 3 shows the calculated R_{piezo} and $dR_{2\,\text{term}}/dB$. We can confirm that there is qualitatively good agreement with the experimental curve. The two curves are similar but not identical, and the detailed peak structures are different. This is not only because the whole support area is incoherent, but also we have a strain distribution along the supports. Even the feature that the R_{piezo} includes more low frequency components than $dR_{2\,\text{term}}/dB$ looks well reproduced in the calculation. This agreement strongly supports our assumption that the aperiodic oscillation in the MPR is caused by quantum interference, which induced the conductance fluctuation in the MR.

Sample misalignment with respect to the direction of the magnetic field can cause a change in the perpendicular magnetic field component by the cantilever deflection, inducing an *apparent* PR, which is also proportional to $dR_{2\,\text{term}}/dB$. The average amplitude is expected to be proportional to B, and the detailed peak structures, as well as the feature of weak localization in a low magnetic

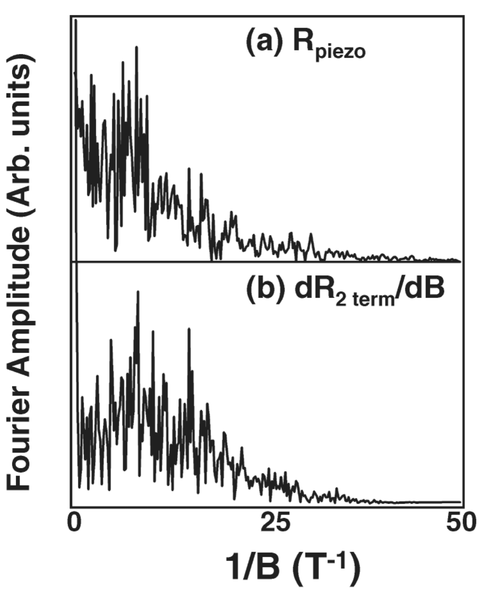

FIG. 2. Fourier transforms obtained for (a) the magnetopiezoresistance [Fig. 1(b)] and (b) the differential magnetoresistance [Fig. 1(c)].

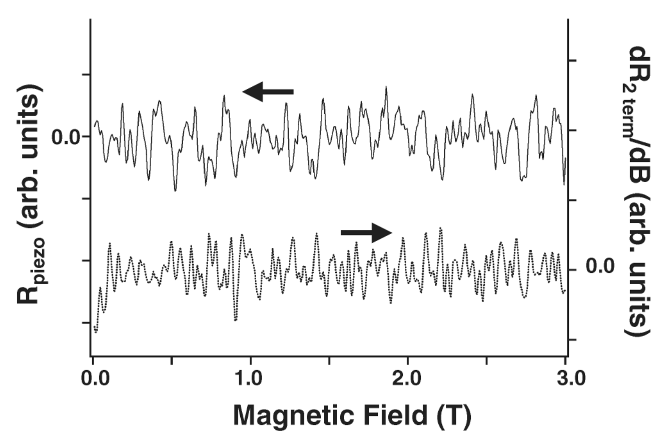

FIG. 3. Calculated magnetopiezoresistance and differential magnetoresistance.

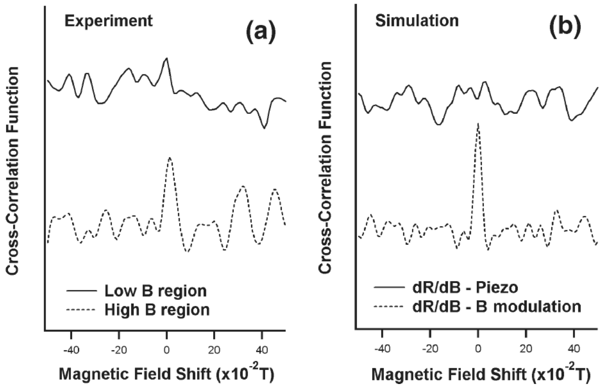

FIG. 4. Cross-correlation functions evaluated for the correlation between (a) experimentally obtained $dR_{2\,\mathrm{term}}/dB$ and R_{piezo} curves for low (0–2 T) and high (5–7 T) magnetic field regions, and (b) numerically obtained $dR_{2\,\mathrm{term}}/dB$ and strain-induced R_{piezo}, and also $dR_{2\,\mathrm{term}}/dB$ and apparent R_{piezo}.

field region, are expected to appear similar for the two curves. This was not the case with the measured curves, so we can rule out the influence in our data in the relatively low magnetic field region. The amplitude of the observed aperiodic oscillation was, however, increased with further increases in the magnetic field, and misalignment is a possible origin of the PR in such a high magnetic field region. This apparent PR was introduced by the position-dependent magnetic field modulation, leading to more similar peak structures than the strain-induced "real" PR. For more quantitative comparison, we calculated a normalized cross-correlation function, $\int dB\Delta R'_{2\,\mathrm{term}}(B)\Delta R_{\mathrm{piezo}}(B+B_{\mathrm{shift}})/\langle\Delta R'_{2\,\mathrm{term}}\rangle_{\mathrm{rms}}\langle\Delta R_{\mathrm{piezo}}\rangle_{\mathrm{rms}}$, where $\Delta R'_{2\,\mathrm{term}}(B) = dR_{2\,\mathrm{term}}(B)/dB - \langle dR_{2\,\mathrm{term}}/dB\rangle$ and $\Delta R_{\mathrm{piezo}}(B) = R_{\mathrm{piezo}}(B) - \langle R_{\mathrm{piezo}}\rangle$ [Fig. 4(a)]. The peak height at zero-magnetic-field shift shows the similarity in the peak positions between two curves. Although the two curves showed similar Fourier spectra in both magnetic field regions, the cross correlation is much larger in high field region than in the low region. This can be compared with the cross-correlation function calculated from our tight-binding simulations [Fig. 4(b)]. No significant peak can be confirmed at zero-magnetic-field shift in the cross-correlation function of calculated $dR_{2\,\mathrm{term}}/dB$ and R_{piezo}, but that of $dR_{2\,\mathrm{term}}/dB$ and calculated apparent PR shows a clear peak even when we took into account the position-dependent B modulation. This comparison also suggests that the low-field PR is caused by the strain in the support but that the high-field PR can be apparent and caused by the sample misalignment.

In conclusion, we have studied the MPR of a micromechanical InAs/AlGaSb conductive cantilever at liquid helium temperatures. We confirmed that there was a strong aperiodic oscillation in the MPR. A comparison with a tight-binding model calculation strongly suggests that the large change in the PR is induced by the quantum interference in the Q1D channels in the cantilever supports.

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