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Micromechanical Quantum Electron Transport

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Abstract. We have studied quantum effects on the piezoresistance (PR) of various kinds of low-dimensional heterostructures. The PR is strongly enhanced by electron interference in Q1D electron systems, by Landau quantization in 2DEG systems, and also by the localized-delocalized electronic state transition in quantum Hall systems. We have also studied PR for superconductor/semiconductor junctions and found that PR was enhanced at the critical current. In each system, the nonlinear response of device conductance against the change of magnetic field or bias current is responsible for the resistance change against the strain.

1. Introduction

The coupling of electronic and mechanical properties on micro/nanomechanical beams and cantilevers has received increasing attention, not only for practical device applications but also in terms of fundamental physics, such as quantum Hall magnetometry [[1],[2]], single spin sensing [[3]], and the detection of the quantized mechanical motion of nanoscale cantilevers [[4],[5]]. Piezoresistive properties are some of the most significant examples of the coupling of two properties. They are particularly important in highly accurate displacement sensing at low temperatures and for reducing structure size to the nanometer scale [[6],[7]].

Piezoresistance (PR) is the change in resistance caused by induced strain and has larger values in semiconductors than in metals [[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. PR has long been employed in practical sensors, and it is extremely important in recent micro/nanoelectromechanical systems (MEMS/NEMS), where the mechanical signal is transduced into an electrical signal using PR. Until now the operation has been based on PR as a bulk property, and the transducer efficiency has been simply determined by the geometrical shape of the mechanical structure and the piezoelectric coefficient of the material used.

We have studied quantum effects on the PR of various kinds of low-dimensional heterostructures. In each system, the nonlinear response of device conductance against the change of magnetic field or bias current is responsible for the resistance change against the strain. We have confirmed significant change in the piezoresistance by electron interference in quasi-one-dimensional (Q1D) electron systems [[9]], by Landau quantization in two-dimensional (2D) electron systems [[10]], and also by
the localized-delocalized electronic state transition in quantum Hall systems [[11]]. We have also confirmed that the strain-induced resistance change for superconductor/semiconductor junctions is enhanced at the critical current [[12]]. In this paper, we review these quantum effects on the PR in semiconductor-based low-dimensional structures.

2. Q1D electron systems

A piezoresistive cantilever was fabricated from an InAs/Al$_{0.5}$Ga$_{0.5}$Sb single heterostructure grown on a GaAs (111)A substrate, which has a temperature-independent electron mobility of 5,000 cm$^2$/Vs with a carrier concentration of 2.4x10$^{12}$ cm$^{-2}$. A square cantilever pad 10-μm long and 14-μm wide is suspended by two 10-μm long and 4-μm wide supports. The resistance was measured by flowing a current between two AuNiGe Ohmic contacts, each of which connects to the support, through the pad [Fig. 1(a)]. Because the estimated electron elastic mean free path of the 2D InAs channel is 0.13 μm, the processed structure is expected to behave as a diffusive system. In particular, the two 4-μm-wide supports, where strain concentrates when deflecting the cantilever, exhibit diffusive Q1D transport characteristics.

Figure 1. (a) Scanning electron microscope (SEM) image of a fabricated InAs/AlGaSb piezoresistive cantilever. The bar shows the length scale of 10 μm. (b) Piezoresistance as a function of magnetic field measured at 2.5 K. (c) The two-terminal magnetoresistence of the same sample obtained after measuring (b) and the derivative with respect to the magnetic field.

The cantilever thickness of 300 nm gives the resonance frequency of 283.16 kHz with a quality factor of 12,000 at 2.5 K in vacuum. The cantilever was actuated at its resonance frequency by a piezoelectric ceramic, on which the sample was mounted. The strain-induced resistance change, i.e., the PR, was measured using a heterodyne technique to avoid the large capacitance crosstalk. Figure 1(b) shows the measured PR as a function of applied magnetic field. The PR exhibited aperiodic oscillation. This aperiodic oscillation was reproducibly obtained in repeated measurements, but showed a different oscillation pattern when the sample was heated to 150 K and then cooled again to 2.5 K [[9]]. This “magnetofingerprint” behavior is similar to that observed in the magnetoresistance (MR) of Q1D systems and known as a universal conductance fluctuation. In fact, the MR of the same sample shows a similar, but not identical, aperiodic oscillation pattern as shown in Fig. 1(c).
Two major mechanisms cause the influence of conductance fluctuation on the PR. One is the modulation of the Fermi energy by the induced strain. The induced PR is, therefore, not caused by the phase modulation in the local interference loops but by the wavelength modulation in them, although both cause aperiodic conductance oscillation as a function of magnetic field. The other is a rather “apparent” effect caused by the small cantilever tilt. When the cantilever normal is slightly tilted from the direction of the magnetic field even by a very small angle (say 2 or 3 degrees), its mechanical vibration modulates the perpendicular component of the magnetic field. As a result, the phase of electron interference is modulated, leading to a change in device conductance. In contrast to the former mechanism, where the oscillation amplitude has small magnetic field dependence, the latter causes a linear magnetic field dependence of the oscillation amplitude. A detailed analysis of our data has revealed that the strain-induced Fermi energy modulation is dominant in the low-magnetic-field region (0-2T) and that the “apparent” piezoresistance is dominant in the high-magnetic-field region (2-7T) \([9]\).

3. 2D electron systems

We also measured the PR of 2D electron systems. The induced strain modulates the relative position of the Fermi level to the DOS profile, causing strong Landau quantization effects on the PR. Piezoresistive cantilevers were fabricated from two different heterostructures. One is an InAs/Al0.5Ga0.5Sb quantum well (QW) on a GaAs (111)A substrate \([10]\), and the other is a GaAs/AlGaAs modulation-doped heterostructure \([11]\). They have mobilities of \(6.3 \times 10^4\) and \(2.7 \times 10^6\) cm\(^2\)/V\(s\) with carrier concentration of \(1.2 \times 10^{12}\) and \(4.7 \times 10^{11}\) cm\(^{-2}\), respectively, at liquid-helium temperature.

![Figure 2](image_url)

**Figure 2.** (a) Piezoresistance of the InAs/AlGaSb QW sample as a function of magnetic field measured at 2.5 K. (b) The two-terminal magnetoresistance and its derivative with respect to the magnetic field of the same sample.

The cantilever fabricated from the InAs QW has the same dimensions as that in Fig 1(a) except for the thickness of 700 nm. Figure 2 shows the magneto-piezoresistance and magnetoresistance obtained for the InAs QW sample. The magneto-piezoresistance curve shows the feature of Schubnikov de-Haas (SdH) oscillations as well as the conductance fluctuation \([10]\). This SdH feature is also a result of the Fermi energy modulation and the perpendicular magnetic field modulation due to the sample tilt. The maximum piezoresistance was obtained at 7.695 T [indicated by a solid arrow in Fig. 2(a)] and, with the bias current of 40 \(\mu\)A, we obtained an enhanced displacement sensitivity of about \(10^{-11}\) nm/Hz\(^{0.5}\), which corresponds to the force sensitivity of \(10^{-12}\) N/Hz\(^{0.5}\).
The GaAs/AlGaAs sample was processed into a 1.3-µm-thick micromechanical cantilever, which is 200-µm long and 60-µm wide, and a 2DEG mesa with Hall-bar geometry for the measurement of strain-induced resistance change, i.e. the PR, was integrated near the support [Fig.3 (a)]. This device design enables us to measure the piezoresistive gauge factor quantitatively.

The measured four-terminal PR as a function of the magnetic field is shown in Fig. 3(c). In Fig. 3(b), the longitudinal magnetoresistance is shown for comparison. The magnetic field dependence shows the feature of SdH oscillation in the low magnetic field region (B<2T), as has already been confirmed for InAs QW sample. A much more pronounced feature in the PR is observed at the transition between the localized and extended electronic states induced by the quantum Hall effect.

Figure 3. (a) Fabricated micromechanical cantilever integrating 2DEG Hall bar. (b) Four-terminal magnetoresistance curve at 2.5 K. The bias current was 0.1 µA. (c) Four-terminal magneto-piezoresistance at 2.5 K. The bias current was 1.0 µA.

The strongly enhanced PR at the transition point could be caused by the strain-induced transition between localized and extended electronic states. The strain modifies the position of the Fermi level relative to the formed Landau levels through the deformation potential and piezoelectric field. This shift of the relative Fermi level position induces the transition between localized and extended states, which is expected to be abrupt as a function of the Fermi energy. Using the estimation of cantilever apex displacement proposed in [[10]], we obtain the resistance change per unit apex displacement at the higher magnetic field side of the v=4 quantum Hall state of 0.1 Ω/nm, which corresponds to a piezoresistive gauge factor as high as 25,000. This value is more than two orders of magnitude higher than that of commercially used p-type bulk Si.

4. Superconductor-semiconductor hybrid systems

Finally, we discuss the piezoresistive properties of a Nb/InAs superconductor-semiconductor hybrid system [[12]]. The cantilever was processed also from an InAs/Al0.5Ga0.5Sb single heterostructure grown on a GaAs (111)A substrate with the thicknesses of InAs and Al0.5Ga0.5Sb films of 15 and 700 nm, respectively. Figure 4(a) shows a SEM image of the fabricated cantilever. The length and width of the cantilever are 200 and 60 µm, respectively. The existence of an InAs channel
between the two 0.3-μm-separated Nb-electrodes is confirmed by a magnified SEM image of the Nb-InAs-Nb junction [Fig. 4(b)]. A cross-sectional view of the junction is also illustrated in Fig. 4(c).

Figure 4. (a) SEM image of the piezoresistive cantilever that integrates a Nb-InAs-Nb junction. (b) Magnified SEM image of the integrated junction. (c) Schematic illustration of the cross section.

Figure 5. (a) The measured voltage – current characteristics at 30 mK. (b) The measured piezoresistance as a function of bias current at 30 mK.

We measured the voltage – current characteristics of the Nb/InAs/Nb junction at 30 mK [Fig. 5(a)]. The result shows that a supercurrent flows through the junction with the maximum Josephson current of $I_c \sim 327 \, \mu$A as has already reported in previous studies [[13],[14]]. In Fig. 5(b), we plot the measured PR as a function of the bias current. We can confirm that the PR has a strong dependence on the bias current around $I_c$. When $I_{bias} < 326 \, \mu$A, we cannot find any resistance change, i.e., the resulting frequency response is constant, because the junction is in the super conducting state. The resistance change for resistive state ($I_{bias} > 328.0 \, \mu$A) is almost constant to 0.3 mΩ. At the transition state ($I_{bias} \sim 327.2 \, \mu$A), the PR is strongly enhanced by more than one order of magnitude compared to that in the resistive state.

The mechanism of this strong enhancement is considered to be as follows: The key transport parameter for the diffusive semiconductor channel is the diffusion constant $D$ given by $D = \frac{\pi h^2 N_s \mu}{m e}$, where $N_s$ is the carrier concentration, $\mu$ the mobility, and $m$ the effective mass.
When strain is induced at the InAs channel, \( N_s \) and \( P \) are influenced by the strain and \( D \) is modified. The modified \( D \) changes the superconducting coherence length \( \xi_T \) because \( \xi_T \) is given using \( D \) by \( \xi_T = \sqrt{\hbar D / 2\pi k_B T} \) in the dirty limit [13]. Since the superconducting critical current is influenced by \( \xi_T \) as \( I_c \approx \exp(-L / \xi_T) \) [15], the proximity-induced supercurrent is modulated by the induced strain and enhanced piezoresistance is obtained around \( I_c \), where an excellent nonlinearity appears in the conductance. By utilizing the superconducting proximity effect, we succeeded in increasing the piezoresistance by more than one order of magnitude.

5. Conclusions
In conclusion, we have studied quantum effects on the piezoresistance (PR) of various quantum low-dimensional structures. Utilizing the high nonlinear response of device conductance to the magnetic field or bias current, an enhancement of PR was confirmed for the electron interference in quasi-one-dimensional Q1D electron systems, Landau quantization in 2D electron systems, the localized-delocalized electronic state transition in quantum Hall systems, and superconductor proximity effects in Nb/InAs systems. The quantum effects seen in the PR are promising for sensitive mechanical detection systems.

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