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Displacement Sensing using Quantum Mechanical Interference

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1. Introduction

The detection of mechanical displacement in micromachined beams and/or cantilevers plays an essential role in the recent progress in microelectromechanical systems (MEMS). The use of piezoresistive cantilever is important in the applications that do not allow the optical access, such as low temperature scanning probe microscopy, integrated mechanical circuits, and also nanoelectromechanical systems (NEMS). Piezoresistive cantilevers are generally fabricated by placing a thin semiconductor conductive layer in one surface side of a mechanical cantilever. When the apex of the cantilever is displaced, a strain is applied on the conductive layer leading to the modulation in the position of Fermi level relative to the energy band structure through the deformation potential and piezoelectric effects. This modulation induces a conductance change and the displacement can be electrically detected by measuring the change in device resistance. Highly sensitive piezoresistive cantilevers have been fabricated and are already commercially available [1].

We here propose to use quantum mechanical low dimensional systems in order to further improve displacement sensitivity. In these systems, large nonlinearity appears in the dependence of conductance (σ) on the Fermi level (E_F) due to quantum mechanical interference and/or resonance effects. The nonlinearity causes non-constant $d\sigma/dE_F$, which is roughly proportional to the piezoresistance, i.e., the resistance change induced by the cantilever deflection, as a function of controllable parameters, such as gate voltage and magnetic fields. If sufficiently large variation is obtained in $d\sigma/dE_F$, a high piezoresistance can be obtained by appropriately choosing these parameters. This approach is different from the previous reports [2-4], in which the use of a semiconductor heterostructure improved the sensitivity but not due to quantum mechanical resonance/interference effects. We confirmed nearly one order of magnitude enhancement of piezoresistivity in micromachined InAs/AlGaSb cantilevers by applying a magnetic field at liquid helium temperature. This enhancement is caused by the quantum interference at the quasi-one-dimensional channel in the cantilever supports and the result demonstrates the displacement sensing using quantum mechanical interference for the first time.

2. Results and discussion

InAs/AlGaSb heterostructure displacement sensors made from InAs/AlGaSb/GaAs heterostructures grown on (111)A substrates by molecular beam epitaxy [5] [Fig.1 (a)] were used for the studies. A square cantilever pad with the length and width of 10 μm and 14 μm, respectively, is suspended by two 10 μm-long and 4 μm-wide supports, which lead a current path from one metal contact to the other through the cantilever pad. The sample was mounted on a piezoelectric actuator and mechanically driven by applying alternate voltage on the actuator. The sample was placed in a vacuum chamber and cooled in a standard liquid helium cryostat. The resistance change induced by the mechanical displacement of the dc-biased cantilever was measured as a function of the drive frequency using a network analyzer. Figure 1(b) shows the frequency response at 2.5K clearly indicating the mechanical resonance of the cantilever at f_{res} = 283.16kHz with a quality factor (Q) of about 12,000. This value is much higher than that of the same device at room temperature (~2,200) because of the reduction in internal friction at low temperatures [6].

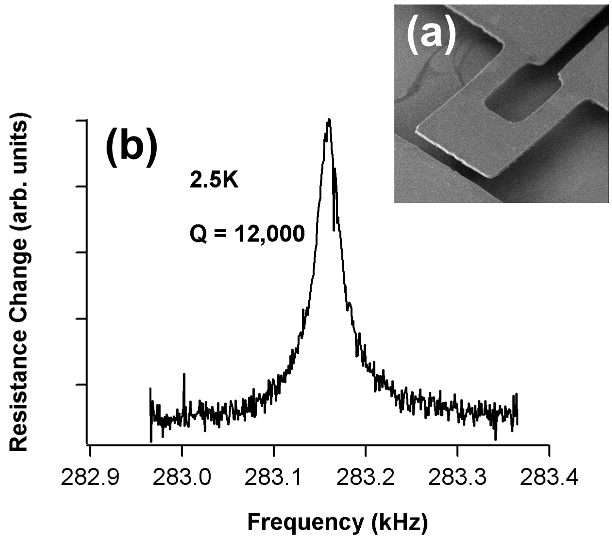

Fig.1 (a) Fabricated InAs/AlGaSb displacement sensor. (b) The change in 2-terminal resistance as a function of drive frequency.

The drive frequency was then fixed at f_{res} and the piezoresistance was measured as a function of magnetic field applied in perpendicular to the sample surface. We used a heterodyne technique in order to avoid the large capacitance cross-talk of drive voltage in the piezoresistance signal. The device is biased by an alternate current with the frequency of f_{bias} = 270.46 kHz, which is slightly different from f_{res}, and the piezoresistance was detected by a lock-in amplifier at the difference frequency (f_{res}-f_{bias} = 12.7 kHz).

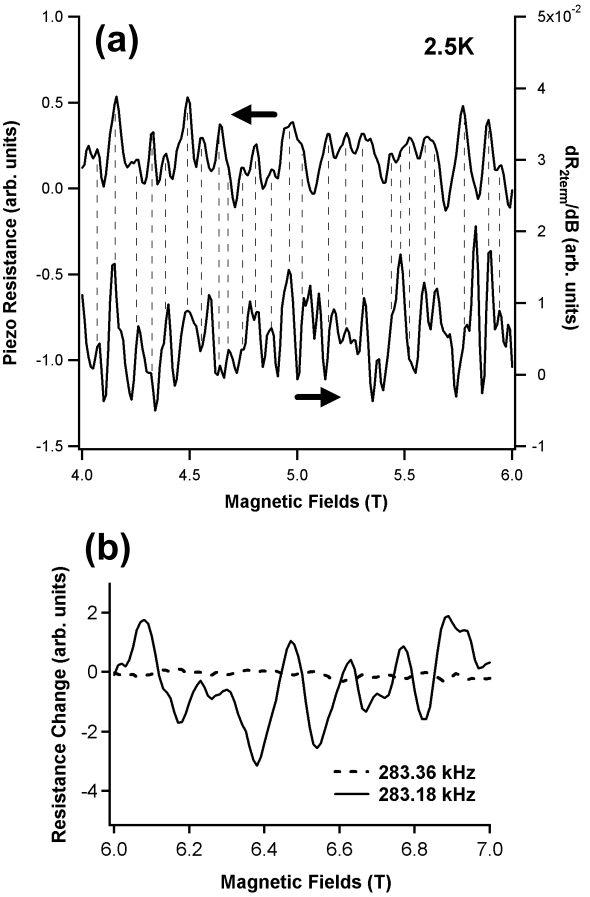

Fig. 2(a) Measured piezoresistance and the derivative of two-terminal resistance (dR_{2term}/dB) as a function of applied magnetic field (B). The dashed lines are guides to the eye to indicate the similarity in the peak positions between two curves. (b) The measured resistivity change under on-resonance (283.18kHz) and off-resonance (283.36kHz) conditions.

Figure 2(a) shows the measured piezoresistance and the derivative of two-terminal resistance (R_{2term}) as a function of applied magnetic field (B). The piezoresistance showed a strong B-dependence, which was reproducible for repeated measurements but unreproduced when the sample temperature was once increased to room temperature. This behavior is similar with that of universal conductance fluctuation (UCF), which is often observed for diffusive quasi-one-dimensional (Q-1D) mesoscopic systems. The fluctuating piezoresistance is, in fact, similar (but not identical) to dR_{2term}/dB curve, where clear UCF is observed probably because the 4-μm-wide supports behave as Q-1D channels. The fluctuating piezoresistance was, however, not confirmed at an off-resonance drive frequency [Fig. 2(b)], confirming that it is not directly caused by the conductance variation but induced by the mechanical motion of the cantilever.

The detailed comparison between these two curves indicates that many peaks are commonly observed in the two curves at same magnetic fields but different relative peak heights [see dashed lines in Fig. 2(a)]. This similarity in two curves can be explained as follow. With the magnetic field at which the dR_{2term}/dB curve has local maximum, the conductance is highly sensitive to the change in the magnetic field due to the quantum interference. Under this conduction, the conductance is expected to be highly sensitive also for the change in E_F so that a large piezoresistance is obtained at the same magnetic field. The relative peak height difference can be caused by the difference in geometrical position of the interference loops, which are formed by the scattering impurities and causing UCF. The strain induced by the cantilever displacement is position dependent and has larger value when it is closer to the cantilever support edge. Therefore, when the position of the interference loops that gives majority contribution to the noticed peak becomes closer to the cantilever edge, the induced strain on the loop region becomes larger so that the piezoresistance is increased. This result suggests that the peak height ratio between these two curves reflects the information on geometrical position of the interference loops and the detailed analysis for the device with more advanced mechanical structures with various vibration modes has the possibility to clarify the geometrical distribution of interference loops.

3. Conclusions

In conclusion, we characterized the piezoresistance of an InAs/AlGaSb heterostructure cantilever as a function of magnetic field at a liquid helium temperature. The piezoresistance showed a similar B-dependence to the UCF, which was observed in two-terminal resistance, indicating that the quantum mechanical interference significantly modulates the piezoresistance. This novel quantum effect is promising for realizing highly sensitive displacement detection and also for studying the detailed mechanism of quantum mechanical interference.

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