Nanomechanical displacement sensing using a quantum point contact

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We describe a radio frequency mechanical resonator that includes a quantum point contact, defined using electrostatic top gates. We can mechanically actuate the resonator using either electrostatic or magnetomotive forces. We demonstrate the use of the quantum point contact as a displacement sensor, operating as a radio frequency mixer at the mechanical resonance frequency of 1.5 MHz. We calculate a displacement sensitivity of about 3×10^{-12} m/Hz$^{1/2}$. This device will potentially permit quantum-limited displacement sensing of nanometer-scale resonators, allowing the quantum entanglement of the electronic and mechanical degrees of freedom of a nanoscale system. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1497436]

The observation of quantized plateaus in the conductance of high-mobility quantum point contacts[1,2] has generated significant interest in both the physics and application of these devices. The highly sensitive dependence of the source-drain conductance of a quantum point contact (QPC) on electrostatic fields provides a straightforward means of detecting very small electronic signals. The QPC has been used, for example, to detect charge motion and controllably introduce quantum decoherence in the electron transport through an electron interferometer.[3,4] A QPC has been demonstrated[5] as a scanned charge-imaging sensor, with a measured charge noise of about 0.01 e/Hz$^{1/2}$ at 1 kHz.

Of further interest is the potentially extremely large bandwidth attainable using a QPC, due to the very small intrinsic capacitance ($\sim$100 aF) and short electron transit times ($\sim$1 ps); the QPC should in principle respond at frequencies up to of order 10 THz.[6] However, the relatively large resistance of the QPC, coupled with unavoidable stray cabling capacitance, typically limits its practical bandwidth to the order of 10^4–10^5 Hz. The QPC has however recently been demonstrated[7] to work well as a radio frequency (rf) mixer, by employing the nonlinearity in the QPC current–voltage characteristic to generate harmonic multiples of the applied rf signals. A local oscillator (LO) at a frequency ω_{LO}, combined with a signal at ω_S, will, through the QPC nonlinearity, generate signals at the sum and difference frequencies $|\omega_{\mathrm{LO}}\pm\omega_S|$. For a sufficiently small intermediate frequency (IF) $\omega_{\mathrm{IF}}=|\omega_{\mathrm{LO}}-\omega_S|$, the difference frequency will lie within the output bandwidth of the QPC, and the signal can thereby be detected. Mixing has been demonstrated[8] at frequencies up to 2.9 GHz, with an optimal conversion loss of -13 dB.

In this work we demonstrate the use of a QPC mixer as a displacement detector, where we take advantage of the piezoelectric effect in GaAs to modulate the current through an integrated QPC. Previously, a micromachined GaAs mechanical resonator that included an integrated field-effect transistor (FET) has been demonstrated,[9,10] with a measured displacement sensitivity of 10^{-9} m/Hz$^{1/2}$. A significant limitation in this device was the low output bandwidth, of order 10^3 Hz.

Our device is shown in Fig. 1. The structure was etched from a single-crystal GaAs heterostructure grown by molecular beam epitaxy, comprising a bulk ⟨100⟩ GaAs wafer, 700 nm of $Al_{0.7}Ga_{0.3}As$ (the sacrificial layer), 600 nm of GaAs, 40 nm of $Al_{0.3}Ga_{0.7}As$, a Si delta-doped layer, 70 nm of $Al_{0.3}Ga_{0.7}As$, and a 10 nm GaAs capping layer. The suspended mechanical structure includes all layers above the sacrificial layer (see below). The two-dimensional electron gas (2DEG) in which the QPC is formed is at the lower GaAs–$Al_{0.3}Ga_{0.7}As$ interface, where similar samples[11] had a carrier density of $\sim1.4\times10^{15}/\mathrm{m}^2$, and a mobility of $\sim40\ \mathrm{m}^2/\mathrm{V\,s}$ at 4.2 K. In our device the 2DEG mobility was significantly degraded by processing.

We used photolithography to define a set of NiAuGe ohmic contacts to the 2DEG. Next electron-beam lithography was used to define Ti/Au (5 nm/40 nm) electrodes for the top gates, as well as for actuation of the mechanical structure. A second photolithography step defined Ti/Au (5 nm/110 nm) wire-bond pads to make contact with the metal electrodes and ohmic contacts. A second electron beam li-

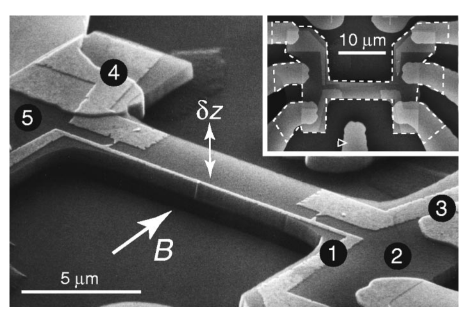

FIG. 1. SEM micrograph of the QPC electrodes defined on the surface of a suspended beam. The magnetic field B used for magnetomotive actuation is indicated, as is the direction of flexure δz. The numbers identify the electrodes: (1) is the drive electrode that also serves as a QPC gate, (2) and (5) define the source and drain ohmic contacts, (3) and (4) the other sides of the two QPC gates. Only one QPC was used at a time. Inset: Larger scale image of the structure, with the dotted line outlining the suspended area.

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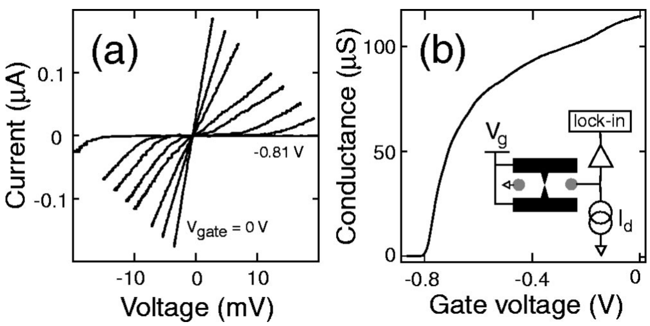

FIG. 2. (a) Current–voltage characteristic for the QPC, measured for different gate voltages $V_g = 0, -0.64, -0.73, -0.76, -0.77, -0.78, -0.79$, and -0.81 V. (b) Conductance at zero bias as a function of gate voltage. Inset: Schematic of measurement setup.

thography step then defined the structural masking layer. The unmasked area of the heterostructure was etched using $SiCl_4$-based reactive ion etching, etching to a depth of about 800 nm, almost through the sacrificial layer. The sacrificial layer was then etched using a timed submersion in concentrated hydrochloric acid, followed by a 10% solution of hydrofluoric acid. This step was timed to suspend the lateral area shown by the dotted outline in Fig. 1, creating a structure with a suspended length of roughly 45 μm and a thickness of 0.72 μm.

The sample was placed in a vacuum can that was submerged in liquid He at 4.2 K. A magnetic field B could be applied in the plane of the sample (see Fig. 1).

We recorded the current–voltage characteristics of the QPC as a function of the voltage applied to the top gate electrodes, numbered 1 and 4 in Fig. 1, as shown in Fig. 2(a). In Fig. 2(b) we show the zero-bias conductance as a function of gate voltage. Quantized steps are not visible in this measurement at 4.2 K. We then characterized the response of the QPC as a rf mixer, by applying a combination of a local oscillator and a signal to the gate electrode 1, and measuring the current through contacts 2 and 5 at the intermediate frequency ω_{IF}. We found that the mixer operates well up to a LO frequency of about 20 MHz, and for intermediate frequencies up to about 2 kHz; these frequencies are limited by the particular measurement configuration rather than by the QPC itself.[12] For a typical configuration with a gate voltage of -0.8 V, dc bias voltage across the QPC of 60 mV, and a LO power of -11 dBm, the IF current i_{IF} through the QPC was linear in the signal voltage v_S, with $i_{IF} \approx 0.9 v_S$ μA/V.

We characterized the mechanical properties of the suspended structure by applying an in-plane magnetic field B, and measuring the resulting electrical impedance of the drive electrode 1. This impedance acquires additional real and imaginary frequency-dependent terms due to the combination of Lorentz-force actuation and the resulting electromotive voltage developed as the structure moves in the magnetic field.[13,14] The fundamental resonance frequency is $\omega_0/2\pi = 1.503$ MHz, with a quality factor $Q \approx 3000$. In Fig. 3(a) we display the response for $B = 5$ T. Shifts in the resonance frequency are apparent, due to the nonlinear response for large motional amplitudes.[15,16]

We employed the QPC to detect the motion: In-plane strain in GaAs, generated by out-of-plane flexure, will generate out-of-plane piezoelectric fields.[17] These modulate the

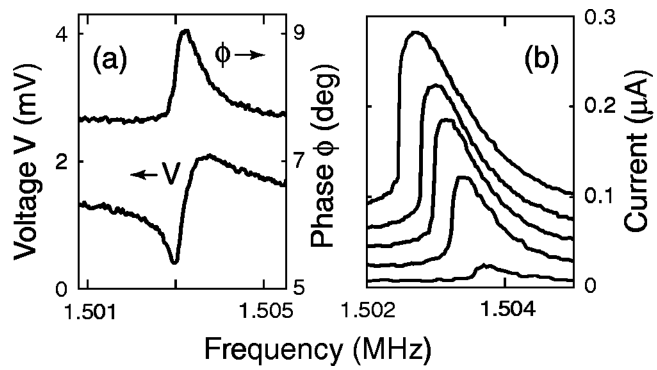

FIG. 3. (a) Amplitude and phase of signal reflected from magnetomotive drive electrode. Measurements made with applied power of -70 dB in a magnetic field of 5 T; (b) intermediate frequency current through QPC for same applied power to magnetomotive drive electrode, in magnetic fields of 1, 2, 3, 4, and 5 T. IF frequency was $\nu_{IF} = \omega_{IF}/2\pi = 13.7$ Hz, with 100% amplitude modulation of the LO signal.

QPC conductance in a manner analogous to the top gate. In Fig. 3(b) we display the measured QPC current i_{IF} when the drive electrode 1 was driven with an amplitude-modulated signal, which served to both generate magnetomotive actuation of the structure, and as a local oscillator for the QPC mixer. The change in the QPC mixer response as a function of ω_{LO} is due to the generation of a frequency-dependent piezoelectric voltage at ω_{LO} between the 2DEG layer and the top gates, and the amplitude modulation of the gate drive then mixes this voltage to the intermediate frequency ω_{IF}, permitting detection of the motion. Data are for a range of magnetic fields, with the expected B^2 dependence for the peak amplitude.

We could also actuate and sense the structure in the absence of a magnetic field; in Fig. 4 we display the QPC current as the LO frequency is swept through the mechanical resonance, for different LO powers. Mechanical actuation occurs due to the electrostatic interaction between the drive electrode 1 and the substrate, and the QPC detects both this frequency-independent voltage, and the resonant piezoelectric voltage due to the strain in the structure.

We can estimate the displacement sensitivity of the QPC from our measurements; using the magnetomotive reflec-

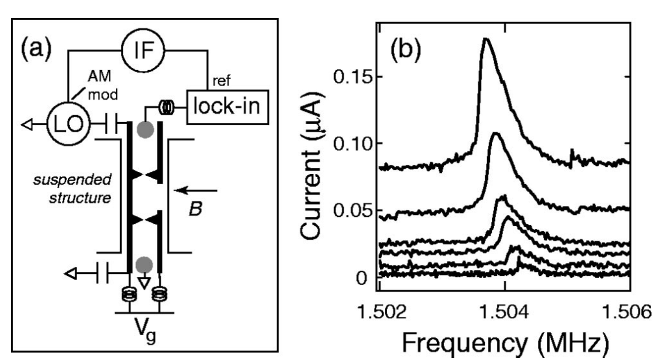

FIG. 4. (a) Measurement schematic for electrostatic drive and detection using the QPC. The LO drive signal is capacitively coupled to electrode 1, and is amplitude modulated at the IF frequency $\omega_{IF}/2\pi = 13.7$ Hz. The QPC current is lock-in detected with the IF signal as a reference. Care was taken to ensure that no spurious mixing signals were detectable. (b) IF current through the QPC for a range of applied LO powers, with $P_{LO} = -61, -56, -53.5, -51$, and -48.5 dB. The remnant magnetic field is estimated from magnetomotive measurements to be less than 0.01 T.

tance measurements, we can calculate the midpoint displacement δz of the structure, and from the corresponding magnitude of the IF current i_{IF}, we find the responsivity $i_{\mathrm{IF}} \approx 28\ \delta z$ nA/μm. Our current detection is limited by the voltage noise in the IF preamplifier, and corresponds to a noise of $\delta z_{\mathrm{rms}} \approx 3 \times 10^{-12}$ m/Hz$^{1/2}$, better than what is achieved with optical interferometry.[18] The corresponding force noise is about $\delta F_{\mathrm{rms}} \approx 0.3$ nN/Hz$^{1/2}$. We note that the thermal force noise $\sqrt{4k_B T m \omega_0 / Q} \approx 1$ fN/Hz$^{1/2} \ll \delta F_{\mathrm{rms}}$, well below our electrical noise level. As noted by Beck *et al.*,[10] the sensitivity *improves* with reduction in size scale, due to the increase in strain for a given displacement. Our device geometry allows for significantly smaller structures, with correspondingly higher frequencies, potentially approaching 1 GHz. The delicate sensitivity of the QPC can therefore potentially be employed as a quantum-limited displacement sensor, and allow the entanglement of a phase-coherent electron transmission sensor with a mechanical resonator.[19]

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