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Magnetotransport in freely suspended two-dimensional electron systems for integrated nanomechanical resonators

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Abstract

We present magnetotransport measurements on freely suspended two-dimensional electron gases. Samples are prepared from GaAs/AlGaAs-heterostructures containing an additional sacrificial layer. The electronic properties of the system are characterized in standard magnetotransport measurements whereas the mechanical degrees of freedom are investigated in radio frequency resonance experiments. The interplay of both can be exploited for ultrasensitive displacement detection.

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In this work, we present magnetotransport measurements on low-dimensional high mobility electron systems embedded in a freely suspended GaAs/AlGaAs-heterostructure. Such suspended nanocrystals are ideal candidates for studies of electron–phonon coupling and for integrated nano-electromechanical systems (NEMS). NEMS promise to be extremely fast and sensitive tools for sensor and communication technology and may also be regarded as 'quantum-mechanical' resonators when operated at several GHz and ultra-low temperatures [1–3]. Here, we report on the fabrication of suspended two-dimensional electron gases and of the integrated nanomechanical devices. Then the focus will be on measurements for characterization of both.

Samples were fabricated from MBE-grown GaAs/AlGaAs-heterostructures containing an additional 400 nm $Al_{0.8}Ga_{0.2}As$ sacrificial layer. The succeeding active layer has a total thickness of 130 nm. It contains a high mobility two-dimensional electron gas (2DEG) situated 40 nm below the sample surface which is surrounded by spacer, donor and cap layers on both sides [4]. Processing three-dimensional nanostructures involves a series of both optical and electron beam lithography steps followed by several pattern transfer steps. First of all, standard AuGe/Ni/AuGe ohmic contacts are fabricated and annealed. Second, Au bondpads and alignment marks as well as gate contacts are evaporated. In a third optical lithography step, the mesa is defined and etch-protected with a

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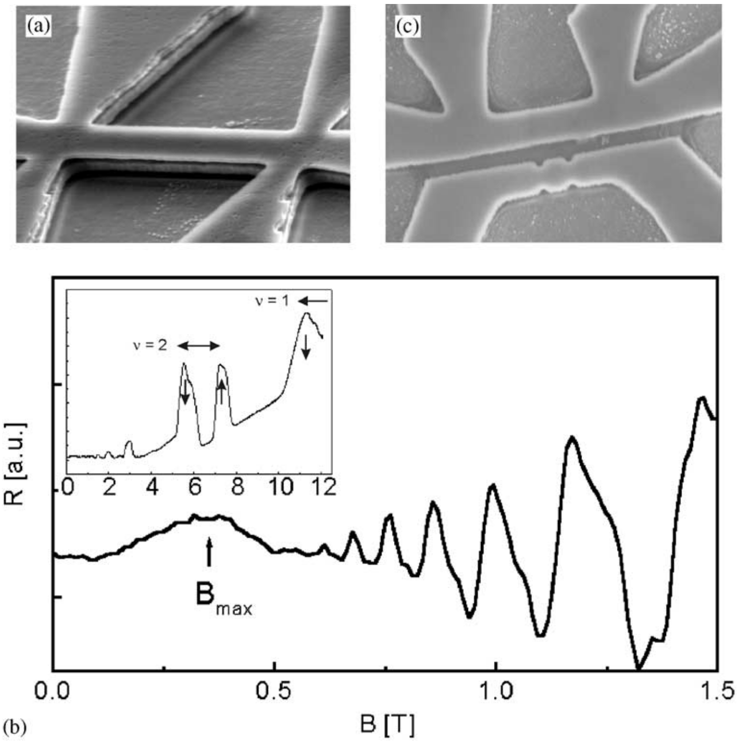

Fig. 1. (a) Freely suspended hallbar with dimensions $l = 3$ μm, $w = 600$ nm and $d = 130$ nm. (b) Shubnikov–de Haas oscillations measured at $T = 1.5$ K. The arrow indicates the observed geometrical resonance at $B_{\max}$. The inset shows the magnetoresistance for high magnetic fields with spin-splitting for $\nu = 1$ and 2. (c) Top view of a suspended hallbar and quantum dot structure.

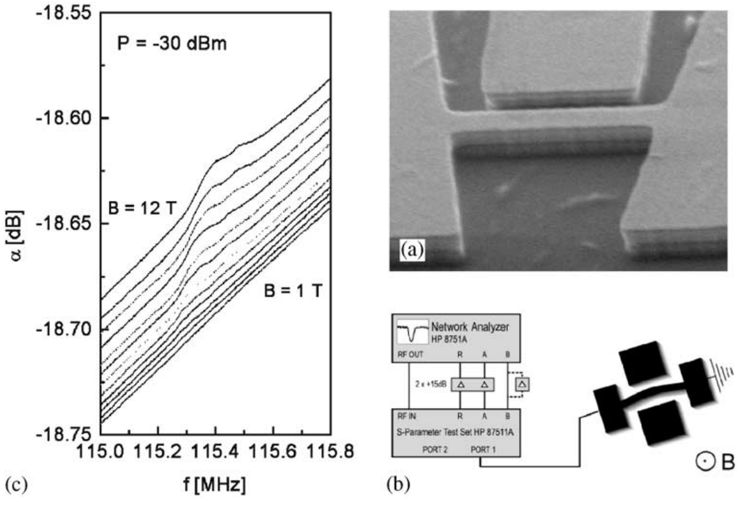

Fig. 2. (a) Nanomechanical resonator machined from GaAs (in [1 1 0] orientation). (b) Schematic of the experimental setup. (c) Measured resonance at 115.4 MHz for magnetic fields B from 1 to 12 T applied perpendicular to the mechanical beam.

layer of Ni. Hallbar and quantum dot structures (see Fig. 1(a) and (c)) as well as beam-shaped nanomechanical resonators (see Fig. 2(a)) are patterned using electron-beam lithography and etch-protected with an evaporated Ni or Au layer, respectively. The sample geometry is transferred into the heterostructure by reactive ion etching (RIE) using silane gas. Subsequently, the Ni etch mask is removed in a solution of iron-(III)-chloride. In order to finally suspend the nanostructure, the sacrificial layer is removed by wet etching in a 1% solution of hydrofluoric acid followed by critical point drying of the remaining free-standing structures.

The electronic properties of the 2DEG can be investigated in standard low temperature four-terminal magnetotransport experiments carried out in a variable temperature insert. Shubnikov–de Haas oscillations in the longitudinal resistance of a freely suspended hallbar at $T = 1.5$ K are depicted in Fig. 1(b). Via the standard relation $\Delta(1/B) = g_s e/hn_s$, with spin degeneracy factor $g_s = 2$, the carrier density was determined to $n_s = 3.19 \times 10^{11}$ cm^{-2}. In addition, at magnetic fields $B > 5$ T we find evidence for spin splitting at this temperature. The conductivity at zero magnetic field $\rho_0 = 1/e\mu n_s$ results in a mobility of $\mu = 5.75 \times 10^4$ cm^2/V s. The obtained properties of the 2DEG imply an improvement compared to previous work [4].

Further information about the electron system can be extracted from additional structure in the longitudinal low-field magnetoresistance [5,6]. The observed maximum can be explained as a geometrical resonance of the classical cyclotron radius $R_c = \hbar k_F/eB_{max}$, with $k_F = \sqrt{2\pi n_s}$: According to Ref. [6], the maximum in the low-field magnetoresistance occurs if R_c is about two times the effective wire width $W_{eff} \approx 0.55 R_c$. In our case $B_{max} = 0.37$ T, which corresponds to $R_c = 251$ nm and $W_{eff} \approx 140$ nm. With a given lithographical width $W_{lit} = 600$ nm of the hallbar, the depletion length from the sample edges can be estimated to be $W_{dep} = 230$ nm which is in the same order of magnitude as measured previously [4].

As depicted in Fig. 1(c), the aim of this work is to combine low-dimensional electronic systems, such as 2DEGs, quantum wires and dots with NEMS. This allows detailed studies of the electron–phonon interaction and to reach the ultimate limit of displacement detection. In first studies, we integrated a low-temperature HEMT close to a NEMS circuit for capacitive detection in order to obtain an increased sensitivity [7]. The mechanical resonator investigated ((0.17 × 0.19 × 4.8) μm^3) is covered with a thick Au layer and magneto-motively excited. Due to its displacement, the capacitance between the beam and a sidegate is modulated. Amplification of the small voltage signal $\delta C_{res} \sim \delta V_{res}$ is obtained by an on-chip preamplifier (Fujitsu FUX35X) [7]. The transistor, in general, serves as an impedance converter. The large input capacitance $C_{in} \gg C_{res}$ of the transistor limiting the sensitivity of the setup can be reduced by direct integration of the HEMT. A further increase is achieved by direct integration of a suspended 2DEG with a nanomechanical resonator. A typical resonator fabricated from GaAs with dimensions (0.20 × 0.19 × 2) μm^3 is shown in Fig. 2(a). It is also driven magneto-motively through the Lorentz force generated by a radio frequency current along the beam in a strong perpendicular magnetic field. The induced change in impedance is detected by tracing the reflected power using a network analyzer combined with a scattering parameter test set (see Fig. 2(b)). Fig. 2(c) shows a resonance at $f = 115$ MHz, slowly vanishing for decreasing magnetic fields. The quantum limit will be reached for nanomechanical resonators showing eigenfrequencies of the order of 500 MHz at transistion temperatures of about 25 mK, which is in the accessible range.

We have shown how to fabricate freely suspended electron gases in AlGaAs/GaAs-heterostructures for integration with nanomechanical resonators. In the first step, we characterized the electronic properties of the suspended hallbars and the mechanical response of GaAs-resonators separately. In combination, this setup will allow ultra-sensitive displacement detection, possibly at the quantum limit.

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