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# Effects of electron confinement on the acoustoelectric current in suspended quantum point contacts

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An acoustoelectric current driven through a quantum point contact (QPC) on a suspended nanobridge by surface acoustic waves displays a non-trivial behavior in the presence of a perpendicular magnetic field. Our study reveals that the dependencies of this current on the QPC gate voltage and magnetic field can be explained by a variable material parameter $\sigma_m$. We develop a theoretical model for this phenomenon based on the modification of the Coulomb interaction and, correspondingly, the electron-SAWs coupling in the presence of the electron confinement. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4984228]

In a two-dimensional electron gas (2DEG), the motion of the charged carriers is confined to a plane. The interaction with external magnetic fields strongly affects the transport properties of these 2D systems, and quantum effects can emerge.[1,2] By additionally restricting the lateral motion of the electrons to a nanosize scale, quantum effects can arise even in the absence of external fields.

In this letter, we scrutinize a quantum point contact (QPC) on a suspended 2DEG nanobridge. QPCs limit the lateral electron motion through electrostatic gates that locally deplete the 2DEG and force the electrons to pass through a nanoscale gap. We study the interaction of electrons in this structure in the presence of an external magnetic field and with surface acoustic waves (SAWs).[3] The SAWs, i.e., the mechanical waves travelling along the heterostructure that confines the 2DEG, mobilize the electrons with an acoustic velocity and drives an acoustoelectric current through the QPC. We find that this current displays a non-trivial behavior in the presence of a magnetic field and that the effects are very strong due to the enhanced coupling of the SAW in the suspended bridge. The experimental results are consistent with a theoretical model that assumes a modified Coulomb interaction inside the QPC, which renders the material parameter $\sigma_m$ a function of the experimental parameters, i.e., the magnetic field and the QPC gate voltage.

The device under test, as shown in Fig. 1, consists of a suspended nanobridge of 1.5 $\mu$m width and 90 nm thickness. It was fabricated from a GaAs/$Al_xGa_{1-x}As$ heterostructure which confines a 2DEG 40 nm below the surface. Five pairs of metallic gates that form a corresponding number of QPCs and two interdigitated transducer (IDT) structures (not shown) that generate the SAWs were patterned on top. For the experiment, only the central QPC was activated, with the two IDTs placed at opposites sites, each at a distance of 232 $\mu$m. The details of the device preparation are given in Ref. 6. The 2DEG has an electron carrier density of $n_e = 4.2 \times 10^{15}\,\mathrm{m}^{-2}$ and an electron mobility of $\mu_e = 2.57 \times 10^5\,\mathrm{cm^2/Vs}$. The rf power applied to the IDT electrodes was $-12$ dBm at an operating frequency of 1.488 GHz. All measurements were carried out at a liquid Helium temperature of 4.2 K.

The results of our experiment are presented in Fig. 2, which shows the acoustoelectric current as a function of the voltage applied to the QPC gates, $V_{\mathrm{gate}}$, and the magnitude of the perpendicular magnetic field, $B$.

The acoustoelectric current, $I$, exhibits a non-trivial dependence on the experimental parameters. One of the features is the diminishing of the current with an onset at a gate voltage of approximately $-0.45$ V. Henceforward, we study the underlying mechanism that is responsible for this current decrease at small gate voltages. The negative current and the current oscillations at even larger negative gate voltages are related to different physical mechanisms as addressed in Ref. 6.

We attribute the current decrease that occurs at small gate voltages to two mechanisms: (i) the formation of a nanosize conductive gap formed by the split gates, which create "soft boundaries,"[5] and (ii) the Landau quantization of the density of states due to the perpendicular magnetic field and the formation of edge states at the "hard walls" produced by sample etching.

To understand this current decrease, we use the fact that the acoustoelectric current in 2DEG is proportional to the attenuation[7] given by

$$\Gamma = k\frac{K_{eff}^2}{2}\frac{\sigma_0/\sigma_m}{1+(\sigma_0/\sigma_m)^2}. \tag{1}$$

Here, $k$ is the wave number, $K_{eff}$ is the electromechanical coupling coefficient for GaAs, $\sigma_0 = e^2 n_e \tau/m^*$ is the Drude conductivity, and $\sigma_m$ is the material parameter characterizing the strength of the Coulomb interaction. This parameter is usually assumed to be a constant [$3.3 \times 10^{-7}\ (\Omega/\square)^{-1}$ for GaAs using the results of Ref. 8], and it has been shown[9] that

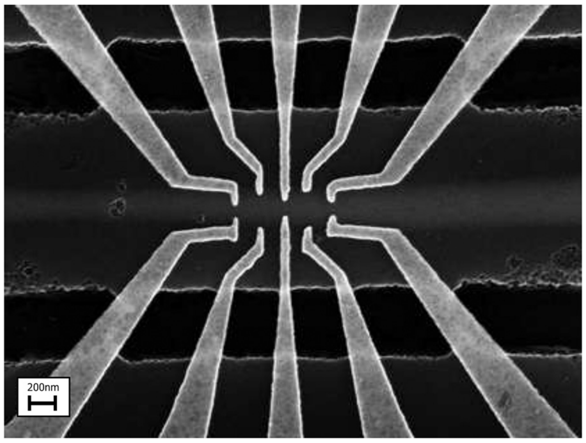


FIG. 1. A micrographic image of the suspended nanobridge with patterned gate pairs that form five QPCs. The interdigitated transducers (IDTs) that generate the SAW are located on either side of this structure (not shown due to the scaling).

it is not changed when the magnetic field is applied to the 2DEG. However, in the presence of the electron confinement induced by the negative voltage applied to the QPC gates and by the magnetic field, the Coulomb interaction is modified and $\sigma_m$ (as well as the conductivity $\sigma$) becomes the function of these parameters. Accordingly, the current at an applied magnetic field and gate voltage can be written as

$$\frac{J(V_g,B)}{J(0)} = \frac{\sigma(V_g,B)/\sigma_m(V_g,B)}{1+\left(\sigma(V_g,B)/\sigma_m(V_g,B)\right)^2} \Big/ \frac{\sigma_0/\sigma_m(0,0)}{1+\left(\sigma_0/\sigma_m(0,0)\right)^2}. \tag{2}$$

The dependence of the conductivity on the gate voltage and the magnetic field magnitude can be evaluated as

$$\sigma(V_g,B) = \sigma^{\exp}(V_g) f(B), \tag{3}$$

where the dependence of the conductivity on the gate voltage, $\sigma^{\exp}(V_g)$, can be taken from the experimental data of Ref. 6. The effect of the magnetic field is given by[10]

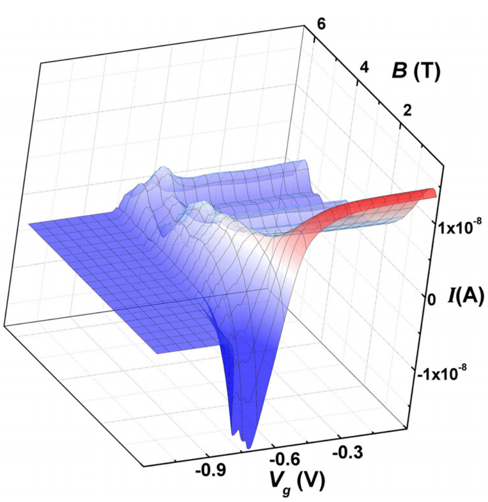


FIG. 2. Dependencies of acoustoelectric current on the QPC gate voltage and the magnitude of the magnetic field.

$$f(B) = \frac{1}{1+\omega_c^2\tau^2}\left(1 - \frac{2\omega_c^2\tau^2}{1+\omega_c^2\tau^2}\frac{2\pi^2 k_B T}{\hbar\omega_c}\mathrm{csch}\left\{\frac{2\pi^2 k_B T_e}{\hbar\omega_c}\right\}\right.$$
$$\left.\times \cos\left\{\frac{2\pi^2 E_F}{\hbar\omega_c}\right\}\exp\left\{-\frac{\pi}{\omega_c\tau}\right\}\right), \tag{4}$$

where $\omega_c$ is the cyclotron frequency and $\tau$ is the scattering time.

With $\sigma(V_g,B)$ determined, it is possible to extract the function $\sigma_m(V_g,B)$ from Eq. (2) and experimental data of Fig. 2.

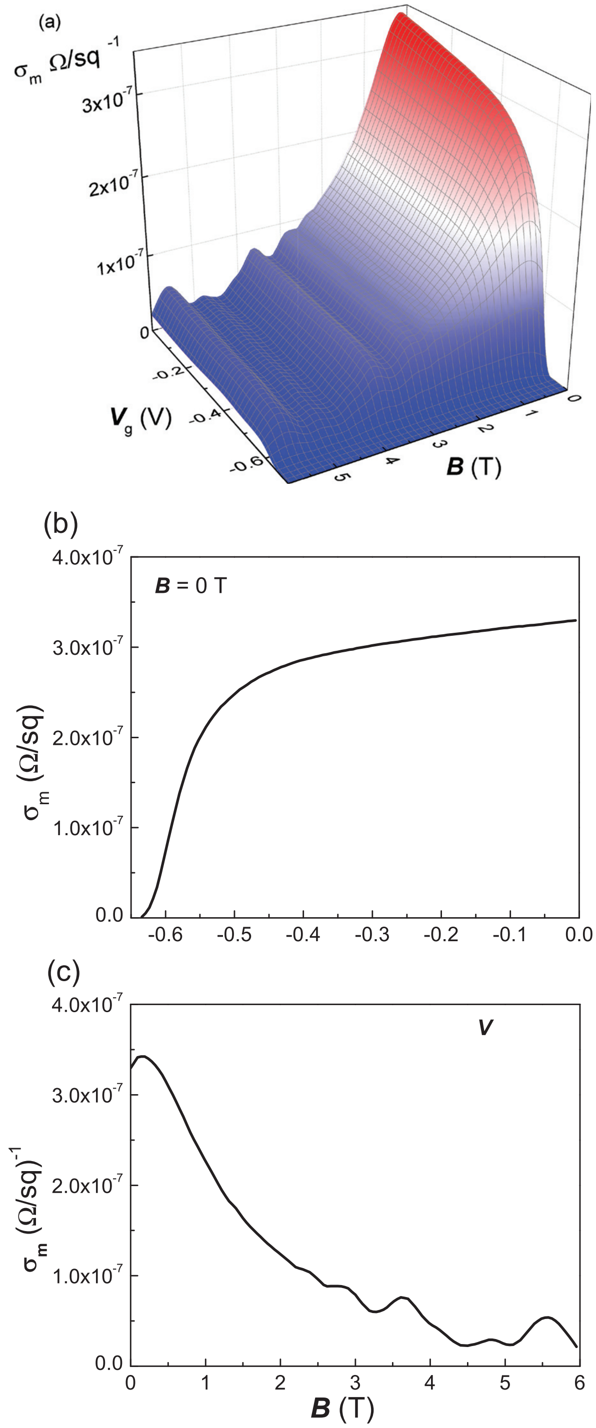


FIG. 3. (a) Dependencies of $\sigma_m$ on the QPC gate voltage and magnitude of the magnetic field. (b) Dependence of $\sigma_m$ on the gate voltage for the zero magnetic field. (c) Dependence of $\sigma_m$ on the magnetic field for zero gate voltage.

The obtained function is shown in Fig. 3. The value of $\sigma_m$ (0,0) is taken as $3.3 \times 10^{-7}$ $(\Omega/\square)^{-1}$.

One can see that $\sigma_m$ decreases with both the increasing applied magnetic field and negative gate voltage. This behavior can be explained on the basis of the usual definition of $\sigma_m$ as[4]

$$\sigma_m = \frac{v_S}{v(k)k}, \tag{5}$$

where $v(k)$ is the Fourier transform of the Coulomb interaction including the effects of the electron confinement and image charges. The convolution of the charge distribution and the electrostatic interaction has the following form:

$$v(k) = \frac{1}{2\pi}\int dk_y v\left(k_{||}\right) f\left(k_y\right) \tag{6}$$

with $k_{||} = \sqrt{k^2 + k_y^2}$ and $v(k_{||})$ calculated in Ref. 5 for 2DEG located at the distance $d$ from the surface of a dielectric slab of the thickness $L$ and the dielectric constant $\varepsilon$ surrounded by a material of the dielectric constant $\varepsilon_b$, as

$$v\left(k_{||}\right) = \frac{1}{2\varepsilon_0\varepsilon}\beta\left(k_{||}\right)\left(1 + \zeta e^{-2k_{||}d} + \zeta^2 e^{-2k_{||}L} + \zeta e^{-2k_{||}(L-d)}\right), \tag{7}$$

where

$$\zeta = (\varepsilon - \varepsilon_b)/(\varepsilon + \varepsilon_b)$$

and

$$\beta\left(k_{||}\right) = \frac{1}{1 - \zeta^2 e^{-2k_{||}L}}. \tag{8}$$

The confinement factor $f(k_y)$, i.e., the Fourier transform of the charge distribution, was calculated in Ref. 5 for the one-dimensional harmonic confinement caused by split gates as $f(k_y) = \exp\{-k_y^2 r_\perp^2/2\}$, where $r_\perp$ is the channel width. When the magnetic field is applied to the etched structures such as the one used in our experiment, edge states are formed with the spatial extension of the magnetic length, $l_B = \sqrt{\hbar/eB}$. Accordingly, the confinement factor is given by $f(k_y) = \exp\{-k_y^2 l_B^2/2\}$. In both cases, the relative carrier distance decreases, which results in an increase in the effective Coulomb coupling strength. Correspondingly, the material parameter $\sigma_m$, which is inversely proportional to this strength, decreases, as evident from Eq. (5). The initial increase in $\sigma_m$ at small magnetic fields occurs when the edge states are not formed yet. Additional oscillations of $\sigma_m$ at large fields are probably caused by the fact that Eq. (4) is strictly valid for moderate fields only.

In summary, we observe the decreasing acoustoelectric current through a quantum point contact formed on the two-dimensional electron gas on the suspended nanobridge, as the negative split gate voltage and/or the applied magnetic field increase. We explain this phenomenon as a consequence of the electron confinement caused by the split gates and by the edge state formation in the presence of a perpendicular magnetic field. Such confinement brings electrons closer to each other, thus modifying their Coulomb interaction and the coupling of electrons to the surface acoustic waves.

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