Phonon–mediated non–equilibrium interaction between nanoscale devices

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Interactions between mesoscopic devices induced by interface acoustic phonons propagating in the plane of a two–dimensional electron system (2DES) are investigated by phonon–spectroscopy. In our experiments ballistic electrons injected from a biased quantum point contact emit phonons and a portion of them are reabsorbed exciting electrons in a nearby degenerate 2DES. We perform energy spectroscopy on these excited electrons employing a tunable electrostatic barrier in an electrically separate and unbiased detector circuit. The transferred energy is found to be bounded by a maximum value corresponding to Fermi–level electrons excited and back–scattered by absorbing interface phonons. Our results imply that phonon–mediated interaction plays an important role for the decoherence of solid–state–based quantum circuits.

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Nanoscale electronic circuits dominate present information technologies. Based on their coherent dynamics they are also considered as candidates for future quantum information processing [1 2]. Therefore, it is important to understand and control decoherence–inducing processes, such as the non–equilibrium back–action of a biased quantum point contact (QPC), widely used as single electron detector. However, the details of the relevant back–action mechanisms are not yet understood and a matter of ongoing investigations [3 4 5 6 7].

Phonon–induced currents in a two–dimensional electron system (2DES) have been evidenced in thermopower experiments [8 9] and also directly imaged with ballistically injected phonons [10]. In our experiments we employ a spectrometer, conceptually similar to a so–called lateral tunneling hot–electron amplifier [11], to analyse the energy of excited electrons in a 2DES and to study energy transfer mechanisms between mesoscopic circuits.

The inset of Fig. 1a sketches the calibration procedure of the energetic height $E_{Ba}$ of an analyzer barrier Ba to be employed for quantitative energy spectroscopy. Hot electrons, injected across a barrier Bi into a degenerate Fermi–sea of cold electrons, move ballistically with an excess kinetic energy of $E_{kin} – E_F \leq |eV_{SD}|$ towards Ba. As long as $E_{Ba} < E_{kin}$ some of these electrons pass Ba resulting in an analyzer current $I_a$, while $I_a$ vanishes for $E_{Ba} > E_{kin}$. The onset of $I_a(V_{SD})$ at $E_{Ba} = E_F + |eV_{SD}|$ serves as calibration of the barrier height $E_{Ba}$. The result of such a calibration measurement is plotted in Fig. 1a, displaying $I_a$ (gray scale and contour lines) as a function of the gate voltage $V_{Ba}$ and the bias $V_{SD}$. The ballistic motion of the electrons insures a straight line of current onset (purple), converting the gate voltage $V_{Ba}$ (bottom scale of Fig. 1a) to the barrier height $E_{Ba}$ (top scale). For $E_{Ba} < E_F$ a calibration is obtained by utilizing quantization of the electronic density of states into Landau levels with well known energies in a perpendicular magnetic field [12 13]. Note that one calibration point, namely for $E_{Ba} = E_F$, is in addition obtained by applying a voltage across Ba and measuring the linear response current. Importantly, at $E_{Ba} = E_F$ all three calibration methods are consistent.

A scanning electron micrograph of our spectrometer is pictured in Fig. 1b. It is a mesoscopic Hall–bar shaped by wet–etching from a GaAs/AlGaAs heterostructure. The Hall–bar contains 90 nm below the surface a 2DES with a Fermi energy of $E_F \simeq 14$ meV and an electron elastic mean free path of $l_m \simeq 14 \mu m$. Three 300 nm wide top gates (light gray in Fig. 1b) are designed to cross the entire Hall–bar. By applying negative voltages to these gates, tunable potential barriers (B1, B2, and B3), completely suppressing tunneling, can be realized [14]. In addition, at each end of the Hall–bar a QPC can be electrostatically defined by a pair of top gates. All experiments are performed in a dilution refrigerator at a base temperature of $T_{sath} = 20$ mK.

To spectroscopically study the energy transfer mechanisms between two adjacent mesoscopic devices we bias one of the barriers (B1) with a large negative voltage. As a result B1 is opaque for electrons and electrically separates the driven injector circuit from an unbiased detector circuit. As sketched in Fig. 2a, hot electrons injected across a QPC (QPC1) move ballistically along the Hall–bar until they are reflected at barrier B1 and eventually leave the Hall–bar via a grounded side–contact. In the detector circuit barrier B2 is left open for electrons ($E_{Bi} < E_F$) and B3 is used as analyzer barrier.

Although the detector circuit is unbiased we observe a current $I_3$ across the analyzer barrier B3. Hence, energy is transmitted across B1 while electrons are always reflected. In Fig. 2a the measured $I_3$ is displayed for a large bias regime $–60$ mV $\leq V_{SD} \leq 0$ and as a function of the excess barrier height $E_{B3} – E_F$. Strikingly, even at a large energy of injected electrons $|eV_{SD}| = 60$ meV,
the analyzer current vanishes whenever the analyzer barrier height exceeds \( E_{B3} \approx E_F + 1.3 \text{meV} \). This observation implies that the maximum energy that can be transferred to equilibrium electrons in the detector circuit is \( \Delta E_{\text{max}} = E_{\text{kin}} - E_F \approx 1.3 \text{meV} \). To further illustrate this exceptional behavior several \( I_3-E_{B3} \) traces at constant \( V_{SD} \) (indicated by horizontal lines in Fig. 2a) are plotted in Fig. 2b. The larger the injection energy \(|V_{SD}|\) the sharper is the current onset at \( E_{B3} - E_F \approx \Delta E_{\text{max}} \).

At low temperatures energy exchange between mesoscopic circuits is usually attributed to Coulomb interaction as indeed observed in Coulomb-drag experiments \cite{15 16 17 18}. Here, in our experiments, the upper bound \( \Delta E_{\text{max}} \) of energy quanta transferred between

Figure 2: **Phonon-driven current:** (color online) (a) Analyzer current \( I_3 = I_a \) (gray scale, color for \( I_3 \geq 50 \text{fA} \)) as a function of its energetic height \( E_{B3} - E_F \) in the bias range \( 0 \geq V_{SD} \geq -60 \text{mV} \) applied across QPC1 (as emitter). Barrier B1 is opaque for electrons and separates emitter and detector as sketched in the inset. B2 is left open \( (E_{B2} \ll E_F) \). Contour lines of constant current are spaced by a factor of 1.7. \( \Delta I_3 \) traces along the horizontal lines in a. The inset sketches relevant phonon absorption processes for an electron at the Fermi–level \( E_F \). (c) Analyzer current \( I_3 \) in the bias range \( 3 \text{mV} \geq V_{SD} \geq -3 \text{mV} \). Currents comparable to those at larger bias are achieved by lowering the injector barrier resistance. For the detailed configuration see main text. (d) \( I_3 - V_{SD} \) traces along the vertical lines in c. Also plotted is the injector current \( I_{SD} \) (rhs–axis).
emitter and detector reflects that the energy is mediated by interface acoustic phonons: Hot injected electrons can relax by emission of acoustic phonons [19]. In contrast to electrons, acoustic phonons can pass the electrostatic barrier (B1) between emitter and detector circuits. Energy and momentum conservation restrict the emission of interface acoustic phonons by electrons with momentum \( hk_e \) to momenta \( k_{ph} < 2hk_e \), corresponding to backscattered electrons in the 2DES. With the same consideration only interface acoustic phonons with \( k_{ph} < 2h\nu_F \) can be absorbed by equilibrium electrons in the detector. This situation is indicated in the inset of Fig. 2, picturing the parabolic electron dispersion relation within the 2DES. The blue line indicates all possible states the electron (black circle), originally at the Fermi-energy, can be scattered in the bias-range \(-V_{SD}\) in the detector circuit. With the upper bound \( \Delta E_s \) we obtain with \( \Delta \) \( s \) assured and the known Fermi momentum \( h\nu_F \).

In Fig. 2 we find \( I_3 > 0 \) independent of the sign of \( V_{SD} \). Clearly, the detector circuit acts as a uni-directional current source, driven by phonons originating in the emitter. In the electrically separate detector electrons absorb such interface phonons predominantly close to the emitter. Then the excited electrons move in the direction of the transferred momentum towards barrier B3 where they can contribute to the analyzer current \( I_3 \). The latter is considerably smaller for \( V_{SD} > 0 \) compared to the case of \( V_{SD} < 0 \). We relate this to the initial momentum of the hot electrons in the emitter which is for \( V_{SD} > 0 \) directed away from the detector. In this case and in contrast to \( V_{SD} < 0 \) an additional scattering process is needed to reverse the momentum towards the detector.

Compared to elastic scattering of ballistic electrons at the Fermi–surface [24] non–equilibrium interactions at higher energies remain a challenging subject. Hot electrons can relax their excess energy either via electron–electron scattering [25–28], via electromagnetic fields generated by charge fluctuations [3, 5, 6], or via the emission of phonons [19, 29, 30]. Inelastic electron–phonon scattering in the 2DES for electrons with an excess energy of \( \Delta E \simeq 1 \text{ mV} \) results in a mean–free path of \( l_{ph} \sim 100 \mu \text{m} \) [19, 27, 31] considerably longer than the electron–electron scattering length of \( l_{ee} \sim 8 \mu \text{m} \) [32]. Both length scales are longer than the elastic mean–free path of electrons, limited to \( l_{ee} \sim 1 \mu \text{m} \) by the geometric boundaries of the device. In Fig. 3 we investigate the length scale \( l_{ph} \) of the reabsorption of interface acoustic phonons within the 2DES. We compare two different experimental situations as sketched in the inset of Fig. 3. Configuration #1 is essentially identical to the one established in the experiment of Figs. 2 and 2a and displays the phonon–driven current as a function of \( V_{SD} \) with the analyzer barrier adjusted to \( E_{B3} \simeq E_F \). In configuration #2 an additional barrier (B2) is raised well above the Fermi level \( (E_{B2} \gg E_F) \). Now the resulting phonon–driven current is about a factor of ten smaller compared to configuration #1 but exhibits almost the same dependence on \( V_{SD} \). This finding implies that most phonons passing B1 are reabsorbed by the 2DES before reaching barrier B2 and thus cannot contribute to the phonon–driven current. As the distance between barriers B1 and B2 is 1 \( \mu \text{m} \) we consider this as an upper limit for the interface phonon mean–free path \( l_{ph} \). The corresponding...
Figure 3: Mean–free–path of interface acoustic phonons: (color online) Analyzer current $I_3$ as a function of the emitter bias $V_{SD}$ for the two experimental setups sketched in the inset. In setup #1 B2 is left open (as for Fig. 2) while in setup #2 both barriers B1 and B2 are opaque for electrons. The analyzer barrier is tuned to $E_{ph} \simeq E_F$. In setup #2 $I_3$ is reduced by about a factor of ten. Hence, the distance between B1 and B2 of about 1 μm roughly corresponds to the phonon mean–free–path.

transition rates of $\sim (200 \text{ ps})^{-1}$ agree roughly with theoretical estimates [19, 31] and $l_{pe}/l_{wp}$ is of the order of the ratio of sound and Fermi velocity, as expected.

In conclusion, our experiments on interacting non–equilibrium mesoscopic circuits underline the importance of energy transfer mediated via interface acoustic phonons and generated by ballistically moving electrons driven out of equilibrium. In particular, they demonstrate conclusively that this energy transfer between a non–equilibrium nanoscale circuit, serving as emitter, and an adjacent detector circuit in equilibrium is bounded by the energy of interface acoustic phonons with momentum $2\hbar k_F$. This is the maximum momentum that can be transferred to equilibrium electrons under conservation of momentum and energy. Since such phonon–mediated interactions reduce the coherence times of quantum states in confined electron systems their study and understanding is important for the realization of semiconductor–based coherent quantum devices. Beyond we establish a method to spectroscopy interface acoustic phonons in a new regime up to momenta of $2\hbar k_F$.

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