Generation of energy selective excitations in quantum Hall edge states

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We operate and on-demand source of single electrons in high perpendicular magnetic fields up to 30 T, corresponding to a filling factor v below 1/3. The device extracts and emits single charges at a tunable energy from and to a two-dimensional electron gas, brought into well defined integer and fractional quantum Hall (QH) states. It can therefore be used for sensitive electrical transport studies, e.g. of excitations and relaxation processes in QH edge states.

Charge transport in two-dimensional electron gases placed in a strong perpendicular magnetic field is ruled by chiral edge states. These edge states are now being exploited routinely in fundamental physics experiments, e.g. in electron interferometers. Moreover, gapless neutral edge excitations have been predicted, though not yet directly observed in experiments using quantum point contacts to generate edge excitations, as performed in e.g. Refs. 8 and 9. Additional counterpropagating edge excitations in the fractional quantum Hall (QH) state have also been predicted, but were not found in studies of edge magneto plasmons. Only very recently a shot noise experiment found first indications for a neutral counterpropagating mode.

In this paper we demonstrate a new method to generate triggered single energy selective excitations in integer and fractional QH edges to probe possible edge excitations and relaxation processes. Furthermore, this method allows to precisely control the emission statistics of the electrons, which opens the possibility for efficient time resolved measurements.

We adapt a structure that has previously been employed as high precision current source, both in the dc and ac regime. A schematic of our device and an electron micrograph are shown in Fig. 1a. It was realized in an AlGaAs/GaAs heterostructure. A 700 nm wide constriction was wet-etched inside a two-dimensional electron gas. The device was contacted at source (S) and drain (D) using an annealed layer of AuGeNi. The constriction is crossed by Ti-Au finger gates G1 and G2. A quantum dot (QD) with a quasibound state is formed by applying voltages V1 and V2 to G1 and G2, respectively; a third gate G3 is not used and set to ground. The corresponding potential landscape along the constriction is shown in Fig. 1b. An additional sinusoidal signal of power PRF and frequency f is coupled to G1 and varies both the height of the barrier and the energy ε(t) = ε1 cos ωt + ε0 of the quasibound state (ω = 2πf).

During the first half cycle ε(t) drops below the chemical potential μS and ψ is loaded with an electron with energy μS − EL [see Fig. 1b]. During the second half-cycle, ε(t) is raised sufficiently fast above μD and the electron can be unloaded to the drain with an excess energy EUL. This process, resulting into a quantized current I = e · f with e the electron charge, is non-adiabatic and requires that the loaded QD state is raised sufficiently fast through the chemical potentials μS/D to avoid unwanted charge transfer. The scheme can be generalized to a quantized transport of n electrons per cycle, i.e. I = n · e · f, where n can be derived from the decay cascade model.

The current is accompanied by a periodic excitation in the drain at energy EUL above μD. Upon application of a strong perpendicular magnetic field B, transport in S and D takes place via edge channels, marked symbolically with green arrows in Fig. 1a. Using the dynamical QD it is now possible to trigger single energy selective excitation quanta of the QH edge state.

The number of electrons emitted into D per cycle may be tuned using V2, as shown in Fig. 1b, for a measurement carried out in a 3He cryostat with a base temperature of 300 mK. Under zero-field conditions approximately one
The distribution of the emission times is peaked and depends exponentially on \( \varepsilon \). To obtain an expression for \( \varepsilon \), we assume that \( \Gamma \) are the maximal and minimal tunnel rates during one cycle of modulation, where \( \Gamma \) is indicated by the dashed arrow, beyond which the quantized regime breaks down. Inset showing \( I/\varepsilon \) as the bias \( V_B \) is varied.

The emission energy \( E_U \) depends on \( \varepsilon \), as well as on the bias voltage, \( V_B \), and \( V_2 \). It may be determined experimentally using gates as energy filter, for instance used in Ref. [18]. We have obtained a first estimate for \( \Delta E = E_U + E_L \) at \( B = 0 \) T based on the variation of the \( e\ell \)-plateau lengths along \( V_1 \) as function of \( P^{R} \). For the studied device \( \Delta E \approx 14 \) to \( 17 \) meV for frequencies ranging from \( 50 \) to \( 300 \) MHz, and for \( V_2 \) set to the negative side of the plateau (\( V_2 = V_T \), see Fig. 2).

In the following we estimate the distribution of the energy of the emitted electrons, \( p(E_U) \), based on the Master equation model of Ref. [14]. The sharpness of the distribution, \( \Delta E_U \), can be tuned by the selectivity \( s \equiv g/\varepsilon_1 \) of the barrier at \( G_2 \) with \( g \equiv \ln \Gamma_{2}^{\max}/\Gamma_{2}^{\min} \). Here \( \Gamma_{2}^{\max} \) are the maximal and minimal tunnel rates during one cycle of modulation, where we also assume that \( \Gamma_2 \) depends exponentially on \( \varepsilon \). To obtain an expression for the energy distribution we consider the case when unloading \( (\varepsilon \geq \mu_D) \) takes place during the phase when \( \varepsilon \) changes most rapidly, such that \( \varepsilon(t) \approx \varepsilon_1 \omega t + \mu_D \). The problem can then be simplified to a dynamic QD completely occupied at \( t \to -\infty \) which unloads to drain via \( G_2 \) with increasing rate \( \Gamma_2(t) = \Gamma_0 \exp \left( \frac{\mu_D}{\varepsilon_1} t \right) \), where \( \Gamma_0 \) is the escape rate when \( \varepsilon(t) = \mu_D \). With these assumptions the distribution of the emission times is peaked at \( t_c = \beta^{-1} \ln \left( \beta/\Gamma_0^2 \right) \) with \( \beta = g \omega/2 \). The width of the corresponding energy distribution is then given by \( \Delta E_U = 2/\beta \). Hence, to obtain a narrow emission energy distribution one may optimize the barrier shape of \( G_2 \) to maximize \( s \). The lowest achievable \( \Delta E_U \) is limited by the quantum-mechanical uncertainty of energy, on the order of \( h\Gamma_2(t_c) = (g/2)\hbar \omega \). For the frequencies chosen in this experiment the minimal \( \Delta E_U \) lies in the \( \mu eV \) range.

The derivation above also shows that the emission energy \( E_U = \varepsilon(t_c) - \mu_D \) depends on the frequency \( \omega \) and the tunnel rate \( \Gamma_0^2 \) logarithmically,

\[
E_U \approx \varepsilon_1 \omega t_c = \Delta E_U \ln \left( \frac{\varepsilon_1 \omega}{\Delta E_U \Gamma_0^2} \right). \tag{1}
\]

Since typically \( \Gamma_0^2 \) depends on \( V_2 \) exponentially, the gate voltage can be readily used to tune the emission energy, i.e. \( E_U \propto -|\varepsilon|V_2 \). To ensure single triggered excitation events (within a certain error margin) \( V_2 \) may be tuned only within the plateau voltage range, i.e. close to the negative side of the plateau where \( \Gamma_0^2 \) is minimal (see Fig. 2). From Eq. (1) it follows that increasing the modulation amplitude \( \varepsilon_1 \) enhances \( E_U \) only logarithmically. To extend the energy range efficiently, the bias voltage \( V_B = (\mu_D - \mu_S)/|e| \) may be made more negative, decreasing \( \Gamma_0^2 \) since the condition \( \varepsilon = \mu_D \) will then take place earlier in the cycle, i.e. \( E_U \propto -|\varepsilon|V_B \). At the same time the chance for emitting an additional electron increases, as seen from the inset in Fig. 2. This behaviour is consistent with the decay cascade model, considering that the time \( t_c \) at which the decay cascade starts is given by \( \varepsilon(t_c) = \mu_S \). The corresponding escape rate at \( G_1, \Gamma_1(\varepsilon(t_c)) \), controls the number of electrons captured per cycle. To remain in the quantized regime, \( V_2 \) and consequently \( \Gamma_0^2 \) have to be decreased as indicated by the arrow in the inset of Fig. 2 leading to an additional enhancement of \( E_U \) according to Eq. (1). Hence, combining the \( \varepsilon \), \( V_B \) and \( V_2 \) dependence an excitation energy range up to several tens of meV should be possible using this technique. Despite the potentially large energy, the heating of the edge state can be kept at a minimum by choosing a sufficiently low frequency. Furthermore, this energy selective and time controlled excitation source could be combined with selective edge mode detection and a time-gated detector technique for sensitive studies of the underlying transport processes.

For the presented excitation source we require that the gates \( G_1 \) and \( G_2 \) coincide with the border of the undisturbed QH liquid, in order to avoid broadening of the energy distribution \( p(E_U) \). In previous studies of this dynamical QD in perpendicular magnetic field, such as in Refs. [21] and [22] the electron density of states and the corresponding filling factor of the leads connecting to the QD via \( G_1 \) and \( G_2 \) could not be established. In those works a wire of constant nominal width was employed, where side wall depletion may result in varying electron densities inside the wire, different from the undisturbed
section was quenched for...have been chosen to remain in the decay cascade regime. The colors and contours in the diagramme correspond to those in Fig. 2.

FIG. 3. (color online) Normalized current $I / \varepsilon f$ as a function of $V_2$ and $B$, as well as Hall resistance $R_H$ as a function of $B$. The power and frequency have been chosen to remain in the undisturbed QH liquid. The tapered channel geometry used in the present work intends to avoid this complication. Fig. 3 demonstrates the clocked capturing of electrons directly from a fractional QH edge state. In Ref. 17 quantization was quenched for $B \geq 1 T$ and no clear comparison seems possible. The periodicity observed in Ref. 22 does not correspond to the $R_H$ variation inferred from the charge carrier density specified. This observation indicates emission into a localized region of reduced electron density inside the etched channel.

Finally we note that charge pumping from fractional edge states as demonstrated here may be developed further into the realization of a fractional charge pump as proposed by Simon, which may be used as a measurement of the charge of the fractional quantum Hall quasiparticle.

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