Generation of energy selective excitations in quantum Hall edge states

C Leicht, P Mirovsky, B Kaestner, F Hohls, V Kashcheyevs, E V Kurganova, U Zeitler, T Weimann, K Pierz and H W Schumacher

1 Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
2 Faculty of Physics and Mathematics, University of Latvia, Riga LV-1002, Latvia
3 Faculty of Computing, University of Latvia, Riga LV-1586, Latvia
4 High Field Magnet Laboratory, Institute for Molecules and Materials, Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands

E-mail: Christoph.Leicht@ptb.de

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Abstract
We operate an on-demand source of single electrons in high perpendicular magnetic fields up to 30 T, corresponding to a filling factor \( \nu \) 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. We discuss ways to tune the emission energy as well as the sharpness of its distribution. We conclude that it can be used for sensitive electrical transport studies, e.g. of excitations and relaxation processes in QH edge states.

1. Introduction
Charge transport in two-dimensional electron gases placed in a strong perpendicular magnetic field is ruled by chiral edge states [1–3]. These edge states are now being exploited routinely in fundamental physics experiments, e.g. in electron interferometers [4, 5]. Moreover, gapless neutral edge excitations have been predicted [6, 7], though not yet directly observed in experiments using quantum point contacts to generate edge excitations, as performed in e.g., [8] and [9]. Additional counterpropagating edge excitations in the fractional quantum Hall (QH) state have also been predicted [3, 10], but were not found in studies of edge magneto plasmons [11, 12]. Only very recently a shot noise experiment found first indications for a neutral counterpropagating mode [13].

In this paper we discuss a new method to generate triggered single energy selective excitations in integer and fractional QH edges to probe possible edge excitations and relaxation processes. Hence, unlike methods based on energy selective detection, as demonstrated, for instance, in [8, 9, 14, 15] here we propose a method for precise energy selective emission, which may lead to different relaxation mechanisms [16]. Furthermore, this method allows us to precisely control the emission statistics of the electrons, which opens the possibility of efficient time-resolved measurements.

2. Device structure
We adapt a structure that has previously been employed as high-precision current source, both in the dc [17] and ac regime [18]. A schematic of our device and an electron micrograph are shown in figure 1(a). 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 \( G_1 \) and \( G_2 \). A quantum dot (QD) with a quasibound state \( \psi \) is formed by applying voltages \( V_1 \) and \( V_2 \) to \( G_1 \) and \( G_2 \), respectively; a third gate \( G_3 \) is not used and set to ground. The corresponding potential landscape along the constriction is shown in figure 1(b). An additional sinusoidal signal of power \( P_{\text{RF}} \) and frequency \( f \) is coupled to \( G_1 \) and varies both the height of the barrier and the energy \( \varepsilon(t) = \varepsilon_1 \cos \omega t + \varepsilon_0 \) of the quasibound state (\( \omega = 2\pi f \)).

During the first half cycle \( \varepsilon(t) \) drops below the chemical
potential $\mu_S$ and $\psi$ is loaded with an electron with energy $\mu_S - E_L$ (see figure 1(b)). During the second half-cycle, $\varepsilon(t)$ is raised sufficiently fast above $\mu_D$ and the electron can be unloaded to the drain with an excess energy $E_U$. This process, resulting into a quantized current $I = e \cdot f$ with $e$ the electron charge, is non-adiabatic and requires that the loaded QD state is raised sufficiently fast through the chemical potentials $\mu_{S/D}$ to avoid unwanted charge transfer [17]. The scheme can be generalized to a quantized transport of $n$ electrons per cycle, i.e., $I = n \cdot e \cdot f$, where $n$ can be derived from the decay cascade model [19].

3. Device characterization

The current is accompanied by a periodic excitation in the drain at energy $E_U$ above $\mu_D$. 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 figure 1(a). Using the dynamical QD it is now possible to trigger single energy selective excitation quanta of the QH cascade model [19].

The number of electrons emitted into $D$ per cycle may be tuned using $V_2$, as shown in figure 2 for a measurement carried out in a $^3$He cryostat with a base temperature of 300 mK. Under zero-field conditions approximately one electron is emitted per cycle to $D$ for $V_2 = -135, \ldots, -120$ mV. If a perpendicular magnetic field is applied it has been found previously in acoustically driven dynamical QDs that quantization is quenched for $B \geq 1$ T [20]. In the present case, where the dynamic potential is generated directly by gates, quantization can be achieved up to very high magnetic fields, as shown in figure 2. Here emission of single charges into $D$, i.e. quantized charge pumping, at $B = 25$ T is shown, corresponding to a fractional filling factor $\nu = 1/3$ of the undisturbed QH liquid.

The emission energy $E_U$ depends on $f$ as well as on the bias voltage, $V_b$, and $V_2$. It may be determined experimentally using gates as energy filter, as for instance used in [21]. We have obtained a first estimate for $\Delta E = E_U + E_L$ at $B = 0$ T based on the variation of the $ef$-plateau lengths along $V_1$ as a function of $P_{RF}$ [22]. 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 ($V_2 = V_f$, see figure 2).

4. Energy distribution of emitted electrons

In the following we estimate the distribution of the energy of the emitted electrons, $p(E_U)$, based on the Master equation model of [17]. The sharpness of the distribution, $\Delta E_U$, can be tuned by the selectivity $s \equiv g/e\omega$ of the barrier at $G_2$ with $g \equiv \ln \Gamma_{\max}/\Gamma_{\min}$. Here $\Gamma_{\max}$ and $\Gamma_{\min}$ are the maximal and minimal tunnel rates during one cycle of modulation, where we also assume that $G_2$ depends exponentially on $\omega$. To obtain an expression for the energy distribution we consider the case when unloading ($e \geq \mu_D$) takes place during the phase where $\varepsilon$ changes most rapidly, such that $\varepsilon(t) \approx \varepsilon(t_0) + e \cdot t$. 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 $\Gamma_2(t) = \Gamma_2^0 \exp(\frac{1}{2}t)$, where $\Gamma_2^0$ is the escape rate when $\varepsilon(t) = \mu_D$. With these assumptions the distribution of the emission times is peaked at $t_e = -\ln \left(1/e \cdot \Gamma_2^0 \Gamma_2^0 \beta \right)$ with $\beta \equiv g \omega/2$. 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 $\hbar \Gamma_2(t) = (g/2)\hbar \omega$. 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 \( \Gamma_2^0 \) logarithmically:

\[
E_U \approx \varepsilon_1 \omega t_c = \Delta E_U \ln \left( \frac{\varepsilon_1 \omega}{\Delta E_U \Gamma_2^0} \right).
\]

Since typically \( \Gamma_2^0 \) depends on \( V_2 \) exponentially, the gate voltage can be readily used to tune the emission energy, i.e., \( E_U \propto -|e| V_2 \). To ensure single triggered excitation events (within a certain error margin) \( V_2 \) may be tuned only within the plateau voltage range, i.e., where \( I \approx e f \). The highest energy is obtained for the transition voltage, \( V_T \), where \( I = ef \) switches to \( I = 0 \), i.e., close to the negative side of the plateau where \( \Gamma_2^0 \) is minimal (see figure 2). From equation (1) it follows that increasing the modulation amplitude \( \varepsilon_1 \) enhances \( E_U \) only logarithmically. To extend the energy range efficiently, the bias voltage \( V_B \equiv (\mu_D - \mu_S)/|e| \) may be made more negative, decreasing \( \Gamma_2^0 \) since the condition \( \varepsilon = \mu_D \) will then take place earlier in the cycle, i.e., \( E_U \propto -|e| V_B \). At the same time the chance for emitting an additional electron increases, as seen from the inset in figure 2. This behaviour is consistent with the decay cascade model [19], considering that the time \( t_c \) at which the decay cascade starts is given by \( \varepsilon(t_c) \equiv \mu_S \). The corresponding escape rate at \( \Gamma(t_c) \equiv \varepsilon(t_c) \), controls the number of electrons captured per cycle. To remain in the quantized regime, \( V_2 \) and consequently \( \Gamma_2^0 \) have to be decreased as indicated by the arrow in the inset of figure 2, leading to an additional enhancement of \( E_U \) according to equation (1). Hence, combining the \( f \)-, \( V_B \)- 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 [23] and a time-gated detector technique [12] for sensitive studies of the underlying transport processes.

5. Emission characteristics in quantum Hall regime

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 [24] and [25], 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 QH liquid. The tapered channel geometry used in the present work intends to avoid this complication. Figure 3 shows evidence that in the case of the tapered channel shape the QD interacts directly with the QH liquid. We conclude this from the oscillations in \( V_T(B) \) which coincide with the superimposed Hall resistance \( R_H \) determined for the undisturbed QH liquid. We relate these oscillations to the variations in \( \mu_{S/D} \) for transitions between different integer and fractional filling factors [26] modifying the decay rates which \( V_T \) is sensitive to. In particular, the data in figure 3 demonstrate the clocked capturing of electrons from the QH liquid with fractional filling factor.

Similar oscillations at lower magnetic fields have also been reported in [20] and [25]. In [20] quantization was quenched for \( B \geq 1T \) and no clear comparison seems possible. The periodicity observed in [25] 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.

6. Conclusion

We have demonstrated an on-demand source of single electrons in high perpendicular magnetic fields up to 30T, corresponding to a filling factor \( \nu \) below \( 1/3 \). We have discussed ways to tune the emission energy as well as the sharpness of its distribution. In particular we predict an emission energy of up to several tens of meV, which may allow the probing of nonlinearly dispersing one-dimensional electron systems [27]. Of particular interest might be the fact that the device not only excites electrons in the drain leads, but also holes in the source lead. The latter process occurs during the loading cycle, as shown in figure 1(b). Finally we note that despite device operation in the fractional quantum Hall regime, fractionalization in the current characteristics is not expected, because the QD is initialized with less than four electrons. We note however, that by employing a different QD geometry, a fractional charge pump may be developed, which may be used as a measurement of the charge of the fractional quantum Hall quasiparticle, as envisaged by Simon [28].

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