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Long time relaxation phenomena of a two-dimensional electron system within integer quantum Hall plateau regimes after magnetic field sweeps

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For investigating a two-dimensional electron system (2DES) in high magnetic fields and at temperatures below 0.1 K a single electron transistor (SET) is directly fabricated on top of a GaAs/AlGaAs heterostructure containing the 2DES underneath the surface. By using the SET as a highly sensitive electrostatic potential probe, the variation of the local electrostatic potential in the 2DES under the SET can be observed. Sweeping the magnetic field over a Hall plateau regime, a characteristic hysteresislike dependence of the local electrostatic potential between up and down sweep is observed indicating a nonequilibrium state for the 2DES. Stopping the magnetic field in a Hall plateau regime, the relaxation of the nonequilibrium potential distribution within the 2DES into the thermodynamic equilibrium at very low temperatures can elapse over several hours. The hysteresis effect is interpreted as the fingerprints of eddy currents which are driven by induced electrochemical potential gradients across the incompressible regions of the 2DES.

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I. INTRODUCTION

Since the discovery of the integer quantum Hall effect (IQHE),[1] there has been no microscopic picture to describe the phenomenon entirely. In textbooks, the so-called edge channel model[2,3] for two-dimensional electron systems (2DES) of finite width combined with the Landauer-Büttiker formalism is frequently used for explaining the quantization of the Hall resistance.[3,4] However, it was always pointed out[5,6] that the externally biased current might flow through the bulk of the 2DES, supported for instance by experiments inductively probing respective samples.[7,8] According to advanced theoretical calculations[9–11] the depletion region of a 2DES in high magnetic fields is more complex: From the edge to the bulk of the system an alternating sequence of compressible and incompressible strips is formed—which show metal-like and insulatorlike screening properties, respectively. Recent scanning force microscope investigations of IQHE samples have demonstrated[12–14] the importance of the innermost incompressible strip along the edges for the Hall potential distribution and therefore for the paths the biased current takes through the 2DES. Moreover, these experiments have shown[14] that not only along mesa edges compressible and incompressible strips exist but also along the borderlines to alloyed ohmic contacts with the consequence that the biased current does not pass potential probing contacts. In a Hall plateau regime, the bulk is mainly incompressible—with embedded compressible regions due to inhomogeneities on the length scale of several hundred nanometers—and is electrically decoupled from the edges. In subsequent work we have investigated the time evolution of the local electrostatic potential of the bulk of a 2DES within the integer quantum Hall regime (IQHR) during and after magnetic field sweeps.

II. MOTIVATION

Under thermodynamic equilibrium the electrochemical potential μ_{elch}, described within a Thomas-Fermi approximation by the sum of the local chemical potential $\mu_{\mathrm{ch}}(\vec{r},B)$ and the local electrostatic energy $-e\phi_{\mathrm{el}}(\vec{r})$, is constant within the whole 2DES. In the magnetic field range between two Hall plateaus the 2DES behaves metal-like in the bulk and a change $d\mu_{\mathrm{ch}}$ of the local chemical potential due to a sweep dB of the magnetic field B applied perpendicularly to the 2DES is immediately adjusted by an adequate variation of the local electrostatic potential $d\phi_{\mathrm{el}}=d\mu_{\mathrm{ch}}/e$ because the electrons of the compressible 2DES can be easily redistributed between the 2DES and a contact of fixed electrochemical potential at the boundary of the 2DES. However, within the Hall plateau regime, where the bulk of the 2DES behaves mostly incompressible, the relaxation of the local electrostatic potential takes much longer than in the case of a compressible 2DES since the longitudinal conductivity of the bulk gets too small to establish immediately thermodynamic equilibrium in the whole 2DES. That way, a nonequilibrium state is induced within the quantum Hall regime and it will take some time for the 2DES to equilibrate after the magnetic field sweep.

Moreover, the 2DES is supposed to react on the time-dependent magnetic field change by inducing a current which tries to compensate for the variation of the magnetic field. These so-called eddy currents could already be experimentally observed around integer filling factors as large spikelike signals either in the magnetic moment of the 2DES (Refs. 15,16) measured on Hall bars or as a voltage signal between the inner and outer contact of Corbino devices.[17,18] The latter experiments were inspired by Laughlin's gedanken experiment[19] and interpreted as a charge transfer between inner and outer contact due to the magnetic flux change penetrating the circular Corbino device. After the magnetic field sweep has stopped at a certain value in a Hall plateau the induced eddy currents fade away due to dissipation[15] and the 2DES relaxes into thermodynamic equilibrium which is associated with a continuous change of the local electrostatic potential.

For investigating this nonequilibrium state and the subsequent relaxation of the bulk of the 2DES within the Hall plateau regime a metal single-electron transistor (SET) is used in this work as a highly sensitive stationary potential probe to measure the local electrostatic potential variation of the 2DES as a function of time and the applied magnetic field. This skillful setup[20–22] allows the direct observation of the dynamics of the nonequilibrium state of a 2DES under quantum Hall condition.

III. EXPERIMENTAL SETUP

The sample used in this experiment is based on a GaAs/$\mathrm{Al_{0.33}Ga_{0.67}As}$ heterostructure. The 2DES is located at the GaAs/AlGaAs heterojunction 97 nm below the surface and has a sheet electron concentration of $n_s^{\mathrm{bulk}}=(2.05\pm0.05)\times10^{11}\ \mathrm{cm^{-2}}$ with an electron mobility of $\mu_s=(1.28\pm0.04)\times10^{6}\ \mathrm{cm^2/Vs}$ at a temperature of $T=4.2$ K. In the first step, a standard Hallbar mesa is etched and ohmic contacts are alloyed to the 2DES. In a second step, a metal SET is fabricated on top of the Hallbar mesa by using a shadow-evaporation technique[23] with aluminum.

Figure 1(a) shows a scanning-electron-microscope (SEM) image of the SET on the sample surface. The SET island has a size of $0.9\ \mu\mathrm{m}\times0.1\ \mu\mathrm{m}$ and is connected by tunnel junctions of about $0.1\mu\mathrm{m}\times\ 0.1\ \mu\mathrm{m}$ size to aluminum source and drain contacts. The Coulomb energy $e^2/2C_\Sigma$ which is required for charging an additional electron to the SET island is measured to be 0.05 meV, where C_Σ is the total capacitance of the island. Since the SET is situated directly on the heterostructure [Fig. 1(c)] the 2DES below the surface couples capacitively to the SET and acts as a gate electrode for the SET island. With changing the externally applied voltage V_{2DES} between SET and 2DES a sequence of conductance peaks in the transport through the SET is observed with a period $\Delta V_{\mathrm{2DES}}^{p}$ of about 1 mV—the so-called Coulomb-blockade oscillations (CBO's).[24] Since the Coulomb-blockade characteristic of the SET is highly sensitive to electrostatic potential changes in the vicinity of the SET island, the SET can be used as a local electrometer where the spatial resolution is limited by the island size and the distance to the 2DES under the SET.

By changing the magnetic field B which is applied perpendicularly to the plane of the 2DES within a range out of a Hall plateau where the 2DES behaves metal-like, the corresponding shift of the CBO in the ΔV_{2DES} axis monitors the change of the local electrostatic potential related to the chemical potential variation of the 2DES:[20] $d\phi_{\mathrm{el}}=d\mu_{\mathrm{ch}}/e$. This can be done in a more elegant way by using a feedback circuit [Fig. 1(b)] which keeps the current through the SET constant by applying an external voltage dV_{FB} to the 2DES which compensates the variation of the local electrostatic potential[20] $-dV_{\mathrm{FB}}=d\phi_{\mathrm{el}}=d\mu_{\mathrm{ch}}/e$.

Since the presence of the SET on the surface of the heterostructure induces an inhomogeneity in the electron concentration of the 2DES, a bias voltage V_b [Fig. 1(b)] is applied to the 2DES in order to adjust the electron concentration below the SET to the bulk value n_s obtained from Hall measurements. The correct voltage V_b is determined by the methods described in Ref. 22. All measurements were done in a ^{3}He-^{4}He dilution refrigerator at the base temperature of $T=30$ mK in a magnetic field up to $B=16$ T applied perpendicularly to the plane of the 2DES.

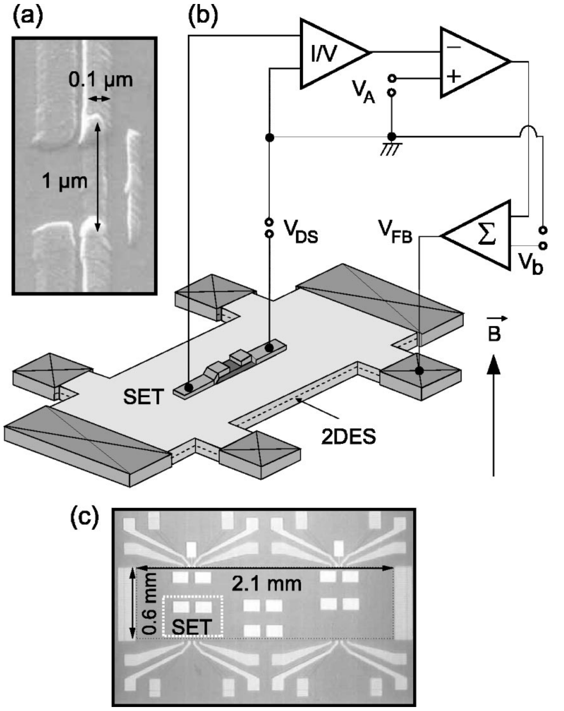

FIG. 1. Experimental setup: (a) SEM picture of a metal SET. (b) The feedback circuit is used to keep the current through the SET constant by applying an external voltage V_{FB} to the 2DES. This voltage consequently reflects the variation of the local electrostatic potential under the SET. (c) Top view on the Hall bar mesa (metal in light): Six SET's are directly fabricated on top of the heterostructure—including its contact pads which are the only SET parts visible at this resolution. The SET used in the experiment is marked by "SET." Gate electrodes on this Hall bar structure for decoupling ohmic contacts to the 2DES by electrostatic depletion are not used in these experiments.

IV. PROBING THE LOCAL ELECTROSTATIC POTENTIAL AT LOW FILLING FACTORS

Figure 2 shows the changes dV_{FB} of the measured feedback signal as function of the magnetic field B around Landau level filling factor $\nu=12$ and $\nu=14$ for increasing and decreasing sweep direction. The shaded background marks the inaccuracy in determining the filling factor values $\nu=h/e\times n_s^{\mathrm{bulk}}/B$ from the transport data. Between the Hall plateaus, the slope in the feedback voltage dV_{FB} directly reflects the expected variations of the local chemical potential[20] of few hundred μV due to the increase of the cyclotron energy with magnetic field. However, within a Hall

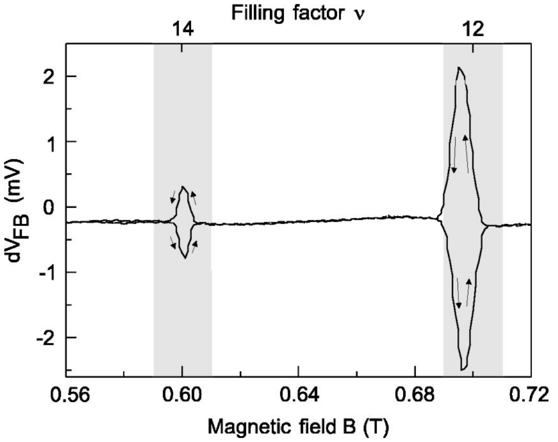

FIG. 2. Feedback voltage dV_{FB} in dependence of the magnetic field B around filling factor $\nu = 12$ and $\nu = 14$ for increasing and decreasing sweep direction indicated by arrows. The shaded background marks the inaccuracy in determining the filling factor values from transport data.

plateau where the jump of the chemical potential occurs at integer filling factors due to passing rapidly the gap between Landau levels, the measured feedback signal dV_{FB} is dominated by large voltage spikes where the sign depends on the direction of the magnetic field sweep.

Furthermore, these hysteresislike signals are also clearly observed around other filling factors. As another example, such curves around $\nu = 5$ are shown in Fig. 3—in addition, for different sweep rates. At first, the maximum value of the hysteresis seems to increase with the sweep rate but then turns into saturation.

The magnitude of these voltage signals cannot be explained by the drop in the chemical potential due to the depopulation of the highest Landau level, which is still observable when comparing the both sides of the spikes. Obviously, in these filling factor regions the feedback voltage, i.e., the variation of the local electrostatic potential, depends not only on the chemical potential change. These spikelike feedback signals around integer filling factors are interpreted in the following as the fingerprints of eddy currents which are induced by the variation of the magnetic field with time within the 2DES. The observed hysteresislike variation of the local electrostatic potential around integer filling factors is therefore related to the change of the Hall voltage $dV_{\mathrm{eddy}}^{\mathrm{Hall}}$ of these eddy currents which is consequently monitored in the feedback signal since it is superimposed to the contact voltage between the SET and the 2DES.

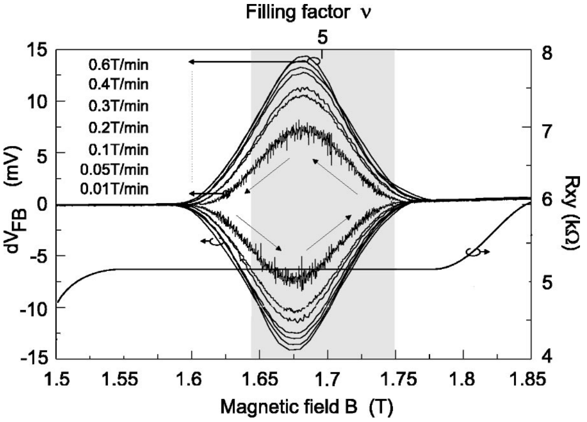

FIG. 3. Feedback voltage dV_{FB} in dependence of the magnetic field B around filling factor $\nu = 5$ for different sweep rates. The larger the sweep rate, the larger the signal. The quantum Hall curve R_{xy} measured on this 2DES is shown for comparison.

So far, it still has to be clarified where the induced eddy currents flow within the 2DES which cannot be derived directly from the experimental data. With the following discussion we suggest a microscopic picture of the physical processes which might take place.

(I) A finite 2DES exposed to a perpendicular magnetic field will try to compensate for the change of the applied magnetic field inducing a circulating current, i.e., an eddy current. In general, a nonequilibrium current can flow in the compressible and incompressible regions. The latter is possible in presence of an electric field E_y driving a dissipationless Hall current j_x in perpendicular direction which can be formally expressed by $j_x = \nu E_y e^2/h$, where ν denotes the local filling factor of the incompressible region. Scanning force microscope investigations have indeed shown[12–14] that in a QHE experiment most of the externally biased current is flowing along such incompressible regions even in noninteger filling factor regime. The respective electric fields or Hall voltages are due to charging, shifting or reshaping the compressible regions in comparison to thermodynamical equilibrium.

(II) According to Faraday's law, an electric field is induced along a closed loop penetrated by the magnetic field variation. The borderline between incompressible and compressible regions along the periphery of a 2DES form such a distinct closed loop. The respective Hall currents perpendicular to this borderline lead to a redistribution of electrons against the background charges, and therefore to a voltage $dV_{\mathrm{eddy}}^{\mathrm{Hall}}$ which is built up between the bulk and the compressible edge region of the 2DES. As a consequence, a dissipationless Hall current—the eddy current—circulates in the incompressible region between the compressible regions driven by the Hall voltage drop $dV_{\mathrm{eddy}}^{\mathrm{Hall}}$. That way, capacitive and inductive energy is stored in this region due to the charge shift and the circulating eddy current, respectively.[15] Actually, any compressible droplet in the 2DES offers a distinct closed loop along its contour line and therefore reshapes with the magnetic field variation, changing the local electric field in its vicinity and consequently creating eddy currents in the incompressible region around it. Nevertheless, these currents are supposed to be much less significant then the eddy currents near the edge due to the comparatively smaller magnetic flux penetrating the respective area. Therefore, it can be assumed that most of the induced voltage drops close to the edge driving eddy currents in this region.

(III) With stopping the magnetic field variation, a defined electrochemical potential landscape is present leading to a certain eddy current distribution. The decay into thermal equilibrium requires dissipation which dominantly occurs by electron scattering between the compressible regions of different electrochemical potential. Since these scattering pro-

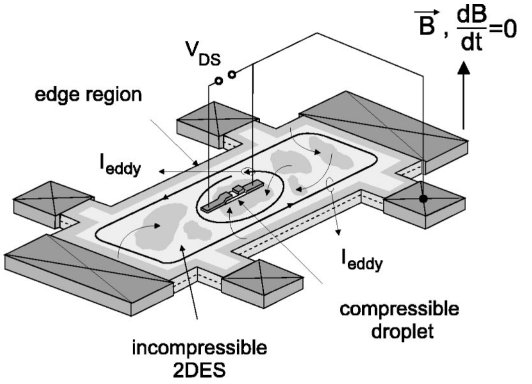

FIG. 4. The eddy currents flow within the whole incompressible bulk driven by the induced gradient in the electrochemical potential which exists between the single compressible droplets. The scattering of electrons between compressible regions of different electrochemical potential is indicated by arrows. Note, although the 2DES is in the IQHR, a compressible strip encircles the whole 2DES [known from scanning force microscope investigations (Ref. 14)].

cesses are most likely to happen when a compressible network is present in the bulk of the 2DES, i.e., in the regime around half filling factor values, the eddy currents cannot develop outside the Hall plateau regime. In contrary, around an integer filling factor, the scattering is much less probable due to the extended incompressible regions—except for higher values of the filling factor where the insulating behavior is less pronounced. This can be derived from the observed saturation of the maximum value of the hysteresis signals shown in Fig. 3: At a slow sweep rate the magnitude of the induced voltage signals are comparatively smaller than for faster sweep rates since the induced electrochemical potential gradient is simultaneously reduced by the scattering of electrons. When the magnetic field sweep is stopped on a hysteresis peak, the feedback voltage returns on a short time scale to the value expected due to the chemical potential variation only. Reversing the direction of the magnetic field sweep from up to down leads immediately from the upper to the lower hysteresis curve shown in Figs. 2 or 3.

Important to note from this picture is the interplay between compressible and incompressible regions leading to these non-equilibrium eddy currents. The compressible regions within a 2DES allow for the electron redistribution in the system creating the necessary electric field for driving the dissipationless eddy currents in the incompressible regions in between. This situation is schematically depicted in Fig. 4. After stopping the magnetic field in an integer filling factor regime, the equilibration process starts from the edges and shifts the electrochemical gradients—driving the eddy current—into the bulk until they vanish.[25]

Obviously, the magnitude and the relaxation time of the hysteresis signals strongly depend on how good the induced electrochemical potential gradient can be maintained within the 2DES. Thus, at smaller integer filling factors, the relaxation of the 2DES into thermodynamic equilibrium should take much longer due to the more insulating behavior of the bulk and the induced eddy currents might even become persistent over the observation time interval which is discussed in the next section.

V. PROBING THE RELAXATION OF A 2DES INTO THERMODYNAMIC EQUILIBRIUM

Around smaller filling factors our feedback circuit can no longer follow the variation of the local electrostatic potential since the 2DES becomes insulating and the region below the SET is decoupled from the ohmic contact where the feedback voltage is applied. Instead, charge fluctuations are observed indicating that the bulk of the 2DES has lost its good screening properties. Since the experimental approach using a feedback circuit consequently fails in this regime, the variation of the local electrostatic potential within these Hall plateaus can only be measured by simply monitoring the current through the SET.

For investigating the relaxation of the local 2DES after having disequilibrated the system by sweeping the magnetic field from a fixed initial point B_0 to a certain magnetic field B_{relax} within a Hall plateau regime [Fig. 5(a)], the current through the SET is monitored versus time at constant magnetic field B_{relax}. Figure 5(b) shows the measured $I_{\mathrm{SET}}(t)$ characteristics for different magnetic field values around filling factor $\nu=1$. After a period of about an hour the current through the SET shows Coulomb blockade oscillations as a function of time which can be related to a continuous relaxation of the local electrostatic potential under the SET. Since each oscillation is equivalent to a period $V_{\mathrm{2DES}}^{\mathrm{P}}=1$ mV of the Coulomb blockade characteristic of the SET, the time dependence of the local electrostatic potential variation $\phi_{\mathrm{el}}(t)$ can be derived from the $I_{\mathrm{SET}}(t)$ characteristic which is shown in Fig. 5(c) for $B_{\mathrm{relax}}=8.6$ T ($\nu\approx1$). Strikingly, the total change in the local electrostatic potential of more than 40 mV during the period of oscillation exceeds significantly the possible value related to the variation of the chemical potential around the respective integer filling factor value. Obviously, the change in the local electrostatic potential under the SET is related to the induced electrochemical potential difference which leads to the hysteresis effects discussed in the previous section. Another striking feature of the measured data depicted in Fig. 5(b) is the long time constant of the relaxation process at filling factor $\nu=1$. It can be derived from the oscillating current through the SET that the 2DES takes up to twenty hours to reach thermodynamic equilibrium at a temperature smaller than 0.1 K. This remarkably long time has to be generally considered when measurements are performed within the quantum Hall regime.

These experimental observations can be interpreted according to the hysteresis signals discussed in the last section: As long as the magnetic field is swept to the constant point B_{relax} within a quantum Hall plateau, eddy currents circulate within the incompressible regions of the 2DES. This situation is schematically depicted in Fig. 4. When the magnetic field variation stops at a certain point within a Hall plateau, the capacitive and inductive energy stored in the 2DES has to be dissipated for reaching thermal equilibrium. Obviously, this is not achieved by a simple move of the compressible strips into their former position. According to our micro-

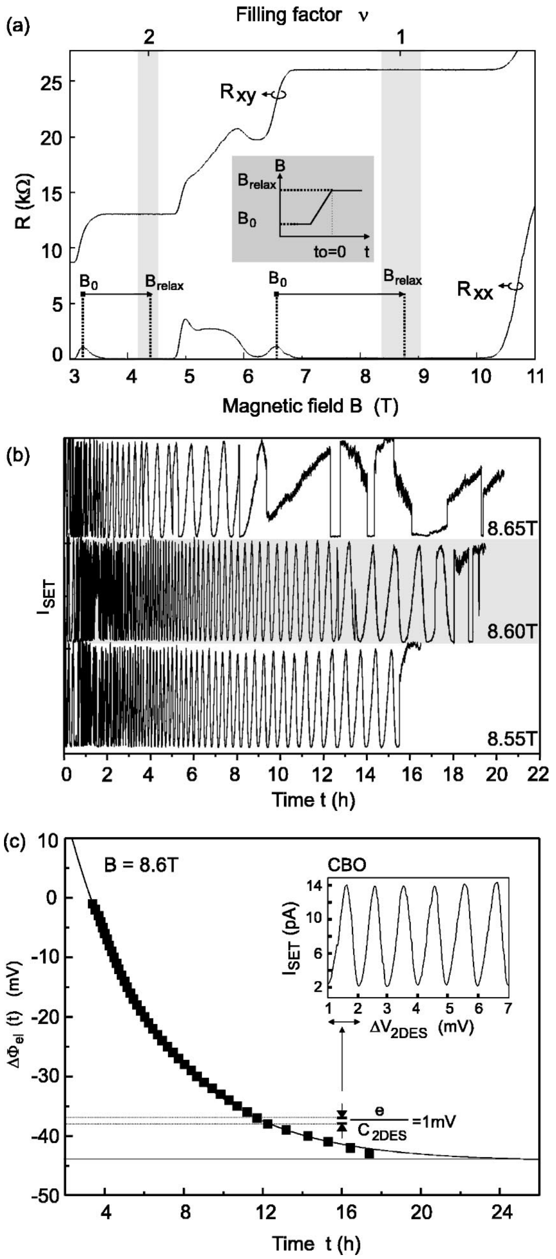

FIG. 5. (a) For investigating the relaxation of the local 2DES after having disequilibrated the system by sweeping the magnetic field from a fixed initial point B_0 to a certain field B_{relax} within a Hall plateau, the current $I_{\mathrm{SET}}(t)$ through the SET is monitored versus time at a constant magnetic field which is shown in (b) for different magnetic field values around filling factor $\nu=1$. Each oscillation is equivalent to a period $V_{\mathrm{2DES}}^{\mathrm{P}}=1$ mV of the CBO of the SET. (c) Time dependence of the local electrostatic potential variation $\phi_{\mathrm{el}}(t)$ derived from the characteristic for (b). The solid curve represents an exponential fit to the data points.

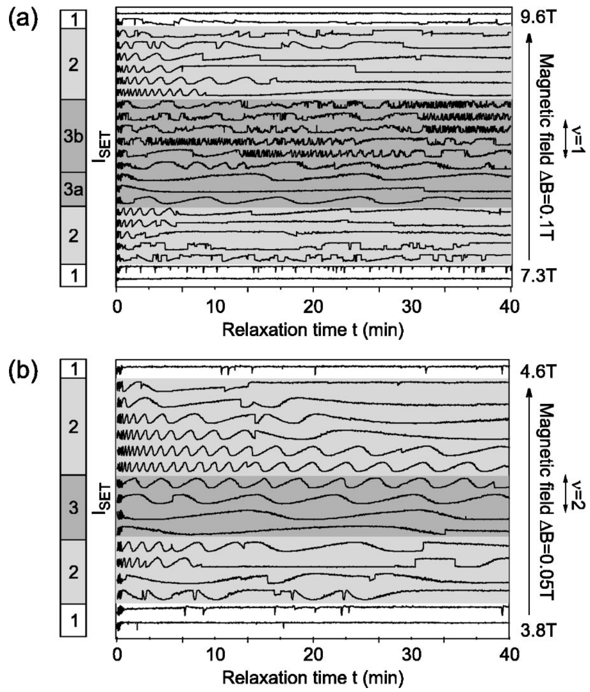

FIG. 6. (a) $I_{\mathrm{SET}}(t)$ characteristic for different magnetic field values within the Hall plateau of filling factor (a) $\nu=1$ and (b) $\nu=2$. The different sections marked by 1 to 4 on the left side are discussed in the text. On the right side, the magnetic field range is indicated, as well as the range where filling factor $\nu=2$ is expected due to transport measurements.

scopic picture, the necessary dissipation is reached by the redistribution of charges between the different compressible regions due to the scattering of electrons in the direction of the electrochemical potential gradient. Consequently, the observed slow variation of the local electrochemical potential versus time mirrors the lack of dissipation for relaxation of the 2DES into thermodynamic equilibrium. Figure 6 shows the $I_{\mathrm{SET}}(t)$ characteristic for magnetic field values around the filling factors $\nu=1$ and $\nu=2$. Within these quantum Hall plateaus different magnetic field intervals concerning the relaxation behavior can be identified marked by (1), (2), (3a), and (3b).

(1) No relaxation observed: In the outer region of the Hall plateaus the 2DES behaves almost metal-like and thermodynamic equilibrium is reached as soon the magnetic field sweep stops. The observation is similar to the situation around filling factor $\nu=5$ discussed in the previous section where the time scale of the relaxation is very short which makes it impossible to be resolved with our setup.

(2) The continuous variation of the local electrostatic potential under the SET island, indicated by the oscillating current through the SET, is related to the relaxation of the 2DES into thermodynamic equilibrium—as discussed before. The single jumps in the $I_{\mathrm{SET}}(t)$ characteristics can be explained by charge fluctuations in the vicinity of the SET island due to scattering processes of single electrons.

(3a) The almost equidistant oscillations indicate a very long time constant of the relaxation process.

(3b) This range is a section of Fig. 5(b) for the time up to 40 min after the magnetic field sweep has stopped. The dynamic and irregular current signal through the SET hints at low-frequency charge fluctuations in the vicinity of the SET island. These irregular potential fluctuations detected by the SET might be due to the breakdown[16] of the quantum Hall state in the bulk of the 2DES.

VI. CONCLUSIONS

A metal SET directly fabricated on top of a 2DES is used as a highly sensitive electrometer for the local 2DES under the SET island. This experimental approach allows the direct observation of the dynamics of the nonequilibrium state of a 2DES under quantum Hall condition which is induced by the varying magnetic field. That way, a hysteresislike variation of the local electrostatic potential is observed which is interpreted as the fingerprints of dissipationless eddy currents driven by an induced gradient in the electrochemical potential over the incompressible regions. The relaxation of these eddy currents depends on the remaining bulk conductivity of the 2DES within a Hall plateau. With our setup, the time dependence can only be resolved around filling factor $\nu=1$ and $\nu=2$. There, the relaxation of the 2DES can elapse over several hours at temperatures smaller then 0.1 K. It shows that, when measuring the Hall resistance while sweeping the magnetic field, the 2DES cannot be considered as being at thermodynamic equilibrium at each magnetic field value.

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[25] Also the experiment and description of Yahel *et al.* (Ref. 8) is consistent with the presented picture: There a Hall current is induced by changing the voltage applied to a backgate causing due to the capactiance coupling an electrochemical potential gradient between bulk and edge region of the 2DES.