Bias-induced breakdown of electron solids in the second Landau level

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Reentrant integer quantum Hall (RIQH) states at \( \nu = 2 - 4 \) are believed to be electron solid phases, though their microscopic description is unclear. As bias current increases, thereby increasing the Hall electric field, these states break down via several distinct stages with sharp transitions in between. The electronic temperature of RIQH states appears to stay cold even during breakdown, unlike neighboring fractional quantum Hall states whose breakdown is consistent with simple Joule heating. Detailed measurements of the RIQH breakdown process and its temperature dependence provide new insights into the nature of these states.

A variety of exotic electronic states emerge in high mobility 2D electron gases (2DEGs) at very low temperature, and in a large out-of-plane magnetic field. The most robust are the integer quantum Hall states, described by discrete and highly degenerate Landau levels. When the uppermost Landau level is partially filled, electrons in that level may reassemble into a fractional quantum Hall (FQH) liquid as composite Fermions [1–3]. Or, they may condense into charge-ordered states ranging from Wigner crystals to nematic stripe phases [4–8].

The electronic ground state at a particular magnetic field is determined by the filling factor \( \nu = h n_s / eB \), the ratio between areal densities of magnetic flux quanta (eB/h) and conduction electrons \( n_s \). Filling factors 0 to 2 correspond to partial filling of the first spin-degenerate Landau levels with orbital quantum number N=0; from \( \nu = 2 - 4 \) the first (N=0) level is completely filled and the second (N=1) is partially filled, etc. Large magnetic fields \( \nu < 2 \) tend to favour FQH states, with vanishing longitudinal resistance, \( R_{xx} \rightarrow 0 \), and transverse resistance \( R_{xy} \rightarrow h/e^2 \nu \) quantized at fractional values of \( \nu \).

At much lower fields \( \nu > 4 \), Coulomb interactions dominate over magnetic energies, favouring charge-ordered electron solids over FQH liquids. Electron solids at \( \nu > 4 \) span a phase diagram that includes a stripe phase with highly anisotropic resistivity near half-filling, flanked on either side by ‘bubble’ or liquid crystal phases whose longitudinal resistivity vanishes isotropically. Transverse resistance is quantized at the nearest integer value of \( \nu \) in bubble and liquid crystal phases, so they are often called reentrant integer quantum Hall (RIQH) states. Their transport characteristics result from the ‘freezing’ of electrons in the partially filled Landau level, which then do not contribute to transport.

The nature of electron solid states at intermediate filling factors, \( 2 < \nu < 4 \), is much less clear. Here, the N=1 Landau level is partially filled and competition between Coulomb and magnetic energies intersperses multiple FQH and RIQH states within a narrow range of magnetic field (Fig. 1a).[9] One important puzzle is why four RIQH states appear between \( \nu = 2 \) and \( \nu = 3 \), or between \( \nu = 3 \) and \( \nu = 4 \), but only two such states appear at each higher filling factor. Experimental input is important, as many theoretical tools used to understand RIQH states at high filling factor become less trustworthy below \( \nu = 4 \).[7, 10] From a practical point of view, however, RIQH states from \( 2 < \nu < 4 \) are extremely fragile, limited to temperatures below 40 mK and the highest mobilities samples.[11–14]

Much of what is known about these states comes from monitoring their collapse at finite temperature.[11, 12] For example, melting temperatures for \( \nu = 2 - 4 \) RIQH states scale with Coulomb energy, indicating that they are stabilized by interactions (as expected for electron crystals).[11] But large differences in melting temperature below and above \( \nu = 4 \) may indicate that the crystal structure changes with filling factor.[15]

Like other charge ordered systems across the field of strongly-correlated electronics, RIQH states are susceptible to destabilization by an electric field, which depins the crystal from an underlying disorder potential or reforms it with altered long-range order.[16–18] Experimental measurements of the bias-driven sliding dynamics of charge density waves date back to work on NbSe\(_2\) nearly four decades ago, and remain an area of active research.[19–21] Transport signatures of depinning, whether for RIQH states or transition metal oxides, include sharp transitions out of the insulating state for increased bias, and excess resistance noise in the transition region.[16, 17]

In this work, we present the first high bias measurements of RIQH states in the second Landau level, offering new insights into the nature of electron solids that may be stabilized in this regime of competing energy scales.
Several finely-featured phase transitions appear as a function of bias current, before the state melts completely at very high bias. Extremely low electron temperatures even in the (unmelted) high bias phases indicate strong electron-phonon coupling, pointing to the role of suppressed screening in favouring Coulomb-dominated over FQH states. A dramatic contrast between differential (AC) and static (DC) resistances at high bias may indicate a nearly-frictionless sliding mechanism that is activated above a critical electric field.

Measurements were performed on a 300 Å symmetrically doped GaAs/AlGaAs quantum well with low temperature electron density \( n_e = 3.1 \times 10^{11} \text{ cm}^{-2} \) and mobility \( 15 \times 10^6 \text{ cm}^2/\text{Vs}. \) [22] FQH characteristics were optimized following Ref. 23, in a dilution refrigerator with base temperature \( T_{\text{mix}} \sim 13 \text{ mK} \). Sample temperature was controlled using the mixing chamber heater or a thermometer/heater pair on the back of the chip carrier for faster response. Electronic temperature, \( T_e \), at low bias was monitored using temperature-dependent features in \( R_{xx} \), and confirmed to follow \( T_{\text{mix}} \) down to 13 mK. [11]

During extended high bias measurements, the chip carrier (and therefore the GaAs lattice) warmed by up to 2 mK above \( T_{\text{mix}} \).

Electrical contact to the 2DEG was achieved by diffusing indium-tin beads into the corners and sides of the 5×5 mm chip (Fig. 1a inset). Differential resistances \( \tilde{R}_{xx} \equiv \partial V_{xx}/\partial I_b \) and \( \tilde{R}_{xy} \equiv \partial V_{xy}/\partial I_b \) were measured by lockin amplifier with an AC current bias, \( I_b^{ac} = 5 \text{ nA} \), at 71 Hz. An additional DC current bias \( I_b^{dc} \) induced a Hall electric field in the plane of the sample and transverse to the current direction.

Characteristic \( \tilde{R}_{xx} \) and \( \tilde{R}_{xy} \) traces at \( I_b^{dc} = 0 \) show well-developed fractional quantum Hall states at filling factors \( \nu = 2 \pm 1/5, 2+1/3, 2+1/2, 2+2/3 \) and \( 2+4/5 \) (Fig. 1a). Four RIQH states are seen, labelled R2a-R2d following conventional notation. \( \tilde{R}_{xx} \) traces over the R2c reentrant state change as \( I_b^{dc} \) is increased (Fig. 1b), mapping out a typical 2D fingerprint with sharply delineated regions. Data for different cooldowns or measurement configurations were slightly different in the details, but qualitative characteristics were consistent for every realization of a well-developed reentrant state in the second Landau level (see supplement). Sharp transitions of the type seen in the RIQH state breakdown are entirely absent from the neighbouring \( \nu = 5/2 \) state, a distinction seen for all RIQH states compared to all fractional states (see supplement).

The diamond of \( \tilde{R}_{xx} \) features surrounding the center of the reentrant state can itself be divided into three distinct subregions, labelled ‘A’, ‘B’, and ‘C’ in Fig. 1b. [18] Region A is characterized by very low \( \tilde{R}_{xx} \); here the electron solid state is presumably pinned and completely insulating. A sharp transition is observed to region B, where \( V_{xx} \) grows rapidly with \( I_b \) giving a large \( \tilde{R}_{xx} \). High-
The noise previously reported in a high-bias phase analogous to region C appears only at high bias, after passing the highly-dissipative region B, it may be tempting to associate it with a RIQH state that has been destroyed by bias-induced heating. It is clear, however, that C does not represent the molten remains of a RIQH electron crystal. Such a melting transition is observed for even higher biases (dashed boundary in Fig. 2a, up to 600 nA), where $R_{xx}$ becomes again nearly flat with temperature-independent resistance. On the contrary, region C appears to be anomalously cold, significantly colder than might be expected by balancing the measured dissipation in the sample with electron-phonon cooling into the lattice.[24] As discussed below, the fact that region C stays cold even with significant bias heating implies extremely weak screening for this state, a characteristic that may aid in understanding RIQH breakdown at a microscopic level.

Figure 2 illustrates an extreme sensitivity of high bias data to small increases in lattice temperature. $R_{xx}$ data at $T_{mix} = 14$ mK exhibits numerous sharp features that shift smoothly in bias and magnetic field (Figs. 2a,b). Increasing $T_{mix}$ from 14 to 15.6 mK (Fig. 2c) melts all of these features within region C, though a small amount of rippling remains and a sharp transition is still observed at the high-bias boundary (transition to hatched region in the figure). This strong temperature dependence indicates that the electronic system remains tightly coupled to $T_{mix}$ even at extremely low temperature, and even with hundreds of nA of bias current applied.

Conventional methods of electron temperature estimation, such as Arrhenius plots of resistivity, are not relevant in region C where some breakdown has already occurred. However, and order-of-magnitude estimate of electron overheating by dissipation in region C can be extracted from the observation that qualitative characteristics (sharp features inside region C) appear similar in the low and high bias regions in Fig. 2b (14 mK), whereas the character at both low and high bias changes dramatically after only a 1.6 mK increase in mixing chamber temperature (Fig. 2c). In other words, raising the bias from 200 to 400 nA apparently heats the electron gas less than raising the mixing chamber from 14 to 15.6 mK. More compactly, the electron temperature at $T_{mix}$ with a bias of $I_b$ can be expressed as $T_e|_{I_b,T_{mix}}$. With this notation, the observation above implies $T_{e|_{200,14}} \lesssim T_{e|_{200,15.6}}$. In the paragraphs that follow we consider the implications of this inequality on electron cooling in reentrant states.

Phonons provide the dominant cooling mechanism for a macroscopic region of electron gas in the quantum Hall regime, as Wiedemann-Franz thermal conductivity collapses with longitudinal conductivity, $\sigma_{xx} = \rho_{xx}/\rho_{xy}^2$, in large magnetic fields (see supplement).[24–28] The cooling power from electrons in a 2DEG at temperature $T_e$, into phonons in the GaAs lattice at temperature $T_l$, has been calculated for the “hydrodynamic” regime of small $\sigma_{xx}$, and confirmed experimentally in both integer and fractional quantum Hall regimes.[24] One expects:

$$P_{e-ph}/A[W/m^2] = \gamma/\sigma_{xx}(T_e - T_l)$$

where $A = 2.5 \times 10^{-5}$ m$^2$ is the area of the chip and the prefactor $\gamma = 2.6 \times 10^{-6}$ W/m$^2$K$^4$Ω describes the
efficiency of electron-phonon coupling, including details of the phonon spectrum and dielectric properties of the 2DEG. Eq. 1 differs from the conventional result[25] by a reduced temperature exponent ($T^4$ instead of $T^5$) and by the $\sigma_{xx}$ in the denominator because the static Thomas-Fermi screening approximation breaks down in the hydrodynamic limit: the charge density profile of a low-conductivity 2DEG cannot be assumed to respond instantaneously to electric fields associated with phonons in a piezo-electric crystal.

The inequality $T_{c}\lesssim T_{c1.4}$ extracted from Fig. 2, together with Eq. 1, can be used to extract a lower limit for $\gamma/\sigma_{xx}$ in this experiment. The Joule power dissipated into the 2DEG at 200 nA (Figs. 2a-c) is $P_J = V_{xx}I_b = 10$ pW, and at 400 nA it is 30 pW. ($V_{xx}$ at high bias was obtained by integrating $\tilde{R}_{xx}$, confirmed to match the value $V_{xx}$ measured directly within 20%). Equating Joule power dissipated into the 2DEG with power emitted into lattice phonons (Eq. 1), the inequality above implies $\gamma/\sigma_{xx} > 0.04$. [29] Using the value $\gamma = 2.6 \times 10^{-6}$ W/m$^2$K$^2$Ω from Ref. 24, calculated for phonon emission from a GaAs 2DEG, one would obtain an exceedingly small $\sigma_{xx} < 7 \times 10^{-8}$Ω$^{-1}$, that is, $\rho_{xx} < 7\Omega$.

Rather than proceeding with the quantitative analysis above, it is worth remembering that of Eq. 1 represents the interactions of phonons with single-particle-type excitations of the Fermi sea. Given that the state in region C is almost certainly not composed of free particles (the RIQH state is not yet melted)[30], it is more useful to consider the physical interpretation of the prefactor $\gamma/\sigma_{xx}$: As longitudinal conductivity decreases, it is harder for currents to flow in response to dynamic fluctuations in the potential. Screening of the piezoelectric field fluctuations associated with a passing acoustical phonon are reduced, and electron-phonon interactions become stronger.

The extremely small value of $\sigma_{xx}$ implied by the calculation above should therefore be taken not as a real conductivity to be compared to the experimental value (it would be an order of magnitude too low), but rather as an indication of very weak screening in the RIQH state. In fact, this indication of extremely weak screening helps to understand why electron solids can be stabilized in the partially filled N=1 Landau level, in the face of a competing magnetic energy scale that would tend to favour FQH liquids.[7] Minimal screening allows for a long range Coulomb interaction, thereby reducing the energy of electron crystals with long range order. RIQH states stabilize in the range of filling factors with the least possible screening, i.e. the best coupling to the phonons and the most effective cooling.

Figure 3 draws attention to the fact that the DC resistance $V_{xx}/I_{b}^{sc}$ remains large into region C, even though the differential resistance $R_{xx}$ (measured simultaneously) drops to a very small value. This characteristic of the breakdown process can help to rule out some breakdown mechanisms, while supporting others. For example, one model of quantum Hall breakdown is that a narrow channel of conducting liquid through the insulating bulk might appear at high bias, like a lightening bolt through conducting plasma in the otherwise-insulating air.[31] In this case $V_{xx}$ would be strongly reduced, inconsistent with the data.

Instead, the data in Fig. 3 might be explained by an electron crystal state that slides freely above a certain longitudinal electric field, like marbles rolling down a tilted washboard potential. As in a conventional diode, the longitudinal voltage (electric field) across the sample would be locked to the breakdown field independent of the sliding velocity, that is, independent of the bias current. Although this scenario is qualitatively consistent with existing predictions for sliding dynamics[32], a more quantitative analysis of this mechanism awaits further theoretical consideration.

In conclusion, we measured the high bias phase diagram of RIQH states in the second Landau level, where the microscopic description of the states even at zero bias is still under debate. A small region of high $\tilde{R}_{xx}$ is followed by a much larger region in which $\tilde{R}_{xx}$ is nearly zero, but DC longitudinal voltage remains large. This region is decorated by multiple fine features that show an extreme sensitivity to lattice temperature even down to 14mK. The strong electron-phonon interaction implied by this observation indicates that screening is strongly
suppressed, and may help in understanding the thermodynamic stability of competing RIQH and fractional states.

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SUPPLEMENT

I: On the dominance of phonon- vs electron-mediated cooling of the bulk of a FQH samples

In the filling factor range $2 < \nu < 3$, source and drain ohmic contacts are separated from the 2DEG by $\sim 10k\Omega$ contact resistance, and longitudinal conductivity per square through the 2DEG is $< 10^{-4} \Omega^{-1}$ ($\sigma_{xx} = \frac{\rho_{xx}}{\rho_{xy}^2}$). Together, these numbers give a Wiedemann-Franz (WF) thermal conductivity from source or drain into the bulk of the 2DEG that is vanishingly small, $< 10^{-10}$ nW/mK or less at 15 mK. By comparison, the interior 3 mm x 3 mm region of the 2DEG is coupled to phonons with a thermal conductivity that is many orders of magnitude larger, between $10^{-6}$ and $10^{-2}$ nW/mK depending on 2DEG conductivity[1, 2]. This massive discrepancy between WF coupling and coupling to phonons ensures that electrons in the bulk of the 2DEG (though not the ones right next to source and drain contacts) are locked to the phonon temperature of the chip rather than to the electron temperature of the leads.

II: How does a quantum Hall sample measured at high bias stay cold?

Although the dissipation in the bulk of the 2DEG was quite small in this experiment—10’s of picowatts at most—the total Joule power dissipated at the sample was much larger (almost 2 nW at 400 nA) because the two-probe resistance between source and drain (mostly $R_{xx}$) is much larger than $R_{xy}$. Here we address the question: how can 2 nW be dissipated at the sample without raising its temperature significantly above the mixing chamber temperature?

Almost all heat dissipation in the quantum Hall regime occurs in the source and drain contacts. With half of the power, 1 nW, dissipated in a single contact, the rise in contact temperature is set by the thermal resistance from the contact, through a bond wire and a chip carrier connector, to well-cooled measurement wires at the mixing chamber temperature. This thermal resistance can be estimated from the measured cooling power when heat was applied to a resistor mounted directly to the back of the chip carrier. Any heating applied to the chip carrier had to be carried away by the 16 leads bonded to the carrier backplane. 6 nW of power applied to the heater on the back of the chip carrier was seen to warm the sample by 11 mK, giving a thermal resistance through each lead of $29 \text{mK/nW}$. That is, 1 nW into the source or drain would warm it to a temperature around 40 mK. Is it possible to keep 2DEG cold with if source and drain contacts are at 40 mK?

Supplement section I shows that the temperature of electrons in the bulk of the 2DEG is set by the phonon temperature, not by the electron temperature in the leads. With source and drain at 40 mK, and the chip backplane at 15 mK, the phonon temperature will then be determined by the relative areas of source/drain contacts ($\sim 0.25 \text{ mm}^2$ for each) compared to the area of contact to the backplane ($\sim 25 \text{ mm}^2$). Even taking into account that phonon heat flux through the boundary at 40 mK is 10 times higher than at 15 mK, the phonon temperature will stay close to the (cold) backplane temperature.

Note that through these calculations we have assumed a homogeneous phonon temperature throughout the chip, despite the fact that heating is localized at source and drain contacts while cooling is spread across the backplane. This approximation can be justified by comparing lateral phonon thermal resistivity per square through the 0.3 mm-thick GaAs chip itself ($2 \times 10^8 \text{K/W}$, estimated from Ref. 3), compared to the thermal boundary resistance $3.5 \times 10^8 \text{mm}^2\text{K/W}$ estimated from Ref. 4. Together these give a characteristic thermal “spreading” length of 1.3 mm from each contact, close to half of the chip dimension.

III: Comparison of two different cool downs, for the full range $\nu = 2 - 3$

Figure S:1 shows $\tilde{R}_{xx}$ high bias data from $\nu = 2$ to $\nu = 3$ for two different cooldowns, illustrating to what extend the qualitative breakdown characteristics of both FQH and RIQH states are independent of sample details. For the RIQH states in both cooldowns, one can easily identify insulating region A, initial break down of the reentrant states in B, and ripples/sharp features in region C. These three regions are especially visible for the two strongest reentrant states R2c and R2a. In contrast to reentrant states, the insulating regions corresponding to 5/2, 7/3, 8/3 and 12/5 FQHE plateaus do not demonstrate sharp breakdowns, even in the case of a weak 12/5 state, which disappears under biases above 100 nA.

It is also interesting to note an apparent competition between FQHE and RIQHE. Comparing the two cooldowns one notices that the stronger RIQH states in cooldown 1 (that is, wider in magnetic field at zero bias) correspond to weaker FQH states. Apparently, the relative strength of reentrant and fractional states can differ from cool down to cooldown, and is not defined only by the mobility of the sample.
FIG. S:1. $\tilde{R}_{xx}$ dependence on bias and magnetic field between $\nu = 2-3$ for different cool downs. The one with stronger RSs demonstrates weaker fractional plateaus even in the limit of the high biases, where RIQHE and FQHE states are separated by region of free electrons.
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