Temperature-Dependent High-Current Breakdown of the Quantum Hall Effect

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We have developed a model of the high-current breakdown of the integer quantum Hall effect, as measured in contactless experiments using a highly-sensitive torsion balance magnetometer. The model predicts that, for low-mobility samples, the critical current for breakdown should decrease with, and have a linear dependence on, temperature. This prediction is verified experimentally with the addition of a low-temperature (< ~ 300 mK) saturation of the critical current. It is shown that this saturation is consistent with quasi-elastic inter-Landau-level scattering when the maximum electric field in the sample reaches a large enough value.

Shortly after the discovery of the Integer Quantum Hall Effect (IQHE) [1], in transport measurements on Two-Dimensional Electron Systems (2DESs) using Hall bar geometry, it was found that the associated dissipationless state, $\rho_{xx} = 0$, would break down if a sufficiently large current was passed through the device [2]. These early measurements ascribed a critical current density of approximately 0.5 A m^{-1} [2], corresponding to a critical Hall electric field of the order of 10^4 V m^{-1}. Later work on Hall bars with narrow constrictions [3] gave much higher critical fields of the order of 10^5 V m^{-1}. Further work has since shown that sample geometry, mobility and contact configuration can all affect the measured critical current [4]. For this reason, a contactless geometry is desirable for IQHE breakdown measurements.

Currents can be induced in a 2DES by subjecting it to a time-varying magnetic field. These induced Eddy Currents (ECs) become large as ρ_{xx} tends to zero at integer, and some fractional, values of the Landau Level (LL) filling factor, ν. These ECs can be detected *via* their associated magnetic moment, M, using a torsion balance magnetometer [5], figure 1.

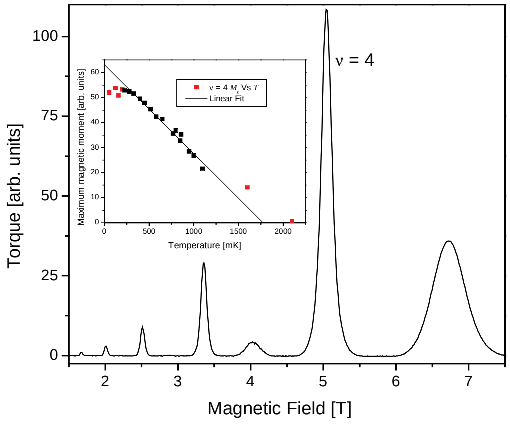

Figure 1. Induced eddy currents, shown as their resultant torque, in a low-mobility 2DES. Inset: the temperature dependence of M_s.

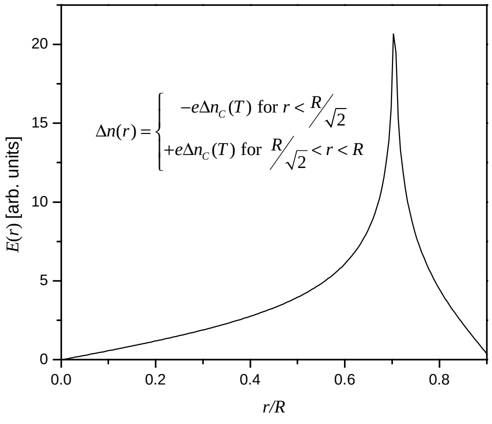

Figure 2. The calculated field profile, $E(r)$, for the shown charge redistribution in the 2DES plane.

The magnitude of the ECs saturates to some value, M_s, at sufficiently fast sweep rates [5], and M_s is dependent on temperature, figure 1 (inset). Previous measurements have found that this temperature dependence is very different for, emperically, 'high'- and 'low'-mobility samples [6] and the crossover between the two types of behaviour occurs at μ > 80 $\mathrm{m^2\,V^{-1}\,s^{-1}}$ in GaAs 2DESs. Here we shall provide a model that explains several astounding features of the ECs in *low-mobility* samples which cannot be explained using existing theories of IQHE breakdown:

- ECs are only seen at low temperatures (<~1K), much smaller than the cyclotron energy.
- M_s can achieve greater values in 'dirty', more disordered (low-mobility) samples.
- In low-mobility samples the temperature dependence of M_s is approximately linear.
- These results are general: the same effects are observed in GaAs 2DES and in SiGe 2D Hole S.

M can the be written as the integral of the tangential current density, $j_\phi(r)$, over the sample area,

$$M = \pi\int_0^R j_\phi(r)r^2dr = \pi\int_0^R \sigma_{xy}E_r(r)r^2dr\,.$$

Our model of breakdown, developed from an original idea due to Dyakonov [7], is based on the fact that the radial electric field results from a redistribution of charge, by $\Delta n(r)$ away from the equilibrium configuration, throughout the plane of the 2DES. This redistribution shifts the Fermi level away from its initial position and the probability of thermal activation of charge carriers is exponentially dependent on this shift. As a consequence, σ_{xx} should demonstrate threshold-type behaviour: once the probability of activation becomes high enough the radial electric field, and hence the EC, cannot be sustained. Therefore, there is also a temperature dependent threshold value of $\Delta n(r)$, $\Delta n_c(T)$.

The amount by which the Fermi-level is shifted is related to the density of localised states between LLs, ρ_L. If, as can be expected in low-mobility samples, ρ_L is approximately constant then it can be shown that the temperature dependence of M_s should be of the form

$$M_s(T) = A - BT\,,$$

as seen experimentally, figure 1 (inset). The low-temperature saturation is, however, not explained by this alone.

As the size of M_s increases, so too does the magnitude of $E(r)$. Large electric fields can cause IQHE breakdown by QUasi-elastic Inter-Landau-Level Scattering (QUILLS) [8]. In order to calculate $E(r)$ a form of $\Delta n(r)$ needs to be assumed. The obvious first guess to give the largest radial field possible would be as shown in figure 2 (or the same with the opposite sign, depending on the direction of the magnetic-field sweep). This distribution provides overall neutrality of the sample, while maximum possible charge is moved. If a value of $\Delta n_c(T)$ is chosen such that the QUILLS breakdown condition is met only in the region of largest electric field, it is possible to calculate M_Q, the QUILLS limited maximum magnetic moment. We find that M_Q agrees very well with the low-temperature saturation value of M_s.

Hence, in low-mobility samples at low temperatures, it is possible to induce large enough currents to cause IQHE breakdown by QUILLS. At elevated temperatures the size of the induced currents is limited by the strongly non-linear dependence of the conductivity on the charge distribution in the 2DES plane.

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