# QUANTIZED DISSIPATION OF THE QUANTUM HALL EFFECT AT HIGH CURRENTS*†

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## Abstract

Quantized dissipative voltage states are observed when large currents are passed through high-quality quantized Hall resistance devices. These dissipative states are interpreted as occurring when electrons make transitions between Landau levels and then return back to the lowest-filled levels.

## Introduction

The quantum Hall effect occurs when current is passed through a two-dimensional electron gas formed in a semiconductor device which is cooled to very low temperatures in the presence of a large magnetic field. In high-quality devices the current flow within the two-dimensional electron gas is nearly dissipationless for currents around 25 μA. At high currents, however, energy dissipation suddenly appears in these devices [1,2]. This is called breakdown of the quantum Hall effect.

The dissipation voltage $V_x$ can be detected by measuring voltage differences between potential probes placed on either side of the device in the direction of current flow. We found [2] in 1983 that there is a distinct set of dissipative voltage states, with transient switching observed on microsecond time scales among the states. A very high-quality device is required to observe the discrete voltage states; otherwise, ohmic heating dominates, and the breakdown effects disappear. Bliek *et al.* [3] in 1987 then observed quantized dissipative states for samples with narrow constrictions. Cage *et al.* [4] in 1990 then found that, in wide samples, the distinct states are quantized in voltage. Many other laboratories have observed dissipative voltages at breakdown of the quantum Hall effect, but none have yet confirmed that these voltage states are quantized. We show in this paper that the voltage is indeed quantized, but that the quantization is more complicated than previously thought.

## Summary

Our sample is a $GaAs/Al_xGa_{1-x}As$ heterostructure grown by molecular beam epitaxy with $x = 0.29$. It is designated as GaAs(7). It has a zero magnetic field mobility of 100,000 $cm^2/(V \cdot s)$ at 4.2 K, exhibits excellent integral quantum Hall effect properties, and is used as the new United States resistance standard. The sample is 4.6 mm long and 0.4 mm wide. The two outer Hall potential probe pairs are displaced from the central pair by ±1 mm.

We made multiple plots of $V_x$ versus the magnetic field $B$ for the $i = 2$ (12,906.4 Ω) quantized Hall resistance plateau at a current of 210 μA and a temperature of 1.3 K. This current is approaching the 230 μA critical current value at which $V_x$ never reaches zero. The plots yielded clearly-defined, quantized, voltage states with voltage separations of order 5 mV.

The quantized Hall resistance occurs only when the conducting electrons in the two-dimensional electron gas occupy all the allowed states of the filled Landau levels. We therefore assume that the quantized dissipation voltages arise from transitions between Landau levels. States within originally empty Landau levels $N'$ are populated by electrons excited from the originally full ground Landau level $N$. The dissipation results from transitions of those electrons back to the ground state Landau level. The electrical energy loss per carrier for $M$ Landau level transitions is $M\hbar\omega_c$ where $M = N' - N$, $\omega_c = eB/m^*$ is the cyclotron angular frequency, and $m^*$ is the reduced mass of the electron (0.068 times the free electron

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mass in GaAs). The measured energy loss per carrier is $eV_x$. If all the electrons of both spin sublevels of a Landau level undergo the transitions then $eV_x = M\hbar\omega_c$. If the ground state involves several filled Landau levels, and if we assume that only the highest filled Landau level undergoes transitions, then $eV_x = (2/i)M\hbar\omega_c$, where $i$ is the Hall plateau number. If only a fraction $f$ of the electrons make the transitions then $eV_x = f\,(2/i)M\hbar\omega_c$. Thus

$$fM = \left(\frac{i}{2}\right)\left(\frac{m^*}{\hbar}\right)\left(\frac{V_x}{B}\right). \qquad (1)$$

$V_x$ and $B$ are measured quantities, $M$ can be readily deduced from our data, and $i$, $m^*$, and $\hbar$ are constants. Therefore, $f$ can be determined from the $V_x$ vs $B$ plots and Eq. (1).

The fraction $f$ of conducting electrons that make these transitions can be quite large, but is not necessarily 100%. Also, we find that $f$ has a constant value for a fixed value of $B$, and is independent of $M$. However, when $B$ is varied, $f$ does not remain constant, but rather varies smoothly with magnetic field. This variation is many times larger than the variation of the magnetic field itself. Therefore, $f$ is a function of $B$. These facts can greatly complicate the identification of voltage quantization for most breakdown data because the voltage separations will not be constant if $f$ is not constant, so the voltages will not appear to be quantized even when they actually are.

We suggest that the Landau level transition mechanism responsible for the quantized dissipation is that employed by Heinonen, Taylor, and Girvin [5], which was later used in the QUILLS model of Eaves and Sheard [6], with refinements and extensions by Cage *et al.* [7].

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