# Equilibrium Magnetisation Measurements of Two-Dimensional Electron Systems


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The thermodynamic equilibrium magnetisation of two-dimensional electron systems, embedded in GaAs–(Ga,Al)As heterojunctions, has been measured in the temperature range 50 mK to 1 K in experiments using a highly sensitive torsion balance magnetometer. Clear de-Haas–van-Alphen oscillations are observed for Landau level filling factors between 4 and 52. Theoretical fits to the data show that the Landau levels are close to the idealised $\delta$-function density of states. The small residual width of the levels, typically less than 0.3 meV, fits equally well to either Gaussian or Lorentzian level broadening. There is a residual density of states between Landau levels which can be described by introducing a constant background density of states or, in some cases, by the tails of Lorentzian broadened Landau levels. In one of the samples studied we find the surprising result that on illumination, there is a 60% *increase* in Landau-level broadening, despite an increase in transport mobility of about the same percentage. Analysis of the de-Haas–van-Alphen oscillations at small odd-integer filling factors reveals a *g*-factor exchange-enhanced by up to 15 times.


In a perpendicular magnetic field $B$, the density of states (DOS) of an ideal 2-dimensional electron gas (2DEG) will split into a series of Landau levels (LLs) which are of the form of $\delta$-functions, separated by $\hbar\omega_c$. Here $\omega_c = eB/m^*$ is the cyclotron frequency of an electron. The magnetisation is predicted to oscillate periodically in a sawtooth manner as a function of the LL filling factor, $\nu$, the de-Haas–van-Alphen (dHvA) effect. For an isolated 2DEG the sharp jump occurs on the high field side of each sawtooth. In reality the degeneracy of each LL will be lifted, resulting in a finite characteristic width $\Gamma$, because of impurity scattering and the electron-electron interaction. Information about these effects can be obtained by measuring the shape of the DOS from the deviation of the dHvA oscillations from their ideal sawtooth form.

Extensive studies of dHvA oscillations of 2DEGs have been carried out both theoretically and experimentally since the discovery of the integer quantum Hall effect. Störmer and co-workers [1] made the first convincing measurement of dHvA oscillations in a 2DEG by using a DC SQUID magnetometer. The shape of the LLs has since been examined quantitatively in the magnetometry studies of Potts *et al.* [2], which suggested that the DOS consists of a series of Lorentzian-broadened LLs with $\Gamma$ independent of $B$. At lower fields they found that Gaussian-shaped LLs with width of $\Gamma \propto B^{1/2}$ gave indistinguishable numerical fitting results.

We have made magnetisation measurements on $\delta$-modulation-doped and bulk-modulation-doped GaAs–(Al,Ga)As heterojunctions at temperatures between 50 mK and 1 K using a highly-sensitive torsion-balance magnetometer [3]. Clear sawtooth dHvA oscillations are observed for LL filling factors between 3 and 52. The large number of well-resolved oscillations enables us to estimate accurately the LL line width.

The numerical fitting was carried out based on the method reported by Potts *et al.* [2], in which the 2DEG is treated as an ideal, spinless, Fermi system and the DOS is assumed to have the form

$$D(B,E) = \alpha\frac{m^*}{\pi\hbar^2} + (1-\alpha)\frac{2eB}{\pi\hbar}g(E).$$

The first term represents a constant background DOS, and the second term is the DOS of the LLs. $\alpha$ is the proportion of states making up the background, and $g(E)$ describes the shape of the LLs. We model the LLs as being either Gaussian or Lorentzian in shape and let $\Gamma$ take the form $\Gamma = \Gamma_0 B^p$ with $p = 0$ or $p = 1/2$. An example of the success of this fitting procedure is shown in figure 1.

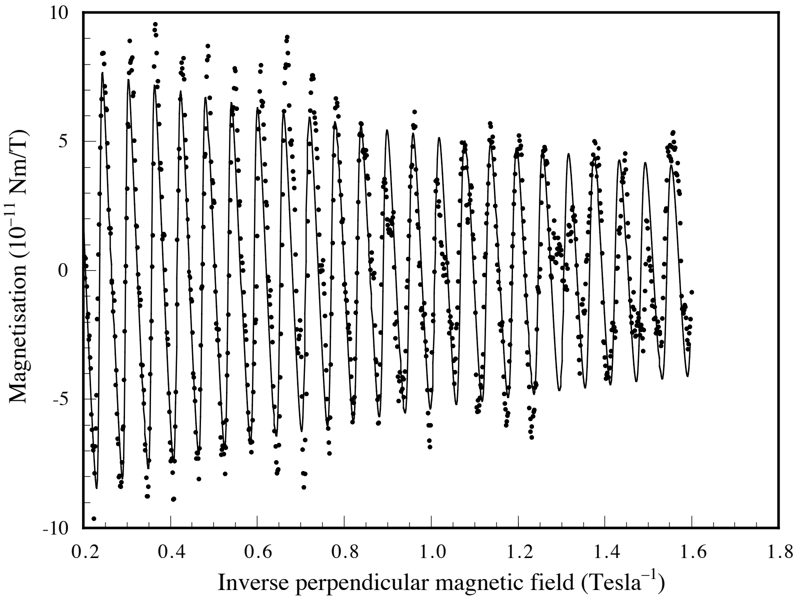


Figure 1. dHvA oscillations measured on the δ-modulation-doped sample [•], after removal of a smooth background signal, along with the results of our numerical fitting procedure [–], assuming a Lorentzian DOS. The sample parameters obtained from the fit were: number density = $8.6 \times 10^{15}$ m$^{-2}$; $\Gamma$ = 0.10 meV; and $\alpha$ = 0.11.

The fitted LL widths (0.1 meV ~ 0.4 meV) are much smaller than in the study of Potts *et al.* [2], demonstrating the improved quality of these 2DEGs. The LL shape is described equally well by a Gaussian or a Lorentzian function, with a width independent of magnetic field. In almost all cases we have to invoke a significant background density of states between LLs, which is larger when the Gaussian shape is assumed.

A surprising result was obtained after inducing persistent photoconductivity by brief illumination of the samples. While in the δ-modulation-doped sample, a reduction in $\Gamma$ was observed, consistent with the increase in transport mobility that accompanies illumination, in the bulk-modulation-doped sample $\Gamma$ *increased* by about 60%, while the mobility *increased* by about the same proportion. This strongly suggests that the mechanisms for scattering influencing the mobility are quite different from those causing broadening of the thermodynamic DOS.

At high magnetic fields the spin splitting of the LLs becomes resolved, leading to dHvA oscillations at odd LL filling factors. A comparison of the size of the oscillations at odd and even filling factors enables us to estimate that the *g*-factor is enhanced by up to 15 times its bare value, due to the strong exchange interaction in these high quality 2DEGs.


[1] H L Störmer *et al.*, J. Vac. Sci. Technol. B1 423 (1983)
[2] A Potts *et al.*, J. Phys. Condens. Matter 8 5189 (1996)
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