Phase diagram for the quantum Hall effect in a high-mobility AlGaN/GaN heterostructure

2001 J. Phys.: Condens. Matter 13 L175

(http://iopscience.iop.org/0953-8984/13/8/102)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **13** (2001) L175–L181 www.iop.org/Journals/cm PII: S0953-8984(01)19822-X

LETTER TO THE EDITOR

Phase diagram for the quantum Hall effect in a high-mobility AlGaN/GaN heterostructure

J J Harris[1,4] **K J Lee**[1], **D K Maude**[2], **J-C Portal**[2], **T Wang**[3] **and S Sakai**[3]

[1] Department of Electronic and Electrical Engineering, University College, London WC1E 7JE, UK
[2] CNRS-MPI High Magnetic Field Laboratory, 25 Avenue des Martyrs, BP166 F38046 Grenoble Cèdex 9, France
[3] Satellite Venture Laboratory, Department of Electrical and Electronic Engineering, University of Tokushima, 2-1 Minami-Josanjima, Tokushima 770-8577, Japan

Received 6 December 2000, in final form 23 January 2001

Abstract

The magnetoresistance behaviour of a high-mobility AlGaN/GaN heterostructure has been studied at low temperatures under magnetic fields of up to 28 T. Clear dissipationless minima in the Shubnikov–de Haas curves, for both cyclotron-split and spin–split Landau levels, have been observed. The temperature dependence of the widths of these minima have enabled a phase diagram for breakdown of the integer quantum Hall effect to be partially mapped out, and compared with similar results obtained for AlGaAs/GaAs heterojunctions. A distinctive feature of this sample is the variation of low-field electron mobility between different voltage probes, and corresponding differences in the quantum Hall breakdown behaviour are seen.

1. Introduction

In the extreme quantum limit at low temperatures and high magnetic fields, magnetotransport measurements on good quality two-dimensional electron gas (2DEG) samples show dissipationless conductance in the integer and fractional minima of the Shubnikov–de Haas (SdH) oscillations. The extent of the dissipationless regions is a function of temperature and electric current, and recent experiments on these quantum Hall breakdown effects in GaAs/AlGaAs 2DEGs [1,2] have suggested that the behaviour can be described by a phase diagram similar to that proposed by Gorter and Casimir for superconductivity [3]. If $B_c(\nu, T)$ is the width of the dissipationless region corresponding to an integer filling factor ν at temperature T, then for even filling factors the phase diagram can be expressed in the form

$$B_c = B_{c0}^H\left(\frac{1}{\nu^2} - \frac{1}{\nu_0^2}\right)\left[1 - \left(\frac{T}{T_{c0}^H/\nu}\right)^2\right] \qquad (1)$$

---

[4] Present address: Thermo V G Semicon, The Birches Industrial Estate, Imberhorne Lane, East Grinstead, West Sussex RH19 1XZ, UK.

where B_{c0}^{H}, ν_0 and T_{c0} are parameters determined from the data fits to equation (1). For GaAs/AlGaAs samples [1], this dependence has been seen in even filling factor minima with $\nu \geqslant 8$, in the temperature range of ~1 to 7 K. Below 1 K, the data rises above the values predicted by equation (1), and a second phase region is apparent, described by a variation on equation (1), in which the critical temperature no longer scales with the cyclotron gap, i.e. T_{c0}^{H}/ν is replaced by T_{c0}^{L}:

$$B_c = B_{c0}^{L}\left(\frac{1}{\nu^2} - \frac{1}{\nu_0^2}\right)\left[1 - \left(\frac{T}{T_{c0}^{L}}\right)^2\right]. \tag{2}$$

For odd integer (i.e. spin–split) minima, it has been suggested [2] that the minima widths obey a similar scaling law of the form

$$B_c = B_{c0}\left(\frac{1}{\nu^\alpha} - \frac{1}{\nu_0^\alpha}\right)\left[1 - \left(\frac{T}{T_{c0}/\sqrt{\nu}}\right)^2\right] \tag{3}$$

with the scaling parameter α ~1 to 1.5.

In this letter, we report on a preliminary investigation into the temperature dependence of the quantum Hall breakdown in an AlGaN/GaN heterojunction. The poorer quality of this materials system (due to its polycrystallinity, lower mobility, etc) compared to AlGaAs/GaAs, together with the restricted data set currently available, makes a definitive analysis difficult; however, the results obtained indicate strongly that this material, too, displays behaviour consistent with equations (1)–(3).

2. Experimental method

The sample studied here is a near state-of-the-art AlGaN/GaN heterojunction grown by MOCVD on a sapphire substrate. After a low-temperature GaN buffer layer, 2 μm of GaN and 120 nm of $\mathrm{A1_{0.18}Ga_{0.72}N}$ were grown at a conventional temperature [4]. The structure was undoped, but piezoelectric and spontaneous polarization effects created a 2DEG with a sheet carrier density, n, of 5.8×10^{12} cm^{-2} at the heterojunction. The sample was processed into a Hall bar pattern with three equally-spaced potential probes along each side, using Ti/Al ohmic contacts. Other aspects of the magneto-transport in this material have been described previously [4–7], but here we report its low-temperature properties in a magnetic field of up to 28 T, using the 20 MW resistive magnet facility at the High Magnetic Field Laboratory in Grenoble.

A distinctive feature of this sample is that, although the same carrier density was measured from the SdH periodicities and for all three pairs of Hall probes, the resistivity varied along the channel, corresponding to an unusually high mobility, μ, of 28 500 cm^2 Vs^{-1} in one region of the Hall bar, compared to values closer to 10 000 cm^2 Vs^{-1} in the other parts. This has been ascribed to local variations in the average grain size [7], and an interesting comparison can be made between the results for the two regions. This will be discussed later in the letter.

Resistivity and Hall effect measurements were made as a function of magnetic field and temperature in a dilution refrigerator with a base temperature in magnetic field of ~100 mK. 10.7 Hz ac currents of 100 nA were used to avoid sample heating effects, and signals were detected using standard lock-in techniques. Unfortunately, eddy-current heating caused the temperature to rise during the field sweep, but by assuming this rise was linear with time, it was possible to make an allowance for it when plotting the results corresponding to specific minima. In addition, this effect restricted the size of temperature interval which could be used, and only a limited number of points in the range 100 mK to 900 mK could be obtained.

Nevertheless, clear variations in the minima widths could be seen, and the results are discussed below.

3. Results and discussion

Figure 1 shows the resistivity versus magnetic field sweep at base temperature for the lowest resistivity contact pair on the Hall bar (designated J401X, corresponding to a mobility value of 28 500 cm^2 Vs^{-1}). Clear dissipationless minima are observable for the even integer filling factors above 12 T and for the spin–split, odd integer filling factors above 18 T (the highest field minimum at ~26 T corresponds to a filling factor, $\nu = 9$). A qualitatively similar plot was obtained for one of the the higher resistance contact pairs (designated J401Y, with mobility of 9 500 cm^2 Vs^{-1}), but with narrower dissipationless regions. Previously published data [8] on a similar density sample in this field range, but at ~0.5 K, did not show zero-resistance behaviour, although a lower density sample (~2×10^{12} cm^{-2}) did. Enlarged plots of the $\nu = 10$ minimum are shown in figure 2, for the two contact pairs, X and Y; 100 mK results are plotted in figure 2(a), and 800 mK data in figure 2(b). Other filling factors showed similar behaviour. It can be seen that the high mobility region of the sample gave dissipationless minima which were ~50% wider than the lower mobility areas, and that the relative reductions in width on heating the sample to 800 mK were similar for both regions, in this case to ~50% of the 100 mK value. These observations are surprising, since the usual interpretation of dissipationless conduction as occurring when the Fermi level lies within the energy range of the localized states between Landau levels would suggest that this region is in fact wider in the high mobility sample. However, this interpretation cannot be universally valid, since it would predict that the clearest minima would occur in very low mobility material, whereas it is well recognized that a minimum quality needs to be achieved before any minima are observable. A possible explanation is therefore that the low mobility regions of the sample are only just above this threshold; this is supported by the lack of zero-resistance minima in a sample with $\mu = 4\ 200$ cm^2 Vs^{-1} [8]. (For comparison, the lowest resistivity in the $\nu = 4$ SdH minimum of GaAs-AlGaAs 2DEGs has been shown to rise rapidly for mobilities below ~100 000 cm^2 Vs^{-1} [9].)

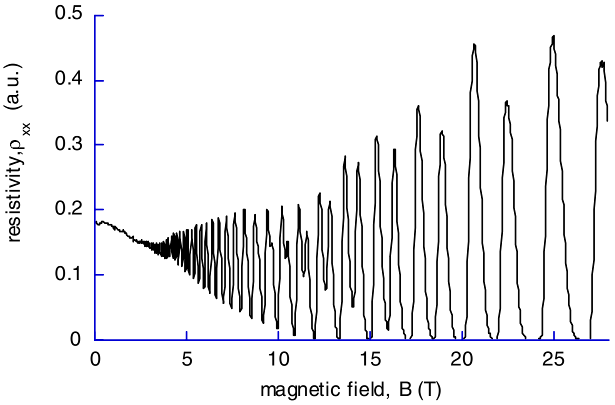
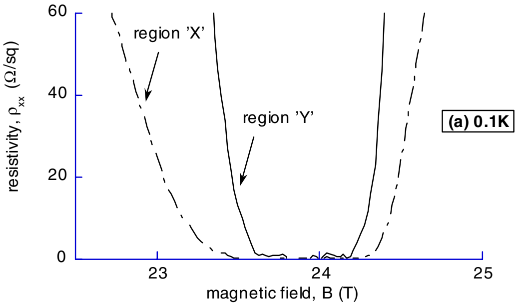
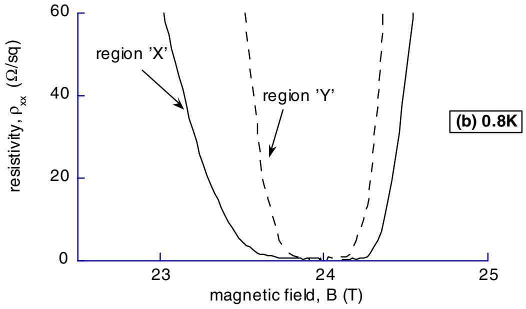


Figure 1. Shubnikov–de Haas oscillations for the high-mobility portion, X, of sample J401, measured at 100 mK.



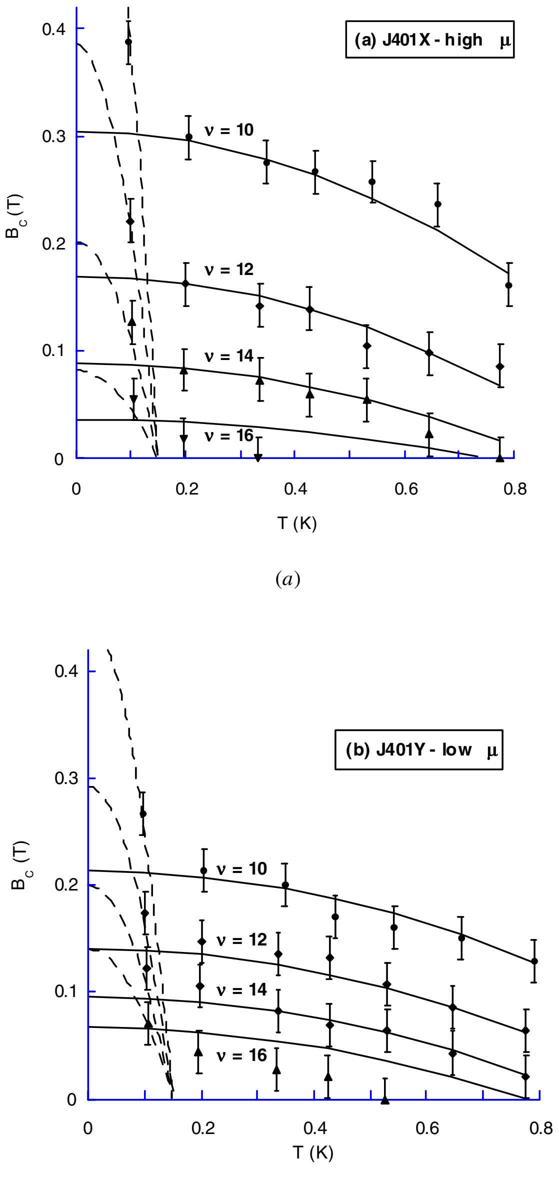
(*a*)



(*b*)

Figure 2. Comparison of the dissipationless minima at $\nu = 10$ for regions X and Y of the sample, (a) at 100 mK and (b) at 800 mK.

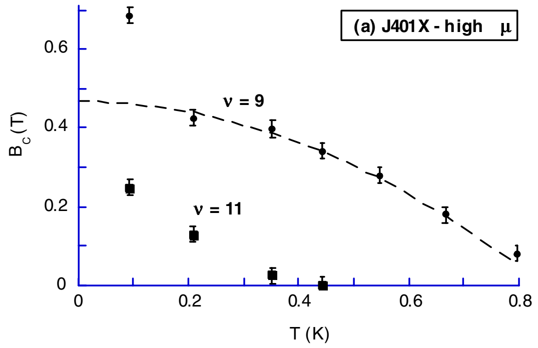
In order to plot out the phase diagram for the critical breakdown field, we have followed the approach used earlier [1,2] and measured the width of the minima, $2B_c(\nu, T)$, at a resistivity value which is a fixed fraction of the zero-field value. Because the onset of breakdown is rather gradual in the present samples, we have chosen a much smaller fraction, $R = 1\%$, compared to the 5% figure used in the GaAs/AlGaAs layers reported earlier. This data is plotted as a function of temperature in figures 3 and 4 for the even and odd integer minima respectively, for the contact pairs X and Y. In figure 3(a), the results for the high mobility region, X, are compared with theoretical curves based on equation (1), for the superconducting phase boundary. With the exception of the points at ~0.1 K, using the fitting parameters $B_{c0}^H = 44$ T, $\nu_0 = 18$ and $T_{c0}^H = 12$ K in equation (1) gives quite a convincing agreement for $\nu = 10$, 12 and 14. This behaviour shows the correct scaling with the cyclotron energy gap. As expected, the higher level of disorder occurring in the present sample has resulted in extracted fitting parameters which, although physically reasonable, are significantly different in value from those reported for GaAs/AlGaAs in [1] ($B_{c0}^H = 6.7$ T, $\nu_0 = 30$ and $T_{c0}^H = 54$ K for a sample with $n = 7.3 \times 10^{11}$ cm^{-2} and $\mu = 110\,000$ cm^2 Vs^{-1}). For $\nu = 16$ at T above 0.1 K, the experimental points fall more rapidly than the theoretical curves; however, this fraction is the largest for which dissipationless behaviour is seen, and for such marginal cases the value of R at which the width is measured can significantly influence the analysis, especially close to T_{c0}^H. The data at ~0.1 K for all filling factors lie above the corresponding theoretical lines, suggesting the start of a second, lower temperature phase, as observed for GaAs/AlGaAs 2DEGs [1]. This is indicated by the dashed curves in figure 3(a), which corresponds to equation (2) with the parameters $B_{c0}^{L} = 100$ T, $\nu_0 = 18$ and $T_{c0}^{L} = 0.15$ K, but clearly the limited number of data points makes these values highly speculative.



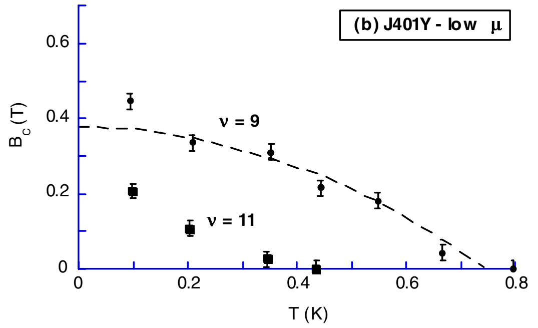
(*a*)

(*b*)

Figure 3. Plots of the temperature dependence of the critical magnetic field, $B_c(\nu, T)$, for even filling factors, $\nu = 10, 12, 14$ and 16 in (a) region X and (b) region Y. Solid curves—fit to 'superconductivity' formula, equation (1); dashed curves—fit to low-temperature formula, equation (2).



(*a*)



(*b*)

Figure 4. Plots of the temperature dependence of the critical magnetic field, $B_c(\nu, T)$, for odd filling factors, $\nu = 9$ and 11 in (a) region X and (b) region Y. Broken curves—fit to equation (3).

Figure 3(b) shows similar behaviour for measurements on region Y, although the presence of narrower minima here results in a slightly different set of fitting parameters: $B_{c0}^{H} = 24$ T, $\nu_0 = 30$ and $T_{c0}^{H} = 12.5$ K for the high-temperature range, and $B_{c0}^{L} = 50$ T, $\nu_0 = 30$ and $T_{c0}^{L} = 0.15$ K for the low-temperature portion.

The data obtained from the odd integer minima are harder to quantify. For GaAs/AlGaAs layers, it has been proposed [2] that, in the higher temperature range, the dependence should have the form given in equation (3). Figures 4(a) and 4(b) show that a variation as $A[1-CT]^2]$ is reasonable for both $\nu = 9$ curves, with $A = 0.47$ and 0.38, and $C = 1.40$ and 1.77, for regions X and Y respectively. If equation (3) is assumed to be valid, then the values of C correspond to $T_c = 4.0$ and 4.4 K respectively, but it is not possible to extract values for B_{co} and ν_0 from A for a single value of ν. Unfortunately, the curves for $\nu = 11$ showed similar marginal behaviour to those for $\nu = 16$, and could not be included in the analysis. Once again, at ~0.1 K there is an apparent upturn in the data which could signify the start of a second phase.

4. Conclusions

A preliminary investigation of the breakdown of the quantum Hall effect in an AlGaN/GaN heterojunction has been undertaken by measuring the widths of the dissipationless minima as a function of temperature below 1 K in a magnetic field of 28 T. The resulting phase diagrams showed features which were qualitatively similar to those previously observed in GaAs/AlGaAs layers, namely (i) a 'superconducting' phase transition for even integer minima which followed the Gorter–Casimir law (equation (1)), with strong evidence of the correct scaling with the energy gap, (ii) similar behaviour for the $\nu = 9$ minimum, although the expected modified characteristics given by equation (3) could not be verified, and (iii) the suggestion of a lower temperature second phase below $\sim$0.1 K. As expected from the difference in material quality, the fitting parameters obtained from this data are significantly different to those from higher mobility GaAs/AlGaAs samples, but are nevetheless physically reasonable.

This work is partly funded by EPSRC grant GR/M28200 and the Training and Mobility of Researchers scheme of the EC, contract no. ERBFMGECT950077.

References

[1] Rigal L B, Maude D K, Potemski M, Portal J C, Eaves L, Wasilewski Z R, Hill G and Pate M A 1999 *Phys. Rev. Lett.* **82** 1249
[2] Rigal L B, Maude D K, Potemski M, Portal J C, Eaves L, Wasilewski Z R, Hill G, Pate M A and Toropov A I 2000 *Physica* E **6** 124
[3] Gorter C J and Casimir H B G 1934 *Physics (Utrecht)* **1** 306
[4] Wang T, Ohno Y, Lachab M, Nakafawa D, Shirahama T and Sakai S 1999 *Appl. Phys. Lett.* **74** 3531
[5] Wang T, Bai J, Sakai S, Ohno Y and Ohno H 2000 *Appl. Phys. Lett.* **76** 2737
[6] Lee K J, Harris J J, Kent A J, Wang T, Sakai S, Maude D K and Portal J-C 2001 *Appl. Phys. Lett.* unpublished
[7] Harris J J, Lee K J, Wang T, Sakai S, Bougrioua Z, Moerman I, Thrush E J, Webb J B, Tang H, Martin T, Maude D K and Portal J-C 2001 *Semicond. Sci. Technol.* unpublished
[8] Wong L W, Cai S J, Li R, Wang K, Jiang H W and Chen M 1998 *Appl. Phys. Lett.* **73** 1391
[9] van der Wel W, Haanappel E G, Mooij J E, Harmans J C P M, Andre J P, Weimann G, Ploog K, Foxon C T and Harris J J 1989 *J. Appl. Phys.* **65** 3487