International Journal of Modern Physics B
Vol. 18, Nos. 27, 28 & 29 (2004) 3665–3670
© World Scientific Publishing Company

World Scientific
www.worldscientific.com

MAGNETIZATION OF A BILAYER 2D ELECTRON GAS

I. M. A. BOMINAAR-SILKENS*, M. R. SCHAAPMAN, U. ZEITLER,
P. C. M. CHRISTIANEN and J. C. MAAN

High Field Magnet Laboratory, NSRIM, University of Nijmegen,
Toernooiveld 7, 6525 ED Nijmegen, The Netherlands

D. REUTER and A. D. WIECK

Angewandte Festkörperphysik, Ruhr-Universität Bochum,
Universitätsstrasse 150, D-44780 Bochum, Germany

Int. J. Mod. Phys. B 2004.18:3665-3670. Downloaded from www.worldscientific.com
by RADBOUD UNIVERSITY NIJMEGEN UNIVERSITY LIBRARY on 11/27/12. For personal use only.

We present torque-magnetometry measurements of a bilayer two-dimensional electron gas (2DEG) with an inter-well barrier thin enough to enable a strong coupling between the quantum wells. We observe magnetization steps related to symmetric–anti-symmetric (SAS) transitions. Increasing the in-plane magnetic field leads to a reduction of the SAS splitting. Surprisingly, the heights of the magnetization steps related to Landau-level transitions are reduced relative to those measured for single-layer 2DEGs, suggesting that an in-plane magnetization component plays a role. Finally, at total filling factor $\nu = 4$, we observe an unidentified magnetization peak superposed upon the Landau-level step.

Keywords: Magnetization; bilayer 2DEG; SAS.

1. Introduction

A two-dimensional electron gas (2DEG) in a perpendicular magnetic field $B_\perp$ is subject to Landau quantization. This quantization of the energy levels gives rise to sawtooth-shaped oscillations in the 2DEG magnetization. The oscillatory behavior of the magnetization has been predicted theoretically already in 1930 by Landau[1] and is now known as the de-Haas–van-Alphen (dHvA) effect. Because the oscillations are extremely small, it took years to develop techniques sensitive enough to measure the signals. The first measurements of the dHvA effect of many parallel 2DEGs became possible just in 1983,[2] and the sawtooth behavior was measured only recently in single 2DEGs.[3–5]

The sawtooth-shaped oscillations in the magnetization are related to oscillations in the chemical potential μ of the 2DEG, which is at $T = 0$ K equal to the Fermi energy. Since the degeneracy $eB_\perp/h$ of the energy levels is dependent on the magnetic field $\mathbf{B}$, the number of filled levels, *i.e.* the total filling factor ν, depends on $\mathbf{B}$. At the magnetic field where an energy level empties, the Fermi energy jumps to

*Corresponding author: irissilk@hfml.kun.nl

Int. J. Mod. Phys. B 2004.18:3665-3670. Downloaded from www.worldscientific.com
by RADBOUD UNIVERSITY NIJMEGEN UNIVERSITY LIBRARY on 11/27/12. For personal use only.

the level below; this step in the Fermi energy is directly reflected as a change $\Delta\mu$ in the chemical potential.

The chemical potential μ of the 2DEG is related to the magnetization by a Maxwell equation, which reduces to

$$\frac{\Delta\mu}{B} = \frac{\Delta M}{N} \tag{1}$$

at the step $\Delta\mu$. The change in chemical potential is seen to be directly proportional to the change ΔM in the magnetization of the 2DEG.[3]

An additional degree of freedom can be added to a 2DEG by using a bilayer, a system with two 2DEGs separated by a thin inter-well barrier.[6] The two quantum wells are, therefore, strongly coupled and this coupling gives rise to an additional energy level splitting: each Landau level now consists of a symmetric and an anti-symmetric state, which are each spin-split. The energy gap that is associated with this symmetric–anti-symmetric (SAS) splitting is denoted ΔSAS. The SAS splitting is electronic in nature and does not involve a direct change in spin or orbital angular momentum. However, because ΔSAS, representing a step in the Fermi energy, should give rise to $\Delta\mu$, we expect to observe this electronic splitting as an oscillation in the magnetization of the 2DEG.

This paper presents the magnetization measurements we performed on a bilayer 2DEG using a torque magnetometer with optical detection.[7] We observed the sawtooth-shaped oscillations related to Landau-level transitions and to enhanced spin transitions, and also steps reflecting the SAS transitions. Since an in-plane magnetic field $B_{\|}$ is known to influence ΔSAS,[6,8,9] we investigated the magnetization of the bilayer for two different configurations, realized by mounting the sample at different angles. We will discuss the $B_{\|}$- and B-dependence of the observed SAS transitions, and we will explain why the measured Landau-level step heights are seen to be reduced relative to those observed for single-layer 2DEGs. Finally, we will focus on a peculiar peak, appearing in the magnetization on top of the Landau-level step at $\nu = 4$, of which the origin remains yet unknown.

2. Experiment

Our sample is an MBE-grown GaAs/AlGaAs double quantum well with a 25 Å thick $Al_{0.35}Ga_{0.65}As$ inter-well barrier and an area of 0.78×0.64 cm^2. After illumination, the total electron density is $n_{\text{total}} = 7.4 \cdot 10^{11}$ cm^{-2} with a mobility of $2 \cdot 10^5$ cm^2 V^{-1} s^{-1}.

The sample is mounted onto a thin wire of a home-built torque magnetometer[7] with the normal to the sample tilted an angle θ with respect to the magnetic field direction. If the magnetization $\mathbf{M}$ is perpendicular to the 2DEG, $\mathbf{M}$ causes a torque $\mathbf{\Gamma}$ to be exerted on the sample:

$$\Gamma = MB\sin(\theta) \tag{2}$$

Here we conform to the definition used by Shoenberg[10] that the magnetization $\mathbf{M}$ of a 2DEG equals its magnetic moment. The torque will rotate the sample, and, using

Int. J. Mod. Phys. B 2004.18:3665-3670. Downloaded from www.worldscientific.com
by RADBOUD UNIVERSITY NIJMEGEN UNIVERSITY LIBRARY on 11/27/12. For personal use only.

the back of the sample to reflect a laser beam, this rotation is detected optically as the displacement of the laser spot on a detector. The sample is mounted together with a current coil, which is used for feedback: by sending a current through the coil a magnetic moment is created that exactly counteracts the magnetization of the 2DEG. The 2DEG magnetization is now defined as the magnetic moment of the feedback coil, *i.e.* a directly measurable quantity. Operating our magnetometer in feedback mode offers the additional advantages that the sample stays in a fixed angular position and that mechanical oscillations can be damped actively.

3. Results and Discussion

Figure 1 shows the magnetization of the bilayer as a function of total filling factor $\nu = hn_{\mathrm{total}}/eB_{\perp}$ for the tilt angles $\theta = 13°$ and $\theta = 23°$, measured at a temperature of 1.2 K. The magnetization is normalized to the total number of electrons N_{total} in the bilayer 2DEG. The steps in the magnetization that are visible in the figure originate from Landau-level (LL) and SAS (SAS) transitions. Enhanced spin (S) transitions are also indicated. At the given experimental temperature all Landau-level and SAS steps have reached their saturation heights.

We will first consider the SAS transitions. Although it is clear from thermodynamics that any change in chemical potential, $\Delta\mu$, is always accompanied by a corresponding change in the size of the magnetic moment of the 2DEG, it is still surprising to observe the purely electronic SAS transition as a step in the magnetization of the bilayer. Figure 1 shows such SAS transitions at total filling factors 6, 10 and 14 for both tilt angles. The heights ΔM of the steps, which are measures of the energy gaps $\Delta\mathrm{SAS} = \Delta M/N \times B$ (see Eq. (1)), are smaller for the higher tilt angle, indicating that an increase in θ, *i.e.* an increase in in-plane magnetic field, decreases the coupling between the layers. A further observation is that, surprisingly, the step heights are roughly independent of total filling factor, and, thus, of

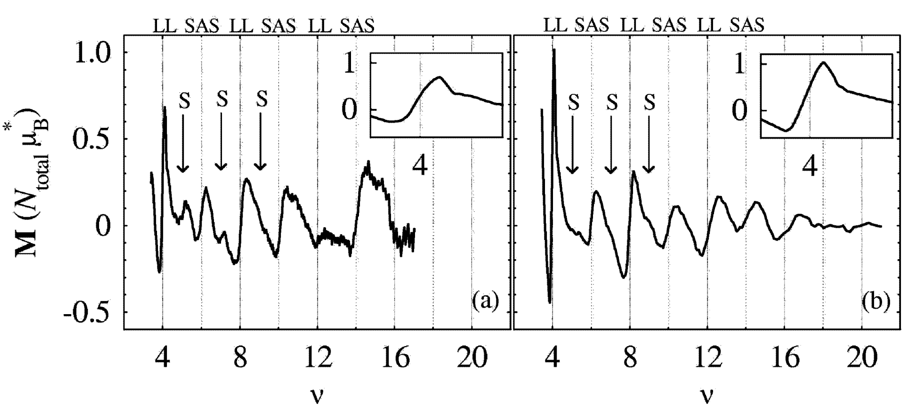

Fig. 1. Magnetization of our bilayer as a function of total filling factor for two different tilt angles: $\theta = 13°$ (a) and $\theta = 23°$ (b). The insets show enlargements of the steps at $\nu = 4$.

Int. J. Mod. Phys. B 2004.18:3665-3670. Downloaded from www.worldscientific.com by RADBOUD UNIVERSITY NIJMEGEN UNIVERSITY LIBRARY on 11/27/12. For personal use only.

magnetic field. Therefore, ΔSAS must be strongly dependent on B (see Eq. (1)), contradicting the picture that ΔSAS is determined solely by the confining potential. This discrepancy is brought about by the assumption that ΔSAS is equal to $\Delta\mu$, which is only valid in the case of an ideal density of states (DOS). Nonetheless, our data show magnetization steps of a finite width, indicating that a background DOS is present with an average, constant fraction of states in the gap of 6% (determined using the approach described in Ref. 3). Figure 2 depicts the influence of the shape of the DOS. An ideal DOS of δ-functions leads to an infinitely sharp step, whereas a DOS consisting of a constant background and broadened peaks invokes a rounded step of finite width. The finite step width makes that the gap $\Delta\mu = \Delta M/N \times B$, deduced from the measured magnetization step ΔM, is smaller than ΔSAS. At higher filling factors the Landau levels are steeper, and, considering Fig. 2, it is clear that steeper Landau levels result in smaller steps $\Delta M/N \times B$, while ΔSAS remains constant. When we calculate ΔM, using the ΔSAS value of 1.6 meV from our self-consistent calculations and taking the finite step width into account, we find that we can reproduce the observed SAS step heights for $\theta = 13°$. For the larger in-plane magnetic field, $\theta = 23°$, a smaller ΔSAS value of 1.4 meV is needed to give results of the same quality.

Landau-level transitions are observed at total filling factors 4, 8, and 12. The additional feature that is superposed upon the Landau-level step at $\nu = 4$ will be discussed in detail later. It is clear from Fig. 1 that the Landau-level step heights decrease with increasing ν. A decrease of energy gap with increasing ν is characteristic for Landau-level gaps, since this gap increases linearly with magnetic field, and a further decrease in magnetization step height with ν is caused by the non-ideal shape of the DOS, discussed in the previous paragraph on the SAS transitions. Figure 1 also shows us that all Landau-level steps are considerably reduced in height in comparison to those determined for a single-layer 2DEG with only one filled sub-band: for a single-layer 2DEG the step heights saturate to a magnetization of

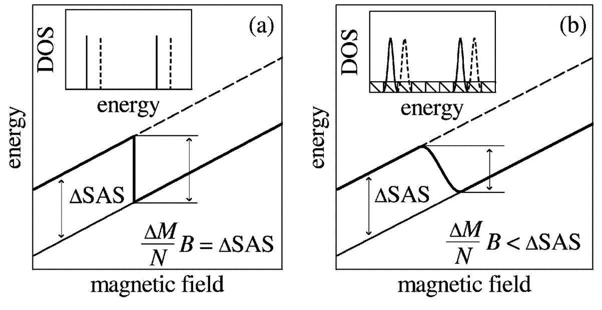

Fig. 2. Effect of the shape of the DOS (insets) on the transition from the anti-symmetric energy level (dashed line) to the symmetric energy level (thin solid line) for a DOS of δ-functions (a) and for one consisting of a background and broadened peaks (b).

Int. J. Mod. Phys. B 2004.18:3665-3670. Downloaded from www.worldscientific.com
by RADBOUD UNIVERSITY NIJMEGEN UNIVERSITY LIBRARY on 11/27/12. For personal use only.

2 N_{total} μ_B^* at low ν,[5] whereas we find 0.7 N_{total} μ_B^* for the bilayer 2DEG. This height reduction cannot be explained by the two effects mentioned above, since these occur in both single-layer and bilayer 2DEGs. A step height decrease that is, however, typical for the bilayer is associated with ΔSAS: in a bilayer the Landau-level transition is a transition from the symmetric energy level in the higher Landau level to the anti-symmetric energy level in the Landau level below. Nevertheless, ΔSAS is too small to explain the observed large reduction in step height relative to Landau-level steps measured for single-layer 2DEGs. Since it is rather unlikely that the cyclotron energy itself is reduced, we have to take a closer look at which quantity we really measure in our experiment: the torque. The torque Γ is given by Eq. (2), which is only valid if the direction of **M** is perpendicular to the 2DEG. If, however, the direction of **M** deviates an angle ϕ away from the normal to the 2DEG, the torque is given by

$$\Gamma = MB\sin(\theta - \phi) \tag{3}$$

Assuming $\phi = 0°$ then leads to an underestimation of the actual magnetization.

We will now concentrate on the additional feature that is visible superposed upon the Landau-level step at $\nu = 4$. Magnifications of this step are shown in the insets in Fig. 1. At $T = 1.2$ K, the height of the additional peak measures 0.3 N_{total} μ_B^* for $\theta = 13°$ and it increases to 0.5 N_{total} μ_B^* for $\theta = 23°$. We observed the extra feature only at temperatures below 2 K, and we found that its height increases with decreasing temperature. We studied the sweep-rate dependence of the peak, and, since we did not observe any dependence on the sweep rate of the magnetic field, the results demonstrate that this peak is not due to an eddy current.[11] We did, however, notice a dependence on the sweep direction. A typical example of $\nu = 4$ is shown in Fig. 3 for both sweep directions; in both cases the additional feature is clearly visible. Since the height difference between the peaks of both sweep directions is smaller than the smallest of the two peaks, we are convinced that this feature presents a real magnetization signal. From a thermodynamical point of view such a

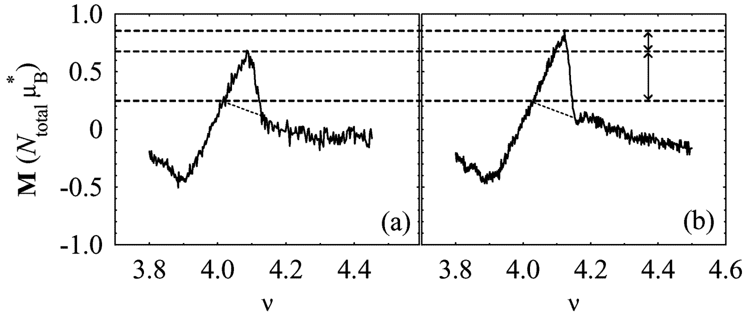

Fig. 3. Typical example of a magnetization measurement for $\nu = 4$, where (a) shows the result for the positive sweep direction of **B** and (b) the result for the negative one.

Int. J. Mod. Phys. B 2004.18:3665-3670. Downloaded from www.worldscientific.com
by RADBOUD UNIVERSITY NIJMEGEN UNIVERSITY LIBRARY on 11/27/12. For personal use only.

peak in the magnetization hints toward an enhancement of the chemical potential just before the second Landau level empties. However, the physical origin of the effect still remains unknown.

4. Conclusions

We measured the magnetization of a bilayer 2DEG for two different tilt angles. We observe steps in the magnetization arising from SAS transitions, and we find that ΔSAS decreases with in-plane magnetic field, agreeing with the expectation that an in-plane magnetic field decreases the inter-layer coupling. When a DOS consisting of a background and broadened peaks is regarded, the observed step heights are accounted for by the constant ΔSAS values of 1.6 meV for $\theta = 13°$ and 1.4 meV for $\theta = 23°$. Furthermore, we observe Landau-level steps that are reduced in height relative to those measured for single-layer 2DEGs. We tentatively suggest that this reduction is caused by a magnetization component parallel to the 2DEG. Additionally, at temperatures below 2 K a peculiar peak is visible superposed upon the Landau-level step $\nu = 4$, and we observe that the height of this feature increases with decreasing temperature. We rule out the possibility that the magnetization peak is due to an eddy current, but we are not yet able to explain its actual origin.

References

1. L. Landau, *Z. Phys.* **64**, 629 (1930).
2. H. L. Störmer, T. Haavasoja, V. Narayanamurti, A. C. Gossard, and W. Wiegmann, *J. Vac. Sci. Tech.* **B1**, 423 (1983).
3. S. A. J. Wiegers, M. Specht, L. P. Lévy, M. Y. Simmons, D. A. Ritchie, A. Cavanna, B. Etienne, G. Martinez, and P. Wyder, *Phys. Rev. Lett.* **79**, 3238 (1997).
4. M. P. Schwarz, M. A. Wilde, S. Groth, D. Grundler, Ch. Heyn, and D. Heitmann, *Phys. Rev.* **B65**, 245315 (2002).
5. M. R. Schaapman, U. Zeitler, P. C. M. Christianen, J. C. Maan, D. Reuter, A. D. Wieck, D. Schuh, and M. Bichler, *Phys. Rev.* **B68**, 193308 (2003).
6. For an overview, see, e.g., S. Das Sarma and A. Pinczuk, *Perspectives in Quantum Hall Effects* (Wiley, New York, 1997).
7. M. R. Schaapman, P. C. M. Christianen, J. C. Maan, D. Reuter, and A. D. Wieck, *Appl. Phys. Lett.* **81**, 1041 (2002).
8. G. S. Boebinger, H. W. Jiang, L. N. Pfeiffer, and K. W. West, *Phys. Rev. Lett.* **64**, 1793 (1990).
9. Y. W. Suen, J. Jo, M. B. Santos, L. W. Engel, S. W. Hwang, and M. Shayegan, *Phys. Rev.* **B44**, 5947 (1991).
10. D. Shoenberg, *Magnetic oscillations in metals* (Cambridge University Press, Cambridge, 1984).
11. C. L. Jones, A. Usher, M. Elliott, W. G. Herrenden-Harker, A. Potts, R. Shepherd, T. S. Cheng, and C. T. Foxon, *Sol.-St. Comm.* **97**, 763 (1996).