# Rotation of a $Cd_{1-x}Mn_xTe$ Two-Dimensional Electron Sample at Low Temperature and High Magnetic Field

**Abstract** The resistance of a two dimensional $Cd_{1-x}Mn_xTe$ quantum well at 270 mK was measured under a perpendicular magnetic field swept up to +9 Tesla. The sample was rotated between 0 and 60°, and the $R_{xx}$ and the $R_{xy}$ of the sample at different tilt angles to the magnetic field were compared. As the tilt angle increases, we see that not only the Shubnikov-de peaks but the ferromagnetic peaks as well shift their position to lower magnetic fields.

## Introduction

In 1968 the Physical Review published "Effects of a Tilted Field on a Two-Dimensional Electron Gas" written by F. F. Fang and P. J. Stiles. These two scientists pioneered a new area of research. They argued that Landau Levels are dependent "soley upon the normal component of the magnetic field with respect to the surface [of the sample]," but noting that spin splitting is dependent on total magnetic field (Fang and Stiles, 1968). This is argued here too. By using a two-dimensional sample and tilting the magnetic field, we can distinguish the difference between orbital and spin effects of the electron. In affect we deepen our knowledge of how the electron behaves.

In the last twenty years, two of the Nobel Prizes in Physics have been awarded to scientists studying two-dimensional electron systems. In 1985, Klaus von Klitzing won the Prize "for the discovery of the quantized Hall effect", and in 1998 Robert B Laughlin, Horst L Stormer, and Daniel C. Tsui won the Prize "for their discovery of a new form of quantum fluid with fractionally charged excitations"(Nobel, 2002). Although many discoveries in this field have been made, there is still much left to explore. Advancements in this field impact the world greatly—computers are built from such two-dimensional devices and rely on research such as this for improvements.

## Methods and Materials

Sample

The two-dimensional CdTe is a diluted magnetic semiconductor meaning that Mn, the doping element, is randomly distributed throughout the sample; it was grown in Warsaw. The contacts were already annealed when we received it. Indium was used to sodder the copper wires to the sample. Characterizations were done on half a dozen samples before we chose this particular sample as our best candidate for testing.

Building rotator

Although much can be learned from studying a semiconductor in the presence of a perpendicular or parallel magnetic field, as is pointed out in the introduction, much of how electrons work and interact can be seen in a two-dimensional electron system when it is placed in a magnetic field with varying angles. In building our rotator we had to take two obstacles into account: high magnetic fields and low temperatures. Obviously, we needed to use a nonmagnetic metal. High magnetic fields can only be reached in small areas, restricting the size of the rotator. Our rotator was made of brass with a 0.8inch diameter. The larger the diameter, the more accurately you can calculate the angle; we

used the largest diameter that would fit in the probe, and thus is the bore of the magnetic field.

Higher sensitivity to mechanical and electronic noise and expanding/contracting of materials occur at low tempertaures. We used well-insulated, copper wires to decrease interference of noise. Copper is less pliable at low temperatures, so the thinner the copper, the more easily they will move as the rotator moves. Using thinner wire increases noise interference. We struggled to find an optimum wire thickness, 0.45mm diameter. We had to keep a vacuum system to sustain the below liquid He temperature. The rotator was attached to the "cold finger" of the $^3$He fridge. We used a vacuum-safe vernier to draw the rotator up and down. Kevlar string was attached to the vernier and wrapped around the edge of the rotator to change the tilt angle. Kevlar was also attached to a rubber band to draw the slack as the rotator moved. Kevlar is used by NASA and will not expand nor contract greatly with temperature. The rubber band was kept at room temperature to avoid affects of low temperatures. This system worked much like a pulley.

Field Measurements

The rotator we built was placed into the probe of an Oxford $^3$He fridge. The fridge was cooled to approximately 270mK. An Oxford Magnet Power Supply was used to sweep the magnetic field up to 9T. These are standard procedures used for this type of measurement.

Illuminating sample

We had to illuminate our sample for it to work. By illuminating our sample we were able to tune the electron density allowing persistent photoconductivity. Our LED's would not light at liquid He temperatures, so we had to illuminate at 77K and then cool the sample.

Finding zero θ

Due to expanding/contracting of materials, we had to determine at what string length our sample was perpendicular to the magnetic field, or theta equals zero between normal and sample surface. We rotated the sample in both directions and took data. We plotted the magnetic fields for the largest resulting peak as a function each rotation. The zero θ occurs where the peak position is at a minimum as a result of the law of cosines. We modeled a curve through our data to give us the minimum.

**Results**

As we increased the tilt angle, our peaks shifted to higher $B_{Total}$ fields as seen in Figure 1. We must take into account that only the perpendicular component of the magnetic field should be taken into consideration when comparing resistances at different tilt angles.

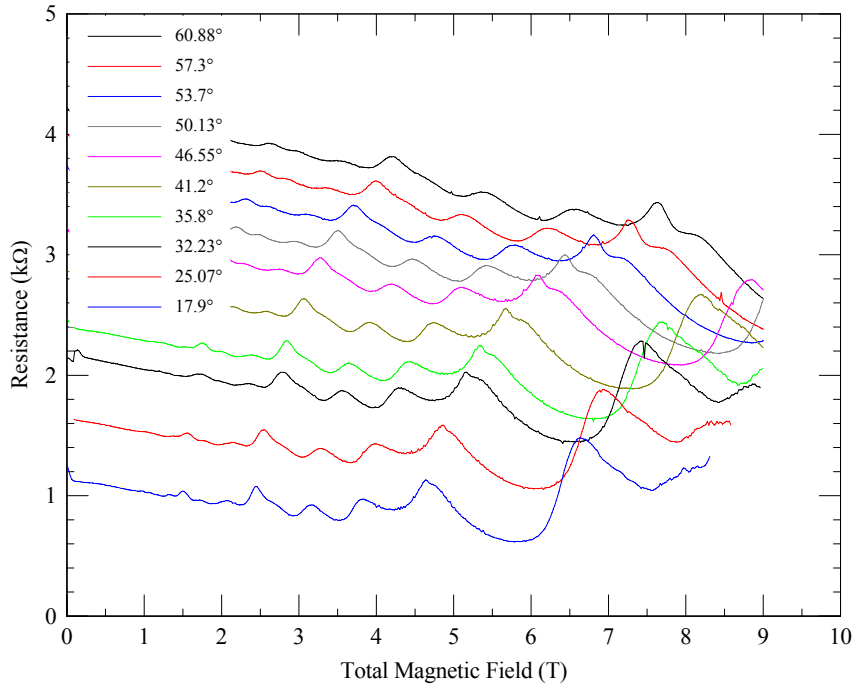


**Figure 1** The Shubnikov – de Haas (SdH) and ferromagnetic peaks are at higher $B_{Total}$ fields for higher tilt angles.

Figure 2 shows the transformation of the graph after multiplying the $B_{Total}$ field by the cosine of θ.

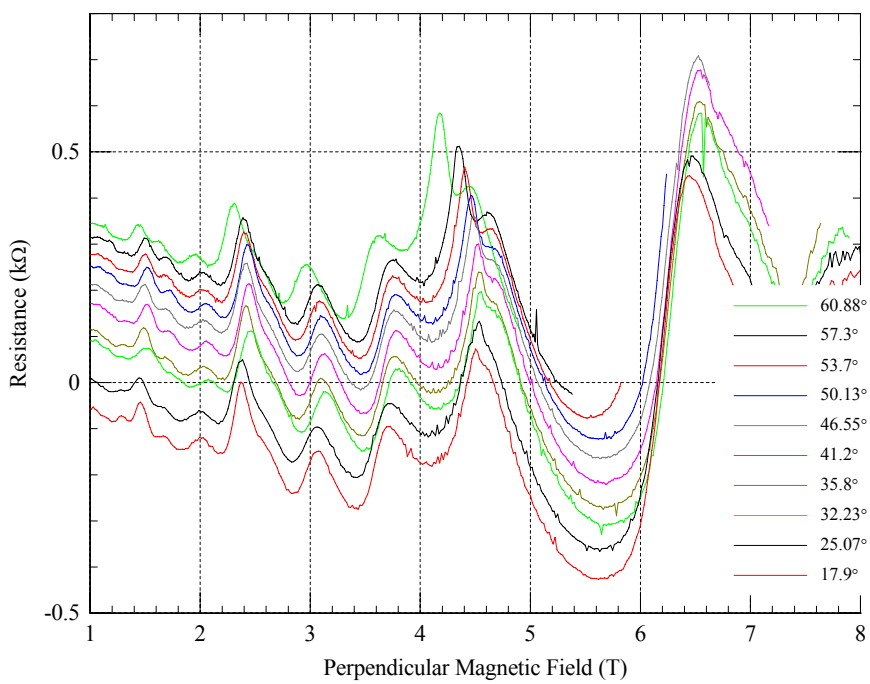


**Figure 2** The peaks shift to smaller $B_{\perp}$ fields as the tilt angle increases.

Figure 2 shows the resistances as a function of the $B_{\perp}$ for our varying tilt angles. The peaks occur at the same $B_{\perp}$ field until the tilt angle reaches approximately 50°. At these

higher tilt angles the peaks shift their position to lower and lower magnetic fields. The higher the tilt angle, the greater increment the peaks shifts.

**Discussion**

In the presence of a magnetic field, electrons in a two-dimensional system, such as we studied, occupy discrete energy levels know as Landau Levels. These levels split due to the spin up and spin down of the electrons; this is known as spin splitting. Spin splitting was discovered by Zeeman when he was studying spectral lines of elements. Zeeman explained that in the presence of a magnetic field, energy levels that were once occupied by two electrons of spin up and spin down split due to their different alignment with the applied magnetic field.

Two distinct phenomena cause resistance to increase in a two-dimensional system. One is caused by the crossing of Landau Levels, and the other is caused by ferromagnetic ordering. The split LL's of spin up can cross those of spin down. The exchange between the electron spin of the doping element Mn and the electron spin of the CdTe causes huge spin splitting. The LL's are nonlinear, as seen in Figure 3, allowing levels of opposite spin to cross. When LL's cross, the density of the energy state is increased. Increased density results in increased scattering of electrons, and thus resistance is increased. When the Fermi Energy bisects a LL, SdH peaks result. When this bisection occurs where two LL's have crossed, there is even greater resistance. This increased resistance is the cause of many the peaks seen in the graphs.

Ferromagnetic peaks are can be even greater in resistance than the SdH peaks. At a particular alignment of the magnetic field, electrons interact by ordering themselves ferromagnetically, ultimately forming a magnetic domain. The scattering of electron of the walls of this domain cause large and sharp peaks, ferromagnetic peaks. An example is labeled in figure 2.

The shifts of peaks due to increased tilt angle can be explained by spin splitting. Given a fixed $B_{Total}$ field, as the $B_{\perp}$ field is decreased because of increasing tilt angle, the spin splitting is also decreased. Figure 3 shows the decrease and resulting shift; the spin up and spin down LL are squeezed together when the $B_{\perp}$ field is decreased. When the split is decreased, the position at which the LL cross shifts to lower B fields. These theories are illustrated by our results.

This does not, however, explain the shifts in the ferromagnetic peaks. The increase in amplitude and shifts in these peaks are of greater magnitude than those of the SdH peaks. These are phenomena that deserve futher investigation.

Diluted magnetic semiconductors are candidates for application in the newly pioneered field of spintronics. By using electron spin, the time it takes for a computer to read magnetic order, which stores information, is dramatically decreased. This field of research has many possibilities.

**Acknowledgements**

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**References**

Fang, F. F. and P. J. Stiles (1968) Effects of a Tilted Field on a Two-Dimensional Electron Gas. Physical Review, vol. 174: 823-828.
www.nobel.se/physics/laureates/

**Figures**

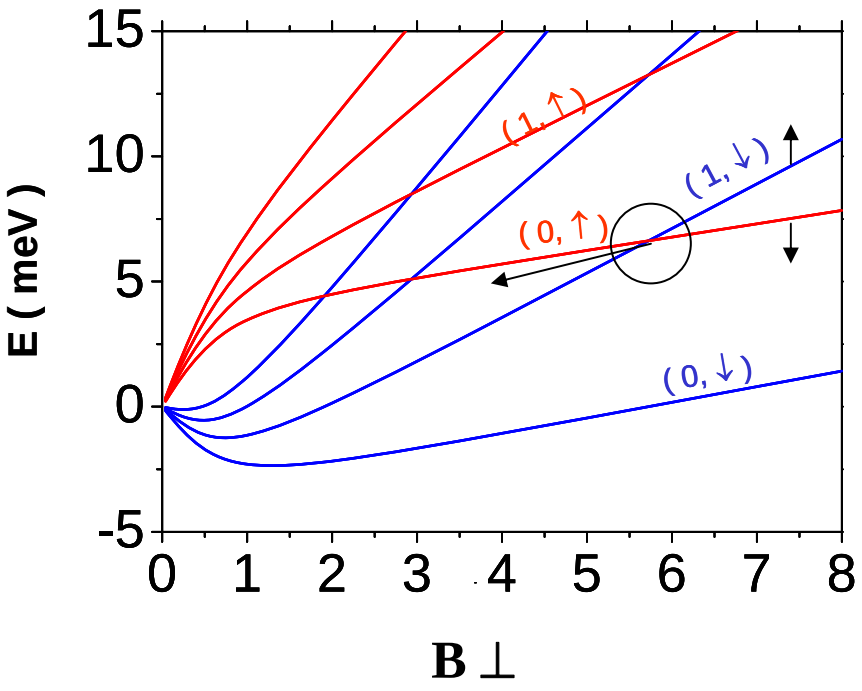


Figure 3 **The crossing of split LL in the presence of a magnetic field**