An extensive comparison of anisotropies in MBE grown (Ga,Mn)As material

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Abstract. This paper reports on a detailed magnetotransport investigation of the magnetic anisotropies of (Ga,Mn)As layers produced by various sources worldwide. Using anisotropy fingerprints to identify the contributions of the various higher-order anisotropy terms, we show that the presence of both a [100] and a [110] uniaxial anisotropy in addition to the primary ([100] + [010]) anisotropy is common to all medium doped (Ga,Mn)As layers typically used in transport measurement, with the amplitude of these uniaxial terms being characteristic of the individual layers.

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1. Introduction

A key prototypical material for investigations into spintronics is the ferromagnetic semiconductor (Ga,Mn)As. The marriage of magnetic and semiconductor properties brought about by strong spin–orbit coupling, which ties the density of states of this material to its magnetic properties, offers a host of new and exploitable magnetotransport effects. As investigations into this material continue to progress, it has become clear that a detailed understanding of the underlying magnetic anisotropy is a key issue in device design and optimization.

This magnetic anisotropy in (Ga,Mn)As is very rich and complicated, which led to various reports over the past decade that superficially appeared to be contradictory. In general, depending on growth strain, doping density and temperature, the material can have an easy axis of magnetization either perpendicular to the plane, or in the layer plane [1, 2], and in the latter case, the primary anisotropy can be either biaxial along [100] and [010], or uniaxial along either [110] or [−110] [3, 4].

It is generally accepted that for typical medium-doped transport samples with ∼3 to 6% Mn, grown with compressive strain and measured at 4.2 K, the primary anisotropy is a biaxial term with easy axes along the [100] and [010] crystal directions. Second-order terms are also widely reported in the form of a uniaxial easy axis along [110] or [−110] [5] of various relative strengths, or a uniaxial along [010] [6].

Since it is well known in the community that the detailed properties of (Ga,Mn)As depend on exact growth conditions such as substrate temperature, growth rate, flux ratios, etc [7]–[9], it was initially widely assumed that the observation of these different higher-order anisotropy terms was primarily a result of the distinct properties of the various layers used.

It is now realized that part of the confusion arose from the fact that the various transport measurements from which these terms had been extracted differ in sensitivity to the different anisotropy terms. For example, in the non-volatile tunneling anisotropic magneoresistance (TAMR) experiments [6], the [010] plays a crucial role, whereas the [110] anisotropy is nearly irrelevant, because it has a significant impact only for volatile effects occurring at higher fields. On the other hand, the [010] term plays only a secondary role in the planar Hall measurements of Hall bars along the [110] direction [5].

Moreover, because these second-order uniaxial anisotropy terms are significantly weaker than the primary biaxial anisotropy, they cannot be reliably characterized by direct magnetization measurements such as superconducting quantum interference device (SQUID) or vibrating sample magnetometer (VSM). The challenge of fully characterizing the
complex anisotropies in (Ga,Mn)As was recently successfully addressed with the development of an ‘anisotropy fingerprint’ technique [10], which consists of taking magnetotransport measurements for magnetic fields swept in multiple directions.

Using this method, we recently investigated [11] various transport samples produced on wafers grown in a given molecular beam epitaxy (MBE) system at Würzburg University, and showed that in all cases, a detailed investigation revealed the presence of both [010] and [110] uniaxial terms, with the sign and relative amplitude of these two terms varying from sample to sample. In the present paper, we expand this investigation to samples grown by multiple groups and show that indeed the co-existence of all anisotropy terms is a general property of (Ga,Mn)As, and that only the relative strength of the terms is characteristic of the layer growth.

2. Anisotropy fingerprints

All investigations are performed using Hall bars of the configuration shown in figure 1(a) produced by standard optical lithography followed by chemically assisted ion beam etching (CAIBE). Magnetoresistance measurements are carried out in a magnetocryostat equipped with a vector field magnet capable of producing fields of up to 300 mT in any spatial direction. For the measurement discussed in this paper, fields are always applied in the plane of the sample, and the direction of the magnetic field is given by the angle $\phi$ relative to the [100] crystal direction.

(Ga,Mn)As exhibits a strongly anisotropic magnetoresistance (AMR) where the resistivity $\rho_\perp$ for current flowing perpendicular to the direction of magnetization is larger than $\rho_\parallel$ for current along the magnetization [12]. As a result of this anisotropy in the resistivity tensor, the longitudinal resistivity $\rho_{xx}$ is given by [13, 14]:

$$\rho_{xx} = \rho_\perp - (\rho_\perp - \rho_\parallel) \cos^2(\vartheta),$$

(1)

where $\vartheta$ is the angle between the direction of magnetization and the current. Note that there is also a dependence of the resistivity on the angle between the direction of magnetization and the underlying crystal orientation [15]. This additional term modifies the resistivity value for a given magnetization direction, but does not affect the field position of the magnetization reorientation events, and can thus be neglected for the purposes of the present analysis.

For each sample, we measure the four terminal longitudinal resistance using the lead configuration given in figure 1(a) by passing a current from the $I_+$ to the $I_-$ contacts, and measuring the voltage between $V_1$ and $V_2$. We scan the magnetic field from $-300$ to $+300$ mT along a given direction $\phi$, and repeat this procedure for multiple angles. A simulation of such a scan for the case of $\phi = 70^\circ$ is given in figure 1(c), and shows two switching events, labeled $H_{c1}$ and $H_{c2}$, associated with the two sequential $90^\circ$ domain wall nucleation/propagation events which account for the magnetization reversal in this material [16]. In order to analyze the data, the positive field half of each of these scans is converted to a sector of a polar plot as shown in figure 1(d). The two switching events then show up as abrupt color changes as indicated in the figure. The compilation of all the sectors required for a full revolution produces an anisotropy fingerprint resistance polar plot such as the one simulated in figure 2(a).

For the purposes of characterizing the various anisotropy terms, the most important part of the data is the innermost region whose boundaries are formed by the loci of first switching events ($H_{c1}$). Figure 2(b) shows a zoomed-in view of this region for an experimental measurement on a characteristic piece of (Ga,Mn)As.
Figure 1. (a) Layout of the Hall bar used in the experiments. (b) Configuration for the simulation of a magnetoresistance scan along $\phi = 70^\circ$ (c) showing the two switching events $H_{c1}$ and $H_{c2}$ corresponding to the two subsequent $90^\circ$ domain wall propagation events. These data are then converted (d) to a sector of a resistance polar plot.

For the model case of a purely biaxial anisotropy, this inner region would take the form of a perfect square with corners along the easy axis and the length of the half diagonal given by $\varepsilon$, the domain wall nucleation/propagation energy scales to the volume magnetization (figure 3(a)). The inclusion of a uniaxial anisotropy bisecting two of the biaxial easy axes moves the resulting easy axes towards the direction of the uniaxial anisotropy [17] and elongates the square into a rectangle as schematically depicted in figure 3(b). The strength of the uniaxial anisotropy constant in the [110] direction $K_{110}$ relative to the biaxial anisotropy constant $K_{\text{biax}}$ can be extracted from the angle $\delta$, as defined in figure 3(b), by which the angle between two easy axes is modified. The relationship is given by [11]:

$$\delta = \arcsin \left( \frac{K_{\text{uni}[110]}}{K_{\text{biax}}} \right).$$  \hspace{1cm} (2)

In practice, because the mixing of the anisotropy terms leads to a rectangle with open corners, it is often more convenient to work with the aspect ratio of the width ($W$) to the length ($L$) of the rectangle, instead of the angle $\delta$, which is related to the anisotropy terms as:

$$\frac{K_{\text{uni}[110]}}{K_{\text{biax}}} = \cos \left( 2 \arctan \left( \frac{W}{L} \right) \right).$$  \hspace{1cm} (3)

If a uniaxial anisotropy is instead added parallel to one of the biaxial easy axes, an asymmetry arises in the energy required to switch between the two biaxial easy axes. Essentially, the energy required to switch towards the easier of the two biaxial easy axes is less than that to switch towards the second biaxial. The inner pattern is then comprised of parts of an inner and an outer square, and the difference in the length of their half diagonal is a measure of $K_{010}$ (figure 3(c)), where $K_{010}$ is the [010] anisotropy constant. Because of deformation of the...
Figure 2. (a) Simulation of a full resistance polar plot comprised of sectors as in figure 1. (b) Measurement of the inner region of the polar plot. The red ‘I’ indicates the direction of current flow during the measurement.

fingerprint near the corners of the rectangle, which results from mixing of the anisotropy terms, it is often easier to identify the presence of an [010] uniaxial easy axis by looking at the spacing between the sides of the squares (or rectangles in the case that a [110] uniaxial term is also present), as indicated by the yellow line in figure 3(c), which of course has a length equal to $\sqrt{2}K_{010}$. 

New Journal of Physics 10 (2008) 055007 (http://www.njp.org/)
Figure 3. Sketches of the expected shape of the inner region for (a) a sample with only a ([100] and [010]) biaxial anisotropy, (b) a sample with a biaxial plus a [110] uniaxial easy axis and (c) a sample with a biaxial plus a [010] uniaxial easy axis. Note that the axes are in magnetic field units scaled to the volume magnetization ($M$).

Figure 4. Resistance polar plots taken at two different locations of the same (Ga,Mn)As layer.

3. Characteristics of a wafer

We have previously shown [11] that the fingerprint technique can be used to characterize the properties of a given wafer, and for macroscopic-sized devices, the fingerprint is a signature of the underlying material. As an example of this, we present in figure 4 the fingerprints for two Hall bars patterned from different locations on the same (Ga,Mn)As wafer, and oriented orthogonal to each other. An inspection of both fingerprints shows that the pattern is identical, as would be expected from a homogeneous wafer. The colors are inverted because of the 90° difference in current orientation. Both fingerprints yield the values of 1 mT for $K_{010}/M$, 18% for $K_{110}/K_{\text{biax}}$ and 18 mT for $\varepsilon/M$. 
Figure 5. Resistance polar plots taken (a) near the center of a (Ga,Mn)As wafer, (b) about 4 mm from the edge of the wafer and (c) about 1 mm from the edge.

Next, we demonstrate how this technique can also be used as a quality control process. Figure 5 shows three fingerprints from three pieces of the same (Ga,Mn)As layer, taken near the center of the 2 inch wafer, and 4 and 1 mm from the edge. Because of the geometry of the Würzburg MBE chamber, and given that the substrate is rotated during growth to enhance radial homogeneity, the uniformity of the sample is nearly perfect near the center and any fingerprint taken in that region is identical to that of figure 5(a). From the figure, we see that the central part of the sample has rather typical values of 16% for $K_{110}/K_{biax}$, 0.7 mT for $K_{010}/M$ and 9.2 mT for $\varepsilon/M$. Because of nonlinearities in the molecular beam profile, stoichiometric deviations in the epilayer become significant near the edge of the wafer. The outermost 5 mm of samples are thus significantly less uniform. This area is normally discarded, and certainly not used for device studies. The fingerprint in figure 5(c), taken on a piece 1 mm from the edge, very clearly shows why. It presents a fingerprint pattern very different from the homogeneous center, with an enormous discontinuity in the edges of the squares corresponding to a very large value of $K_{010}/M = 3.8$ mT for the [010] uniaxial anisotropy term. This is well outside the range of what is found on the homogeneous part of any (Ga,Mn)As. The deformation is sufficient that it is impossible to reliably extract values $K_{110}$ or $\varepsilon$. The fingerprint of figure 5(b), on a piece 4 mm from the edge, is just outside the region that is normally considered usable. It has approximately the same value of $\varepsilon$ and $K_{010}$ as the central part and is only slightly deformed with a smaller $K_{110}/K_{biax}$ of 12%. These numbers are still within the typical range for (Ga,Mn)As, but show a change in layer properties as one approaches the edge.

4. Comparison of wafers from multiple sources

In order to confirm that the coexistence of both the [010] and [110] uniaxial anisotropy terms is not a particularity of (Ga,Mn)As grown in a certain MBE chamber or under particular conditions, but is indeed ubiquitous to the material, we now present the results of measurements performed on samples patterned from layers grown in various laboratories and thus under varied growth conditions.

Figure 4 shows fingerprints from a fairly typical layer grown in Würzburg, albeit one with a relatively large domain wall nucleation propagation energy. To illustrate the typical spread that can be expected, we present in figure 6 two additional Würzburg layers with rather pronounced
Figure 6. Fingerprints from (Ga,Mn)As layers grown in various laboratories. (a) and (b) are layers grown in Würzburg with strong [010] and [110] easy axes, respectively. The other fingerprints are from layers grown at (c) IMEC, (d) Nottingham, (e) Tohoku and (f) Notre Dame.
Table 1. Characterization parameters extracted from the anisotropy fingerprints on various layers.

|                  | \( \varepsilon/M \) (mT) | \( K_{110}/K_{\text{biax}} \) (%) | \( K_{010}/M \) (mT) |
|------------------|---------------------------|----------------------------------|----------------------|
| Würzburg from figure 4 | 18                        | 18                               | 1.0                  |
| Würzburg with large [010] | 8.5                       | 7                                | 1.4                  |
| Würzburg with large [110] | 12                       | 21                               | 0.7                  |
| IMEC             | 7.8                       | 11                               | 0.7                  |
| Nottingham       | 7.1                       | 9                                | 0.65                 |
| Tohoku           | 12                        | 4                                | 1.25                 |
| Notre Dame       | 16                        | 9                                | 0.75                 |

[010] (figure 6(a)) or [110] (figure 6(b)), components. In figure 6(c)–(f) we compare these to fingerprints on layers grown at IMEC, Nottingham, Tohoku, and Notre Dame. Values of the various parameters extracted from all these layers are given in table 1. The figure illustrates that not only the amplitude, but also the sign of the two uniaxial components can vary between samples. For the [110] uniaxial, this change in sign can be seen by a 90° rotation of the long axis of the rectangle, whereas the sign of the [010] is determined by whether the quarter of the rectangle with its primary diagonal along [010] is larger or smaller than that with the diagonal along [100]. Note that the sign of the color scale (determining which regions are red and which are black) is determined by the direction of the current flow during the measurement, and is irrelevant to the current investigation.

As is clear from the table, all samples show a significant contribution of both a [110] and a [010] uniaxial anisotropy component. The values of the parameters that can be extracted from the fingerprints show variance from sample to sample, and typically fall in the range of some 7–18 mT for \( \varepsilon/M \), 0.6–1.5 mT for \( K_{010}/M \) and 4–20% for the ratio of \( K_{110}/K_{\text{biax}} \). Note that while the fingerprint technique cannot be used to reliably extract exact values for \( K_{\text{biax}} \), the shape of the curve as the magnetization rotates away from the easy axis towards the external magnetic field at higher fields can be used to estimate the strength of \( K_{\text{biax}}/M \). All samples investigated showed a value of approximately 100 mT for this parameter, which means that the values of \( K_{110}/K_{\text{biax}} \) quoted in percentage in the table are also estimates of \( K_{110}/M \) in mT.

While the table clearly shows significant variation from sample to sample, it nevertheless allows the extraction of useful rules of thumb for relative amplitude of the various terms. As a general statement, the ratio of \( K_{\text{biax}}:K_{110}:K_{010} \) is of the order of 100:10:1, and the domain wall nucleation/propagation energy is of the order of 10% of the biaxial anisotropy constant.

The range of values for \( K_{010}/M \) and \( \varepsilon/M \) seen in the samples discussed in this study is a fair representation of (Ga,Mn)As in general. The span of values for the \( K_{110}/K_{\text{biax}} \) ratio, which is already in the table larger than the other parameters, is however only a reflection of the subset of samples that we investigated. In general, this ratio can easily be tuned over a much larger range, for example as a function of hole concentration [4] or of temperature [11]. No systematic distinction is observed between samples from various sources.
5. Conclusions

In conclusion, we have used the anisotropy fingerprint technique to analyze the magnetic anisotropy properties of multiple (Ga,Mn)As layers. We have shown that this technique is a reliable means of characterizing a given layer and that it can be used as a quality control check of the growth. Moreover, we have examined pieces of (Ga,Mn)As grown in various laboratories around the world, and found that all samples exhibit three magnetic anisotropy components: a biaxial anisotropy along [100] and [010], a uniaxial along [110] (or [110]) and a second uniaxial along [100] (or [010]), showing that the existence of all three terms is an inherent property of (Ga,Mn)As and that it is only the relative strength of the terms which varies from sample to sample. As a rough rule of thumb, the ratio of the biaxial anisotropy, the [110] uniaxial and the [010] uniaxial is of the order of 100 : 10 : 1.

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