Magnetoresistance Anisotropy of a Bi Antidot Array

G. J. Strijkers, F. Y. Yang, D. H. Reich, C. L. Chien, P. C. Searson, Y. M. Strelniker, and D. J. Bergman

***Abstract*—We have measured the magnetoresistance of a Bi antidot array film. The magnetoresistance exhibits a pronounced angular dependence on the direction of the magnetic field, e.g., the longitudinal relative magnetoresistance at 5 K displays an angular variation between 1.8 and 3.4 in a field of 4.9 T. The effect is the result of the interference between cigar-shaped regions of strong current distortions around the voids in the Bi film. The measurements can be understood and quantitatively reproduced by theoretical calculations.**

***Index Terms*—Bi, magnetoresistance, periodic composite structures.**

I. Introduction

A FEW YEARS AGO, a new effect was predicted for the classical macroscopic electrical conductivity of a composite medium with a microstructure of insulating inclusions [1], [2], e.g., a conducting thin film with an array of insulating cylindrical voids (antidot array). It was shown that a void causes a cigar-shaped region of strong current distortion in the host material. This distortion becomes larger with increasing magnetic field, resulting in a positive magnetoresistance. Furthermore, when the inclusions are arranged periodically in an array, distortions from different voids may interfere, leading to a strong angular dependence of the magnetoresistance, reflecting the symmetry of the periodic array.

More specifically, the length of the cigar-shaped region of strong current distortion is $L = R\mu|B|$, where R is the radius of the holes, μ the carrier mobility of the host material and B the applied magnetic field (Note that $\mu|B|$ is also the Hall-to-Ohmic resistivity ratio). To observe the predicted angular dependence of the magnetoresistance experimentally $\mu|B|$ must be sufficiently large so that current distortions from different voids can overlap. Previously, experimental evidence for these effects has been observed in fields up to 12 T ($\mu|B| = -3$) in an antidot array of n-doped GaAs [3].

In this paper, we present measurements and analysis of the magnetoresistance anisotropy in a Bi antidot array. Because of its large $\mu|B|$ value, which may exceed 10 in single-crystal Bi, and long electron mean free path of up to 11 μm at 5 K [4]–[6], Bi is ideally suited to study these new anisotropy effects.

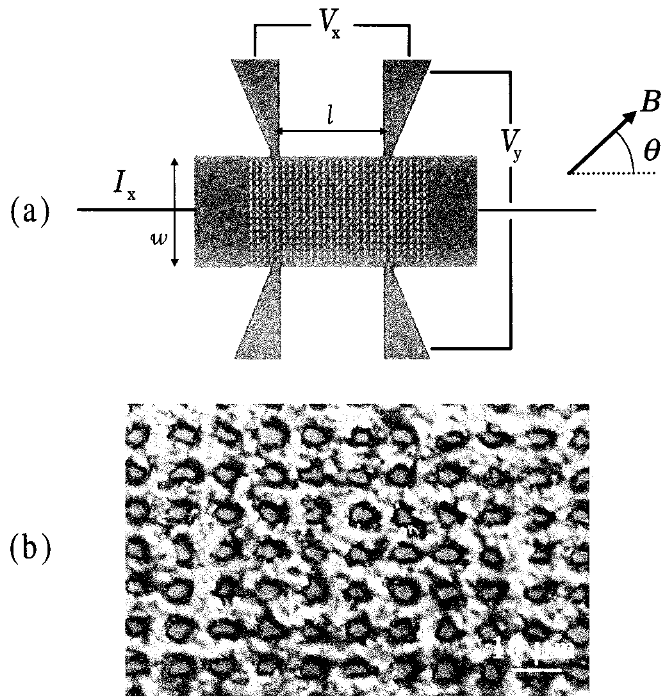

Fig. 1. (a) Overview of the Hall bar structure and the measuring geometry with $l = w = 350$ μm (for clarity the separation between the holes is 20 μm for this specific structure). (b) Close-up of the Bi Hall bar showing the array of holes. The pictures were taken with an optical microscope.

II. Experimental

In order to measure the angular dependence of the magnetoresistance we have made a Bi Hall bar structure, as shown in Fig. 1. The structure was fabricated as follows. First a Cr(10 Å)/Au(100 Å) Hall bar structure with current and voltage leads was deposited on a Si substrate using magnetron sputtering and a standard optical lithography and lift-off technique. Next, a square array of cylindrical holes with a diameter of 7 μm and center-to-center separation of 9 μm was introduced in the Cr/Au by optical lithography and chemical etching. Finally, 2 μm thick Bi was deposited onto the Cr/Au by electrodeposition from a bismuth nitrate pentahydrate solution. Since the Bi will grow only on the conducting Cr/Au layer and not on the Si substrate, the result is the Bi Hall bar structure with holes shown in Fig. 1. Because of three-dimensional growth during the electrodeposition process, the holes will partly close when the thickness of the Bi increases. The final diameter of the Bi holes is therefore approximately 4 μm. After the deposition, the structure was annealed in Ar for 8 h at 265 °C to promote

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the formation of large grains [4]–[6]. X-ray diffraction shows that the Bi is polycrystalline after annealing.

The experiments were done at $T = 5$ K in a liquid helium cryostat equipped with a superconducting magnet. The resistivity components $\rho_{xx} = (dw/l)V_x/I_x$ and $\rho_{xy} = dV_y/I_x$ were measured as function of the angle θ between current I_x and magnetic field B applied in the plane of the structure, as schematically shown in Fig. 1(a). Here w is the width, l is the length, and d is the thickness of the Bi. The angular variation of the magnetoresistance is best visualized in an experiment where current I and magnetic field B are fixed with respect to each other, while the antidot array is rotated by an angle α. Although this is experimentally very hard to realize in a single sample, $\rho_{xx}(\theta)$ and $\rho_{xy}(\theta)$ can be easily transformed into the longitudinal resistivity $\rho_{\|}(\alpha)$ $(I \parallel B)$ and the transverse resistivity $\tilde{\rho}_{\perp}(\alpha)$ $(I \perp B)$ by a rotation transformation (see for details [1]). The magnetoresistance is defined as $\delta\rho_{\|}/\rho_0 = (\rho_{\|}(B) - \rho_0)/\rho_0$ and $\delta\tilde{\rho}_{\perp}/\rho_0 = (\tilde{\rho}_{\perp}(B) - \rho_0)/\rho_0$, with ρ_0 the resistivity in zero field.

III. Results and Discussion

Fig. 2 shows the angular dependence of the longitudinal and transverse magnetoresistance, $\delta\, \rho_{\|}/\rho_0$ (left panel) and $\delta\, \tilde{\rho}_{\perp}/\rho_0$ (right panel) for $B = 0.2$, 1.0, 3.0, and 4.9 T. Note that in this figure the magnetoresistance is shown as function of the rotation of the antidot array, while B is fixed with respect to I. For $B = 0.2$ T, both $\delta\, \rho_{\|}/\rho_0$ and $\delta\tilde{\rho}_{\perp}/\rho_0$ are nearly isotropic. At higher fields a distinct anisotropy in the magnetoresistance develops, with four maxima and minima for $B = 1.0$ T, and with eight maxima and minima for $B = 3.0$ T and $B = 4.9$ T. The anisotropy is quite large, e.g., $\delta\rho_{\|}/\rho_0$ displays an angular variation between 1.8 and 3.4 in a field of 4.9 T.

This anisotropy is entirely due to the effects of the insulating voids. It is not observed for a Bi reference sample without holes. Since the Bi is polycrystalline the observed anisotropy cannot be attributed to the intrinsic anisotropy of the Bi Fermi surface [7], [8]. Moreover, a three-fold symmetry would be expected for the anisotropy of a single crystal film with the trigonal axis perpendicular to the plane, incompatible with four-fold symmetry in Fig. 2.

The results of Fig. 2 can be qualitatively understood with the help of Fig. 3, which shows schematically the interference between the cigar-shaped current distortions around the voids. For $B = 0.2$ T [Fig. 3(a)], the current distortions do not overlap leading to an isotropic longitudinal and transverse magnetoresistance. However, for $B = 1.0$ T [Fig. 3(b)] current distortions for nearest neighboring voids start to overlap, when the orientation of the antidot array is along $\alpha = j\pi/2$ ($j = 0$, 1, 2, 3). On the other hand, when the orientation of the array is rotated to $\alpha = \pi/4 + j\pi/2$ ($j = 0$, 1, 2, 3), no overlap occurs, because the separation between the holes in this direction is $\sqrt{2}$ times larger. The overlap leads to changes in the current flow patterns that are experimentally observed as a change in the magnetoresistance. For $B = 1.0$ T there are four angles at which the current distortions overlap for α in the range of 0 to 2π and consequently four maxima and minima in the magnetoresistance are observed. When the size of the current distortions become even larger in higher magnetic fields, finally interference between the

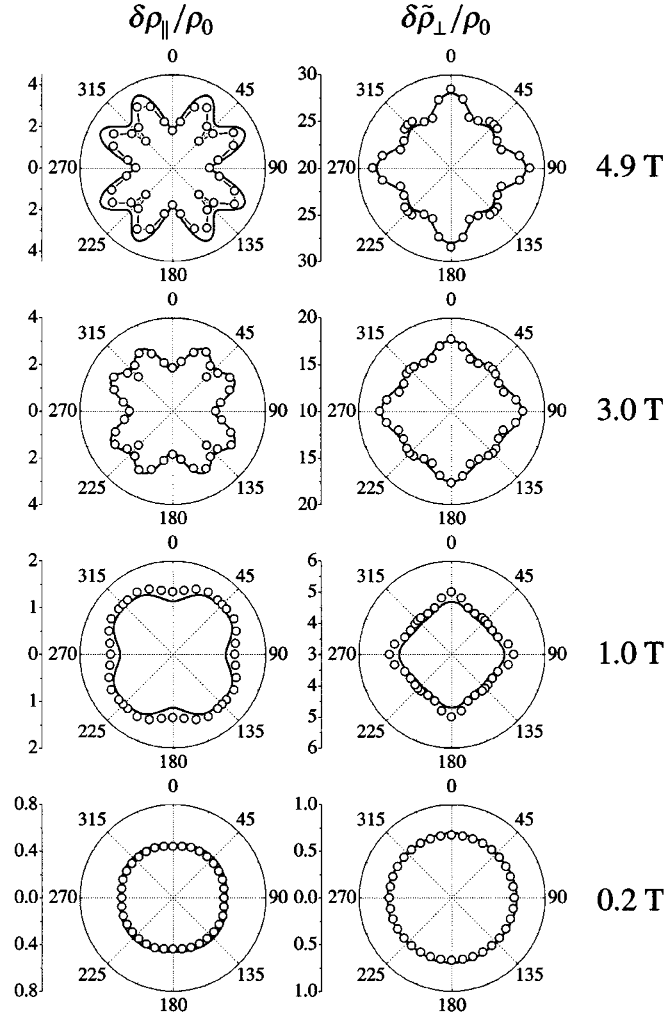

Fig. 2. Angular dependence of the longitudinal and transverse magnetoresistance, $\delta\rho_{\|}/\rho_0$ and $\delta\tilde{\rho}_{\perp}/\rho_0$, respectively, for $B = 0.2$, 1.0, 3.0, and 4.9 T at temperature $T = 5$ K. The open circles are the experimental data and the solid lines are the fits. Note that the y-axes do not always start at zero.

current distortions takes place for $\alpha = \pi/4 + j\pi/2$, as shown schematically in Fig. 3(c). Since now there are eight angles for which the current distortions overlap for α in the range of 0 to 2π, there are correspondingly eight maxima and minima in the magnetoresistance.

Interference between the current distortions can lead to a maximum or a minimum in the magnetoresistance, because the interference can be either destructive or constructive, depending on the direction of I with respect to B [9], [3]. For the longitudinal magnetoresistance $(I \parallel B)$ overlap between two current distortions is destructive, effectively cancelling the two distortion patterns, hence reducing the magnetoresistance. Indeed, Fig. 2 (left hand side) shows distinct minima in $\delta\rho_{\|}/\rho_0$ for angles with overlapping current distortions. However, for the transverse resistance ($I \perp B$, right hand side) overlap leads to a constructive interference, amplifying the distortion patterns and leading to maxima in the transverse magnetoresistance $\delta\tilde{\rho}_{\perp}/\rho_0$.

The experimental results can be reproduced quantitatively with the calculation techniques described in detail in Refs.

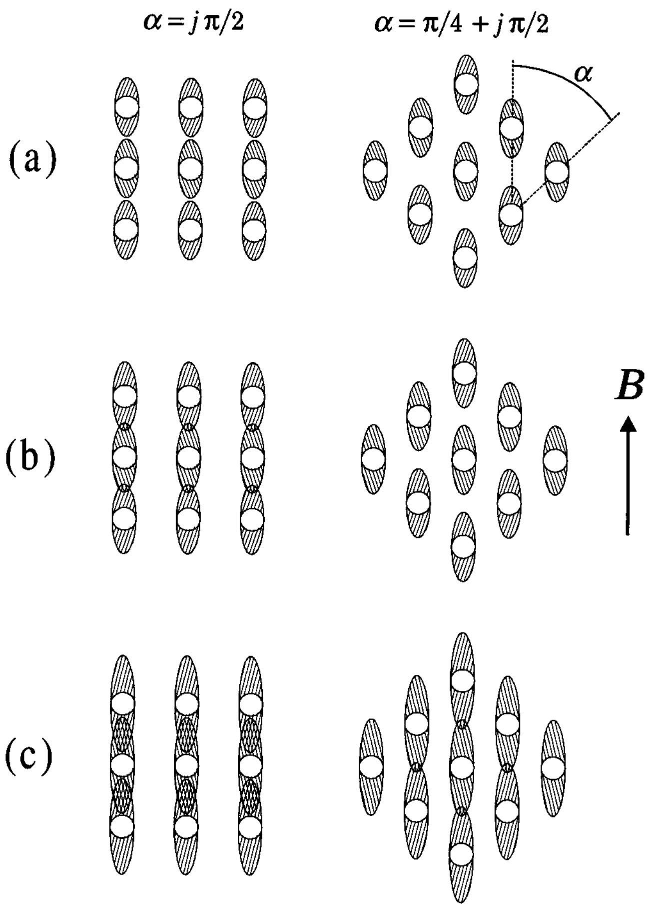

Fig. 3. Schematic drawing of the interactions between the cigar-shaped current distortions for (a) $B = 0.2$ T, (b) $B = 1.0$ T, and (c) $B = 3.0$ T and $B = 4.9$ T. The current I is parallel (perpendicular) to B for the longitudinal (transverse) magnetoresistance. The left- and right-hand side show the current distortions for a rotation of the antidot array of $\alpha = j\pi/2$ and $\alpha = \pi/4 + j\pi/2$ ($j = 0$, 1, 2, 3), respectively.

[1], [10]. In short, the magnetoresistance is numerically calculated by solving the classical current continuity equation $\nabla \cdot [\hat{\sigma}(\mathbf{r})\nabla\phi(\mathbf{r})] = 0$ for the local electric potential $\phi(\mathbf{r})$, using the resistivity tensor for Bi $\hat{\rho}(\mathbf{r}) = \hat{\sigma}(\mathbf{r})^{-1}$. In the calculation it is assumed that the insulating holes are perfect cylinders with an effective diameter of 0.44 (ratio of diameter and separation), and top and bottom surface are assumed perfectly flat. The conductivity tensor for Bi was experimentally determined from an unstructured Bi Hall bar reference film without holes. However, due to the nature of the electrodeposition process and the annealing procedure, which results in different grain sizes for the film with and without holes, the experimentally determined conductivity tensor is only approximately correct for the Bi antidot film. Therefore, after calculating the components of the resistivity tensor of the microstructured film $\hat{\rho}$, using the experimentally measured field dependent resistivity of the unstructured Bi film, we replaced $\hat{\rho}$ by a simple linear expression $a\hat{\rho} + b$. The field independent constants a, b were determined so as to fit the experimental results for the transverse resistivity as function of $|B|$, when B lies along a principal axis of the antidot array.

The resulting fits to the experimental data obtained in this fashion are shown in Fig. 2 by the solid lines. As can be seen in the figure, the calculated and experimental angular dependence of the magnetoresistance agree very well. The experimental magnetoresistance displays somewhat sharper minima and maxima as compared to the calculations. The reason for this is not completely clear, but possibly this is related to the shape of the holes, which is far from a perfect cylinder [see Fig. 1(b)], and the roughness of the top surface.

IV. Conclusions

In conclusion we have measured the magnetoresistance of a Bi antidot array film. The magnetoresistance shows a pronounced angular dependence that can be understood by the interactions between cigar-shaped regions of strong classical current distortions around the voids. This shows that Bi is a suitable template to test the remarkable new classical phenomena predicted in periodic composite materials. Further experiments in higher magnetic fields and with increased angular resolution are in progress.

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