Anisotropic magnetoresistance in a two-dimensional electron gas in a quasirandom magnetic field

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We present magnetotransport results for a two-dimensional electron gas (2DEG) subject to the quasirandom magnetic field produced by randomly positioned submicron Co dots deposited onto the surface of a $GaAs/Al_xGa_{1-x}As$ heterostructure. We observe strong local and nonlocal anisotropic magnetoresistance for external magnetic fields in the plane of the 2DEG. Monte Carlo calculations confirm that this is due to the changing topology of the quasirandom magnetic field in which electrons are guided predominantly along contours of zero magnetic field.

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The transport properties of a two-dimensional electron gas (2DEG), subject to a spatially random magnetic field, have attracted great theoretical interest recently.[1,2] This is partly due to its relevance to the fractional quantum Hall effect, which can be understood in terms of composite fermions moving in an effective random magnetic field.[2] The problem of a 2DEG subject to strong random magnetic fields, with correlation lengths that are small compared to the electron mean free path, is particularly interesting because the transport properties are predicted to be dependent on semiclassical "snake orbit" trajectories in which electrons are guided along lines of zero magnetic field.[2] In a previous study we demonstrated that such snake orbits can lead to very large magnetoresistances when a 2DEG is subject to large-amplitude periodic magnetic fields.[3]. In this paper we show that electrons are indeed guided in the direction of the contours of zero magnetic field in a quasirandom magnetic field and that this gives rise to a new type of anisotropic magnetoresistance.

The devices investigated in this study are hybrid ferromagnetic/semiconductor structures in which the magnetic field at the 2DEG is produced by randomly positioned submicron Co dots fabricated on the surface of a GaAs-based heterostructure. Recently, there has been considerable interest in the properties of hybrid ferromagnetic/semiconductor devices due to their potential applications as magnetic field sensors[4] and magnetic storage devices.[5] There have been several previous experimental studies of a 2DEG subject to a random magnetic field. However, these concerned weak random magnetic fields,[6] or random magnetic fields with correlation lengths approximately equal to[7] or much larger than[8] the electron mean free path. Recently, we showed how large amplitude, short correlation length random magnetic fields can be realized by using the naturally occurring domain structures of CoPd films.[9] Larger amplitude, short correlation length random magnetic fields may have been achieved in experiments using Dy dots, but the field amplitude is unknown in this case.[10] The method considered here also produces a relatively large-amplitude, short correlation length, random magnetic field, but has the particular advantage that the topology of the field can be controlled by an external in-plane magnetic field.

Our device consists of a $GaAs/Al_xGa_{1-x}As$ heterostructure containing a 2DEG 35 nm below the surface. At 1.3 K the electron density $n=3.8\times10^{15}\ \mathrm{m}^{-2}$ and the mobility $\mu=45\ \mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, corresponding to a mean free path $\lambda=4.5\ \mu\mathrm{m}$. The device design is shown in Fig. 1(a). The random magnetic field is produced by depositing a randomly distributed pattern of Co dots onto the surface of the Hall bar. This is represented by the shaded area in the figure. The Co dots have a diameter of 500 nm and a thickness of 70 nm. The pattern was produced using electron beam lithography and dc magnetron sputtering to deposit the Co. A computer program was used to generate the positions of the dots that cover 50% of the surface area and are distributed so that they can touch each other, but not overlap [Fig. 1(b)].

Figure 2 shows the longitudinal magnetoresistance of the covered section of the device measured at 1.3 K with a magnetic field applied parallel to the plane of the 2DEG. The magnetoresistance is defined as $\Delta R/R_0=(R-R_0)/R_0$, where R is the measured resistance of the covered section when the magnetic field is applied and R_0 is the resistance of the uncovered section in zero field. Results are shown for angles of 0°, 50°, and 90° between the current along the Hall bar and the direction of the applied field. We observe a positive magnetoresistance for all angles that saturates at approximately ±0.2 T. The size of the magnetoresistance is largest when the field is applied in the direction of the current and decreases as the angle between the field and the current is rotated to 90°. The presence of hysteresis in the measurements is consistent with the fact that sputtered Co films tend to have the easy axis of magnetization in the plane.[11] Indeed, we carried out transport measurements with the magnetic field applied perpendicular to the device and no hysteresis was observed.

We have shown previously that the resistance of a 2DEG increases with increasing random magnetic field amplitude.[9] The magnetization state of the dots is not known at zero external magnetic field. However, we expect the formation of multidomain or vortex states, as has been observed by Miramond *et al.*[12] for dots of diameter greater than 50 nm. Such states have a high degree of, but not complete, flux closure and the small net stray field will produce a small-amplitude random magnetic field at $B=0$ T. This may contribute to the positive value of $\Delta R/R_0$ at $B=0$ T. Additionally, a strain-

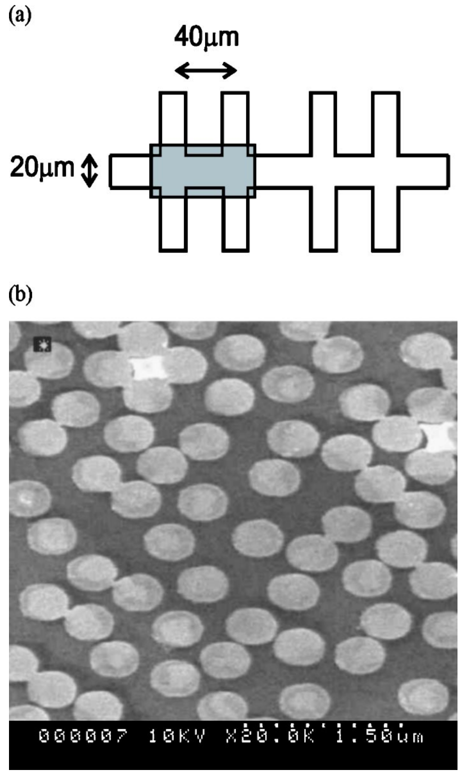

FIG. 1. (a) Standard Hall bar design of the device. The shaded area represents the region where the Co dots are deposited. (b) A scanning electron microscope image of the Co dot pattern.

induced electrostatic field, due to the deposition of Co onto the surface, may also be a factor. With increasing external field, domains aligned with the applied field will grow until, eventually, the magnetization of the dots is saturated in the direction of the applied field. The amplitude of the random magnetic field at the 2DEG will therefore grow with increasing external field until saturation magnetization is reached. This will lead to the observed increase and then saturation of the measured resistance.

We now restrict ourselves to analyzing the resistance when the magnetization of the dots is saturated. The magnetic field profile at the site of the 2DEG due to the random array of Co dots can be calculated numerically, since we know the positions of all the Co dots. The dynamics of the 2D electrons are only sensitive to B_z, the component of the magnetic field perpendicular to the 2DEG. We have calculated B_z for our device and find that the rms amplitude is 0.13 T at saturation. This is not quite in the strong field limit as defined in Ref. 2. Figure 3 shows the contours of zero field (B_z=0 T) calculated for the case when the magnetization of the dots is saturated in the x direction. It can be seen that the contours are preferentially aligned in the direction perpendicular to the magnetization of the dots. Using the calculated magnetic field profile we have calculated the expected device resistance using the semiclassical Kubo formalism. The method involves calculating the trajectories of electrons with the Fermi velocity in the random magnetic field profile. By averaging the velocity-velocity correlation function over all of the trajectories the diffusivity tensors for the system can be calculated using the Kubo formula:[13]

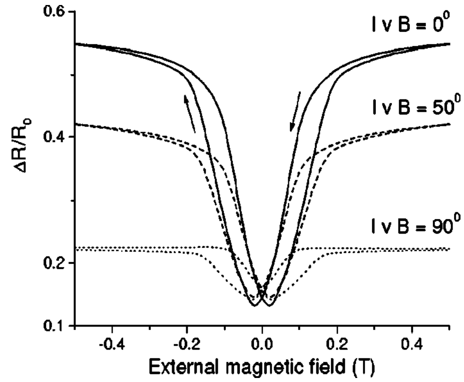

FIG. 2. The longitudinal magnetoresistance measured at 1.3 K with the magnetic field applied parallel to the plane of the 2DEG. Results are shown for angles of 0°, 50°, and 90° between the current and the applied field. The arrows show the direction that the magnetic field is sweeping.

$$D_{xx} = \int_0^\infty \langle v_x(0) v_x(t) \rangle dt. \qquad (1)$$

Here the x axis is parallel to the direction of the applied field. We can then calculate the magnetoresistance. Scattering is included in the model by randomizing the electron direction using a Monte Carlo method with appropriate probability distributions for the scattering angle and scattering time. Figure 4 shows the calculated final positions of 10 000 electrons starting at the same initial position (0,0) with the Fermi velocity and initial angles spread evenly over 360°. Each electron is allowed to travel 6 momentum relaxation mean free path lengths. The results show that the electrons are preferentially guided in the direction of the B_z=0 T contours. Our calculations show that this leads to an enhancement of the ratio D_{yy}/D_{xx}. In the case of a 1D periodic sign alternating magnetic field profile this arises from snake orbits in the y direction.[3] In the present case electron trajectories are preferentially guided along contours of B_z=0 T, but the

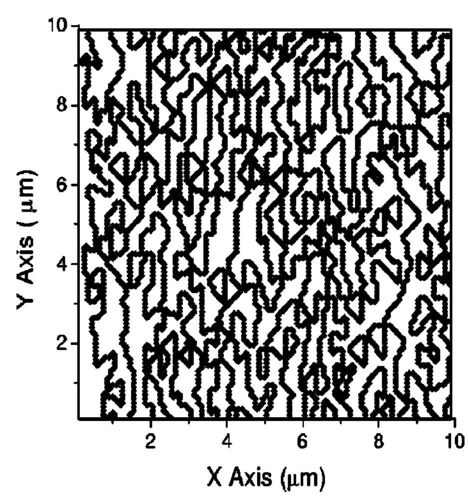

FIG. 3. The contours of zero magnetic field (B_z=0 T) taken from the calculated magnetic field profile at the site of the 2DEG due to a random array of Co dots. The magnetization of the Co dots is along the x axis.

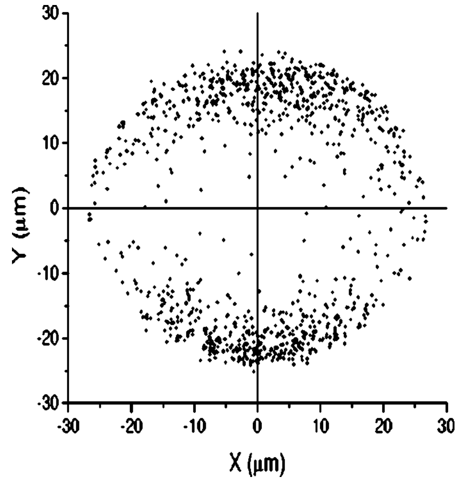

FIG. 4. The final positions of 10 000 electrons starting at the coordinates (0,0) with the Fermi velocity and initial angles spread evenly over 360°. The electron trajectories were calculated within the field profile used to produce Fig. 3.

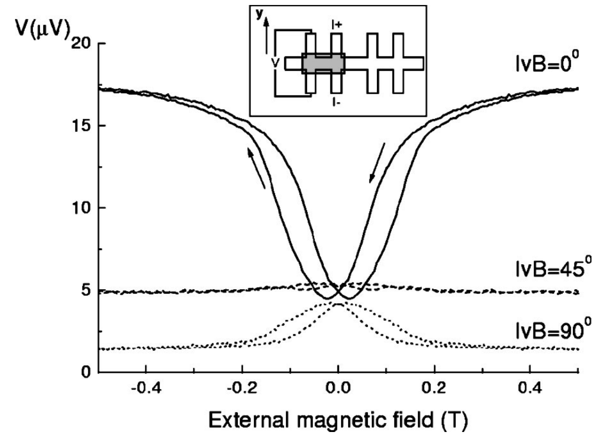

FIG. 6. The inset shows the experimental arrangement for the nonlocal measurement. The measured voltage is shown for the external magnetic field applied in the plane of the 2DEG at angles of 0° (solid curve), 45° (dashed curve), and 90° (dotted curve) to the direction of the current.

probability of an electron completing a full snake orbit is small.

Figure 5 shows the magnetoresistance, measured for an in-plane field of 0.5 T, against the angle between the current and the applied field. If the anisotropic magnetoresistance is due to only the induced magnetization and the samples have no additional intrinsic anisotropy, arising from anisotropy in the dot positions for example, then one expects[14]

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

where $\rho_{\parallel}$ is the measured resistivity for $\theta=0°$ and $\rho_{\perp}$ is the measured resistivity for $\theta=90°$. The dashed line in Fig. 5 shows that this gives an excellent fit to our data. Also shown are the results of numerical calculations of the conductivity tensors. The fit was obtained by using the thickness of the Co dots as the only adjustable parameter. We see excellent quantitative agreement to our data when a thickness of 75 nm is

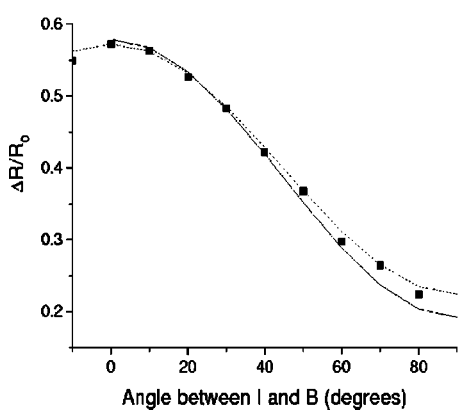

FIG. 5. The magnetoresistance, measured with an in-plane field of 0.5 T, plotted against the angle between the current and the magnetic field. The dashed line is a fit of Eq. (2) to the data using the measured values of $\rho_{\perp}$ and $\rho_{\parallel}$. The solid line shows the results of the numerical calculations.

used, which is in very close agreement with the nominal thickness of 70 nm.

Another clear example of the effect of contours of $B_z = 0$ T guiding the electron motion can be observed by performing measurements in a nonlocal geometry. The inset to Fig. 6 shows the experimental arrangement. A constant ac current of 300 μA is passed between two voltage probes in the y direction, across the Hall bar, and the voltage is measured between two adjacent voltage probes. The external magnetic field is applied parallel to the plane of the 2DEG. Figure 6 shows the measured voltage, as the external magnetic field is swept to ±0.5 T, for angles of 0°, 45°, and 90° between the current and the field. When the magnetic field is parallel to the current, the contours of $B_z=0$ T will guide electrons in the x direction, perpendicular to the direction of net current flow, i.e., the current will tend to spread along the Hall bar. This results in an increase in the measured voltage. When the magnetic field is perpendicular to the current, the contours of $B_z=0$ T will tend to focus electrons along the y direction, resulting in a decrease in the measured voltage. For 45° one expects the existence of the orientated zero field contours to have no effect.

In conclusion, we have observed an anisotropic magnetoresistance and demonstrated that this arises from the dependence of the anisotropy of the quasirandom magnetic field on the direction of the net magnetization. In particular, we have shown the strong influence of the contours of zero magnetic field, which has been predicted theoretically.[2] We note that a previous study of electron transport in a periodic magnetic field considered an anisotropic magnetic field profile as a possible explanation for the effects observed, but a detailed study was not presented.[15]

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[1] J.T. Chalker, D.G. Polyakov, F. Evers, A.D. Mirlin, and P. Wölfle, Phys. Rev. B **66**, 161317 (2002).

[2] F. Evers, A.D. Mirlin, D.G. Polyakov, and P. Wölfle, Phys. Rev. B **58**, 15 321 (1998); J. Wilke, A.D. Mirlin, D.G. Polyakov, F. Evers, and P. Wölfle, *ibid.* **61**, 13 774 (2000), and references therein.

[3] A. Nogaret, S. Carlton, B.L. Gallagher, P.C. Main, M. Henini, R. Wirtz, R. Newbury, M.A. Howson, and S.P. Beaumont, Phys. Rev. B **55**, R16 037 (1997).

[4] B.L. Gallagher, V. Kubrak, A.W. Rushforth, A.C. Neumann, K.W. Edmonds, P.C. Main, M. Henini, C.H. Marrows, B.J. Hickey, and S. Thoms, Physica E (Amsterdam) **11**, 171 (2001); V. Kubrak, A. Neumann, B.L. Gallagher, P.C. Main, M. Henini, C.H. Marrows, and B.J. Hickey, J. Appl. Phys. **87**, 5986 (2000); A.K. Geim, S.V. Dubonos, J.G.S. Lok, I.V. Grigorieva, J.C. Maan, L. Theil Hansen, and P.E. Lindelof, Appl. Phys. Lett. **71**, 2379 (1997).

[5] M. Johnson, B.R. Bennett, M.J. Yang, M.M. Miller, and B.V. Shanabrook, Appl. Phys. Lett. **71**, 974 (1997).

[6] A.K. Geim, S.J. Bending, I.V. Grigorieva, and M.G. Blamire, Phys. Rev. B **49**, 5749 (1994); A.K. Geim, S.J. Bending, and I.V. Grigorieva, Phys. Rev. Lett. **69**, 2252 (1992); A. Smith, R. Taboryski, L.T. Hansen, C.B. Sørensen, P. Hedegard, and P.E. Lindelof, Phys. Rev. B **50**, 14 726 (1994); L.T. Hansen, R. Taboryski, A. Smith, P.E. Lindelof, and P. Hedegard, Surf. Sci. **362**, 349 (1996).

[7] G.M. Gusev, A.A. Quivy, J.R. Leite, A.A. Bykov, N.T. Moshegov, V.M. Kudryashev, A.I. Toropov, and Y.V. Nastaushev, Semicond. Sci. Technol. **14**, 1114 (1999).

[8] F.B. Mancoff, R.M. Clarke, C.M. Marcus, S.C. Zhang, K. Campman, and A.C. Gossard, Phys. Rev. B **51**, 13 269 (1995).

[9] A.W. Rushforth, B.L. Gallagher, P.C. Main, A.C. Neumann, C.H. Marrows, I. Zoller, M.A. Howson, B.J. Hickey, and M. Henini, Physica E (Amsterdam) **6**, 751 (2000).

[10] P.D. Ye, D. Weiss, G. Lütjering, R.R. Gerhardts, K. v. Klitzing, and K. Eberl, in Proceedings of the 23rd International Conference on the Physics of Semiconductors, edited by Scheffler and Zimmermann (World Scientific, Singapore, 1996), p. 1529.

[11] O. Kohmoto and T. Yamamoto, J. Magn. Magn. Mater. **71**, 33 (1987); H. Qui, T. Ohbuchi, H. Nakai, and M. Hashimoto, Appl. Surf. Sci. **92**, 47 (1996); O. Kohmoto, Phys. Status Solidi B **176**, 1039 (1999).

[12] C. Miramond, C. Fermon, F. Rousseaux, D. Decanini, and F. Carcenac, J. Magn. Magn. Mater. **165**, 500 (1997).

[13] C.W.J. Beenakker and H. Vanhouten, Solid State Phys., Adv. Res. Appl. **44**, 1 (1991).

[14] T.R. McGuire and R.I. Potter, IEEE Trans. Magn. **MAG-11**, 618 (1973).

[15] Dieter Weiss, Peide D. Ye, and Rolf Gerhardts, in Proceedings of the 23rd International Conference on the Physics of Semiconductors, edited by Scheffler and Zimmermann (World Scientific, Singapore, 1996), p. 2367.