Fabrication and characterization of micromagnet arrays on top of GaAs/AlGaAs heterostructures

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Using nanolithographic techniques we deposit an array of ferromagnetic dysprosium dots with period $a=500$ nm on top of GaAs–AlGaAs heterojunctions. The spatially periodic stray fields affect drastically the magnetotransport properties of the electrons in the underlying two-dimensional electron gas and give rise to the long predicted *magnetic* commensurability oscillations. We show that such a semiconductor-ferromagnet hybrid system can be used to study the magnetic properties of nanoscale particles. © *1995 American Institute of Physics.*

Nanometer scale ferromagnetic particles are expected to display unusual magnetic behavior.[1] Depending on the size of the particles the magnetic properties could be tuned from single domain to multidomain behavior. Arrays of such magnetic "quantum dots" may also be of interest for magnetic storage applications where storage densities of 100 Gbit/in.[2] can be envisaged using advanced lithographic techniques. Different routes can be taken to fabricate magnetic structures ranging from the micron to the nanometer regime by using, e.g., electron beam lithography,[2] metalorganic chemical vapor deposition with a tunneling microscope tip[3] or the deposition of submonolayer magnetic films on Au(111) surfaces.[4] To investigate the magnetic properties of such small particles large arrays ($\sim 10^6$ in Ref. 2) can be used and the macroscopic stray fields can be measured conventionally. Other methods to obtain magnetic information about individual ultrafine particles involve an elaborate microsusceptometer technique based on dc superconducting quantum interference devices,[5] scanning magnetometers,[6] Hall effect measurements employing two-dimensional electron systems,[7] magnetic force,[8] and Lorentz microscopy.[9]

In this letter we use the *ballistic motion* of electrons in a two-dimensional electron gas (2DEG) to obtain information about the stray fields of periodically arranged micromagnets (dysprosium dots) deposited on top of a semiconductor heterojunction as is shown in Fig. 1. We find pronounced oscillations in the resistance of the 2DEG as a function of the externally applied magnetic field B_0 reflecting the presence of a periodically (period $a=500$ nm) modulated magnetic field in the plane of the electron gas. The size of the arrays investigated was $\sim 100\times 100\ \mu m^2$ containing approximately 4×10^4 ferromagnetic dots. We note that the sensitivity of the device is not restricted to such macroscopic sizes; using a reduced area of the 2DEG (for example, a quantum dot) allows us in principle to investigate a single magnetic dot.

Our samples are fabricated from different high-mobility GaAs–AlGaAs heterojunctions. Since the basic results are identical for all the samples investigated we concentrate on a device where the electron gas used as a probe of the stray field is located ~100 nm below the sample surface. The mobility of the electrons at 4.2 K was 130 m^2/V s and the carrier density n_s was $2.1\times 10^{15}\ m^{-2}$. This gives an electron mean-free path of $\sim 10\ \mu$m which is by a factor of 20 longer than the period a of the magnetic lateral superlattice. Using conventional photolithography and wet etching, mesa Hall bars like the one sketched in Fig. 1(c) were fabricated. AuGe/Ni pads alloyed at 450 °C in a reducing atmosphere contact the 2DEG. Before deposition of the micromagnets we evaporate a 10 nm thin NiCr layer on the active area which defines an equipotential plane and improves the adhesion of the ferromagnetic dots. The NiCr gate also allows to

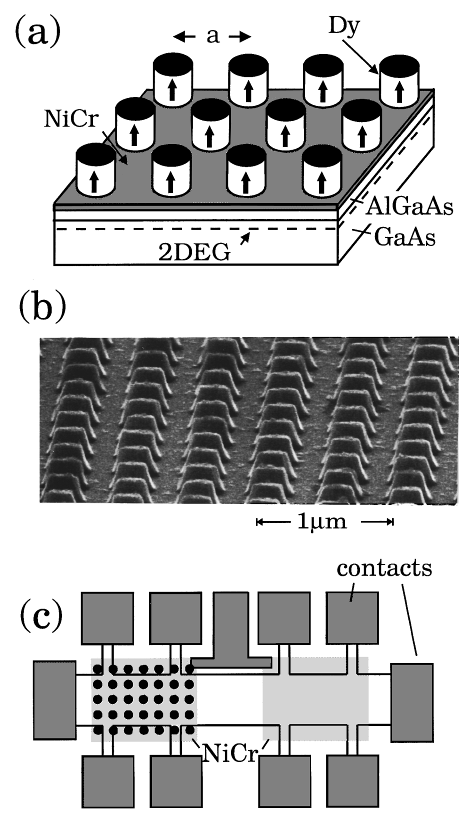

FIG. 1. (a) Sketch of the two-dimensional ferromagnetic Dy dot lattice on top of a GaAs–AlGaAs heterojunction. The corresponding electron micrograph of a tilted sample is shown in (b). Period of the square array: 500 nm; height of the dots: 200 nm. (c) Device geometry containing the Dy dot array and a NiCr coated, unpatterned reference area.

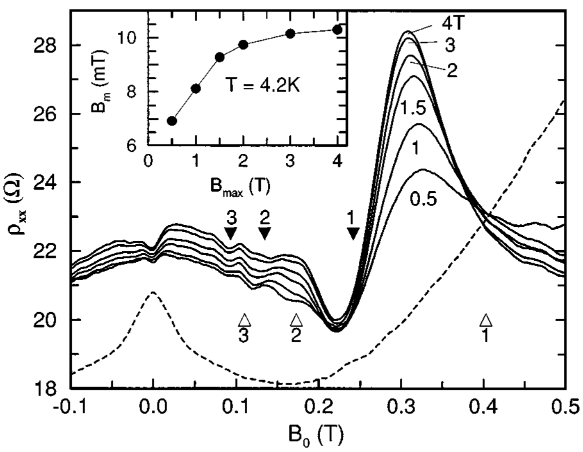

FIG. 2. ρ_{xx} as a function of the external magnetic field B_0 with the maximum applied field B_{max} (0.5–4 T) as parameter. The filled arrows mark the minima positions of ρ_{xx} predicted by Eq. (1), the empty ones mark the corresponding minima for a periodic electrostatic potential. The inset displays the strength B_m of the stray field normal to the 2DEG estimated [Eq. (2)] from the ρ_{xx} maxima at $B_0 \sim 0.3$ T for different B_{max}. The dashed line is the resistivity ρ_{xx} of the unpatterned reference device which shows no dependence on B_{max}.

vary the carrier density n_s. Then we used electron beam lithography to define a square array of holes in a double layer of polymethylmethacrylate (PMMA) of molecular weights 200 000 and 950 000 which were 400 and 200 nm thick, respectively. The pattern in the PMMA was developed in methylisobutylketone (MIBK) and isopropyl alcohol (1:3) for 3 min. In the next step a 200 nm thick layer of dysprosium was thermally evaporated. After lift-off of the remaining PMMA in acetone we obtain micromagnet arrays like the one shown in the electron micrograph in Fig. 1(b). The flower-pot shaped dots have a diameter of ~200 nm on top and a height of ~200 nm. We used the rare-earth metal Dy which has a ferromagnetic ordering for temperatures $T<85$ K since the magnetic polarization in crystalline Dy can be as high as 3.8 T.[10] The low-temperature resistance of the 2DEG was measured in a ^{4}He cryostat with superconducting coils which provide the external magnetic field B_0 pointing normal (z direction) to the plane of the 2DEG. To determine the four-point resistance an ac current with amplitude 1 μA at ~13 Hz was applied between the current probes and the voltage drop between the potential probes [see Fig. 1(c)] was measured using conventional lock-in techniques.

Magnetoresistance data taken at 4.2 K from a 2DEG underneath a square array with $a=500$ nm are displayed in Fig. 2. The six traces, labeled 0.5–4 T, differ in their magnetic history. After the initial cooldown the 0.5 T trace was taken after the external magnetic field B_0 was swept to a maximum value of $B_{max}=+0.5$ T. For the next trace, B_0 was ramped up to $B_{max}=+1$ T and the ρ_{xx} data in Fig. 2 were taken while the magnetic field was swept down. By successively sweeping to higher B_{max} we increase the magnetic polarization of the Dy dots and, hence, the stray field of the micromagnets in the plane of the 2DEG. The increasing strength of the micromagnets leaves distinct signatures in the resistivity ρ_{xx}. With increasing B_{max} a pronounced maximum emerges around $B_0=0.3$ T while at lower B_0 the resistance oscillates. These oscillations have been long predicted[11] and reflect the commensurability between the classical cyclotron radius $R_c=\hbar\sqrt{2\pi n_s}/eB_0$ of the electrons at the Fermi energy in the 2DEG and the period a of the transverse component $B_m(x)$ of the periodic stray field. For a one-dimensional periodic magnetic field in the x-direction minima in ρ_{xx} are expected when[11–13]

$$\frac{2R_c}{a}=\lambda+\frac{1}{4} \tag{1}$$

holds, where λ is an integer oscillation index. These oscillations are closely related to the magnetoresistance oscillations found in a weak *electrostatic* periodic potential and can be understood as a consequence of a modified Landau level structure.[14–16] The periodic magnetic field (or electrostatic potential) transforms the degenerate Landau levels into Landau bands with a magnetic field dependent width. The characteristic difference between *magnetic* and *electric* commensurability oscillations is their phase: ρ_{xx} of an electrostatically modulated 2DEG has minima when $2R_c=(\lambda-1/4)a$ holds, while for the same condition the resistance of a magnetically modulated 2DEG displays maxima. Our devices clearly show the magnetic commensurability oscillations. The ρ_{xx} oscillations become more pronounced with increasing B_{max} and the minima positions lie closely at the positions predicted by Eq. (1). By varying the gate voltage and, hence, the electron density we checked that the ρ_{xx} minima shift with $\sqrt{n_s}$ as is expected from Eq. (1). Slight deviations of the minima positions in Fig. 2 probably originate from the presence of a weak electrostatic potential caused by strain. This strain, not dependent on B_{max}, is due to the different thermal expansion coefficients of GaAs and Dy.[17–19] The corresponding shift of the resistance minima positions away from the one predicted by Eq. (1) were recently studied in detail for an one-dimensional periodic magnetic field.[20,21] The strain induced electrostatic potential is the reason why the magnetic commensurability oscillations were not detected in earlier experiments where different ferromagnetic materials with weaker magnetic polarization were used.[17,19] The amplitude B_m of a cosine stray field $B_m \cos Kx$ with $K=2\pi/a$ can be estimated from the amplitude of the resistance maxima.[12,20]

$$\frac{\Delta\rho_{xx}}{\rho_0}=\frac{B_m^2\mu^2 a}{\pi^2 R_c}\sin^2\left(KR_c-\frac{\pi}{4}\right). \tag{2}$$

Here, $\Delta\rho_{xx}=\rho_{xx}-\rho_0$ with ρ_0 the zero field resistance of the unpatterned 2DEG. We used $\rho_0\approx 20.8$ Ω, taken from the zero field resistance of the unpatterned reference sample, to determine $\Delta\rho_{xx}$. The B_m values estimated with Eq. (2) from the ρ_{xx} maximum at $B_0\sim 0.3$ T are displayed in the inset of Fig. 2. The normal component of the stray field, $B_m(x)$, saturates for magnetic fields higher than $B_{max}>3$ T (note that B_m depends on both B_{max} and B_0) indicating that essentially all magnetic moments point in the direction of the externally applied field B_0. Equation (2) predicts a decrease of $\Delta\rho_{xx}/\rho_0$ with decreasing mobility μ: This we checked experimentally by varying the mobility using a reduced electron density and found quantitative agreement. At lower magnetic fields, B_m decreases as is suggested by the strong damping of the magnetic commensurability oscillations. However, their amplitudes are too small for a reliable estimate of the magnetic field modulation. At zero B_0 the 2DEG is still subjected to a magnetic field modulation as can be seen by the increase of the zero field resistance $\rho_{xx}(B_0=0)$ with increasing $B_{\max}$. So far no theory is available to estimate the modulation strength B_m from the change of $\rho_{xx}(B_0=0)$. The minima positions at $B_0=0$ are essentially independent of $B_{\max}$ indicating that the magnetized micromagnets add no offset magnetic field. Consistent with this we find no difference in the Hall resistance of patterned and reference areas of our devices. The normal component of the stray field alternates such that the average field in the plane of the 2DEG is zero. While surprising on a first glance it is a simple consequence of magnetostatics demanding that a periodic array of magnets cannot generate an additional constant magnetic field to be superimposed on the external one. The small additional Hall voltage found in recent work underneath a small array of magnets[7] we ascribe to stray fields connected to the finite size of the array. In the magnetically modulated 2DEG we find a positive low-field magnetoresistance which grows with increasing $B_{\max}$. This is in contrast to the magnetoresistance of the reference sample where a negative magnetoresistance is observed. A positive magnetoresistance is a characteristic feature of electron transport in an electrostatic periodic potential,[14] ascribed to open trajectories in the lateral superlattice.[22] We assume that a similar mechanism is responsible for the positive slope of ρ_{xx} in a lateral *magnetic* superlattice. Finally, we note the peculiar asymmetry of ρ_{xx} around $B_0=0$. If the external magnetic field is reversed, the positive low-field resistance saturates at significantly lower B_0's indicating a further reduction of B_m.

In summary, we have shown results of the magnetoresistance in semiconductor–micromagnet hybrid systems. Information on the stray field of these micromagnets can be obtained directly from an analysis of the magnetoresistance traces. An improved theory of magnetotransport in the presence of a magnetic field, modulated on a length scale small compared to the electron mean-free path, should give further insights.

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