Effect of ferromagnetic nanoparticles on the transport properties of a GaMnAs microbridge

M. V. Sapozhnikov, a) A. A. Fraerman, S. N. Vdovichev, B. A. Gribkov, S. A. Gusev, A. Yu. Klimov, and V. V. Rogov

Institute for Physics of Microstructures, Russian Academy of Sciences, GSP-105, Nizhny Novgorod 603950, Russia

Joonyeon Chang, b) Hyungjun Kim, Hyun Cheol Koo, and Suk-Hee Han

Center for Spintronics Research, Korea Institute of Science and Technology, Seoul 136-791, Korea

S. H. Chun

Department of Physics, Sejong University, Seoul 143-747, Korea

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A chain of Co nanoparticles was formed along a GaMnAs microbridge by electron beam lithography. The magnetic state of the particles was manipulated by a magnetic force microscope probe. It was found that resistance of the microbridge depended on the state of the particles and was different for the particles in the single-domain and vortex states. The resistance exhibited steplike behavior in an external magnetic field. This behavior was the result of the effect of the inhomogeneous stray fields of the particles on the microbridge resistance. The observed phenomenon can be used as an alternative way to control GaMnAs transport properties. © 2007 American Institute of Physics. [DOI: 10.1063/1.2768304]

The main idea of spintronics1 is to combine, in the same device, methods of information processing based on the electron charge used in semiconductor electronics and magnetic information storage methods based on the physics of electron spins. Diluted magnetic semiconductors (DMSs) are promising materials for use in spintronics. Since II–VI DMSs exhibit very large Zeeman splitting and a very high g factor of up to 500,2 an external magnetic field can significantly alter the energy of their charge carriers. III–V DMSs such as GaMnAs are assumed to have a large g factor3 also. It has been predicted that under appropriate conditions, inhomogeneous magnetic fields can influence the properties of GaMnAs films and even result in the formation of traps for spin polarized carriers.4 An appropriate and controllable source for such an inhomogeneous field can be obtained by placing an array of ferromagnetic nanoparticles on the surface of DMS film.5 It has previously been reported that the presence of a regular array of ferromagnetic nanoparticles can change the transport properties of superconductors6,7 and Josephson junctions.6,8,9 In this work, we fabricated a device consisting of a chain of Co nanoparticles on a GaMnAs microbridge and demonstrated that its transport properties depend qualitatively on the magnetic states of the particles, and thus can be controlled by manipulating magnetization distribution in the system of nanomagnets.

An initial 100 nm thick Ga1−xMnxAs layer (x = 5%) was grown on a semi-insulating (001) GaAs substrate in a molecular beam epitaxy system under ultrahigh vacuum conditions with a base pressure of ~2 × 10−10 Torr. The Curie temperature of the as-grown GaMnAs film was determined from magnetization versus temperature measurements and found to be around 110 K. Standard UV photolithography was used to fabricate a 1 μm wide and 10 μm long GaMnAs microbridge with four contact probes from the DMS film.

A chain of Co particles was fabricated on the surface of the GaMnAs microbridge with electron beam lithography. We used a double-layer mask containing C60 film as a sensitive layer and Ti film as a transmitting layer. The Co and Ti layers were prepared by using magnetron sputtering. C60 film was deposited by sublimation at a temperature of 350 °C in a vertical reactor with hot walls while cooling the substrate with liquid N2. C60 films have an amorphous structure and so act as negative resistance to an irradiated electron beam. The C60 film was patterned with a JEM-2000 EX electron microscope used in scanning electron microscopy mode under an accelerating voltage of 200 kV. The dose of electron beam irradiation was 0.05–0.1 C/cm2. The exposed samples were developed in toluene for 1 min, and then the patterns were transferred to the Ti layer by plasma etching in a CF2Cl2 atmosphere. The last step in fabricating magnetic particles was the Ar+ ion milling of the Co films by using this double-layered mask. Prior to deposition of the Co film, the GaMnAs microbridge was covered with a 50 nm thick SiO2 layer to prevent direct electrical contact between DMS and Co nanoparticles. This also eliminated the effects of exchange interactions between the Co particles and the DMS material.

Preliminary investigation of the GaMnAs bridge prior to the fabrication of the Co nanoparticles showed that the empty bridge had anisotropic magnetoresistance that is typical of GaMnAs (Refs. 10 and 11) (Fig. 1). The highest resistance was obtained when the applied field was perpendicular to the current direction, and the lowest resistance was obtained when the field was parallel to the current direction. It has been shown that critical fluctuations lead to an increase in resistance of the GaMnAs film close to the temperature of the magnetic phase transition.12,13 This maximum is shifted to higher temperatures when an external field is applied due to the suppression of these fluctuations. It turns out that the position of the maximum and the value of the Curie tempera-

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a)Electronic mail: msap@ipm.sci-nnov.ru
b)Electronic mail: preston@kist.re.kr
In this study, the size and the shape of the particles are very sensitive to the quality of the DMS film. Therefore, we measured the dependence of the resistance on the temperature after every stage of the lithography process to be sure that the DMS film had not been damaged.

The magnetic state of the particles was studied with a magnetic force microscope (MFM) (Fig. 2). Depending on the size and the shape of the particles, their magnetic state can be either a vortex or a single domain. Both states are stable for intermediate sizes of particles. The magnetic state of such particles can be manipulated by using a MFM technique. In this study, the size and the shape of the particles were carefully chosen to obtain magnetic states. We designed elliptic Co particles with different aspect ratios, where the long axis of the ellipsoid was either parallel or normal to the current direction along the GaMnAs bridge. The parameters of the investigated samples are summarized in Table I.

The MFM measurements showed that in a zero external magnetic field, the magnetization of the Co particles in samples 1 and 2 was always in the vortex state, whereas the nanoparticles in samples 3 and 4 were always in the single-domain state. Depending on the initial conditions, the nanoparticles in sample 5 were either in the vortex and or in the single-domain state.

The dependence of heterostructure resistance on the external magnetic field was measured at 4.2 K in a magnetic field up to 3 kOe. In general, the magnetoresistance of the samples (1–4) had the same anisotropic character as that observed for a pure GaMnAs bridge without Co particles (Fig. 1); the lowest resistance was obtained when the field was parallel to the current direction. Nevertheless, the longitudinal magnetoresistance curves of samples 1–4 (Fig. 3) were qualitatively different from the curve for a pure GaMnAs bridge without Co particles [Fig. 1(b)]. In the case of the samples with particles in the vortex state (I and II), the curves contained only one step which appeared upon the reversal of the magnetization of the sample. This step corresponded to the magnetization reversal of the DMS material itself and was similar in nature to the step in the curve for a pure GaMnAs bridge [Fig. 1(b)]. If we magnetized the sample in the same direction for a second time, no steps were observed as there was no magnetization reversal in the system. Since the magnetization of each particle took place by a gradual shift of the magnetic vortex under the external field, its stray fields were also gradually altered. Thus, this stray field, in addition to the external one, qualitatively altered the shape of the magnetoresistive curve of the DMS, as shown in Fig. 3 (I and II), but did not produce any additional internal step.

The opposite was true for the heterostructures with single-domain particles (III and IV). An additional step in the curve for fields of 0.4–0.5 kOe was observed. The MFM measurements showed that the magnetization reversal field of corresponding Co particles was about 500 Oe at room temperature, which was approximately the same value as that obtained for the second step in the magnetoresistive curves (Fig. 3, III and IV). This result indicates that this additional step was due to the reversal of the magnetization of the Co particle chain. This reversal was accompanied by a sudden change in the stray field distribution emanating from the chain of Co particles to the DMS and resulted in an appreciable (0.3%) change in the heterostructure resistance. Note that no significant changes were found in the magnetoresistive curves in the case of a transverse field for samples 1–4.

Another interesting result was found for sample 5. Figure 4 shows the transverse magnetoresistance of sample 5 when the Co particles were in a single-domain magnetic state. This sample did not have an insulating SiO₂ sublayer between the Co particles and DMS. Nevertheless, its magne-

![FIG. 1](image1.png)

![FIG. 2](image2.png)

**TABLE I. Parameters of the investigated heterostructures:**

<table>
<thead>
<tr>
<th>No.</th>
<th>a (nm)</th>
<th>b (nm)</th>
<th>d (nm)</th>
<th>SiO₂ sublayer</th>
<th>State at H=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900</td>
<td>650</td>
<td>400</td>
<td>yes</td>
<td>v</td>
</tr>
<tr>
<td>2</td>
<td>650</td>
<td>900</td>
<td>100</td>
<td>yes</td>
<td>v</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>450</td>
<td>400</td>
<td>yes</td>
<td>sd</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>750</td>
<td>250</td>
<td>yes</td>
<td>sd</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>700</td>
<td>150</td>
<td>no</td>
<td>v or sd</td>
</tr>
</tbody>
</table>
The longitudinal magnetoresistances of samples 1–4 (see Table 1) correspond to I–IV, respectively, in the graphs. $a$ indicates the steps due to reversal of the magnetization of the DMS and $b$ indicates the steps due to reversal of the magnetization of the Co nanoparticle subsystem. The steps were observed only in the case of magnetization reversal.

toresitive curves were very similar to those of sample 4, which also had single-domain Co particles elongated perpendicular to the bridge. This result indicates that only the magnetic stray fields of the particles played a major role in determining the transport properties of the DMS, and that the exchange interaction between the particles and the DMS was negligible. As it turned out, it was possible to identify the steps in the curve of the transverse magnetoresistance that corresponded to the reversal of the magnetization of the individual particles (Fig. 4). These steps were present only if the magnetization of the system was reversed and were absent if the system was magnetized in the same direction one more time. This result was confirmed by MFM observations of Co particles in the heterostructure. The left MFM image in Fig. 4(b) shows excellent alignment of the single-domain configuration which was observed immediately before the formation of the step. In contrast, the MFM image on the right shows that reversal of the magnetization of a few particles occurred after going over the step.

Since both the single-domain and vortex states were stable in a zero external field for sample 5, we compared the resistance of the sample with particles in the vortex state to that of the same sample with particles in the single-domain state. Initially, the particles were transferred into the vortex state by using MFM manipulation techniques. At 4.2 K, the resistance in the vortex state was found to be 0.3% lower than in the single-domain state. Although this increase was not large, it means that the change in the magnetic state resulted in a different distribution of the inhomogeneous magnetic field configuration in the DMS. Therefore, it was possible to control the resistivity of the sample by manipulating the magnetic states of the particles.

In summary, we have developed a method for controlling the transport properties of a GaMnAs bridge by manipulating the magnetic states of Co nanoparticles placed on top of it. The magnetoresistance of the device depends on the magnetic state of the Co particles. The reversal of the magnetization of the single-domain state yields a step in the magnetoresistance curve. The effect of stray fields of the particles is the dominant contribution, whereas that of the exchange interaction between GaMnAs and the Co particles is negligible. We have thus demonstrated that the resistance of the sample depends on the inhomogeneous stray fields of the ferromagnetic particles.

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