Semiconductor Physics, Quantum Electronics & Optoelectronics. 2003. V. 6, N 1. P. 53-54.

PACS: 75.50.Pp; 75.75.+a; 85.80.Jm

Magnetic point contact in ferromagnetic semiconductor (Ga,Mn)As

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Abstract. We show that narrow constrictions, a few hundred nanometers wide, in ferromagnetic-semiconductor (Ga,Mn)As layer exhibit large spin-related magnetoresistance. Moreover, we demonstrate that application of oxygen-ions implantation, instead of chemical etching, is much better method of tailoring nanometer-size circuits in (Ga,Mn)As suitable for future spin electronics.

Keywords: ferromagnetic semiconductors, magnetoresistance, nanostructures, ion implantation

Paper received 25.11.02; accepted for publication 18.03.03.

1. Introduction

Use of the electron spin instead of (or in addition to) the electron charge for the transmitting and processing information is nowadays an ambitious challenge for solid-state scientists. Recently grown GaAs layers containing a few percents of Mn atoms become ferromagnetic at low temperatures. Despite a rather limited usefulness of low-temperature ferromagnetics in practice, they might serve as model materials suitable for experiments with nano-size devices and circuits prospective in future spin electronics.

The aim of the present study was to fabricate and investigate a simple magnetoresistive nanodevice formed by a narrow constriction in the ferromagnetic semiconductor layer, which might be called the magnetic point contact [1] (Fig. 1a). It has been predicted that a boundary between the two ferromagnetic domains is to be locked at the constriction. Then, charge carriers passing through the constriction, which carry also the spin, would be scattered at the boundary Bloch wall. After applying an external magnetic field, which orders the spin alignment in the whole layer, the wall disappears and so will do the relevant resistance of the constriction.

2. Experimental

We performed experiments on 50 nm-thick layers of $Ga_{0.99}Mn_{0.01}As$ grown by a low-temperature molecular-beam epitaxy on GaAs substrates, which were either semi-insulating or doped to *n*-type. The manganese atoms in the layer give rise to the appearance of both the electron acceptors and localized unpaired spins. The layers became ferromagnetic below a temperature of 17 K, as we found by magnetic susceptibility measurements. The origin of ferromagnetism is likely the Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction between Mn spins (S_{Mn} = 5/2 for Mn^{2+} charge state), mediated by holes [2,3].

At first we fabricated narrow (of the order of a few hundred nanometers) constrictions in the (Ga,Mn)As layers using standard electron-beam lithography and chemical etching (Fig. 1b). Unexpectedly, so-obtained constricted samples, grown on semi-insulating substrate, lost their electrical conductivity at liquid helium temperatures. Probably, charge carriers have been captured in surface states appearing on an extra surface area denuded by the etching. The sample conductance could be, however, induced by illumination of the sample with a light generating electron-hole pairs in the layer. The constricted samples displayed under illumination a large magnetoresistance, whose magnitude varied non-monotonously with the magnetic field (Fig. 2).

Wishing to avoid the effect of vanishing conductance in nanometer-size etched structures, we applied in the following a novel method of tailoring the constriction [4]. We have discovered that an implantation of (Ga,Mn)As layers with oxygen ions both inactivates Mn acceptors and suppresses ferromagnetism (Fig. 3).

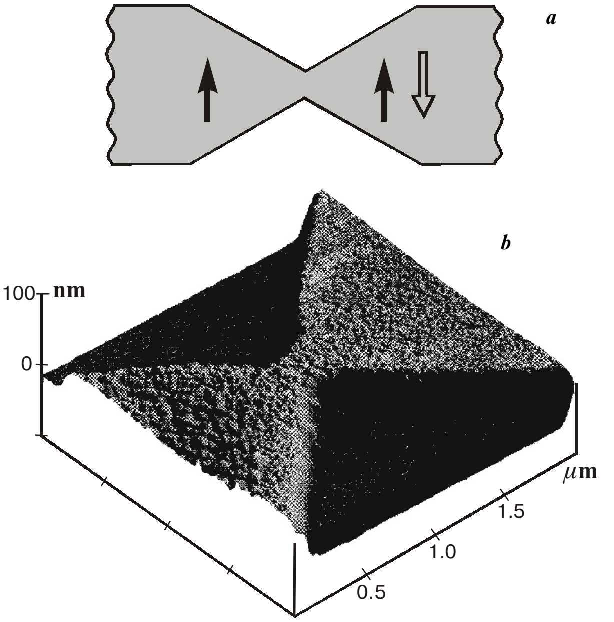

Fig. 1. *a* – scheme of a constriction showing possible spin orientations in the adjacent ferromagnetic domains with and without magnetic field. *b* – atomic-force-microscopy image of the constriction fabricated in (Ga,Mn)As layer with use of electron-beam lithography and chemical etching.

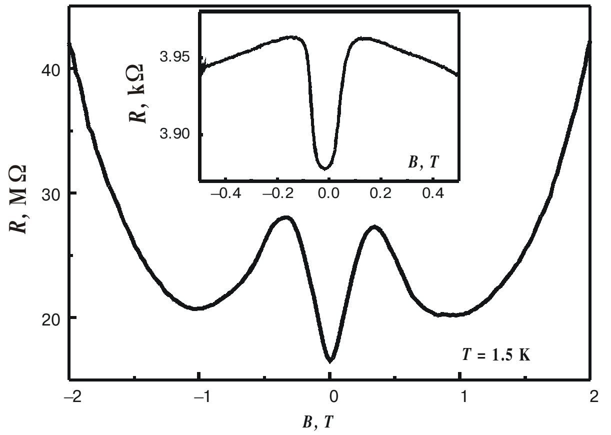

Fig. 2. Resistance of the $Ga_{0.99}Mn_{0.01}As$ constricted sample, fabricated with use of chemical etching, as a function of a magnetic field perpendicular to the layer plane, measured at 1.5 K under illumination. Inset: same for the reference sample having no constriction.

We implanted oxygen ions of the energy of 25 keV into the (Ga,Mn)As layer covered with a 500 nm-thick resist (PMMA), on which constriction designs were patterned by means of electron-beam lithography. We applied a dose of $5 \cdot 10^{13}$ O^+-ions/cm^2. In accord with our expectations, so-obtained constricted samples were conducting even at liquid helium temperatures. Measurements, being presently performed, show an intriguing behavior of the magnetoresistance in the samples obtained in this way.

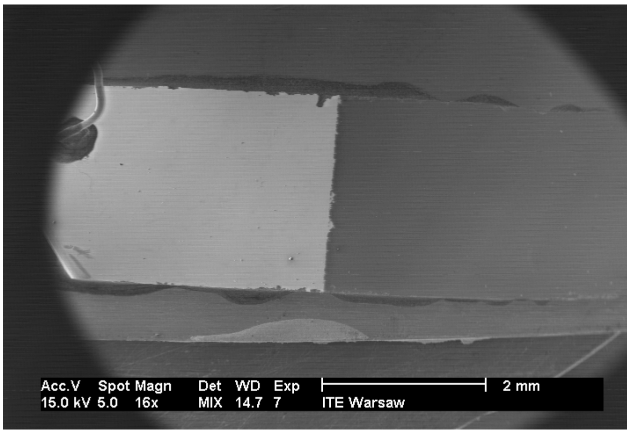

Fig. 3. Micrograph of combined EBIC (electron-beam induced current) and SEI (secondary electron image) in a scanning electron microscope of (Ga,Mn)As layer grown on *n*-type GaAs substrate. The right-hand half of the sample, which does not display an EBIC contrast, has been subjected to oxygen ion implantation.

3. Conclusions

The principal result obtained in this study is that the low-field magnetoresistance of the constricted samples is more than one order of magnitude larger than that of the reference sample without constriction. Our investigations demonstrate also that the oxygen ion implantation might be a prospective method for the fabrication of microcircuits in future spin electronics based on III-V semiconductors containing manganese. The essence of this method – inactivation of Mn acceptors by the implanted oxygen ions – is not fully understood yet.

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