Microelectronic Engineering 86 (2009) 561–564

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

The AFM LAO lithography on GaMnAs layers

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ARTICLE INFO

Article history:
Received 30 September 2008
Received in revised form 13 November 2008
Accepted 21 November 2008
Available online 3 December 2008

Keywords:
Local anodic oxidation
Atomic force microscopy
Ferromagnetic semiconductor
Magnetoresistance

ABSTRACT

We prepared constrictions on ferromagnetic GaMnAs layer by the local anodic oxidation (LAO) using the atomic force microscope (AFM). These oxide lines, produced by the negatively biased AFM tip, formed the electrical barrier to the conducting holes in the layer. The constricted samples were characterized at low temperature (12 K). They showed magnetoresistance effect specific for nanoconstrictions during in-plane magnetic field sweep in both polarities for the different mutual orientation of magnetic field and current. The LAO appears to become a useful patterning technique for research of ferromagnetic semiconductor nanostructures. Further optimization of LAO parameters for reaching better homogeneity of the oxide lines is needed.

1. Introduction

The LAO by the proximal probe, first reported by Dagata et al. [1] is one of the lithography techniques applicable for fabrication of nanometre structures and devices. The LAO by the AFM is based on a direct oxidation of the sample by the negatively biased AFM tip with respect to the sample. The oxidized surface constitutes an energy barrier for charge carriers either in metal or in a semiconductor heterostructure. Forming thin film nanodevices by AFM presents several advantages over other techniques like e-beam lithography (EBL). In contrast to EBL, LAO can achieve a good resolution with relatively inexpensive equipment. Excellent privilege of this technique is the ability to fabricate the nanostructures and examine them at almost the same time. On the other hand, the LAO is restricted to shallow modification of a limited number of materials and suffers from a poor reproducibility [2].

The typical widths of the LAO lines reported recently are on the level of 100 nm. Some groups [3] present better resolution with feature size below 60 nm. The lateral resolution is found to be largely determined by the defocusing of the electric field by a water film, surrounding the tip, whose extent is a function of ambient humidity. Better height uniformity of the oxide regions can be obtained by controlling the AFM tip current through a feedback on the tip bias voltage.

Recently the LAO of GaAs based layers with the oxide line height up to 10 nm is intensively studied. AFM nanopatterning of a high mobility shallow 2D hole gas allows to fabricate high quality quantum point contact [4], quantum dots, tunnelling barriers [5], quantum ring structures [6] and finite antidot arrays [7].

Very few reports are presented about the LAO on the ferromagnetic GaMnAs layers [8]. This material is very promising for the spintronic applications. Spin-valve and spin-filtering effects has been observed in the ferromagnetic nanostructures with the domain-wall pinning on the patterned nanoconstrictions [9]. These constrictions are laterally defined by the oxide insulating barriers produced by the LAO. We expect the oxide line depth to be approximately the same as its height above the surface as we presented previously [10]. The GaMnAs layers are still ferromagnetic to minimal thickness 5–10 nm. The LAO oxide line height should therefore be greater than 10 nm to make the good electrical barrier for the lateral confinement of holes in such constrictions.

2. Experimental

The ferromagnetic $Ga_{1-x}Mn_xAs$ layers for the LAO process were prepared by low temperature (LT) MBE growth. The sample consisted of GaAs buffer layer of about 200 nm thick followed by 5 nm of LT GaAs and 10 nm of LT GaMnAs layer ($x = 0.07$) grown at approximately 200 °C. The LAO lithography was carried out by using the AFM Smena/Ntegra NT-MDT at room temperature in a semi-contact regime with enabled feedback. AFM body was placed in a hermetically sealed cap with controlled humidity in the range 50–80%. Water vapour was developed in a bubbler with a controlled air flow and temperature. The sample was positively biased from 6 to 24 V with respect to the AFM tip. DCP11 standard cantilevers with a conducting diamond coating with a radius of 30 nm were utilized for the oxidation. The tip speed during the

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doi:10.1016/j.mee.2008.11.035

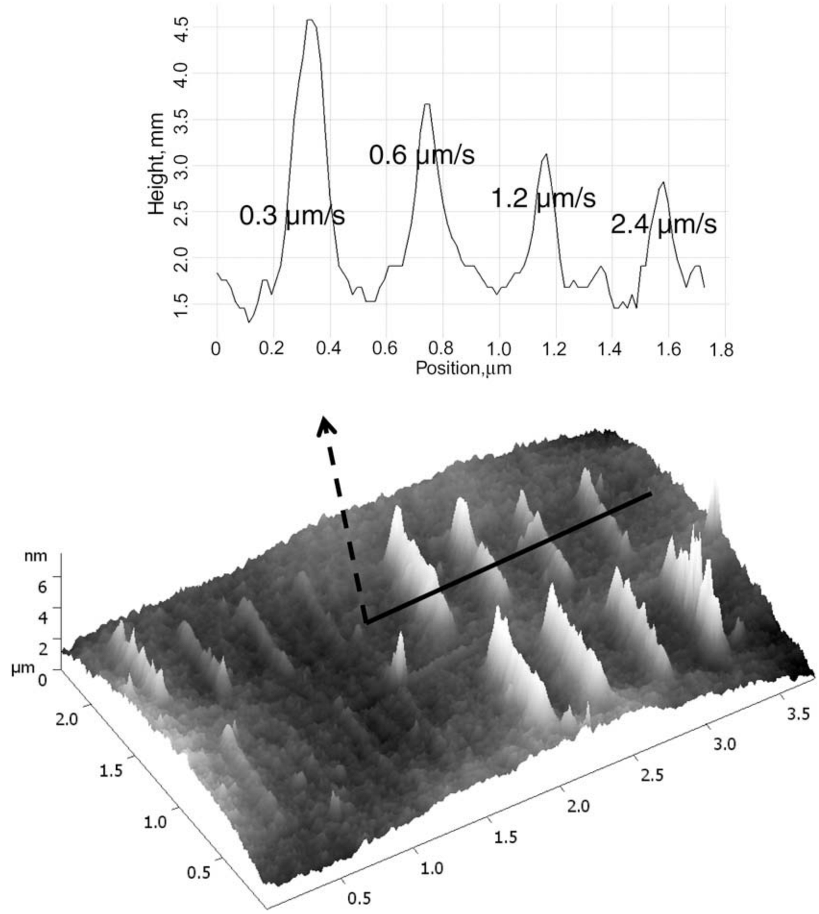

Fig. 1. Oxide lines produced by different tip velocities (0.3, 0.6, 1.2 and 2,4 μm/s) and voltages (8 V four left bottom lines, 10 V four left top lines, 12 V four right top lines +1D profile and 14 V four right bottom lines).

oxidation was changed from 300 nm/s to 2.4 μm/s. Resulting oxide lines are shown in Fig. 1 for different voltages. Setting the original set point at 50% of the free cantilever oscillation magnitude enables to keep the tip-surface force to be the same at the start of each oxidation. The tip force was then increased by lowering the set point value to 80%–20% of its original value reached after auto set point procedure. To produce oxide lines with height greater than 10 nm, we increased the negative voltage on the tip to

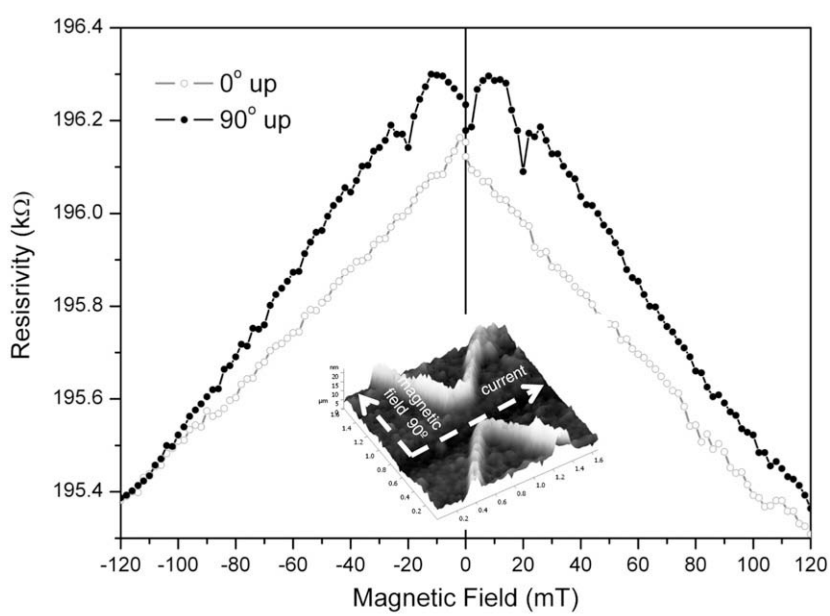

Fig. 2. Tunnelling anisotropic magnetoresistance in the structure A with the constriction width 150 nm (inset). Resistivity vs. magnetic field with different in-plane orientations at 12 K. Arrows represent magnetic field sweep direction.

24 V. The tip speed 0.5 μm/s, the tip force at 50% of the original set point value and 75% ambient humidity were chosen as further optimal values for the LAO process. Then we patterned three different oxide constrictions on the identical 20 μm wide Hall-bars made by the optical lithography: Structures A (Fig. 2) and B (Fig. 3) represent single and double constrictions, respectively, while structure C (Fig. 5) was prepared for the gate control of the constriction width in further research (not reported here). The constricted Hall-bars were characterized by LT transport measurements in the magnetic field of different orientations. The closed-cycle helium cryostat was used for the sample cooling to12 K. The magnetic field was produced by the electromagnet with the arbitrary in-plane rotation.

3. Results and discussion

As a result of the LAO, the height of oxide nanolines increased to 18 nm as we reported in [10]. The width of these lines was approximately 100 nm at half maximum. The lines showed a worse homogeneity in comparison with those created by lower voltage. The lateral structure A (inset in Fig. 2) had relatively wide constriction (150 nm) and showed only a little effect on magnetoresistance at temperature 12 K and in-plane magnetic field with orientations both parallel and perpendicular to the current direction (Fig. 2). The structure B had two constrictions with narrow width (~30 nm) and a quantum dot in-between (inset in Fig. 3). Relatively significant resistance maxima were observed in all the magnetic

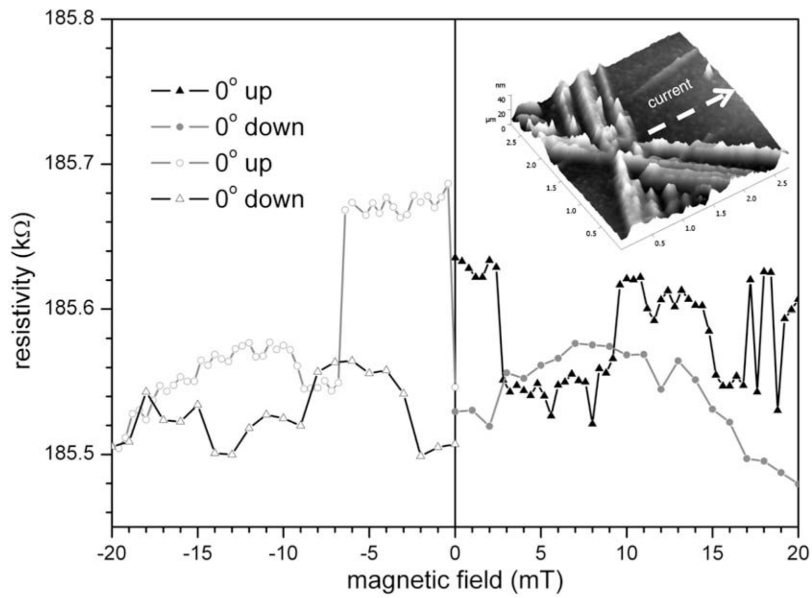

Fig. 3. Tunnelling anisotropic magnetoresistance in the LAO patterned nanostructure with the quantum dot in between two constrictions with low constriction width - structure B (inset). Resistivity vs. magnetic field in parallel direction at 12 K.

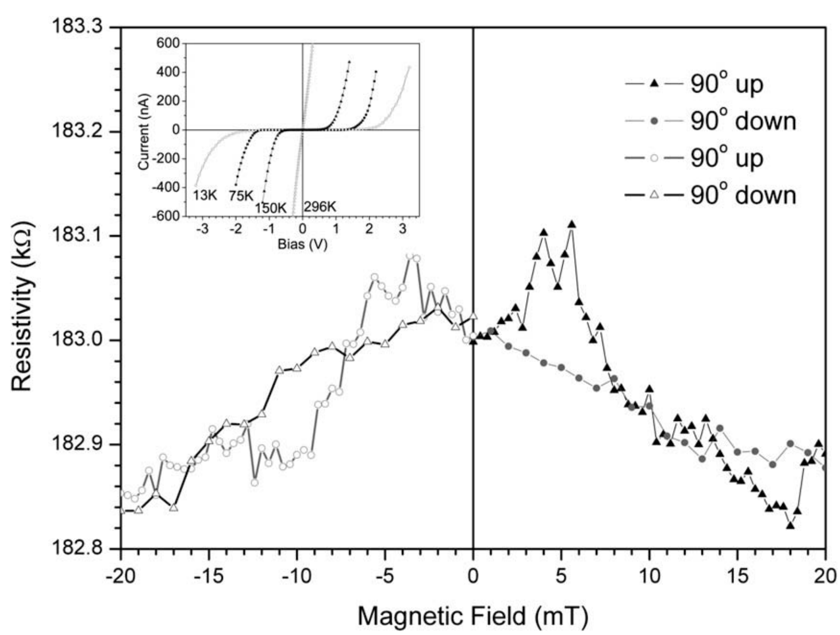

Fig. 4. Resistivity vs. magnetic field in perpendicular direction in the structure B at 12 K. Current–voltage characteristics of the oxide tunnel barrier as a function of temperature are in the inset.

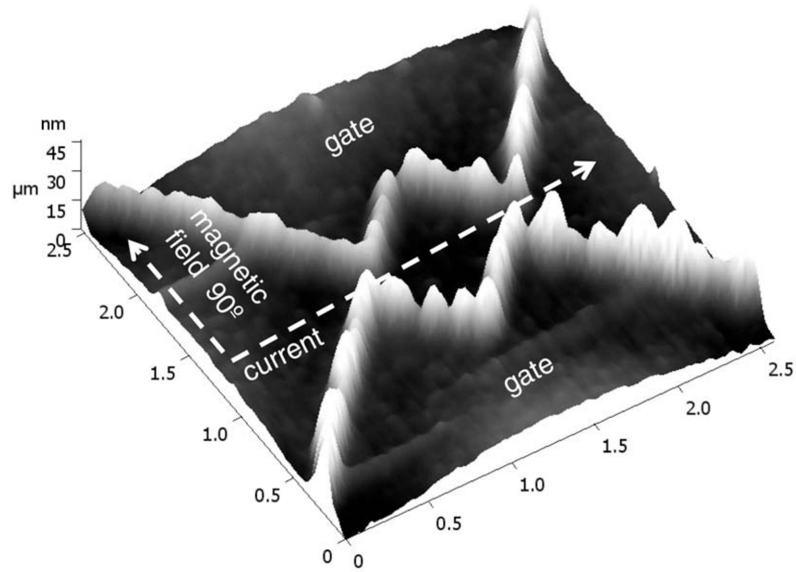

Fig. 5. Structure C prepared for the gate control of the constriction width.

field orientations in the interval of 0–10 mT by the magnetic field sweep in both polarities. In the orientation parallel to the current flow the resistivity was almost constant up to 7 mT and then sharply dropped down (Fig. 3). In the perpendicular orientation the resistance had a double peak at 5 and 7 mT (Fig. 4). These effects may be connected with the domain-wall pinning at the constriction. The resistivity was calculated from the current by the bias 100 mV for all the cases. Temperature dependence of *I–V* curves (in the inset) showed tunnelling through narrow constriction.

4. Conclusions

Our target was the preparation of very high oxide lines to make the good electrical barrier in the GaMnAs ferromagnetic layers. We used higher voltage, low tip velocity and high humidity for the LAO process. The maximum height of the obtained oxide lines was 18 nm by 24 V applied on the layer in respect to the AFM tip. The optimal oxidation speed of 500 nm/s and ambient humidity of about 75% was found. Nanostructures with the different constriction dimensions were fabricated. Low temperature magnetotransport experiments show only small magnetoresistance effects. Further optimization of the effective constriction width using biased lateral gates could give improved sensitivity to the magnetic field. The structure C designed for this purpose will be analyzed in further research.

Acknowledgement

The work was supported by the Grants Nos. 102/06/0381 GACR, KAN400100652 GA CAS and MSM 6840770014, The Ministry of Education CR.

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