Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp1138-1139

Large magnetoresistance of $Ge_{1-x}Mn_x$ single films and heterostructures with magnetic nanocolumns

Shinsuke Yada, Ryohei Okazaki and Masaaki Tanaka

Dept. of Electrical Eng. and Information Systems, The University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
Phone: +81-3-5841-6729, Fax: +81-3-5841-0525 E-mail: yada@cryst.t.u-tokyo.ac.jp

1. Introduction

For Si-based spin-electronic applications, group-IV compatible materials, such as Si- and Ge-based ferromagnetic semiconductors (FSs), have been investigated for the past decade. Since Ge plays an important role for advanced CMOS devices [1], Mn doped Ge ($Ge_{1-x}Mn_x$) [2-7] has been investigated as a Ge based FS with considerable attention.

In our previous study, it was shown that the origin of ferromagnetism in $Ge_{1-x}Mn_x$ is nano-sized columnar precipitation of amorphous $Ge_{1-y}Mn_y$ with high Mn content y [3], which means that $Ge_{1-x}Mn_x$ films investigated so far were not FS. Here, x is the average Mn content in the whole film and y is the local Mn content in the precipitated nanocolumns, and $x < y$. Nanocolumnar structures in GeMn were widely reported [4-7], where specific features were observed such as positive magnetoresistance (MR) [4, 5], high T_C [4], and controllability of the magnetization of nanocolumns [6]. Although $Ge_{1-x}Mn_x$ with nanocolumns is not FS, it may be used as a group-IV based functional spin-electronic material.

In this paper, we investigate the magneto-transport properties of single $Ge_{1-x}Mn_x$ films and magnetic-tunnel-junction-like heterostructures, which consist of $Ge_{1-x}Mn_x$ / SiGe / $Ge_{1-x}Mn_x$, where $Ge_{1-x}Mn_x$ contains $Ge_{1-y}Mn_y$ nanocolumns.

2. Sample preparation

We prepared single $Ge_{1-x}Mn_x$ films and heterostructures using $Ge_{1-x}Mn_x$ with nanocolumns, which are grown on Ge (001) substrates ($p \sim 1\times10^{18}$ cm^{-3}) by low temperature molecular beam epitaxy (LT-MBE). A 30-nm-thick single $Ge_{1-x}Mn_x$ film with x = 0.11 and 0.28 was grown on a 15-nm-thick Ge buffer layer at a growth rate R_G = 150 nm/h and a substrate temperature T_S = 100°C, in which $Ge_{1-y}Mn_y$ nanocolumns are known to be formed. Fig. 1 shows (a) a schematic sample structure of the single films and (b) a cross-sectional TEM image of a single $Ge_{0.94}Mn_{0.06}$ film grown at R_G = 150 nm/h and T_S = 100°C, where amorphous $Ge_{0.91}Mn_{0.09}$ nanocolumns and surrounding $Ge_{0.97}Mn_{0.03}$ matrix are formed.

We also grew heterostructures using $Ge_{1-x}Mn_x$, whose schematic structures (S0367 and S0373) are shown in fig. 2. As the bottom magnetic layer, a 30-nm-thick $Ge_{0.94}Mn_{0.06}$ film was grown at R_G = 150 nm/h and T_S = 100°C. The barrier layer was a 6-nm-thick $Si_{0.2}Ge_{0.8}$ film grown at R_G = 30 nm/h and T_S = 100°C. The top magnetic layer was a 30-nm-thick $Ge_{0.89}Mn_{0.11}$ (S0367) and $Ge_{0.72}Mn_{0.28}$ (S0373) films grown at R_G = 150 nm/h and T_S = 200°C. (In this growth condition, Mn_5Ge_3 intermetallic clusters with surrounding Ge matrix are formed in a $Ge_{1-x}Mn_x$ film.) After growing the single films and heterostructures, we fabricated mesa diodes 200-μm in diameter with a Pt contact and a 50-nm-thick SiO_2 passivation layer.

3. Magneto-transport of the single $Ge_{1-x}Mn_x$ films

Fig. 3 shows *I-V* characteristics of the single film ($Ge_{0.89}Mn_{0.11}$ and $Ge_{0.72}Mn_{0.28}$) mesas at 15 K. Although the *I-V* characteristics at room temperature showed ohmic contact behavior, strong rectification was observed at 15 K, which is probably caused by the Schottky contact between the $Ge_{1-x}Mn_x$ and Pt layers.

Fig. 4 shows magnetic field dependence of resistance (MR curve) of the single $Ge_{0.89}Mn_{0.11}$ and $Ge_{0.72}Mn_{0.28}$ film mesas measured at 15 K and applied bias of -5 mV. The vertical axis of fig. 4 shows MR ratio, which is defined as

$$\left(R - R_0\right)/R_0 \times 100(\%), \qquad (1)$$

where R is the resistance of the sample and R_0 is the minimum resistance in the measured range of a magnetic filed (-0.8 - 0.8 T). In fig. 4, large positive MR was observed in both single film samples, the MR ratio increased with increasing x. Bias voltage dependence of the MR ratio of the $Ge_{0.89}Mn_{0.11}$ mesa is also shown in fig. 4. The MR ratio at 0.8 T is higher than 2000% at a bias of -1 mV.

Positive MR is often observed in granular systems and nano-/micro-composites. Although the mechanism of the present large positive MR is not clear, this is related to nanocolumnar structure of the $Ge_{1-x}Mn_x$ films.

4. Magneto-transport of the $Ge_{1-x}Mn_x$ heterostructures with nanocolumns

Fig. 3 also shows *I-V* characteristic of one of the heterostructure mesas (S0367) measured at 15 K. Negative bias rectification was also dominant in *I-V* characteristics.

Fig. 4 shows MR curves of the heterostructure mesa (S0367) measured at 15 K at various biases of -20, -30, and -40 mV. Large positive MR was also observed, which may originate from the bottom nanocolumnar layer. Fig. 5 shows MR curves of the heterostructure mesa (S0373) measured at 15 K at various biases of -5, -10, -15, -20, and -40 mV. (Note that offsets were added on some MR curves in fig. 5 for viewability.) In addition to the large positive MR, hysteretic behavior was observed in the MR curves at the biases less than -20 mV. Black and gray arrows in fig. 5 indicate scanning directions of magnetic field for the MR curve at a bias of -5 mV.

The origin of the hysteretic behavior is not clear. However, some relation exists between the hysteretic behavior and coercive forces of the top and bottom layers. The coercive force of a $Ge_{0.94}Mn_{0.06}$ film grown with the same growth condition as the bottom layer of the heterostructures measured by magnetic circular dichroism (MCD) was very small (lower than 0.01 T), which corresponds to the sharp decrease of the MR with increase of magnetic field around 0 T. The coercive of a $Ge_{0.72}Mn_{0.28}$ film with Mn_5Ge_3 precipitation, which is approximately considered as that of the top $Ge_{0.76}Mn_{0.24}$ layer, was roughly 0.1 T, witch corresponds to the peak of the hysteretic behavior around 0.1 T. This indicates that the hysteretic behavior originates from, or is related to the magnetization of the top and bottom layers of the heterostructure mesa (S0373).

5. Summary

In the single $Ge_{1-x}Mn_x$ films and heterostructures, we observed large positive magnetoresistance with MR ratio over 2000% at 0.8 T and hysteretic behavior. Although the mechanism is not clear, these phenomena are caused by the nanocolumnar structure and may be used for advanced nanoscale spin devices based on group-IV semiconductors, such as magnetic sensors and magnetic recording devices.

Acknowledgments

All the samples in this paper were grown by Si-MBE system in Prof. Sugahara's laboratory, at Tokyo Institute of Technology. One of the authors (S. Y.) gratefully acknowledges Research Fellowships of JSPS for Young Scientists. This work was partly supported by Grant-in-Aids for Scientific Research, the Special Coordination Funds for Promoting Science and Technology, R&D for Next Generation Information Technology by MEXT, and Asahi Glass Foundation.

References

[1] T. Maeda, K. Ikeda, S. Nakaharai, T. Tezuka, N. Sugiyama, Y. Moriyama, and S. Takagi, IEEE EDL **26** (2005) 102.

[2] Y. D. Park, A. T. Hanbicki, S. C. Erwin, C. S. Hellberg, J. M. Sullivan, J. E. Mattson, T. F. Ambrose, A. Wilson, G. Spanos, B. T. Jonker, Science **295** (2002) 651.

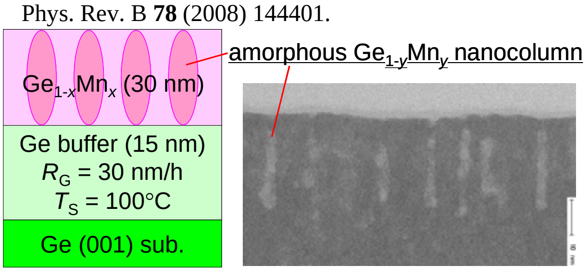
[3] S. Sugahara, K. L. Lee, S. Yada, and M. Tanaka, Japan. J. Appl. Phys. **44** (2005) L1426.

[4] M. Jamet, A. Barski, T. Devillers, V. Poydenot, R. Dujardin, P. Bayle-Guillemaud, J. Rothman, E. Bellet-Amalric, A. Marty, J. Cibert, R. Mattana, and S. Tatarenko, Nature Materials, **5** (2006) 653.

[5] A. P. Li, C. Zeng, K. van Benthem, M. F. Chisholm, J. Shen, S. V. S. N. Rao, S. K. Dixit, L. C. Feldman, A. G. Petukhov, M. Foygel, and H. H. Weitering, Phys. Rev. B **75** (2007) 201201(R).

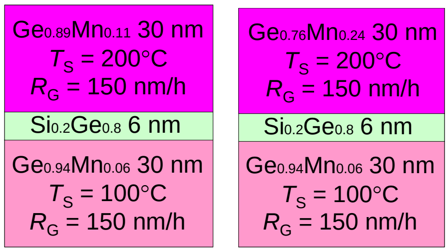
[6] S. Yada, S. Sugahara, and M. Tanaka, International Conference on Solid State Device and Materials (SSDM 2008), C-3-2, Tsukuba, Sep. 2008.

[7] V. Holy, R. T. Lechner, S. Ahlers, L. Horak, T. H. Metzger, A. Navarro-Quezada, A. Trampert, D. Bougeard, and G. Bauer, Phys. Rev. B **78** (2008) 144401.



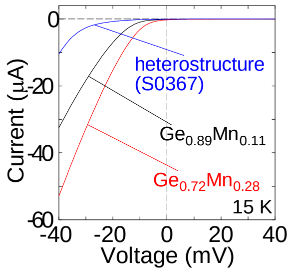
(a) (b)

Fig. 1 (a) Schematic sample structure of the single $Ge_{1-x}Mn_x$ films and (b) a cross-sectional TEM image of a $Ge_{0.94}Mn_{0.06}$ film, where amorphous $Ge_{0.91}Mn_{0.09}$ nanocolumns are precipitated in the $Ge_{0.97}Mn_{0.03}$ matrix.



(a) (b)

Fig. 2 Sample structures of the tri-layer heterostructures; S0367 (a) and S0373 (b).



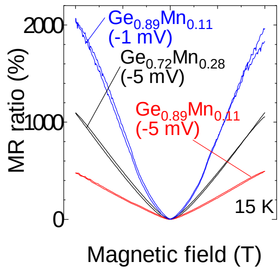
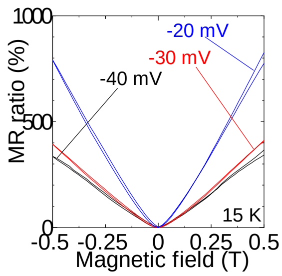


Fig. 3 (left) *I-V* characteristics of the $Ge_{0.89}Mn_{0.11}$ and $Ge_{0.72}Mn_{0.28}$ single films, and heterostructure mesa (S0367) at 15 K.

Fig. 4 (right) Magnetic field dependence of the MR ratio of the $Ge_{0.89}Mn_{0.11}$ mesa measured at 15 K at -1 and -5 mV, and the $Ge_{0.72}Mn_{0.28}$ mesa at -5 mV.



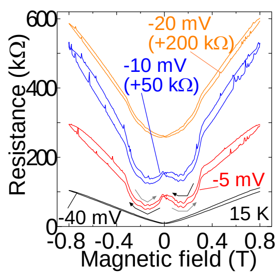


Fig. 5 (left) Magnetic field dependence of the MR ratio of the heterostructure mesa (S0367) measured at 15 K at -20, -30 and -40 mV.

Fig. 6 (right) Magnetic field dependence of resistance of the heterostructure mesa (S0373) measured at 15 K at biases of -5, -10, -15, -20, and -40 mV.