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著者	水口　将輝
journal or publication title	Applied Physics Letters
volume	76
number	18
page range	2600-2602
year	2000
URL	http://hdl.handle.net/10097/46991

doi: 10.1063/1.126421

APPLIED PHYSICS LETTERS VOLUME 76, NUMBER 18 1 MAY 2000

Room-temperature photoinduced magnetoresistance effect in GaAs including MnSb nanomagnets

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(Received 30 August 1999; accepted for publication 9 March 2000)

We show a photoinduced positive magnetoresistance (MR) effect (about 20%) under a low magnetic field (less than 0.1 T) at room temperature. The photoinduced MR effect has been observed in GaAs including nanoscale MnSb islands, when photons with the energy above the band gap of GaAs irradiated the sample. The photoinduced phenomena are due to an enhancement of tunneling probability between MnSb islands by photogenerated carriers in the GaAs matrix. © *2000 American Institute of Physics.* [S0003-6951(00)02718-2]

Control of magnetic properties by photogenerated carriers is one of the main challenges in the research of ferromagnet/semiconductor hybrid structures as the striking attribute, compared with standard full-metal magnetic heterostructures.[1] The light-induced interlayer coupling was demonstrated in Fe/SiO and Fe/(Fe–Si) multilayers.[2,3] These results suggested the possibility of modulation of the magnetic interlayer coupling by light, but a thermal effect on the observed phenomena was not completely excluded. Recently, Koshihara *et al.* reported a ferromagnetic order induced by photogenerated carriers in magnetic III–V semiconductor heterostructures of (In, Mn)As/GaSb.[4] Carriers generated by light in the GaSb layer are transferred to the layer of (In, Mn)As, then the transferred carriers enhance the ferromagnetic spin exchange between Mn ions. The ferromagnetic order is surely photoinduced phenomenon, but the phenomenon can be observed only below the ferromagnetic transition temperature of (In, Mn)As, 35 K. It should be noted that the optically induced ferromagnetic transition was also implied in magnetoresistive manganites.[5,6] The transition is, however, observable at low temperatures.

Formation of magnetic clusters embedded in a semiconductor and the magnetic properties have been investigated intensively.[7–10] The magnetoresistance (MR) effect was observed in MnAs:GaAs granular systems, which were prepared by the low-temperature molecular beam epitaxy (MBE)[11] and the manganese-ion implantation.[12] The huge MR effect, up to 3 orders of magnitude, was also reported in ErAs:GaAs nanocomposites.[13] The strong negative MR effect was explained by hopping of bound magnetic polarons between ErAs nanoparticles. Although the ferromagnet/semiconductor granular systems are expected to be promising materials which possess the photoinduced magnetic phenomenon, few experimental observations have been reported so far;[14] furthermore, the magnetotransport properties have been studied only at low temperatures, because the MR effect was prominent at low temperatures. We now report *photoinduced* MR changes at *room temperature* in nanoscale MnSb islands embedded in GaAs.

MnSb islands were grown on semi-insulating ($>1 \times 10^7\ \Omega$ cm) (111)B GaAs substrates by a Riber 32P MBE system. In the bulk, MnSb is a ferromagnetic compound (the Curie temperature, $T_c, \cong 590$ K) with a NiAs-type crystal structure ($a \cong 4.13$ Å, $c \cong 5.78$ Å) and the easy magnetization is along the *a* axis.[15] Detailed growth conditions have been reported in our previous report.[16] The growth orientation of MnSb is (0001), and the atomically flat interface with no intermixing can be realized in (0001)MnSb/(111)B GaAs. When the growth is performed on the atomically flat (111)B GaAs surface, the initial growth of MnSb is three-dimensional. The MnSb island growth is shown in the high-resolution cross-sectional transmission electron microscopy (TEM) image of Fig. 1(a). The nominal thickness of MnSb is 3 monolayers (ML).[17] As shown in the figure, the nanoscale plano-convex islands with the hexagonal crystal structure are grown on the (111)B GaAs substrate with the atomically flat interface. It was difficult to evaluate the lateral size distribution of the island by the TEM observation, but the almost uniform height of about 2 nm was observed within the wide searching areas. The MnSb islands were capped by the GaAs layer with the thickness of 20 nm. The epitaxial growth of the cap layer was done at 200 °C. Extra spots appeared in the reflection high-energy electron diffraction (RHEED) pattern when the thickness reached 5 nm, then the spotty streak pattern was observed from the surface of the GaAs cap layer. This fact agrees with the fact that many structural defects exist in the cap layer as shown in Fig. 1(a). (The granular trilayer film is referred to hereafter as GaAs/MnSb-island/GaAs.) Figure 1(b) shows the x-ray diffraction pattern of the GaAs/MnSb-island/GaAs film with the nominal MnSb thickness of 3 ML. A broad peak originating form (0004) MnSb indicates the strong strain in the MnSb crystal. Some parts in the MnSb island show the elongation of the *c* axis as is seen in Fig. 1(a), which is in good agreement with the x-ray diffraction pattern, and the in-plane compressive strain has been consistently observed in the initial growth of (0001)MnSb on (111)B GaAs by RHEED.[16] Magnetization curves measured by a superconducting quantum interference device (shown in

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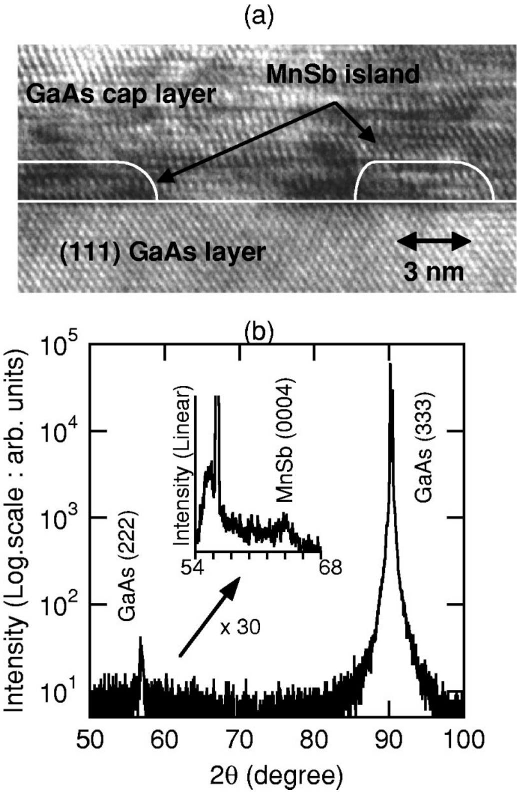

FIG. 1. (a) High-resolution cross-sectional TEM image of MnSb islands grown on the (111)B GaAs substrate, and capped by the GaAs layer. The nominal MnSb thickness is 3 ML. White lines are guides to indicate their interfaces. (b) The x-ray diffraction patterns of the GaAs/MnSb-island(3 ML)/GaAs film. The inset shows the diffraction pattern measured by higher-power x ray of 8 kW.

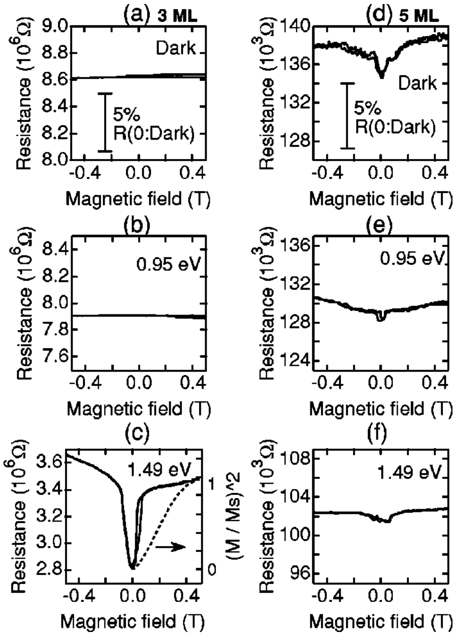

FIG. 2. The laser irradiation effects on MR curves of GaAs/MnSb-island/GaAs films with the nominal MnSb thicknesses of 3 and 5 ML are shown in (a)–(c) and (d)–(f), respectively: (a) and (d) without the laser irradiation (in the dark), (b) and (e) under the laser irradiation of $\lambda = 1308$ nm ($h\nu = 0.95$ eV, below the band gap of GaAs), (c) and (f) $\lambda = 830$ nm ($h\nu = 1.49$ eV, above the band gap of GaAs). The MR curves were measured by applying a constant voltage of 100 V between two electric contacts. The scales in (a) and (d) indicate 5% of the resistance with no magnetic field and no laser irradiation. Each scale-bar is valid in each series of figures, (a)–(c) and (d)–(f). The curvature of the square magnetization of the GaAs/MnSb-island(3 ML)/GaAs film normalized by the saturation magnetization, M_s, is shown by the broken line in (c). The direction of the magnetic field was parallel to the film plane.

Fig. 2) indicate the superparamagnetic behavior of MnSb islands. The saturation magnetization exhibited a linear relationship to the nominal thickness of MnSb (from 1 to 5 ML). By the extrapolation of the linear relationship to zero magnetization, the nominal thickness of the magnetic dead layer, which may arise at the heterointerface by the intermixing, was estimated as less than 0.05 ML.

After unloading the epitaxial film from the MBE chamber, the stripe-shape sample, typically $4\,\mathrm{mm}\times 2\,\mathrm{mm}$, was cleaved from the wafer and the electrical contacts were made at the opposite ends by indium solder. The magnetotransport properties, the magnetoresistance, and the magnetic-field dependent current–voltage ($I-V$) curves, were measured in the same configuration of two-probe method at room temperature in air. The magnetic field up to 1.5 T was applied parallel to the film plane for both measurements. The MR curves were measured by applying a constant voltage using a conventional MR measurement setup. The sweep rate of the magnetic field was kept at about 0.005 T/s. The $I-V$ curves were measured using a HP4156 precision semiconductor parameter analyzer. The voltage was scanned from -100 to $+100$ V with the scan rate of about 5 V/s. Low power (2 mW) laser diodes (830 and 1308 nm) were used to illuminate the sample. These photon energies correspond to ''above (1.49 eV)'' and ''below (0.95 eV)'' the band gap of GaAs, respectively. The sample including the electrical contacts was exposed to the unfocused laser beam. The direction of the beam was perpendicular to the film plane. The power of commercial laser diodes was recalibrated by a Newport optical power meter equipped with 818-series semiconductor detectors of Si and Ge.

Figure 2 shows MR curves of GaAs/MnSb-island/GaAs films with the nominal MnSb thicknesses of 3 and 5 ML. The photoinduced MR effect is clearly demonstrated in the photon energy dependence of MR curves from Figs. 2(a) to 2(c). The obvious change in the positive MR effect appears within a low magnetic field of about 0.1 T. Here we have to emphasize that the effect occurs in the sample of the nominal MnSb thickness of 3 ML, where MnSb islands are isolated and embedded in GaAs matrix as shown in Fig. 1(a). When the sample is irradiated by the laser beam with the photon energy below the band gap of GaAs, the MR curve remains the same as that under no illumination and no positive MR effect is observed. By the laser irradiation with the photon energy above the band gap, the positive MR curve emerges as shown in Fig. 2(c). The MR ratio, defined as $\Delta R/R(0T) = [R(H)-R(0)]/R(0)$ in this letter, reaches about 20% at $H = 0.08$ T. The photoinduced phenomena strongly depend on the nominal thickness of MnSb. No distinct change by the laser irradiation is observed in MR curves of the sample with the nominal MnSb thickness of 5 ML. Since the resistance becomes more than one order smaller than that of the sample of 3 ML, it is reasonably thought that the MnSb island does not exist apart from the others in the GaAs/MnSb-island(5 ML)/GaAs film but the coalescence of MnSb islands starts at the nominal thickness between 3 and 5 ML. The small positive MR effect is observed even under no irradiation. The

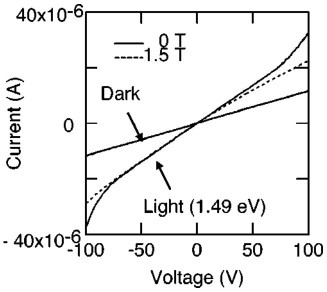

FIG. 3. The laser irradiation ($h\nu = 1.49$ eV) effect on $I-V$ characteristics of the GaAs/MnSb-island/GaAs film with the nominal MnSb thickness of 3 ML. The $I-V$ curves measured under the magnetic fields of zero and 1.5 T are shown by solid and broken lines, respectively. Without the laser irradiation, these curves are superimposed.

MR effect under the laser irradiation becomes smaller than the MR effect in the dark.

The drastic change of the MR effect by the laser irradiation with the photon energy above the band gap of GaAs is observed in the GaAs/MnSb-island/GaAs film where MnSb islands are separated by the GaAs matrix, but less change in the GaAs/MnSb-island/GaAs film where the metallic conduction path by the MnSb-islands connection are percolated macroscopically between the electrical contacts. These facts definitely show the origin of the photoinduced MR effect. The photogenerated carriers excited in the GaAs matrix reduce the depletion region of the Schottky barrier at the heterointerface between MnSb and GaAs. The reduction of the depletion region causes the photoconductivity. The spin dependent transport between MnSb islands through the GaAs matrix is thought to be triggered by the photoconductivity. However, there are two questions which we must elucidate: the magnetic field sensitivity and the sign of the MR effect. Generally the MR behavior of granular materials is described by the square of the magnetization,[18] but the observed curvature is much steeper than that of the square magnetization as shown in Fig. 2(c). The higher magnetic field sensitivity indicates the observed MR effect is mainly attributable to MnSb islands with the smaller size in the distribution. Within the standard giant MR model of magnetic granular materials,[18,19] where the spin-dependent scattering probability of carriers between magnetic dots decreases as the direction of the magnetization of the dots aligns with the increasing external magnetic field, the observed positive MR is hardly explained. To make clear the phenomenological feature of the positive MR effect, the $I-V$ characteristics are measured. Figure 3 shows the change of $I-V$ curves by the applied magnetic field and the laser irradiation. Without the laser irradiation, the $I-V$ curve is linear (ohmic-like) and shows almost no magnetic field dependence up to 100 V. On the other hand, by the laser irradiation, so-called breakdown behavior of the Schottky junction appears at the higher voltage region. The applied magnetic field restores the junction from the breakdown, as shown in the figure. The magnetic-field induced restoration arises reproducibly in case that the sharp positive change is observed in the MR curve.[20] The reason of the magnetic field driven restoration of the junction has not yet been fully investigated.

In conclusion, we have presented experimental evidence for the positive MR effect induced by the photogenerated carrier in the material of MnSb islands embedded in GaAs. By the laser irradiation with the photon energy above the band gap of GaAs, the MR ratio of $\Delta R/R(0T)$ increases from 0% to 20% in the GaAs/MnSb-island/GaAs film with the nominal MnSb thickness of 3 ML. The change of the resistivity as a function of the magnetic field is much faster than that of the square magnetization. The sign of the MR effect cannot be explained in the standard giant MR model based on the spin asymmetry of the electron scattering. Nonetheless, the relatively large photoinduced MR effect with the high magnetic sensitivity provides insight to explore a novel spin-dependent phenomena in a semiconductor and will be of technological importance in the magnetoelectronic industry.[21]

This work was performed at JRCAT under the joint research agreement between NAIR and the Angstrom Technology Partnership (ATP), and JRCAT and University Tokyo. This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) and partially by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture, Japan.

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[21] The down-sizing of the device, namely decreasing the number of MnSb/GaAs junctions between two electrical contacts, is a promising direction to reduce the resistance and the threshold voltage of the breakdown (see Fig. 3) to meet practical conditions from a possible application viewpoint.