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Metal-Semiconductor Hybrid Granular Films Designed for High-Sensitive Magnetic Field Sensors

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1. Introduction

There has been increasing interest in magnetoresistance (MR) effect with a view to its application in various magnetic devices, such as a magnetic field sensor. Positive MR effect of a two-dimensional electron gas with high mobility in III-V based semiconductor heterostructures has been studied for the magnetic field sensor in automotive technology [1]. InAs/(Al,Ga)Sb quantum well structures for the magnetic-field sensing showed the excellent room-temperature operation of both magetoresistors and Hall elements [2]. A spin-dependent MR effect in artificial structures, such as metallic multilayers and tunnel junctions, have also attracted much attention, raising scientific and technological issues [3, 4]. Rapid increase in the recording density of hard disk drives requires the continuous development of the magneto-electronics devices. Recently, a large MR effect up to 50 % at room temperature (RT) was reported in the ferromagnetic tunnel junction [5]. The tunnel MR has been also intensively studied for magnetic data storage devices, such as magnetoresistive random access memory [6].

In this contribution, new MR materials consisting of nanoscale metal islands that are grown on a GaAs substrate are shown. The material shows more than thousandfold MR change under a relatively low magnetic field, even at RT. Section 2 deals with the growth of the hybrid granular material in ultra-high vacuum (UHV) chambers. The typical MR curve is shown in section 3. The origin of the effect is discussed in terms of the magnetic-field dependence of the avalanche breakdown at the interface between metallic clusters and the GaAs substrate. The prospect of this study toward high-sensitive magnetic-field sensor development is described in section 4.

2. UHV growth procedure

The new MR material shown in this contribution is the hybrid granular film consisting of nanoscale Au islands fabricated on a semi-insulating (111)B GaAs substrate. The deoxidization of the substrate and the MBE growth of the GaAs buffer layer were performed in an UHV molecular-beam epitaxy (MBE) chamber. The Au thin film with the nominal thickness of 0.2 nm was deposited on the GaAs buffer layer in the other UHV chamber, which connected to the MBE chamber. Due to the terrace structure of the surface of the GaAs buffer layer, the Au island with the sub-micron area size appeared on the (111)B GaAs surface as shown in the atomic force microscopy (AFM) image of figure 1. Finally the island structure was capped by an Sb thin layer with the thickness of 5 nm in the MBE chamber. It should be noted that the huge magnetoresistance effect presented in this contribution is very sensitive to the morphological condition of the granular film. By further deposition of Au, the coalescence of the islands occurs, then the huge magnetoresistance effect completely disappears.

3. Magnetotransport measurements

After unloading the granular film from the MBE chamber, the magnetotransport properties were investigated at room temperature (RT) in air. The current – voltage (*I-V*) characteristics of the film were measured by a two-probe method. The magnetic field was applied parallel to the film plane and in the same direction of the current.

Figure 2 shows the *I-V* characteristics and the magnetic field dependence of the hybrid granular film. The *I-V* curve shows non-linear behavior, as is seen in the figure. Under zero magnetic fields, the curve switches abruptly from the low-current (high-resistance) state to the high-current (low-resistance) state at around 80 V in the increase voltage scan. The switch shows the hysteretic behavior in the decrease-voltage scan, and the high-current state changes to the low-current state at around 60V. It is interesting to note the fact that the threshold voltage of the switch shifts to the higher voltage side by applying magnetic fields. When the magnetic field of 1000 Oe is applied to the structure, the switch does not occur below 90 V. Finally, the switch disappears completely under the magnetic field of 15000 Oe. Figure 2 shows that the switch of two resistance states is driven by an electric field (voltage) and suppressed by a magnetic field. We term this

effect magnetoresistive switch (MRS) [7].

The origin of the magnetoresistive switch effect has not yet been fully understood. Preliminary experiments showed that the threshold voltage of the magnetoresistive switch effect decreased with the decrease of temperature. It is well known that the temperature dependence is a characteristic feature of an avalanche breakdown. It is reasonably thought that the avalanche breakdown is the essential process of the magnetoresistive switch effect. Since the resistance of the GaAs substrate is large enough to neglect the contribution to the observed transport phenomena and the resistance of the Sb cap layer shows the very high resistance, probably due to the oxidization, the breakdown is thought to occur at the heterointerface consisting of Au islands between Sb and GaAs layers.

4. Prospect

The present hybrid granular film shows the highest magnetic-field sensitivity compared with the existent MR materials and devices in the magnetic-field range of a few hundred Oe. By using standard lithography processes, we have already succeeded in decreasing the threshold voltage down to less than 10 V [8]. The response time of the MR effect should be investigated for the magnetic field sensor application.

Acknowledgements

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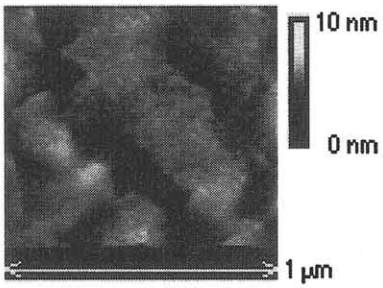

Fig. 1 Typical AFM image of Au islands formed on the GaAs (111)B substrate.

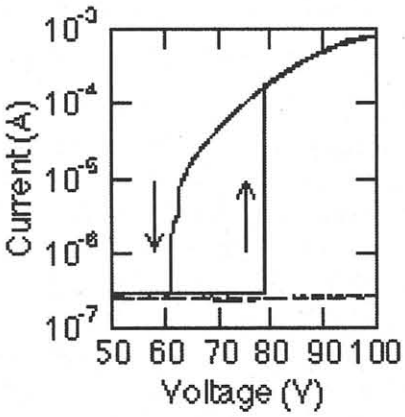

Fig. 2 The magnetic field dependence of *I-V* characteristics of the Au / GaAs hybrid granular film, measured at room temperature in air. The *I-V* curves under the magnetic fields of 0 and 15000 Oe are shown by solid and broken lines, respectively. The arrows next to the hysteresis indicate the sweep direction.