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Enhanced Hall voltage in a gate-controlled InSb Hall device

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We present an enhanced Hall voltage from the gate-controlled Hall device incorporating a micron-scaled InSb semiconductor cross junction and a single ferromagnetic element. Magnetic fringe field at an edge of the ferrogmanetic element gives rise to the Hall voltage, which shows hysteretic behavior upon magnetic-field sweep. The Hall effect is amplified by a factor of ~40% when a gate voltage of −25 V is applied. The increase is largely attributed to the reduction of carrier density affected by the gate confinement effect. The InSb Hall device controlled by gate voltage demonstrates a possible application for active nonvolatile memory cells and logic gate. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1855231]

I. INTRODUCTION

A spintronic device based on hybrid ferromagnet/semiconductor microstructures has recently attracted considerable interest due to the possibility of device applications such as magnetic-field sensors and integrated nonvolatile memory cells.[1–3] A hybrid-type device incorporating a semiconductor cross junction and a single ferromagnetic metal film is very useful for easy manipulation of magnetization and strong ferromagnetism even in a micron scale. It has been demonstrated that large local fringe fields emanating from an edge of a ferromagnetic element on GaAs (Ref. 1) and InAs (Ref. 2) two-dimensional electron gas (2DEG) have a strong perpendicular magnetic component, generating a Hall resistance at room temperature.

InSb semiconductor has intriguing properties such as high room-temperature mobility and narrow energy band gap so that it is widely used as Hall sensors and infrared detectors.[4–6] Especially, the high magnetoresistance (MR) of InSb resulting from an ideal combination of ordinary MR (OMR) and geometric MR (GMR) makes it useful for read-head sensors for ultrahigh-density magnetic recording.[5,6] Hall mobility of a single crystalline of InSb grown by molecular-beam epitaxy (MBE) was reported to show 27 000 $cm^2/V\,s$ at room temperature.[7] In practice, however, polycrystalline InSb thin film prepared by thermal evaporation method on an oxidized Si substrate and soft magnetic NiZn ferrite have been used for commercial Hall sensors owing to their low cost and simple process for mass production.[8]

The device used in the experiment is a gate-controlled Hall-effect device, in which a ferromagnetic element is deposited on top of an insulated InSb Hall cross. The result shows that magnetic fringe fields from a ferromagnet are effective to generate Hall voltage and to create hysteresis in the Hall resistance. The Hall voltage is amplified by a factor of ~40% when a gate voltage of −25 V is applied. The increase is responsible for the reduction of carrier density affected by the gate confinement effect.

II. EXPERIMENT

1-μm-thick InSb film was deposited on an oxidized (100) Si substrate in a thermal evaporation system with a base pressure of 5×10^{-6} Torr. Prior to the evaporation of InSb, a 200-nm-thick SiO_2 insulating layer was first deposited on a Si substrate by plasma-enhanced chemical-vapor deposition process. The bulk InSb crystal was used for source material of the evaporation. The substrate and source material were heated up to 400 and 800 °C, respectively, in a vacuum chamber during the deposition. The thermal evaporation process readily produces uniform polycrystalline InSb thin film whose grain size was measured to 1.2 μm by linear counter method. All the films exhibit n-type characteristics, with a carrier density $n=3\times10^{16}$ cm^3 and mobility $\mu_H=6236$ $cm^2/V\,s$ at room temperature. Grain-boundary scattering in polycrystalline InSb lowers the electron mobility of a thermally evaporated InSb than that of a MBE-grown one.[9]

As-grown InSb film was patterned into a four-point bridge-type Hall bar where the cross junction is 5×5 μm^2 using standard wet-etch photolithography. After the junction patterning, a 50-nm-thick SiO_2 insulating layer was deposited in order to electrically isolate the InSb layer from the ferromagnetic thin film. Then, a 100-nm-thick Au gate electrode was fabricated to cover all Hall crosses on which $Ni_{80}Fe_{20}$ (permalloy) was deposited in a dc magnetron sputtering system with a base pressure of 4×10^{-8} Torr. Both structures were patterned by optical lithography followed by

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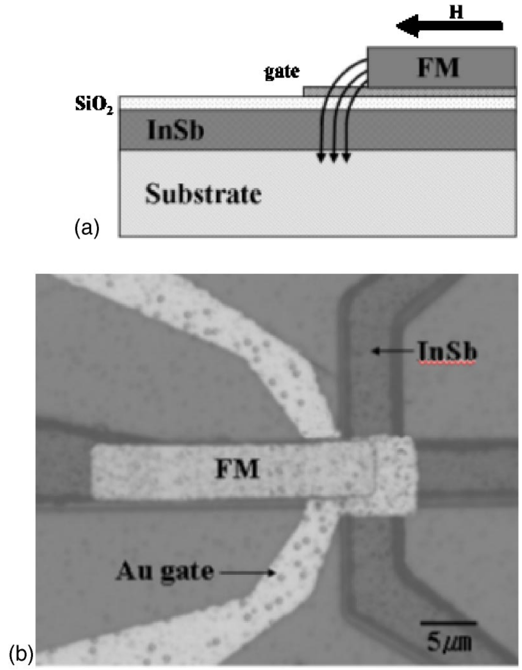

FIG. 1. A schematic diagram of a cross-section view of the gate-controlled InSb Hall device (a) and an optical micrograph of the fabricated device (b).

lift-off process. Ti/Au electrodes for electrical contact pad and leading wires were fabricated by lift-off process. A conventional four-probe ac magnetotransport measurement was made on these devices using physical property measurement system (PPMS) (Quantum Design) at room temperature while an in-plane field was swept over roughly ±200 Oe at room temperature.

III. RESULTS AND DISCUSSION

Figure 1 presents (a) a schematic diagram of a cross-section view of the Hall cross junction on which both the Au gate and ferromagnetic element were patterned and (b) an optical micrograph of the fabricated InSb Hall device with a Au gate. The bright rectangle in the middle of the InSb Hall cross junction of Fig. 1(b) represents a Py ferromagnetic element below which the Au gate is located. When the external magnetic field along the axis of the rectangle ferromagnetic film is swept between the positive and negative directions, the magnetization of the ferromagnetic film is switched between bistable states $\pm M$. The fringe field also switches according to the magnetization flip, producing the perpendicular magnetic field. Since the Hall voltage is proportional to the perpendicular magnetic field passing through the InSb Hall cross, the sign of the Hall voltage changes as the fringe field reverses its direction. As a consequence, the Hall voltage reflects the hysteresis of the magnetization of the ferromagnetic film.[1,3] To check the operation of the gate electrodes, we applied a negative voltage to the gate electrodes and measured the conductance between the two cross ends.

Figure 2 shows the resultant conductance of the device depending on applying the gate voltage at room temperature. The gate electrode starts to affect the conductance as soon as the negative voltage is applied. As more negative voltage is applied, the electron channel is continuously pinched off but

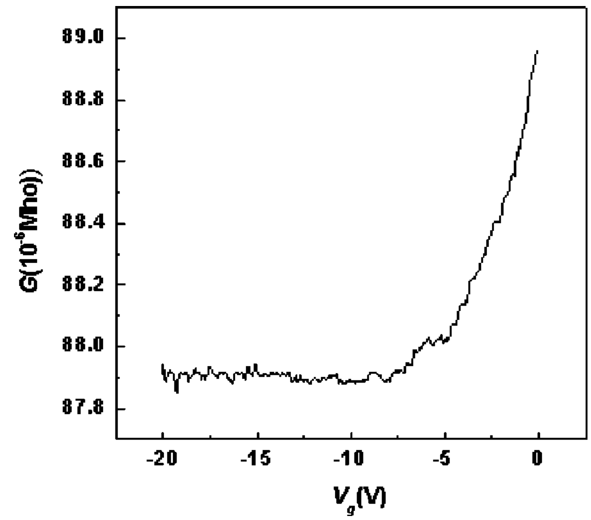

FIG. 2. Conductance of the device as a function of gate voltage.

is not completely closed. The conductance starts to be saturated at $V_g = -10$ V and a further confinement of the gate is not observed. By this measurement, we believe that the gate voltage does not completely deplete the InSb channel but substantially operates. The incomplete operation of the gate electrode is probably due to the current passing through the grain boundary in the polycrystalline InSb Hall cross and high leakage current through the 50-nm-thick SiO_2 insulating layer. In addition, the 1-μm-thick InSb film is too thick to deplete completely.

Figure 3 shows the Hall resistance at a given gate voltage of $V_g = 0$ and -25 V as a function of the magnetic field applied in the direction of the ferromagnetic film axis. A clear hysteresis loop was found to appear in the Hall resistance for the InSb cross junction incorporating with the $5 \times 25\ \mu m^2$ Py ferromagnetic element. This indicates that the local fringe field from the ferromagnetic element induces a Hall voltage. The abrupt change in the Hall voltage occurs at ±12 Oe, corresponding to the switching fields of Py. The hysteresis in the Hall resistance gets larger under a −25 V of gate voltage compared to that of zero gate voltage. The degree of hysteresis is described by the difference of the two

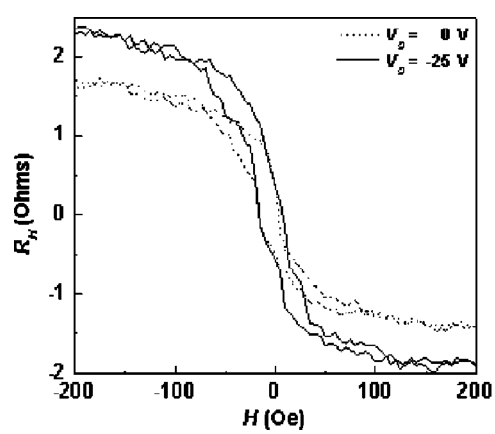

FIG. 3. Hall resistance at a given gate voltage of $V_g = 0$ and -25 V as a function of the magnetic field applied in the direction of the ferromagnetic film axis.

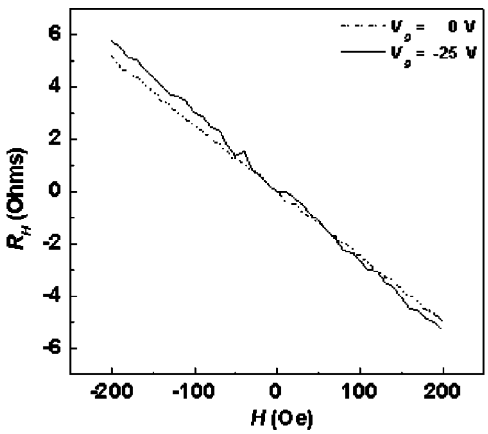

FIG. 4. Hall resistance at $V_g=0$ and -25 V as a function of the magnetic field applied in the direction perpendicular to the device surface.

Hall resistances at zero magnetic field, $2\Delta R_H$. $2\Delta R_H$ is 2.5 Ω at zero gate voltage and 3.5 Ω at $V_g=-25$ V. The Hall effect has been amplified by a factor of ~40% when $V_g=-25$ V in comparison with that of $V_g=0$.

The Hall resistance is proportional to the average magnetic field in the InSb Hall cross and inversely proportional to the carrier density. The average magnetic field is obtained by the fringe field emanating from an edge of the ferromagnetic element. The magnitude of the fringe field decays as $t^2/[x^2+(t^2/4)]$, where x is the distance from the edge of the ferromagnetic film and t is the film thickness.[10] The fringe field is strongest at the edge of the ferromagnet, and hence it becomes the largest around the center of the Hall cross. Since the ferromagnet is located at the center of the Hall cross, the fringe field is comparatively uniform along the axis of the ferromagnet.

The carrier density of the Hall bar changes as the gate voltage is applied. It is obtained from the slope of the Hall voltage as a function of the magnetic field, which is applied in the direction perpendicular to the device surface. Figure 4 shows the resultant Hall resistance of the device depending on the gate voltage. The carrier density of the InSb Hall bar at zero gate voltage is 3×10^{16} cm^3. It decreases to 2.5 $\times10^{16}$ cm^3 at $V_g=-25$ V. From the measurement, the reduction of the carrier density should enhance the Hall voltage.

In the present work, we successfully demonstrate the gate-controlled Hall device using commercially available polycrystalline InSb thin film, although we fail to obtain a complete gate operation. The hysteric Hall resistance combined with good remanence and substantial increase in $2\Delta R_H$ suggests that the hybrid-type gated Hall device is a strong candidate for active nonvolatile memory cells and logic gate.

IV. CONCLUSION

We have investigated gate-controlled Hall-effect device incorporating a micron-scaled InSb semiconductor cross junction and a single microstructured ferromagnetic element. A clear hysteresis loop was found to appear in the output signal (R_H vs H) for the cross junction with a ferromagnetic element. The gate voltage does not completely deplete the channel but substantially operates in the device. The hysteresis in the Hall resistance gets larger under -25 V of gate voltage, $2\Delta R_H$ is 2.5 Ω at zero gate voltage and 3.5 Ω at $V_g=-25$ V. The Hall effect is amplified by a factor of ~40% when $V_g=-25$ V. The increase is largely attributed to the reduction of carrier density affected by the gate confinement effect. The InSb Hall device controlled by the gate voltage presented in the study demonstrates a possible application for active nonvolatile memory cells and logic gate.

ACKNOWLEDGMENTS

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