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Enhanced extraordinary magnetoresistance in the semiconductor-metal hybrid structure with three current leads

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Earlier researches show that nonmagnetic semiconductor-metal hybrid structures exhibit a very large magnetoresistance effect, the so-called extraordinary magnetoresistance effect. Here, we designed a modified semiconductor-metal hybrid device with *IVIVI* configuration, where *I* and *V* represent current lead and voltage probe, respectively. In this device, applied magnetic field can lead to the current redistribution between the two output current leads. The change of the output currents reaches 62.4% under magnetic field of 5 T. As a result, the magnetoresistance value is 2.4–3.7 times higher than that of the traditional semiconductor-metal hybrid device with *IVVI* configuration. The sensitive position dependence of magnetic bit on output current shows that this device could be potentially used as magnetic sensor. © *2006 American Institute of Physics*.

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It was shown recently that nonmagnetic semiconductor-metal hybrid structures can exhibit a very large geometrical magnetoresistance effect, the so-called extraordinary magnetoresistance (EMR) effect.[1–5] Enhancement of the resistance as high as $(7.5\times 10^5)\%$ has been observed under magnetic fields $B=4$ T relative to zero field at room temperature. Especially, Moussa *et al.*[6] and Holz *et al.*[7] reported a further improved response by about 60% via interchanging a current lead (*I*) a voltage probe (*V*) from the so-called *IVVI* to the *VIVI* configuration. A mesoscopic nonmagnetic magnetoresistive read-head sensor, which was fabricated from a narrow-band-gap Si-doped InSb quantum well,[8,9] has a conservatively estimated areal density of 116 Gbits/in.^{2} and is not subject to magnetic noise that limits conventional sensors to 100 Gbits/in.^{2} It has been further pointed out that read heads for magnetic recording with an EMR sensor can reach storage densities in the range of 1 Tbit/in.^{2} Therefore these hybrid structures are considered to be of enormous technological interest for the development of magnetic-field sensors and ultrafast read heads.

The theoretical studies show that the EMR effect is attributed to the magnetic-field-dependent redistribution of current density between the semiconductor and metal.[1,3,7,10] Under zero field, the EMR device has a very small resistance since the metal layer with low resistance has a large current density. With increasing the magnetic field, the current redistribution starts to be changed. Due to the effect of Lorentz force on the carries, more current distribution transfers to the semiconductor from the metal. It is significant that the resistance of the device increases. Earlier works mainly focused on the optimization of geometrical and material parameters of four-probe EMR device. Here, we designed a modified device with *IVIVI* configuration using the finite-element methods. It was very interesting to find that the current redistribution between the two output current leads can reach about 62.4% and 74.5% under magnetic fields of 5 and 10 T, respectively. This design results in the significant enhancement of EMR value compared to the traditional device. In addition, the sensitive position dependence of magnetic bit on output current shows that this device could be potentially used as magnetic sensor.

The rectangular hybrid structure used for the calculation is depicted schematically in Fig. 1. The top and bottom layers represent the metal and semiconductor, respectively. The three current leads I_+, I_{1-}, and I_{2-}, as well as the voltage probes V_1 and V_2, which make the *IVIVI* configuration, are shown in the bottom of the figure. Here, I_+ represents the input current lead, while I_{1-} and I_{2-} represent the two output leads. A homogenous magnetic field *B* is applied perpendicular to the *x*-*y* plane. We assume the device length $L=200$ μm, the semiconductor width $W_1=10$ μm, and the metal width $W_2=50$ μm, which are similar to those reported in Refs. 11 and 12 in size. For evaluating the potentials, the voltage probes are treated as point contacts of zero width. To calculate magnetoresistance response to the position of magnetic bit, the dimensions of the bit are set to 20×10 μm^2. The magnetic bit passes over the semiconductor layer from left to right.

The current density in the semiconductor-metal hybrid structure is given by Ohm's law $\mathbf{j}=\sigma\mathbf{E}$, where σ is the conductivity tensor and $\mathbf{E}$ is the electric field. The conductivity tensor depends both on material parameters and magnetic field. For the two-dimensional problem, it is given by

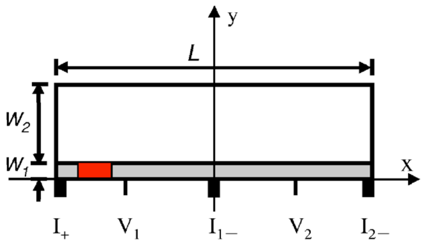

FIG. 1. (Color online) Sketch of the semiconductor-metal hybrid structure used for simulation. The input current lead is labeled as I_+ and the two output current leads are labeled as I_{1-} and I_{2-}. The two voltage probes are marked as V_1 and V_2. The red block represents the magnetic bit.

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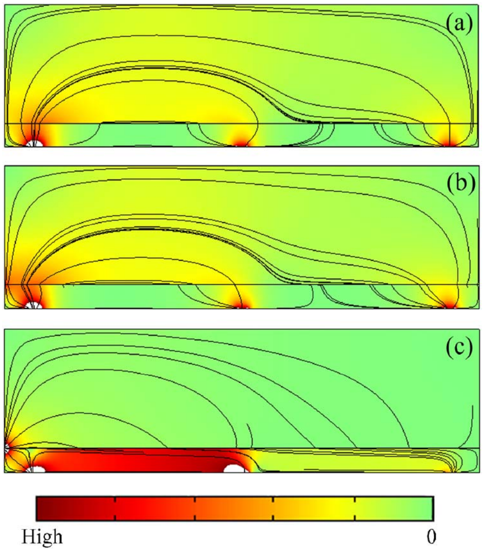

FIG. 2. (Color online) Current density distribution in the semiconductor-metal hybrid device at different magnetic fields. (a) $B=0$ T, (b) $B=0.1$ T, and (c) $B=5$ T. The color represents the strength of current density. The white color near the current leads means the current density is very high.

$$\sigma(\beta)=\sigma_0\big/1+\beta^2\begin{pmatrix}1 & -\beta\\ \beta & 1\end{pmatrix},$$

where $\beta=\mu B$ and μ is the mobility of the carriers. The Drude conductivity at zero field is given by $\sigma_0=ne\mu$, where n is the carrier density and e is the electronic charge. In this work, we take $\mu_s=4.55\ \mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ and $n_s=2.55\times10^{22}\ \mathrm{m}^{-2}$ for the semiconductor, and $\mu_m=5.3\times10^{-3}\ \mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ and $n_m=5.9\times10^{28}\ \mathrm{m}^{-2}$ for the metal.[1] By means of the continuity equation, the problem of determining the current and the electrical field in the semiconductor-metal hybrid structure reduces to the solution of Laplace's equation for the electrostatic potential, i.e., $\nabla\cdot[\sigma\nabla\phi(\mathbf{x},\mathbf{y})]=0$, where $\phi(x,y)$ is the electrical potential. This partial differential equation can be solved numerically by means of finte-element method as discussed in detail in Refs. 13 and 14. At the current leads, the configuration of current density in this work is different from that of Refs. 6, 7, 13, and 14. Since there are only two current leads in traditional *IVVI* or *IVIV* configurations, i.e., one input and one output leads, the current density perpendicular to the device boundary should be fixed. However, for the *IVIVI* configuration in this work, the current density perpendicular to the boundary of the two output current leads cannot be fixed with the change of magnetic field. Instead, we use the lowest electrostatic energy state to get the current configuration between the two output leads.

Figure 2 shows the current density distribution in the semiconductor-metal hybrid device at different magnetic fields. The color represents the strength of current density. The white color means the current density near the current leads is very high. The black lines illustrate the current flows from the input lead to output leads. As shown in Fig. 2(a), one observes that the current flows straight from the current lead into the metal film at zero field, i.e., the length of the current path in the semiconductor is minimized. This phenomenon is similar to that of the hybrid structure with traditional *IVVI* configuration.[14] It is due to the fact that the resistivity of the metal is far lower than that of the semiconductor. In addition, the output current density for the two output leads is almost equal, which also should be attributed to the high conductivity of metal layer. Under the influence of magnetic field, the current paths begin to bend to the left side due to the Lorentz force, as shown in Fig. 2(b). However, the current density distributions near the three current leads are rarely changed since the magnetic field is low. With increasing magnetic field, the current paths show further bent to the left hand side. When magnetic field is high enough, for example, $B=5$ T, the current density thus peaks the left edge of the semiconductor-metal interface, as shown in Fig. 2(c). More Interestingly, the current density between I_+ and I_{1-} leads is very high, while that between I_{1-} and I_{2-} leads is very low. This redistribution of current density will lead to larger I_{1-} and samller I_{2-} due to the Lorentz force.

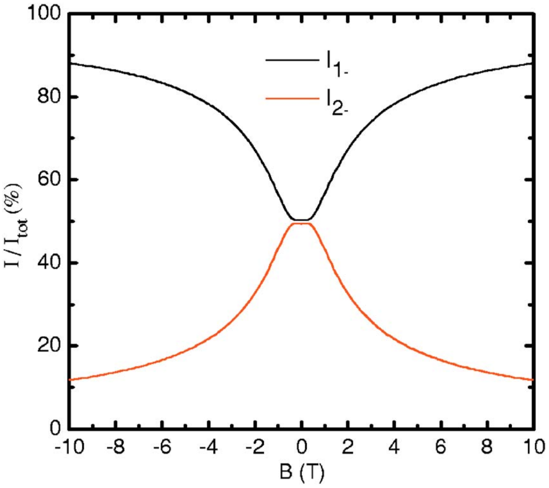

FIG. 3. (Color online) Influence of magnetic field on the output currents.

Figure 3 shows the influence of magnetic field on the two output currents. It shows that the currents are hardly changed under weak field $B\leqslant0.4$ T, which is consistent with the results of Fig. 2(b). In this case, even if the magnetic field can change the current flows near the semiconductor/metal interface, it cannot influence of the current density distribution near current leads since the electrostatic energy density near current leads is very high. With field increasing, the redistribution of current density near the current leads becomes more obvious under the influence of higher magnetic-field energy. As a result, the current of middle leads, I_{1-}, increases quickly with field increasing, while I_{2-} decreases fast. The redistribution of the two output currents (defined as $\Delta I=[I(B)-I(0)]/I(0)$) can reach about 62.4% under magnetic field of 5 T. When applied field is higher than 5 T, ΔI changes slowly since the current flows mainly inside the semiconductor region and its redistribution is not significant. For example, ΔI is only 74.5% under 10 T.

The magnetoresistance is defined as $\mathrm{MR}=[R(B)-R(0)]/R(0)$, where $R(B)$ is the resistance at magnetic field B. Since R is always defined as the ratio of the voltage obtained via two voltage probes divided by the current applied via the current leads, there are three MR values for the three current leads in this work. We defined them as $\mathrm{MR}(I_+)$, $\mathrm{MR}(I_{1-})$, and $\mathrm{MR}(I_{2-})$ for the EMR value of current leads I_+, I_{1-}, and I_{2-}, respectively. Figure 4 shows the relation between EMR and magnetic field for different current leads. It can be seen that $\mathrm{MR}(I_+)<\mathrm{MR}(I_{1-})<\mathrm{MR}(I_{2-})$ under any magnetic field since $I_+>I_1->I_{2-}$. Especially, $\mathrm{MR}(I_{2-})$ is far higher than the other two values under high field because I_{2-} is far lower than the others when $B\geqslant0.4$ T. To compare the

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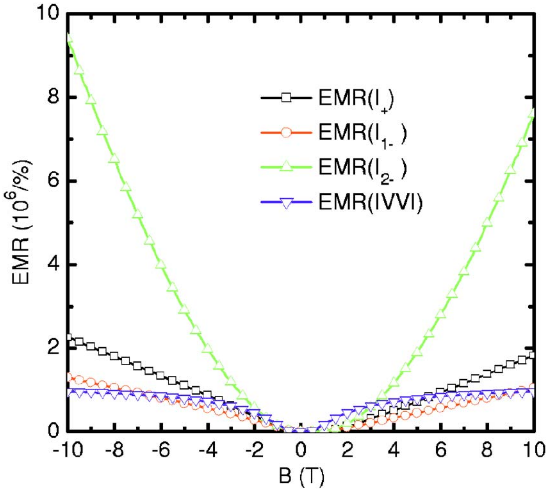

FIG. 4. (Color online) Relation between EMR and magnetic field at different current leads. The EMR values of traditional *IVVI* configuration are also included.

result with traditional *IVVI* configuration, Fig. 4 also gives the calculated EMR value using *IVVI* configuration. The EMR value of the *IVVI* configuration is about $(7.2\times10^5)\%$ at $B=4$ T and almost saturated at high field. These results are similar to those of Refs. 1 and 13. However, it is interesting to find that the EMR values of *IVIVI* configuration are unsaturated even at $B=10$ T. The MR(I_{2-}) values are $(1.9\times10^6)\%$ and $(7.6\times10^6)\%$ at $B=5$ and 10 T, respectively, which are 2.4 and 7.9 times that of *IVVI* configuration. Since *IVIVI* is not a symmetrical probe configuration, the voltage potential redistribution along the edge of semiconductor is different when the device is affected under positive and negative magnetic fields. Thus, the EMR-*B* curves are not symmetrical for *IVIVI* configuration, as given in Fig. 4. The MR(I_{2-}) values are $(2.9\times10^6)\%$ and $(9.41\times10^6)\%$ at $B=-5$ and -10 T, which are 3.7 and 9.8 times that of *IVVI* configuration.

The response of magnetoresistance to a magnetic bit is very important for the EMR devices as magnetic sensors. Moussa *et al.* reported the response of EMR on magnetic bit via its influence on voltage for the traditional EMR device.[6] Here, we find that the output currents varies with the bit position for the *IVIVI* devices. Figure 5 gives the response of output current I_{1-} to the position of magnetic bit with different fields. The output current of I_{1-} decreases as the magnetic bit moves near to the I_{1-} lead and recovers as it leaves. On the contrary, I_{1-} has a reversed peak as magnetic bit passes the I_{2-} lead. In addition, the current response to bit becomes more obvious with higher magnetic field of bit. Since the current paths will deflect due to the Lorentz force, the current becomes more difficult to pass the current lead when magnetic bit moves near to the lead. This is the reason why I_{1-} will decrease as magnetic bit moves near to I_{1-} lead and increase as magnetic bit moves near to I_{2-} lead.

In summary, we designed a modified semiconductor-metal hybrid device with *IVIVI* configuration using the finite-element methods. In this device, magnetic field can lead to the current redistribution between the two output current leads. The change of output currents can reach about 62.4% and 74.5% under 5 and 10 T, respectively. As a result, the EMR values are 2.4–3.7 times and 7.9–9.8 times higher than those of the traditional semiconductor-metal device, respectively. It is interesting to find that the output currents varies with the position of magnetic bit. This *IVIVI* device could be potentially used as magnetic sensors.

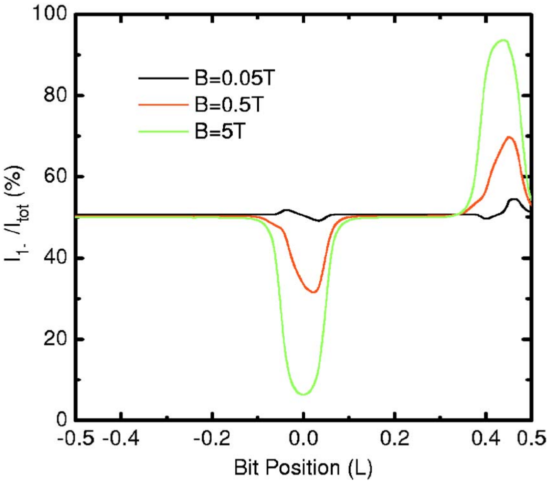

FIG. 5. (Color online) Calculated output current I_{1-} as a function of bit position for different magnetic fields of bit. The magnetic bit moves longitudinally along the rectangular semiconducting bar (see Fig. 1). The dimensions of the magnetic bit are 20×10 μm^2.

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