Optimization of the extraordinary magnetoresistance in semiconductor-metal hybrid structures for magnetic-field sensor applications

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Abstract

Semiconductor-metal hybrid structures can exhibit a very large geometrical magnetoresistance effect, the so-called extraordinary magnetoresistance (EMR) effect. In this paper, we analyze this effect by means of a model based on the finite element method and compare our results with experimental data. In particular, we investigate the important effect of the contact resistance $\rho_c$ between the semiconductor and the metal on the EMR effect. Introducing a realistic $\rho_c = 3.5 \times 10^{-7}$ $\Omega \text{cm}^2$ in our model we find that at room temperature this reduces the EMR by 30% if compared to an analysis where $\rho_c$ is not considered.

Key words: EMR, magnetoresistance, contact resistance

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1. Introduction

Recent studies showed that semiconductor-metal hybrid structures can exhibit a very large geometrical magnetoresistance effect, the so-called extraordinary magnetoresistance (EMR) effect. Enhancements of the resistance as high as 750,000 % at $B = 4$ T have been observed [1]. The EMR effect has also been found in hybrid structures involving a two-dimensional electron system (2DES) in an InAs heterostructure [2,3]. The EMR effect is of enormous technological interest, e.g., it has been pointed out [4] that read heads for magnetic recording with an EMR sensor can reach storage densities in the range of 1 Tb/in$^2$. In this paper, we study the EMR effect in rectangular hybrid structures using the finite element method (FEM). It has been shown that the FEM, which is a numerical technique for solving partial differential equations, provides a powerful means of analyzing the EMR effect [5,6]. Here, we are particularly interested in the effect of the specific contact resistance $\rho_c$ of the semiconductor-metal interface on the optimization of the EMR effect.

2. Model and Potential Distribution

We consider a rectangular hybrid structure as shown in Fig. 1 in the diffusive transport regime. The magnetic field $B$ is applied perpendicular to the $x, y$ plane.
The current flow $j$ is given by Ohm's law

$$j = \sigma E,$$  

(1)

where $\sigma$ is the conductivity matrix and $E$ is the electric field. All three quantities depend on the position in the hybrid structure. The conductivity matrix is given by

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

(2)

with dimensionless field $\beta = \mu B$. The Drude conductivity at $B = 0$ T is

$$\sigma_0 = ne\mu,$$  

(3)

where $n$ and $\mu$ are the carrier concentration and mobility, respectively. By means of the continuity equation, for the steady state we obtain

$$\nabla \cdot [\sigma \nabla \Phi(x, y)] = 0$$  

(4)

for the electrical potential $\Phi(x, y)$. Inhomogeneous Neumann boundary conditions are imposed at the current contacts, while homogeneous Neumann boundary conditions are given on the rest of the device boundary. Eq. 4 can be solved numerically using the FEM [5,6]. In particular, the effect of a magnetic field $B$ on $\Phi(x, y)$ can be studied in detail. An example is given in Fig. 2. Numerical results for the potential distribution from Eq. 4 are shown for a magnetic field of $B = 0$ T [Fig. 2(a)] and $B = 500$ mT [Fig. 2(b)]. One observes a pronounced voltage drop over the current contacts. The metal film, of course, is an equipotential surface. At a magnetic field of 500 mT the maximum potential in Fig. 2(b) is increased. Also, the potential distribution becomes more asymmetric.

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Fig. 1. The geometry of a rectangular EMR device (top view). The contacts labelled by 1 and 4 are used as current contacts, while the contacts labelled by 2 and 3 are used as voltage probes.

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Fig. 2. The potential distribution $\Phi(x, y)$ in an InAs(2DES)/Au hybrid structure with dimensions $W = 70 \, \mu m$ and $L = 200 \, \mu m$ for (a) $B = 0$ T and (b) $B = 500$ mT. The semiconductor is to the front, the metal to the back of the figure. One observes a pronounced slope of the potential at the places of the current contacts. Here, we assumed $\mu = 2.09 \, T^{-1}$, $n = 3.5 \times 10^{11} \, cm^{-2}$, and $\rho_{Au} = 2.2 \times 10^{-8} \, \Omega m$. The values of the potential are normalized to a current of 1 mA, so that the potential difference in mV between two points yields directly the resistance in $\Omega$ measured between them.
In the following, we give results based on an InAs(2DES)/Au hybrid structure studied experimentally by Möller et al. [2] with $L = 200 \ \mu m$ and $W = 70 \ \mu m$. At room temperature, the carrier concentration in the 2DES is $n = 3.5 \times 10^{11} \ cm^{-2}$ and the carrier mobility is $\mu = 2.09 \ T^{-1}$. The resistivity of the metal is $\rho_{\text{Au}} = 2.2 \times 10^{-8} \ \Omega m$. Potential distributions in such a device have been shown in Fig. 2. In Fig. 3, the resistance $R$, i.e., the voltage between the contacts 2 and 3 divided by the current applied through the contacts 1 and 4, is shown as a function of magnetic field. The cases of, both, zero contact resistance and of contact resistance $\rho_c = 3.5 \times 10^{-7} \ \Omega cm^2$ (best fit to experimental data) are shown. The experimental curve is also included. One observes a good agreement for the experimental data and the simulated curve with $\rho_c = 3.5 \times 10^{-7} \ \Omega cm^2$. Hence, it is essential to include $\rho_c$ in the analysis. We find that the value of $\rho_c$ at room temperature is larger by a factor of 10 if compared to the value obtained at $T = 4.2 \ K$, where our model has given $\rho_c = 3.3 \times 10^{-8} \ \Omega cm^2$ for a hybrid structure from the same fabrication process [6]. A possible explanation is that at elevated temperatures additional scattering of the electrons due to bulk and interface phonons reduces the conductivity of the semiconductor-metal interface. For technological purposes, the value of $\rho_c$ at room temperature is most important. It is found to be higher than at low $T$. This result suggests that the contact resistance plays a crucial role in the optimization of EMR devices at room temperature and should be included in the modeling. This is done in the following, when we investigate the interplay of the mobility $\mu$ with $\rho_c$ for low and high magnetic fields, i.e., for $B = 50 \ mT$ and $B = 1 \ T$, respectively.

4. Effect of Mobility on Magnetoresistance

An increased electron mobility $\mu$ in the semiconductor affects the EMR behavior of the device with regard to two aspects. First, the zero-field conductivity (Eq. 3) increases, i.e., the zero-field resistance $R(0)$ diminishes. Second, the dimensionless field $\beta = \mu B$ becomes larger. Fig. 4 shows the effect of $\mu$ on the relative resistance change $MR = [R(B) - R(0)]/R(0)$ at $B = 50 \ mT$ [Fig. 4(a)] and at $B = 1 \ T$ [Fig. 4(b)]. For a field of $B = 1 \ T$ and under the impact of a contact resistance $\rho_c = 3.5 \times 10^{-7} \ \Omega cm^2$, a maximum occurs in $MR(\mu)$ at about $5 \ T^{-1}$ in Fig. 4(b). This entire data set is considerably below the trace of $\rho_c = 0$. A large value of $\rho_c$ thus limits the sensitivity of EMR devices. In Figs. 4(a) and (b), this effect is already prominent at $\mu = 2.09 \ T^{-1}$, which is the experimentally observed value for the device of Fig. 3. In Fig. 4(b) the experimental $MR$ (gray cross) is smaller by about 30% if compared to the case of $\rho_c = 0$. Increasing $\mu$ to $5 \ T^{-1}$ would restore only part of the reduction. To obtain the maximum $MR$ in Figs. 4(a) and (b), i.e., to provide an optimized magnetic-field sensor, a high mobility $\mu$ and, simultaneously, a low specific contact resistance $\rho_c$ are required. This is true for the low and the high magnetic field regime.

5. Conclusions

We have shown that the EMR effect can be modeled using the FEM. In particular, the potential distribution for a realistic device was calculated. We analyzed the effect of contact resistance and showed that controlling
Fig. 4. The resistance enhancement $MR$ at (a) $B = 50$ mT and (b) $B = 1$ T. The curves for $\rho_c = 0$ (dark lines) and $\rho_c = 3.5 \times 10^{-7} \Omega \text{cm}^2$ (gray lines) are included. Please note that displayed ordinate interval in (b) is 10 times larger than in (a).

$\rho_c$ is important for the optimization of high-sensitive EMR magnetic-field sensors.

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