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Delta-doping-controllable magnetoresistance device in a magnetically modulated semiconductor nanostructure

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ABSTRACT

A magnetoresistance (MR) device was proposed by depositing two parallel ferromagnetic stripes on top and bottom of a semiconductor heterostructure [Solid State Commun. 141 (2007) 248]. In order to manipulate its performance, we dope a tunable δ-potential into the device by atomic layer doping technique. Transmission, conductance and MR ratio are calculated for the δ-doped MR device. It is confirmed that an obvious MR effect still exists in the device even though a δ-doping is comprised. Results show that the MR ratio varies intensely with the weight and/or the position of the δ-doping. Therefore, one can manipulate structurally the MR device by altering the δ-doping, and a tunable MR device can be obtained for magnetic information storage.

1. Introduction

Recently, the magnetoresistance (MR) effect [1] in the magnetically modulated semiconductor nanostructure (MMSN) [2] has attracted a considerable attention [3–15], because it has caused a lot of significant and practical applications in magnetic information storage [16,17], such as read heads, random access memories, magnetic field sensors, etc. Experimentally, by restricting the motion of a high mobility two-dimensional electron gas (2DEG) in a modulation-doped semiconductor heterostructure with an inhomogeneous magnetic field on the nanometer scale, e.g., by depositing nanosized ferromagnetic (FM) stripe on the surface of the semiconductor heterostructure [18], one can fabricate a MMSN, such as magnetic barriers, magnetic wells and magnetic superlattices, etc. In fact, the MMSN is the hybrid of the magnetic material and the semiconductor, where the magnetic material supplies an inhomogeneous magnetic field locally influencing the motion of the electron in the semiconductor heterostructure. On the other hand, being distinct from the usual MR effect, the MR effect in the MMSN has nothing to do with the spin degree of freedom [3], and its physical origin comes mainly from the dependence of the electron transport on the magnetic configuration. Moreover, the MMSN-based MR device possesses generally a very high MR ratio.

The beginning of this kind of MR effect was found by Zhai et al. [3] when they were studying the magnetotransport properties for the electron through a δ-function-shaped magnetic-barrier MMSN. Their study showed that the MR effect in this MMSN was unrelated to the spin freedom of the electrons, which was due to the significant transmission difference for electrons passing the parallel (P) and antiparallel (AP) magnetization configurations. It is also shown that the MR ratio

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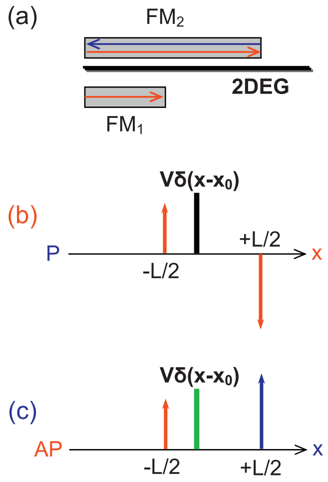

Fig. 1. (a) Schematic illustration of the MR device, where two FM stripes deposited on top and bottom of the semiconductor heterostructure, as well as (b) P and (c) AP magnetization alignments, where the δ-doping is expressed as $V\delta(x-x_0)$.

can approach 10^6% although the average magnetic field of the structure is zero. Immediately, replacing the ideal δ-function magnetic barriers, Lu et al. [4] have revealed the MR effect for realistic MMSNs. Thus, their results are more universal and closer to the actual situation. Then, Yang et al. [5] investigated the relationship between the MR ratio and the number of periods in a periodically modulated δ-function magnetic-barrier MMSN, and found that the linear characteristic of the MR effect in this MMSN by applying a uniform perpendicular magnetic field to the system [6]. While G. Papp et al. [7] studied the influence of finite temperature on the MR effect in a MMSN, they found that the MR ratio was sensitive to the temperature, and the MR ratio decreased rapidly with the temperature rising. The MR effect in other MMSNs also have been reported; see partial references [8–15].

Recently, based on a MMSN, Lu et al. [19] theoretically proposed a MR device, which can be realized by depositing two parallel FM stripes on top and bottom of a semiconductor heterostructure. They found that there exists an evident MR effect in such a device. A controllable MR device is particularly desired for the application of magnetoelectronics [20]. Therefore, in this work, we will explore detailedly the manipulation to the MMSN-based MR device with the help of the δ-doping technique or the atomic layer doping technique [21–23], such as molecular beam epitaxy (MBE), metal-organic chemical vapor deposition (MOCVD), etc. As an example, we introduce a δ-doping with an adjustable weight and a changeable position into the MR device proposed by Lu et al. [19], and will focus our attention on the influence of the δ-doping on the MR ratio of the MR device. Theoretical analysis shows that the device still possesses a large MR effect, because the transmission for electrons passing the P and AP magnetization configurations is entirely different after the δ-doping is contained. Numerical calculations show that the MR ratio is correlative of weight and/or position of the δ-doping. In other words, one can effectively manipulate the performance of the MR device by changing the δ-doping. Thus, a structurally-tunable MR device can be obtained for magnetoelectronics applications.

2. Model and formulas

The MR device [19] under consideration is schematically depicted in Fig. 1(a), which can be realized by depositing two parallel FM stripes on the top and bottom of a semiconductor heterostructure in experiments [24]. Here, Fig. 1(b) and (c) are the distributions of magnetic field corresponding to the parallel (P) and antiparallel (AP) magnetization configurations. And, a tunable δ-doping, $V\delta(x-x_0)$, is comprised into the MR device by using atomic layer doping technique. These two FM strips are considered to be asymmetric in length, their right edges are L, and the distance to the 2DEG are also different, which lead to the magnetic barriers of the two FM stripes having unequal magnetic strengths. However, the magnetic profile has been approximated as δ-function shapes and is expressed as [25,26]

$$B_z(x) = [B_1\delta(x+L/2) - \chi B_2\delta(x-L/2)], \tag{1}$$

where B_1 and B_2 are the magnetic strengths of two δ-function barriers, L is their separation, and χ stands for the magnetization configuration ($\pm$ 1or P/AP). In the single particle, effective mass approximation, the Hamiltonian of such a system can be written as

$$H = \frac{p_x^2}{2m_e^*} + \frac{[p_y + (e/c)A_y(x)]^2}{2m_e^*} + \frac{eg^*}{2m_e}\frac{\sigma_z\hbar}{2c}B_z(x) + V\delta(x-x_0), \tag{2}$$

where m_e^* and m_e are the effective mass and free mass of electron, respectively, (p_x, p_y) the electronic momentum, g^* the effective Landé factor, $\sigma_z = +1/-1$ is for spin-up/spin-down electron, and the magnetic vector potential of the device can be