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Letter to the Editor

Spin-dependent current in resonant tunneling diode with ferromagnetic GaMnN layers

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ABSTRACT

The spin-polarized tunneling current through a double barrier resonant tunneling diode (RTD) with ferromagnetic GaMnN emitter/collector is investigated theoretically. Two distinct spin splitting peaks can be observed at current–voltage (*I*–*V*) characteristics at low temperature. The spin polarization decreases with the temperature due to the thermal effect of electron density of states. When charge polarization effect is considered at the heterostructure, the spin polarization is enhanced significantly. A highly spin-polarized current can be obtained depending on the polarization charge density.

1. Introduction

Resonant tunneling involving electron spin is attracting much attention, because it will enable developing new functional spin-dependent devices in future electronics [1–3]. The magnetic resonant tunneling diode (RTD) made of II–VI semimagnetic semiconductor ZnMnSe is first suggested by Egues [4] and demonstrated by Slobodskyy et al. later [5]. In this experiment, a giant Zeeman splitting between spin-up and -down electron states is produced by external magnetic field. The corresponding resonance peaks in the electron current separate as a function of the bias voltage and the electron spin currents are controlled by voltage. Although their experimental results give a spin selection demonstration, the high magnetic field and low temperature are disadvantageous for applications.

The development of ferromagnetic semiconductor offers the opportunity to split electron spin without the aid of magnetic field. A magnetic RTD structure with ferromagnetic GaMnAs was reported, on which the spin splitting was also observed at low temperature [6]. The ferromagnetic order is, however, dependent on the temperature. When temperature is above Curie temperature, ferromagnetic phase in the diluted magnetic semiconductor is vanished. The high Curie temperature diluted magnetic semiconductor has greater potential for real applications. Many experiments showed that GaMnN and ZnMnO can exhibit ferromagnetism above room temperature (RT) [7,8]. However, it is still controversial if the observed RT-ferromagnetism is intrinsic or due to some non-resolved precipitates. Several theoretical mechanisms have been proposed to account for the observed ferromagnetic order [9,10]. In GaMnN, the exchange splitting of the conduction band is reported to be about a few tens of meV [11] and the ferromagnetic order sustains in thin layers of a few nanometer width, regardless of the underlying mechanisms [12]. Therefore, it is possible to fabricate RT-spin RTD with the ferromagnetic semiconductor.

To be specific, a ferromagnetic RTD consisted of a GaMnN emitter/collector with AlGaN/GaN two-barrier structure is theoretically studied in this paper. By selfconsistent calculation of the current–voltage (*I*–*V*) characteristics, a clear spin splitting current and temperature dependence of spin polarization can be observed in spin RTD structure. In addition, effect of charge polarization at the interface on spin polarization has also been investigated.

2. Theoretical model

In order to investigate the *I*–*V* characteristics of magnetic RTD, the classic treatment of transport in nonmagnetic RTD is

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employed, where coherent transport in the whole active device region is assumed [13,14]. The spin scattering is neglected here, since the spin scattering length is comparable to the size of the RTD structure [15]. Exploiting the symmetry of the Hamiltonian due to translations in the plane perpendicular to the growth direction z of the heterostructure, the Schrödinger equation can be reduced to a one-dimensional problem. The system Hamiltonian along the growth direction can be described by

$$\left[-\frac{\hbar^2}{2}\frac{d}{dz}\frac{1}{m(z)}\frac{d}{dz}+U_\sigma(z)\right]\psi_\sigma(z)=E\psi_\sigma(z) \quad (1)$$

with

$$U_\sigma(z)=E_c(z)-e\phi(z)+\sigma\Delta_{ex}(z)$$

here, m denotes the effective electron mass, and E the longitudinal energy of the electron, $E_c(z)$ denotes the conduction band discontinuity along the transport direction, $\phi(z)$ the electrostatic potential, Δ_{ex} exchange splitting of the conduction band, and σ spin quantum number ($\pm 1/2$). The electrostatic potential ϕ is obtained from the Poisson equation

$$\frac{d}{dz}\varepsilon(z)\frac{d}{dz}\phi(z)=\frac{e}{\varepsilon_0}[n(z)-N_d(z)] \quad (2)$$

where ε denotes the static dielectric constant, ε_0 is the permittivity of the vacuum, N_d and n are the doping and charge density, respectively. The electron density can be written as

$$n(z)=\frac{1}{4\pi}\sum_{i,\sigma,\sigma'}\int_{U_{i,\sigma'}}^{\infty} dEf_i(E)|\psi_\sigma^{i,\sigma'}(z)|^2\frac{1}{\hbar\upsilon_{i,\sigma'}} \quad (3)$$

where f_i is the Fermi–Dirac distribution function integrated over the transverse momentum

$$f_i(E)=\frac{mk_BT}{\pi\hbar^2}\ln(1+\exp((\mu_i-E)/k_BT)) \quad (4)$$

Here, $U_{i,\sigma'}$ and $\upsilon_{i,\sigma'}$ are spin-dependent potential energy and longitudinal group velocity of the electron in the left and right lead, respectively, μ_i is the chemical potential. The Poisson equation (2) has to be solved together with the Schrödinger Eq. (1) in a selfconsistent way. After obtaining the selfconsistent potential profile the current density is calculated in the framework of the Landauer–Büttker formalism

$$J=\sum_\sigma\frac{e}{4\pi\hbar}\int_{U_{i,\sigma'}}^{\infty} dET_\sigma[f(E)-f(E+eV_a)] \quad (5)$$

where T_σ denotes electron transmission matrix, V_a is applied voltage.

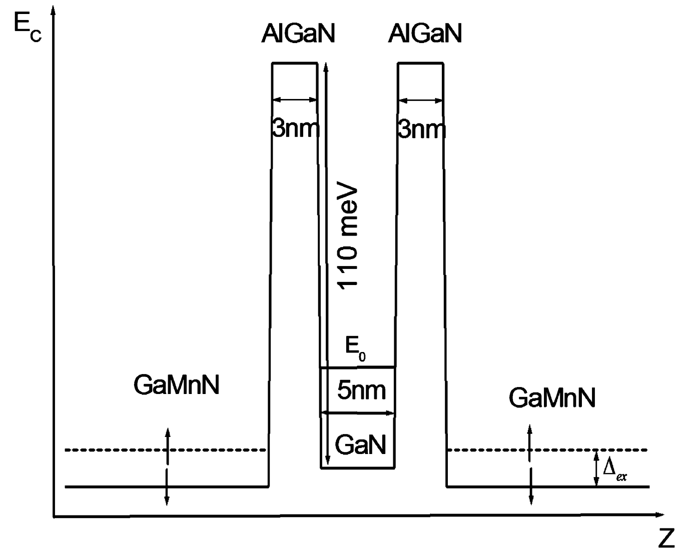

Fig. 1. Schematic conduction band profile of a two-barrier resonant tunneling diode with ferromagnetic GaMnN emitter/collector. Arrow indicates spin orientation.

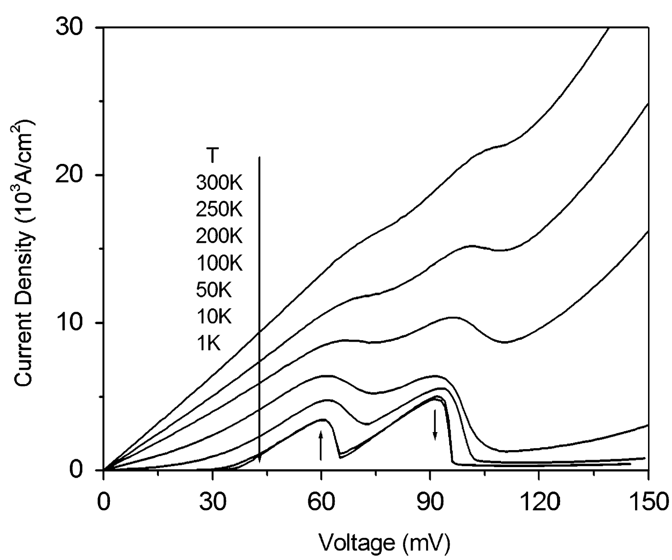

Fig. 2. Temperature dependence of *I–V* curves.

3. Results and discussion

In numerical calculations, we assume that the band parameters of GaMnN are the same as those of GaN. An electron effective mass $m/m_0 = 0.228$ and relative dielectric constant $\varepsilon = 9.5$ are employed for both GaMnN and GaN. The conduction band profile of GaMnN ferromagnetic RTD is schematically shown in Fig. 1. We consider a two-barrier semiconductor quantum well (QW), GaMnN/$Al_xGa_{1-x}N$/GaN/$Al_xGa_{1-x}N$/GaMnN, where an Al concentration of $x = 10\%$ is assumed in the barrier. The band discontinuity between AlGaN and GaN is about 110 meV [16]. The widths of AlGaN barriers and GaN QW are 3 and 5 nm, respectively. The whole structure is considered to be sandwiched between two leads consisting of 25 nm long n-doped GaMnN layers ($n = 4\times10^{17}\,cm^{-3}$). The spin splitting energy Δ_{ex} in the GaMnN barrier is assumed to be 10 meV.

The conduction band of emitter/collectors splits into a spin-up and -down bands due to the energy splitting in the ferromagnetic semiconductor GaMnN. The quasibound energy level is identical for both spin-up and -down electrons since the barrier height is independent of electron spin. Numerical calculation shows that the first quasibound state (E_0) is about 28.1 meV with respect to the conduction bottom of GaN QW. Due to the spin splitting of emitter, the resonant quasibound level is closer to spin-up band than spin-down band. Thus, resonant current corresponding to spin-up electrons appears first when the bias voltage is applied. Therefore, spin-up and -down currents are shifted each other, resulting in occurrence of spin polarization. The current spin polarization is then determined by $P = (J_\uparrow - J_\downarrow)/(J_\uparrow - J_\downarrow)$.

Fig. 2 shows the *I–V* characteristics as a function of temperature. Two clear distinguishable spin splitting peaks exist at the resonant region at low temperature (<100 K). At low voltage, resonant energy level closes more to spin-up band of the emitter, resulting in spin-up current dominant before 60 mV. The spin