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Spin–orbit interaction modulation by asymmetric quantum wells structure

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ABSTRACT

We designed two different kinds of asymmetric quantum wells and theoretically investigated the modulation of the Rashba spin–orbit interaction by varying the internal structure inversion asymmetry of these asymmetric quantum wells in the absence of electric and magnetic fields. Our goal is to increase the strength of the Rashba spin–orbit interaction by studying the mechanism of the strength increasing of Rashba spin–orbit interaction. Designing asymmetric quantum wells structure is an effective way to control electron spin–orbit interaction.

1. Introduction

Electron spin has aroused a variety of interest both in theoretical and experimental research due to its potential application in spintronic devices [1–3] and quantum computing [4]. The effective manipulation of electron spin is a necessary precondition to implement spintronic devices in semiconductor system [5,6]. Electron spin can be manipulated by two kinds of spin–orbit interaction (SOI) in nonmagnetic semiconductor low-dimensional structure, one being the Rashba SOI which originates from the structure inversion asymmetry (SIA) of a quantum well (QW) [7], the other one the Dresselhaus SOI which comes from the bulk inversion asymmetry (BIA) of semiconductor crystal [8]. The interaction between them can result in persistent spin helix effect [9,10], making the spin relaxation time reach a maximum. Long spin relaxation time is a necessary precondition to implement spin-field-effect transistors (SFET). The spin relaxation time of a QW can be maximized by manipulating the strengths of the Rashba and linear Dresselhaus SOIs. The Rashba SOI arises from asymmetry in the confinement potential of the electrons, and the linear Dresselhaus SOI is related to the degree of electron confinement [10]. Usually, the Rashba SOI can be varied by an external electric field [11,12] or intrinsic polarization field [13,14], and the linear Dresselhaus SOI can be tuned by changing the width of a QW [10]. We have found that the Rashba and linear Dresselhaus SOIs can both be changed by varying the structure of the asymmetric QW which has internal SIA in the absence of an electric field [15]. The persistent spin helix can be reached only by designing an appropriate structure of asymmetric QWs. Moreover, the Rashba SOI of an asymmetric QW can also be manipulated by an electric field. So there are more ways to tune the Rashba SOI of an asymmetric QW than a symmetric QW which does not have internal SIA in the absence of an electric field.

Designing asymmetric QW structure to manipulate SOIs is key issue for controlling spin relaxation in QWs. Symmetric AlAs/GaAs/AlAs QW and AlAs/$Al_xGa_{1-x}As$/AlAs ($x < 0.4$) QW cannot result in Rashba SOI in the absence of electric and magnetic fields. A new QW can be realized by sandwiching an AlAs/GaAs/AlAs QW and an AlAs/$Al_xGa_{1-x}As$/AlAs ($x < 0.4$) QW between AlAs barriers, and the central AlAs barrier between the two wells is thin to make sure that the two wells are coupling. As long as $x \neq 0$ or the widths of the two wells are different, this QW is an asymmetric structure, which is called AQW1 in this paper. The inset of Fig. 1(a) shows schematics of the conduction energy band diagrams of AQW1. By sandwiching a symmetric AlAs/$Al_xGa_{1-x}As$/AlAs ($x < 0.4$) QW and an asymmetric AlAs/GaAs/$Al_{0.3}Ga_{0.7}As$ QW between AlAs and $Al_{0.3}Ga_{0.7}As$ barriers, another asymmetric QW (AQW2) is realized. The schematics of its conduction energy band diagrams is shown in the inset of Fig. 6(b). The two kinds of QW are different from that in Ref. [16]. The QWs in Ref. [16] include a step QW, so they are always asymmetric. While in this paper, the QWs we assessed do not include step QW, they can be asymmetric or symmetric, depending on their structure parameters. Investigation about the Rashba SOI modulation by the internal SIA of different kinds of AQW can contribute to the control of electron spin relaxation and give some new hints to make use of electrons spin. In this paper, the modulation of

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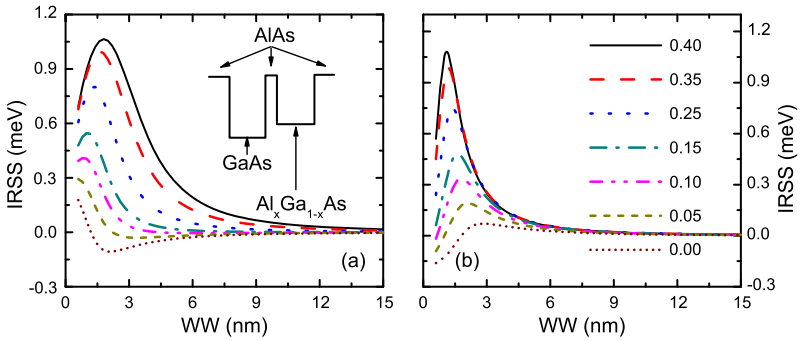

Fig. 1. (a) Interface-related Rashba spin splitting (IRSS) of the AQW1 as a function of the width of the $Al_xGa_{1-x}As$ well (WW), the width of the GaAs well is 1.2 nm. (b) IRSS of the AQW1 as a function of the width of GaAs well (WW), the width of the $Al_xGa_{1-x}As$ well is 1.8 nm. The Al concentration x is 0.00, 0.05, 0.10, 0.15, 0.25, 0.35 and 0.40, respectively. The inset in (a) shows schematics of the conduction energy band diagram of the AQW1.

the Rashba SOI which comes from the internal SIA of two kinds of AQWs is theoretically investigated, and the mechanism of the strength increase of the Rashba SOI is analyzed and discussed.

2. Methods

The former and latter interfaces of the AQWs cannot transform into each other by a mirror reflection in the well plane. So the inherent SIA of the AQWs arises from the potential discontinuity at every interface, and the Rashba SOI is localized at the interfaces. The effect of the interfaces on the Rashba SOI of the AQWs can be described by a coefficient, which can be written as $\alpha_I = \sum_i (\frac{V_{iL}-V_{iR}}{V_0} P\delta(z-z_i))$, where z_i denotes the ith interface, $(V_{iL}-V_{iR})$ is the band offset of the ith interface, and V_0 is the band offset of AlAs and GaAs. The δ function shows that the Rashba SOI is localized at the interfaces [17,18]. P is the interface parameter of the AlAs/GaAs interface. We simulate the results of Ref. [19] to extract the value $P \approx -100$ meV nm^2 for the AlAs/GaAs interface.

The Rashba SOI, which comes from the internal SIA of the AQW, is called the interface-related Rashba SOI (IRSOI) in this paper. The AQWs are grown along the [001] direction in this paper, the IRSOI can be written as [20,16] $H_I = \alpha_I(\sigma_x k_y - \sigma_y k_x)$, where k_x and k_y are the wave vectors, σ_x and σ_y are the spin Pauli matrices. Assuming that only the first electron subband is populated, the Dresselhaus SOI can be written as [21,22] $H_D = \gamma[\sigma_x k_x(k_y^2 - \langle k_z^2\rangle) + \sigma_y k_y(\langle k_z^2\rangle - k_x^2)]$, where $\langle k_z^2\rangle$ is squared operator $(-i\partial/\partial z)$ averaged over the ground state. γ is the cubic Dresselhaus coefficient, and $\beta = \gamma\langle k_z^2\rangle$ is the linear Dresselhaus coefficient. We adopt $\gamma = 17$ eV Å^3 for GaAs, $\gamma = 12$ eV Å^3 for AlAs [23], and $k_F = 2.0\times10^6$ cm^{-1} along [$\bar{1}$10] direction. The conduction Hamiltonian can be written as $H = -\frac{\hbar^2}{2m^*}\nabla^2 + V(z) + H_D + H_I$, where m^* is the electron effective mass, $V(z)$ is the potential of the AQWs. The Schrödinger equation is solved by the method of finite difference. The calculation method has been shown in Ref. [15]. The spin-dependent eigenenergies $E^{\pm}$ can be obtained, and the spin splitting can be written as $SS = E^+ - E^-$. If $E^+ > E^-$, the spin splitting is positive. If $E^+ < E^-$, the spin splitting is negative.

3. Results and discussion

The IRSOI results in Rashba spin splitting which is called the interface-related Rashba spin splitting (IRSS) in this paper. Along [$\bar{1}$10] direction, the spin splitting from the linear Dresselhaus SOI (LDSS) is negative, while the sign of the IRSS depends on the structure parameter of QWs. By changing the structure parameter, the magnitude of the IRSS and LDSS can be the same and the signs of them are opposite, the total spin splitting disappear and the spin relaxation time reaches a maximum. The IRSOI and the IRSS of the AQW1 can be tuned by three structure parameters, i.e., the width of the AlAs/GaAs/AlAs well (GaAs well), the width of the AlAs/$Al_xGa_{1-x}As$/AlAs well ($Al_xGa_{1-x}As$ well) and the Al concentration x in the $Al_xGa_{1-x}As$ well. The central AlAs barrier between the two wells in the AQWs is set to be 0.6 nm to make sure that the two wells are coupling.

Fig. 1(a) shows the change of the IRSS with the width of $Al_xGa_{1-x}As$ well (WW_{AlGaAs}) and Al concentration x. The Al concentration x determines not only the magnitude and sign of IRSS, but also the change of IRSS with WW_{AlGaAs}. $x < 0.1$, the IRSS first decreases to zero, then increases to a negative maximum, and then decreases again. According to the expressions $SS = E^+ - E^-$, the change in sign can be attributed to the energy change of spin up and spin down electrons. WW_{AlGaAs} is less than a certain value, $E^+ > E^-$, IRSS is positive; WW_{AlGaAs} is bigger than the certain value, $E^+ < E^-$, IRSS is negative. $x > 0.1$, the IRSS first increases to a positive maximum, and then decreases, E^+ is always bigger than E^-, IRSS is always positive. Moreover, when WW_{AlGaAs} $(x > 0.1)$ is given, bigger Al concentration x causes larger IRSS. Fig. 1(b) displays the IRSS as a function of the width of GaAs well (WW_{GaAs}). The magnitude and sign of IRSS as well as the change of IRSS with WW_{GaAs} also depend on x.

The IRSS comes from the internal SIA of AQW1. Two factors determine the internal SIA: Al concentration x and size disparity between the two wells in AQW1. The magnitude and sign of IRSS changing with the structure parameter can also be explained by the change of the electron probability density (EPD). We have demonstrated that the IRSS is proportional to $dEPD = \sum_i (\frac{V_{iL}-V_{iR}}{V_0}|\psi^0(z_i)|^2)$ [20], where $\psi^0(z_i)$ is the zeroth-order envelope function of the first subband at the i-th interface. So the EPD at every interface of AQW determines the magnitude and sign of IRSS. $dEPD$ can also be written as $dEPD = dEPD_{left} + dEPD_{right}$, where $dEPD_{left}$ is determined by the band offsets and EPDs at the two interfaces of the well (left-well) on the left side of the central barrier, and $dEPD_{right}$ depends on the band offsets and the EPDs at the two interfaces of the well (right-well) on the right side of the central barrier. $dEPD_{left}$ is negative and $dEPD_{right}$ is positive. If $dEPD_{right} > |dEPD_{left}|$, IRSS is mainly determined by the two interfaces of right-well, $dEPD > 0$ and IRSS is positive. If $dEPD_{right} < |dEPD_{left}|$, IRSS is mainly determined by the two interfaces of left-well, $dEPD < 0$ and IRSS is negative. If $dEPD_{right} = |dEPD_{left}|$, $dEPD = 0$ and IRSS is zero.

Fig. 2(a)–(d) show the EPD of AQW1 changing with WW_{AlGaAs} $(x = 0)$. The two wells are both GaAs well. The internal SIA only depends on the size disparity between them. The widths of the two wells are different, the AQW1 bears internal SIA, which results in IRSS. Though the peak of the EPD appears in the wider well, the EPDs at the two interfaces of the narrower well determine the magnitude and sign of the IRSS. The right-well is $Al_xGa_{1-x}As$ $(x = 0)$ well and the left-well is GaAs well. In Fig. 2(a),