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Magnetic control of Rashba splittings in symmetric InAs quantum wells

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ABSTRACT

We propose a mechanism to control the Rashba-induced subband splitting by a magnetic field using a symmetric double quantum well (QW) system, where the lowest two subbands are coupled by a position-dependent Rashba parameter $\alpha(z)$. In such a system, all subbands are spin degenerate due to the time reversal symmetry and the spatial inversion symmetry at zero magnetic field, despite the presence of the Rashba spin–orbit interaction. Applying an external magnetic field parallel to the QW plane ($\mathbf{B}\|\hat{\mathbf{y}}$) lifts this spin degeneracy breaking the time reversal symmetry, where the spin splitting energies are controllable in the range between zero and 2.9 meV, the latter being on the same order of magnitude as a typical Rashba splitting in a narrow asymmetric QW. We find that the first and second subband energy levels for a selected spin state with $\mathbf{k}_\| = (k_F,0,0)$ anticross each other, and that the energy of the subband splitting Δ_0, equivalent to the Rashba splitting for the case of single QWs, can be determined from the value of the anticrossing magnetic field B_{ac}. These results suggest that the investigation in the symmetric double QWs would provide useful approaches for quantitative understanding of the Rashba spin–orbit interaction.

There have been much interest in spin–orbit interactions in narrow gap semiconductors for manipulating quantum spin rotation without magnetic fields and for application to semiconductor-based spintronics devices [1]. Spin–orbit interactions in semiconductors are classified into two types: the Rashba effect, due to the structural inversion asymmetry [2,3] and the Dresselhaus effect, due to the bulk inversion asymmetry [4]. The Rashba effect has been expected to provide a useful way of controlling spins by an electric field [5–7]. The Dresselhaus effect, which is not explicitly controllable by gate, is also present in narrow gap semiconductors. Precise values of these spin–orbit coupling constants are important for understanding physics of spin–orbit interaction and to implement spintronics devices. The spin–orbit coupling constants have been investigated by various methods including observation of beating in Shubnikov-de Haas (SdH) oscillations [8–11], weak antilocalization [12], spin interference in mesoscopic loop arrays [13,14], and spin Galvanic effect [15]. However, as the origin of the beating in SdH oscillations is still under the debates [16,17], no single measurement has provided reliable values for the spin–orbit coupling constants yet. We also point out that most investigations on the Rashba spin–orbit effect, thus far, utilized asymmetric quantum well (QW) potentials, i.e., the systems *without* structural inversion symmetry, since a net electric field within the QWs is considered to be essential for the Rashba splitting. Recently, however, it has been shown that the Rashba spin–orbit interaction has some roles even in *symmetric* QWs because of its position-dependence in $\alpha(z)$ [see Fig. 1(b)] reflecting the position-dependence of the local electric field [18,19].

In this paper, we propose to use symmetric double QWs to clarify the Rashba effect quantitatively. This approach has two advantages: (1) we can prepare systems that have a known electric field within the QW and (2) we can utilize an external magnetic field to further control the spin splitting energies, which would provide quantitative insight into the Rashba spin–orbit interaction. We employ the effective mass approximation to calculate spin-resolved subband energy splittings in the conduction band of symmetric AlSb/InAs/AlSb QWs (well-thickness d_{QW}=30–60 nm) with a fixed electron density $N_s = 3.0 \times 10^{16}\,\mathrm{m}^{-2}$. We will show that the lowest two subbands of a selected spin state exhibit a level-anticrossing at a small magnetic field B_{ac}. We will then discuss that the determination of B_{ac} has a direct relevance to the quantitative determination of α value for a given QW with a known electric field.

The Hamiltonian for an electron in the QW is given by $H = H_0 + H_R$. Here, H_0 is the spin-independent unperturbed Hamiltonian,

$$H_0 = \frac{\hbar^2}{2m_\|^*}\{(k_x + eBz/\hbar)^2 + k_y^2\} - \frac{d}{dz}\frac{\hbar^2}{2m_z^*(z)}\frac{d}{dz} + V(z), \quad (1)$$

where the in-plane and out-of-plane effective masses within the InAs layer are chosen to be $m_\|^* = 0.03m_0$ and $m_z^* = 0.026m_0$,

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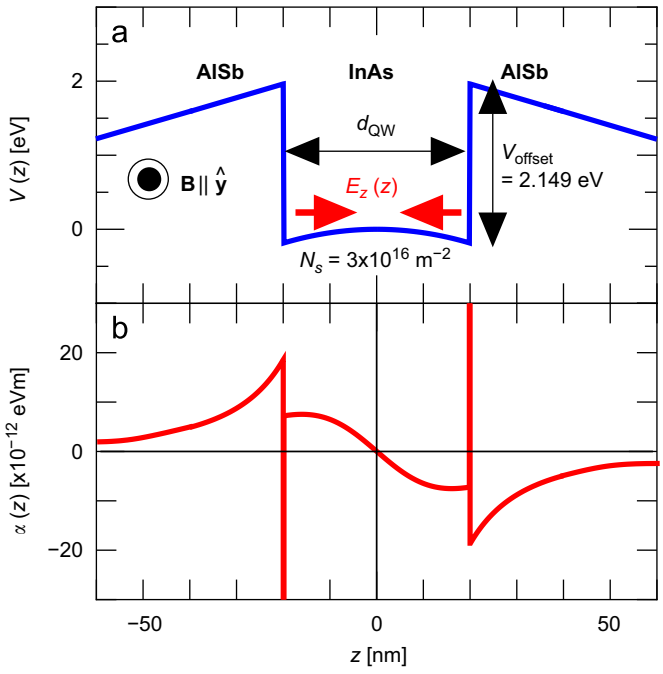

Fig. 1. (a) Schematic diagram of a symmetric double well potential of a AlSb/InAs/AlSb heterostructure. The red arrows indicate directions of the internal electric fields $[E(z)=(1/e)dV(z)/dz]$ at up $(z>0)$ and down $(z<0)$ sides of the well. (b) Position-dependent Rashba parameter $\alpha(z)$ calculated from a potential profile in (a) using Eq. (3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respectively. m_z^* value used for the AlSb barrier layer is $0.14m_0$. We also consider a kinematic shift in the momentum operator $\mathbf{p}\rightarrow\mathbf{p}+e\mathbf{A}$ in Eq. (1), assuming the presence of an in-plane magnetic field ($\mathbf{B}\|\hat{\mathbf{y}}$) using a vector potential $\mathbf{A}=(Bz,0,0)$. The confinement potential $V(z)$, which has been bent by the Hartree potential due to the electrons within the QW, forms a symmetric double QW for the conduction electrons, as shown in Fig. 1(a). To calculate the Hartree potential, we assumed a homogeneous charge distribution $\rho(z)=-eN_s/d_{QW}$ for simplicity. While this assumption tends to overestimate the values of internal electric field for large d_{QW}'s ($\gtrsim 60$ nm), the calculated potential profiles well-approximated those that the more accurate self-consistent Poisson–Schrödinger solutions would predict for $d_{QW}\lesssim 60$ nm.

The Rashba Hamiltonian H_R, including the kinematic shift of $\mathbf{p}$ as described above, is given by

$$H_R=\alpha(z)\{k_y\sigma_x-(k_x+eBz/\hbar)\sigma_y\}, \tag{2}$$

where σ_x and σ_y are Pauli's spin matrices. We note that the Rashba parameter α retains z-dependence through the $\mathbf{k}\cdot\mathbf{p}$ formalism [6,10],

$$\alpha(z)=\frac{\hbar^2E_P}{6m_0}\frac{d}{dz}\left\{\frac{1}{E_F-E_{\Gamma_7}(z)}-\frac{1}{E_F-E_{\Gamma_8}(z)}\right\}, \tag{3}$$

where E_F is the Fermi energy, and we use $E_P=21.5$ eV for the $\mathbf{k}\cdot\mathbf{p}$ interaction parameter [10,20]. Similarly with $V(z)$, the spin split-off band energy $E_{\Gamma_7}(z)$ and the valence band edge energy $E_{\Gamma_8}(z)$ are even functions of z [21]. As the derivative of these energies, $\alpha(z)$ is an odd function of z [see Fig. 1(b)]. From the Schrödinger equation with the full Hamiltonian $H=H_0+H_R$ in the absence of B, we obtain the electron eigenenergies $E_{n,\sigma}(\mathbf{k}_\|)$, and the eigenstates (basis) $|\Psi_{n,\mathbf{k}_\|,\sigma}\rangle=\Psi_{n,\mathbf{k}_\|,\sigma}(z)e^{i\mathbf{k}_\|\cdot\mathbf{r}_\|}|\sigma\rangle$, where $n=1,2,3,\ldots$ is the subband index due to the quantization by $V(z)$ and $\sigma=\uparrow$(up) or $\downarrow$(down) is the index for spin eigenstate (basis) whose spin axis depends on $\mathbf{k}_\|$. We ignore the Zeeman effect, since the Zeeman splitting energies are much smaller than the subband and/or Rashba splitting energies for $B<100$ mT, where we can expect the most interesting phenomena in the current investigation. The effect of Dresselhaus term was not included for simplicity, but will be considered in the future works.

The results of the calculation for the lowest four subband energies, $E_{1,\sigma}$, $E_{2,\sigma}$, $E_{3,\sigma}$, and $E_{4,\sigma}$, for $\mathbf{k}_\|=0$ and $B=0$ as a function of the well-thickness d_{QW} are shown in Fig. 2(a). All subbands are spin degenerate since both the Rashba effect and the *orbital* Zeeman effect, which is associated with the kinematic shift of $\mathbf{p}$, are absent because $\mathbf{k}_\|=0$ and $B=0$ are assumed. Note that the kink (in the energies $E_{1,\sigma}$ and $E_{2,\sigma}$) at $d_{QW}=43$ nm is due to the electron occupation of the fourth subband. Fig. 2(b) shows the dispersion relations of the electrons for the symmetric QW with $d_{QW}=45$ nm along the k_x direction at $B=80$ mT. Since the in-plane $\mathbf{B}$ breaks the time reversal symmetry, the Kramers degeneracy $[E_{n,\uparrow}(\mathbf{k}_\|)=E_{n,\downarrow}(-\mathbf{k}_\|)]$ is lifted, while the relation $E_{n,\sigma}(\mathbf{k}_\|)=E_{n,\sigma}(-\mathbf{k}_\|)$ remains to hold due to the spatial inversion symmetry. This spin splitting contrasts with the zero-field Rashba splitting in a single asymmetric QW, where the Kramers degeneracy is kept hold but the latter relation $[E_{n,\sigma}(\mathbf{k}_\|)=E_{n,\sigma}(-\mathbf{k}_\|)]$ does not hold. We will not discuss the spin splitting energies for subbands with $n\geq 3$ here because they are very small relative to those for $n\leq 2$.

Fig. 3 illustrates how the relative subband energies, $E_{1,\sigma}$ and $E_{2,\sigma}$ for $|\mathbf{k}_\||=k_F$, where k_F is the Fermi wave number [see the inset of Fig. 2(b)], evolve with (a) well-thickness, (b) magnetic field, and (c) azimuthal angle θ_k [$\mathbf{k}_\|=(k_F\cos\theta_k,k_F\sin\theta_k)$ as shown in the inset of Fig. 3(c)]. In each graph, the gray broken curves represent the results without the Rashba term H_R (only with H_0) for comparison. We find, in Fig. 3(a), that the subband splitting $\Delta_0\equiv E_{2,\sigma}-E_{1,\sigma}$ at $B=0$ decreases with increasing d_{QW} for $d_{QW}\lesssim 42$ nm, due to the decrease of the quantum confinement effect. The deviation of the black $(E_{1,\uparrow/\downarrow})$ and the blue $(E_{2,\uparrow/\downarrow})$ curves from the gray broken curves (results without H_R) is the effect of H_R. We also find that, for $d_{QW}\gtrsim 50$ nm, the energy splitting stays almost constant ($\Delta_0\sim 2.9$ meV) when the effect of H_R is taken into account, while it decays to negligibly small values

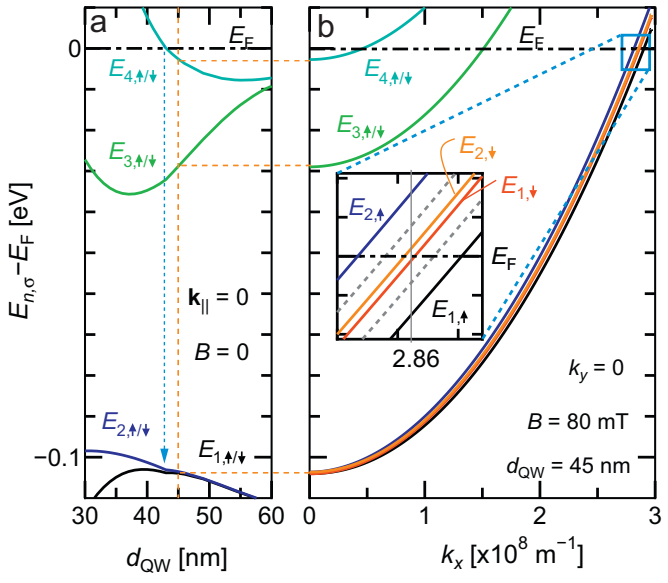

Fig. 2. (a) Spin degenerate subband energies at $B=0$ as a function of the well-thickness d_{QW} for $\mathbf{k}_\|=0$. (b) Dispersion relation along $\mathbf{k}_\|=(k_x,0,0)$ for $d_{QW}=45$ nm at $B=80$ mT [$\mathbf{B}=(0,B,0)$]. Inset: a magnification of the lowest four spin-subbands around the Fermi energy. Dotted lines represent the first and second subband energies at $B=0$. The Fermi wave number k_F for the fixed electron density $N_s=3.0\times10^{16}$ m^{-2} is 2.86×10^8 m^{-1} for $d_{QW}=45$ nm.