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Spin-Orbit Coupling Through Inelastic Scattering on Intrasubband Spin Density Excitation

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ABSTRACT We have studied the spin-orbit coupling via inelastic scattering on the intrasubband spin density excitation. Resonant in elastic scattering was applied to the probe of the anisotropic spin splitting of two dimensional hole systems in p-modulation doped gallium arsenide quantum wells. Intrasubband spin density excitations on a sample was used where evidence of the persistent spin helix was shown by direct spatial mapping. We found approximately equal strengths of Rashba and Dresselhaus spin-orbit coupling and anisotropy maximal. The spin splitting for in plane spin was also found maximal and in the perpendicular [110] direction was smaller. The spin splitting of in plane of about 0.18 meV and in the perpendicular in plane direction was found to be smaller than 0.05 meV. We have theoretically studied that only spin flip transitions between the spin orbit split conduction band subbands contributed significantly to the intrasubband spin-density excitation in quasi-backscattering geometry. The obtained results were found in good agreement with previously obtained results.

KEYWORDS Spin-orbit, Coupling, Inelastic Scattring, Intrasubband, Spin-Density Excitation, Splitting.

INTRODUCTION

In a two dimensional electron system the spin-orbit coupling leaded to a spin splitting of the free electrons, even at zero external magnetic field, which depends on $k_{\parallel}$, the wave vector of the electron in the plane of the two dimensional electron system.

Jusserand et al.[1], Richards et al.[2] and Allan et al.[3] have shown the anisotropy of the spin-splitting of the electrons in the plane of the two dimensional electron system can be probed by inelastic light scattering on spin flip single particle transitions in highly doped GaAs-Al GaAs quantum wells. Ganichev et al.[4] reported that by angle-dependent investigations of spin photocurrents, employing the spin-galvanic effect, the anisotropic orientations of spins in k space can be probed directly. Hirmer et al.[5] studied resonant inelastic light scattering was applied to probe the anisotropic spin splitting of two dimensional hole systems in p-modulation doped GaAs-AlGaAs quantum wells. Averkiev and Golub[6] studied the spin splitting anisotropic for a two dimensional system in Zinc blende type quantum wells but a giant spin-dephasing anisotropy was predicted for electrons with in plane spin orientation. Kainz et al.[7] presented that the anisotropy should be maximal if strengths are equal. For this Schliemann et al.[8] presented a spin transistor device which have used diffusive transport. The predicted spin-depending anisotropy was experimentally verified by Averkiev et al.[9] by polarization resolved photoluminescence and by time resolved Kerr rotation by Liu et al.[10] and Stich et al.[11]. Bernevig et al.[12] proposed that for this case a new type of SU(2) spin rotation symmetry should be present which should give rise to a persistent spin helix for spins which are initially oriented out of the plane of a (001)-oriented two dimensional electron system. Experimental evidence of the persistent spin helix was reported by Koralek et al.[13] by transient spin grating spectroscopy, directly mapping via time and spatially resolved Kerr microscopy[14] and weal localization / antilocalizaton experiments[15]. Jha and Kumar[16] studied transient scattering analysis on geometrical theory of diffraction. They presented the back scattered fields of perfectly conducting circular disc were analysed from a transient signature view point. These significant dominant scattering mechanisms were identified for both principal polarizations at a variety of angles. Such type of study is useful in the field of Radar. Pandey[17] studied the electron transmission through impurity in quantum wire. He has presented that when the magnetic field entered along the small axis of cross section, electron transmission is strongly enhanced since the overlap between incident and reflected wave functions became smaller and back scattering was decreased. When the magnetic field entered along the large axis of the cross section, the overlap between wave functions became larger, then backward scattering enhanced and transmission was suppressed. Jee et al.[18] studied the scattering of electrons by equilibrium phonons in two subband quasi two dimensional electron gas in a quantizing magnetic field. The electron phonon coupling constant is nearly equal to the magnetic field, the phonon induced longitudinal conductivity at high enough magnetic fields may be comparable with impurity induced longitudinal conductivity. A resonant enhancement of the conductivity was found due to interaction of two Landau level. Gupta et al.[19] studied that passive and active microwave remote sensing microwave emissivity and radar backscattering coefficient of contaminated soil with crude oil was estimated by model calculation. They found that the contamination effect on radar back scattering coefficient was not much significant for horizontal polarization. Dresselhaus[20] studied the bulk inversion asymmetry of the crystal lattice Dresselhaus effect. Bychkov and Rashba[21] presented a structure inversion asymmetry was present in the sample due to electric fields, caused by external gate and or modulation doping. Salis et al.[22] presented that a transient in energy shift due to a finite excitation spot size was included in the analysis yielding estimates for energy shift were slightly too small. The obtained results were compared with the previous obtained results.

METHOD

The spin-orbit Hamiltonian of an electron in (001) orientated quantum is given by.

$$H_{so} = \alpha\left(k_y\sigma_x - k_x\sigma_y\right) + \beta\left(k_x\sigma_x - k_y\sigma_y\right) \qquad \text{... (A)}$$

when only terms linear in $k_{\|}$ have been considered. x, y and z directions are parallel to the [100] and [001] crystal directions. α and β are assumed to be positive quantities for a gallium arsenide quantum well, that is, the electric field in the quantum well is pointing in the [001] direction. An effective $k_{\|}$ dependent spin-orbit field h is usually defined via a Zeeman type Hamiltonian $H_{so} = \hat{\sigma}h$, where $\hat{\sigma} = \left(\sigma_x, \sigma_y, \sigma_z\right)$ is the vector of the pauli spin matrics. With this the spin orbit field is given by

$$h = \left(\sigma k_y + \beta k_x\right)e_x + \left(-\alpha k_x - \beta k_y\right)e_y \qquad \text{... (B)}$$

where k is linear in approximation. When $\alpha = \beta$ the unique situation arised where the spin-orbit field reduced to

$$h = \alpha\left(k_x + k_y\right)\left(e_x - e_y\right) \quad \text{... (C)}$$

The direction of the spin-orbit field h is for all $k_{\parallel} = \left(k_x, k_y\right)$, either parallel or antiparallel to the [110] in plane direction if the sum $\left(k_x + k_y\right)$ is either positive or negative. Regarding the energy of an electron, this leaded to the constant energy where the energy parabolids for electron with spin oriented in plane parallel or antiparallel to h are shifted by Δk relative to each other in the two dimensional k space. The magnitude of Δk is given by

$$\Delta k = \frac{4m^{*}\alpha}{\hbar^{2}} \quad \text{.... (D)}$$

where m^{*} is the effective mass of an electron. At the same time, Δk is the wave vector of the persintent spin helix (PSH) for out of plane spin excitations, which is expected in the $\left[1\bar{1}0\right]$ direction and is connected to its wavelength λ_{PSH} via $\Delta k = \frac{2\pi}{\lambda_{\mathrm{PSH}}}$.

The Fermi energy connected to Δk via

$$\Delta E_{S.[110]} = \frac{\hbar^{2}}{m^{*}} k_F \Delta k \quad \text{... (E)}$$

Where k_F is the Fermi wave vector of the two dimensional electron gas. We have considered inelastic scattering process on the intrasubband spin density excitations. In this scattering a virtual electron-hole pair is created by absorption of a laser photon. Either the electron or the hole is scattered by the creation of a spin density excitation in the system. For the whole process energy and momentum conservation holds good. The energy of the created excitation and the wave vector component parallel to the translationally invariant quantum well plane q is transferred to the excitation ie to the spin-density excitation. Macroscopically an intrasubband spin density excitation is a spin wave, which travels in the plane of the two dimensional electron system with wave vector q. The possibility to excite spin density excitations in inelastic scattering is generally a consequence of spin-density fluctuations of the electron system and of spin-orbit interaction in the zinc blende structure. The scattering amplitude A_{fi} for inelastic scattering by spin density fluctuations where an electron is excited from state ψ initial to state ψ final is given by

$$A_{fi} = \gamma\left(e_i \times e_s^{*}\right)\left\langle \psi_{final} \left| \hat{\sigma} \right| \psi_{initial} \right\rangle \quad \text{... (F)}$$

Where $e_i\left(e_s\right)$ is the polarization vector of the scattered wave, γ is a factor which contains resonance enhancement effects.

The two possible spin eigen functions for in plane spins are

$$\psi_{\pm k} = \frac{e^{i\frac{\pi}{8}}}{\sqrt{2}}\left[\left|\uparrow\right\rangle \pm \frac{1}{\sqrt{2}}(1-i)\left|\downarrow\right\rangle\right]$$

The plus minus sign corresponds to a spin oriented in the $\left[1\bar{1}0\right]$ $\left(\left[\bar{1}10\right]\right)$ direction.

RESULTS AND DISCUSSION

Figure (1) (a) shows that a wave q was transferred in the [110] in plane direction and graph (1)(b) shows it is parallel to $[1\bar{1}0]$. The sharp cutoff at about 0.5meV in the bottom spectra of both plots is due to the cutoff of the triple Raman spectrum. The strong elastically scattering is visible around zero Raman shift. The spectra are horizontally shifted so that the maxima in the spectra are approximately vertically aligned. The spectra of the intrasubband spin density excitation in Figure (1) (b) is closely resemble the asymmetric Lindhard-Mermin line shape of single particle intrasubband excitations. For these excitations the high energy cutoff E_q, which appeared at around 1.6 meV in the bottom spectrum as shown in graph (1)(b) is determined by the Fermi wave vector k_F and the wave vector q via

$$E_q = \frac{\hbar^2}{m^*} k_F q$$

Assuming a parabolic band and $q << k_F$, we have determined the carrier density $n = \frac{k_F^2}{2\pi}$ of the two dimensional electron system by analyzing E_q in the spectra depending on q. From this analysis we have obtained $n = (4.40 \pm 0.75) \times 10^{15} m^{-2}$ for the electron density of the two dimensional electron system. The spectra in graph (1) (a) where q was transferred parallel to the $[110]$ in plane direction exhibited two maximas which are shifted against each other by about (0.37 ± 0.05) meV, nearly independent of transferred wave vector q. These spectra resemble the spectra on highly doped asymmetric gallium arsenide quantum wells with relatively large spin splitting. In the $[1\bar{1}0]$ direction where the spin splitting $\Delta E_{S,[1\bar{1}0]}$ is close to zero, only a single maximum is observed in graph (1) (b). In the $[110]$ direction as shown in graph (1) two maxima are observed which are equally shifted to both sides are present. Fermi energy with $|k_\|| \sim k_F$ contributed to the observed excitation. The spin flip transition energies $E_\pm(k_\|)$ for fixed direction of q are given by

$$E_\pm(k_\|) = E_q \cos(\delta_k - \delta_q) + \Delta E_S(k_\|)$$

Where δ_q is the fixed angle between q and the [110] axis, δ_k is the corresponding angle between $k_\|$ and the $[100]$ axis. $E \pm (k_\|)$ is maximal for $\delta_q = \delta_k$, which is the situation we have assumed. Figure (2) (a) shows the spectra for $q = 6.47 \times 1^6 m^{-1}, \theta = 24^\circ$. The different maxima in both spectra are closely recognized. Figure (2) (b) shows the analysized line shapes of the spectra for larger wave vector transfer for $q = 9.79 \times 10^6 m^{-1}$, where two maximas less well pronounced. Figure (2) (c) shows the dependence of the peak positions in both scattering configurations depending on the wave vector transfer q. The exact positions were derived from the spectra as shown in Figure (2) (c). We have found a double peak structure only in the [110] direction and that the single peak, which is observed in $[1\bar{1}0]$ direction, is energetically in the middle of these two maximas. We have found that sample has almost balanced Rashba and Dresselhaus spin-orbit strength. The obtained results were compared with previously obtained result of many workers and were found in good agreement.

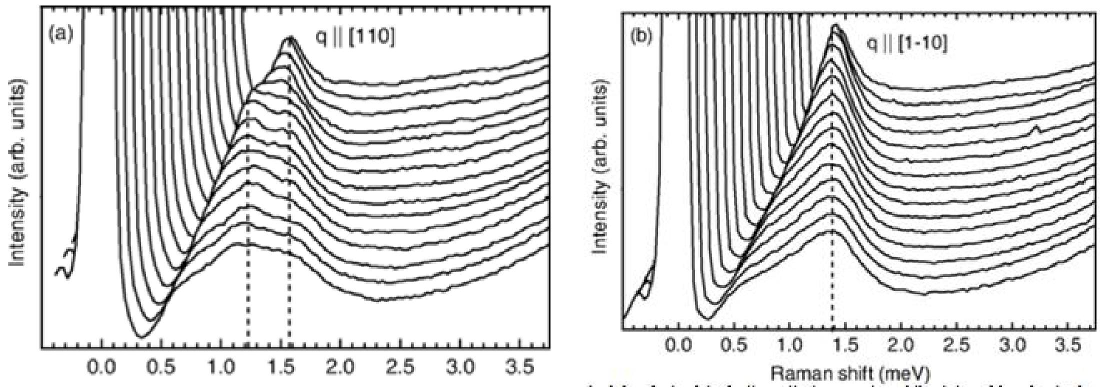

Figure 1: Plot of depolarized inelastic scattering spectra of the intrasubband spin density excitation for different wave-vector transfers q in the [110] in plane direction.

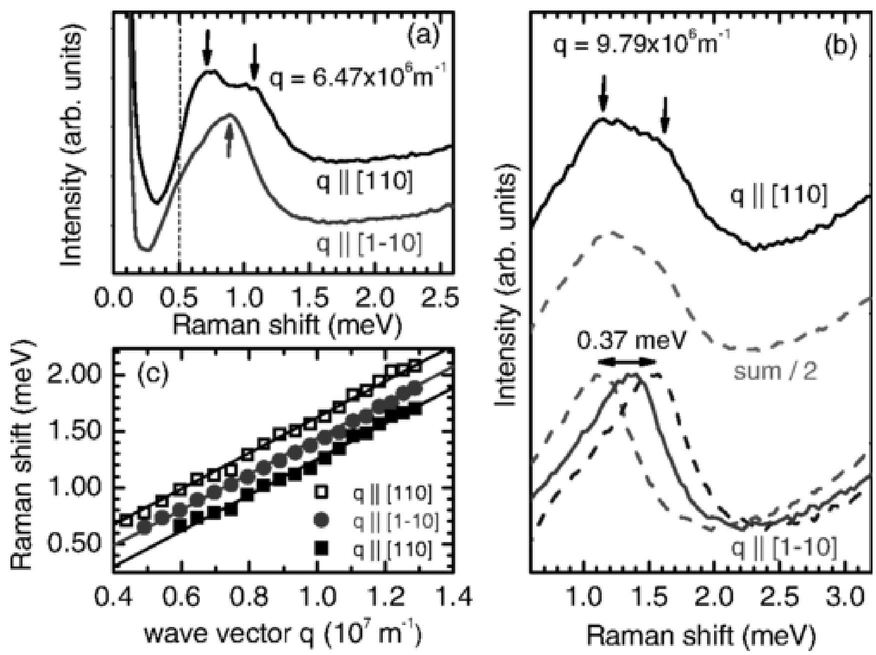

Figure 2: Positions of the maxima in the spectra of the intrasubband spin density excitation for different directions of wave vector transfer q vs q.

CONCLUSION

We have studied spin-orbit coupling through inelastic scattering on intra-subband spin density excitation. The study was made in the case of intrasubband spin-density excitation in an asymmetrically doped gallium arsenide single quantum well with balanced Rashba and Dresselhaus spin-orbit interaction strength by inelastic scattering. We have used spin-orbit field either parallel or antiparallel to the $[1\bar{1}0]$ in plane direction of the quantum well for all waves vectors of the two dimensional reciprocal space. We have found that in backscattering geometry the spin density excitation was formed by spin flip intrasubband transitions of the spin-split subband. Due to this we have derived the result directly from the spectra of the spin density excitation. The spin splitting of the conduction band for the different in plane directions and confirmed the conduction for the persistent spin helix in the sample. We have found that a spin splitting of in plane spins of 0.18meV and in perpendicular case it is 0.05 meV. It was also found that only spin-flip transitions between different spin subband were present. The deviation from exact backscattering geometry induced non spin flip transitions via δ_x and δ_y components in the matrix element. . The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.

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