Zero-field spin-splitting in InAs/AlSb quantum wells

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Abstract

Zero magnetic field spin-splitting of two-dimensional conduction band electrons in InAs/AlSb multi-quantum wells is observed in intersub-band absorption experiments. An in-plane magnetic field induces combined spin–flip intersub-band transitions, which for magnetic fields $B > 0$ T are separated in energy by as much as $\Delta E = 17$ meV. With increasing magnetic field this separation diminishes and a crossover between both resonances occurs at $\sim B \sim 12$ T. The excitation of spin–flip resonances, as well as the zero-field spin-splitting, are direct consequences of the bulk inversion asymmetry of InAs, providing two independent methods of determining the relevant band-structure parameter.

1. Introduction

The inversion asymmetry present in III–V semiconductors with zinc-blende structure is manifested in two prominent physical effects. First, the bulk crystalline electric field is Lorentz-transformed in the frame of a moving electron into an effective magnetic field B_{int} lifting the spin-degeneracy of the conduction band [1] for all directions in $\boldsymbol{k}$-space except for $\boldsymbol{k}\{100\}$ and $\{111\}$ [2]. A $\boldsymbol{k}^3$ term in the electronic dispersion, whose strength is determined by a parameter γ, makes the electronic energy spin-dependent and thus accounts for the so-called zero-field spin splitting [3]. Such a spin splitting of the conduction band has been experimentally observed and theoretically described for bulk materials [4] as well as for two-dimensional electron systems (2DES) confined in semiconductor heterostructures [5,6]. Secondly, the additional spin-dependent terms in the Hamiltonian allow the excitation of electric-dipole induced spin–flip resonances. These have been investigated in detail for bulk InSb [7]. To the best of our knowledge, however, there is no experimental evidence that both effects – the zero-field spin-splitting in combination with the excitation of spin–flip resonances – have been observed simultaneously, thus allowing independent determination of the strength of the bulk inversion asymmetry.

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2. Experiment

Here, we report on the spectroscopic observation of combined spin–flip intersub-band transitions in a symmetrically doped InAs/AlSb multi-quantum well structure. The oscillator strength of the resonances is found to increase strongly with an external magnetic field applied parallel to the plane of the layers. The excitation of the spin–flip transitions is made possible by a combination of both the in-plane magnetic field and the bulk inversion asymmetry of InAs [8]. In the framework of an eight-band matrix Hamiltonian, the resonance strength is determined by inversion asymmetry terms $\propto GP_iP_j$ with the canonical momentum $P_{i,j}$ and $i,j \in x,y,z$ [8]. The combined spin–flip intersubband transitions remain spin-split even for $B \to 0$ [9] with a large energetic separation of $\Delta E = 17$ meV. This is caused by the high carrier density (large $\boldsymbol{k}$ vector) in our samples and the narrow band gap of InAs. Hence, we are able to determine directly the material constant γ, as the spin-splitting at finite magnetic fields is about an order of magnitude larger than the magnetic energies in the experiment. Thus the oscillator strength of the excitations and the zero-field splitting constitute two different methods to deduce experimentally the strength of the bulk inversion asymmetry.

The InAs/AlSb multi-quantum well structures were grown on a GaAs substrate followed by a 1 μm AlSb buffer and a ten-period superlattice [10] to accommodate the strain between the substrate and the active layers. The 20-period multi-quantum well consists of 15 nm InAs layers stacked between Te-δ-doped AlSb barriers of 10 nm width. Hall-effect measurements at low temperatures revealed a carrier density per well of $N_s = 2.5 \times 10^{12}$ cm^{-2}.

Mid-infrared (MIR) spectra were taken using a rapid scan Fourier transform spectrometer with the sample mounted in multiple reflection path geometry (MRPC, inset of Fig. 1). Experimentally, we determined the relative change in MIR transmission $T(B \neq 0)/T(B=0)$ of the unpolarized radiation for different in-plane magnetic fields B. All experiments were performed at low temperatures ($T = 4.2$ K).

In Fig. 1 we depict typical relative transmission spectra taken at different in-plane magnetic fields $B \leq 13$ T ratioed against a reference spectrum at $B = 0$ T. We observe two well-separated resonances (I and II), both of which gain oscillator strength as the field is increased. There is no resonant absorption of the 2DEG detectable at $B = 0$ T, which could be confirmed in a separate experiment by ratioing against a reference substrate. As the magnetic field is increased, the low-energy resonance (I) shifts to higher energies, whereas the

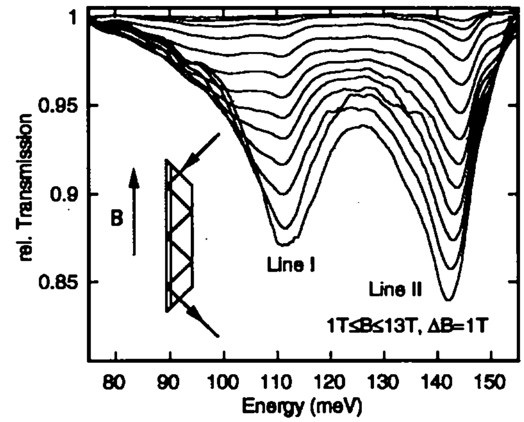

Fig. 1. Relative transmission spectra for $B \leq 13$ T with $\Delta B = 1$ T in the multiple reflection path geometry (inset). At high magnetic fields two resonances (I and II) can be seen which both gain oscillator strength as the field is increased. At low fields resonance I splits into two lines, giving experimental evidence for a zero-field spin-splitting.

position of the high-energy line (II) remains almost constant.

This peculiar magnetic-field dependence of the observed resonances has been observed and described in detail for a similar structure mounted in Voigt geometry [8]. We found that the radiation component perpendicular to the magnetic field induces both spin-conserving as well as spin–flip transitions. In these terms, line II is a superposition of the two allowed spin-conserving resonances $|0\uparrow\rangle \to |1\uparrow\rangle$ and $|0\downarrow\rangle \to |1\downarrow\rangle$, while line I corresponds to a superposition of the spin–flip excitations $|0\uparrow\rangle \to |1\downarrow\rangle$ and $|0\downarrow\rangle \to |1\uparrow\rangle$. Both lines I and II are separated in energy by the depolarization shift. While line II is induced by the parallel magnetic field, the spin–flip transition of line I is made possible by a combination of the parallel magnetic field and the bulk inversion asymmetry of InAs. The combined resonances can only be excited at high $\boldsymbol{k}_\parallel$ values, as the transition matrix elements turn out to be strongly $\boldsymbol{k}_\parallel$-dependent.

In MRPC as described here, the magnetic-field orientation is the same as in the Voigt geometry. In contrast to the latter, where we observed only a pronounced asymmetry of line I, this resonance is now split into two well-separated spin–flip transitions (Ia and Ib) at low magnetic fields ($B \leq 8$ T), as depicted in Fig. 2a. For $B \to 0$ the energetic difference is approximately $\Delta E = 17$ meV, and decreases with increasing magnetic field. With increasing B the low-energy line (Ia) shifts to higher energies, while the position of the high energy transition line (Ib) remains roughly constant up to $B = 13$ T (Fig. 2b). As can be seen from Fig. 2b, the lines cross each other at $\sim B \sim 12$ T.

3. Interpretation

Following Eppenga et al. [11], the zero-field spin splitting ΔE may be expressed as

$$\Delta E = 2\gamma\sqrt{\mathbf{k}_x^2\left(\mathbf{k}_y^2-\mathbf{k}_z^2\right)^2+\mathbf{k}_z^2\left(\mathbf{k}_x^2-\mathbf{k}_y^2\right)^2},$$

with a calculated value of $\gamma(\mathrm{InAs}) = 130$ eV Å^3 [12]. The $\boldsymbol{k}$ value along the direction of electric confinement y is taken to be $\boldsymbol{k}_y = \pi/L$ for the ground-state sub-band (well width L), and $\boldsymbol{k}_x$ and $\boldsymbol{k}_z$ denote the in-plane wave vectors. An analogous calculation for the first sub-band with $\boldsymbol{k}_y = 2\pi/L$ yields the $\boldsymbol{k}_\parallel$ dependence of the splitting between the $|0-\rangle \to |1+\rangle$ and $|0+\rangle \to |1-\rangle$ combined spin–flip resonances. For $\boldsymbol{k} \approx \boldsymbol{k}_F$ this calculation agrees reasonably well with the experimentally determined value of the splitting. Therefore, our experiment confirms the calculated value of γ from Ref. [12]

We now turn to the comparison of γ as inferred from the zero-field spin-splitting to its value deduced from the magnetic-field dependence of the oscillator strength. In the eight-band matrix formalism the oscillator strength of the combined resonances is well described by the G value of InSb, $G = 3\hbar^2/2m_0$ [8]. According to Cardona et al. [13] the parameter γ can be approximated by

$$\gamma = \frac{4}{3}\, G\hbar\kappa\, \frac{\Delta}{E_g(E_g+\Delta)}.$$

Taking $E_g = 0.42$ eV, the spin-orbit splitting $\Delta = 0.38$ eV, and the Kane energy $2m_0\kappa^2 = 22.9$ eV, we find $\gamma = 150$ eV Å^3. This is in good agreement with the above result of the experiment as well as the theoretical value.

The magnetic-field dependence of the spin-split lines Ia and Ib (Fig. 2b) may be qualitatively understood as follows. The crossover at $B = 12$ T is a clear signature that the sum of the effective g factors in the respective sub-bands must be equal to zero. In other words, the Zeeman term cancels the zero-field spin-splitting, causing the effective g factor to change its sign analogous to the Faraday configuration [3]. This cancellation occurs at different magnetic fields for the two sub-bands because of the different values of $\boldsymbol{k}_y$ and the energy-dependent g factors.

4. Conclusion

We observe combined spin–flip intersub-band transitions in a parallel magnetic field B which are

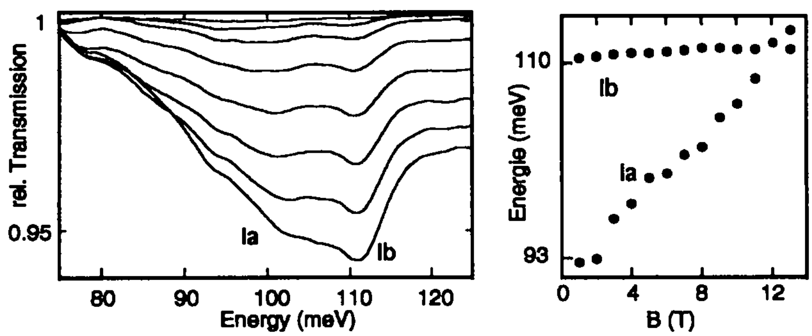

Fig. 2. The spin–flip resonances can be clearly resolved at low magnetic fields ($B \leq 8$ T with $\Delta B = 1$ T). Transition Ib is roughly constant in energy and has a greater oscillator strength (area under the curve) than transition Ia. Line Ia, on the other hand, shifts to higher energies as the magnetic field is increased.

made possible by the bulk inversion asymmetry and the narrow band-gap of InAs in combination with the large Fermi wave-vector. The large splitting of $\Delta E = 17$ meV for $B > 0$ T is caused by the lack of inversion asymmetry in zinc-blende materials lifting the spin-degeneracy for finite $\boldsymbol{k}$. The observed oscillator strength of the combined resonance, as well as the value of the zero-field splitting, enables us to determine the inversion asymmetry parameter experimentally. Reasonably good agreement is found between these independent methods as well as with the theoretical value. The crossover of the lines at $B = 12$ T can be explained by the influence of a parallel magnetic field on the electronic energies in a quantum well.

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