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Physica E 13 (2002) 186–189

PHYSICA E

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Heterostructure interface effects on the far-infrared magneto-optical spectra of InAs/Gasb quantum wells

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Abstract

The electronic and optical properties of InAs/GaSb heterostructures depend on the type of bonding at the interfaces, InSb bonds or GaAs bonds. We have studied cyclotron resonance (CR) in the far-infrared on two samples, each consisting of a single 30 nm InAs quantum well surrounded by thick GaSb barriers. The only intended difference between the samples is the interface bonding type, Ga–As bonds and In–Sb bonds. The CR for the sample with Ga–As interface bonds shows two lines whose positions are determined by nonparabolicity effects, whereas the sample with In–Sb bonds shows multiple lines due to strong cross-interface coupling between the InAs conduction band Landau levels (LLs) and the valence band LLs in GaSb. We find that the CR is a sensitive probe of interface bonding type for such structures. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 78.20.Ls; 78.66.−w

Keywords: Interface; InAs/GaSb; Hybridization; Cyclotron resonance

Heterostructures based on the InAs/GaSb materials system have been of considerable interest because of their Type II, broken gap band alignment. This gives rise to interesting and unusual electronic properties, such as hybridization of the conduction InAs and valence GaSb band states due to coupling across the interface [1–3] and spatial separation of electrons and holes. A number of unique devices have been conceived and produced based on these special properties, e.g., infrared detectors and lasers, resonant interband tunneling diodes, and high-electron mobility transistors [4,5]. Recently, additional interest in this system has derived from its possible spintronics and spin-photonics applications [6]. One of the most appealing features of the InAs/GaSb heterojunction in this context is its ability to support coherent interband tunneling from the GaSb valence band (VB) to the InAs conduction band (CB), and vice versa, in this way transferring the hole transport in GaSb (which can be made ferromagnetic [7,8]) to electron transport in InAs. A novel spin device based on this system is the ferromagnetic resonant interband tunneling diode [9].

Because the InAs/GaSb heterojunction has no common atoms, two types of interfaces can be formed, Ga–As bonds or In–Sb bonds. Given the large difference between the band gap and other bulk physical

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PII: S1386-9477(01)00516-1

properties of InSb and GaAs, one expects that the electronic features of InAs/GaSb heterostructures will be very sensitive to the interface bonding type, and this is supported by theoretical work [10].

Several experiments also have explored the influence of the interface formation on quantities such as the VB offset, electron and hole densities, and electron mobility [11,12]. The overlap integral between the wave functions for electronic states in the GaSb VB and electronic states in the InAs CB is very sensitive to interface effects, and therefore to interface bonding type. A measurable quantity, which depends quite strongly on this wave function overlap, is the hybridization minigap. In the present experiments we explore the effects of interface bonding type through detailed cyclotron resonance (CR) experimental studies of two InAs/GaSb single-quantum-well (QW) structures.

Due to the overlap between the bottom of the InAs CB and the top of the GaSb VB, there is a crossing of the unperturbed bands at some value of $\boldsymbol{k}$ in the heterostructure plane ($\boldsymbol{k}_{\|}$) as shown in Fig. 1(a). These bands are resonantly coupled near this value of $\boldsymbol{k}_{\|}$ through the $\boldsymbol{k} \cdot \boldsymbol{P}$ interaction, and this leads to significant hybridization of the InAs and GaSb electronic states and the opening of a minigap. A great deal of experimental and theoretical work has been done to study mixing of states and the minigap that opens due to level repulsion [1–3,13]. In the envelope function approximation the strength of coupling across the interface depends on the overlap integral between the InAs CB and the GaSb VB envelope functions perpendicular to the plane. A particularly useful theoretical approach is that described in Ref. [13], which relates directly the strength of coupling to the overlap integral.

A very rough qualitative impression for the effects of different interface bonding, i.e., Ga–As vs. In–Sb bonds, on the electronic states can be obtained by considering that the GaAs or InSb monolayers that comprise the interfaces that have the same properties and band alignments as the corresponding bulk materials [10]. The resulting band diagrams for both interfaces are shown in Fig. 2. (The light–hole $|\frac{3}{2}, \frac{1}{2}\rangle$ VB edge is drawn.) Here the effects of strain (matching to GaSb) on the interface and InAs band edges have been taken into account using the model solid theory of Van de Walle [14]. From these diagrams it is seen that one

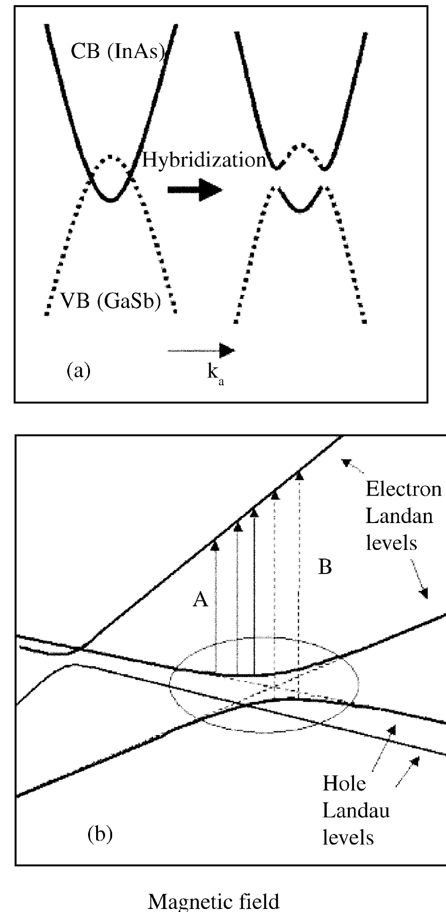

Fig. 1. (a) Schematic diagram of the hybridization effect as function of $\boldsymbol{k}$ in the plane ($\boldsymbol{k}_{\|}$); (b) schematic diagram of conduction–valence band LL mixing effect for e2 and hh2 subbands showing how CR transitions relate to the hybridization gap at the magnetic field of measurement.

expects a larger overlap integral for In–Sb interface bonds than for Ga–As interface bonds, and thus a larger degree of hybridization for the former case.

Two InAs/GaSb samples grown by MBE were studied. Both samples consist of a single 30 nm InAs quantum well surrounded by GaSb barriers of 100 and 2000 nm grown on GaAs. The only intended difference between the samples is the interface bonding between the InAs wells and the GaSb barriers, which was controlled during growth: Ga–As bonds (sample 1) and In–Sb bonds (sample 2). Extensive X-ray diffraction and Raman scattering measurements were

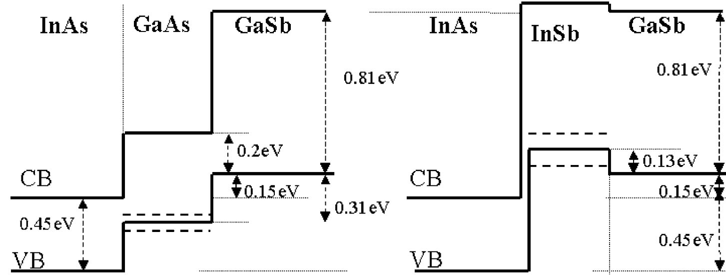

Fig. 2. Bandedge alignment diagram for InAs/GaSb heterointerfaces with Ga–As interface bonds (left) and In–Sb interface bonds (right). Strain has been taken into account in determining the offsets and gaps as discussed in the text. The light–hole valence band edge is shown.

employed to develop the growth procedures used to control the interface type [15,16]. Migration enhanced epitaxy was found to be the most effective method to control the interface type and was employed for the growth of the samples in this study [15].

We performed far-infrared (FIR) CR measurements on these samples with a BOMEM FTIR spectrometer and an Apollo submillimeter laser in conjunction with a Ge:Ga photoconductive detector and light–pipe/condensing cone optics. Shubnikov–deHaas measurements were also carried out on these two samples at 4.2 K in magnetic fields up to 15 T to determine carrier densities and subband occupancy.

In Fig. 3 we show the CR results for both samples. The CR spectra for sample 1 (Ga–As bonds) are mostly governed by nonparabolicity effects at the Fermi energy for the two occupied conduction subbands in the InAs well. The two lines observed at high fields are attributed to Landau transitions from the highest occupied Landau level (LLs) to the next unoccupied LL for these two subbands. The difference in the CR energy is due to nonparabolicity and the difference in energy between the Fermi level and the bottom of the InAs conduction band for the self-consistent potential at the position of maximum probability density for the two subbands. Spin splitting is not resolved. The higher energy points correspond to CR from the lowest subband, which has the smallest nonparabolicity effects at the Fermi energy. These transitions show oscillations in line width and amplitude, which are related to the relatively weak hybridization, and concomitant weak, unresolved, anti-level crossings, compared to the larger effects discussed below.

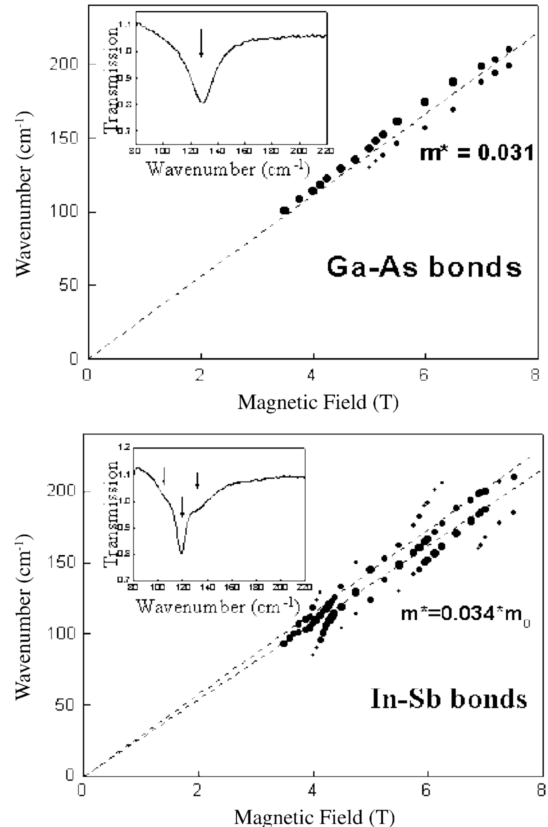

Fig. 3. Cyclotron resonance spectra for the two samples. Upper panel: summary plot of the CR positions vs. magnetic field for the sample with GaAs interface bonds; inset, transmission spectrum at 4.5 T. Lower panel: summary plot of the CR positions for the sample with InSb interface bonds; inset, transmission spectrum at 4.5 T.

The CR for sample 2 (InSb bonds) shown in the lower panel of Fig. 3, exhibits a much more complex behavior. There are multiple "CR" lines, with strong curvature in the field dependence (both positive and negative), away from the "average" CR positions (shown by the dashed lines). These absorption peaks decrease rapidly in strength as they diverge from the average CR position, both above and below. These results are consistent with strong conduction-to-valence-band LL mixing across the interface in sample 2 (the magnetic field analog of the hybridization shown schematically in Fig. 1(a). Indications of this have been seen by others [1,2]. The electron densities of the two samples were determined independently from Shubinkov de Haas measurements and from integrated absorption away from the region of strong LL coupling. The two methods yield densities that are in reasonable agreement. The results are: $1.15\times10^{12}\,e/cm^2$ for sample 1 and $1.34\times10^{12}\,e/cm^2$ for sample 2, and when combined with self-consistent calculations for these structures confirm that two subbands are occupied in the InAs quantum wells. The electron mobility in sample 1 is lower than that for sample 2 (40, 000 and $75,000\,cm^2\,V^{-1}\,s^{-1}$, respectively).

The fact that two bands are occupied in the InAs well brings an additional complexity to the interpretation of these experiments. However, the following picture provides a reasonable account of the results.

The CR lines, whose field dependencies exhibit positive and negative curvature between 3.7–4.5 T in Fig. 3 (lower panel), correspond to transitions from hybridized states like A and B in Fig. 1(b). The strongest anti-level crossing should occur at the field position for which LLs from electron subband 2 (e2) in InAs cross appropriate LLs from heavy hole subband 2 (hh2) in GaSb. The envelope functions for these subbands along the growth direction are more extended than those for e1 (InAs) and hh1 (GaSb), and hence the overlap integral is expected to be larger. We find that the observed line-splitting in Fig. 3 corresponds to a magnetic minigap of 4.1 meV.

In summary, the CR data for an InAs/GaSb QW structure having In–Sb interface bonds is very different from the CR from a nominally identical sample having Ga–As interface bonds. The conduction–valence-band LL mixing or hybridization due to coupling across the spatial interface is stronger for the sample with In–Sb bonds than for the sample with Ga–As bonds. This is consistent with the well (barrier)-like VB profile at the interface for the former (latter) case, which promotes (inhibits) wave function overlap.

This work is partially supported by the Office of Naval Research.

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