PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN 49 (1980) SUPPL. A p. 1009-1012

ELECTROREFLECTANCE STUDY OF SEMICONDUCTOR SUPERLATTICES

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The band structure of $In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ superlattices has been investigated by means of the electroreflectance technique. We have observed transitions associated with E_1 and $E_1 + \Delta_1$. For $x=y \leq 0.2$ the spectral structures occur at energies in good agreement with the corresponding transitions of the host semiconductors. On the other hand, for $x=y > 0.2$ the structures shift, for some compositions, by as much as 0.3eV with respect to those of the hosts.

I. Introduction

Experimental studies in semiconductor superlattices of both GaAs-GaAlAs and InGaAs-GaSbAs have hitherto been confined to the subband structure at the center of the Brillouin zone. The question as to the general effect of the periodic potential on the band structure of superlattices remains unanswered. This paper reports the results of the first experimental investigation of optical transitions at points away from the zone center in both GaAs-GaAlAs and InGaAs-GaSbAs superlattices by the use of the electrolyte electroreflectance (EER) technique. In this article we will emphasize our work on the latter materials; the detailed results for GaAs-GaAlAs will be given elsewhere [1].

The GaAs-GaAlAs system is such that the conduction and valence bandedges of GaAs are higher in energy than the valence bandedge of GaAlAs but lower than its conduction bandedge. As a consequence, the GaAs layers serve as potential wells for both electrons and holes. On the other hand, in InGaAs-GaSbAs the conduction and valence bandedge energies of InGaAs are lower than those of GaSbAs, respectively [2]. As a result, the InGaAs and GaSbAs layers serve as potential wells for electrons and holes, respectively. In $In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ superlattices having small x and y, the bottom of the conduction band of $In_{1-x}Ga_xAs$ is located very close to or even below ($x=y< 0.3$) the top of the valence band of $GaSb_{1-y}As_y$, giving rise to a strong interaction between the two bands. Such interaction is bound to generate a greater anomaly in the E-k relationship.

Sharp EER features were observed and interpreted in terms of the E_1 and $E_1 + \Delta_1$ transitions ($\Lambda_{3v} - \Lambda_{1c}$) of the superlattice host semiconductors [3]. The transitions ascribed to E_1 and $E_1 + \Delta_1$ for samples in most of the alloy range occur at significantly higher energies than their corresponding values in either of the host semiconductors, which shows evidence for the effect of the superlattice potential away from the zone center.

II. Experimental Results and Discussion

Periodic structures consisting of alternating layers of $In_{1-x}Ga_xAs$ and $GaSb_{1-y}As_y$ (x=y) were grown on (100) GaAs (for $x > 0.5$) or GaSb (for $x < 0.5$) substrates by molecular beam epitaxy, throughout the entire alloy composition. A typical structure consisted of 100 periods of 50Å($In_{1-x}Ga_xAs$)-50Å($GaSb_{1-y}As_y$). Both the thicknesses and the compositions were determined from the growth rates, calibrated previously by x-ray analyses. In addition, several InAs-GaSb superlattices were prepared with different layer thicknesses in the range 23Å-220Å.

The electroreflectance measurements were carried out at room temperature in the energy range 1-4eV, using a KCl aqueous electrolyte. A square-wave modulating voltage at 200Hz and a negative bias voltage relative to a platinum electrode was applied to the samples. The normalized spectra, $\Delta R/R$, were taken automatically using an experimental setup similar to that described previously [4].

Shown in the uppermost part of Fig. (1) is an EER spectrum of a 65Å(InAs)-80Å(GaSb) superlattice. Sharp structures are observed at around 2.1eV and 2.5eV with a weaker feature at 2.8eV. For comparison, EER spectra of bulk GaSb and InAs are shown in Fig. (1). It is clear that the first structure observed in the superlattice can be associated with the E_1 transition of GaSb and the third structure (2.8eV) with the $E_1 + \Delta_1$ transition of InAs. The structure at 2.5eV represents a mixture of E_1 (InAs) and $E_1 + \Delta_1$ (GaSb). Furthermore, when a lineshape calculation using the three-point method is performed [5] a very good agreement is found between the transition energies of the InAs-GaSb superlattice and the corresponding energies of the host semiconductors.

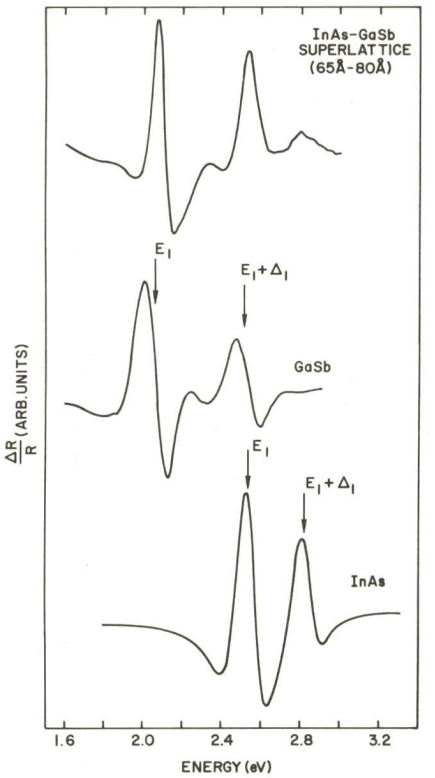

Fig. 1 Room-temperature electroreflectance spectra of InAs-GaSb superlattice and bulk GaSb and InAs

Six InAs-GaSb superlattices of different layer thickness, d, ranging between 23Å and 220Å have been studied. In all cases similar agreement was found between the positions of the superlattice EER structures and those of the host materials. The only difference among the spectra of those samples was that the intensity of the 2.8eV structure relative to that of the 2.1eV structure decreased with increasing layer thickness and eventually disappeared for d = 220Å. This result is just a consequence of the small penetration depth of the light in this energy range and the fact that the uppermost layer of the InAs-GaSb superlattices was GaSb. For thick samples, the light only probes the first layer and thus no structure associated with InAs is observed. More significant is that even for samples with layer thickness as small as d = 23Å two distinct sets of structures are observed. This

observation is important because it shows that for superlattices with layers as thin as 4 GaSb lattice constants, the energy-band structure is directly related to that of the bulk host semiconductors and not similar to that of the corresponding random alloy. This result has a special significance in view of a recent controversy [6] about the validity of considering ultrathin heterostructures (layer thicknesses of the order of a few lattice constants) as new materials instead of random alloys with the same composition.

Figure (2) shows EER spectra of various 50Å($In_{1-x}Ga_xAs$) - 50Å($GaSb_{1-y}As_y$) alloy superlattices, together with the corresponding spectrum of a 65Å(InAs)-80Å(GaSb) superlattice. A trend is observed, with increasing values of x, from two sets (x=0) to one set of structures (x=0.81). For $x \leq 0.2$, the transition energies are in good agreement with those of the host semiconductors, but for $x > 0.2$ the transition energies are invariably higher than those corresponding to the hosts. The situation is shown in Fig. (3), where we depict the E_1 and $E_1 + \Delta_1$ transition energies of $In_{1-x}Ga_xAs$ (continuous line) and $GaSb_{1-y}As_y$ (discontinued line) which we measured independently throughout the entire alloy range of both ternary systems. Represented by closed circles in Fig. (3) are the transition energies of the superlattices with similar alloy composition. The dots connecting those circles were drawn based on the lineshapes of the observed spectral structures. As Fig. (3) shows, the upward shift in energy is clear, being greater than 0.3eV for some compositions. For values of x (or y) approaching unity this shift decreases and eventually would be zero for x=y=1 (GaAs).

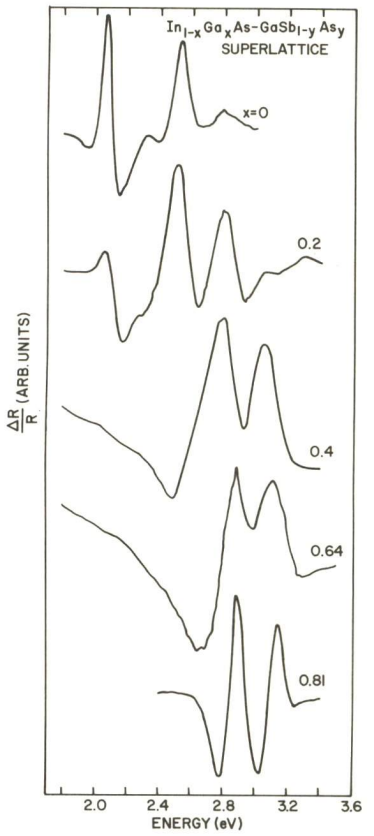

Fig. 2 Room-temperature electroreflectance spectra of various $In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ superlattices

The different behavior of $In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ superlattices for values of x below or above 0.2 is striking and its origin unknown to us. A Krönig-Penney model was unsuccessfully used, trying to explain the observed shifts. It is significant, however, that for $x \sim 0.3$ a cross-over occurs between the minimum of the conduction band of $In_{1-x}Ga_xAs$ and the maximum of the valence band of $GaSb_{1-y}As_y$. It is likely that the strong interaction arising from the cross-over affects dramatically the entire band structure of the superlattice, as our results suggest.

GaAs-$Ga_{1-x}Al_xAs$ superlattices with typically 50Å layer thickness were also studied throughout the entire composition range [1]. Two sets of structures associated with E_1 and $E_1 + \Delta_1$ of the corresponding host materials were observed. The transition energies associated with GaAs are monotonically shifted to higher energies with increasing values of x, the shift being ~ 0.1eV for the GaAs-AlAs superlattice. This shift can be explained with a Krönig-Penney model, when appropriate values for the barrier height and effective masses at the L point of the Brillouin zone are used. As a contrast, the shifts observed in

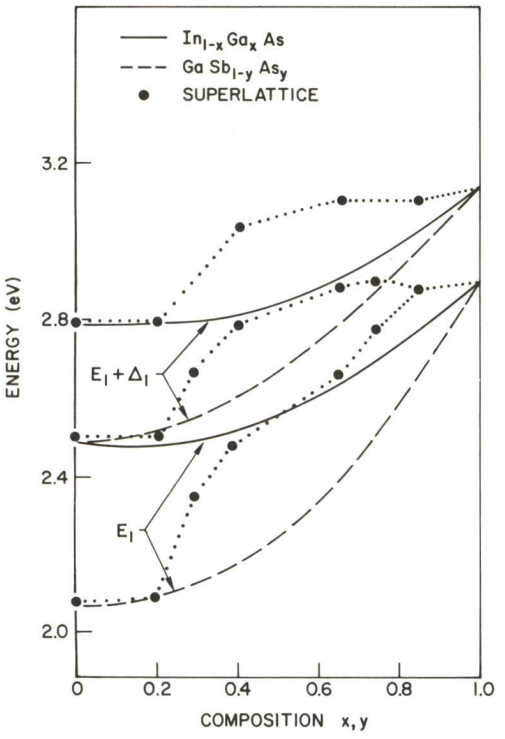

Fig. 3 Variation of the E_1 and $E_1 + \Delta_1$ transitions with composition for $In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ superlattices and for the $In_{1-x}Ga_xAs$ and $GaSb_{1-y}As_y$ systems

$In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ could not be explained on the basis of the Krönig-Penney model, indicating the difference in character of the periodic potential in the two types of superlattices.

In summary, we have given experimental evidence for the effect of the superlattice potential away from the Brillouin zone center in multilayer $In_{1-x}Ga_xAs$-$GaSb_{1-y}As_y$ and GaAs-$Ga_{1-x}Al_xAs$ heterostructures. We hope that these results will stimulate further theoretical calculations that may lead to a better understanding of the electronic band structure of semiconductor superlattices.

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