Optical absorption of biased semiconductor superlattices

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Abstract. We report the first experiment which relates electronic transport and intraband optical absorption in a biased superlattice. Wannier–Stark-ladders far in the continuum and strongly coupled by Zener resonances are observed in an n-type GaAs/AlGaAs superlattice using infrared spectroscopy. Additional transport measurements reveal the formation of electric-field domains, with electrons tunneling resonantly to the next-nearest superlattice period. A theoretical description of the optical data is presented and we are able to reproduce most of the important features in the experimental traces.

Introduction

The physics of semiconductor superlattices has been the subject of intense research, in particular in relation to phenomena as Wannier–Stark ladders. If an electric field is applied perpendicular to the layers of a periodic superlattice, the "minibands" are known to split up into a ladder of localized states [ ], the Wannier–Stark ladders (WSL). It was not only until recently that a simultaneous investigation of the transport and the intraband optical properties of a biased semiconductor has been performed by Helm *et al* [ ].

1   Experimental results

The superlattice (SL) studied consists of 300 periods of GaAs quantum wells (50 Å wide) and $Al_{0.29}Ga_{0.71}As$ barriers (81 Å wide). In this way the system has a rather narrow first subband ($\Delta_1 = 1.2$ meV), but a relatively wide first excited miniband ($\Delta_2 = 30$ meV) which is located in the continuum above the barriers.

Transport by tunneling

By applying an electric field, F, one can measure the current-response of this system (see Fig. 2 in Ref. [ ]). At low bias voltage (< 0.5 V) the conduction is ohmic and proceeds by ground-state to ground-state tunneling [ ]. At higher voltage the SL breaks up into a low-field and a high-field domain; in the latter electrons tunnel from the ground state in one well to an excited state in a subsequent well. Its extent increases with increasing bias, until the field distribution is again homogeneous and the current rises steeply. In the present SL this occurs at 27 V and the voltage drop per period is (27 V)/300 = 90 meV. Knowing that the energy difference between ground state and first excited state $E_2 - E_1 = 170$ meV $\approx$ 2×90 meV, we conclude that the electrons tunnel through 2 barriers (and one well).

Optical IR absorption

For the measurement of the IR absorption spectrum, the transmission change $T(F)/T(0)$ is measured by dividing the signal during a short electric-field pulse, $T(F)$, by the signal a few ten μs after the pulse, $T(0)$. This is shown in Fig. 1 for increasing voltage. Notice that minima correspond to absorption lines induced by the electric field. The positions of the maxima and minima hardly change, but grow in amplitude as the electric field increases.
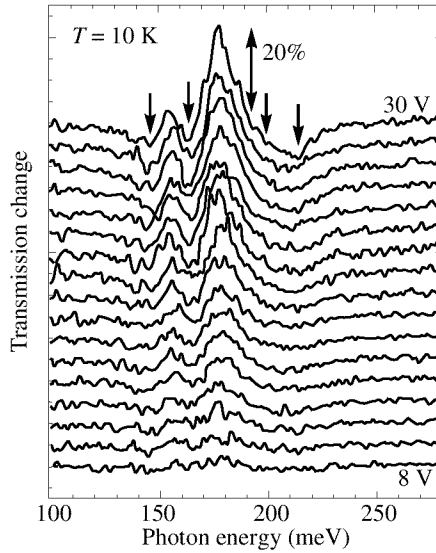
Fig. 1. Differential transmission spectrum $(T(F)/T(0))$ of the superlattice for a series of bias voltages between 8 and 30 V. Minima essentially correspond to electric-field-induced absorption lines.

2 Theoretical calculations

Experimental analysis

In order to obtain an understanding of the IR absorption experiments we have performed energy level calculations for a finite SL system. The results of such a calculation is shown in Fig. 2 together with an absorption spectrum for this system (left). The SL potential is shown in gray, the relevant wavefunctions $\psi_n(z)$ are shown with an offset equal to their energy E_n. The classification (m, p) of the energy levels is as follows: m $= 1, 2, \ldots$ is the (zero field) miniband index, and p $= \ldots, -1, 0, 1, \ldots$ is the spatial index relative to the central quantum well. Notice that only the ground states (1,p) are confined in the wells, all other levels are in the continuum. The main transitions (which are also visible experimentally) are, from low to high energies $(3, -1)$, $(2, 0)$ (main transition), $(4, -2)$ and $(3, 0)$. Besides the two direct transitions, we also observe indirect transitions up to the next-nearest downhill QW.

Biased finite superlattice systems

The effect of the electric field on the energy levels of the SL can be shown by taking a SL with a finite number, N, of quantum wells and plotting the energy for the 3 lowest minibands. This is shown in Fig. 3 for $N = 9$. In this calculation we have taken the experimental parameters for the well width (50 Å), the barrier width (81 Å) and the well depth (232 meV). With these parameters the important features of a finite biased SL are clearly visible. Fig. 3(a) shows the behaviour of all the energy levels in the 3 lowest minibands as the field increases. At an electric field $F = 0$ we show 3 minibands (with band widths: $\Delta_1 = 1.84$ meV, $\Delta_2 = 31.8$ meV and $\Delta_3 = 77$ meV) and there are two degenerate states at 280 meV and 396 meV. These states are the so-called edge states and are intrinsic to a finite system. Notice that the energy of the edge states do not cross the SL
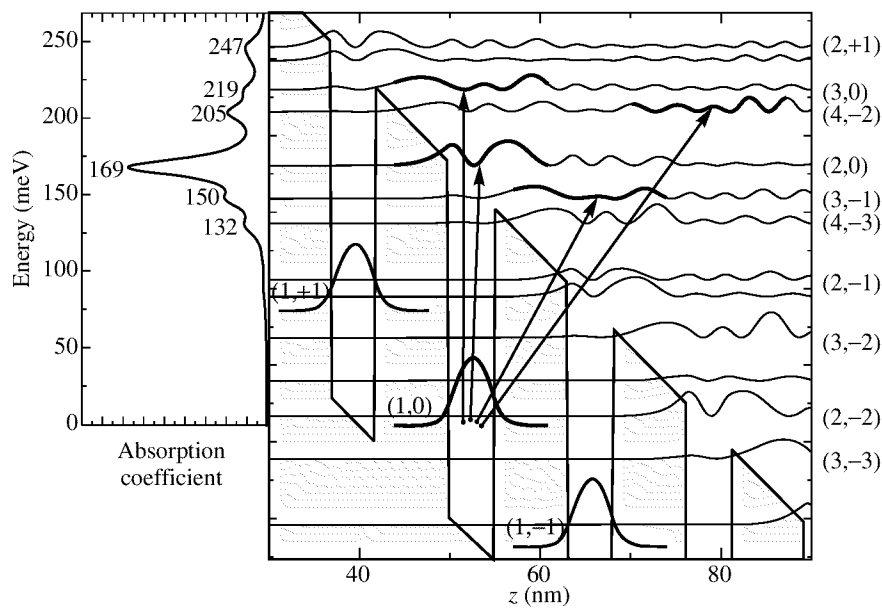
Fig. 2. Conduction profile, energy levels and electron distributions for four superlattice periods with an electric field of 60 kV/cm. The experimental observed transitions are indicated by arrows. The calculated absorption coefficient is shown on the left.
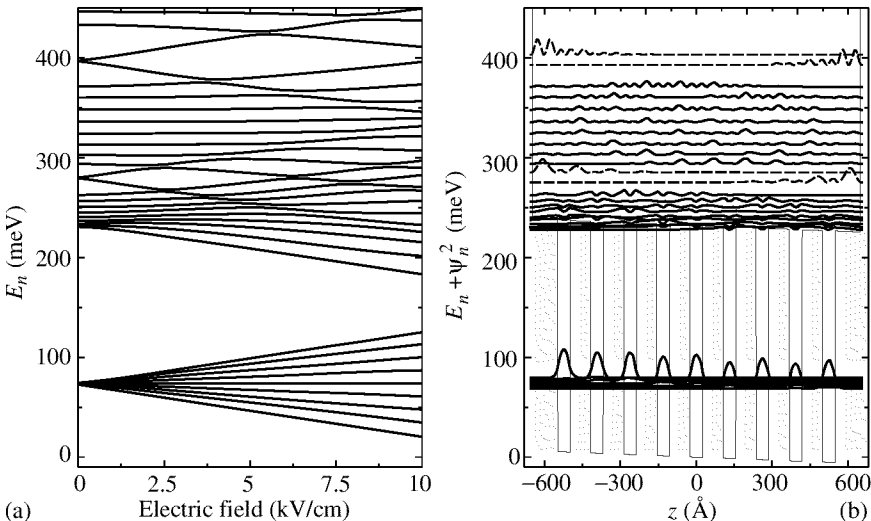

Fig. 3. (a) Energy bands split up into a ladder of localized states. The system investigated is a GaAs/AlGaAs superlattice with well width = 50 Å, barrier width = 81 Å and well depth = 232 meV. We see that each miniband contains about $N = 9$ states, and also observe some extra edge states (at zero field these are at 280 meV and 396 meV). (b) The electron distributions for all states in the 3 lowest minibands are shown at an electric field of 0.5 kV/cm. The edge states are depicted in dashed lines to show the difference with the SL-states (full). The SL potential is shown in gray.

levels, there is a clear anti-crossing. In Fig. 3(b) we have shown the electron distributions of all levels in the 3 lowest minibands at an electric field of 0.5 kV/cm. At this field, the edge states (dashed) can be well distinguished from the SL-states (full).

3   Conclusions

We have performed energy level calculations on biased finite SL systems which reveal the existence of minbands and edge states at zero field. Applying an electric field splits up the minibands in a ladder of localized states, the double degenerate edge states also split up and mix with the localized states without interfering them. By calculating absorption spectra for a GaAs/AlGaAs superlattice we where able to explain the transmission spectra measured by Helm *et al.* [ ].

References

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