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ELECTRIC FIELD ENHANCEMENT OF OPTICAL ABSORPTION IN GaAs-AlAs TYPE-II SUPERLATTICES

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Abstract: The spatial separation of electrons and holes in GaAs/AlAs "indirect"-type superlattices is evidenced by the enhancement of optical transition probability under a longitudinal electric field.

The electronic properties of GaAs-AlAs short period superlattices (SL) have been recently investigated with renewed interest, due to the ability of such "new materials" to be used as pseudo-alloys instead of the disordered Ga_{1-x}Al_{x}As alloys. Special attention has been paid to the nature of the direct gap to indirect gap transition when the average Al concentration \( \bar{x} \) is increased. In the following, \( \bar{x} \) will be defined as \( L_{AlAs}/P \), where \( L_{AlAs} \) is the width of AlAs slabs and \( P \) is the period of the superlattice. It has been shown that such a transition occurs at \( \bar{x}=0.35 \) for very short periods, (say smaller than 4 nm), and when \( L_{AlAs}<4 \) nm in larger period systems. These typical values are strongly related to the offset parameter \( \Delta E_{\Gamma}/\Delta E_{X}=0.67 \), which is the value obtained in Ref. 1.

For this value, the potential well for electronic states built from \( \Gamma \) extrema of the zincblende Brillouin zone is the AlAs layer while GaAs remains the potential well for holes. The system is thus a type-II superlattice, and the associated optical transitions are weak. However, since no-phonon transitions may be observed from \( \Gamma[001] \)-like conduction states, the related energy gap is referred to as "pseudo-direct". Let us keep in mind that the system built from \( X \)-like electronic states is the usual type-I structure in which electrons and holes are essentially located in the the same layer.

This paper presents a straightforward evidence for the spatial separation of particles in GaAs-AlAs "indirect", or "pseudo-direct" SL. Applying an electric field perpendicular to the layers, we expect the envelope functions of both electrons and
holes to be drawn to the same GaAs-AlAs interface, thus increasing their spatial overlap and the optical transition probability. It should be the opposite of the quantum confined Stark effect, well-established in GaAs/GaAlAs systems since the pioneer work of Mendez et al.\textsuperscript{5}

The studied structures have been grown by Molecular Beam Epitaxy and are described in Fig. 1. The 1 \(\mu\)m-thick superlattice of interest is not intentionally doped and inserted between a \(p^+\)-GaAs substrate and an undoped (slightly \(p\)) GaAs buffer layer in the one hand, and a 0.1\(\mu\)m-thick \(n^+\)-GaAs contact layer on the other hand. The latter is thin enough to permit optical transmission while being equipotential across the 10\(\mu\)m spacings of an evaporated metallic grid electrode. In such structures, a 1V reverse voltage corresponds typically to an applied electric field \(F=10\text{KV/cm}\).

Two different types of structures were grown, with period and average composition checked by X-ray simple and double diffraction. In the first one, the inserted SL is a direct type-I system with \(P=16.3\) nm and \(\mathcal{X}=0.51\). In the second one, it is a "pseudo-direct" type-II SL, with \(P=10.8\) nm and \(\mathcal{X}=0.77\). In both cases, periods have been chosen large enough to enhance the spatial localization of both carriers in their well layers.

At low temperature in the dark, our structures exhibit the rectifying \(I(V)\) profile of a classical \(p-i-n\) diode. The reverse current is typically 1 \(\mu\)A at \(V=10\) volts. Under illumination, it remains very weak up to a voltage threshold \(V_{\text{th}}\), depending upon the exciting wavelength. For example, when the excitation energy is slightly above the pseudo-direct gap of the type-II structures, the reverse photocurrent is negligible up to \(V_{\text{th}}=9\) Volts.

The low temperature photoluminescence (PL) spectra of the structures are those of good quality GaAs/AlAs SL, except for wide bands in the 1.4 - 1.5 eV energy range, which we attribute to the highly doped GaAs layers. The type-I structure exhibits an intense, sharp line at 1.58 eV, which corresponds to the expected \(E_{1}-HH_{1}\) recombination in the 8 nm well. When applying an electric field, the PL intensity decreases and the line is shifted to lower energies (0.6 meV/V), as expected in type-I systems\textsuperscript{5}.

We now focus our attention on the type-II structure. The envelope function calculation of energy gaps\textsuperscript{1} was done. We obtain \(E_{c}^{}=1.88\text{eV}, \ E_{X}^{}=1.79\text{eV}\) and \(E_{\mathcal{X}}^{}=1.82\text{eV}\), respectively the direct gap related to \(\Gamma\) states, the pseudo-direct related to \(X\{-[001]\}\) states, and the indirect gap related to the other \(X\) minima. The PL spectrum
shows several lines around 1.7 eV which could be attributed to impurities or phonon-assisted recombinations, related to $E^*$ or $E'$. Due probably to long lifetimes, the PL spectrum shape is very dependent on excitation intensity: it is broadened for pump density typically higher than 100 W/cm². The PL excitation spectrum indicates the absorption threshold related to $E^*$ at 1.88 eV. For excitation energies $h\nu$ situated between $E^*$ and $E'$, the global radiative efficiency is 3 orders of magnitude smaller than for $h\nu>E^*$. Presenting our first results, we restrict ourselves to the following conditions: particles are created in well-confined states ($h\nu<E^*$), transport through the layers is negligible ($V<V_{th}$) and the PL spectrum is clearly structured (low excitation density). As shown in Fig.2, the PL spectrum is significantly changed under electric field. A new line arises at 1.78 eV, very close to the calculated $E^*$ energy, while the former PL lines vanish. Moreover, the new line shifts towards high energies ($2$ meV/V).

We suggest we observe the increasing probability of type-II excitons radiative recombination, with respect to phonon-assisted recombination or impurity trapping. These excitons may be trapped on interface fluctuations, as suggested by the structures appearing on the new line.

On the other hand, the total PL intensity increases under electric field, due to both absorption of exciting light and emission enhancement. In Fig.2, a factor $=3$ is observed at $V=6$ volts. But the effect becomes huge for $V>V_{th}$, since we measured an increase by a factor up to 50 at $V=12$ volts. However, in these conditions, the photocurrent becomes non negligible, and the PL spectrum is broadened, which intricates the physical situation. Complementary experiments are required, to separate the increase of the optical matrix element from population effects in various excitation and voltage conditions.

The high energy shift of the new line with increasing electric field forms a matter of additional evidence for spatial separation of electrons and holes: contrasting with the situation in type-I systems, the main effect of the field is to increase linearly the difference of potential energy between the center of two adjacent layers: $s=e.F.P/2$ (see Fig.3). It prevails (with opposite sign) over the decrease of particle confinement energy and the increase of exciton binding energy.
An attempt to evaluate the overlap of electron and hole wavefunctions has been done following the variational approach of Bastard et al.\textsuperscript{4} The calculated squared overlap increases linearly with the field and is doubled at $F=100$ kV/cm. This calculation, which does not include the enhancement of excitonic oscillator strength due to the field, seems to underestimate the effect for $V<V_{nn}$ and is probably inadequate at higher voltages.

Figure 3: Schematic band diagram of a type-II superlattice, tilted by an electric field (to scale except the band gap energy). Calculated envelope functions show that Stark shift mainly affects X-like electrons. The main energy change is due to $E$.

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References:


for more recent theoretical works, see for example:


for an example of recent work in this rapidly developing subject, see:
