Stark-Wannier States in Nanostructures

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We study tlie effects of a longitudinal-external-electric field on tlie electronic properties of a multiple open-quantum-dot structure. The transmission coefficients between two quasi-two dimensional reservoirs through tlie structure are calculated. This structure presents the forination of two different gaps, oiie associated with tlie periodicity of tlie structure imposed upon the 1D mode aiid tlie other associated to the destructive interference between tlie 1D band and the quantum-dot states band. Tlie electric field localizes the levels into Wannier-Stark states. Tlie iiiterplay between tlie 1D mode and tlie Starli ladder formed by the dot levels is discussed.

I. Introdu:tion

Mesoscopic systems have been intensively studied in tlie recent years[1]. With tlie improvement of nano-scale fabrication :echniques, it has been possible to design a whole new kind of structures based on tlie high-mobility two-dimensional (2D) electron gas formed iii GaAs-(Ga,Al)As heterojunctions. The physics behind these systems is b ised on tlie lateral confinement whicli binds the carriers in one or two additional dimensions besides the epitaxial one. Recently, the interplay between oiie- and zero-dimensional levels lias been considered. Particularly, an open-quantum-dot superlattice was built and transmission gaps were observed[2]. The existence of carrier confinement in open cavities is well known since the wcrks by Schult et al[3], van der Marel[4] and Peeters[5]. Ulloa et al.[6] discussecl tlie effects of a periodic quanium-dot structure superimposed on a. one-dimensional channel. Brum[7] discussed the effects of the interplay between tlie cavity confined states and the superlattice states. More reccntly, other structures based on the same principles have been considered[8,9]. The effects of a longitudinal-external-electric field, F, in a single constriction and quantum chains, have been studied by Castaño et. al.[10]. Their emphasis was on the nonlinees transport characteristics in these nanostructures.

An electric field superimposed on a periodic potential leads to the replacement of the band structure by a. ladder of spatially localized states, Wannier-Stark states (WSS), equally spaced in energy by eFd, where d is the periodicity of the structure[11]. Their observation in bulk crystals has been a matter of controversy[12]. With the advent of the artificial semiconductor structures, it has been possible to observe these states[13] and recently, tliey have been observed in one-dimensional semicoiiductor superlattices[14,15]. The coupling among WSS originated from different subbands has also been considered[16,17].

In this work, we discuss the effects of an external electric field applied along an asymmetric-multiple-open-quantum-dot structure (AMOQDS) and uur main interest is on their electronic properties. They will be probed by the transmission coefficient through the structure enclosed by two quasi-two-dimensional reservoirs. Our structure is similar to the one discussed previously by one of us[7] and the one studied by Kouwenhoven et al.[2]. A laterally patterned GaAs/(Ga,Al)As heterojunction is considered. We assume a strong confinement along the z-direction so that the system is in the Electric Quantum Limit with respect to quantization of motion in this direction. The lateral confinement is sketched in Fig. 1. Two structures are studied: One with a single quantum dot and the other with three quantum dots. We perform a multi-mode transmission calculation following the same method as in previous work[7,12]. We approximate tlie electric field effects by considering only the potential drop from one layer respective to the other. Inside each layer, a flat band is assumed (see Fig. 2). Our calculations for a large number of dots have shown that three dots are already enough to reflect the main superlattice effiects. Basically, the structures are formed by periodic indentations superimposed oii one side of a one-dimensional (1D) channel. The carriers are assumed to be ballistic. They are linked to tlie two wide regions which behave as quasi-two dimensional reservoirs. The indentations give origin to a zero-dimensional confinement potential. At least one zero-dimensional state is energetically below the first 1D mode. Tlie higher dot states will then be resonances in thc 1D modes.

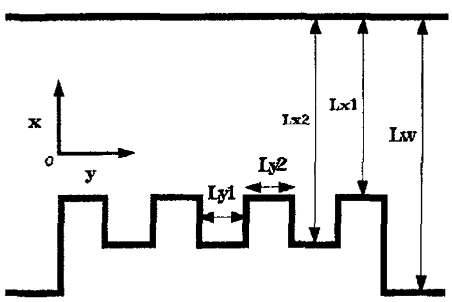


Figure 1: Top view of the potential of thc asymmetric-open-quantum-dot structure.

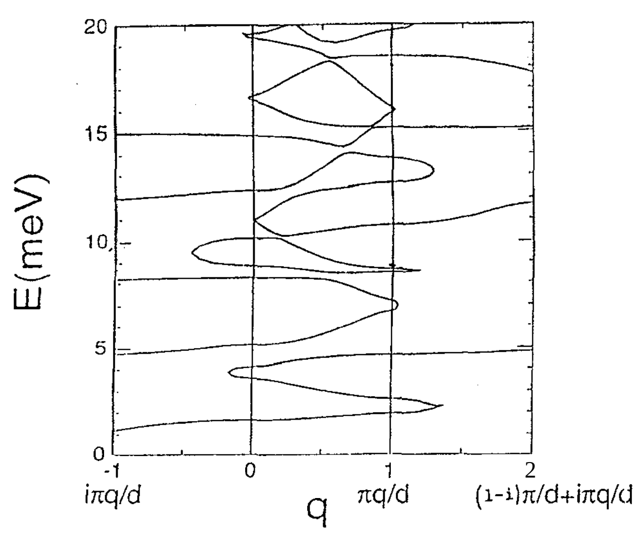


Figure 2: Scheme of tlie energy profiles of tlie striicture of Fig. 1 under a longitudinal electric field.

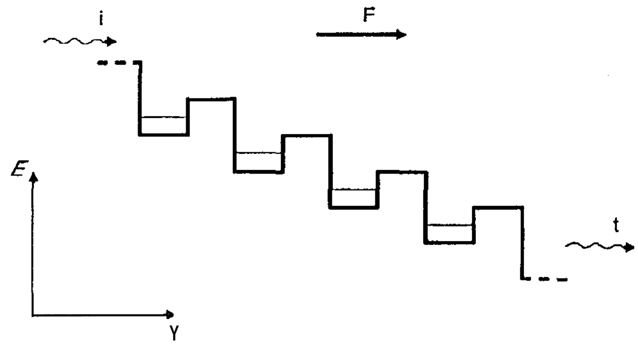


Figure 3: Miniband dispersion for tlie structure of Fig. 1.

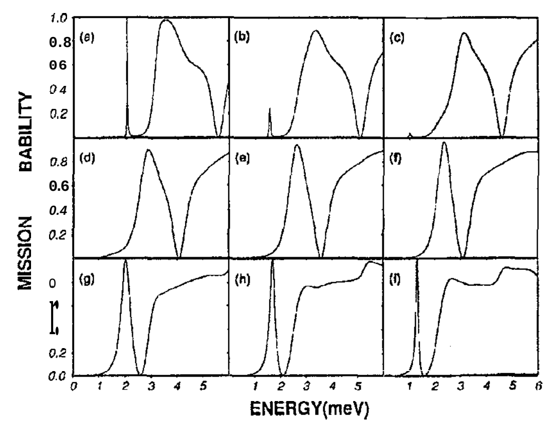


Figure 4: Transmission probabilities for an one-asymmetric-open-quantum dot structure as a function of the incoming energg. $L_w = 4000$ Å, $L_{y1} = L_{y2} = 500$ Å, $L_{x1} = 500$ Å, $L_{x2} = 800$ Å. a) F = 0 kV/cm; b) F = 0.067 kV/cm; c) F = 0.134 kV/cm; d) F = 0.2 kV/cm; e) F = 0.267 kV/cm; f) F = 0.334 kV/cm; g) F = 0.4 kV/cm; h) F = 0.467 kV/cm and i) F = 0.534 kV/cm.

Basically, the one-dot structure can be viewed as a wide 1D band, the 1D mode, with a ground-OD state at energy below the 1D band and excited OD states degenerated and coupled to the 1D band. The former gives a peak in the transmission, as it is expected in resonant tunneling. The later states give origin to a situation typical of Fano resonances[18] with a dip associated to the peak due to the localized state. In tlie transmission coefficients, however, whenever the 1D mode is fully open for transmission, the peak associated with the OD state disappears and only the dip is present.[8] This is associated with the strong anti-resonance present in the transmission coefficients.

For the three-dots structure, in spite of the limited number of dots, the results show aspects of a finite superlattice. The wide 1D band folds into the new

Brillouin zone, introduced by the periodicity. Tlie OD states give origin to narrow bands. Tlie folded bands are still wice in comparison to tlie bands formed by tlie OD stat s. These two set of bands are intrinsically coupled. When the narrow band is degenerated with tlie wide band, tliey actually anti-cross. As a consequence of the anti-crossing, a gap in tlie band structure is opened and tlie transmission falls to zero in this region. In our case, the anti-crossing coming from tlie coupling is arger than the band width of tlie narroiv bands. Therefore, tlie transmission does not reaches values above one. Additionally to the transmission gaps due to tlie anti-crossings, we observe the gaps associated to tlie periodicity imposed upon tlie 1D mode, as it should be expected.

Tliis is ivell illustrated in Fig. 3, where tlie miniband dispersion is plotted. The imaginary-q part of the dispersion is also described. The two gaps sliow a qualitativ difference in respect to tlie imaginary-q dispersion. The bands originated from the folding of tlie 1D band are connected at imaginary values of q. The bands separated by tlie anti- crossing due to tlie coupling of the narrow and wide bands do not connect at finite values of q. This is expected since the gap is originated from the anti-crossing between the localized and extended states.

The transmission probabilities, in tlie absence of electric field, are shown in Figs. 4 (a) and 6 (a) for tlie one and tliree dots structures. At energies below the first-1D mode, we observe tlie peaks with unitary transmission associated to the ground-OD levels. At energies above the first- 1D mode, transmission gaps are superimposed on the step quantization of tlie transmission. The cliaracter of tlie gaps is well illustrated with tlie wave-functions. Fig. 5(a) shows tlie wave-function probabilities for a one-open- quantum-dot for an energy at the second transmission maximum in the absence of electric field. Fig. 7(a) shows tlie wave-function probability for a three-open-quantum-dot structure, for an energy at tlie third peak of the first transmission band maximum, in the absence of the electric field. Fig. 5(a) shows maxima of probability of finding the electron at the narrow constrictions characterizing the states as 1D mode-like. On the other hand, the third peak of the first transmission band maximum, Fig. 7(a), shows the maximum of tlie wave-function probability at the wide constriction, i.e., at the quantum dots.

Figs. 4 (a-i) shows the transmission probability for tlie one-dot case as a function of the electron incoming energy for several values of electric field. At weak electric fields, we clearly observe a linear shift in energy of the first transmission peak. This peak is associated with tlie tunneling through the fundamental quantum dot state below the first 1D mode. The anti-resonance gap, associated to the second dot state, shows an identical shift, as it is expected. For the same range of electric field, the transmission maxima fall to values lower than one. This is a consequence of the break of symmetry in the barriers through which the electron has to tunnel[19]. As the electric field increases, the first peak is suppressed since it shifted to energy values below the emitter minimum.

At intermediate fields, we observe the evolution of tlie transmission band towards a sharp peak. Originally, this band is associated with the first 1D mode. With tlie electric field, the first 1D mode hybridizes with tlie dot state giving origin to a sharp transmission. Again, the level is an extended state and the transmission reaches the unitary value. This is illustrated in Figs. (5a) and 5(b) where the wave-function probability for the second transmission maximum is plotted for zero electric field and for F=0.53 kV/cm. We clearly observe its evolution from a 1D mode toward a 1D-OD hybrid state.

For tlie three dots structure, the electric-field effects

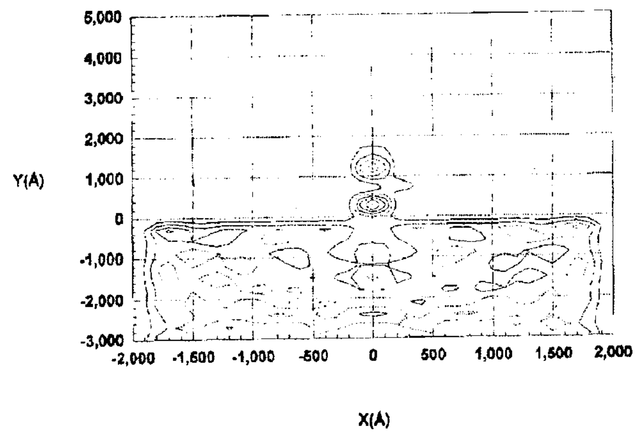


Figure 5a: upper panel

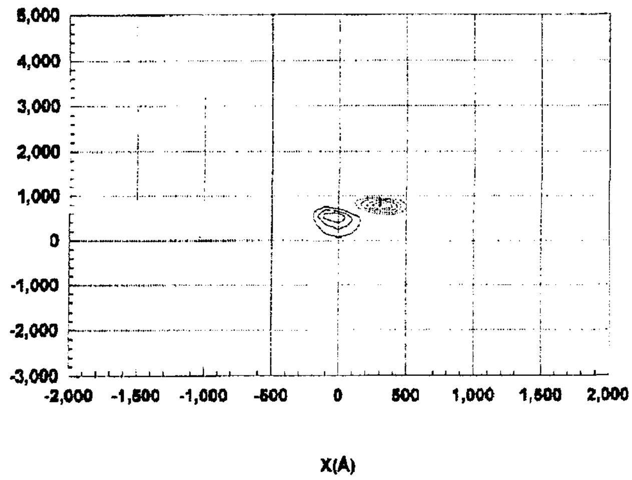


Figure 5b: upper panel

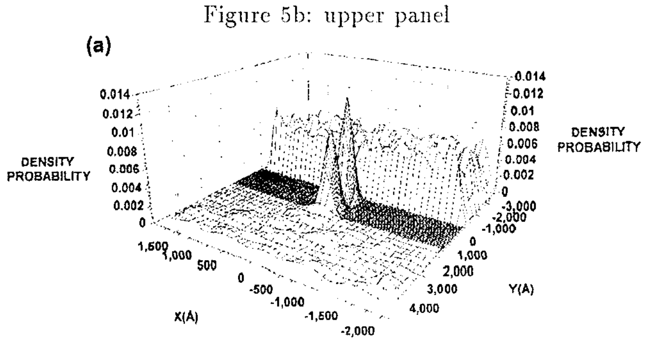
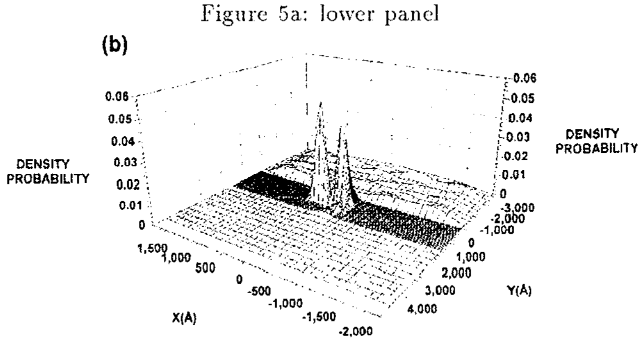
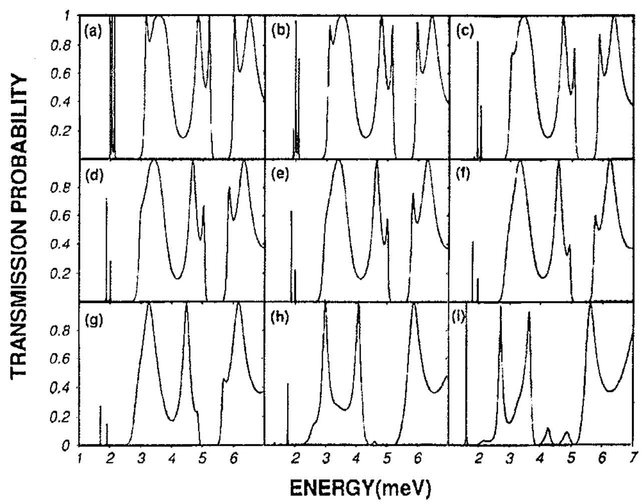


Figure 5a: lower panel



Figiire 5b: lower panel

Figure 5: Wave-function probabilities (upper panel: 3D plot; lower panel: 2D projection) for the same structure as Figure 2 for a) F=0 kV/cm, E = 3.6 meV; b) F = 0.534 kV/cm and E = 1.3 meV.



Figiire 6: Transmission probabilities for a three-asymmetric-open-quantum dot structure as a function of tlie incoming energy. a) F = 0 kV/cm; b) F = 0.004 kV/cm; c) F = 0.008 kV/cm; d) F = 0.01 kV/cm; e) F = 0.012 kV/cm; f) F = 0.016 kV/cm; g) F = 0.02 kV/cm; h) F = 0.04 kV/cm and i) F = 0.06 kV/cm. The other parameters are the same as in Fig. 2.

can be analyzed in terms of the different kinds of bands. The continuous band is replaced by a ladder of bound levels evenly spaced by eFd. Tlie localization of the states goes with eFd 4, where 4 is the band width. As me increase tlie electric field, the narrow band break immediately into the Stark ladder. The energy difference among the levels increases linearly with the field and the wave-function localizes in the dot. On the other hand, for the wide bands, at sizable electric fields, the states remain extended over a large number of wells. Tlie description of a continuous band, or an open 1D mode, is still valid. The coupling of these two bands gives a new behavior in the Stark laclder effects.

Fig. 6 (a-i) shows the three-dots' structure transmission probability as a function of the electron incoming energy for several electric fields. The first series of maxima in the transmission are associated to the narrow band formed by the confined-fundamental-dot states. The second transmission band is associatecl with tlie 1D mode. After that, we observe a strong reduction in the transmission probability which is related to the gap forined by tlie periodicity of the structure. The next gap is due to the anti-crossing between the 1D

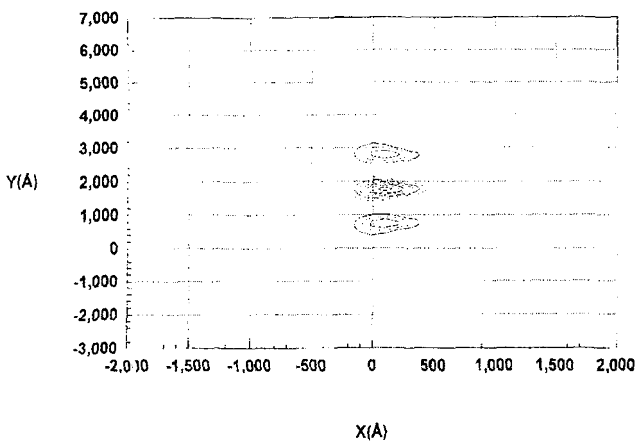


Figure 7a: lower panel

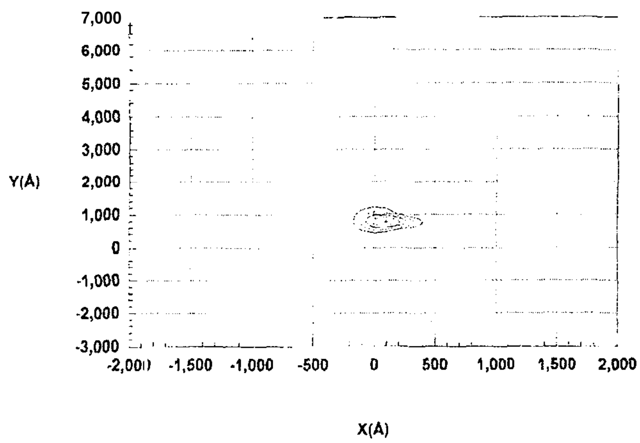


Figure 7b: lorver panel

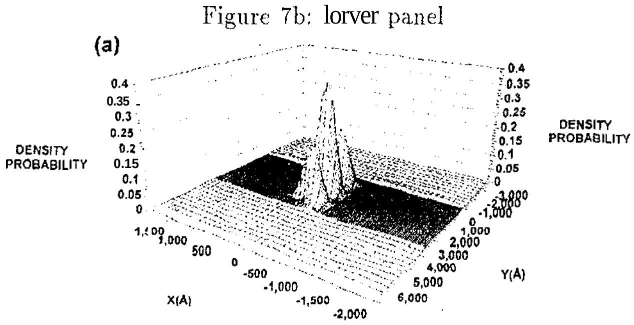


Figure 7a: upper panel

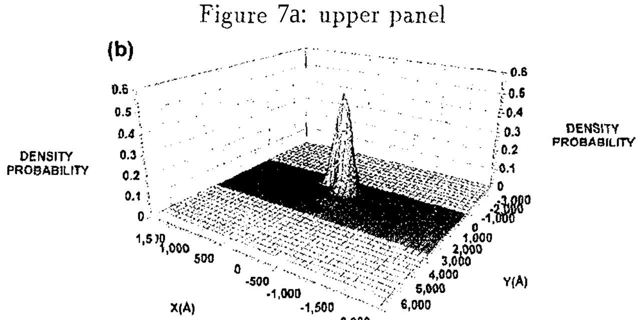


Figure 7b: upper panel

Figure 7: Wave-function probabilities (upper panel: 3D plot; lower panel: 2D projection) for the same structure as Fig. 6 for a) F = 0 kV/cm, E = 2.1 meV, b) F = 0.06 kV/cm and E = 1.6 meV.

mode and the dot bands. This gap is strongly marked even for a small number of periods[7] as a consequence of the behavior of band dispersion at the anti-crossing for imaginary values of q.

At weak electric fields, the first band shows a similar behavior as the single dot case: a linear energy sliift is observed accompanied by the fall of the transmission probability. At higher electric fields ($F > 0.02$ kV/cm) tlie trasmission peaks again for a single level, reaching tlie unitary value for the level associated to the first dot. The other levels have practically disappeared. This is easily understood in terms of the symmetry of the effective barriers through which the state has to tunnel. At very weak fields, the degeneracy among the dot states is already broken, the state which localizes in the first dot sees an effective barrier on the left whicli is narrower than the effective barrier on the right. The latter is formed by three narrow constrictions and tiro wide constrictions wliile the former is just one narrow constriction. As a consequence of the asymmetry, the transmission peak is below one[19]. As the field increases, the right effective barrier decreases. At a precise value of the electric field, the two effective barriers are equal and we have a symmetric tunneling, recovering the unitary transmission. As we further increase the field, tlie right effective barrier becomes narrower than the left one and the tunneling is again through asymmetric effective barriers. The transmission peak falls again below one.

The other bands have a different behavior as a consequeiice of tlie ivide band width. The states remain delocalized along the whole structure for most of the fields considered here. As a consequence, the one 1D mode is fully open for transmission and its value remains equal to one. Only at higher fields, as the states start to localize, the transmission begins to fall to lower values. This behavior gives a measure of the localization of the wave-function in the structure. For larger structures, that is, a larger number of periods, the transmission falls to values below one for lower values of the electric field. This is expected since to have the 1D mode opened means that the wave-function has to be delocalized along a larger number of periods.

The narrow band, which is degenerated with tlie 1D mode, breaks into the Stark ladder for very weak electric fields. For a range of values of the electric field, we have the coexistence of WSS coupled to a 1D band. As for the zero field case, the localized states open an anti-resonance gap. If the energy separation among the WSS is smaller than the coupling among them and the extended state, the transmission remains equal to zero and the gap increases slightly with the electric field. However, when tlie energy separation among the WSS is of the order of the coupling, then some transmission is possible between tlie states. This is well illustrated in Figs. 6 (a-i) by the evolution of the transmission with the electric field. The transmission correspondent to the 1D band remains equal to one except for tlie last value of electric field considered. At the same time, the anti-resonance gap is always present, increasing with the field up to values foi. which the Stark ladder splitting is of the order of the coupling and the gap is destroyed. This happens for fields around 0.06 kV/cm which corresponds to a splitting of 0.6 meV. This value is of tlie order of the coupling as it can be estimated from Fig. 4 (a) by the width at half height *of* the anti-resonance gap.

A direct observation of the above effects depends on several additional effects. Conductance measurements have been one of the most powerful experimental tools to probe similar effects[1,2]. However, some aspects remain to be cleared: charge effccts. sucli as Coulomb blockade, may hamper their observation foi the state-of-art of the niesoscopic systems. Another difficulty is in the connection among transmission probabilities and conductance measurements, particularly in the presence of nonlinear effects. A complete solution of the transport problem in these systems is beyond the scope of this work. Nevertheless, we believe that tlie effects discussed here should be reflected in the electronic properties of actual systems and should be considered whenever confined cavity states are coupled to 1D modes.

Acknowledgments

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