Wannier–Stark localization in asymmetric double-well superlattices

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The Wannier–Stark localization of miniband states has been investigated in an asymmetric double-well superlattice. The period consists of 3.4 and 2.0 nm GaAs quantum wells separated by 1.4 nm $Al_{0.15}Ga_{0.85}As$ barriers. Photocurrent spectra at 6 K reveal that the lowest excitonic peak near flat band splits up into eight peaks at moderate electric fields. At very high fields only one peak remains. The observed transitions are attributed to the Stark ladder splitting of the wide-well miniband only. This type of superlattice introduces a new degree of freedom for the tailoring of electro-optic devices. © *1996 American Institute of Physics.* [S0021-8979(96)05510-6]

An electric field induces dramatic effects on the electronic properties of semiconductor nanostructures, which have been used in many electro-optic devices.[1] In superlattices the field splits a miniband into a Stark ladder of levels, whose states localize at high fields in individual wells.[2–4] This effect, called Wannier–Stark localization, was predicted several decades ago for crystals, but was first observed in superlattices only some years ago.[5,6] Since then a great deal of work has been done on this subject,[4] using different materials, techniques, and field ranges. However, most of the investigations have dealt with the simplest possible superlattice, in which a period consists of only one well and one barrier.

The next logical step is to introduce more than one well within a period. Wannier–Stark localization has already been observed in symmetric double-well superlattices, where the period contains two identical wells separated by barriers of two different thickness. In this type of superlattice the Stark ladders of the symmetric and the antisymmetric minibands strongly interact.[7–9]

In this article we present the investigation of an asymmetric double-well superlattice [see Fig. 1(a)], in which the period consists of two wells of different thickness. The wide well contains only one confined electron state, whose energy is well below the narrow well level. We have observed the formation of a Stark ladder in the electron miniband originating from the wide-well states only.

The sample was a *p-i-n* diode structure grown by molecular beam epitaxy on a (001) n^+-doped GaAs substrate. The doped layers and the device fabrication have been described in detail elsewhere.[10] The intrinsic part consisted of the superlattice sandwiched by 35 nm GaAs layers. The superlattice had 55 periods formed by 3.4 and 2.0 nm GaAs wells separated by 1.4 nm $Al_{0.15}Ga_{0.85}As$ barriers, as sketched in Fig. 1. The electric field due to an externally applied voltage V is $\mathcal{E} \approx (V_{bi} - V)/W$, where V_{bi} is the built-in voltage ($V_{bi} \approx 1.6$ V) and $W = 522.4$ nm is the total intrinsic layer width. In the experiments the device was illuminated with light from a Xe lamp mechanically chopped and filtered by a double monochromator. The photocurrent was detected on a single mesa with a lock-in amplifier.

Figure 2 shows the photocurrent spectra measured at 6 K for selected values of the applied voltage. Near flat band the spectrum contains a sharp excitonic feature at 1.6109 eV and a much broader feature at 1.702 eV. At a finite electric field a number of peaks emerge from the peak at 1.6109 eV, their separation increasing with the field. Below −3 V all but the central peak (labeled 0) disappear. The behavior resembles very much the Wannier–Stark localization observed in su-

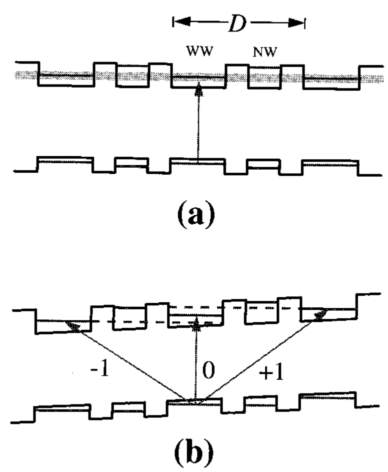

FIG. 1. Schematic potential profile for a GaAs/(Al,Ga)As asymmetric double-well superlattice. One period (length D) contains a wide well (WW) and a narrow well (NW). (a) Near flat band wide-well electron states couple to form a miniband (grey band in plot). (b) At some electric field the miniband splits into Stark ladder states. Wide-well heavy-hole excitonic transitions are shown by arrows.

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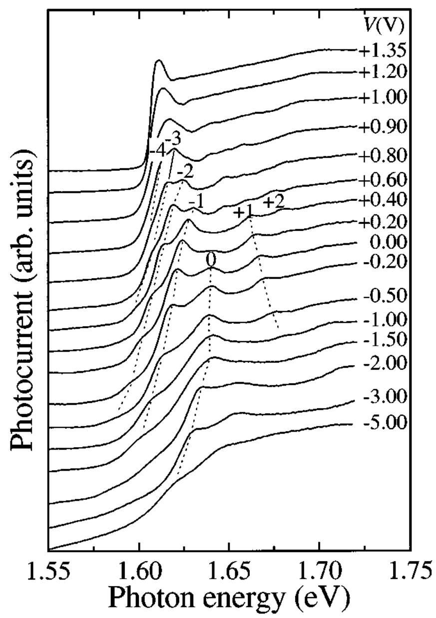

FIG. 2. Photocurrent spectra measured at 6 K for selected values of the applied voltage. Spectra have been offset vertically for clarity. Dotted lines are a guide to the eye. Labels represent the Stark-ladder transition index.

perlattices with a single well and barrier.[5,11] This similarity is even more apparent when the transition energies are plotted as a function of the applied voltage as shown in Fig. 3. The dots represent the transition energies obtained from the second numerical derivative of the photocurrent spectra. Their size scales roughly according to the strength of the transition.

We have calculated the miniband structure at zero electric field for the conduction and the valence bands using a modified Kronig–Penney model.[12] In the conduction band there is one miniband in the energy range (41.6, 107.7) meV above the conduction band edge of GaAs. We have also done

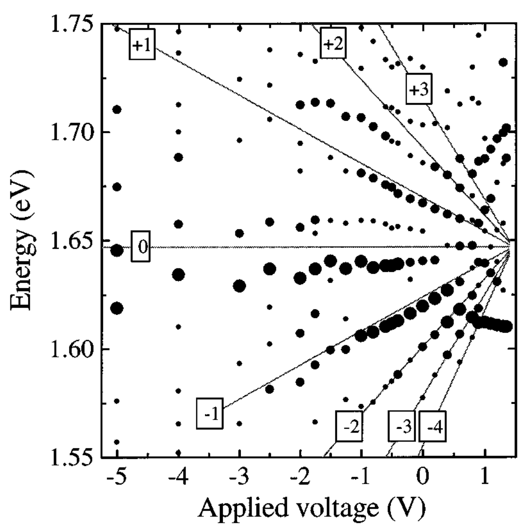

FIG. 3. Excitonic transition energies obtained from the second numerical derivative of the photocurrent spectra (black dots). Dot size is a measure of the transition strength. The solid lines indicate the transition energies for a superlattice formed only by the wide wells according to $E_p(\mathscr{E})=E_0+pe\mathscr{E}D$. The labels refer to the value of p.

the calculation for isolated individual wells and for an isolated complete period. In the first case the levels of the wide well and the narrow well are, respectively, at 79.3 and 104.5 meV. When the full period is considered the interaction between the two wells repels their levels, moving them, respectively, to 66.6 meV and just above the barrier. Therefore, the miniband originates only from the coupling of the wide-well states. To have an intuitive picture, the system can be treated as a *virtual superlattice* with the same period D, but formed only by the wide wells. The narrow wells and the barriers are replaced by an effective barrier. The structure of the wide-well minibands for electrons, heavy holes, and light holes can be very well reproduced using a virtual 3.4–4.8 nm GaAs–$Al_{0.09}Ga_{0.91}As$ superlattice. The effect of the narrow wells is to lower the effective barrier (increase the coupling).

Based on the calculations we assign the peak at 1.6109 eV (see Fig. 2) to the lowest transition from the heavy hole to the electron wide-well minibands [vertical arrow in Fig. 1(a)], whose calculated energy is 1.5832 meV without considering excitonic effects. The calculated light-hole transition energy is 1.5866 meV. Its proximity to the stronger heavy-hole transition could explain why it does not appear in the spectra. The calculated values differ from the observed ones because we have not fitted any parameter.

At a finite electric field $\mathscr{E}$ the wide-well miniband splits into a Stark ladder. The peaks observed in Fig. 2 originate from the heavy-hole excitonic transitions between Stark ladder levels [Fig. 1(b)]. The transition energies are given approximately by $E_p=E_0\pm ep\mathscr{E}D$ (as shown by straight lines in Fig. 3), where p is an integer number and D is the superlattice period. The energy E_0 of the miniband center, which corresponds to the single-well transition of the wide well at zero electric field, was taken as 1.6470 eV to get the best fit with the experimental points. Having the same period the virtual superlattice would give similar results.

In the spectra both the heavy- and the light-hole *intrawell* ($p=0$) transitions are observed (see Figs. 2 and 3). At -5.0 V they are, respectively, at 1.6189 and 1.6455 eV. At high fields they deviate from the horizontal straight line in Fig. 3 because in reality their energy is field dependant. This is due to the well-known Stark shift of single-well levels.[13,14]

Since the heavy-hole states are localized in a single well at rather low fields, the number of observed interwell transitions is a measure of the spatial extent of the electron wave function.[11] At low fields one observes up to nine transitions. This sets a minimum value of 73.8 nm for the coherence length of the electron wavefunction at flat band. This value compares very well with the values obtained for superlattices with a single well and a single barrier per period. Considering that in our case the number of interfaces doubles, it seems that interfaces do not drastically reduce the coherence length.

The critical electric field necessary to achieve complete localization of the Stark ladder states is $\mathscr{E}_c\approx\delta E/eD$, where δE is the miniband width. For heavy holes $\mathscr{E}_c\approx 11$ kV/cm (≈ -1.0 V). For electrons $\mathscr{E}_c\approx 82$ kV/cm (≈ -2.6 V). Below this voltage interwell transitions disappear (see Fig. 2). For higher fields only the intrawell transitions remain.

The difference between the center of the miniband as determined from the fan chart in Fig. 3 and the band gap at very low fields (1.35 V) corresponds to half the miniband width neglecting excitonic effects. The value for $\delta E/2$ of 35 meV agrees well with the calculated miniband width of 66 meV given above.

For optoelectronic applications the most important characteristics are the single-well transition energy E_0, the critical electric field $\mathscr{E}_c$, and the electron miniband width δE, which determine, respectively, the light wavelength, the operating voltage, and the blueshift. In simple superlattices these values depend on the well width, the band offset, and the period. Sometimes one parameter is already determined by additional constraints. For example, the band offset is fixed in superlattices that are lattice matched to a substrate of a different material.[15] In order to optimize the device performance in these cases it is necessary to include additional degrees of freedom. The asymmetric double-well superlattice offers the advantage that the effective band offset of the virtual superlattice can be tuned by the narrow well width.

In summary, we have observed Wannier–Stark localization in a semiconductor superlattice with a complex period, consisting of two wells of different thicknesses. In the region of the wide-well transitions the system behaves in a way similar to a virtual superlattice formed only by the wide wells with the same period, but with lower barriers. This heterostructure has more design parameters than a conventional superlattice, allowing for a larger freedom in the design of electro-optic devices with specific performances.

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