Photoluminescence excitation spectroscopy of Be-remotely-doped wide parabolic GaAs/$Al_xGa_{1-x}As$ quantum wells

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p-type, remotely doped, wide (~ 1000 Å) parabolic GaAs/$Al_xGa_{1-x}As$ quantum wells were investigated by photoluminescence excitation spectroscopy. For three samples, with valence-band edge curvatures equivalent to the potentials of fictitious uniform slabs of charge with three-dimensional (3D) densities of 0.2, 3, and 4×10^{16} cm^{-3}, the spectra show uniformly spaced peaks with spacings which scale with these 3D densities. This peak structure is similar to that observed for *n*-type, remotely doped parabolic GaAs/$Al_xGa_{1-x}As$ quantum wells. A simple single-particle model is presented which is quantitatively consistent with the spectra for the three samples, assuming the hole gas forms a wide slab in the valence band with density given by the designed 3D density. These results support the conclusions from transport measurements of the existence of wide hole-gas layers in these structures.

Wide layers ($\gtrsim 700$ Å) of high mobility, low-density hole gas have recently been created[1] using the technique of parabolic well (PBW) confinement, analogous to that which has been used for electron gases.[2,3] By varying the Al content in an $Al_xGa_{1-x}As$ heterostructure quadratically in the growth direction, one can create a structure with band-edge PBW's in the conduction band (CB) and valence band (VB), as shown in Fig. 1(a). When electrons are added to the well by remote doping, self-consistent quantum-mechanical calculations[4] verify semiclassical arguments, that the electrons become distributed as a nearly uniform density slab. The potential of the electron slab cancels the band-edge potential over the width of the slab w_e, which is proportional to the filling, leaving a flat bottomed effective potential in the CB. This behavior has been substantially verified by transport measurements.[3,5] Investigations of the wide, uniform density electron-gas slab created by this technique have revealed new electronic and optical phenomena.[6,7]

By analogy, it was speculated that if, instead of electrons, holes are added to this PBW system by remotely doping with Be, a slab of nearly uniform density hole gas would be created, with 3D density given by $p_{3D}=2\Delta E_{VB}\varepsilon/\pi e^2 L_z^2$, determined by the bare parabolic curvature of the VB.[1] Here ΔE_{VB} is the difference between the band-edge energies at the center of the VB PBW and at the edge, ε is the dielectric constant, e is the electron charge, and L_z is the width of the well. The potential of the hole gas slab cancels the PBW potential in the VB over the width of the slab w_h, which is proportional to the filling, i.e., $w_h=p_s/p_{3D}$, where p_s is the hole sheet density. This leaves a flat bottomed effective potential well in the VB as shown in Fig. 1(b). This hole-gas system, however, is not entirely analogous to the electron-gas system created in the *n*-type doped PBW structure because of the valence-band degeneracy, and so the validity of this model is not obvious.

The successful realization of this system would open up new opportunities for investigating the electronic and optical properties of wide, low-density hole-gas layers at low temperatures. Initial magnetotransport and

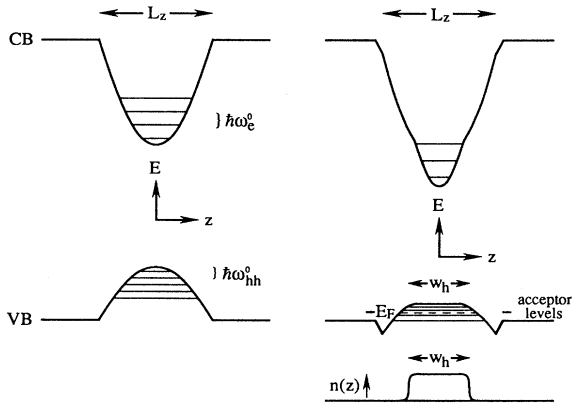

FIG. 1. Schematic illustration of the conduction- and valence-band-edge profiles in (a) an empty $Al_xGa_{1-x}As$ parabolic well, with *z*-confined energy levels simple-harmonic-like (evenly spaced) in the CB and VB, and (b) a *p*-type remotely doped parabolic well, with energy levels simple-harmonic-like in the CB, but square-well-like in the VB. (The square-well level spacings are shown greatly expanded for clarity, and only the heavy-hole levels in the VB are shown.) The effective width of the square well is given approximately by the width w_h of the hole slab indicated by the charge-density profile shown at the bottom of (b).

capacitance-voltage measurements on remotely Be doped PBW's have verified the creation of wide, high mobility hole-gas layers in these structures.[1] Further understanding of this system could be obtained from measurements of the subband energy-level structure. We report here an investigation of this system using photoluminescence excitation spectroscopy (PLE), which gives spectra with peaks at the energies of exciton absorption transitions between occupied VB subbands and unoccupied CB subbands.[8]

The PBW samples were fabricated by molecular-beam epitaxy on GaAs (100) substrates, as discussed by Hopkins, Campman, and Gossard.[1] The parabolic band-edge variations were constructed from 20-Å period superlattices, each period containing a GaAs and an $Al_xGa_{1-x}As$ layer, with the relative width of the two layers varied using a computer controlled shutter to produce an average Al concentration with a parabolic profile, with x near zero at the center. The holes were introduced in the VB well from Be δ-doped regions set back 100 Å on each side.

Three structures with different design densities p_{3D} and sheet densities p_s were studied, and are labeled samples 1, 2, and 3 in the order of increasing p_{3D}. Sample 1 had $L_z=5200$ Å, with a design density of $p_{3D}=0.2\times10^{16}$ cm^{-3}. It was made with $GaAs/Al_{0.3}Ga_{0.7}As$ layers with the average x given by $x=0.005$ at the center of the well and $x=0.233$ at the edge. It had a measured sheet density and mobility of $p_s=0.75\times10^{11}$ cm^{-2} and $\mu=18\,000$ $cm^2V^{-1}sec^{-1}$, respectively, determined by the Hall effect at 4.2 K. Sample 2 had $L_z=2400$ Å, with a design density of $p_{3D}=3\times10^{16}$ cm^{-3}. It was made with $GaAs/Al_{0.69}Ga_{0.31}As$ layers with the average x given by $x=0.015$ at the center of the well and $x=0.69$ at the edge. It had a measured sheet density and mobility of $p_s=2.3\times10^{11}$ cm^{-2} and $\mu=15\,000$ $cm^2V^{-1}sec^{-1}$, respectively, measured by the Hall effect at 4.2 K. Sample 3 was extensively studied.[1] It had $L_z=1000$ Å, with a design density of $p_{3D}=4\times10^{16}$ cm^{-3}. It was made with $GaAs/Al_{0.35}Ga_{0.65}As$ layers with the average x given by $x=0.01$ at the center of the well and $x=0.2$ at the edge. The sheet density and mobility were $p_s=3\times10^{11}$ cm^{-2} and $\mu=23\,000$ $cm^2V^{-1}sec^{-1}$ respectively, measured by the Hall effect at 0.1 K. Low-temperature ($T\lesssim4.2$ K) capacitance-voltage measurements indicated that the hole gas had roughly uniform density and a width of $w_h\sim700$ Å, in rough agreement with the expected width of $w_h=p_s/p_{3D}$.

Figure 2 shows PLE spectra for the three samples at 2.2 K, taken in the backscattering configuration with power density of 0.1 W/cm^2 and instrumental resolution of 0.1 meV. Each of the three spectra is seen to have a relatively sharp peak (compared to the higher-energy structures) at the band edge. For higher energies each spectrum is dominated by a series of uniformly spaced peaks, with spacings which scale with the design density p_{3D}. The uniform spacings are not the result of optical interference in the sample or apparatus. For all samples the peak positions were independent of the angle of the sample with respect to the incident and scattered light,

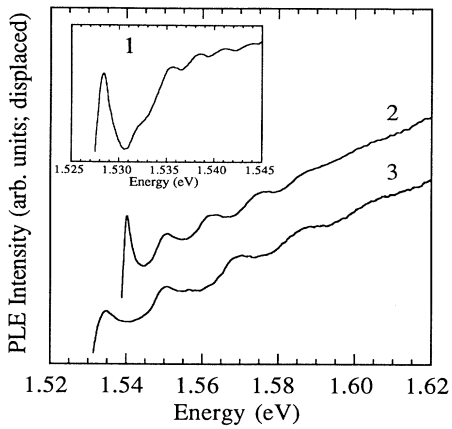

FIG. 2. PLE spectra, taken in the backscattering configuration at 2.2 K, of three remotely Be doped $Al_xGa_{1-x}As$ parabolic wells. Sample 1 (inset), sample 2, and sample 3 have design densities of $p_{3D}=0.2$, 3, and 4×10^{16} cm^{-3} respectively, and sheet densities of $p_s=0.75$, 2.3, and 3×10^{11} cm^{-2}, respectively. The spectra were scanned at a constant power density of 0.1 W/cm^2. The resolution is 0.1 meV.

and the peaks were observed to shift rigidly with temperature with the temperature dependence of the GaAs band gap. Also, PLE measurements on empty PBW's and remotely Be doped single heterojunctions with similar sheet densities did not show the uniformly spaced peaks observed in the doped PBW's. Thus this behavior seems to be related to the presence of a hole gas in a PBW potential.

The structure of the PLE spectra for remotely Be doped PBW's is similar to that observed for remotely n-type doped PBW's, for which uniformly spaced peaks with spacings scaling with the CB design density were reported.[7] For the remotely n-type doped PBW system a simple model based on single-particle transitions between the VB and CB subband levels determined by the effective potentials was suggested.[7] A related model can account for the uniformly spaced peaks in the remotely Be doped PBW PLE spectra. Due to the hole slab in the VB, the self-consistent effective potential for the holes is not parabolic, but square-well-like, giving a nonuniform energy-level spacing [see Fig. 1(b)]. However, a uniform spacing survives in the CB, since the self-consistent effective potential in the CB is still parabolic, but with the spacing determined by the sum of the bare band-edge curvatures of the CB and VB. This gives a CB subband energy-level spacing given by

$$\Delta E=\hbar\left[\frac{K_{CB}+K_{VB}}{m_e^*}\right]^{1/2}, \tag{1}$$

where $K_{CB,VB}=d^2E_{CB,VB}/dz^2=8\Delta E_{CB,VB}/L_z^2$ and m_e^* is the electron effective mass in the CB. Due to the large size of the heavy-hole mass ($m_{hh}^*\approx0.51m_0$) and the wide ($\gtrsim700$ Å for all three samples) flat bottomed effective well in the VB, for the first several occupied (by electrons) VB subbands, the subband spacing is very small ($\ll1$ meV). Thus allowed transitions from the low-energy,

nearly degenerate occupied subbands of the VB to the more widely spaced CB subbands are expected to be separated by approximately ΔE. A plot of the measured peak spacing vs the calculated ΔE for the three samples is shown in Fig. 3, with the line representing the prediction of the model. The figure shows that this simple model fits the data well within the error bars for samples 1 and 2, and just within the vertical error bar for sample 3. The vertical error bars come primarily from the uncertainty in the well width L_z, which is $\sim 20\%$ for sample 3 due to the measurement being taken from a sample near the edge of the nonrotated wafer. The fit occurs with no adjustable parameters for the samples with design densities ranging in magnitude by a factor of ~ 20.

Though this single-particle model for the uniformly spaced PLE peaks for this p-type doped PBW structure is certainly not proved, it is remarkable that closely related single-particle models quantitatively account for uniformly spaced peaks in the spectra for both the n-type and p-type doped PBW structures, in spite of the different potentials and effective masses of the two bands, CB and VB, containing the particle gas in the two cases.[7] For the n-type doped PBW structure the potentials are the reverse of that shown in Fig. 1(b), with the square-well-like effective potential in the CB and the PBW-like effective potential in the VB. The single-particle model offered as an explanation of the uniformly spaced peaks in these PLE spectra gives a peak spacing ΔE given by Eq. (1), but with m_e^* replaced with $m_{\rm hh}^*$ and with an additional factor 2 multiplying the right-hand side of the equation.[9] The factor 2 occurs because in this case, due to the much lighter electron mass, the square-well-like levels in the CB are spaced by energies on the order of 1 meV and thus cannot be considered degenerate. Therefore, comparing a particular strongly allowed transition (one between VB and CB subbands with the same quantum number) with other strongly allowed transitions, the energy differences are not spaced by the VB harmonic-oscillator spacing. However, for a given final CB state (with definite parity), allowed transitions occur from VB states of the same parity, i.e., from alternate VB harmonic-oscillator levels, thus giving rise to peak separations of *twice* the VB harmonic-oscillator spacing. Transitions to other CB states have the same energy separations, thus preserving the periodicity in the PLE spectra. What the two models for the two complementary structures have in common is that the slab of charge in one of the two bands in each case results in an effective potential in the other band which remains parabolic, and this gives rise to strong periodic oscillations in the PLE spectra (or equivalently the absorption spectra[8]).

This model for the optical transitions in p-type doped PBW structures, if valid, has several implications for the Be doped PBW samples investigated here. The uniform spacing of the peaks and their quantitative agreement with ΔE give further verification of the creation of wide

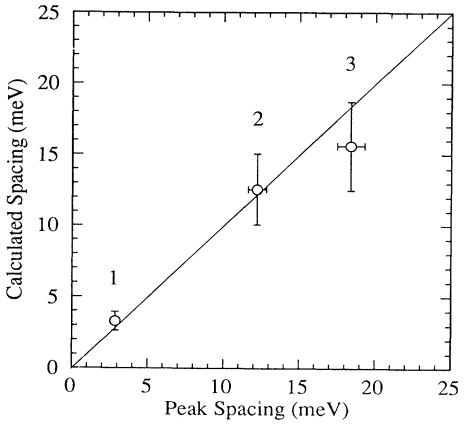

FIG. 3. Comparison of the measured peak spacing vs the calculated CB effective parabolic well energy-level spacing ΔE, Eq. (1), for three remotely doped PBW's. Samples 1, 2, and 3 have VB band-edge curvatures corresponding to three-dimensional densities of 0.2, 3, and 4×10^{16} cm^{-3}.

hole-gas slabs in these structures. The extent to which the uniformly spaced peaks range in energy above the low-energy edge of each spectrum gives a lower bound for the width of the slab for that sample. This is because, as seen in Fig. 1(b), for transitions to CB states near or above the band-edge energy corresponding to the edge of the hole slab, the energy-level spacing changes. For example, the extent of the uniformly spaced peaks in sample 3 implies a uniform slab width of $\gtrsim 500$ Å, compared to a value of 700 Å determined by capacitance-voltage measurements. The uniformity of the peak spacing in principle gives some measure of the uniformity of the hole-gas density over the layer width, although this is difficult to quantify. Nevertheless, large deviations from uniform density can be ruled out by the peak spacing uniformity, in this model.[10]

In conclusion, PLE measurements of three Be-remotely-doped PBW's show uniformly spaced peaks whose uniform spacing scales with valence-band-edge PBW curvature, or 3D design density $p_{\rm 3D}$. This behavior is similar to that observed for n-type remotely doped PBW's, for which a simple single-particle model was found quantitatively consistent with the measurements. For the Be doped PBW's a related single-particle model is found quantitatively consistent with the spectra for the three samples, assuming the hole gas forms a roughly uniform density slab with density given by the design density $p_{\rm 3D}$.

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[9]We have verified the quantitative agreement between the calculated ΔE and the uniformly spaced PLE peak separations for the *n*-type doped PBW system for samples with a wider range of band-edge curvatures than reported previously (Ref. 7), and we have also observed the uniform peak spacing in the photocurrent spectra of the samples. [J. H. Burnett, H. M. Cheong, W. Paul, P. F. Hopkins, R. M. Westervelt, and A. C. Gosard (unpublished)].

[10]For example, a first-order perturbation-theory calculation shows that deviations from uniform density of 50% or more due to a quadratic variation in the density profile would give rise to observable deviations from peak spacing uniformity, which are not seen in the spectra.