

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

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Photoluminescence excitation (PLE) spectroscopy was performed on an undoped and several remotely doped wide parabolic GaAs/Al_xGa_{1-x}As wells of various well widths and electron sheet densities. For an undoped parabolic well of width 4640 Å, the PLE peak energies are consistent with calculated energies of allowed exciton transitions. The spectra for a remotely doped well of the same width are dominated by a series of uniformly spaced peaks with spacing (~3.1 meV) approximately equal to the harmonic-oscillator spacing of the bare parabolic conduction-band-edge curvature. Measurements of the dependence of the peak spacing on well width and electron sheet density are presented.

Remotely doped GaAs/Al_xGa_{1-x}As wide parabolic wells have generated recent interest because they can create relatively thick (> 1000 Å) layers of uniform density, high-mobility electron gas.¹⁻⁴ As illustrated in Fig. 1(a) parabolic wells are created in the conduction band (CB) and the valence band (VB) by varying the average Al concentration in a parabolic profile. For an empty well this results in simple-harmonic-oscillator (SHO) energy levels for electrons, heavy holes, and light holes, with energy spacings $\hbar\omega_{0e}$, $\hbar\omega_{0hh}$, and $\hbar\omega_{0lh}$, respectively. Photoluminescence excitation (PLE) spectra for empty parabolic wells give peaks at exciton absorption energies with spacings given by the sum of electron and hole spacings.⁵

When electrons are added to the well by remote doping, they distribute themselves as a slab of width w_e with roughly uniform charge density profile that cancels the parabolic potential over width w_e , as shown in Fig. 1(b).^{3,6} As a result, the total self-consistent potential for the electrons is approximately a square well, and for holes a parabolic well of greater curvature $d^2E_v/dz^2 = K_{CB} + K_{VB}$, where K_{CB} and K_{VB} are the curvatures for the corresponding empty well. Thus the optical interband transitions would not be expected to be simply related to the empty well spectra. We report here investigations of interband optical excitations of these wells of various curvatures and electron concentrations using PLE spectroscopy.

The parabolic wells were fabricated using molecular beam epitaxy, as described by Sundaram *et al.*¹ They were made as fine superlattices of GaAs and Al_{0.3}Ga_{0.7}As layers, each pair 20 Å thick, with the relative width of the GaAs and Al_{0.3}Ga_{0.7}As layers varied using a computer-controlled shutter to produce an average Al concentration with a parabolic profile, with $x=0$ at the

well center and $x=0.3$ at the edges. The wells were remotely doped by Si-doped layers, set back from both sides of the well in the Al_{0.3}Ga_{0.7}As barriers.

Figure 2 shows PLE spectra taken at $T=2.2$ K for three 4640-Å-wide parabolic well samples (1, 2, 3) with different electron fillings determined by Hall measurements. All three parabolic well samples were made with identical growth parameters, except for the remote Si doping; sample 1 was undoped, and thus ostensibly empty. After laser illumination the doped samples 2

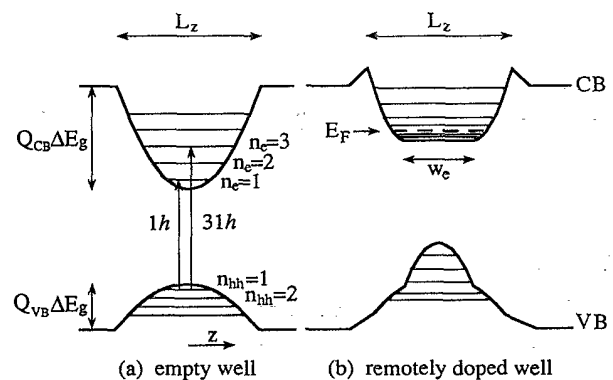


FIG. 1. Schematic illustration of conduction- and valence-band-edge profiles in (a) an empty well and (b) a remotely doped well. (a) Quantized energy levels along the growth direction and some allowed optical transitions are illustrated. Electron and hole levels are labeled by $n_e = 1, 2, 3, \dots$. Only heavy-hole levels are shown. (b) In a remotely doped well, electron-level spacings below the Fermi energy are similar to those of square wells, but become more evenly spaced for energies high above the Fermi level. The valence-band edge has larger curvature compared with the case of an empty well due to the potential of the electron slab.

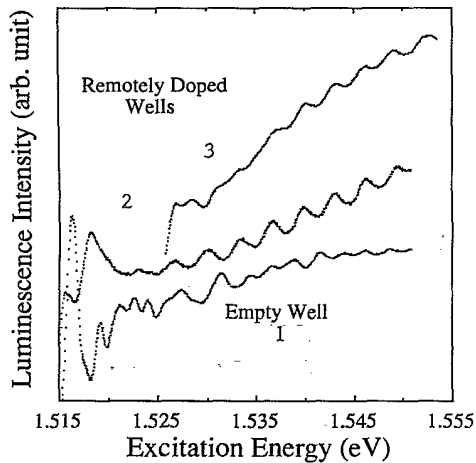


FIG. 2. PLE spectra taken in the backscattering configuration at $T=2.2$ K of an empty parabolic well (sample 1) and two remotely doped parabolic wells (samples 2 and 3), all of width 4640 \AA . Detection set at 1.5142 , 1.5136 , and 1.5249 eV , respectively. All samples have the same design parameters except that samples 2 and 3 are remotely doped, having sheet densities of $n_s=2.3\pm 0.2$ and $1.7\pm 0.2\times 10^{11} \text{ cm}^{-2}$, respectively. Spectra scanned at constant power density of 0.10 W/cm^2 . Resolution is 0.1 meV .

and 3 had measured mobilities of $\mu=0.7$ and $1.2\times 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$, respectively, and sheet densities of $n_s=(2.3\pm 0.2)$ and $(1.7\pm 0.2)\times 10^{11} \text{ cm}^{-2}$, respectively. Calculations show that for symmetric filling with these sheet densities, the number of occupied subbands was 7 and 5, respectively.⁶

For all the doped parabolic well samples measured, the peak separations and relative intensities were found to be independent of illumination power density from $0.4 \mu\text{W/cm}^2$ to 0.4 W/cm^2 , except for a slight broadening of the lowest two peaks at the highest powers. The PLE spectra were found to be nearly independent of position on the sample, with a shift in energy of no more than 0.2 meV .

For the empty well sample 1, the PLE peak positions and intensities agree well with those calculated for exciton transitions between SHO levels.^{5,7} The comparison of the spectra of the doped samples with that of the empty well sample in Fig. 2 shows two striking differences. First, the low energy peak structure ($\approx 10 \text{ meV}$ above the lowest energy peak) of the empty well spectrum is changed for the doped samples. Major differences are expected as a result of electron filling: calculations⁶ show that the CB subband spacing is strongly reduced near and below the Fermi level, and optical transitions at 2.2 K can only occur to unoccupied states above the Fermi level.

The other difference between the empty and doped well spectra is that the peaks $\geq 10 \text{ meV}$ above the lowest energy peaks for the doped wells are evenly spaced and have relatively uniform amplitudes. The uniformity of the peak spacing is displayed in Fig. 3, which plots the peak energies versus peak number for the two doped 4640-\AA wells, samples 2 and 3, and also for a doped 5680-\AA para-

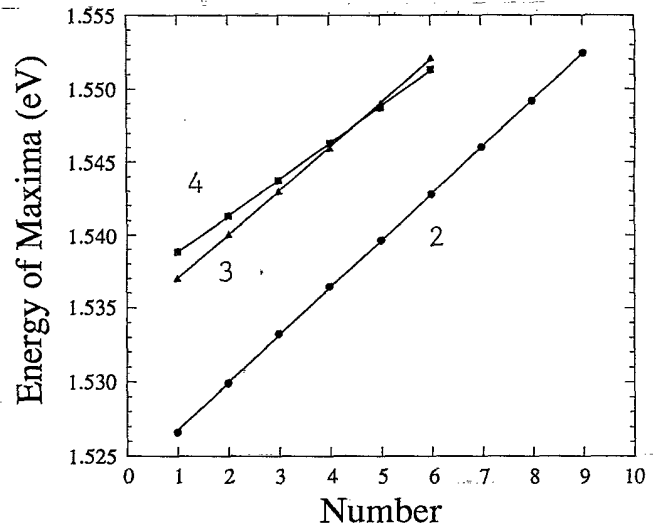


FIG. 3. Peak maxima vs peak number for three parabolic wells. Samples 2 and 3 are 4640 \AA wide and sample 4 is 5680 \AA wide. The lines are the least-squares linear fits. The peak spacings given by the slopes are 3.2 , 3.0 , and 2.5 meV , respectively.

abolic well sample 4. The lines represent least-squares linear fits to the data, and their slopes give the peak spacings. We have checked that these peaks are not the result of optical interference in the sample or the apparatus. The peak spacings are independent of the angle of the sample with respect to the incident and scattered light, and the peaks shift rigidly with the temperature dependence of the GaAs band gap. A uniformly spaced peak structure in the PLE spectra was not observed for several doped square wells with comparable sheet densities and widths chosen to give similar zero-point energies to those of the parabolic well samples. Nor are evenly spaced peaks reported in other investigations of PLE spectra of doped square wells.⁸⁻¹¹

The dependence of the PLE peak spacing on the well width and electron filling is indicated in Fig. 4, which plots the average peak separation for three samples versus the bare parabolic well energy-level spacing corre-

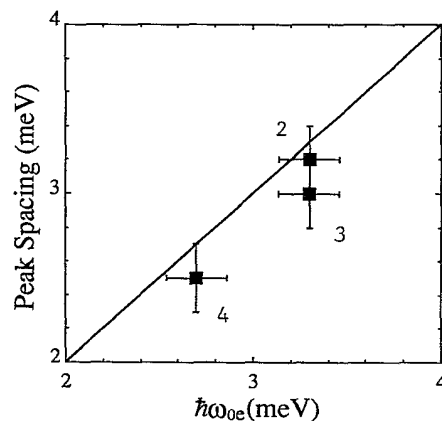


FIG. 4. Comparison of average PLE peak spacings and calculated bare parabolic well SHO spacings $\hbar\omega_{0e}$ for three different remotely doped parabolic well samples (2, 3, and 4).

sponding to the particular CB curvature. It shows that the peak spacing is approximately equal to the bare parabolic well spacing, independent of electron filling. This is surprising since the self-consistent potential of the electrons is approximately a square well of width equal to that of the electron layer, giving a distinctly nonuniform CB subband spacing.⁶

It has been shown that for doped parabolic wells there exists a set of plasmonlike collective excitations associated with the center-of-mass motion of the electron gas in the direction of the parabolic potential variation, with energy spacing identically equal to the bare SHO spacing in the CB.¹² Earlier reports of evenly spaced oscillations in the photoconductivity spectra of doped InSb,^{13,14} GaSb,¹⁴ and Ge,¹⁵ and of defected Si,¹⁶ have been ascribed to excitations of longitudinal optical phonons. By analogy, our observed oscillations in the PLE spectra may be associated with the excitation of these plasmonlike collective modes, either in the absorption or the thermalization processes. However, the problem of coupling and the high number of oscillations observed make these models difficult to accept.¹⁷

A single-particle-picture explanation follows from the fact that, while the self-consistent energy-level spacing in

the conduction band becomes nonuniform with the addition of electrons, a periodicity survives in the VB. This periodicity is determined by the sum of the band-edge curvatures of the CB and VB. For allowed transitions from alternate heavy-hole levels to a single conduction-band level the spacing is given by

$$\Delta E = 2\hbar\sqrt{(K_{CB} + K_{VB})/m_{hh}^*} \approx 0.93\hbar\omega_{0e}, \quad (1)$$

which is consistent with the data. The superposition of spectra resulting from transitions to different electron levels preserves this periodicity in the PLE spectra.

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