Enhanced exciton absorption and saturation limit in strained InGaAs/InP quantum wells

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A new approach for enhancing the exciton absorption and increasing the saturation limit in quantum wells (QWs), using tensile strain, is proposed. Because of the valence-band mixing in a strained QW, the in-plane hole mass can become very large or negative. This leads to a heavy electron-hole reduced mass (exciton mass), and therefore to a small exciton radius. Exciton absorption is substantially increased because of the increased electron-hole overlap probability in these small-radius excitons. The effects of saturation are also substantially reduced because of decreased charge-screening effects for small-radius excitons and because the rapid dispersal of the photon-generated excitons reduces the Pauli exclusion effect.

I. INTRODUCTION

Strained quantum well (QW) structures have been attracting increasing interest. QW lasers with compressive strain have shown improved performance over conventional lasers,[1] because of the reduced in-plane hole mass and density of states. On the other hand, QWs with tensile strain can change the in-plane hole mass in the opposite way and, therefore, increase the joint density of states for optical absorption. The use of QWs with tensile strain is therefore expected to improve the performance of optoelectronics devices that depend on optical absorption.

The discovery of the room-temperature Stark shift of the exciton-absorption peaks in QWs,[2,3] has made possible the fabrication of novel devices, such as multi-quantum well (MQW) self-electro-optic-effect devices (SEEDs) and electro-optic modulators.[4] To achieve good device performance, it is always desirable to have as large a differential absorption and saturation limit as possible.

Kothiyal *et al.*[5] used MQW structures with tensile strain to merge the heavy-hole and light-hole exciton absorption peaks, and observed a twofold increase in the peak exciton absorption from the lattice-matched QWs. However, these structures only increased the absolute value of the exciton absorption, but reduced the differential absorption because the Stark shifts are different for the heavy-hole and light-hole exciton absorption peaks. For these devices, the absorption coefficient of the ON state is the sum of the tails of the heavy-hole and light-hole exciton absorptions, whereas the absorption coefficient of the OFF state is only the absorption coefficient of the heavy-hole exciton-absorption peak. Although this disadvantage can be overcome by improved design, the added stringent requirement for device fabrication does not justify the small amount of increase in the absorption coefficient.

In this work we propose another approach: to dramatically increase the lowest-lying exciton-absorption peak by producing heavy excitons in strained QW structures. As we will discuss in detail, the heavier the exciton the smaller its radius, and therefore the larger the overlap probability for the electron and hole that form the exciton. In turn, the exciton-absorption coefficient, which is proportional to the electron and hole overlap probability, is also larger. Not only is the exciton-absorption peak increased, as we will see in the following discussion, but this new approach has another salutary effect: it increases the absorption-saturation limit as well.

The following model serves the purpose of demonstrating the idea. However, a more precise model is needed to obtain quantitative results.

II. EXCITON IN A QUANTUM WELL

With Coulomb attraction, an electron and a hole can bind together and form an exciton. Excitons in a QW can be described by the effective mass theory with a two-dimensional (2-D) Coulomb potential. The overall wavefunction of the exciton in a QW can be written as[6,7]

$$\Psi = u_c(\mathbf{r}_c)u_v(\mathbf{r}_v)f_c(z_c)f_v(z_v)F_{\mathbf{K};n,m}(\mathbf{R},\mathbf{r}), \tag{1}$$

where the u_i are the bulk Bloch functions, $\mathbf{r}_c$ and $\mathbf{r}_v$ are the coordinates for the electron and hole, respectively, z_i are the coordinates perpendicular to the well, $\mathbf{R}$ and $\mathbf{r}$ are the 2-D center of mass and relative-motion coordinates of the electron and hole, the f_i are the carrier envelope functions in a QW, v is h for a heavy hole and l for a light hole, $\mathbf{K}$ is the center of mass wave vector of the 2-D exciton, and m and n are the angular and radial quantum numbers, respectively. F is the exciton wave function, which can be written as

$$F_{\mathbf{K};n,m}(\mathbf{R},\mathbf{r}) = e^{i\mathbf{K}\cdot(\mathbf{R}+\lambda\mathbf{r})}R_{n,m}(r)e^{im\phi}, \tag{2}$$

where

$$\lambda = \frac{m_c - m_v}{2(m_c + m_v)}. \tag{3}$$

The radial part of the exciton wavefunction $R_{n,m}$ is the solution of

$$\left[-\frac{\hbar^2}{2m_r}\left(\frac{1}{r}\frac{d}{dr}r\frac{d}{dr}+\frac{m^2}{r^2}\right)-\frac{e^2}{\epsilon r}\right]R_{n,m}(r) = E_{n,m}R_{n,m}(r), \tag{4}$$

where

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$$m_r = \frac{1}{1/m_c + 1/m_v} \tag{5}$$

is the reduced mass of the electron and hole pair, and is also the exciton mass, and ϵ is the dielectric constant. The corresponding eigenvalues of Eq. (4) are:

$$E_{n,m} = -\frac{\hbar^2}{2m_r(4a_0)^2}\frac{1}{(n-\frac{1}{2})^2}, \tag{6}$$

and the corresponding eigenfunctions are

$$R_{n,m} = \frac{1}{\sqrt{N}} x^m e^{-x/2} L_{n-|m|-1}^{2|m|}(x), \tag{7}$$

where N is a normalization constant

$$x = \frac{2m_r e^2}{\hbar^2 \epsilon}\frac{r}{n-1/2}, \tag{8}$$

and

$$a_0 = \frac{\hbar^2 \epsilon}{4m_r e^2} \tag{9}$$

is the exciton radius and L is the associated Laguerre polynomial.

The exciton binding energy is

$$E_{\mathbf{K},n,m} = \frac{\hbar^2 K^2}{2(m_c+m_v)} + E_{n,m}. \tag{10}$$

An exciton is called a direct exciton if $\mathbf{K}=0$, and otherwise is called an indirect exciton.

III. ENHANCED EXCITON ABSORPTION

For direct excitons, the absorption coefficient can be written as[7,8]

$$\alpha(\omega) = \frac{4\pi^2 e^2}{dncm_0^2\omega}\sum_n |M_r G(l_c,l_v) F_{\mathbf{K}=0;n,m=0}(0)|^2 \delta(E_g + E_{n,m=0} - \hbar\omega), \tag{11}$$

where d and n are the well width and index of refraction, respectively, m_0 is the free electron mass, G is the overlap of the electron and hole envelope functions, and M_r is the bulk-transition matrix element. The absorption spectrum in Eq. (11) is composed of delta-function sharp lines. However, with scattering by phonons and interface imperfections, the absorption lines are broadened and the delta functions are replaced by lineshape functions $f_n(\omega)$ of finite bandwidth and height. Therefore, the exciton absorption coefficient becomes

$$\alpha(\omega) = \frac{4\pi^2 e^2}{dncm_0^2\omega}\sum_n |M_r G(l_c,l_v) F_{\mathbf{K}=0;n,m=0}(0)|^2 f_n(\omega). \tag{12}$$

The exciton transition is allowed only for direct excitons with $m=0$.

From Eq. (12) we can see that no matter what shape the lineshape functions $f_n(\omega)$ take, the exciton absorption peaks are always proportional to $|F_{\mathbf{K}=0;n,m=0}(0)|^2$. That is, the height of an exciton absorption peak is proportional to the overlap probability of the electron and hole in the exciton.

From Eqs. (2) and (7), the overlap probability for the ground-state exciton is

$$|F_{\mathbf{K}=0;1,m=0}(0)|^2 = \frac{1}{\pi a_0^2} = \frac{1}{\pi}\left(\frac{4m_r e^2}{\hbar^2\epsilon}\right)^2. \tag{13}$$

It is inversely proportional to the square of the exciton radius and thus is proportional to the square of the exciton mass m_r. Therefore, the heavier an exciton is, the smaller the exciton radius is and larger the absorption peaks are.

In a strained QW, the in-plane hole masses are altered because of the valence-band mixing.[9] The in-plane hole mass of a subband at the zone center can be either increased or decreased, and can even be changed to a negative value by the strain and quantum confinement of the structure. When the hole mass m_v increases from m_c to infinity, the exciton mass m_r increases from $m_c/2$ to m_c and the height of exciton absorption peak increases four times. However, when the hole mass m_v is negative and increases from negative infinity to $-m_c$, m_r increases from m_c to infinity. In a QW in which $m_v = -m_c$, the curvature of the conduction subband near the zone center approaches that of the valence subband, and the joint density of states can be significantly large depending on the curvatures of the subbands. This corresponds to a critical point in the joint density of states of electrons and holes and is very similar to the E_l and $E_l + \Delta$ critical points in bulk semiconductors.[10] Studies of critical point excitons of this type in bulk semiconductors[10] and saddle point excitons in bulk materials[11] and superlattices (quasi-3-D)[12] have shown profound exciton-absorption peaks and features in the dielectric spectra. Of course, the hydrogen exciton model, which is based on two-particle interactions, will certainly break down before m_v approaches $-m_c$. Nevertheless, it demonstrates the trend that the exciton-absorption peak continues to increase dramatically as m_r increases from negative infinity to $-m_c$.

With biaxial tensile stress applied to a QW it is possible to change the hole mass m_v to the desired value. Figure 1 shows the hole in-plane dispersion relation in $In_xGa_{1-x}As/InP$ QWs of well width $d = 80$ Å for $x=0.3$, 0.4, and 0.53. A two-band model is used in the valence-band calculation, and infinite barrier height is assumed.[13] Figure 2(a) shows the first heavy-hole and light-hole subband energies at the zone center in QWs of well width $d=80$ Å, for $x=0.15$–0.54. The first heavy-hole subband is the lowest-lying subband for $x>0.33$, whereas the first light-hole subband is the lowest-lying subband for $x<0.33$. Figure 2(b) shows the in-plane masses for the first heavy-hole and light-hole subbands. The light-hole mass $m_l < -m_c$ for $x<0.33$. Figure 3 shows the square of the reduced mass, m_r^2, of an electron-hole pair from the lowest-lying subbands. The quantity m_r^2 is singular at $x=0.33$, where $m_l = -m_c$. The value of m_r^2 at $x=0.32$, where about 2% strain is applied to the well, is more than two orders of magnitude larger than that for the lattice matched QW, for which $x=0.53$.

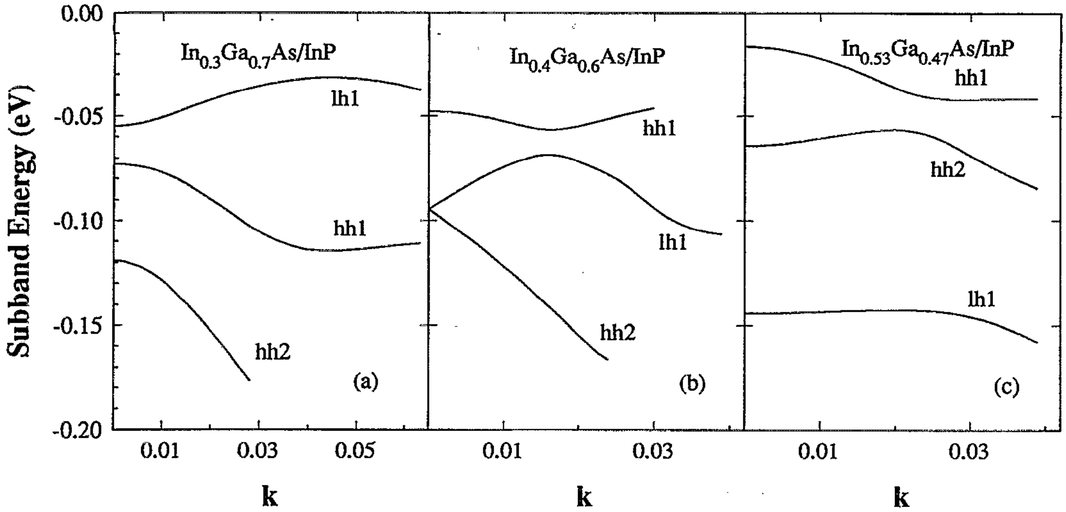

FIG. 1. The first three lowest lying hole-subband dispersion relation in $In_xGa_{1-x}As/InP$ QWs of well width $d = 80$ Å, for (a) $x = 0.3$, (b) $x = 0.4$, and (c) $x = 0.53$.

IV. REDUCTION OF SATURATION EFFECT

One problem encountered in devices based on the Stark shift of the exciton-absorption peaks in QWs is the relatively low saturation limit. When the light is intense, the absorption is reduced. According to Ref. 14, the reduction in absorption coefficient can be approximately described by a Lorentzian saturation function

$$\alpha(I) = \frac{\alpha_0}{1 + I/I_s}, \tag{14}$$

where I and I_s are the light intensity and the saturation intensity, respectively, and α_0 is the absorption coefficient

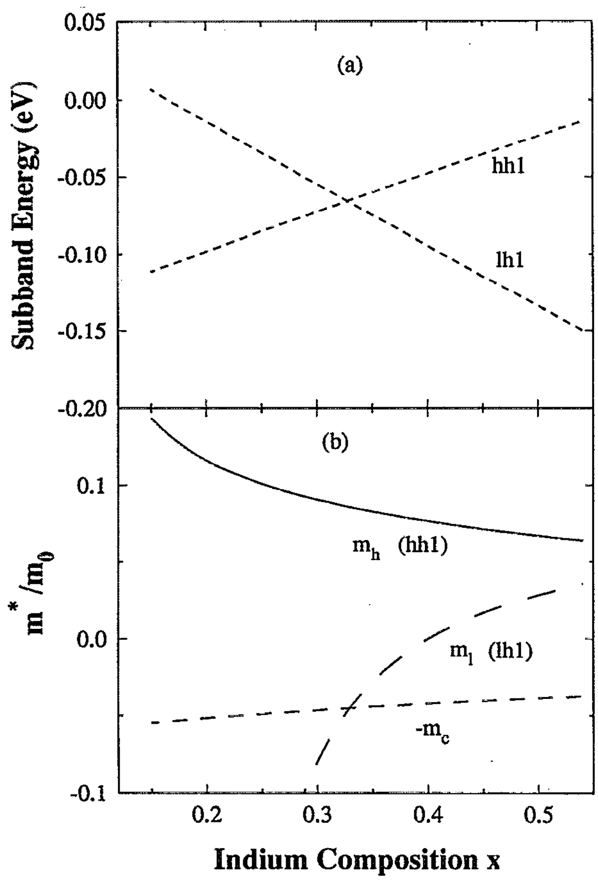

FIG. 2. (a) The first heavy-hole and light-hole subband energies at the zone center in QWs of well width $d = 80$ Å, for $x = 0.15$–0.54. The lowest lying subband is the first heavy-hole subband hh1 for $x > 0.33$, and is the first light-hole subband lh1 for $x < 0.33$. (b) In-plane hole masses for the first heavy-hole and light-hole subbands. The light-hole mass $m_l < -m_c$ for $x < 0.33$.

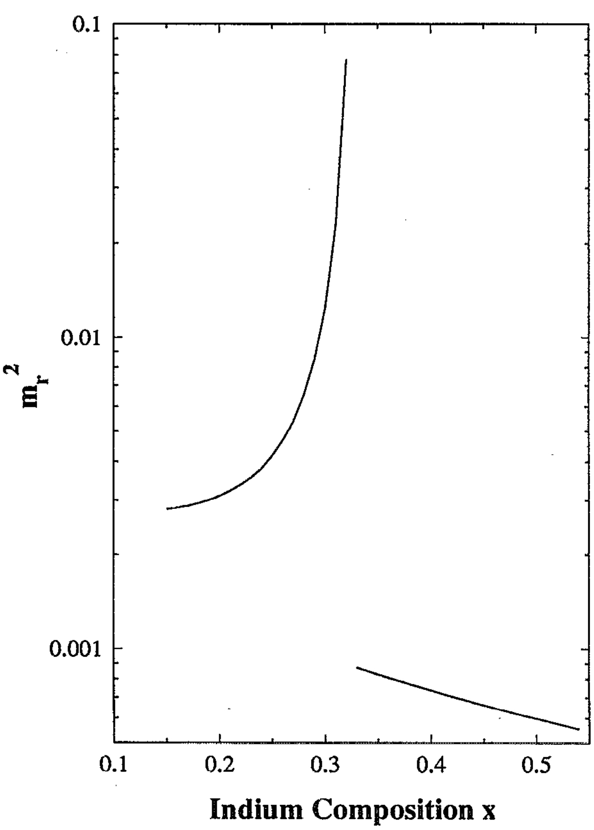

FIG. 3. Square of reduced mass m_r^2 of the electron-hole pair of the lowest-lying subbands as a function of x. The quantity m_r^2 is singular at $x = 0.33$ where $m_l = -m_c$.

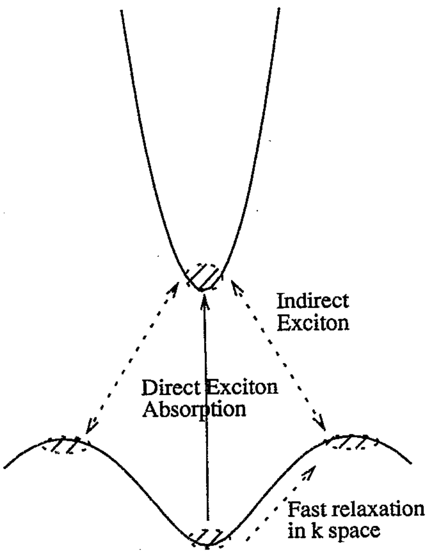

FIG. 4. The photon-generated direct excitons are quickly dispersed to lower energy states (indirect excitons) by emission of phonons. And the lifetime of the direct excitons are determined by the intra-band relaxation time, which is orders of magnitude shorter than the optical transition time.

at low intensities. The saturation intensity in a GaAs QW is about an order of magnitude lower than in bulk GaAs.

There are two major saturation mechanisms. One is due to the Pauli exclusion effect. When the lower exciton states are occupied by the accumulated excitons, the Pauli exclusion principle prevents more excitons from being generated.[2,15] The other is due to the Coulomb screening effect. When a large number of free carriers and bound carriers (excitons) are accumulated, they form a screening cloud and reduce the electron-hole Coulomb interaction. When the charge screening effect is large enough, the Coulomb interaction is too weak to form bound excitons and further exciton absorption is suppressed. In 3-D systems, screening is the dominant saturation mechanism, whereas in 2-D systems, Pauli exclusion effects are also significant.

With a large or negative hole mass, not only is exciton absorption enhanced, but saturation effects can be reduced as well. The free-carrier screening is effective only when the separation of the electron and hole is larger than the screening length. Therefore, when the exciton mass m_r increases and the exciton radius a_0 becomes smaller (particularly when it is smaller than the screening length) the screening effect on the electron-hole Coulomb interaction is reduced. The second saturation mechanism, a more important one,[15] is reduced in two ways. From one perspective, the Pauli exclusion principle can be viewed as an effect that increases the dielectric constant, reduces the Coulomb interaction[16] and, in turn, reduces the exciton binding energy. But because the increase in exciton mass m_r increases the binding energy, and therefore compensates some of the reduction in the Coulomb potential, the saturation limit is increased. In addition, when the hole mass m_v is negative, as pointed out by Chu *et al.*,[17] the indirect excitons have lower energies than the direct excitons. The photon-excited direct excitons can be quickly dispersed to lower energy states by emission of phonons. And the lifetimes of the excitons are determined by the much shorter intra-band relaxation time (through phonon-carrier interaction), instead of the optical transition time (Fig. 4). Therefore, the saturation intensity due to the Pauli exclusion effect is substantially increased for it is inversely proportional to the exciton lifetime $I_s \propto 1/\tau$.[2,14]

V. CONCLUSION

In conclusion, we have shown in theory that both the exciton-absorption peak and the saturation limit can be substantially increased in QWs with tensile strain because of the increased exciton mass and the lower energy indirect excitons.

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