Magnetoluminescence Characterization of Quantum Well Structures

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Three applications of magnetic field effects upon the photoluminescence spectrum which provide unique information about semiconductor quantum well structures are presented. The first example shows data which provide a quantitative measure of both the conduction- and valence-band energy dispersion curves for an InGaAs/GaAs single-strained-quantum well and a GaAs/AlGaAs lattice-matched single quantum well. The second subject discusses magnetoluminescence data which provides a clear demonstration for the existence of spectral shifts related to ionized-impurity scattering and the third study involves infrared magnetoluminescence measurements on narrow bandgap semiconductor alloys and heterostructures.

INTRODUCTION

Photoluminescence (PL) characterization of semiconductor materials has been a standard nondestructive diagnostic tool for a number of years. With the advent of quantum well structures, the photoluminescence technique has been used to study exciton and impurity states, interface roughness, impurity (dopant) diffusion, quantum-well energy levels, valence-band offset energies, etc. A recent review by Herman et. al.' presents an excellent summary for these kinds of studies. In particular, the use of 2D-excitons to study interface roughness is discussed in detail. However, magnetic field effects on the photoluminescence spectrum were not treated. With the current availability of high-field superconductor magnet systems and the advent of novel semiconductor systems based upon epitaxy growth techniques, magnetoluminescence is becoming a valuable diagnostic tool. In order to demonstrate the utility of the magnetoluminescence technique, we present three examples of magnetic-field dependent PL spectra, each of which provide unique information about the quantum-well.

The first application of magnetic fields concerns the electronic band structures of doped quantum-well structures. From an interpretation of the magnetic field dependent PL spectrum, it will be shown how a simultaneous determination of both the conduction- and valence-band energy dispersion curves can be made from a single sample measurement. Specifically, data for a single-strained-quantum well (SSQW) structure based on InGaAs/GaAs and a GaAs/AlGaAs lattice-matched-single-quantum-well (LMSQW) structure will be presented. It is found that while the valence-bands are highly nonparabolic, the conduction-band energy dispersion curves are nearly parabolic.

The second subject of this paper is the spectral shift of the PL peak resulting from ionized-impurity scattering in highly doped semiconductor quantum wells. Many researchers in the past have used the PL peak as a measure of bandgap energy, or quantum well energies, ground and excited states. Magnetoluminescence data will be presented that graphically demonstrate the importance of these spectral shifts.

The third and final example extends magnetoluminescence measurements to the long, 2 to 5 μm, wavelength range where magneto-excitons are studied in narrow bandgap materials and heterostructures. Analysis of the linear portion of the magnetic-field induced photoluminescence energy shift provides estimates of effective masses and exciton binding energies.

BAND-STRUCTURE STUDIES

The semiconductor quantum-well laser is the principal component for optoelectronic applications. The need for custom laser wavelengths, higher laser powers, and better beam quality or control has led to many different laser diode designs and configurations. The most common combination for semiconductor laser materials for these devices have been GaAs and AlGaAs. The desirability for light-hole valence-band masses for optoelectronic devices, lasers, or high-speed electronic devices has been well documented.

Light-hole valence-band masses have been mainly achieved in layered semiconductor structures by the introduction of compressive biaxial strain in the active quantum layers. The biaxial strain is achieved by growing layered structures from materials with differing lattice constants, e.g., layers of In_xGa_{1-x}As and GaAs. However,
because of level crossing repulsion between the in-plane heavy and light-hole valence-band states, the resulting in-plane valence-band energy dispersion curves (and masses) are nonparabolic. For lattice-matched quantum well devices, the same conditions hold because of the quantum confinement splitting of the heavy and light-hole valence bands. For these structures, the in-plane heavy-hole light-hole mixing and hence valence-band nonparabolicity occurs at small values of the wave vector. For the devices based upon GaAs and AlGaAs, quantum confinement can be an effective method to alter the energy difference \( \Delta E_{\text{HH}} \) between the heavy and light-hole valence bands. However, for wide (~15 nm) GaAs/AlGaAs structures, \( \Delta E_{\text{HH}} \) is small (\( \lesssim 5 \text{meV} \)) and thus the amount of heavy-hole light-hole mixing is large. For these wide quantum well structures, the in-plane valence-band ground state energy is also “heavy,” i.e., for Fermi energies \( E_F > 2 \text{meV} \), the valence-band mass \( m_v = 0.35 m_0 \). By reducing the quantum-well width, the energy difference \( \Delta E_{\text{HH}} \) can be increased by quantum confinement. For GaAs/AlGaAs lattice-matched quantum wells, a maximum \( \Delta E_{\text{HH}} = 30 \text{meV} \) occurs near a quantum-well width of about 4.5 nm.

Valence-band nonparabolicity, for lattice-matched or strained-layer optoelectronic devices, means that with increasing carrier densities the valence-band mass also increases, changing laser threshold currents, modulation frequency response, magneto-optic parameters, device transconductance, etc. Thus a device which performs satisfactory at low power levels, i.e., low-carrier densities, may not perform as expected, under high power or high-current operation. Furthermore, device modeling codes predicting the optical or carrier response function should take into account any effects which can be attributed to valence-band mixing. As digital communication speeds increase, a knowledge of the energy-band dispersion curves is mandatory if these design criteria are to be modeled or achieved.

Recently, it was demonstrated that both the conduction-band and valence-band energy dispersion curves of modulation doped SSQW\(^4\) - 7 and LMSQW\(^8\) structures can be simultaneously determined by magnetoluminescence measurements from a single sample. These papers discuss the importance of the energy difference \( \Delta E_{\text{HH}} \) between the heavy and light-hole valence-bands in determining the degree of mixing between these two valence bands. Large values for \( \Delta E_{\text{HH}} \) not only give rise to the smallest ground-state in-plane light-hole masses, but also help to reduce the valence-band nonparabolicity.

The structures discussed here were prepared using molecular beam epitaxy. The quantum well barrier material was silicon-doped, with a spacing of about 8 nm between the ~3-nm-wide silicon-modulation layer and the quantum well. The SSQW structure (#BC042) consisted of a single 8-nm-wide In\(_{0.20}\)Ga\(_{0.80}\)As strained quantum-well and unstrained GaAs barriers. The energy difference \( \Delta E_{\text{HL}} \) between the heavy-hole and light-hole valence-bands, which includes contributions from both strain effects and quantum confinement, is about 60 meV. The 4-K two-dimensional carrier concentration \( N_{2d} \) and mobility \( \mu \) are respectively \( 5 \times 10^{11} \text{cm}^{-2} \) and \( 1.2 \times 10^4 \text{cm}^2/\text{Vsec} \). The LMSQW GaAs/AlGaAs structure (#G0260) has a 4.5-nm-wide GaAs quantum well with lattice-matched Al\(_{0.25}\)Ga\(_{0.75}\)As barriers, and as previously mentioned, the heavy-hole and light-hole valence-band energy difference \( \Delta E_{\text{HL}} = 30 \text{meV} \). For the LMSQW and T \( T = 4 \text{K} \), \( N_{2d} = 6.6 \times 10^{11} \text{cm}^{-2} \) and \( \mu = 2.2 \times 10^4 \text{cm}^2/\text{Vsec} \). The magnetoluminescence measurements were made in the temperature range of 1.4 and 76 K, and the magnetic fields varied between 0 and 14 T. The luminescence measurements were made with an Argon-ion laser operating at 514.5 nm and CAMAC-based data acquisition system.\(^9\) The direction of the applied magnetic field is parallel to the growth direction, i.e., the resulting Landau orbits are in the plane of the quantum well. With this geometry, all measurements concerning the conduction and valence-band dispersion curves and masses refer to their in-plane values.

A free particle, with mass \( m \) and charge \( e \), moving in a magnetic field \( B \) forms quantized states, Landau levels, with an energy \( E = (n + 1/2)(eB/mc) \), in cgs units, where \( n \) is the Landau index, \( B \) is Planck's constant over \( 2 \pi \), \( c \) is the velocity of light, and \( h \) is the cyclotron energy. The distribution function for a degenerate two-dimensional electron gas (conduction-band states for a n-type material) is determined by the Fermi-Dirac statistics, but because of the very small number of photoinduced two-dimensional hole states, the distribution for the valence-band holes are governed by Maxwell-Boltzmann statistics. At high temperatures, where \( kT \) is much larger than \( \hbar \omega \), the \( n_v = 0, 1, 2, 3, ... \) valence-band Landau levels are populated and all magnetoluminescence transitions between the \( n_e \) and \( n_v \) Landau levels are allowed, obeying the selection rule \( \delta n_{ev} = (n_e - n_v) = 0 \). For these high temperatures, the interband luminescence transition energy \( E \) is given by

\[
E(n) = E_{\text{gap}} + \left( n + \frac{1}{2} \right) \frac{eB}{mc},
\]

where \( E_{\text{gap}} \) is the bandgap energy, \( \mu \) is the reduced mass.
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\( (\mu^{-1} = m_c^{-1} + m_v^{-1}) \) where \( m_c \) and \( m_v \) are respectively the conduction or valence-band effective masses expressed in terms of the free electron mass \( m_0 \). In this paper we assume that the sample temperature is always less than the Fermi temperature, \( kT_f = E_f \), of the degenerate two-dimensional electron gas.

A schematic showing these allowed transitions for a n-type structure is shown in the right side of Fig. 1. The Fermi energy \( E_f \), the bandgap energy \( E_{\text{gap}} \), and the Landau level indices \( n \) are also indicated in the figure. For large magnetic fields and low temperatures \( (h\omega \gg kT) \) only the \( n_v = 0 \) valence-band Landau level is populated. Here, the PL transition between the \( n_c = 0 \) and \( n_v = 0 \) Landau level is allowed while transitions between the higher energy conduction-band Landau levels \( n_c = 1, 2, 3, \ldots \) and the \( n_v = 0 \) ground state valence-band Landau level are zeroth-order forbidden, but are observable due to higher-order ionized-

![Figure 1](image1.png)

**Figure 1.** A schematic representation for the Landau levels in a n-type quantum well. The left side of the figure is the low temperature case, \( \delta E_v \gg kT \), and the right side is the high temperature condition \( \delta E_v \ll kT \).

![Figure 2](image2.png)

**Figure 2.** Magnetoluminescence spectra (\( B = 5.75 \) T) at two temperatures, 4 and 76 K, for an n-type InGaAs/GaAs SSQW showing the allowed, \( \delta n_v = 0 \), and the \( \delta n_v \neq 0 \) zeroth-order forbidden transitions. The energy axes of the two spectra have been shifted in order to compare them.

impurity scattering processes. The left side of Fig. 1 shows the energy level diagram for this case.

Two magnetoluminescence spectra (\( B = 5.75 \) T) at 4 and 76 K at are shown in Fig. 2. The origins of the energy axes of the two spectra have been adjusted in order to allow a comparison of the spacing between the magnetoluminescence transitions. For 4 K, \( E_{\text{gap}} = 1330.1 \) meV while at 76 K, \( E_{\text{gap}} = 1321.1 \) meV. The indices \( n_c \to n_v \) for each peak are labeled in the figure. As can be seen in Fig. 2, all observed transitions for the 76 K data are allowed, i.e., \( \delta n_{cv} = 0 \), while for the 4.2 K data, the only zeroth-order allowed peak is the \( 0 \to 0 \) transition. Because of the Maxwell-Boltzmann statistics for the holes, the energy dependence of the 76 K magnetoluminescence peak-amplitudes are also governed by Maxwell-Boltzmann distribution function. An analysis of the energy dependence of the peak-amplitudes for this spectrum yields a temperature of about 80 K, which is in good agreement with the expected temperature of liquid nitrogen. A theoretical treatment of the energy dependence of the amplitudes of the zeroth-order forbidden transitions has been performed by Lyo and data shown in Fig. 2 is in good agreement with his calculation.

As is obvious from the left-hand side of Fig. 1, where \( h\omega_v \gg kT \), the energy difference \( \delta E \) between the \( E(n_c) \) and \( E(n_c-1) \) magnetoluminescence peaks depends only on the conduction-band cyclotron energy \( h\omega_c \). Setting \( n_c = 0 \) and using (1), the magnetoluminescence transition energy \( E(n_c) \) is given by in terms of the respective conduction and valence-band cyclotron energies as

\[
E(n_c) = E_{\text{gap}} + \left( n_c + \frac{1}{2} \right) h\omega_c + \frac{1}{2} h\omega_v, \tag{2}
\]

where \( n_c = 0, 1, 2, 3, \ldots \). Thus, utilizing low temperatures and measuring the energy differences as a function of magnetic field, (2) provides a method for obtaining all the information about the conduction band energy dispersion curves.

Figure 3 shows the derived low-temperature-derived conduction-band dispersion curve for the InGaAs/GaAs SSQW. The method (and justification) used relating the magnetic field \( B \) to the wavevector \( k \) has been adequately discussed. The maximum value of the wavevector \( k \) of about 3% of the Brillouin zone is determined by the conduction-band Fermi energy \( E_F \) of about 35 meV. The minimum wavevector determinations are limited by our ability to distinguish magnetoluminescence peaks at low magnetic fields. The conduction-band dispersion curve is
found to have a small nonparabolic correction with the zone center conduction-band mass $m_c \sim 0.067m_0$ and at the Fermi energy $m_c \sim 0.069m_0$. Nonparabolic effects upon the cyclotron resonance measured conduction-band masses have been discussed in detail and the magnetoluminescence results presented here are in agreement with that derived by conduction-band cyclotron resonance.

With a knowledge of the conduction-band dispersion curve, we can, using (1), derive the valence-band dispersion curve by performing 76-K magnetoluminescence measurements and analyzing the zeroth-order allowed transition peaks as a function of magnetic field. The valence-band data is shown in Fig. 4 and it is evident that the dispersion curve is nonparabolic. For the range of data shown in the figure, the valence-band effective mass $m_v$ for the SSQW structure BC042 varies between a zone-center 0.11$m_0$ to about 0.3$m_0$ at $E_v(k) \sim 20$ meV. The solid line drawn through the valence-band data is a best-fit nonparabolic curve to the data of the form

$$E(k) = \left(\frac{\hbar^2 k^2}{2m_v^0}\right) \left[1 - \frac{K}{E_{gap}} \left(\frac{\hbar^2 k^2}{2m_v^0}\right)\right],$$

where $m_v^0 = 0.11m_0$ is the zone center valence-band mass and $K \sim 16$ which is about an order of magnitude larger than measured for the conduction band. A comparison with a $k\cdot p$ calculation for the valence-band dispersion, which includes strain and valence-band mixing, is also shown in Fig. 4. The agreement between the $k\cdot p$ calculation and the data is reasonable in view of the fact that the $k\cdot p$ calculation did not include the contributions from the conduction band or split-off valence band. Magnetoluminescence determined valence-band dispersion curves for other samples with varying indium concentration and hence, with differing values for the heavy-hole light-hole valence band splitting $\Delta E_{HL}$, confirm that as $\Delta E_{HL}$ increases the valence-bands become more parabolic and that the ground state in-plane valence-band mass remains relatively constant.

The conduction and valence-band dispersion curves for the GaAs/AlGaAs LMSQW sample were also determined by both low and high temperature magnetoluminescence measurements. The results of the magnetoluminescence data analyses are shown in Figs. 5 and 6, where comparisons with the SSQW data are presented. The conduction-band dispersion curve (Fig. 5) for the LMSQW structure is again nearly parabolic with respective zone-center conduction-band masses of $m_c = 0.085m_0$. The increase to $m_c$ for the LMSQW conduction-band mass $m_c$ between the bulk GaAs $m_c = 0.065m_0$ to $0.085m_0$ is a result of the quantum confinement energy, i.e., increased bandgap energy. In order to verify these masses on our samples, the conduction-band masses for the SSQW and LMSQW structures were measured by far infrared cyclotron resonance techniques with the result that at their respective Fermi energies, $m_c = 0.069m_0$ for the SSQW sample and $m_c = 0.082m_0$ for the LMSQW structure in excellent agreement with the aforementioned magnetoluminescence data.

The LMSQW valence-band dispersion curve can be derived in the same manner as before, e.g., with a knowledge of the conduction-band dispersion curve the magnetic field dependent valence-band energy can be inferred from the high temperature (76 K) magnetoluminescence data using (1). The resulting valence-band dispersion curve for LMSQW sample is shown in Fig. 6. For the range of data shown in the figure, the valence-band mass $m_v$ for the SSQW structure varied between 0.11$m_0$ and
Figure 5. Conduction-band energy dispersion curves for the SSQW and LMSQW samples. The solid lines drawn through the data are best-fit parabolas with masses 0.067m0 (SSQW) and 0.085m0 (LMSQW).

Figure 6. Comparison of the valence-band energy dispersion curves for SSQW and LMSQW samples. The two lines through the data are best-fit of the non-parabolic curve given by (3).

0.22m0. For the LMSQW sample at small wavevectors, mv = 0.15m0 and for larger wavevectors (Ev = 10 meV) mv = 0.35m0. As previously mentioned, the heavy-hole light-hole energy separation ΔEH,L is about 60 meV for the SSQW structure and about 30 meV for the LMSQW sample. It is obvious from Fig. 6, that the valence-band dispersion curve for the SSQW structure is more parabolic than that of the LMSQW sample and this result is due to the increased heavy-hole light-hole energy separation ΔEH,L in the SSQW sample.

SPECTRAL SHIFTS

The PL line shape function in degenerate (doped) quantum wells has recently received attention as a measure of the 2D-carrier concentration. Recently two PL peaks were observed in heavily doped n-type quantum wells and the energy difference between the two peaks was used to measure the difference between the quantum-well's ground state and the first excited state energies. Care must be taken in interpreting the meaning the PL peak energy if this kind of information is vital to the analysis of the transport data as presented in reference 18. For example, spectral shift contributions to the PL line shape could be large and the PL peak energy may be shifted from the actual bandgap energy.

Most calculations for the PL spectral line shape function in doped quantum wells ignore the second-order contributions arising from carrier-impurity scattering. For modulation doped structures, the majority of ionized-impurities are restricted to the modulation layer, located some distance from the quantum well. A microscopic theory for the PL line shape for degenerate semiconductor quantum wells which includes the effects due to ionized-impurity scattering of the carriers is treated in detail. This paper shows that the experimental PL line shape is nearly accounted for by ionized-impurity scattering of the carriers. Also discussed were PL line shape changes as a function of temperature and also distance between the modulation-doped region and the quantum well.

An important result of the line shape calculation is the spectral shift of the line shape, i.e., the peak intensity of the PL spectrum is shifted by from the actual bandgap energy. A complete description of the origins of the spectral shift can be found in reference 19 where it is shown how ionized impurity scattering couples the large number of conduction-band carriers with energies greater than kT with those electrons within kT of the bottom of the band. The photo-generated holes have an energy of ~ kT which is much less than the conduction-band Fermi energy EF ~ 35 meV. The spectral shift is found to be strongly dependent upon the distance between the dopant-layer in the
barrier and the quantum well and also upon the carrier densities. For the SSQW structure discussed earlier, the spectral shift of the PL peak intensity is about 7 meV. However, because of the many contributions to the PL line shape, it is difficult to clearly demonstrate the importance, or size, of the spectral shift by merely presenting agreements between calculated and experimental line shapes.

Referring to the 76-K allowed PL spectrum shown in Fig. 2, the amplitude of the 0→0 peak is the larger than the other transitions. At very high magnetic fields, where the energy spacing between the peaks is large, the line shapes of the allowed transitions are almost gaussian, and the 0→0 transition is dominant. At low magnetic fields, the amplitudes of the Landau level transitions is a convolution of the inherent gaussian line shape with the zero-field line shape function. Thus if there are large spectral shifts, there may be situations where after convolving the two line shapes (gaussian and zero-field), the peak amplitude of the 1→1 transition is larger than the 0→0 transition. Figure 7 is a graphic demonstration for this situation. This data was part of the high temperature spectra used to obtain the valence-band dispersion curves for the SSQW structure. At slightly higher magnetic fields, the spectrum appears normal. The spectral shift is again estimated from Fig. 7 to be of the order of 7 meV.

Thus if zero-field PL spectra are being used to measure bandgap energies in heavily doped semiconductor quantum wells, correct interpretation of the PL line shape must be made to obtain meaningful numbers.

NARROW BANDGAP STRUCTURES

Mid-wave infrared photoluminescence was measured by operating a Fourier transform infrared (FTIR) spectrometer in a double-modulation mode. In the magnetoluminescence experiments, a fluoride optical fiber was used to transmit infrared light in the magnet cryostat. The PL photons were collected by the fiber and analyzed with the FTIR equipped with an InSb photodiode. All measurements were made in the Faraday configuration with the magnetic field parallel to the growth, (001), direction of the sample.

In narrow gap semiconductors, magnetoluminescence measurements are used to estimate effective masses and to identify the ground state of holes in heterostructures. Figure 8 shows spectra for a 9 nm/13 nm-layer-thicknesses InAs$_{0.91}$Sb$_{0.09}$/In$_{0.87}$Ga$_{0.13}$As strained-layer superlattice (SLS) (Fig. 8(c)) are compared with those for unstrained InAs$_{0.93}$Sb$_{0.07}$ (Fig. 8(b)) and InAs (Fig. 8(a)) alloys. Photoluminescence spectra for the SLS and alloys consist of a single peak in the 3-4 μm range, with linewidth ≤ 10 meV. In these unintentionally doped samples, excitonic behavior is revealed in the magneto-photoluminescence results. For all samples, the photoluminescence peak energy is insensitive to magnetic field for B < 2T, characteristic of a diamagnetic exciton, (see Fig. 9) and in the linear region observed at higher fields, the reduced mass values obtained from the free carrier approximation are consistently too large, due in part to the binding energy of the exciton. For each photoluminescence line, the reduced mass, $\mu$, obtained from the free electron-hole approximation for the 0→0 transition is indicated in the figure. The reduced mass of the SLS was less than that of the alloys.
because the in-plane hole mass is significantly decreased in the biaxially compressed InAsSb layers of the SLS.

Using measured parameters for InAs and semi-empirical expressions for high-field line shifts and magneto-exciton energies, we can estimate exciton binding energies and correct the reduced mass values. Including nonparabolicity and magneto-exciton contributions, the "linear" shift of the photoluminescence line at high magnetic field, $B$, is described by \[ \Delta E = \frac{\mu B}{\mu} \left( 1 - \frac{\mu \rho K B}{E_{\text{gap}} \mu} \right) - E_{\text{ex}}(B), \] where $K$ again is the nonparabolicity factor, $E_{\text{gap}}$ is the bandgap energy of the alloy or quantum well material, and $E_{\text{ex}}(B)$ is the magneto-exciton binding energy.

For the three-dimensional case \[ E_{\text{ex}}(B) = 1.6 R \left( \frac{\mu B^2}{\mu R} \right)^{\frac{3}{2}}, \] where $R$ is the exciton Rydberg or zero-field binding energy. Using $R = 1.8$ meV and $K = 1.6$ for InAs, a fit of the data yields $\mu = 0.023m_0$ and $\mu = 0.026m_0$ for InAs and InAs$_{0.93}$Sb$_{0.07}$ respectively. The InAs result is in good agreement with the predicted value for the InAs heavy hole exciton, $\mu = 0.022$. Again using the three-dimensional expression, the data for the SLS are described by a reduced mass $\mu = (0.017 \pm 0.001)m_0$, with an exciton Rydberg $R = (2.5 \pm 1.0)$ meV.

**CONCLUSIONS**

We have shown that magnetoluminescence measurement techniques is a powerful tool for performing single-sample simultaneous measurements of both the conduction and valence-band dispersion curves (and masses). We showed that for quantum-well devices the amount of heavy-hole light-hole splitting is the determining factor for valence-band nonparabolicities and that the larger the heavy-hole light-hole energy difference, the smaller the valence-band nonparabolicity. The experimental agreement with $k \cdot p$ calculations for the valence-band energies is good and with these dispersion curves, it is possible to model not only optoelectronic behavior, but also predict electronic phenomena which rely upon these dispersion curves. In particular, the amount of valence-band nonparabolicity can now be experimentally quantified and predictions for new material systems may be possible.

We also provided a graphical example of large spectral shifts by examining a high-temperature low-magnetic field spectrum of the SSQW data used for the first example.

For characterization of narrow bandgap semiconductors, magnetoluminescence was demonstrated at long wavelength ($< 5 \mu m$). "Free carrier-like" behavior is observed at moderate magnetic fields ($2 - 10$ T) in these low effective mass materials, and electron-hole effective masses can be easily measured. In our example, we demonstrate that the holes in an InAsSb/InGaAs SLS are confined to the $13/2, \pm 3/2>$ state of the InAsSb layer.

Thus in conclusion, magnetoluminescence experiments provide unique quantum well information over a wide range of semiconductor bandgap parameters, and are essential to characterize novel heterostructures containing narrow bandgap semiconductors.

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**REFERENCES**


