Photoluminescence and surface photovoltage spectroscopy characterization of highly strained InGaAs/GaAs quantum well structures grown by metal organic vapor phase epitaxy

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1. Introduction

Long wavelength semiconductor lasers are key components of optical communications, especially in local area networks and fiber-to-home applications. These lasers are required to emits at wavelengths longer than 1.20 μm [1] and to have a low fabrication cost. These long wavelength lasers are conventionally based on the InP material system. However, InP-based lasers have several drawbacks such as poor temperature characteristics and the lack of suitably distributed Bragg reflectors (DBRs) forming vertical cavity surface emitting lasers (VCSELs). In addition, InP-based lasers are not cost effective due to the expensive InP substrates. Several GaAs-based materials have been developed; including type II GaAsSb/GaAsN quantum wells (QWs) [2], InGaAs/GaAs quantum dots [3,4], and dilute-nitride materials [5,6]. However, the threshold current and electron confinement of type II QWs are relatively poor comparing with the conventional type I QW system. The quantum dot lasers also suffer from low material gain and consequently multi-stacks of quantum dot lasers are required to achieve a reasonable gain. The dilute-nitride materials are promising in this area, but the growth of these nitrogen-containing materials is quite challenging and the reliability of this novel material is still questionable. Therefore, the relatively simple and mature InGaAs/GaAs QW system has regained the attention by the scientific community to be a viable candidate for lasers operating in the range of 1.2–1.3 μm. Sung and Lin [7] have reported InGaAs/GaAs QWs lasers operating at 1.24 μm grown by molecular beam epitaxy (MBE) and Chen et al. [8] have reported 1.26 μm VCSELs grown by the metal organic vapor phase epitaxy (MOVPE). For such wavelengths a high concentration of indium is required, leading to a higher strain in the active region of the laser diode. Existence of strain also imparts an upper limit on the layer thickness and indium composition for pseudo-morphic growth of the InGaAs layer on GaAs. This so-called critical thickness, once exceeded can result in threading dislocations and lead to an inferior luminescence efficiency of InGaAs/GaAs QWs. On the other hand, the highly compressive strain between InGaAs

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and GaAs layer can also lead to transition from a uniform layer by layer two-dimensional growth pattern to a three-dimensional island growth mode [9]. Therefore, the emission wavelength of InGaAs/GaAs QWs is quite limited. To avoid the generation of misfit dislocations or transition to three-dimensional growth mode, optimizing the growth conditions of InGaAs/GaAs QWs has become an important issue. Strained InGaAs QWs with indium content exceeding 40% have been reported by using only conventional sources in MOVPE [10].

Various spectroscopic techniques have been widely used to investigate strained InGaAs/GaAs QWs to obtain useful information associated with the growth of QWs. Photoluminescence (PL) is known as one of the most useful optical method for the semiconductor structure characterization, with its powerful and sensitive ability to detect impurity and defect signatures in semiconductors [11]. Very often the PL spectra can also help to determine fundamental transitions of QWs. On the other hand, the surface photovoltage spectroscopy (SPS) technique has been reported to be able to provide additional information of the QWs. SPS has been well established as a powerful technique for studying electronic states of semiconductors [12,13]. A better understanding of the influence of indium composition on the optical properties of highly strained InGaAs/GaAs QWs grown by MOVPE using both PL and SPS techniques can be accomplished and should be beneficial for the crystal growers. However, to date, only limited work has reported the use of complementary PL and SPS techniques [14] on the study of carrier dynamics of highly strained InGaAs/GaAs QWs grown by MOVPE.

In this work, we present a systematic temperature dependent PL and SPS characterization, in the range between 20 and 300 K, of a series of highly strained InGaAs/GaAs quantum well (QW) structures grown by MOVPE with different indium compositions in the range 0.395 ≤ x ≤ 0.44. An S-shaped behavior for the temperature dependent shift of the PL emission is discussed and analyzed. A comprehensive analysis of the anomalous phenomena appeared in the low temperature surface photovoltage (SPV) spectra enables us to determine the band alignment and an accurate evaluation of the conduction band offset of the QW structures. The results demonstrate the usefulness of PL and SPS as techniques for the contactless and nondestructive characterization of highly strained InGaAs/GaAs QW structures.

2. Experimental description

The InGaAs/GaAs QWs were grown on n+ GaAs (100) substrates using MOVPE in an Aixtron 200 horizontal reactor with gas-flow rotation. Under investigations were four samples with indium composition of 39.5%, 41%, 42.5%, and 44%, and designated as samples I, II, III and IV, respectively. The structure of QWs contains a 500 nm GaAs buffer layer, two periods of InGaAs/GaAs (85Å/300Å) QWs. Precursors used for the InGaAs QWs were trimethylindium (TMIn), triethyl-gallium (TEGa), and tertiarybutylarsine (TBA). The growth temperatures of the buffer layer and QWs were 725 and 475 °C, respectively. The thicknesses of well and barrier, and the composition of indium in InGaAs layer were determined by high-resolution X-ray diffraction measurements with a Bede D1 four crystal diffractometer.

The PL spectra were excited using the 512 nm line (~50 mW) of a Nd:YAG laser. The luminescence signals were analyzed by using a Jobin-Yvon “TRIAX 550” spectrometer equipped with a “SIMPHONY” charged-coupled device camera. In the SPS measurement, the contact potential difference between the sample and a reference metal grid electrode was measured in a capacitive manner as a function of the photon energy of the probe beam by holding the grid fixed and chopping the probe beam with a 200 Hz. A soft contact mode was used to enhance the photovoltage signals [15]. The method consisted of placing a thin indium wire around the edge of the sample surface with the metal grid pressing lightly on top. It is known that, under low optical excitation, the SPV is proportional to the absorption coefficient. Therefore, by monitoring the potential change when monochromatic light impinges on surface of the sample, it is possible to obtain relevant information of the joint density of states. A 150 W quartz-halogen lamp filtered by a Photon Technology Inc. 0.25 m monochromator provided the monochromatic light. The incident beam was maintained at a constant level of ~10⁻⁵ W cm⁻². A beam splitter was placed in the path of the incident light. The intensity of this radiation was monitored by a power meter and was kept constant by a stepping motor connected to a variable neutral-density filter placed in the path of the incident light. The induced SPV on the metal grid was measured with a copper bottom as the ground electrode, using a buffer circuit and a lock-in amplifier. The in-phase signal, measured with respect to the light modulation, recorded from a dual phase lock-in amplifier was taken as the SPV signal. For temperature dependent measurements, a closed-cycle cryogenic refrigerated equipped with a digital thermometer controller was used. The measurements were recorded over a temperature range of 20–300 K with a temperature stability of 0.5 K or better.

3. Results and discussion

The temperature dependence of the PL spectra of samples I, II, III, and IV are depicted in Fig. 1(a)–(d). As shown in the PL spectra, only one transition feature is revealed and identified as the lowest subband transition 11H (first electron to first heavy-hole subbands) in the QWs. It can be seen that this energy feature has an energetic redshift with an increase in indium content due to the reduction in the band gap energy of the InGaAs layer. For all samples the spectral linewidth increases with increasing temperature. As the general property of most semiconductors, when the measuring temperature is raised, the spectral feature gets broader due to phonon related homogeneous broadening. In addition, a correlation is also revealed between the indium concentration and the PL linewidth: the higher the indium concentration, the broader the PL linewidth and particularly the linewidth dramatically increased as indium content is beyond 0.41. The substantial inhomogeneous broadening in samples III and IV results from local structural fluctuations and is attributed to the incorporation of more indium atoms into the InGaAs QWs.

Displayed in Fig. 2 is the temperature dependent peak position of PL spectra of samples I, II, III, and IV in the temperature range from 20 to 300 K. It is noticed that decreasing the temperature to ~100 K leads to a blueshift of the PL maximum and then nearly saturates at lower temperature for samples I and II. More interestingly, a so-called S-shaped behavior is observed in samples III and IV, i.e., a red-blue-red-temperature dependent shift of the PL emission, similar to the ternary nitrides InGaN and AlGaN [16,17]. Such anomalous behavior suggests the low-temperature luminescence arises from the recombination of excitons localized at potential fluctuations caused by an increasing degree of compositional and structural disorder with increasing indium concentration in QWs, which will be explored later.

Fig. 3(a)–(d) shows the SPV spectra and the normalized first derivative of the SPV (DSPV) spectra at room temperature for samples I–IV, respectively. All spectral features (11H, 12H, 11L, and 22H) in the range of 0.90–1.30 eV are governed by absorption derivative of the SPV (DSPV) spectra at room temperature for samples I–IV, respectively. All spectral features (11H, 12H, 11L, and 22H) in the range of 0.90–1.30 eV are governed by absorption

Fig. 1. Temperature dependence of PL spectra for In$_x$Ga$_{1-x}$As/GaAs QW samples with indium content: (a) $x = 0.395$, (b) $x = 0.41$, (c) $x = 0.425$, and (d) $x = 0.44$, respectively. The arrows indicate the peak positions of the lowest subband transition 11H at different temperatures.

Function [18]:

$$
\left( \frac{\Delta V_{SPS}/\Delta E}{V_{SPS}} \right) = Re \sum_j C_j e^{\theta_j (E - E_j + i \Gamma_j)^{-m}},
$$

where $C_j$, $\theta_j$, $E_j$, and $\Gamma_j$ are amplitude, phase, transition energy, and broadening parameter of the spectral features, respectively. The parameter $m$ is related with the nature of optical transitions. The value of $m = 2$ corresponds to the first derivative of an excitonic dielectric function with a Lorentzian absorption profile. The DSPV spectra are drawn with solid lines and the peak positions of QW transitions obtained after fitting with Eq. (1) are indicated by arrows in Fig. 3. For purpose of comparison, the energy values of four QW transitions for samples I–IV along with the experimental results from PL measurements are summarized in Table 1.

Many fine QW features are exhibited in the DSPV spectra when compared to the PL spectra. The signatures of higher lying features not visible in PL spectra are more pronounced in the DSPV spectra than those in SPV spectra. It is clearly seen that the spectral features of InGaAs QW transition redshift and broaden with an increase in indium content supporting the PL results. The lowest transition feature 11H in the DSPV spectra lies in close proximity to the energy feature in the corresponding PL spectra, as shown in the inset of Fig. 3. The transition energy and the spectral broadening parameter of the 11H feature in DSPV spectra for sample I are evaluated to be 1.039 eV, and 10 meV, respectively. The corresponding values for sample II are 1.024 eV, and 13 meV, 1.012 eV and 29 meV for sample III, and 0.994 eV and 29 meV for sample IV, respectively. Note that the sharpness and the exciton enhancement of the 11H transition for samples I and II is clearly visible, reflecting the higher homogeneity of the InGaAs layer. In contrast, a drastic increase in the values of the spectral broadening parameter is observed for samples III and IV. The possible origins for inhomogeneous broadening are the presence of In clusters and/or fluctuations in the In composition at the QW interfaces, which leads to a loss of sharpness of the 11H transition. A relatively weak spectral amplitude for a parity forbidden 12H transition is also observed in the DSPV spectra. The appearance of 12H transition feature is further confirmed by contactless electroreflectance (CER) measurements on the same set of samples. The relaxation of the selection rule is most likely due to the distortion of the symmetry of the wavefunctions in the presence of built-in electric field in the QWs. The 11L transition is attributed to a type-II absorption between electrons in the strained

Fig. 2. Temperature dependence of the 11H transition energies of PL spectra for samples I–IV. Note that an S-shaped temperature dependent shift of the PL emission occurs for samples III and IV.

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InGaAs layer and light holes confined in the GaAs layer for reasons stated below.

Plotted in Fig. 4(a)–(d) is the evolution of the experimental SPV spectra of samples I–IV as function of photon energy at several temperatures between 20 and 300 K. As is the case for general semiconductor properties, all QW-related transitions show a blueshift with a decrease in temperature. Comparing to the higher temperature spectra, a distinct difference for the 11L feature can be noticed for temperature below 100 K. This observation indicates that the characteristic of the 11L feature is different from that of the other spectral features. A most probable explanation is that the difference in the band configuration for heavy-hole (HH) and light-hole (LH) bands is due to band splitting introduced by a highly compressive strain, thereby causing the LH valence band to form a type-II configuration and the HH and LH to be confined in different regions of the QWs.

The working characteristic of SPS is a two-step process, involving both absorption and escape of carriers from the QW. Thus, at the QW spectral region, escape of carriers from the well is a crucial step for SPV formation. Two main processes of charge separation are responsible for the SPV formation. One is by the thermal emission of carriers out of QWs, followed by electric field separation and the other is by carriers tunneling through potential barrier, followed by electric field separation [19]. When the temperature is lowered, the thermal activation process decreases and the tunneling effect becomes the dominant mechanism contributing to the SPV. As compared to HH-related features, there could be significant electric field assisted tunneling for the 11L transition in the QW region (which acts like a potential barrier) due to a smaller barrier height and barrier width as illustrated in Fig. 5. These events render the wave function of LHs to be delocalized in the QWs and consequently resulted in the SPV magnitude being less affected by the influence of temperature. Regarding the phenomenon of a reversal of the spectral line shape at temperature below 100 K, it has been ascribed to the resultant effect of carrier tunneling in conjunction with the charge trapping by defect states situated at the buried interfaces.

Since the direction of electric field is not altered at low temperature, the LHs will move in the same direction as the HHs. Therefore, it seems unlikely for the 11L transition to have such a large phase change due solely to the carrier tunneling effect. To concur well with the experimental observation, an additional mechanism in the SPV formation processes has to be taken into account. Few studies showed evidence (e.g., Refs. [20] and [21]) that the defect states are most likely to play an important role in the SPV phase change. The separation of carriers within the QWs themselves with possible capture into interface traps is therefore thought to be responsible for the observed spectral phase change at low temperature.

### Table 1

<table>
<thead>
<tr>
<th>Features Sample</th>
<th>( x = 0.395 )</th>
<th>( x = 0.410 )</th>
<th>( x = 0.425 )</th>
<th>( x = 0.440 )</th>
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<td>PL</td>
<td>Cal.</td>
<td>DSPV</td>
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<td>1.024</td>
<td>1.027</td>
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<td>–</td>
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<tr>
<td>11L</td>
<td>1.176</td>
<td>–</td>
<td>1.165</td>
<td>–</td>
</tr>
<tr>
<td>22H</td>
<td>1.212</td>
<td>–</td>
<td>1.201</td>
<td>–</td>
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</tbody>
</table>

5

Fig. 4. Temperature dependence of SPV spectra for four In$_x$Ga$_{1-x}$As/GaAs QW samples with different indium content: (a) $x=0.395$, (b) $x=0.41$, (c) $x=0.425$, and (d) $x=0.44$, respectively. A reversal of the spectral lineshape of the 11L transition is clearly seen below 100 K and the dashed line is a guide to the eye.

for the phase change. It has been pointed out that there is a significant probability for the optically generated LHs to tunnel across the InGaAs/GaAs QW interfaces in which the trapping centers emerge as a result of alloy disorder. Trapping centers capture carriers and then release them back to the band from which they are captured. Excess electron–hole pairs are generated by light. Instead of recombining directly, some LHs are temporarily captured or trapped. They are subsequently re-emitted into the valence band, and finally recombine with the conduction electrons. Particularly at low temperature, the LHs stay longer in the traps and introduce the phase retardation of the SPV signal. The optical absorption in the interfaces within the sample may contribute to the measured SPV signal because the potential of the free surface is linked to any other illuminated region, no matter how deep it is within the sample, as the energy bands are serially connected. Hence, the sensitivity of SPV measurements to buried interfaces may lead to a reversal of SPV spectral lineshape. The above analysis shows that the band configuration is of mixed type, i.e., conduction-HH band is type I and conduction-LH band is type II. This facilitates the identification of the origins of all optical transitions.

In order to obtain theoretical support for our experimental results, the theoretical calculations, taking into account the quantum confinement effect and strain as well as the binding energy, is performed to identify the nature of the observed spectral features and to explain their dependence on the indium composition.

The details of the strain-induced changes to the band structure of layered semiconductor structures have been presented elsewhere and will only be briefly reviewed here [22,23]. When grown on a GaAs buffer, the In$_x$Ga$_{1-x}$As layers sustain a biaxial in-plane compression and a corresponding extension along the [001] direction.
and LH band gap of the bulk constituent material of the well is for the end compounds of InAs and GaAs. For calculation of the sor, effective mass, and energy band component are estimated by to the unstrained valence band. In the calculation, the strain ten-
acy of the valence band edge at the center of the Brillouin zone
the lattice mismatch strain is to increase the energy gap of the

\[
\varepsilon = \frac{q_{\text{InGaAs}} - q_{\text{GaAs}}}{q_{\text{GaAs}}},
\]

where \(q_{\text{InGaAs}}\) and \(q_{\text{GaAs}}\) are the lattice constants of \(\text{In}_x\text{Ga}_{1-x}\text{As}\) and GaAs, respectively. The strain alters the band structure of the \(\text{In}_x\text{Ga}_{1-x}\text{As}\) QWs. The strain dependence of the conduction (C) to
HH and LH band gap of the bulk constituent material of the well is thus

\[
E_{\text{C,HH}}^0 = E_0([\text{In}_x\text{Ga}_{1-x}\text{As}]) + \delta E_H - \delta E_S,
\]

(3a)

\[
E_{\text{C,LH}}^0 = E_0([\text{In}_x\text{Ga}_{1-x}\text{As}]) + \delta E_H + \delta E_S - \frac{1}{2} \cdot (\delta E_S)^2 \cdot \Delta_0.
\]

(3b)

In Eqs. (3a) and (3b), \(E_0([\text{In}_x\text{Ga}_{1-x}\text{As}])\) is the unstrained direct band gap of the \(\text{In}_x\text{Ga}_{1-x}\text{As}\), assumed to follow the relation

\[
E_0(x) = (1.422 - 1.53x + 0.45x^2)\text{ eV}
\]

with \(x\) being the indium mole fraction at 300 K [24] and \(\Delta_0\) is the spin–orbit splitting. The quantities of hydrostatic-pressure shift \(\delta E_H\) and uniaxial stress-induced valence band splitting \(\delta E_S\) are given by

\[
\delta E_H = 2a \cdot \left[ \frac{C_{11} - C_{12}}{C_{11}} \right] \varepsilon,
\]

(4a)

\[
\delta E_S = b \cdot \left[ \frac{C_{11} + 2C_{12}}{C_{11}} \right] \varepsilon.
\]

(4b)

The parameters \(a\) and \(b\) are the interband hydrostatic-pressure and uniaxial deformation potentials, respectively, and \(C_{ij}\) are the elastic-stiffness constants. The LH valence band has a nonlinear strain dependence because of the strain-induced coupling with the spin–orbit split-off band. Since \(\varepsilon < 0\) for \(\text{InGaAs}/\text{GaAs}\), the effect of the lattice mismatch strain is to increase the energy gap of the \(\text{InGaAs}\) (hydrostatic-pressure component) and split the degeneracy of the valence band edge at the center of the Brillouin zone with uplift of the HH band and down shift of the LH band, relative to the unstrained valence band. In the calculation, the strain tensor, effective mass, and energy band component are estimated by linearly interpolating the values taken from the literature [24,25] for the end compounds of \(\text{InAs}\) and \(\text{GaAs}\). For calculation of the quantized transition energies, the time–independent effective mass Schrödinger equation is solved for electron, HH, and LH wells separately, obeying the boundary conditions for the wave functions.

With the procedure outlined above, we are able to calculate all observed transition energies. For simplicity, we have assumed the same binding energy for all optical transitions except for the 11L transition. Since the oscillator strength of the allowed excitonic transition is proportional to the probability of finding the electrons and holes in the same unit cell [26], it is difficult to form an exciton in this case, where the electrons are confined in the well region and the LHs are in the barrier region. Therefore the binding energy for the 11L transition can be neglected. The 1s–exciton binding energy for the 11H transition has been taken to be equal to 5 meV in a variational approach [27]. The value of the strained conduction band offset ratio \(Q_c (\Delta E_c/\Delta E_g)\) is used as an adjustable parameter. In Fig. 6, the calculated transition energies against \(Q_c\) of four possible optical transitions are given with parameters of sample I. It can be seen that the lower–lying transitions 11H and 12H are insensitive to band offset because HHs are more deeply confined within the QWs than the conduction electrons due to the heavier mass. On the other hand, the transition energies of 11L the 22H transitions have strong dependence on \(Q_c\), which enable us to accurately determine the value of the band offset. The calculated results have shown that the LH bandlineup has changed from type I into type II when \(Q_c\) is above 0.54. Note that the energy redshift of the 11L transition exhibits a rapid increase for type II band lineup (\(Q_c > 0.54\)) when compared with that for the type I case. This indeed represents a property of a type II QW. For \(Q_c = 0.54\), the LH valence band edge in \(\text{InGaAs}\) QWs emerges with the valence band maximum of GaAs barrier. As the value of \(Q_c\) is greater than 0.54, the LH valence subband resides in the GaAs valence band continuum, causing the LHs to be mainly confined in the barrier region. A thicker barrier width (300 Å) has a tendency of shifting the quantized energy level of the first LH subband closer to the band edge of the GaAs barrier, i.e., the energy level is essentially unchanged with the variation of \(Q_c\). As the energy level of the first conduction subband is continuously lowered by the increase of \(Q_c\), an enhanced reduction in the 11L transition energy is expected. For sample I, a value of \(Q_c = 0.67\) fits all the observed transitions as indicated in the shaded region of Fig. 6. The same analysis is performed for all other samples and we have obtained the best agreement between experiments and theoretical calculations for \(Q_c = 0.67 \pm 0.02\). This experimentally determined \(Q_c\) value is comparable to those reported by other groups varying over a wide range from 0.6 to 0.81 for the \(\text{InGaAs}/\text{GaAs}\) system [28,29].
Table 1 lists the experimental and the calculated transition energies for the four samples. A good agreement between theoretical calculation and experimental measurements can be observed and hence support the assignment of the observed spectral features.

So far the interplay between the S-shaped PL property and a reversal of SPV spectral lineshape at low temperature has been demonstrated, and is found to be more relevance with the existence of defect states. In order to gain a more complete understanding of this behavior, the complementary SPV spectroscopic technique is re-utilized in the temperature dependent investigation of the highly strained InGaAs/GaAs QWs.

Fig. 7(a)–(d) plots the energy of the 11H transition extracted from the above PL and SPV spectra. The temperature dependence of the transition energy as given by the behavior of absorption in the SPV is well described by Varshni’s formula (dashed line). For the PL spectra there is an energy shift toward the lower energy with respect to the SPS at low temperatures. The PL technique is usually affected by the localized states at low temperatures due to its emission like character. As a result, at low temperatures, the accuracy of the ground state transition energy from the PL spectra is poor and cannot yield reliable determination in the transition energy. The shift between the PL maximum and the first peak of the SPV is well described by Varshni’s semiempirical relationship. The values of the Stoke’s shift at 20 K for samples I–IV are 4, 9, 15, and 23 meV, respectively. A drastic increase in the Stoke’s shift with increasing indium composition can be explained by a higher defect concentration in these samples, since increasing indium content leads to a stronger influence on defect-related non-radiative processes. For sample IV, the PL peak energy position shifts to lower energy between 20 and 50 K, and then increases between 50 and 77 K. At the temperature above 77 K, the peak position shifts again to lower energy. The anomalous temperature-induced emission shift can be explained in terms of coexistence and competition between localized and delocalized states. The luminescence stems from the recombination of excitons localized at potential fluctuations caused by disordered arrangement of the indium atoms on host lattice that can create the band-tail states in the density of states. The localized states dominate on the lower temperature domain while the delocalized states dominate over the higher temperature domain. Between 20 and 50 K a redshift appears, because the excitons gain sufficient thermal energy to overcome small potential barriers and become trapped in adjacent lower levels of the density of states before they recombine. The subsequent blueshift is a result of thermal population of higher energy states of the density of states. At even higher temperature, the temperature shift of the emission is mainly determined by the behavior of the effective band gap of QWs, thus exhibiting a similar relation between temperature and transition energies as that of absorption-like SPV spectra (see Fig. 7). On the basis of the above analysis, we suggest that indium has a tendency to form localized clusters at QW interface as indium content exceeds 40% rather than forming a uniform distributed ternary compound in the well region. The segregation of indium to the growth interface forming unevenly distributed clusters is the cause for the anomalous temperature dependent behavior of the observed PL spectra.

4. Summary

We have performed a detailed temperature dependent SPS and PL investigation of highly strained In$_x$Ga$_{1-x}$As/GaAs QW structures grown by MOVPE with different indium composition (0.395 ≤ x ≥ 0.44), in the temperature range of 20–300 K. The PL spectra show broadened and red-shifted peaks with increasing indium composition. Compared to the PL, the SPS stands out by allowing the simultaneous measurement of a great variety of optical transitions. The interband transition energies are determined via a lineshape fit to DSPV spectra and exhibit a redshift with increasing indium composition. A considerable increase in the spectral linewidth for higher indium composition samples results from the presence of indium clusters at the QW interfaces.
unusual features exhibited in temperature dependent SPV spectra propose a determination of the band lineup of our QW structures. The process of separation of carriers within the QWs themselves with possible capture of carriers into interface traps plays an important role in the phase change of the SPV signature. Numerical calculation for excitonic transition energies are in good agreement with experimental results, confirming the determination of $Q_c$. The anomalous S-shaped temperature dependent PL spectra have been interpreted by competitive coexistence of localized and delocalized excitons states. The effectiveness of SPS and PL techniques as contactless and nondestructive optical diagnostic methods for the characterization of highly strained QW structures has been demonstrated.

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