Chapter 7

Optical properties of InP/GaAs type-II quantum well superlattice structures

7.1 Introduction and background

Various QW and QD superlattice structures have been investigated in the literature for the detector and solar cell applications [180–183]. Keeping this in mind, we have grown fully strained and partially relaxed InP/GaAs type-II QW superlattice structures by MOVPE technique. Their structural properties and surface morphology have been studied in detail as discussed in chapter 6. In this chapter, optical properties of InP/GaAs type-II QW superlattice structures are discussed. A systematic study of optical properties is essential for the realization of optoelectronic devices like near infrared laser diodes, infrared photo detectors and solar cells based on this material combination.

Apart from this, temperature dependence of the band gap (GS transition energy) for bulk semiconductors (quantum structures) provides important information about the electron phonon interaction [79]. It has been seen that the GS transition energy for thick QWs follows the temperature dependence of the band gap of relevant bulk
material [160,161]. On the other hand, temperature dependence of the GS transition energy is considerably modified by the temperature dependence of the confinement potential and follows the band gap variation of barrier material in case of ultrathin QWs [8]. We have found that the temperature dependence of transition energy of InP/GaAs type-II ultrathin QWs follows the band gap variation of GaAs barrier material [170], which was indicated by the PL measurements as discussed in chapter 5. However, modulation spectroscopy (PR and ER) is a more powerful technique, which has been extensively used to accurately measure the transition energy of thick QWs [85,179], QDs [184,185] and even ultrathin QWs [8]. SPS is another technique available in the literature, which is also based on optical absorption measurements similar to modulation spectroscopic technique. Recently, SPS is applied to study the optical properties of InP/GaAs type-II multiple QDs, where features related to wetting layer and QDs are found at 73 K [186]. However, there is no report of PR, ER and SPS characterization of InP/GaAs type-II quantum structures at room temperature. Therefore, in this chapter, InP/GaAs superlattice structures are characterized by using PR, ER and SPV techniques, where superlattice related excitonic transition is observed in all the strained samples. A thermally active trap level behavior is found in temperature dependent PR measurements. Broadening parameter of superlattice feature in the high temperature region is governed by the scattering of electrons with the LO phonons. It is interesting to note that the built-in electric field in superlattice structure considerably modifies the temperature dependence of superlattice transition energy. For smaller values of electric field, transition energy follows the temperature dependence of band gap of GaAs barrier layer, while it decreases at a faster rate than that of the GaAs material for larger values of built-in
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Table 7.1

<table>
<thead>
<tr>
<th>Sample No</th>
<th>$L_w$ (Å)</th>
<th>$L_b$ (Å)</th>
<th>$N$</th>
<th>Transition energy (eV)</th>
<th>Broadening parameter (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL1</td>
<td>1.8</td>
<td>45</td>
<td>7</td>
<td>1.501 ± 1</td>
<td>7.6 ± 1</td>
</tr>
<tr>
<td>SL2</td>
<td>2.5</td>
<td>46</td>
<td>7</td>
<td>1.489 ± 1</td>
<td>17.3 ± 1</td>
</tr>
<tr>
<td>SL3</td>
<td>3.3</td>
<td>46</td>
<td>7</td>
<td>1.473 ± 1</td>
<td>9.5 ± 1</td>
</tr>
<tr>
<td>SL4</td>
<td>3.3</td>
<td>45</td>
<td>11</td>
<td>1.470 ± 1</td>
<td>17.0 ± 1</td>
</tr>
<tr>
<td>SL5</td>
<td>3.3</td>
<td>45</td>
<td>30</td>
<td>1.471 ± 1</td>
<td>14.3 ± 1</td>
</tr>
</tbody>
</table>

Table 7.1: Structural parameters like superlattice period $N$, thicknesses of InP QWs ($L_w$) and GaAs barrier layer thickness ($L_b$) of fully strained superlattice structures. Transition energy and broadening parameter of the superlattice feature as determined from the low temperature (10 K) PR measurements.

electric field.

7.2 Experimental procedure

InP/GaAs superlattice structures were grown in a horizontal MOVPE reactor (AIX-200) with a rotating substrate holder on nominally (0 0 1) oriented n$^+$-GaAs substrate at 50 mbar of reactor pressure as discussed in chapter 6. The structural parameters of studied superlattice structures like InP QW thickness ($L_w$), GaAs barrier layer thickness ($L_b$), and the superlattice period ($N$) are listed in the Table 7.1.

For PR measurements, light from a 100 W quartz tungsten halogen (QTH) lamp dispersed by a 1/4 m monochromator with a 4 nm band pass was used as the probe beam. The chopped laser beam of a He-Ne laser (pump beam) was used to modulate the built in surface electric field of the sample. Change in the reflectivity ($\Delta R$) due to the modulation as a function of wavelength of probe beam was measured by using a lock-in amplifier at the chopping frequency of the pump beam (330 Hz). The dc part of signal from Si photodiode, which is proportional to the reflectivity (R), was also extracted, and the final spectrum $\Delta R/R$ was obtained by dividing the
ac signal by dc signal. ER measurements were carried out in soft-contact mode by sandwiching the sample between a flat copper electrode and a transparent conducting glass (TCG) coated with indium-tin-oxide, which acts as the second electrode. The surface electric field was modulated by applying an ac voltage of 1.0 V at a frequency of 180 Hz. Source of probe beam was same as it was for the PR measurements. SPS measurements were performed in the chopped light geometry under soft contact mode [132]. Periodic excess carrier generation and subsequent redistribution changes the surface potential, which was picked up by a TCG electrode. A 100 W quartz-tungsten-halogen lamp along with a 1/4 m SCIENTECH monochromator was used as the light source. The ac photovoltage signal was measured with a lock-in amplifier.

### 7.3 Low temperature photoreflectance spectroscopy

Optical properties of fully strained superlattice structures are investigated by carrying out PR measurements at low temperatures (10 K). Energy and broadening parameter of the observed transitions are determined by fitting the experimental PR data by Aspens’s line shape function of the following form [187]

\[
\frac{\Delta R}{R} = \text{Re} \left[ A e^{i\theta} / (E - E_0 - i\Gamma)^m \right] 
\]  

(7.1)

where, \(A\) is the amplitude, \(\theta\) is the phase angle, \(E\) is the energy, \(E_0\) is the critical point energy, \(\Gamma\) is the broadening parameter, and \(m\) is a fitting parameter, which depends on the nature of critical point. For example, for \(m=2\) Aspens’s line shape function is known as a first derivative of Lorentzian line shape (FDLL) which is used to fit the experimental PR data of excitonic transitions [188]. Figure 7.1 depicts...
Figure 7.1: The 10 K PR spectra for the fully strained superlattice samples. Data with symbols show the Aspnes line shape fitting. The feature from the superlattice structure is marked as SL.

10 K PR spectra for all the strained superlattice samples showing the well defined superlattice feature marked as SL towards the lower energy side of the GaAs feature seen at $\sim 1.52$ eV. Experimental PR data of the superlattice related features are nicely fitted by FDLL (solid symbols in Fig. 7.1), which indicates that the observed transition is of excitonic nature for all the superlattice samples. Measured excitonic transition energies (broadening parameter) for the superlattice samples SL1, SL2,
SL3, SL4 and SL5 are 1.501 eV (7.6 meV), 1.489 eV (17.3 meV), 1.473 eV (9.5 meV), 1.470 eV (17.0 meV) and 1.471 eV (14.3 meV), respectively as listed in Table 7.1. It is to be noted that the superlattice feature red shifts from 1.501 eV to 1.473 eV with increase in the InP QW thickness from 1.8 Å to 3.3 Å, which is due to the reduced quantum confinement effect in the superlattice structures. This confirms that the observed transition in 10 K PR data is originating from the superlattice structure marked as SL in Fig. 7.2, where band diagram of InP/GaAs type-II superlattice structure has been drawn. Dotted line indicates the situation for the unstrained InP QW, while solid line presents the band line up for the fully strained InP QW. Strained value of 180 meV for the $\Delta E_C$ has been reported by us from the C-V measurements on single InP/GaAs type-II QWs [171], which is in agreement with the reported value of $\Delta E_C$ by x-ray photoelectron spectroscopy [100, 156]. Unstrained values of band offsets and strained band gaps of heavy and light holes calculated by using the equations reported in the literature [157] are also indicated in the Fig. 7.2. It is found that the measured values of transition energy of the superlattice structure are consistent with the band diagram of the InP/GaAs type-II superlattice structure (Fig. 7.2). It is also noted that the thickness (1.8-3.3 Å) of InP QW has smaller effect on the transition energy of superlattice feature, which may be attributed to smaller values of band offsets in InP/GaAs type-II system as observed from Fig. 7.2. We observe another feature at $\sim$1.49 eV (marked by an arrow) between superlattice and GaAs features in the PR spectrum of sample SL3. It may either be a higher energy transition from the superlattice structure or a carbon related feature from the MOVPE grown GaAs layers [163]. An overlap of superlattice feature with this peak in sample SL2 might be the reason for its relatively large width seen in PR
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\[ E_g^{\text{GaAs}} = 1.52 \]

\[ \Delta E_{\text{C}} = 0.180 \]

\[ \Delta E_{\text{VHH}} = 0.155 \]

\[ \Delta E_{\text{VLH}} = 0.221 \]

\[ E_g^{\text{InP}} = 1.495 \]

\[ E_{\text{VLL}} = 0.245 \]

\[ E_{\text{VHH}} = 0.345 \]

\[ \Delta E_{\text{C}} = 0.210 \]

\[ \Delta E_{\text{VHH}} = 0.155 \]

\[ \Delta E_{\text{VLH}} = 0.221 \]

**Figure 7.2:** Band diagram of InP/GaAs type-II superlattice structure for unstrained and strained InP QWs, shown by dotted and solid lines, respectively. The superlattice feature observed in the PR spectra is marked as SL. Miniband width for both electrons and holes are indicated. All values (at 10 K) are shown in the unit of eV.

Spectrum. Superlattice feature from sample SL4 is relatively broad as compared to that of sample SL3 and SL5. It is noted that these superlattice structures have same thickness of InP QW and GaAs barrier layers. But, superlattice period (N) is different and is 7, 11, 30 for SL3, SL4 and SL5, respectively. Hence, larger value of the broadening parameter for SL5 as compared to SL3 is understandable and is due to the larger number of interfaces present in SL5 resulting from the higher number of superlattice period. But the broadening parameter for SL4 having superlattice period value between that of SL3 and SL5 is largest among the superlattice samples. We note that the feature related to GaAs wafer are significantly broadened as compared to sample SL3. Hence, larger broadening parameter of superlattice feature seen in the PR spectrum of SL4 may be attributed to poor quality of the GaAs substrate.
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Figure 7.3: Temperature dependence of PR spectra for superlattice structures: (a) SL1 and (b) SL2. Superlattice feature is marked by SL.

7.4 Effect of built-in electric field on temperature dependence of superlattice transition energy

In order to obtain the information about the electron-phonon interaction, we have carried out PR measurements at various temperatures between 10 to 300 K. We note that the superlattice peak is merged with the main GaAs feature when temperature is increased from 10 to 110 K for samples SL1 and SL2 as depicted in Fig. 7.3. Thus
for these two superlattice structures (SL1 and SL2), the information about electron-phonon interaction is difficult to obtain. Therefore, we choose samples SL3 and SL5 to perform the temperature dependent PR measurements, because energy separation between superlattice and GaAs features is relatively large. Temperature dependent PR spectra for samples SL3, and SL5 are shown in Fig. 7.4(a) and Fig. 7.4(b), respectively. We observe the excitonic transition right from low temperature (10 K) upto room temperature (300 K) as is evident from the fitting of PR data with FDLL shown in Fig. 7.4. It is interesting to note from Fig. 7.4(a) that the intensity of the superlattice feature for SL3 relative to GaAs feature is continuously decreasing as the temperature is raised from 10 to 40 K and is not measurable in the 50-130 K temperature range. Thereafter, superlattice feature is again observed from 150 to 300 K and its intensity relative to GaAs feature is monotonically increasing in this temperature range. Such behavior can be understood if some thermally active trap states, introduced due to large strain in the superlattice structure, are considered. These states are frozen at very low temperature (10 K) and starts capturing the photogenerated carriers as the temperature is increased from 10-40 K, hence the corresponding intensity of superlattice feature in this temperature range is found to decrease and finally the superlattice feature disappears in 50-130 K temperature range. As the temperature is further raised from 150 to 300 K, the trapped carriers acquire thermal energy sufficient to overcome the barrier produced by the trap levels that leads to the appearance of superlattice feature again and its intensity starts growing with temperature. However, sample SL5 does not show such kind of a behavior and the superlattice related feature is clearly observed from 10 to 300 K, which will be discussed in the later part of the chapter.
Figure 7.4: Temperature dependence of PR spectra for superlattice structures: (a) SL3 and (b) SL4. Superlattice feature is marked by SL.

Figure 7.5(a) depicts the variation of broadening parameter ($\Gamma$) for both the superlattice samples (SL3 and SL5) with $[\exp(E_{LO}/k_B T) - 1]^{-1}$, which is the LO phonon population density [85]. $E_{LO}$ is the LO phonon energy. Broadening parameter is known to have two components where inhomogeneous broadening is independent of temperature, whereas homogeneous broadening increases with the tempera-
Figure 7.5: (a) Variation of the broadening parameter of superlattice features with the LO phonon population density. (b) Behavior of transition energies of superlattice features with respect to temperature along with the Bose-Einstein fitting. (c) Variation of $E(T) - E_B + a_B$ for superlattices, GaAs, and InP materials as a function of temperature.

It is seen that the inhomogeneous broadening dominates between 10-200 K, while above 200 K the temperature dependent homogeneous broadening governs the width of the superlattice feature. $E_{LO}$ is equal to 36 meV and 43 meV for the GaAs and InP materials, respectively. There is not much difference between the values of $E_{LO}$ for GaAs and InP, thus $E_{LO}=36$ meV has been taken. Behavior of the broadening parameter for both superlattice structures is similar and it increases linearly with the LO phonon density in the higher temperature region as shown by the line (guide to eye) in Fig. 7.5(a). This indicates that the increase in broadening parameter with temperature is governed by the scattering of electrons with LO
phonons present in the InP/GaAs superlattice. Finally, the temperature dependence of superlattice transition energy has been analyzed by using Bose-Einstein empirical relation (equation 1.8 in Chapter 1). Figure 7.5(b) depicts the transition energy as a function of temperature for the two superlattice structures. We observe that the transition energy is reasonably fitted by the Bose-Einstein empirical relation and the values of the fitting parameters like $E_B$, $a_B$, and $\theta_{BE}$ are 1.521 eV, 0.048 eV, 220 K; and 1.513 eV, 0.042 eV, 178 K for SL3 and SL5, respectively. The reported values of $a_B$, and $\theta_{BE}$ for GaAs (InP) materials are 0.060 eV (0.054 eV) and 252 K (274 K) respectively [15]. We find that there is not much difference between the values of $a_B$, and $\theta_{BE}$ for GaAs and InP materials and on the basis of the measured values for superlattice structures we can not unambiguously assign whether the temperature dependence of the superlattice transition energy follows the band gap variation of GaAs or InP. For unambiguous assignment similar to that is performed for single InP ultrathin QW cases in Chapter 5, the values of $E(T) - E_B + a_B$ for the superlattice samples SL3, SL5, GaAs and InP are plotted as a function of temperature as shown in Fig. 7.5(c). We clearly note that the temperature dependence of the transition energy for the superlattice structure SL3 follows the band gap variation of GaAs. This is expected because GaAs material is present in larger amount than InP in this sample and thus carriers spend most of their time in the GaAs portion of the superlattice structure. This explains the observed temperature dependence of transition energy of superlattice structure, SL3. It is also consistent with our earlier observations [8, 170] made on InP/GaAs and InAs/GaAs ultrathin QWs where the temperature dependence of the GS excitonic transition energy for ultrathin QWs was found to follow the band gap variation of GaAs barrier material. In contrast, the
behavior of transition energy for the superlattice structure SL5 is quite different than that of SL3 as observed from Fig. 7.5(c). It decreases at a faster rate compared to SL3 and GaAs. Further, the energy separation is gradually increasing with temperature that is \( \sim 20 \text{ meV} \) at room temperature as noted from Fig. 7.5(c). It is noted that both the superlattice structures have identical thickness of InP QW and GaAs barrier layer. The only difference between the two samples is the different number of superlattice period, \( N \). To find out the reason of such different temperature dependent behavior, room temperature PR spectra from both the samples are shown in the broad energy range in Fig. 7.6, where distinct difference is noted in terms of Franz-Keldysh Oscillations (FKOs) [189, 190], which are observed in the above band gap region of GaAs. The FKOIs are much more prominent in SL5 as compared to SL3 indicating that the built-in electric field should be large in magnitude for superlattice structure SL5. The procedure of determining the built-in electric field from the FKOIs is very well described in the literature [189, 190]. The extremum of FKOIs with the built-in electric field can be expressed as

\[
\frac{n\pi}{3} = \phi + \frac{4}{3} \left[ (E_n - E_g) / (h\theta) \right]^{3/2}
\]  

(7.2)

where, \( n \) is the index of \( n^{th} \) extremum, \( E_n \) is the energy of \( n^{th} \) extremum, \( E_g \) is the band gap energy. \( h\theta \) is the characteristic energy, which is given by

\[
(h\theta)^{3/2} = \frac{qFh}{\sqrt{2\mu}}
\]

(7.3)

where, \( q \) is the electronic charge, \( \mu \) is the reduced mass, and \( F \) is the built-in electric field. Thus, if we plot \( 4/3\pi (E_n - E_g)^{3/2} \) as a function of \( n \), then the slope of straight line is proportional to the electric field. Such a plot for both the samples is shown in the inset of Fig. 7.6. Data are nicely fitted with a straight line yielding the electric
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Figure 7.6: Room temperature PR spectra from superlattice structures SL3 and SL5 indicating the FKOs. Inset depicts the graph between $4/3\pi \left[ E_n - E_g \right]^{3/2}$ and $n$ for both superlattices.

field values of $24\pm 2$ kV/cm and $90\pm 5$ kV/cm for samples SL3 and SL5 respectively at room temperature. It is interesting to note that the built-in electric field increases with the superlattice period. The built-in electric field may be related to the point defects, which trap only one type of carrier. The number of point defects are expected to increase with the superlattice period, which may therefore increase the built-in electric field. Absence of measurable PL signal from most of the superlattice structures also indicate the presence of some defects. However, no information about the point defects is available in TEM measurements because of the instrumental resolution (chapter 6). HRXRD also supports a pseudomorphic growth of these superlattice structures. However, presence of point defects can not be ruled out even in HRXRD measurements. Further, it has been reported in an earlier study that the built-in electric field in a GaAs layer decreases with lowering temperature [190].

We also note that the built-in electric field at 10 K in the superlattice structures
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SL3 and SL5 is calculated to be $15\pm2$ kV/cm and $71\pm5$ kV/cm respectively. Thus, the built-in electric field in our superlattice structures is found to increase with temperature. It is to be noted that the superlattice structure SL5 has larger electric field as compared to SL3, which is also reflected in the transition energy of sample SL5 at 10 K that is red shifted by $\sim2$ meV when compared with SL3 as noted from Table 7.1. The magnitude of the built-in electric field for sample SL3 is too small to provide any detectable red shift even at room temperature and this is the reason that temperature dependence of transition energy for this sample follows the band gap variation of GaAs material. On the other hand, larger magnitude of built-in electric field for sample SL5 and its increase with temperature is responsible for the faster decrease in the transition energy with rise in temperature. As mentioned earlier that the superlattice feature is observed right from 10 to 300 K for sample SL5, while superlattice feature for SL3 shows some localization behavior (Fig. 7.4). It is argued here that although some trap states may be present in the sample SL5 and the photogenerated carriers get trapped in it, the trapped photogenerated carriers can be pulled out from these states due to large built-in electric field present in the sample and these carriers are able to modulate the surface electric field resulting in the observation of superlattice feature in the whole temperature range. Some indication on the presence of trap states in sample SL5 can be made from the Fig. 7.5(a), which shows that the variation of broadening parameters with temperature for both the superlattice feature is similar. Further, it is noted from Fig. 7.4(b) that the intensity of the superlattice feature for SL5 is decreasing with temperature although the built-in electric field is relatively large. This can be related to the presence of large number of non-radiative recombination centres generated by large residual
strain due to increased superlattice period. The photogenerated carriers recombine at these non-radiative recombination centers at elevated temperatures, thus reducing the intensity of the superlattice feature.

7.5 Room temperature photoreflectance and electroreflectance spectroscopy

It has been noticed in the previous section that the room temperature PR spectra of the superlattice structures SL3 and SL5 have indicated the presence of superlattice feature along with the FKOIs in PR spectra at room temperature. Thus, it becomes interesting to perform the room temperature PR and ER measurements of all the superlattice structures in a broad energy range. It is found that the superlattice feature is not observed in the room temperature PR spectra for the samples SL1 and SL2, because it merged with the GaAs feature with rise in temperature as shown in Fig. 7.3. However, superlattice feature is observed in room temperature PR spectra for sample SL3 and SL5 as shown in Fig. 7.4. Transition energy of the superlattice feature at room temperature for samples SL3 and SL5 is 1.385 eV.
and 1.365 eV respectively. Fig. 7.7(a) shows PR spectra for the strained (SL5) and partially relaxed (SL6, SL7 and SL8) InP/GaAs type-II QW superlattice structures. We do not observe the superlattice features from the partially relaxed superlattice structures. However, GaAs feature at \( \sim 1.42 \) eV and FKOs in the higher energy region as clearly seen in the PR spectra. Hence, to find out the superlattice feature, ER measurements are performed. ER spectra of the strained superlattice structures are similar to PR spectra of the corresponding superlattice sample. On the other hand, ER spectra of

Figure 7.7: Room temperature (a) PR (b) ER spectra of strained (SL5) and partially relaxed (SL6, SL7 and SL8) InP/GaAs type-II QW superlattice structures. Inset shows the ER spectra of the corresponding partially relaxed superlattice structures in an enhanced energy range. Symbols correspond to the Aspens’s line shape fitting.
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The partially relaxed superlattice structures are quite different in the lower energy range (<1.424 eV), where superlattice feature is clearly observed in Fig. 7.7(b). The energy positions of the superlattice features are determined by using Aspens’s line shape fitting as discussed earlier in this chapter and are listed in Table 7.2. The transition energy of superlattice feature for samples SL5 and SL6 is 1.368 eV and 1.345 eV respectively. Thus, superlattice transition energy red shifts from 1.368 eV to 1.345 eV, when barrier layer thickness of GaAs is decreased from 45 Å to 15 Å. However, it is expected that it should blue shift because quantized hole energy should increase with decrease in the barrier layer thickness as noted from the Fig. 7.2. But, the width of the miniband formed in the conduction and valence bands increases because of the increased overlap of the wave functions of electrons and holes with reduced barrier layer thickness, which effectively decreases the superlattice transition energy. Superlattice transition energy decreases further from 1.345 eV to 1.255 eV with increase of InP QW thickness from 3.3 Å to 5.6 Å and superlattice period from 30 to 50 at constant GaAs barrier layer thickness. The red shift of about 90 meV can be considered as the combined effect of reduced quantum confined effect resulting from increased thickness of InP QW and increased width of the miniband of electrons and holes due to increased superlattice period. The superlattice transition energy decreases from 1.255 eV to 1.235 eV with further increase in the InP QW thickness from 5.6 Å to 6.8 Å. The small red shift of about 20 meV is resulting from the decreased quantum confined effect with increase of InP QW thickness and a small contribution of relaxation (5.9 %) for this superlattice structure. All these results suggest that the observed feature is related to the superlattice structure. Thus, ER measurements provide clear information about the superlattice feature even for
the partially relaxed superlattice structures, where no information can be obtained from PR measurements. The basic difference between PR and ER measurements is that the built-in surface electric field is modulated in an indirect manner by the redistribution of the electron and hole pairs generated by the application of laser light in the PR measurements. On the other hand, in ER measurements, the built-in surface electric field is directly modulated by applying the external electric field. Hence, it seems that the carriers generated in the partially relaxed superlattice structures by laser light in PR measurements are not able to modulate the surface electric field, because these carriers are captured by the defects and/or traps centers created by the relaxation. Direct modulation of the electric field is more effective in modulating the built-in electric field in case of partially relaxed superlattice structures as compared to indirect modulation technique used in PR measurements.

Figure 7.8: Room temperature (a) SPS magnitude (b) its phase for the strained superlattice structures (SL1, SL2, SL3, SL4, and SL5).
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7.6 Room temperature surface photo-voltage spectroscopy

SPS is another powerful technique, which is very sensitive for the measurement of very small values of absorption coefficient for quantum structure like QWs, QDs and even ultrathin QWs. Figure 7.8(a) and Fig. 7.8(b) show room temperature SPS magnitude and its phase at 1 kHz of frequency for all the strained superlattice structures, respectively. The SPS magnitude has been normalized at $\sim 1.54 \text{ eV}$ for the sake of comparison, which is greater than the band gap energy of GaAs ($\sim 1.42 \text{ eV}$). Only GaAs feature at around $1.42 \text{ eV}$ is observed in the SPS magnitude spectra of samples SL1 and SL2, while there is no feature related to the InP/GaAs superlattice structure in the lower energy range ($<1.42 \text{ eV}$). This observation is consistent with the room temperature PR and ER data. However, SPS magnitude starts to increase at about $1.38 \text{ eV}$ for sample SL3 indicating that superlattice feature is contributing in the SPS magnitude in addition to the GaAs feature. The energy position of superlattice feature for sample SL3 is in agreement with the room temperature PR data as shown in Fig. 7.6. SPS magnitude starts increasing at lower energy (at around $1.37 \text{ eV}$) for samples SL4 and SL5 that have larger superlattice period as compared to sample SL3, which is also consistent with the room temperature PR and ER data for these superlattice structures. Phase of SPS spectra for sample SL1 shows change around the GaAs feature ($1.42 \text{ eV}$) indicating the presence of GaAs feature only and there is no phase change corresponding to superlattice related feature in the lower energy range ($<1.42 \text{ eV}$). However, appreciable phase change is occurring from $1.40 \text{ eV}$ for sample SL2 indicating that some other process is also occurring along with the absorption in GaAs. This may be related to the superlattice
structure, although we do not observe the signature of superlattice feature in the SPS magnitude spectra. The phase change starts at lower energies; 1.38 eV for SL3 and 1.36 eV for samples SL4 and SL5, which is consistent with the rise in SPS magnitude for samples SL3, SL4 and SL5. Thus, information extracted from the SPS spectra corroborates with that obtained from the room temperature PR and ER data of the strained superlattice structures. Figure 7.9(a) and Fig. 7.9(b) show the SPS magnitude and its phase for strained (SL5) and partially relaxed (SL6, SL7 and SL8) superlattice structures, respectively. SPS magnitude and phase spectra of partially relaxed superlattice structures are quite different in the lower energy range (<1.42 eV) as compared to the strained superlattice structure. Sufficient absorption in the lower energy region (1.18-1.35 eV) for the partially relaxed superlattice structures is seen as compared to the strained superlattice structure. This is consistent with the transition energies of the partially relaxed superlattice structures as determined...
from the ER data listed in the Table 7.2.

7.7 Summary

Excitonic transitions are observed even up to room temperature for all the strained superlattice samples. The excitonic transition energy in low temperature PR data red shifts with increasing InP QW thickness, confirming that the observed transition originates from the superlattice structure. Temperature dependent PR data show the presence of some thermally active trap states. The variation of the broadening parameter with temperature in the high temperature region is governed by the scattering of electrons from LO phonons. It has been found that built-in electric field considerably modifies the temperature dependence of the transition energy for the superlattice structure. It is unambiguously determined that the temperature dependence of the superlattice transition energy for a superlattice structure with a low electric field follows the band gap variation of the GaAs barrier material. It has been observed that indirect way of modulation of surface built-in electric field in PR measurements is not helpful in obtaining the information about the superlattice features of the partially relaxed structures. However, direct modulation of electric field in ER measurements is more powerful in providing the signature of the partially relaxed superlattice structures. Appreciable changes in SPS magnitude and phase in the lower energy region of the GaAs band gap for the partially relaxed superlattice structures have been assigned due to the absorption in the energy bands corresponding to the superlattice features.