A study of the low-energy interference oscillations in photoreflectance of GaAsSb/GaAs quantum well structures

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We present a room temperature photoreflectance (PR) investigation of GaAsSb/GaAs/AlGaAs quantum well (QW) structures grown on GaAs substrates by molecular beam epitaxy. We encounter strong low energy interference oscillations (LEIO), which tend to obscure any PR signals arising from the QW. By varying the angle of incidence, we exploit the LEIO to estimate the refractive index of the layer responsible and thus identify it. Furthermore, we demonstrate the ability to model the lineshapes of the observed LEIO accurately, through calculations of the Seraphin coefficients. This then allows us to deduce the actual thickness of the layer responsible, which is found to be close to the nominal value. These calculations in turn suggest a way to avoid the LEIO – by shortening the laser excitation wavelength. This successfully reveals good PR signals from the QW region, yielding several transition wavelengths, which we then compare with a theoretical model, assuming a small type II offset between GaAsSb QW and GaAs spacer layers.

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1 Introduction

Semiconductor lasers emitting close to the dispersion minimum of silica fibres at 1.3 μm are of considerable interest for fast fibre-to-the-home based networks. To enable low cost and un-cooled stable operation for these networks, vertical-cavity surface-emitting lasers (VCSELs) are seen as the ideal emitters. However, it is preferable to use GaAs as substrate material for VCSELs, due to the unique suitability of the AlGaAs/GaAs system for producing high quality Bragg mirrors, as demonstrated for 850 nm and 650 nm devices [1].

The InGaAsP active regions used in established, conventional 1.3 μm edge-emitting lasers, which are grown on InP substrates, are unsuitable for GaAs substrates, due to the lattice mismatch. Therefore, to provide photon emission at 1.3 μm , new material for GaAs-based active regions has to be found. Proposals include InAs/GaAs quantum dots and dilute-nitride quantum wells (QWs). For both systems lasers have been demonstrated. However, their performance is non-ideal due largely to inhomogeneities in the growth of quantum dots [2, 3] and high defect densities in the dilute-nitride system [4, 5].

Other important alternatives include GaAsSb/GaAs QWs, which can be used for room temperature VCSEL operation at 1.3 μm , as was recently demonstrated by Dowd et al. [6]. However, there remains considerable uncertainty in this material system about the conduction band alignment between GaAs and GaAsSb, for Sb fractions at about 30–40%, as required for 1.3 μm emission. Some reports in the literature claim that such QWs are weakly type I in nature [7], whilst others suggest weak type II alignment [8–10]. Type I describes a conventional system, where the electrons and holes are confined in the same layer, i.e. the QW, while in a type II system only one carrier is confined in the QW, while the other is not confined in the QW but is drawn to its vicinity by Coulombic attraction to the confined carriers. There-

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fore, the band alignment strongly influences the recombination processes in such structures and its understanding is of utmost importance for successful device optimisation.

As part of a study aimed at providing further evidence to understand the nature of the GaAsSb/GaAs interface, we made detailed spectroscopic investigations of a variety of GaAsSb/GaAs/AlGaAs QW structures designed to emit at $\sim 1.3 \mu\text{m}$. These studies included room temperature photo-modulated reflectance (PR) and photo-luminescence (PL) spectroscopy as functions of temperature and pump laser power. Both studies, PR and PL, used a red HeNe laser for modulation and excitation, respectively. Our PL studies, reported in detail elsewhere [11] gave strong evidence that the GaAsSb/GaAs interface is best described by assuming a small type II band-alignment.

However, these PL studies were unable to probe the full manifold of QW transitions, and yielded only rather broad features from the ground-state QW transition energy, even at low temperatures. It is generally acknowledged that PR is a more versatile optical probe of QW systems since it can reveal not only the ground-state, but also the higher-order QW transitions, yielding resolutions at room temperature equivalent to those of low-temperature PL [12]. Such extra information about the manifold of QW transitions could be valuable in understanding the nature of the conduction band alignment between the GaAs and GaAsSb QWs. Of further use in this respect may be the ability of PR to probe optical transitions in other regions such as the barrier, cladding and confinement layers, even if they are indirect [13]. However, our initial PR studies were disappointing, and, instead of yielding the expected QW signals, gave strong, long-period, non-excitonic oscillations below the bulk GaAs bandgap energy. Such “low energy interference oscillations” (LEIO) have also been observed in some other PR studies in the literature [14, 15], but in the present case they were so strong as virtually to obliterate any PR signals from the GaAsSb QWs. Consequently, here, we make a more detailed investigation of the LEIO and their origin. Firstly, by studying the room temperature PR (using the HeNe modulation laser) as a function of incidence angle [16], we show how to use these LEIO to infer the refractive index of the material responsible for the interference. This allows us to identify which of the layers in the sample structure are likely to be responsible for the LEIO. Following on from this, we then show that the period and lineshape of the LEIO can then be explained theoretically, from a calculation of the Seraphin coefficients for the individual layers in the sample structure. This reveals that only the GaAs buffer and substrate layers exhibit oscillatory Seraphin coefficients consistent with the observed LEIO. These coefficients can then be used in calculations of the theoretical LEIO lineshape, which can be fitted to the measured PR spectra, by slightly modifying the buffer layer thickness only.

Having explained that the LEIO originate from interfaces deep in the sample structures, we then explore various methods of avoiding the LEIO, including changing the penetration depth of modulation laser, by using lasers of different wavelengths. We find that using a suitably short laser wavelength yields clear PR signals from the QW, free from the effects of LEIO. Hence, we are then able to compare the resulting observed ground-state and higher order transition energies of the QW with theoretical calculations based on the solution of the Schrödinger equation for a weakly type II system.

2 Sample structure and experimental techniques

In our original PL and PR investigation of GaAsSb/GaAs interfaces [11], we studied a series of five samples grown on (100) n-type GaAs substrates using solid source molecular beam epitaxy [17]. These comprise a 400 nm GaAs buffer layer, QW region and a 30 nm GaAs top layer. The QW region consists of a 7 nm $\text{GaAs}_{0.64}\text{Sb}_{0.36}$ single QW with GaAs spacers on either side, the width of which varies in the series from 1 to 9 nm, placed within 75 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ carrier-confinement layers, as depicted in Fig. 1.

As mentioned earlier, the PL studies of this series, as functions of temperature, GaAs spacer thickness, and pump laser power are reported in detail elsewhere [11]. Here, we concentrate on the PR spectra, which were also measured for the range of spacer thicknesses in these samples, using a HeNe modulating laser. However, the obtrusive LEIO were found to be similar in all these, and related, samples, and since these are the primary concern here, we shall give results only for a typical sample structure of Fig. 1 – that with the 6 nm GaAs spacers.

Fig. 1 Schematic structure of the GaAsSb quantum well samples with varying spacer thicknesses (1, 2, 3, 6 and 9 nm). All layers are nominally undoped, except the n-type GaAs substrate.

The PR experimental set-up used throughout this study is a fairly typical arrangement consisting of a 150 W tungsten lamp combined with a 0.32 m single-grating spectrometer as a monochromatic light source, a sample stage and an InGaAs photo-detector. In our set-up we are also able to vary the angle of incidence by mounting the sample and detector arm on a computer-controlled turntable arrangement. This was found to be very useful in the present study. A mechanically-chopped laser, initially a HeNe (633 nm, 4 mW) is used for the modulation of the sample. ΔR signals are detected phase-sensitively in the usual fashion with a lock-in amplifier. The DC reflectivity signal R is recorded simultaneously with a multimeter and used for the normalisation $\Delta R/R$. Further details can be found elsewhere [18].

3 Initial angle-dependent PR results using the HeNe laser

The initial PR spectrum was measured at an angle of incidence of 25° and is shown as the lower plot in Fig. 2 (discussed in more detail later). As may be seen, the only sharp features attributable to band-structure critical points are from the GaAs layers, near 1.425 eV and the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ confinement layers near 1.735 eV. The whole lower energy side of the spectrum, below the GaAs bandgap, is dominated by strong oscillatory features, which obscure any signals from the GaAsSb QW, which is expected around 1 eV.

Such features have been observed before by ourselves and other workers. Their broad oscillatory lineshape is suggestive of an optical interference-related origin. To confirm this, one may vary the optical thickness of the layer causing the interference. This can be done, for instance, by thinning this layer using a destructive etching process [19, 20].

However, an easier, non-destructive technique is to change the angle of incidence θ of the probe-light [21]. This allows one to change, in a controllable and reversible way, the optical thickness of any layers responsible for LEIO, and thus their position and spacing in the PR spectrum, while the electronic transition features CANNOT depend on incidence angle, and are therefore static. This then allows us quickly to identify which PR features are due to electronic transitions and which are due to interference [22]. It is well known that, e.g. destructive interference between two rays reflected from the top and bottom of a given uniform layer within a structure, of effective refractive index n , occurs at a wavelength given by:

$$\lambda(\theta) = \lambda(0^\circ) \cdot \sqrt{1 - \frac{\sin^2 \theta}{n^2}}, \quad (1)$$

where $\lambda(0^\circ)$ is the wavelength at normal incidence [23]. In LEIO we expect that the wavelengths of all the features will vary with angle according to Eq. (1).

Fig. 2 Room temperature PR spectra of a 6 nm GaAs spacer sample (see Fig. 1) obtained with a 633 nm HeNe modulating laser, and as a function of incidence angle (indicated to the left). The PR spectra are offset vertically, for clarity. The low energy regime is dominated by LEIO whose peaks and troughs move with angle (indicated by vertical sloping lines). These LEIO are so strong that PR signals from the QW are only visible as a subtle feature near 1.0 eV. The only obvious static electronic features are due to the GaAs, and the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ layers, as indicated.

Figure 2 shows some of the PR spectra obtained at other angles of incidence above 25° , up to 65° . From this it is clear that the LEIO must indeed be interference-related features since their peaks and troughs blue-shift with increasing incidence angle, as predicted by Eq. (1), while the GaAs and the AlGaAs features remain static. These angle dependent studies also hint at a very weak QW feature, which may be seen as a subtle static distortion in the LEIO trough at about 1 eV. We may also note that there are static oscillations above the GaAs bandgap, which we attribute to the usual Franz–Keldysh oscillations (FKO) from bulk-like GaAs.

4 Refractive index of the layer causing the LEIO

Equation (1) indicates that if we plot the squares of the wavelengths of the peaks and troughs of the LEIO, as a function of the square of the sine of angle of incidence, a straight line will result whose gradient is related to the refractive index n of the layer responsible for the LEIO. This was done for all seven of the marked features in Fig. 2 – an example plot is given in the inset of Fig. 3. The resulting values of n are thus obtained as a function of the energy of the associated LEIO feature. It should be noted that n in Eq. (1) corresponds to its value at the normal incidence wavelength $\lambda(0^\circ)$. This is also obtainable from the linear plot of Eq. (1) – from its λ^2 -axis intercept. Thus, Fig. 3 shows a plot of the obtained n values at the normal incidence energies of the corresponding LEIO feature. Generally speaking, the obtained results for n follow the literature values for GaAs. It should be noted that the two highest-energy LEIO features are more strongly perturbed by the proximity of the strong GaAs feature in Fig. 2, which could account for the slightly increased variance of the last two points in Fig. 3. The fact that n is, for the most part, slightly lower than the GaAs values is consistent with the Burstein–Moss effect, where heavily n -doped material has a slightly bigger bandgap and therefore reduced refractive index. Thus, these results indicate that the LEIO originate from a GaAs layer in the structure, and primarily from the substrate since it is the only nominally doped region of the structure (see Fig. 1).

Fig. 3 Inset shows an example plot of Eq. (1), for the LEIO trough near 1.38 eV in Fig. 2, and the linear fit to get refractive index n , as described in the main text. The circles in the main figure show the resulting values of n , at the corresponding photon energies. The solid curve shows the accepted refractive index of undoped GaAs, which is the main component in the structure (Fig. 1). The experimental results are close to the GaAs behaviour, indicating that the LEIO arise from a GaAs layer.

5 Theoretical description of the LEIO

In order to understand the nature of the LEIOs we investigate their origin from theoretical calculations of the PR spectrum. The PR signal can be described by [24]:

$$\frac{\Delta R}{R} = \alpha \Delta \varepsilon_1 + \beta \Delta \varepsilon_2 \quad (2)$$

where α and β are the Seraphin coefficients,

$$\alpha = \frac{1}{R} \frac{\partial R}{\partial \varepsilon_1} \quad \text{and} \quad \beta = \frac{1}{R} \frac{\partial R}{\partial \varepsilon_2}, \quad (3)$$

which describe the relative changes in reflectivity due to the modulation of the real and imaginary parts of the complex dielectric function, ε_1 and ε_2 , respectively. For structures consisting of several layers of different material compositions, Eq. (2) must be extended as follows:

$$\frac{\Delta R}{R} = \sum_j^{\text{all layers}} \alpha_j \Delta \varepsilon_{1j} + \beta_j \Delta \varepsilon_{2j}. \quad (4)$$

In simple bulk and epi-layer structures, α and β are generally treated as constants in the vicinity of the critical points, so that the resulting spectral lineshapes are determined primarily by the modulated dielectric functions $\Delta \varepsilon_1$ and $\Delta \varepsilon_2$. In the vicinity of the fundamental bandgap of a bulk-like semiconductor, in the intermediate electric field regime, these terms can be described using an Airy function formalism [25]. These exhibit the usual FKO behaviour above the bandgap energy, and an exponential-like decaying, non-oscillatory response below. Clearly, such a decaying tail below the GaAs bandgap cannot ex-

plain the LEIO observed in Fig. 2. These LEIO can, therefore, only arise from the Seraphin coefficients in Eq. (4).

In order to calculate these Seraphin coefficients, we must consider their form in more detail. While α and β can be calculated analytically in simple structures from their definitions in Eq. (3) [26], for most semiconductor hetero-structures this calculation becomes too cumbersome when there are more than a few layers, and we must resort to numerical methods [27]. The Seraphin coefficients for each individual layer j in Eq. (4) may be approximated as follows:

$$\alpha_j = \frac{R(\varepsilon_{1j} + \delta\varepsilon_{1j}, \varepsilon_{2j}) - R(\varepsilon_{1j}, \varepsilon_{2j})}{R(\varepsilon_{1j}, \varepsilon_{2j})\delta\varepsilon_{1j}} \quad \text{and} \quad \beta_j = \frac{R(\varepsilon_{1j}, \varepsilon_{2j} + \delta\varepsilon_{2j}) - R(\varepsilon_{1j}, \varepsilon_{2j})}{R(\varepsilon_{1j}, \varepsilon_{2j})\delta\varepsilon_{2j}}, \quad (5)$$

where $\delta\varepsilon_{(1,2)j}$ is a small change in the appropriate dielectric function of layer j , due to the modulation. The reflectivity R can be calculated directly from the thickness and complex dielectric functions of the various layers in Fig. 1, using the Jones matrix method [28, 29]. The resulting Seraphin coefficients for individual layers can then be substituted, together with appropriate forms for $\Delta\varepsilon_{1,2}$, into Eq. (4) to represent the spectra obtained from a PR measurement.

To summarise, the procedure is as follows. Using the sample structure given in Fig. 1, and corresponding wavelength-dependent dielectric functions available from the literature [30], we use the Jones matrix method to calculate the R spectrum, $R(\varepsilon_1, \varepsilon_2)$ at a given angle of incidence. Then we perturb, say, the real part of the material dielectric function of one of the layers by some appropriate small amount $\delta\varepsilon_1$ (here we chose $\delta\varepsilon_1 \approx \varepsilon_1/1000$) and recalculate the perturbed reflectivity $R(\varepsilon_1 + \delta\varepsilon_1, \varepsilon_2)$. Substitution into Eq. (5) then yields a good approximation of the α Seraphin coefficient for this layer, as a function of wavelength. This is repeated for the β coefficient. This calculation has to be performed for every layer in the structure of Fig. 1, and for each angle of incidence studied. An important point to note for the present structure is that, unless there is a sufficient difference in the GaAs buffer and substrate (e.g. in their refractive indices), so that there is some light reflected at this interface, these two layers would have to be treated as a single homogeneous GaAs layer in Eq. (4), with a single pair of Seraphin coefficients.

6 Using the oscillatory Seraphin coefficients in fitting the PR spectra

To confirm the conclusion drawn in the angle-dependent studies in Section 3 about the likely origin of the LEIO, we compared the measured PR spectra with the theoretical modelling, as described in the previous section. We calculated Seraphin coefficients for each individual layer in the nominal structure of Fig. 1. We found firstly that, if the GaAs buffer and substrate layers were treated as a single homogeneous layer, none of the calculated Seraphin coefficients showed any appropriate oscillations consistent with the observed LEIO. However, if the buffer and substrate were treated as distinct layers (e.g. due to slightly different refractive indices, possibly due to different dopings), with some light reflected at their interface, we found that the substrate Seraphin coefficients then had oscillations, which agreed well with the period and angular dependence of the observed LEIO, if the nominal structure of Fig. 1 was assumed. This clearly confirms our earlier suggestion that it is the buffer/substrate interface, which is responsible for the LEIO. In order to achieve a closer match with the PR spectrum at 25° we varied only the width of the GaAs buffer layer and obtained a good agreement using a thickness of 445 ± 10 nm. This is slightly larger than the nominal 400 nm (see Fig. 1), but is within growth tolerances achieved for this structure.

In order to model the measured PR, we note from Eq. (2) that these oscillatory Seraphin coefficients should be multiplied by an appropriate $\Delta\varepsilon$ lineshape. Below the bandgap of GaAs, this has the familiar decaying tail of the FKO [25], which may conveniently be represented here by an empirical exponential-like form. The resulting simulated PR spectrum at 25° is then found to agree very well with the measured LEIO, as shown in the lower plot of Fig. 4. We also found that the calculation at other angles of incidence yielded a similar good agreement with the corresponding observed LEIO, without needing to vary any other parameter (see Fig. 4).

Fig. 4 Measured low-energy interference-oscillations of Fig. 2 (dots) for various angles of incidence together with the modelling (solid curves), using a product of the oscillatory function of the Seraphin coefficient α and an appropriate below-bandgap decay for the GaAs $\Delta\epsilon_1$, as explained in the main text.

7 Photoreflectance at various laser wavelengths

Despite the above successful explanation of the origin of the LEIO, we are still faced with their intrusive influence on the primary objective of this study – to measure the manifold of the QW transition energies with room temperature PR. The Seraphin coefficient calculations reveal that the LEIO arise due to the interference between rays reflected from the upper buffer interface and the buffer/substrate interface. However, they also indicate that if these layers are not appreciably modulated ($\Delta\epsilon \approx 0$ in Eq. (4)) then the LEIO will not be detected.

At first sight this might suggest that we use a longer wavelength laser, such that only the QW would be modulated, but to which all the other layers are transparent. Following this, we tried a 980 nm (1.26 eV) InGaAs semiconductor laser (power ~ 50 mW), and successfully obtained an identifiable PR spectrum from the QW, as may be seen in Fig. 5*. The wavelength of the QW features in this PR spectrum is consistent with the peak of the broad room temperature PL (uppermost plot in Fig. 5). However, this PR signal is very weak, and long signal averaging times were required. Furthermore, the LEIO are not completely eliminated. The disadvantage of using a long wavelength laser arises simply from the fact that PR relies on the chopped laser to modulate any in-built electric field, by periodically exciting electron-hole pairs in the structure. Therefore, the strength of the resulting ΔR signal depends on how strongly the dielectric function is modulated via this effect. A shorter wavelength laser, such as the previously used 633 nm (1.96 eV) HeNe (Fig. 2), is much more strongly absorbed and all layers are modulated. In fact, simple optical absorption calculations, assuming normal incidence and no multiple internal

* Note that this series of experiments of varying the pump laser wavelength were performed on a slightly different sample, which had two additional 8 nm strain compensation AlGaAs layers, as explained in Ref. [11]. However, the slightly increased total sample thickness has no significant influence on the conclusions we draw about the dependence of the QW PR signal on laser wavelength.

Fig. 5 Room temperature PR spectra (at incidence angle of 45°) for a GaAsSb/GaAs/AlGaAs sample, using different modulating lasers whose wavelengths are indicated to the left of each spectrum. Although PR signals from the GaAsSb QW could be obtained with a long-wavelength 980 nm laser (uppermost PR spectrum), the most obvious QW signals were obtained (between ~ 0.90 and ~ 1.15 eV) with the shortest wavelength HeCd lasers available (two lowermost spectra). In these spectra, the low-energy interference oscillations (LEIO) apparent for the HeNe and Ar-ion lasers (centre plots), are suppressed. The room temperature PL spectrum is also shown for comparison. Spectra are offset vertically, for clarity.

reflections, indicate that the incident intensity of the 633 nm HeNe laser is attenuated to $\sim 70\%$ and $\sim 12\%$ at the depths of the QW and buffer/substrate interface, respectively. Thus, the field throughout the structure is modulated with this laser. With the 980 nm laser, however, only the 7 nm-thick QW region is modulated which consequently excites much fewer electron-hole pairs, i.e. solely in the QW, producing only a weak field modulation at that location, and thus a feeble PR signal. In fact, the aforementioned simple optical absorption calculations indicate that less than 2% of the power of the 980 nm laser is absorbed in the whole structure (i.e. in the QW region). This provides a qualitative explanation of the poor signal-to-noise ratio of the QW PR signal for the 980 nm laser.

On the other hand, if we choose a laser wavelength *less than* that of the HeNe, we might be able to reduce the penetration depth so that the buffer/substrate region is modulated by much less. This would then reduce the GaAs PR signal and the associated LEIO, while still hopefully modulating the field near the QW [20]. Following this idea, we used a 514 nm (2.41 eV) Ar-ion ion laser (power ~ 10 mW) as modulation source. This significantly decreases the relative magnitude of the LEIO as expected, but the QW signal is still not clearly revealed, appearing only as a subtle flattening of an interference peak near 1 eV (see Fig. 5). Our simple penetration-depth calculations show that the incident Ar-ion laser intensity is attenuated to $\sim 38\%$ at the QW and $\sim 0.6\%$ at the buffer/substrate interface. The latter figure, which is clearly much smaller than the corresponding result for the HeNe laser, is evidently still enough to cause a significant QW modulation signal.

Consequently, we reduced the excitation wavelength even further, by utilising a HeCd laser with lines at 442 nm (2.81 eV, power ~ 4 mW) and 325 nm (3.82 eV, power ~ 1 mW). As may be seen from Fig. 5, the LEIO are indeed now almost completely suppressed for these two laser lines, and a clear set of signals is revealed near 1 eV, which can only be due to the QW. The absorption calculations indicate that, for the blue line, the incident intensity has fallen to $\sim 9\%$ at the QW but to $<10^{-4}\%$ at the buffer/substrate interface. The corresponding figures for the UV line are $<1\%$ and $<10^{-17}\%$, respectively. For the HeCd UV line, the fact that so little of the laser power survives to the QW region suggests that

the QW field modulation in this case is accomplished predominantly via the strong absorption in the uppermost layers.

To analyse the QW PR spectrum obtained with the 442 nm HeCd laser line, we fitted it with a sum of the following well-known Aspnes oscillatory lineshape functions [31]:

$$\frac{\Delta R}{R} = \text{Re} \left\{ \frac{C e^{i\theta}}{[(E - E_g) + i\Gamma]^n} \right\} \quad (7)$$

where E_g is the transition energy, C an amplitude factor, θ a phase and Γ a broadening term. The exponent n depends on the type of transition and we found $n = 2$ gave the best fit, although the fitted transition energies did not depend crucially on the choice of n . A minimum of three such functions was appropriate to achieve a reasonable fit to the PR spectrum, as can be seen in Fig. 6.

The fitted transition energies are 0.996 eV, 1.026 eV and 1.079 eV (± 7 meV) with broadening factors of 26 meV, 56 meV and 46 meV (± 7 meV), respectively. These room-temperature PR broadenings are much smaller than the corresponding PL broadening of ~ 150 meV (see Fig. 5). Note that the 300 K PL gives no clear indication of any higher-order transitions, and shows essentially only a single broad peak at 0.99 ± 0.02 eV. However, this is in reasonable agreement with the energy of the QW ground-state transition (0.996 eV) determined from the PR.

We are currently performing calculations of the confined states within the GaAsSb/GaAs QW system, using a numerical method to solve Schrödinger's equation. Details of these calculations will be published in due course. However, preliminary results for a symmetric square-shaped potential well show that, by assuming a weakly-type II conduction band offset between the QW and spacer, we can obtain a reasonable match between the three above observed transitions and the theoretical ground state electron-to-heavy-hole (e_1h_1), e_2h_1 and e_2h_2 transitions, respectively, with a variance between theory and experiment of about ± 10 meV. However, the model also predicts other nearby possible QW transitions (e_1h_2 , e_3h_1 and e_3h_2) which may overlap with the observed central and highest-energy features, and which could contribute towards their somewhat larger observed broadening factors. We cannot at this stage give firm conclusions about any such assignments, until the model has been further refined, which will be the aim of future studies of this material system.

Fig. 6 QW region of the room temperature PR spectrum (dots) acquired with the 442 nm HeCd-laser (see Fig. 5), fitted with appropriate lineshape functions (solid curve). Three distinct transition energies could be obtained, at energies indicated by the arrows.

Clearly such PR measurements are potentially very useful in the study of the GaAsSb QW system, especially with regard to identifying the origin of higher-order QW transitions, such as those seen in Fig. 6, and correlating these with the possible band alignment picture – type I or type II – that is still the subject of some controversy in this material system. The present PR study represents initial measurements of a more systematic PR study of these structures, in which the various measured QW transition energies will be compared with appropriate models in order to elucidate the band alignment in these structures, and the impact of structural aspects such as the thickness of the GaAs spacers.

8 Conclusions

We have performed room-temperature photoreflectance (PR) studies, using a red HeNe laser, on selected GaAsSb/GaAs/AlGaAs quantum well (QW) structures grown on GaAs substrates by molecular beam epitaxy. Here, we encountered strong oscillations, which obscured the PR signals from the QW in the low-energy region of the spectra. We found that these features moved as the angle of incidence was altered, while the electronic transition features in the PR spectra did not. This identified the low energy oscillations as being due to optical interference effects. We exploited the angle-dependence of these oscillations in the PR spectra in order to estimate the refractive index of the layer responsible. From this, we were able to deduce that these low energy interference oscillations (LEIO) are due to light rays reflected from the undoped GaAs buffer and its interface with the *n*-doped GaAs substrate. This reflection occurs, and thus the LEIO, only because the buffer and substrate are sufficiently different from each other, such as would occur if they have different doping densities, as is the case here. We modelled these oscillations by means of a calculation of the Seraphin coefficients of the structure and, by matching the predicted LEIO lineshapes with those observed, found that the GaAs buffer layer was some 45 nm thicker than nominal. These calculations also suggested that the LEIO could be avoided if the modulation source, i.e. the laser, did not penetrate the structure deeply enough in order to modulate the buffer/substrate interface.

Following this suggestion, we then confirmed that the interference oscillations could be successfully avoided by changing the laser excitation wavelength from the red (HeNe) to the blue (HeCd). This revealed good room-temperature PR signals from the QW region. Fitting this spectrum yielded the energies of three QW transitions, which could not be obtained from the corresponding room-, or low-, temperature PL spectra. Comparing the measured transition energies with a simple preliminary theoretical model showed a reasonable agreement if one assumes a small type II offset between the GaAsSb and GaAs layers in the QW.

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References

- [1] T. E. Sale, Vertical Cavity Surface Emitting Lasers, (Research Studies Press Ltd., Baldock, 1995).
- [2] I. P. Marko, A. D. Andreev, A. R. Adams, R. Krebs, J. P. Reithmaier, and A. Forchel, *IEEE J. Sel. Top. Quantum Electron.* **9**, 1300 (2003).
- [3] R. Songmuang, S. Kiravittaya, M. Sawadsaringkarn, S. Panyakeow, and O. G. Schmidt, *J. Cryst. Growth* **251**, 166 (2003).
- [4] S. R. Jin, S. J. Sweeney, S. Tomic, A. R. Adams, and H. Riechert, *IEEE J. Sel. Top. Quantum Electron.* **9**, 1196 (2003).
- [5] S. Tomic, E. P. O'Reilly, R. Fehse, S. J. Sweeney, A. R. Adams, A. D. Andreev, S. A. Choulis, T. J. C. Hosea, and H. Riechert, *IEEE J. Sel. Top. Quantum Electron.* **9**, 1228 (2003).
- [6] P. Dowd, S. R. Johnson, S. A. Feld, M. Adamczyk, S. A. Chaparro, J. Joseph, K. Hilgers, M. P. Horning, K. Shiralagi, and Y.-H. Zhang, *Electron. Lett.* **39**, 987 (2003).

- [7] S. R. Johnson, C.-Z. Guo, S. Chaparro, Yu. G. Sadofyev, J. Wang, Y. Cao, N. Samal, J. Xu, S. Q. Yu, D. Ding, and Y.-H. Zhang, *J. Cryst. Growth* **251**, 521 (2003).
- [8] M. Dinu, J. E. Cunningham, F. Quochi, and J. Shah, *J. Appl. Phys.* **94**, 1506 (2003).
- [9] G. Liu, S. L. Chuang, and S. H. Park, *J. Appl. Phys.* **88**, 5554 (2000).
- [10] W. W. Chow, O. B. Spahn, H. C. Schneider, and J. F. Klem, *IEEE J. Quantum Electron.* **37**, 1178 (2001).
- [11] G. Blume, T. J. C. Hosea, S. J. Sweeney, S. R. Johnson, J.-B. Wang, and Y.-H. Zhang, accepted for publication *IEE Proc. Optoelectronics* (Dec. 2004).
- [12] O. J. Glembocki and B. V. Shanabrook, *Photoreflectance Spectroscopy of Microstructures, in Semiconductors and Semimetals, Spectroscopy of Semiconductors*, edited by D. G. Seiler and C. L. Littler (Academic Press, San Diego and London, 1992).
- [13] N. Dai, D. Huang, X. Q. Liu, Y. M. Mu, W. Lu, and S. C. Shen, *Phys. Rev. B* **57**, 6566 (1998).
- [14] S. Hildebrandt, M. Murtagh, R. Kuzmenko, W. Kircher, and J. Schreiber, *phys. stat. sol. (a)* **152**, 147 (1995).
- [15] R. Kudrawiec, G. Sek, K. Ryczko, J. Misiewicz, and J. C. Harmand, *Appl. Phys. Lett.* **84**, 3453 (2004).
- [16] S. B. Constant, S. Tomic, D. Lock, T. E. Sale, S. J. Sweeney, and T. J. C. Hosea, *J. Appl. Phys.* **93**, 9446 (2003).
- [17] S. R. Johnson, S. Chaparro, J. Wang, N. Samal, Y. Cao, Z. B. Chen, C. Navarro, J. Xu, S. Q. Yu, D. J. Smith, C.-Z. Guo, P. Dowd, W. Braun, and Y.-H. Zhang, *J. Vac. Sci. Technol. B* **19**, 1501 (2001).
- [18] S. Constant, S. Ghosh, T. E. Sale, and T. J. C. Hosea, *IEE Proc. Optoelectronics* **148**, 69 (2001).
- [19] D. Huang, D. Mui, and H. Morkoch, *J. Appl. Phys.* **66**, 358 (1989).
- [20] N. Kallergi, B. Roughani, J. Aubel, and S. Sundaram, *J. Appl. Phys.* **68**, 4656 (1990).
- [21] T. J. C. Hosea, *Thin Solid Films* **450**, 3 (2004).
- [22] S. Choulis and T. J. C. Hosea, *IEE Proc. Optoelectronics* **148**, 49 (2001).
- [23] P. J. Klar, G. Rowland, T. E. Sale, T. J. C. Hosea, and R. Grey, *phys. stat. sol. (a)* **170**, 145 (1998).
- [24] B. O. Seraphin, *Electroreflectance, in Semiconductors and Semimetals, Modulation Techniques*, edited by R. K. Willardson and A. C. Beer (Academic Press, New York and London, 1972).
- [25] H. Shen and M. Dutta, *J. Appl. Phys.* **78**, 2151 (1995).
- [26] B. O. Seraphin and N. Bottka, *Phys. Rev.* **145**, 628 (1966).
- [27] T. J. C. Hosea, P. J. Hughes, and B. L. Weiss, *J. Appl. Phys.* **77**, 2672 (1995).
- [28] T. E. Sale, K. Hild, T. J. C. Hosea, M. Hirotsu, and Y. Kato, *Proc. SPIE* **5366**, 191 (2004).
- [29] A. Gerrard and J. M. Burch, *Introduction to Matrix Methods in Optics* (Dover Publications, New York, 1994).
- [30] P. G. Snyder, J. A. Woollam, S. A. Alterowitz, and B. Johs, *J. Appl. Phys.* **68**, 5925 (1990).
- [31] D. E. Aspnes, *Phys. Rev. B* **10**, 4228 (1974).