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In this paper, infrared reflectance spectroscopy was employed to extract information on the optical and electrical properties of metal organic vapour phase epitaxial (MOVPE) grown InAs and InAsSb epilayers. These epitaxial layers were grown on InAs and GaAs substrates and characterised by infrared reflectance spectroscopy and Hall measurements.

1 Introduction The two infrared wavelength ranges from 3–5 µm and 8–12 µm correspond to the transmission windows in the atmosphere where long-range detection is of interest. These ranges are particularly important for military and security applications. InAsSb is a potential candidate for such applications since its cutoff wavelength can be tuned in a wide range (3–10 µm) by controlling the alloy composition. The optical and electrical behaviour of III–V semiconductors has to be understood very well before producing these devices. Moreover, the characterisation of semiconducting materials enables optimisation of the growth procedures, resulting in improved material properties.

Studies on III–V ternary semiconductor materials as candidate replacements for HgCdTe have steadily increased in recent years [1–3]. Among the III–V semiconductors, $InAs_{1-x}Sb_x$ is a potential candidate for such applications, due to its possible room temperature band gap varying from 0.17–0.35 eV [4]. Its band gap varies relatively slowly with Sb composition, making it easy to achieve homogeneous layers. Many researchers have reported on the electrical, optical and structural properties of InAsSb and InAs epitaxial layers grown on InAs, GaAs and GaSb substrates. The first reports on the properties of InAsSb by Woolley and co-workers appeared in the late 1950s [5]. The main focus of this work is to study the optical and electrical properties of MOVPE grown InAs and InAsSb layers.

2 Theory In the infrared region, dielectric parameters are determined mainly by using the classical two–oscillator model that takes into account both the free carriers and the lattice [6]:

$$\varepsilon = \varepsilon_\infty \left[1 - \frac{\omega_P^{\,2}}{\omega(\omega - i\gamma)} + \frac{\omega_L^{\,2} - \omega_T^{\,2}}{\omega_T^{\,2} - \omega^2 - i\omega\Gamma} \right]. \qquad (1)$$

The reflectivity R can therefore be expressed in terms of the complex dielectric function as:

$$R = \left| \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1} \right|^2 . \qquad (2)$$

In Eq. (1), ε_∞ is the high frequency dielectric constant, γ is the free-carrier damping constant, ω_T is the transverse phonon frequency, ω_L is the longitudinal phonon frequency, Γ is the phonon damping constant and ω_p is the plasma resonance frequency. The carrier concentration and mobility of a semiconductor material are related to ω_p and γ respectively, through the following equations:

$$\omega_P^{\,2} = \frac{4\pi n e^2}{m^* \varepsilon_\infty}, \qquad (3)$$

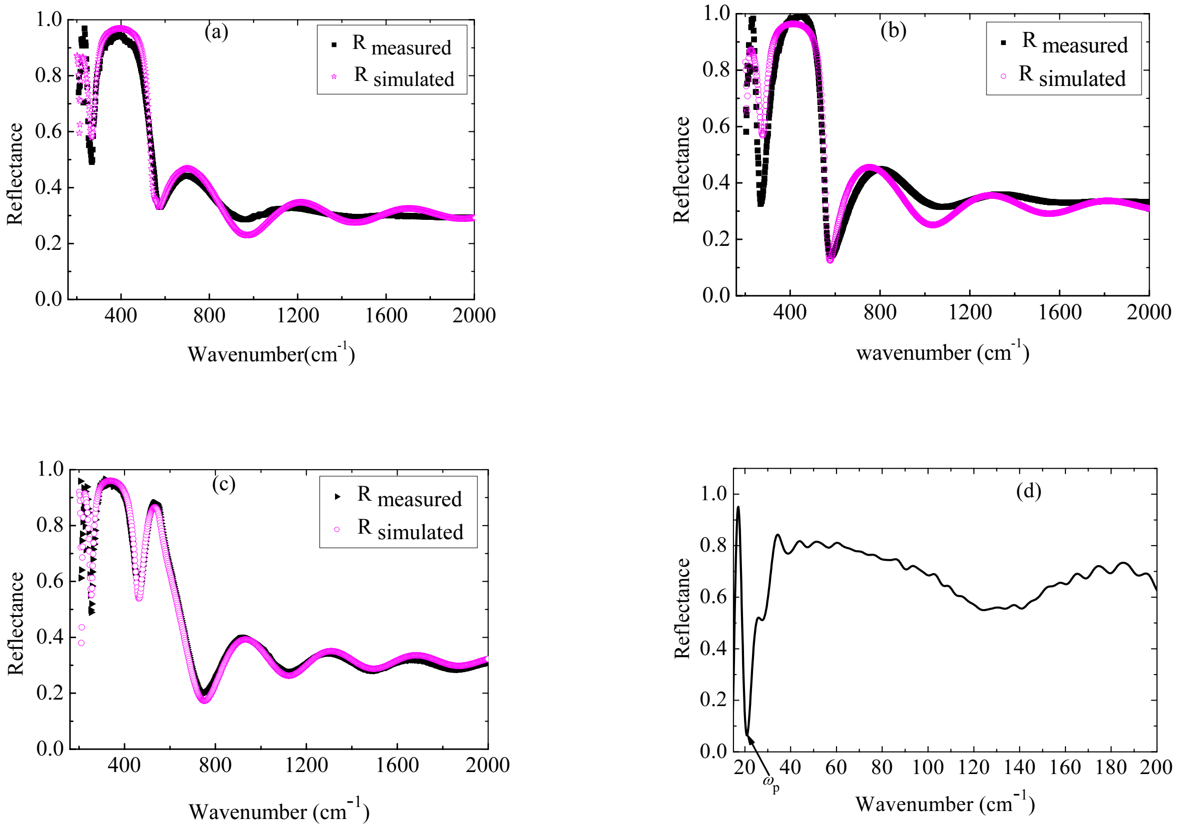

Figure 1 Measured and simulated reflectance spectra of (a) InAs/InAs (M2956), (b) $InAs_{0.87}Sb_{0.13}$/InAs (M2966), (c) $InAs_{0.967}Sb_{0.033}$/InAs (M3037). Typical far infrared (< 200 cm^{-1}) reflectance spectrum of homoepitaxial InAs layer (M3007) is shown in (d).

and

$$\gamma = \frac{e}{m^{*}\mu}\ , \qquad (4)$$

where m^* is the effective electron mass and e is the electronic charge. The values of m^* used for InAs and $InAs_{1-x}Sb_x$ were $m^* = 0.023\ m_o$ [7] and $m^* = (0.023 - 0.039x + 0.03x^2)\ m_o$ [8], respectively.

3 Experimental details

InAs and $InAs_{1-x}Sb_x$ layers were prepared by MOVPE. These epilayers were grown in the temperature range 550 to 650 °C. The V/III ratio in the reactor was varied between 5 and 30 for InAs, while for $InAs_{1-x}Sb_x$ ($0.033 \leq x \leq 0.13$) the V/III ratio ranged between 3 and 50. The epilayers were grown on semi-insulating GaAs substrates to facilitate Hall measurements, and on InAs substrates to minimise the lattice mismatch and for optical characterisation. Infrared reflectivity measurements were performed in the wavelength range 15–2000 cm^{-1} on the 550 Nicolet Magna (> 200 cm^{-1}) and Bomem DA8 FTIR (< 200 cm^{-1}) spectrometers, with a resolution of 4 cm^{-1} at room temperature, taking 100 scans. BMDP® curve fitting software, together with the classical two-oscillator model shown in Eq. (1) was used to analyse the reflectance data. The dielectric parameters and the optical properties were extracted from the simulations. The Sb content in $InAs_{1-x}Sb_x$ was determined from the shift in the 004 diffraction line, using X-ray diffraction, and assuming that Vegard's law holds.

The carrier concentration and carrier mobility for InAs and InAsSb layers were also determined electrically by Hall measurements performed at room temperature. When InAs and InAsSb are electrically characterised using the conventional Hall technique, the low mobility and high carrier concentration of a surface electron accumulation layer significantly shields its bulk properties [9]. In order to extract meaningful information from the Hall data, InAs and InAsSb were treated as a two–layer system comprising a bulk and surface layer. This was done by employing the two–layer model to determine the carrier concentration and mobility for the surface layer and bulk of the InAs and InAsSb [10]. These results were compared with the values obtained by infrared reflectance spectroscopy.

Table 1 Comparison of optically and electrically calculated carrier concentration and mobility of InAs and $InAs_{1-x}Sb_x$ layers from FTIR and Hall measurement data. Values marked by ** were obtained from direct measurements of ω_p in the far infrared.

Sample	FTIR results		Hall results	
number	n (cm^{-3})	μ ($cm^2.V^{-1}.s^{-1}$)	n (cm^{-3})	μ ($cm^2.V^{-1}.s^{-1}$)
M2956 ($x = 0$)				
Layer:	3.6×10^{15} (** 4.4×10^{15})	2.6×10^4	$(7.3 \pm 4.7) \times 10^{15}$	$(1.1 \pm 0.5) \times 10^4$
Substrate:	1.0×10^{18}	2.7	2.0×10^{18}	0.9×10^4
	$\times 10^4$			
M2966 (x~0.13)				
Layer:	3.6×10^{15} (**1.6×10^{15})	5.0×10^4	$(8.1 \pm 5.0) \times 10^{15}$	$(1.4 \pm 0.5) \times 10^4$
Substrate:	1.0×10^{18}	1.9×10^4	2.0×10^{18}	0.9×10^4
M3037(x~0.033)				
Layer:	2.5×10^{15} (**1.7×10^{15})	4.2×10^4	$(7.1 \pm 5.0) \times 10^{15}$	$(2.6 \pm 0.9) \times 10^4$
Substrate:	1.0×10^{18}	1.6×10^4	2.0×10^{18}	0.9×10^4

4 Results and discussion

4.1 FTIR results

Typical measured and simulated spectra for homoepitaxial InAs layers and $InAs_{0.87}Sb_{0.13}$ and $InAs_{0.967}Sb_{0.033}$ heterostructures are shown in Figs. 1(a), (b) and (c), respectively. The plasma resonance frequency (ω_p) peak for the InAs substrates is observed around 580 cm^{-1} in all three spectra. The other two features observed around 245 cm^{-1} and 220 cm^{-1} are associated with the longitudinal (ω_L) and transverse (ω_T) phonon frequencies, respectively. The additional minima observed above 600 cm^{-1} are due to interference effects from the film and their spacing is dependent on the film thickness. Due to the low free carrier concentration in the InAs and InAsSb epitaxial structures, plasma resonance frequency (ω_p) values in the order of 20–30 cm^{-1} were obtained from the simulations of reflectance spectra measured above 200 cm^{-1}. These low values were confirmed by direct measurements of ω_p in reflectance spectra obtained in the range 15–200 cm^{-1}. A typical far infrared reflectance spectrum for homoepitaxial InAs layer is shown in Fig. 1(d), where the ω_p peak is observed around 21 cm^{-1}, which is in good agreement with the value of 20 cm^{-1} obtained from simulations.

4.2 Comparison of FTIR and Hall results

The results obtained from simulations for the three layers (M2956, M2966 and M3037) are presented in Table 1, together with the results from Hall measurements. The carrier concentration for these layers was calculated by using both the simulated and directly measured (< 200 cm^{-1}) values of the plasma resonance frequency, ω_p. These values are also listed in Table 1 (marked with ** in brackets), and they differ by approximately a factor of two. The carrier concentration values extracted optically agree within experimental uncertainty with the values determined from Hall measurements for all layers, while the mobilities differ by a factor of approximately two or higher from the Hall mobilities. These values are nevertheless of the same order of magnitude. Note that the carrier concentration values obtained for the InAs layer (M2956) are relatively high compared to the intrinsic carrier concentration for InAs of 9.2 x 10^{14} cm^{-3} at room temperature [11], indicating significant concentrations of donors resulting from the growth process. The intrinsic carrier concentration of $InAs_{1-x}Sb_x$ depends on the composition and the temperature. The closer the carrier concentration is to the intrinsic value, the purer the material and the better the quality.

The optically and electrically measured carrier concentration values, as well as the mobility values for the InAs substrates in all three cases differ by a factor of approximately two. Similar discrepancies have been reported for *n*-type homoepitaxial GaAs films by other researchers [12, 13].

5 Conclusion

The optical and electrical properties of MOVPE grown InAs and InAsSb epilayers were studied by using infrared reflectance spectroscopy and Hall measurements. The two–layer optical model employed in this study was able to distinguish between the electrical properties of the layer and substrate. Although further measurements should be performed in the far–infrared region (< 200 cm^{-1}), it was reassuring to observe that the plasma resonance frequency obtained by simulating reflectance spectra measured above 200 cm^{-1} correlated very well with values measured directly in the region below 200 cm^{-1}. This gives confidence in the carrier concentration values extracted from this parameter, especially in view of the fact that these values also compared favourably to the values obtained by a proper analysis of the Hall data. Naturally, a technique which provides a direct measure of the electrical quality (i.e. carrier concentration) of the bulk of an epilayer is preferred over one which requires simulations.

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