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Determination of refractive indexes of $In_{0.52}Al_{0.48}As$ on InP in the wavelength range from 250 to 1900 nm by spectroscopic ellipsometry

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Abstract

In a previous paper, we found that between InP and $In_{0.52}Al_{0.48}As$ grown by molecular beam epitaxy, an interface layer exists, owing to the interaction of arsenic with InP in the preheat phase of the MBE growth. To determine the refractive index and thicknesses of the $In_{0.52}Al_{0.48}As$ and the interface layer in the wavelength range from 300 to 1900 nm, layers 10, 20, 200 and 2000 nm thick of MBE-grown $In_{0.52}Al_{0.48}As$ on InP were investigated using spectroscopic ellipsometry.

1. Introduction

The wavelength-dependent refractive index of $In_{0.52}Al_{0.48}As$ layers grown by metallo-organic, vapour phase epitaxy on InP was measured for the first time in 1987 [1] using single wavelength ellipsometry in the range from 400 to 800 nm. These investigations were part of the first German national activities for promising waveguide materials. Spectroscopic ellipsometry is a non-destructive tool with which to determine the optical properties of heterostructures. Since the two measured angles ψ and Δ at a single wavelength are insufficient to determine more than two unknown parameters, such as the thickness d of the natural oxide layer and the refractive index $n-ik$, we apply spectroscopic ellipsometry and single-layer materials.

The first application of spectroscopic ellipsometry to $In_{0.52}Al_{0.48}As$ layers on InP was done by Pickering [2] in the wavelength range from 245 to 1000 nm but his procedure for estimation of the $In_{0.52}Al_{0.48}As$ dielectric functions contained significant errors. We measured [3] layers 0.5 and 2 μm thick of $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ layers grown by molecular beam epitaxy (MBE) on InP, using spectroscopic ellipsometry in the wavelength range from 245 to 845 nm, and fitted n, k dispersion curves. We found that, between the InP substrate and the $In_{0.53}Ga_{0.47}As$ or $In_{0.52}Al_{0.48}As$ layer, an interface layer about 1 nm thick exists. To determine exactly the refractive index in the wavelength range from 900 to 1900 nm, it was necessary to grow thin MBE layers of $In_{0.52}Al_{0.48}As$.

2. Experimental details

The layers were grown in a Varian MOD GENII MBE system on SI InP(100) substrates at growth rates between 0.2 and 0.4 nm s^{-1}. The growth temperatures varied from 500 to 530 °C and the As/(In + Al) beam equivalent pressure (BEP) ratio ranged from 50 to 70. The thicknesses of the layers were 10, 20 and 200 nm.

3. Spectroscopic ellipsometry

3.1. Instrumentation and measurements

The samples were characterized by two ellipsometers of Rudolph Research: namely the manual 436-type for the whole wavelength range from 250 to 1900 nm with a Babinet Soleil Compensator, interference filters, photomultiplier R 928 and IR detector, and the Spectro 2000 with a rotating polarizer, a monochromator from 250 to 840 nm and computer-assisted measurement and evaluation. To determine ψ and Δ with the manual ellipsometer, we used the classical four-quadrant method [3]. With the same method and our Babinet Soleil compensator, instead of the rotating polarizer, we showed [3] that, on the Spectro 2000, the true ψ,Δ couple at each wavelength is the average of the ψ,Δ values measured at the two positions A and B of the fixed polarizer and fixed analyser:

(A) fixed polarizer angle, 0° and fixed analyser angle, +45°;

(B) fixed polarizer angle, 0° and fixed analyser angle, −45°.

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Comparing the ψ,Δ values for the same sample on both ellipsometers, we had discrepancies in ψ and Δ, which differed from wavelength to wavelength. These were due to differences in the angles of incidence at both ellipsometers. Since Aspnes and coworkers [4] found very good agreement between his and our measurements [5], we corrected one angle of incidence. The accuracy of the angle of incidence is one of the main problems for round-robin projects in ellipsometry.

3.2. Evaluation of ellipsometric measurements

ψ,Δ scans of samples can be carried out rapidly with the Spectro 2000 but data interpretation is complex and time consuming [2]. For the determination of the n–k graphs and thicknesses of layered structures with Fresnel formulas, multiple-layer models with abrupt interfaces are necessary. In our first measurements [1, 3, 5], we have determined that InP has the smallest refractive index compared with compounds such as $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ and that, in the wavelength range from 250 to 900 nm, a layer 2 μm thick is thick enough to absorb the light completely. For this reason, light cannot penetrate to the interface of the layer and the bulk material. For wavelengths larger than 1000 nm, light penetrates to the interface of the layer and bulk InP, and it even reaches the rear side of the bulk. Therefore, the rear side of the substrate must be rough enough or inclined, so that the reflected light from this side cannot affect the measurements.

From our first measurements of the refractive index of $In_{0.52}Al_{0.48}As$, we know that even an $In_{0.52}Al_{0.48}As$ layer 2 μm thick is only thick enough to absorb light of wavelength up to 550 nm. Therefore, we had to determine the thicknesses of the native oxide, $In_{0.52}Al_{0.48}As$ and the interface (InAs) layer in the wavelength range from 300 to 550 nm. The thicknesses of the interface layers were uniform, but varied between 0.5 and 1.2 nm. With the three thicknesses and the refractive indexes of the native oxide layer (1.9), of InP and of InAs [3–7], we could determine the refractive index of $In_{0.52}Al_{0.48}As$ in the wavelength λ range from 550 to 1900 nm by minimizing the quantity [3]

$$\sum_{\lambda} \{(\psi_m - \psi_c)^2 + (\Delta_m - \Delta_c)^2\}$$

where the subscript m means measured and c means calculated values.

Pickering *et al.* [2] estimated for $In_{0.52}Al_{0.48}As$ at 2.48 eV = 500 nm a refractive index of $n - ik = 3.950 - 0.800i$. Our result at the same wavelength is $n - ik = 4.090 - 0.371i$. Our n and k values of different samples have uncertainties of ± 0.01. These small deviations may be due to our estimation that the thickness of the natural oxide layer 7 min after exposure to air has the same value (0.8 nm) as those of InP and GaAs.

Our investigations on semi-insulating InP and GaAs bulk materials in the IR showed very good agreement [3] with the results of Pettit and Turner [6] for InP and those of Palik [7] for GaAs. In the case of $In_{0.52}Al_{0.48}As$, we had a five-layer model consisting of

air–oxide–$In_{0.52}Al_{0.48}As$–InAs–InP.

To obtain more information on the interface layer, we have simulated the preheat phase of the MBE growth. We observed that, from $\lambda = 400$ nm upwards, the interface layer can be fitted very well by the refractive index of InAs and a thickness of 0.5–1.2 nm. The dispersion curves $n(\lambda)$ and $k(\lambda)$ for the $In_{0.52}Al_{0.48}As$ layers 10 and 20 nm thick on InP in the wavelength range from 280 to 840 nm are shown in Fig. 1. In Fig. 2, the measured and calculated ψ,Δ curves for the $In_{0.52}Al_{0.48}As$ layer 20 nm thick on InP with a natural oxide layer 2.1 nm thick and an interface layer 0.8 nm thick show very good agreement. Even for the enlargement of the λ,ψ and Δ axes, only small deviations in the Δ curves are visible (Fig. 3). Table 1 gives the

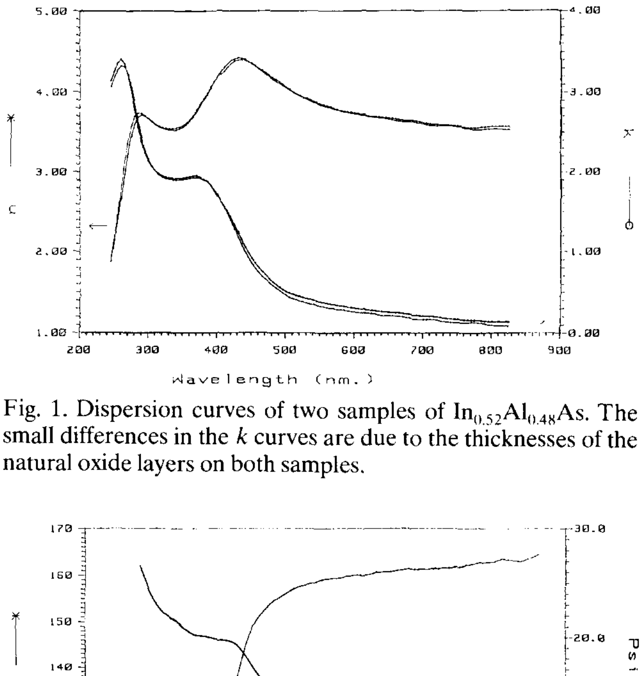

Fig. 1. Dispersion curves of two samples of $In_{0.52}Al_{0.48}As$. The small differences in the k curves are due to the thicknesses of the natural oxide layers on both samples.

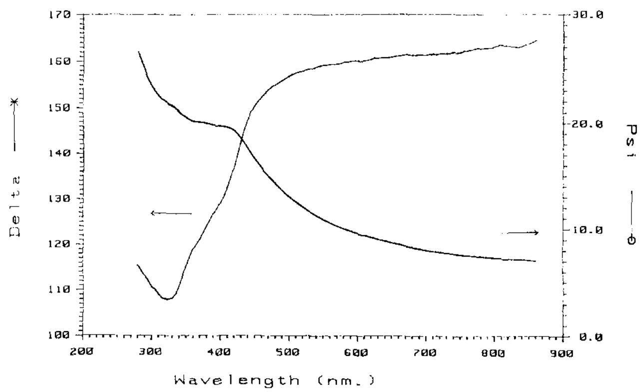

Fig. 2. Comparison of the measured and calculated ψ,Δ curves for the $In_{0.52}Al_{0.48}As$ layer 20 nm thick on InP. No deviation can be seen.

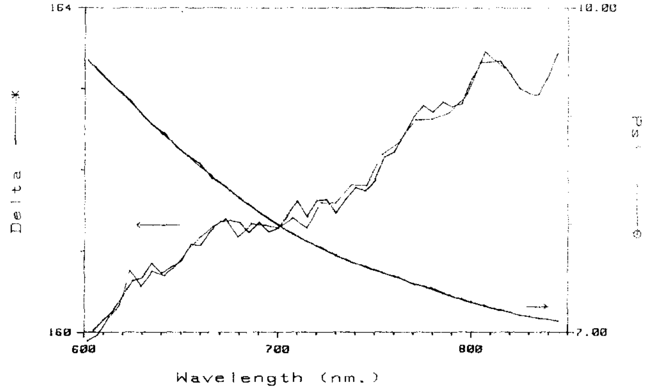

Fig. 3. Enlargement of Fig. 2. Only in the two Δ curves are small deviations visible.

TABLE 1. Refractive indexes of $In_{0.52}Al_{0.48}As$ and InP in the near IR

Wavelength (nm)	$In_{0.52}Al_{0.48}As$		InP	
	n	k^a	n	k^a
546.1	3.895	0.266	3.670	0.411
1000.0	3.398		3.326	
1020.0	3.395		3.323	
1200.0	3.306		3.221	
1300.0	3.286		3.206	
1400.0	3.268		3.195	
1500.0	3.253		3.178	
1600.0	3.236		3.151	
1700.0	3.233		3.148	
1800.0	3.217		3.145	
1900.0	3.209		3.139	

[a]Except at 546.1 nm, all the k values are smaller than 0.0005.

refractive index of $In_{0.52}Alo_{0.48}As$ for 546.1 nm and in the wavelength range from 1000 to 1900 nm in comparison with those of InP; they are higher throughout than those of InP.

4. Conclusions

Comparison of the ψ,Δ couples measured on different ellipsometers needs an exact knowledge of the angle of incidence. Our results on InP and GaAs are in good agreement with the measurements of Aspnes and coworkers [4], Pettit and Turner [6] and Palik [7]. However, for $In_{0.52}Al_{0.48}As$, the estimations of Pickering *et al.* [2] differ from our measurements. A simulation of the preheat process shows that, from a light wavelength of 400 nm upwards, the interface layer can be fitted with the InAs data. In the wavelength range from 1000 to 1900 nm, the refractive indexes of $In_{0.52}Al_{0.48}As$ are higher throughout than those of InP.

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