Ellipsometric characterization of $In_{0.52}Al_{0.48}As$ and of modulation doped field effect transistor structures on InP substrates

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The dielectric function of a thick layer of $In_{0.52}Al_{0.48}As$ lattice matched to InP was measured by variable angle spectroscopic ellipsometry in the range 1.9–4.1 eV. The $In_{0.52}Al_{0.48}As$ was protected from oxidation using a thin $In_{0.53}Ga_{0.47}As$ cap that was mathematically removed for the dielectric function estimate. The $In_{0.52}Al_{0.48}As$ dielectric function was then verified by ellipsometric measurements of other $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ structures, including modulation doped field effect transistors (MODFET), and is shown to provide accurate structure layer thicknesses.

In this letter, we present a measurement of the dielectric function of $In_{0.52}Al_{0.48}As$ and apply it to the ellipsometric characterization of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructures. The main application of $In_{0.52}Al_{0.48}As$ is as a high band gap semiconductor in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructures lattice matched to InP, which are used in a variety of microwave and optical applications.[1] An important property of $In_{0.52}Al_{0.48}As$ is the fact that, unlike InP, it can be grown in thin film form by solid molecular beam epitaxy (MBE), as opposed to phosphorus containing III-V semiconductors which require gas sources. Important parameters for any applications that can be measured by ellipsometry are the thicknesses of the layers, interface quality, and surface contaminations, roughness and oxidation. In addition, the dielectric function of $In_{0.52}Al_{0.48}As$ in the visible may be useful in applications involving waveguides in this spectral range.

Ellipsometry, particularly variable-angle spectroscopic ellipsometry (VASE) in the visible and near UV, has been used to characterize, nondestructively, a variety of modulation doped field effect transistors (MODFETs)[2,3] and optoelectronic structures[4] grown on GaAs substrates. Dielectric functions of the constituents necessary for the ellipsometric analysis were taken from the literature. However, at this time no reliable experimental dielectric function of $In_{0.52}Al_{0.48}As$ has been published. Ellipsometry has been used twice in the past[5,6] to obtain the dielectric function of $In_{0.52}Al_{0.48}As$ in the visible. In Ref. 5, only results for the refractive index were published, while in Ref. 6, the dielectric function of $In_{0.52}Al_{0.48}As$ was estimated by scaling the InP values and using an effective medium model with a 3% negative voids fraction. Clearly, a direct experimental dielectric function for $In_{0.52}Al_{0.48}As$ is preferable.

In most aluminum containing III-V semiconductor ternaries, the top layer of the material will oxidize in air[7] in a time scale of hours. As ellipsometry is very sensitive to the surface conditions, we protected the top layer with $In_{0.53}Ga_{0.47}As$. We kept the thickness of this cap layer to a minimum in order to get reliable results for the $In_{0.52}Al_{0.48}As$ dielectric function in the near UV, where the light penetration depth is very small. As a check of the accuracy of our result, we used our experimental $In_{0.52}Al_{0.48}As$ dielectric function to fit two other $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ structures using two parameter fits only. Finally, we used our result to analyze five MBE grown $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ complete MODFET structures. The MODFETs were grown at two laboratories to make sure that no systematic error in the analysis was carried over from a systematic error in the growth parameters of one group.

All samples, except three MODFETs, were grown at the University of Michigan. The $In_{0.52}Al_{0.48}As$ growth temperature used was the optimum value of 520 °C that was found to result in smooth films with the least amount of clustering.[8] Some of the MODFET structures were grown at 500 °C. The growth rate was in the range 0.6–1.2 μm per hour. The ellipsometric measurements[9] were taken at 3–7 angles of incidence in the range 300–750 nm (i.e., spectral range with reasonable experimental reflectivity) with 10 nm increments. The calibration sample was measured in 5 nm increments for better resolution. Marquardt least square fits were used to estimate the desired parameters.

The calibration sample was a 1-μm-thick $In_{0.52}Al_{0.48}As$ on top of a 30 period 3 nm/3 nm $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ buffer. For ellipsometry purposes, the $In_{0.52}Al_{0.48}As$ was treated as the substrate, assuming it to be optically thick. The free parameters of the model were the oxide and cap layer thicknesses and the values of the $In_{0.52}Al_{0.48}As$ dielectric function at all experimental wavelengths. The calibration functions for the oxide[10] and $In_{0.53}Ga_{0.47}As$[11] were taken from the literature. The resulting $In_{0.52}Al_{0.48}As$ dielectric function ϵ is shown in Fig. 1. The values of the dielectric function for energies below 1.9 eV ($\lambda > 650$ nm) are not as accurate as those above that energy due to the light penetrating into the superlattice region. Conventionally, a layer is considered optically thick if its thickness is greater than 2δ, where δ is the light

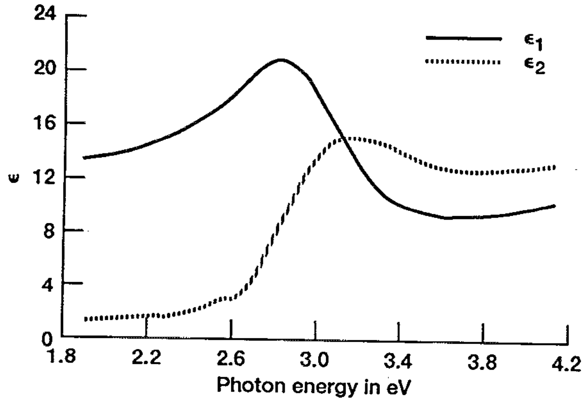

FIG. 1. Dielectric function ϵ of $In_{0.52}Al_{0.48}As$ in the range 1.9–4.1 eV. ϵ_1 and ϵ_2 are the real and imaginary parts of the dielectric function, respectively.

penetration depth.[12] We choose to be more conservative and use a 3δ cutoff criterion. The ellipsometric result also provided best fit values of 2.2 nm of oxide and 1.3 nm of $In_{0.53}Ga_{0.47}As$, which are reasonable values for a native oxide thickness and a nominal 2 nm $In_{0.53}Ga_{0.47}As$ cap. We obtained a mean square error (MSE) for the tan Ψ and cos Δ fit[3] of 1.0×10^{-5}, where Ψ and Δ are the ellipsometric experimental results. This exceedingly low value of MSE is due to the large number of parameters.

Next, two samples of thick $In_{0.52}Al_{0.48}As$ layers were measured, both grown on InP without a superlattice buffer. Sample A had a nominal 2-μm-thick $In_{0.52}Al_{0.48}As$ while sample B had a little over a 1-μm-thick layer. Both had a thicker $In_{0.53}Ga_{0.47}As$ cap layer than the calibration sample. The ellipsometric model used for these samples included two parameters only, the thicknesses of the oxide and the $In_{0.53}Ga_{0.47}As$ cap layer. The $In_{0.52}Al_{0.48}As$ dielectric function used was the result obtained here in the first stage of the work. The results for samples A and B are summarized in Table I. The values of the MSE for these two parameter fits, especially for sample A, are extremely good. In both cases, the $In_{0.53}Ga_{0.47}As$ layer thickness estimated by ellipsometry is smaller than the nominal value. We believe some of the material was oxidized and some error may be due to the growth calibration. However, we did not encounter this discrepancy in MODFET samples made at another laboratory, as will be shown below.

The MODFET structures shown in Table II were made at both the University of Michigan (sample Nos. 1 and 2) and by a commercial vendor[13] (sample Nos. 3, 4, and 5). All structures had complex buffer layers. For example, the University of Michigan samples had the following layers: starting from the semi-insulating InP substrate, a 30 period 3 nm/3 nm $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ buffer layer and a 400 nm undoped $In_{0.52}Al_{0.48}As$ as the lower part of the conduction channel quantum well. The other samples (Nos. 3, 4, and 5) had additional layers below the 30 period lattice, but they had the same buffer structure just below the conduction channel. As the ellipsometric analysis was limited to the device active layers, the 400 nm $In_{0.52}Al_{0.48}As$ layer was regarded as substrate. Thus, we limited our analyses to wavelengths below 540 nm. The layer thicknesses, as estimated by RHEED, are given in Table II. In all samples, the active layers included an undoped $In_{0.53}Ga_{0.47}As$ channel, an $In_{0.52}Al_{0.48}As$ donor layer, and an $In_{0.53}Ga_{0.47}As$ cap layer. The $In_{0.52}Al_{0.48}As$ donor layer had a doped (5×10^{18} cm^{-3}, Si) 15 nm layer on top of a 5 nm undoped spacer. The cap layer was also n doped, at 3×10^{18} cm^{-3}, Si. In the ellipsometric model, doping effects on the dielectric function were neglected.[2,3] The nominal ellipsometric models, including all layer thicknesses for the five samples, are given in Table II under the heading "Nominal." A summary of the ellipsometric results is given in Table II under the heading "VASE." The errors shown are the 90% confidence limits obtained from the least squares fitting.[14] Representative tan Ψ and cos Δ model fits for sample number 5 are given in Figs. 2(a) and 2(b). In general, the quality of the fits, as given by the MSE, is very good, except for sample No. 3. The results for the samples made by the commercial vendor are very illuminating. Sample Nos. 3 and 4 were grown in 1991 and were nominally equivalent, except for the cap layer thickness. The VASE results show that in both samples the $In_{0.52}Al_{0.48}As$ donor layers and the $In_{0.53}Ga_{0.47}As$ channels are much thicker than the nominal values. However, the MSE is much larger for sample No. 3, denoting a poorer

TABLE I. Best fits for layer thicknesses in nm for samples made of a thick $In_{0.52}Al_{0.48}As$ layer, considered as substrate. Analysis range 300–620 nm.

Sample	Oxide		$In_{0.53}Ga_{0.47}As$		MSE
	Nominal	VASE	Nominal	VASE	$\times10^{-4}$
A	···	2.20±0.02	20	13.3±0.1	2.7
B	···	1.3±0.1	40	32.3±0.4	5.1

TABLE II. Best fits for $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MODFET layer thicknesses (in nm). Analysis wavelength range 300–405 nm. 400 nm $In_{0.52}Al_{0.48}As$ layer used as substrate.

Sample number	Oxide		$In_{0.53}Ga_{0.47}As$ Cap layer		$In_{0.52}Al_{0.48}As$ Donor layer		$In_{0.53}Ga_{0.47}As$ Channel layer		
	Nominal	VASE	Nominal	VASE	Nominal	VASE	Nominal	VASE	MSE$\times10^{-4}$
1	···	4.6±0.1	10	4.8±0.1	40	42.2±0.3	55	53.9±0.7	1.6
2	···	2.4±0.1	15	8.8±0.2	45	47.9±0.4	55	56.1±1.0	2.4
3	···	2.6±0.1	5	2.3±0.3	40	46.4±0.3	40	51.2±0.6	4.9
4	···	1.0±0.04	35	40.6±0.4	40	48.4±0.5	40	54.1±1.4	0.7
5	···	1.4±0.1	35	32.9±0.5	40	43.4±1.1	40	41.5±2.1	2.4

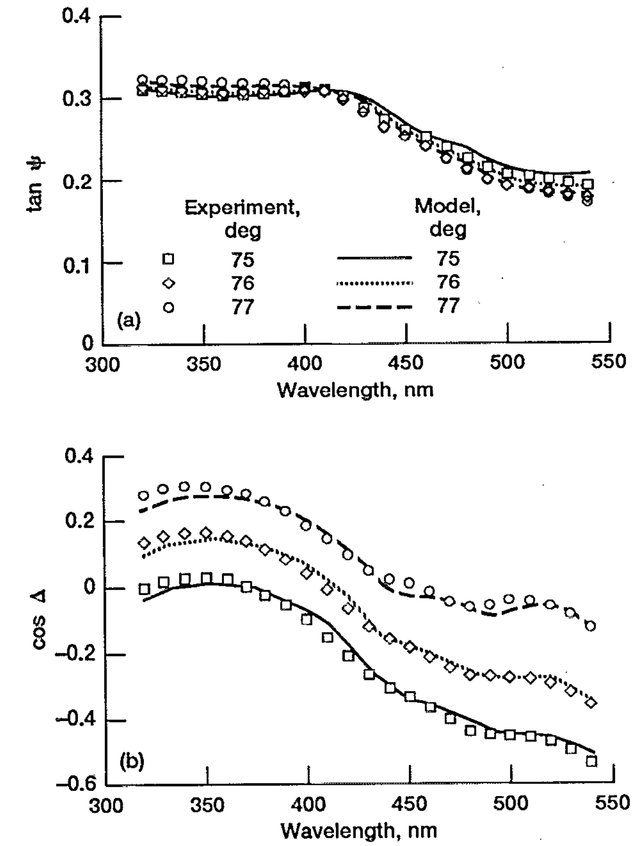

FIG. 2. Experimental and model simulation for (a) tan Ψ (b) cos Δ vs wavelength for sample number 5, Table II, for the following three angles of incidence: □ 75°, ◇ 76°, ○ 77°.

model. We speculate that the problem in this sample originates from the very thin thickness of the cap layer. The $In_{0.53}Ga_{0.47}As$ top layer may be too thin for protecting the $In_{0.52}Al_{0.48}As$ from oxidation, and the sample model shown here did not take this into account. Oxidation problems are encountered in all thin capped MODFET structures (samples No. 1, 2, and 3), where the VASE determined $In_{0.53}Ga_{0.47}As$ layer thickness is very small (see Table II). The large discrepancy between the nominal and the VASE thicknesses of the donor and channel layers in samples 3 and 4 as compared with that of sample 5 can be explained as follows. Sample No. 5 was grown 10 months after the other two samples. In the meantime, several improvements in the nominal thickness calibrations were implemented,[15] including repositioning of the RHEED gun, adjusting the shutters to reduce transients, and a better correlation between RHEED results and ternary alloy thicknesses. Indeed, for sample No. 5, the nominal and VASE thicknesses are the same to within 8% for all layers.

We also analyzed all MODFET samples using the suggested $In_{0.53}Al_{0.47}As$ dielectric function from Ref. 6. The results looked unreliable: the MSE were a factor of 5 to 18 higher for the thin $In_{0.53}Ga_{0.47}As$ capped samples; there was no consistency between sample Nos. 3 and 4; and most thicknesses were far away from the nominal values.

In summary, we have experimentally determined the dielectric function of $In_{0.52}Al_{0.48}As$ in the range 300–650 nm and have successfully applied it in the determination of the active layers' thicknesses of MODFET devices lattice matched to InP grown by MBE. This ellipsometric nondestructive characterization of high performance MODFET's that include $In_{0.52}Al_{0.48}As$ layers not only provided a confirmation of the nominal layer thickness values, but also identified problems in thickness calibrations during growth, as well as cap layer oxidation problems.

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