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S.A. Alterovitz
Lewis Research Center
Cleveland, Ohio

R.M. Sieg
Cleveland State University
Cleveland, Ohio

H.D. Yao, P.G. Snyder, and J.A. Woollam
University of Nebraska
Lincoln, Nebraska

J. Pamulapati and P.K. Bhattacharya
University of Michigan
Ann Arbor, Michigan

P.A. Sekula-Moise
Spire Corporation
Bedford, Massachusetts

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STUDY OF InGaAs-BASED MODFET STRUCTURES USING VARIABLE-ANGLE SPECTROSCOPIC ELLIPSOMETRY

S.A. Alterovitz
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

R.M. Sieg*
Cleveland State University
Department of Electrical Engineering
Cleveland, Ohio 44115

H.D. Yao, P.G. Snyder, and J.A. Woollam
University of Nebraska
Department of Electrical Engineering
Lincoln, Nebraska 68588

J. Pamulapati and P.K. Bhattacharya
University of Michigan
Department of Electrical Engineering and Computer Science
Ann Arbor, Michigan 48109

P.A. Sekula-Moise
Spire Corporation
Bedford, Massachusetts 01730

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SUMMARY

Variable angle spectroscopic ellipsometry (VASE) has been used to estimate the thicknesses of all layers within the optical penetration depth of InGaAs-based MODFET structures. Strained and unstrained InGaAs channels were made by MBE on InP substrates and by MOCVD on GaAs substrates. In most cases, ellipsometrically determined thicknesses were within 10 percent of the growth-calibration results. The MBE-made InGaAs strained layers showed large strain effects, indicating a probable shift in the critical points of their dielectric function toward the InP lattice-matched concentration.

*Undergraduate Student Intern at NASA Lewis Research Center.

INTRODUCTION

$In_xGa_{1-x}As$ can be grown epitaxially on InP or GaAs substrates, mostly as a strained layer. At a concentration of $X = 0.53$, it is lattice-matched to InP. Although many applications in electronics and optoelectronics have been demonstrated using the lattice-matched concentration, superior properties of the strained-layer material have shifted the direction of applied research to $X \neq 0.53$. MODFET's (modulation doped field effect transistor) with a strained-layer InGaAs channel have been demonstrated on InP [1] and on GaAs [2] substrates. Strain effects also play an important role in optoelectronic applications [3], especially near the band edge. Important parameters for any applications are the thicknesses of the layers, composition, interface quality and overlayer contamination or oxidation.

Ellipsometry, particularly VASE in the visible, has been shown to characterize MODFET's [4] and optoelectronic structures [5] in the GaAs/AlGaAs family. This nondestructive optical technique can be used to perform a detailed analysis of all layers within the optical penetration depth. For InGaAs, this depth is of order ~1000 Å, i.e., it covers all interesting layers in a MODFET structure. Ellipsometry has been used in the past only twice for InGaAs-based MODFET's [6,7]. The $In_xGa_{1-x}As$/InP MODFET with $X = 0.53$ made by MOCVD (metalorganic chemical vapor deposition) was analyzed in detail, including interface quality, by Erman et al. [6]. However, the more common MODFET growth technique is MBE (molecular beam epitaxy) rather than MOCVD. In this technique, InP cannot be grown and is replaced by $In_{0.52}Al_{0.48}As$, which is lattice matched to the InP substrate and provides the high bandgap layer needed for the MODFET. Preliminary results on lattice-matched

$In_xGa_{1-x}As$/InAlAs/InP MODFET's were published by Alterovitz et al. [7]. However, no strain effects were reported in [7]. In this paper, we will report on an ellipsometric study showing strain effects for the first time. The work included strained and lattice-matched InGaAs MODFET's made by MBE, as well as strained InGaAs MODFET's made by MOCVD on GaAs and using AlGaAs as the donor layer. Results will be compared with growth-calibration data obtained during the crystal growth.

EXPERIMENTAL

The structures grown on semi-insulating InP substrates were prepared by MBE at the University of Michigan. The structures are shown in Fig. 1. The 30-period 30 Å/30 Å superlattice buffer made of InGaAs/InAlAs acts as a dislocation filter. The role of all other layers is explained in [7]. Growth conditions are given in [8]. For ellipsometry purposes, the 4000 Å thick InAlAs serves as substrate, as the optical penetration depth in most of the experimental range is smaller than the thickness of all layers above the superlattice. Three indium concentrations X were tested: 0.53, 0.65, and 0.70. Nominal channel thicknesses derived from growth-calibration data are shown in Fig. 1.

Three samples grown by MOCVD at Spire Corporation on semi-insulating GaAs were also tested. The structures are shown in Fig. 2. The 1 μm buffer is made mainly of i GaAs and it is regarded as substrate for ellipsometry purposes. Growth parameters are given in [8].

The ellipsometric technique used was similar to that described previously [9]. In this work, we minimized the mean square error σ as defined in Eq. (1)

$$\sigma \equiv (N^{-1}) \sum_{i} [(\tan \Psi_{e,i} - \tan\Psi_{c,i})^2 + (\cos \Delta_{e,i} - \cos \Delta_{c,i})^2] \qquad (1)$$

Here $\tan\Psi_{e,i}$, $\cos \Delta_{e,i}$ are the experimental results and $\tan\Psi_{c,i}$, $\cos \Delta_{c,i}$ are the model calculations. The summation is over all N experimental points, i.e., all wavelengths and angles of incidence. Ellipsometric dielectric calibration functions were taken from the following: $In_xGa_{1-x}As$ from the algorithm developed in [8], AlGaAs from the algorithm given in [10], GaAs from [11], $In_{0.52}Al_{0.48}As$ from previous measurements at NASA Lewis Research Center and the oxide from [12]. The dielectric function for the oxide was measured on GaAs oxides, but it gives a good description of the oxide on $In_{0.53}Ga_{0.47}As$ [13].

RESULTS AND DISCUSSION

Results for three indium compositions grown by MBE are given in Table I. The thicknesses t_i correspond to Fig. 1. The quality of the fits, as measured by the value of the mean square error, is good. However, two features of these results were unexpected: the very low values of the cap InGaAs layers thicknesses and the negative values for the strained layers thicknesses. The low values obtained for the cap layers can be explained by the very short growth time of these layers and the accompanying experimental errors and by possible loss of material due to oxidation. We found this result for the InGaAs cap layer in all our MBE samples. Another explanation might involve an interface layer between the InAlAs and the cap layer. However, for our structures it is almost impossible to study this interface by ellipsometry. We already have 4 to 5 parameters and an interface layer would introduce another parameter. In addition, we have already a high correlation parameter (0.9 or higher) between t_2 and t_3, the cap

layer and the InAlAs layer thicknesses respectively. The correlation problem was discussed in [14,15]. The high correlation between t_2 and t_3 means that ellipsometry has difficulty in estimating accurately the value of each one of these two parameters, but the sum $t_2 + t_3$ is not affected by the correlation. Results given in Table I support this conclusion, with experimental $t_2 + t_3$ values in the range 474 Å to 493 Å, while the nominal value is 500 Å.

The other unexpected result, the negative values for t_4, is definitely related to the special property of this layer, namely that it is a pseudomorphic strained layer. The ellipsometric dielectric calibration functions that were used for the calculations were taken from [8], where a study of strain-free $In_xGa_{1-x}As$ material was done. It is known that the band gap of pseudomorphic InGaAs grown on InP is different from that of unstrained bulk InGaAs [16]. There are no theoretical calculations of the dielectric function of pseudomorphic InGaAs on InP in the visible. However, we expect the critical points and, accordingly, the dielectric function [10] to change continuously as function of composition. In the case of pseudomorphic InGaAs, we get a split of the valence band [16] and the resulting band structure with the associated critical points is expected to be more complex than the case for AlGaAs. However, in a very rough approximation and extension of the result in [16], the bandgap of strained-layer $In_xGa_{1-x}As$ is similar to unstrained $In_YGa_{1-Y}As$, where $X > Y$ for $Y > 0.53$, i.e., for compressive strain. Assuming that all critical points move in the same direction, we have to use as a calibration dielectric function for our strained $In_xGa_{1-x}As$ the dielectric function obtained for unstrained $In_YGa_{1-Y}As$ from [8] with $X > Y$. We used the dielectric function of the

unstrained $In_{0.53}Ga_{0.47}As$ to fit the $In_xGa_{1-x}As$ strained-lattice layers for both X = 0.65 and 0.70. The results are given in Table II. The quality of the fits is good, and there are no unphysical results for layer thicknesses. Results are also shown in Figs. 2(a) and (b) for the fit given in Table II for the X = 0.70 sample. There is a remarkably good fit of the experimental and the modeled data, including the sharp jumps in the values of cos Δ.

Two comments on the results given in Table II will now be discussed. First comment is in regard to correlations. The same correlation problem between t_2 and t_3 mentioned previously was also observed for the results given in Table II. We will now combine the results of Table I (for the lattice-matched sample) and Table II (for the strained-lattice sample) for the parameter $t_2 + t_3$: while the nominal value is 500 Å for all samples, the experimental results' range is 482 Å to 493 Å, even smaller than the range mentioned above. Second comment is in regard to the concentration parameter X, especially for the strained-lattice samples. This parameter was obtained from growth-calibration data, which itself was cross checked by x-rays for strain-free material. A positive confirmation that X for the strained-lattice samples is not 53 percent was obtained from electrical measurements of devices made from the same wafers or similarly prepared wafers [17,18]. The measured device parameters show a clear dependence on the nominal value of X.

Three MOCVD-grown MODFET structures of pseudomorphic $In_{0.3}Ga_{0.7}As$ on GaAs were measured. The results are shown in Table III. For one of the samples, we also show a complete comparison of experiment and model in Fig. 3. The mean square errors σ are much smaller than those for

the InGaAs/InAlAs/InP samples. In addition, all results pertaining to the InGaAs and the GaAs layer thicknesses are in good agreement with the nominal values. There are some discrepancies between the ellipsometric estimates and the AlGaAs nominal concentrations or thicknesses. At the present time, we believe that the ellipsometric result may be a more accurate description of the sample. The low values for σ are probably due to better calibration spectra for the constituents and the fact that the Al concentration in AlGaAs is a free parameter, while the composition of $In_{0.52}Al_{0.48}As$ is held constant.

CONCLUSIONS

A variety of InGaAs MODFET structures, made by both MBE and MOCVD were studied by variable angle spectroscopic ellipsometry. The thicknesses of all layers involved in the electric conduction were estimated and reasonably good fits to the nominal values were obtained. We have clearly seen, for the first time, strain effects in pseudomorphic InGaAs. These effects were explained qualitatively as a shift of the critical points in the strained versus the unstrained InGaAs material. In addition, in the case of MOCVD, we have seen possible problems in a AlGaAs layer, showing that ellipsometry can be used as a quality control tool for a complex material.

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TABLE I. - BEST FITS FOR MBE-GROWN InGaAs/InAlAs MODFET STRUCTURES USING THE STRAIN-FREE CALIBRATION FUNCTIONS

[Wavelength range: 3300 to 7500 Å.]

	X = 0.53		X = 0.65		X = 0.70	
	Nominal	Ellip-sometry	Nominal	Ellip-sometry	Nominal	Ellip-sometry
t_1	0	20.8	0	27.6	0	25.8
t_2	100	45.7	100	41.4	100	50.3
t_3	400	443	400	452	400	424
t_4	150	553	150	-0.5	100	-28.8
t_5	400		400	566	400	559
σ	---	3.2×10^{-3}	---	2.7×10^{-3}	---	1.8×10^{-3}

TABLE II. - BEST FITS FOR MBE-GROWN STRAINED-LAYER CHANNEL SAMPLES, ASSUMING ALL InGaAs LAYERS ARE LATTICE MATCHED TO InP, i.e., X = 0.53

[wavelength range: 3300 TO 7500 Å.]

	X = 0.65		X = 0.70	
	Nominal	Ellipsometry	Nominal	Ellipsometry
t_1	0	27.5	0	26.7
t_2	100	41.5	100	48.9
t_3	400	452	400	433
t_4	150	564	100	530
t_5	400		400	
x	0.65	0.53	0.70	0.53
σ	------	2.6×10^{-3}	------	1.8×10^{-3}

TABLE III. - BEST FITS FOR MOCVD-GROWN InGaAs/AlGaAs MODFET STRUCTURES USING THE STRAIN-FREE CALIBRATION FUNCTIONS

[Wavelength range: 3500 to 6800 Å.]

	MO6-316-3		MO6-332-1		MO6-334-1	
	Nominal	Best Fit	Nominal	Best Fit	Nominal	Best Fit
t_1	20	20.6	20	17.7	20	18.3
t_2	300	341	100	101	100	103
x	0.2	0.223	0.2	0.166	0.2	0.155
t_3	450	374	450	443	450	491
t_4	100	86.0	100	94.5	50	52.8
σ	-----	3.3×10^{-4}	-----	5.7×10^{-4}	-----	5.0×10^{-4}

MBE MODFET Structure

Actual MBE Grown Structure			Nominal Structure for Ellips.		
			t_1	GaAs oxide	0 Å
n^+	$In_{0.53}Ga_{0.47}As$	100 Å	t_2	$In_{0.53}Ga_{0.47}As$	100 Å
i	$In_{0.52}Al_{0.48}As$	200 Å			
n^+	$In_{0.52}Al_{0.48}As$	150 Å	t_3	$In_{0.52}Al_{0.48}As$	400 Å
i	$In_{0.52}Al_{0.48}As$	50 Å			
i	$In_xGa_{1-x}As$	d	t_4	$In_xGa_{1-x}As$	d
i	$In_{0.53}Ga_{0.47}As$	400 Å	t_5	$In_{0.53}Ga_{0.47}As$	400 Å
i	$In_{0.52}Al_{0.48}As$	4000 Å		$In_{0.52}Al_{0.48}As$	-
30 prd 30 Å/30 Å S.L. InGaAs/InAlAs					
SI InP Substrate					

Figure 1.–Actual and nominal structures used in ellipsometry for the MBE grown MODFET structures. d = 150 Å for x = 0.53 and 0.65, d = 100 Å for x = 0.70.

MOCVD MODFET STRUCTURE

Actual Structure			Nominal Structure For Ellipsometry		
			t_1	GaAs Oxide	20Å
n^+	GaAs	100Å	t_2	GaAs	100Å
n^+	$Al_xGa_{1-x}As$	400Å			
i	$Al_xGa_{1-x}As$	50Å	t_3	$Al_xGa_{1-x}As$	450Å
i	$In_{0.3}Ga_{0.7}As$	50Å (100Å)	t_4	$In_{0.3}Ga_{0.7}As$	50Å (100Å)
				GaAs Substrate	
	Buffer	10,000Å			
SI GaAs Substrate					

Figure 2.–Actual and nominal structures used in ellipsometry for the MOCVD structures. The aluminum concentration in $Al_xGa_{1-x}As$ is a variable. Some samples have a 50 Å $In_{0.3}Ga_{0.7}As$ layer and others have a 100 Å layer.

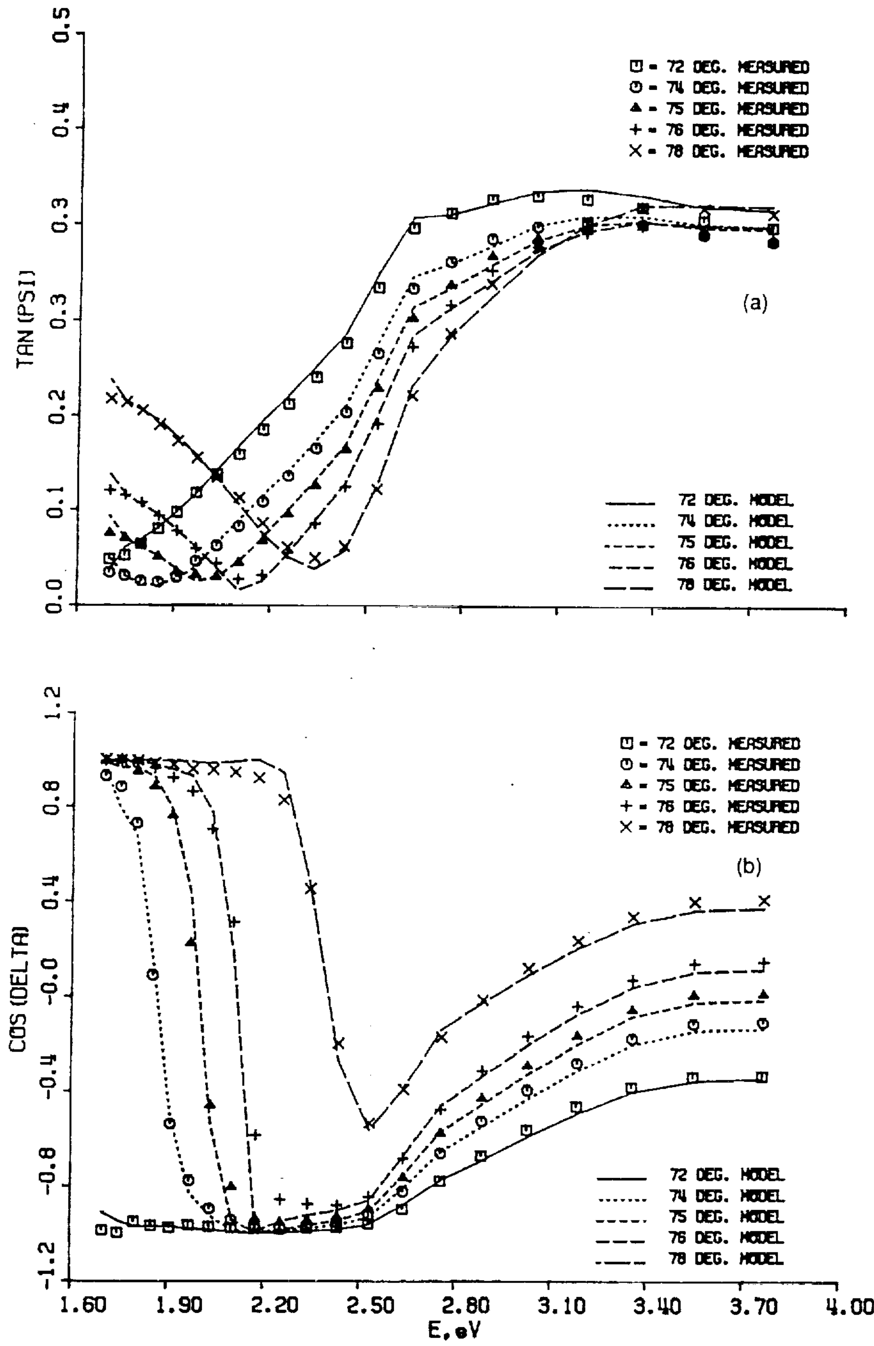

Figure 3.–Experiment and model simulation (a) $\tan\Psi$ and (b) $\cos\Delta$ versus energy for five angles of incidence for the MBE x = 0.70 sample. All of the InGaAs material is assumed to be lattice matched to InP.

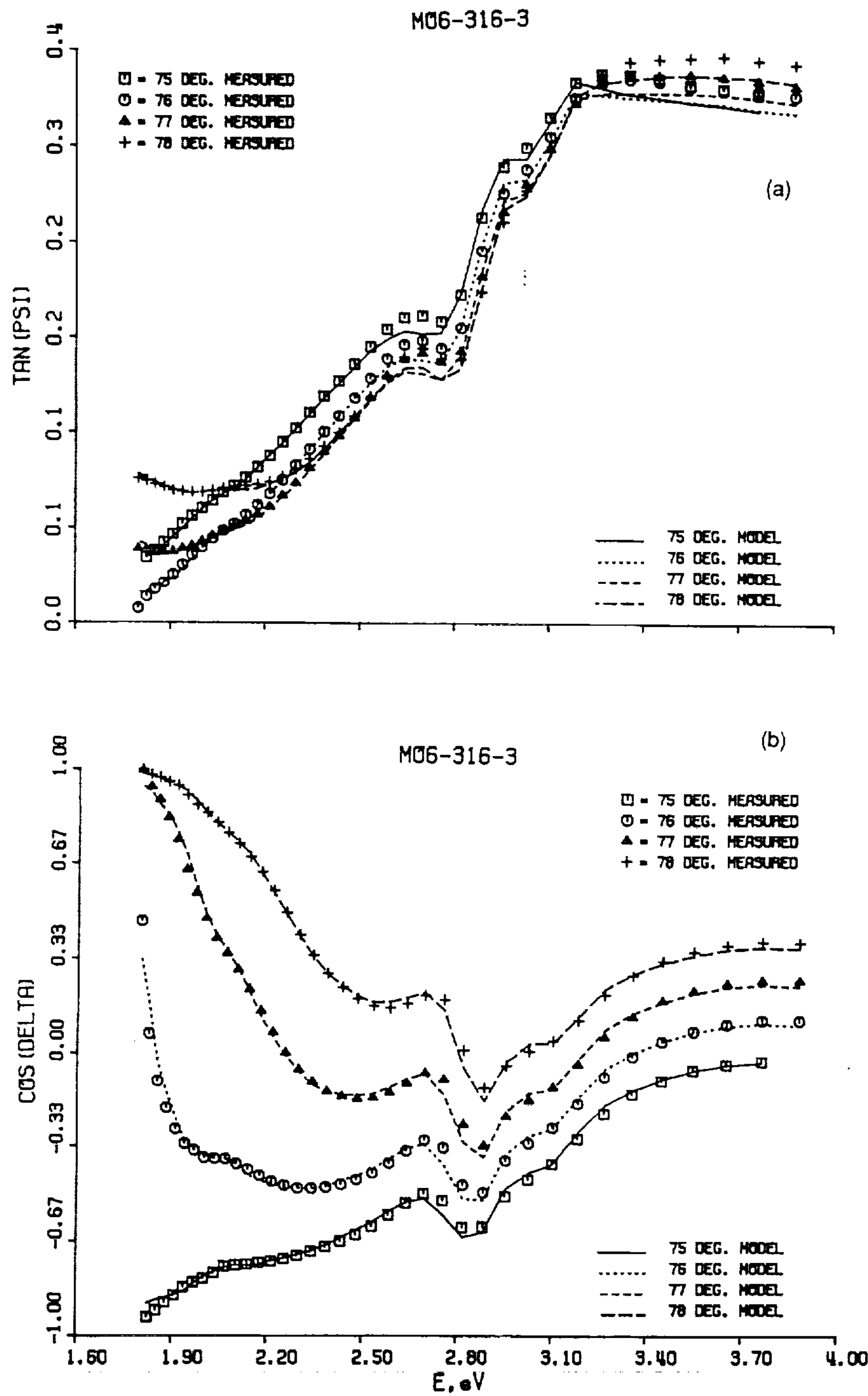

Figure 4.-Experimental and model simulation (a) tan Ψ and (b) cos Δ versus energy for four angles of incidence for a MOCVD x = 0.30 sample.

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16. Abstract
Variable angle spectroscopic ellipsometry (VASE) has been used to estimate the thicknesses of all layers within the optical penetration depth of InGaAs based MODFET structures. Strained and unstrained InGaAs channels were made by MBE on InP substrates and by MOCVD on GaAs substrates. In most cases, ellipsometrically determined thicknesses were within 10 percent of the growth calibration results. The MBE made InGaAs strained layers showed large strain effects, indicating a probable shift in the critical points of their dielectric function toward the InP lattice matched concentration.

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