NASA Technical Memorandum 103246

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Prepared for the
Second International Conference on Electronic Materials
sponsored by the Materials Research Society
Newark, New Jersey, September 17–19, 1990

NASA

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E-5672

ABSTRACT

In this study we report, for the first time, measurements of the dielectric function of thermodynamically stable $In_XGa_{1-X}As$ in the composition range $0.3 \leq X \leq 0.7$. The optically thick samples of InGaAs were made by molecular beam epitaxy (MBE) in the range $0.4 \leq X \leq 0.7$ and by metal-organic chemical vapor deposition (MOCVD) for $X=0.3$. The MBE made samples, usually 1 micron thick, were grown on semi-insulating InP and included a strain release structure. The MOCVD sample was grown on GaAs and was 2 microns thick. The dielectric functions were measured by variable angle spectroscopic ellipsometry in the range 1.55 eV to 4.4 eV. The data was analyzed assuming an optically thick InGaAs material with an oxide layer on top. The thickness of this layer was estimated by comparing our results for the InP lattice matched material, i.e. $X=0.53$, with results published in the literature. We removed the top oxide layer mathematically for $X=0.3$ and $X=0.53$ to get the dielectric function of the bare InGaAs. In addition, we measured the dielectric function of GaAs in vacuum, after a protective arsenic layer was removed. We used our dielectric functions for $X=0$, 0.3, and 0.53 together with the $X=1$ result from the literature to evaluate an algorithm for calculating the dielectric function of InGaAs for an arbitrary value of X ($0 \leq X \leq 1$). We compared results of the dielectric function calculated using the algorithm with experimental data.

INTRODUCTION

$In_XGa_{1-X}As$ is a material with a variety of potential and actual applications. The most commonly studied concentration is $X=0.53$, the InP lattice matched composition. However, strained lattice configurations show great promise for applications both in optoelectronics and in electronic devices. Applications of strained layer, modulation doped, heterostructures using an InGaAs conduction channel on either GaAs [1] or InP [2] substrates, as well as special optoelectronic applications on GaAs substrates, have recently been published. It is clear that an experimental determination of the thermodynamically stable $In_XGa_{1-X}As$ dielectric functions versus the composition, X, will be useful for several reasons. First, the results can be applied directly to the structures that are fabricated from these materials. Second, the results can be used as the starting point in calculating strain effects on the dielectric function. These effects play an important role for optoelectronic applications [3], especially near the band edge.

All published literature regarding the dielectric function of $In_XGa_{1-X}As$ in the visible is dedicated to the concentration $X=0.53$, i.e. lattice matched to InP. Several studies were performed using the highly accurate technique of

ellipsometry [4-7]. The samples were made by liquid phase epitaxy (LPE) [4-6] or by MOCVD [7]. Presently, there are no published reports of the dielectric function of MBE made InGaAs, either lattice matched or strained layer. The most useful data available, to date, is a numerical table [8] of the results presented in [5]. These results were obtained on chemically polished $In_{0.53}Ga_{0.47}As$ made by LPE.

In the present study, we will describe an ellipsometric, experimental determination of the dielectric functions of InGaAs with several indium concentrations (X), both lattice matched and lattice mismatched to InP. We will also present an algorithm that can be used to estimate the dielectric function of InGaAs for any desired value of the concentration X.

EXPERIMENTAL

$In_XGa_{1-X}As$ samples in the range $0.4 \leq X \leq 0.7$, with roughly 0.1 steps in X, were grown on semi-insulating InP substrates. Growth in both types of structures started with a 2000 Å lattice matched $In_{0.53}Ga_{0.47}As$ buffer layer. In the first set, hereafter called set A, this layer was followed by a ~1500 Å thick graded composition region (in multiple steps) to reach the composition of the final layer. The top $In_XGa_{1-X}As$ layer, which is of interest, is 1 μm thick and hence the strain is relieved at the interface with the next lower layer. In the second set of samples, hereafter called set B, a 30 period superlattice (30 Å $In_XGa_{1-X}As$/30 Å $In_XAl_{1-X}As$) was grown at the interface before the top layer, to act as a dislocation filter. All the heterostructures were grown continuously at 520 °C at a rate of 1.2 μm/hr and with a V/III flux ratio of ~30. The MOCVD sample (X=0.3) was grown on n^+ GaAs at Spire Corporation. The thickness was nominally 2 μm and no buffer layers were used. The $In_{0.3}Ga_{0.7}As$ layer was grown at 650 °C at a rate of 1.9 μm/hr and with a V/III flux ratio of ~75.

The GaAs sample was mounted and measured on a high temperature stage inside an ultra high vacuum (UHV) chamber. The sample consisted of a MBE grown GaAs epitaxial layer on a GaAs substrate and was covered with an amorphous arsenic layer for protection of the surface. Prior to the ellipsometric measurement, the protecting layer was evaporated by heating the sample to 350 °C in vacuum for 10 minutes [9]. This procedure [9] yielded a GaAs surface as clean and smooth as the best chemically polished surface reported previously [10].

Ellipsometric measurements were made both at NASA-Lewis and at the University of Nebraska. The technique [11,12] was described previously and will not be repeated here.

RESULTS AND DISCUSSION

The ellipsometric, experimental parameters ψ and Δ were used to find the substrate pseudo-dielectric function, i.e. without taking into account any overlayers. The results of the "pseudo" refractive index, n, for all the concentrations measured are shown in Fig. 1. The X=0.4, 0.6, and 0.7 samples belong to the set A strain release procedure, while the X=0.53 sample was grown using the set B procedure. We also measured samples with X=0.4 and 0.7 from set B. All the graphs clearly show that the E_1 critical point peak is moving to lower energies as the In concentration increases. The difference in the absolute value of n versus X is due not only to changes in the indium concentration, but also to differences in oxide overlayer thickness and surface imperfections. The results for the samples with X=0.4 and 0.7 from set B show the same values of the critical point, E_1, as in Fig. 1, but have slightly higher values for n. This is probably due to a more perfect surface obtained for set B versus set A

samples. Results obtained for the extinction coefficient show that the optical penetration depth for all samples is well below 1000 Å, for wavelengths below 6000 Å, and below 2000 Å anywhere in the spectrum. This result reinforces our assumption that our 1-2 μm films are optically thick.

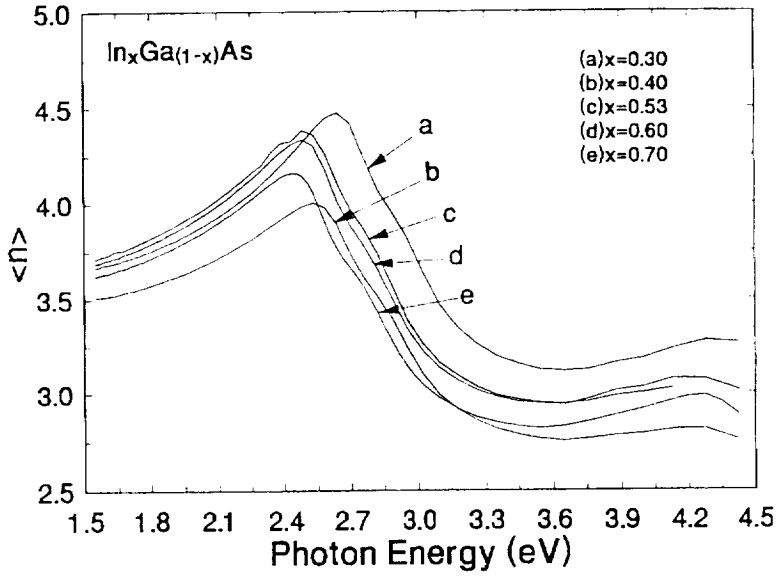

FIGURE 1. - PSEUDO REFRACTIVE INDEX OF FIVE $In_xGa_{1-x}As$ ($0.3 \leq x \leq 0.7$) SAMPLES VERSUS THE PHOTON ENERGY.

There are several ways to remove the contribution of the top oxide layer to the dielectric function. We tried to obtain, simultaneously, the dielectric function of the InGaAs and the oxide layer thickness using our variable angle of incidence capability. However, the rather small thickness of the oxide layer and the large correlations between this thickness and the InGaAs dielectric function prevented us from obtaining reliable results using this method of analysis. A good estimate of the oxide layer thickness, for the lattice matched sample, was obtained using a model in which variable oxide thickness and constant dielectric functions for the $In_{0.53}Ga_{0.47}As$ [8] and oxide [13] were used. This one parameter fit gave an oxide layer thickness of 22.5 Å with an excellent mean square error (M.S.E.) of 0.085 for ψ and Δ fits. Assuming a constant 22.5 Å oxide thickness, we mathematically removed the oxide contribution for all samples. The result for the X=0.53 sample is compared to Aspnes data [8] in Fig. 2. As expected, an almost perfect agreement was obtained between the MBE and LPE grown materials. The real and imaginary parts of the dielectric functions for four indium concentrations in the range $0 \leq X \leq 1$, namely X=0, 0.3, 0.53, and 1, are shown in Figs. 3 and 4 respectively. The functions shown for X=0 [9] are the most recent results, which are very close to the generally accepted data [10]. The InAs functions were taken from the literature [10,14]. We believe that these four functions are more representative of the InGaAs material than those we obtained for other values of X due to the poorer surface quality of the latter samples. We used a numerical interpolation algorithm to calculate the value of the dielectric function for an arbitrary value of X, similar to that used for AlGaAs [15,16]. The algorithm is based on the four functions shown in Figs. 3 and 4 and uses an interpolation of the critical points and the value of the dielectric function.

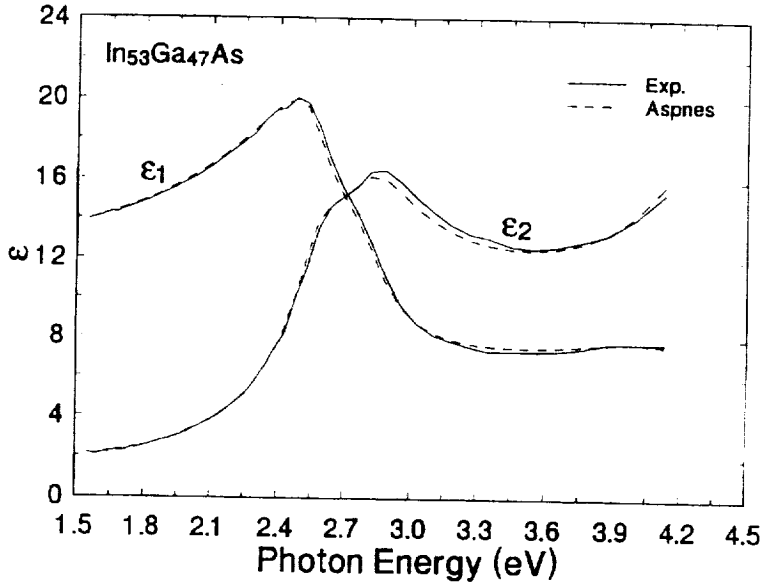

FIGURE 2. - COMPARISON OF PRESENT DATA WITH ASPNES [8] FOR THE DIELECTRIC FUNCTION OF $In_{0.53}Ga_{0.47}As$ VERSUS PHOTON ENERGY.

As a test of the algorithm, we used it to estimate the indium concentration, X, for a sample from set A with nominal concentration X=0.4. We applied a least squares fitting procedure to fit the experimental ellipsometric data to values calculated using the algorithm with X and the oxide overlayer thickness as variables. We obtained an oxide thickness of 31 Å, an indium concentration of X=0.37, and an M.S.E.=0.39 for the ψ and Δ fits. The result is shown in Fig. 5, in terms of the measured and best-fit pseudo-dielectric functions. The lower peak value of the experimental $\langle\epsilon_2\rangle$, compared to the best-fit $\langle\epsilon_2\rangle$, is indicative of a relatively poor surface quality for this sample.

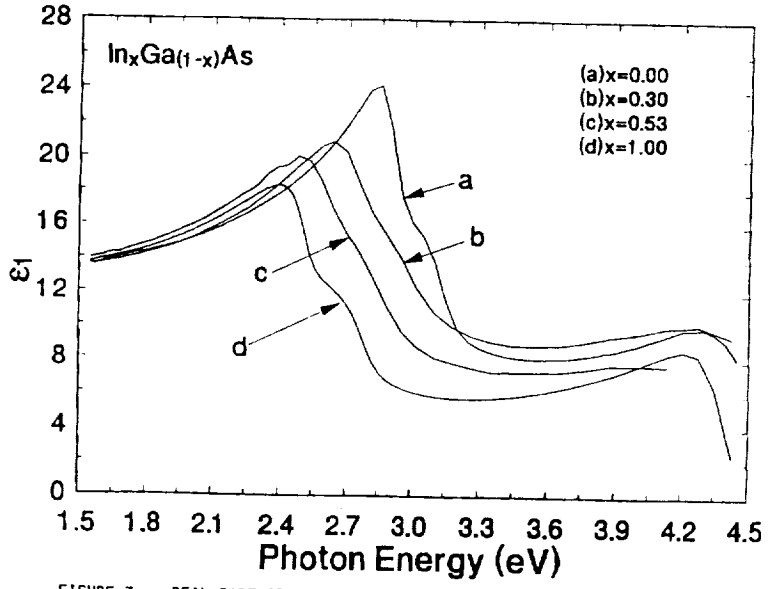

FIGURE 3. - REAL PART OF THE DIELECTRIC FUNCTION OF $In_xGa_{1-x}As$ ($0 \leq x \leq 1$) FOR FOUR SAMPLES VERSUS ENERGY.

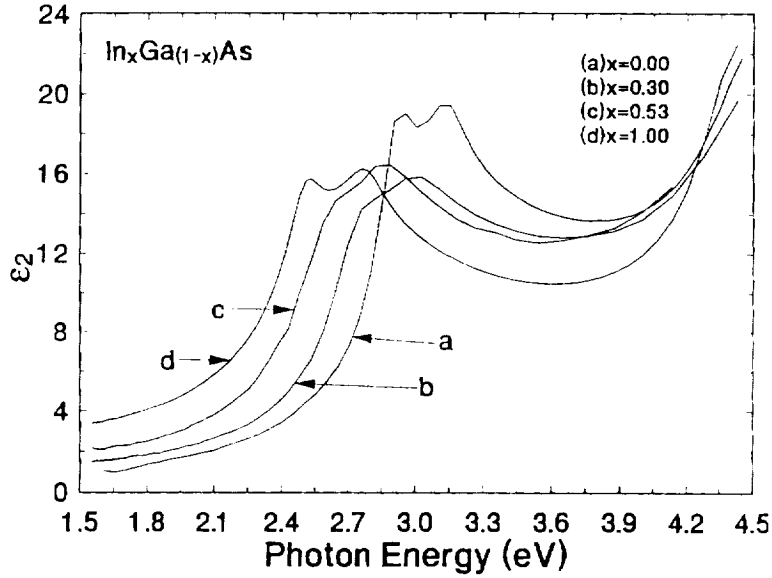

FIGURE 4. - IMAGINARY PART OF THE DIELECTRIC FUNCTION OF $In_xGa_{1-x}As$ ($0 \leq x \leq 1$) FOR FOUR SAMPLES VERSUS ENERGY.

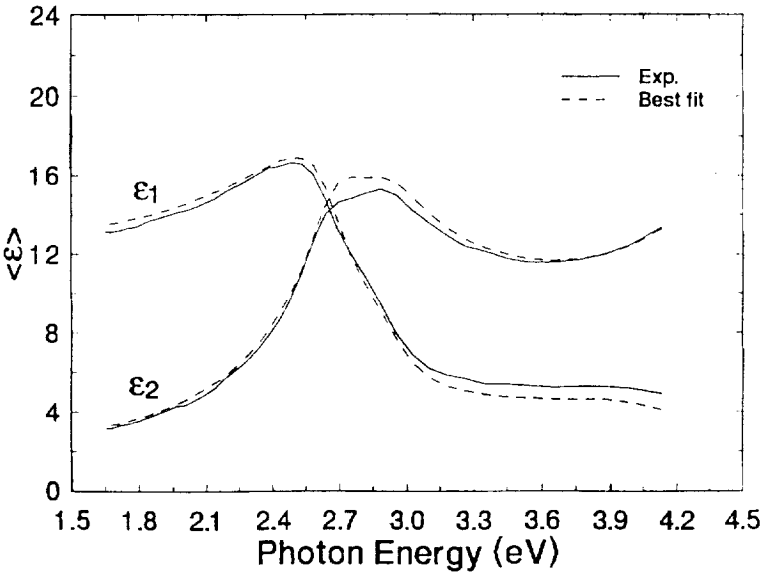

FIGURE 5. - REAL AND IMAGINARY PARTS OF THE EXPERIMENTAL AND BEST-FIT (CALCULATED) PSEUDO DIELECTRIC FUNCTION FOR THE NOMINAL x = 0.4 SAMPLE.

CONCLUSIONS

Thermodynamically stable $In_XGa_{1-X}As$ samples in the range $0.3 \leq X \leq 0.7$ were grown by MBE and MOCVD. Samples were 1-2 μm thick, well above both the optical penetration depth and the dislocation range. The oxide overlayer contribution was estimated by comparison of our results with published data for X=0.53, the lattice matched concentration. After a mathematical removal of the oxide layer, the pseudo-dielectric functions of $In_XGa_{1-X}As$ were obtained for several values of X. These functions were interpolated using a special algorithm to calculate the dielectric function for any value of X. The algorithm was successfully tested versus our experimental result at X=0.4.

ACKNOWLEDGEMENTS

Work at the University of Michigan was supported by grant NAG3-988. Work at Spire Corporation was performed under contract NAS3-25867.

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NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-103246		

4. Title and Subtitle	5. Report Date
Dielectric Function of InGaAs in the Visible	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
S.A. Alterovitz, R.E. Sieg, H.D. Yao, P.G. Snyder, J.A. Woollam, J. Pamulapati, P.K. Bhattacharya, and P.A. Sekula-Moise	E-5672
	10. Work Unit No. 506-44-21

9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	13. Type of Report and Period Covered Technical Memorandum

12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
National Aeronautics and Space Administration Washington, D.C. 20546-0001	

15. Supplementary Notes

Prepared for the Second International Conference on Electronic Materials sponsored by the Materials Research Society, Newark, New Jersey, September 17-19, 1990. S.A. Alterovitz, NASA Lewis Research Center. R.E. Sieg, Cleveland State University, Dept. of Electrical Engineering, Cleveland, Ohio 44115; Undergraduate Student Intern at NASA Lewis Research Center. H.D. Yao, P.G. Snyder, and J.A. Woollam, University of Nebraska, Dept. of Electrical Engineering, Lincoln, Nebraska 68588. J. Pamulapati and P.K. Bhattacharya, University of Michigan, Dept. of Electrical Engineering and Computer Science, Ann Arbor, Michigan 48109 (work supported by NASA Grant NAG3-988). P.A. Sekula-Moise, Spire Corporation, Patriots Park, Bedford, Massachusetts 01731 (work performed under NASA Contract NAS3-25867).

16. Abstract

In this study we report, for the first time, measurements of the dielectric function of thermodynamically stable $In_xGa_{1-x}As$ in the composition range $0.3 \leq X \leq 0.7$. The optically thick samples of InGaAs were made by molecular beam epitaxy (MBE) in the range $0.4 \leq X \leq 0.7$ and by metal-organic chemical vapor deposition (MOCVD) for $X = 0.3$. The MBE made samples, usually 1 micron thick, were grown on semi-insulating InP and included a strain release structure. The MOCVD sample was grown on GaAs and was 2 microns thick. The dielectric functions were measured by variable angle spectroscopic ellipsometry in the range 1.55 eV to 4.4 eV. The data was analyzed assuming an optically thick InGaAs material with an oxide layer on top. The thickness of this layer was estimated by comparing our results for the InP lattice matched material, i.e. $X = 0.53$, with results published in the literature. We removed the top oxide layer mathematically for $X = 0.3$ and $X = 0.53$ to get the dielectric function of the bare InGaAs. In addition, we measured the dielectric function of GaAs in vacuum, after a protective arsenic layer was removed. We used our dielectric functions for $X = 0$, 0.3, and 0.53 together with the $X = 1$ result from the literature to evaluate an algorithm for calculating the dielectric function of InGaAs for an arbitrary value of X ($0 \leq X \leq 1$). We compared results of the dielectric function calculated using the algorithm with experimental data.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Compound semiconductors Ellipsometry	Unclassified – Unlimited Subject Category 76

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	9	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161