Experimental test for elastic compliance during growth on glass-bonded compliant substrates

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Highly mismatched films ($In_{0.44}Ga_{0.56}As$, 3% mismatch) grown well beyond their critical thickness (to 3 μm) on GaAs glass-bonded compliant substrates exhibit surfaces four times smoother and strain distributions twice as narrow as films grown simultaneously on conventional GaAs substrates. The compliant substrates consist of a thin (~10 nm) GaAs template layer bonded via a borosilicate glass to a mechanical handle wafer. The improvement of highly mismatched films grown well beyond their critical thickness on compliant substrate structures is commonly modeled in terms of an elastic partitioning of strain from the film to the thin (~10 nm) single-crystal template layer. The present study is a direct test for this mechanism of elastic compliance. A comparison is reported of the strain in 92 nm $In_{0.09}Ga_{0.91}As$ films and 76 nm $In_{0.03}Ga_{0.97}As$ films grown simultaneously on conventional GaAs substrates and the compliant substrates responsible for the improved structural quality of $In_{0.44}Ga_{0.56}As$ films. Elastic partitioning of strain from the mismatched film to the 10 nm template layer prior to the onset of misfit dislocations is not observed for films grown on these glass-bonded compliant substrates. © *2000 American Institute of Physics.*
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Modification of the relaxation behavior in lattice-mismatched films due to growth on a glass-bonded compliant substrate is well documented.[1,3–5] Compliant substrates consist of a thin (~10 nm) ''template'' layer bonded to a thicker ''handle'' wafer by means of an intermediary glass layer in these studies. Transmission electron microscopy observations have demonstrated a reduced dislocation density of films grown to many times their Matthews–Blakeslee[2] critical thickness h_c on glass-bonded compliant substrates.[3–5] High-resolution x-ray diffraction (HRXD) measurements and atomic-force microscopy characterization were carried out on thick (3 μm), highly mismatched (3%) $In_{0.45}Ga_{0.55}As$ films grown simultaneously on conventional and the compliant substrates that are the focus of the present study. These measurements demonstrated a ~2× reduction in the breadth of the film's strain distribution as determined by triple-crystal diffraction peak widths that decreased from 270″ on a conventional substrate to 155″ on the glass-bonded substrate. In addition, there was a ~4× decrease in the rms roughness of the films from 42 nm rms on a conventional substrate to 10 nm rms on the glass-bonded substrate.[1] These improvements in the structural quality of the thick, highly mismatched, relaxed films on the glass-bonded substrates occurred for a range in glass viscosity of over five orders of magnitude.

A specific mechanism responsible for the changes in relaxation behavior of a mismatched film grown on a glass-bonded compliant substrate is uncertain at present and could be specific to the materials system. The present work is a test for a specific mechanism of compliance in substrates fabricated using a materials system that has been shown to modify the relaxation behavior of thick highly mismatched films. A description of how one mechanism of compliance has been tested and the results of this test follow a brief description of the proposed mechanisms of compliance.

Theoretical treatments of the impact of a compliant substrate on strain relaxation in a mismatched film fall into one of two categories, based upon whether or not the template layer is assumed to move freely in the plane of the bonded interface. When the template layer can move in the plane of the bonded interface, the strain will be partitioned from the film to the template layer before the onset of plastic deformation in the growing film. There have been numerous descriptions in the literature of the effect of an ''elastically compliant substrate'' on film strain during growth.[3,4,6–13] The strain in the film ϵ_f in terms of the film thickness h_f, the template layer thickness h_s, and the mismatch ϵ_0, between the film and substrate due to elastic compliance of the template layer is described by

$$\epsilon_f = \frac{\epsilon_0}{\left(1+\frac{h_f}{h_s}\right)}. \quad (1)$$

The strain relaxation, even in the case when the template

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layer is not free to move in the plane of the bonded interface, can be modified by the introduction of a subsurface glass layer. The relaxation of a film grown thicker than h_c may be modified due to a change in the introduction, propagation, and final distribution of dislocations in the heterostructure resulting from the buried oxide layer.[4] Such ''plastically compliant substrates'' can result in a reduction in the density of threading dislocations present in a relaxed film due to changes in the dislocation dynamics. Image forces due to the presence of a low elastic modulus glass layer can draw threading dislocations, which would otherwise propagate up through the growing film, down through the template towards the bonded interface.[5,6] It has also been proposed that the bonded interface acts as a sink for contaminants that would otherwise result in the nucleation of dislocations in the film.[14]

The observed changes in the strain distribution and film morphology could be due to both elastically and plastically compliant behaviors of the substrate for films grown well beyond their critical thickness. Plastic deformation will not occur, however, on a conventional or compliant substrate for films below or on the order of their critical thickness. In this case, a difference between the strain present in films grown simultaneously on a conventional and compliant substrate is a direct indication of the elastic compliance of the substrate. Inspection of Eq. (1) shows that if h_f is on the order of or less than h_c but still much greater than h_s, a significant change in the strain of the film would be expected if the template is free to move in the plane of the bonded interface. A direct test of elastic compliance is, therefore, executed by measuring the strain state of films whose thicknesses meet the above criteria grown simultaneously on conventional and compliant substrates. This experiment is described below.

The compliant substrates consisted of a $<$10 nm GaAs growth template bonded to a borosilicate glass-coated GaAs handle wafer fabricated through a process reported elsewhere.[15] The thickness of the template layer h_s was measured by spectrally resolved ellipsometry with 1 nm precision prior to growth of the film. The compliant substrates employed a 30 mol % B_2O_3 borosilicate glass as the bonding media. An extrapolation of existing viscosity data for borosilicate glasses[16] estimates the viscosity of the 30 mol % glass to be $\sim 10^{12}$ P at 700 °C.

A total of nine films were grown in four growth experiments under similar growth conditions on these compliant substrates. In each growth experiment, films were grown simultaneously on conventional GaAs substrates and GaAs glass-bonded compliant substrates in a horizontal metal–organic vapor-phase epitaxy reactor at 700 °C. Five of the films were $In_{0.44}Ga_{0.56}As$ (3% mismatch), grown well beyond their critical thickness (to 3 μm). These five films demonstrated the reproducibility of the improvement in the structural quality of thick highly mismatched films due to growth on the compliant substrate structures that was discussed in more depth in a previous publication.[1]

Four films were subsequently grown in two growth experiments to test for the mechanism of elastic compliance. Films of two In compositions were grown simultaneously on compliant substrates and conventional substrates. The first heterostructure was $In_{0.09}Ga_{0.91}As$ grown at a rate of 0.74 $\pm$0.04 nm/s to a thickness of 92$\pm$4 nm on a conventional GaAs substrate and a compliant substrate with a GaAs template of thickness h_s=5$\pm$1 nm. The mismatch in this heterostructure, ϵ_0=0.68% results in a Matthews–Blakeslee critical thickness, h_c=20 nm. The second heterostructure was $In_{0.03}Ga_{0.97}As$ grown at a rate of 0.59$\pm$.06 nm/s to a thickness of 76$\pm$6 nm on a conventional substrate and a compliant substrate with a GaAs template of thickness h_s=8$\pm$1 nm. The mismatch in this heterostructure, ϵ_0=0.24%, results in a h_c=74 nm. Figure 1 shows the thickness and mismatch of the films compared to the critical thickness condition. The influence of dislocation kinetics precludes a quantitative interpretation of the retained pseudomorphic strain solely in terms of the ratio of h_f to the equilibrium value of h_c.[17] The thickness and mismatch of both films are, however, in the regime where much of the pseudomorphic strain is retained when grown on conventional substrates.

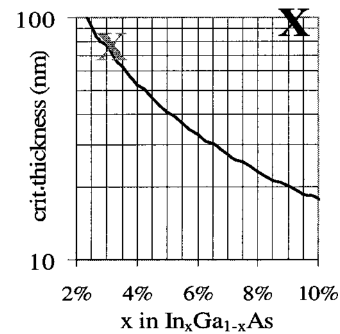

FIG. 1. Comparison of the thickness and mismatch of the films studied with the heterostructures' equilibrium critical thickness. The films are of a thickness and mismatch such that they would be expected to retain a large portion of their pseudomorphic strain when grown on conventional substrates.

X-ray diffraction analyses of the films employed a Bede D^3 diffractometer and Cu $K\alpha$ radiation. The beam was conditioned by a four-bounce Si(220) monochromator before impinging on the sample. The area of the sample probed by the x-ray beam was approximately 1 cm by 1 mm. The thickness of the grown film was determined through the spacing of the interference fringes evident in the HRXD spectra. The relaxed lattice constant of the film a_r, the lattice constant of the film parallel to the film/substrate interface $a_\parallel$, and the lattice constant of the film perpendicular to the film/substrate interface $a_\perp$, were measured through collection of the sym-

TABLE I. Measured thickness, mismatch, and strain of the films grown on conventional and glass-bonded compliant substrates.

	Film 1	Film 2	Film 3	Film 4
h_s	450 μm	8$\pm$1 nm	450 μm	5$\pm$1 nm
%In	3.4$\pm$0.2	3.3$\pm$0.4	9.8$\pm$0.4	8.6$\pm$0.9
ϵ_0 (%)	0.24$\pm$.02	0.23$\pm$.04	0.70$\pm$.04	0.62$\pm$.08
h_f (nm)	76$\pm$6	76$\pm$6	92$\pm$4	92$\pm$4
$a_\parallel$ (nm)	0.5659 $\pm$.0002	0.5657 $\pm$.0004	0.5653 $\pm$.0003	0.5653 $\pm$.0007
a_r (nm)	0.5667 $\pm$.0001	0.5666 $\pm$.0002	0.5693 $\pm$.0002	0.5688 $\pm$.0004
%strain	38%–74%	48%–100%	86%–100%	77%–100%

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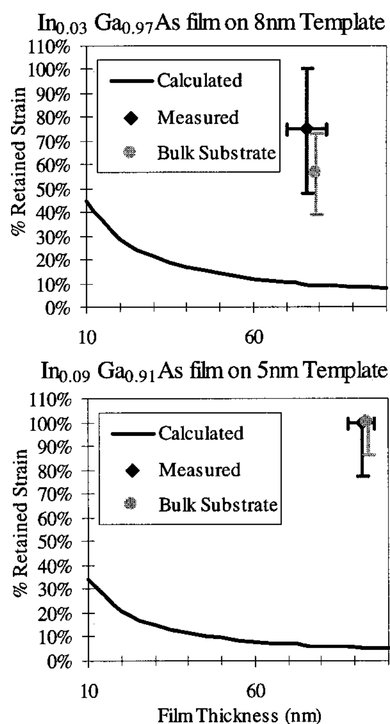

FIG. 2. Comparison of the experimentally measured strain present in the films with the strain that would be present if strain was elastically partitioned to a template layer free to move in the plane of the bonded interface. The substrate is not elastically compliant.

metric 004 and assymetric 224 x-ray diffraction spectra before and after rotating the sample about its surface normal by 180°. The percentage of retained pseudomorphic strain in the films, defined as $\%\text{strain}=100\ [1-(a_{\|}-a_s)/(a_r-a_s)]$, where a_s=the lattice constant of bulk GaAs, was then calculated from these data.

The results of the measurements are tabulated in Table I. The films grown on compliant and conventional substrates all retain most of their pseudomorphic strain. The measured values of the retained strain in the film are compared to that which would be expected if Eq. (1) were to apply in Fig. 2. Since $h_f \gg h_s$ in these heterostructures, the films would be relaxed to a degree that falls well outside the error bars in the measurement if the template were free to move in the plane of the bonded interface.

This study, therefore, concludes that the glass-bonded substrates are plastically compliant substrates. The template is not free to move in the plane of the bonded interface under the application of elastic mismatch stress. In the absence of relaxation due to dislocation formation, the films on the compliant and conventional substrates are similarly strained. The improvements in the morphology and the narrowing of the strain distribution observed in mismatched films grown on these substrates must, therefore, be due to a modification of the dislocation distribution in the heterostructure rather than due to the elastic partitioning of strain that would occur in the absence of dislocations during growth on a freestanding, thin substrate. We believe these results also apply to other materials systems reporting compliant behavior in the literature.[5,18]

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