The Dependence of the Critical Thickness of an InGaAs/GaAs Multi-layer on Quantum Well and Barrier Thicknesses and Number of Periods

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A Threading-Dislocation-Configuration (TDC) model has been used to investigate the stability criteria for selected $In_{0.2}Ga_{0.8}As/GaAs$ multi-quantum wells. It is observed that plots of barrier thickness versus quantum well periods are logarithmic for thicker strained layers and larger period numbers.

1. Introduction

Strained-layer superlatices (SLS's) and multiple-quantum-wells (MQW's) have become increasingly important in electronic and optoelectronic device applications. In these structures, the lattice mismatch in the layers is accommodated coherently without the formation of misfit dislocation at any of the interfaces. Since the individual layer thickness is less than its critical thickness, the SLS will have misfit dislocations at the lowest interface if the whole structure exceeds the critical thickness.

Despite the widespread application of SLS's and MQW's, there have been serious shortcomings in previous attempts [1,2] to predict the stability criteria for multi-layered structures. In view of this, Madebo et al [3] have developed a TDC model that can be applied to any structure to predict its critical thickness. The approach follows the evolution of a threading dislocation's configuration as epitaxial layers are added to the structure. In the TDC model discrete points represent segments of a threading dislocation in a structure. Positions of these points will be determined by the sum of forces acting at each point. Following the Matthews and Blakeslee (MB) force-balance approach [4], the main forces considered are the line tension force $\vec{F}_\ell$, the strain force $\vec{F}_\varepsilon$, the surface tension $\vec{F}_s$ and the Peierls force $\vec{F}_p$. While in a single strained layer the Peierls force opposes the driving strain force, it is not always the case in MQW structures. This is so because during epitaxial growth of a single strained layer, the strain force tends to drive the threading dislocation and this effect will be opposed by the line tension force and the Peierls force. Once the growth of that layer is over and the growth of a new layer begins, the strain force due to that layer remains constant and the line tension force increases from the value that had once given an equilibrium position for the threading dislocation in that layer. The increased line tension will tend to pull back the threading dislocation in that layer to flatten it. That means the forces will no longer be in balance and a net force will act on segments of the threading dislocation in the underlying layer in the direction of the line tension. The Peierls force, whose effect is just to oppose a net force on a threading dislocation, will oppose this effect and be along the direction of the strain force. This is true for all buried layers. This means, there is hysteresis due to the Peierls force which the model takes into account as it mimics the epitaxial growth process. Hence, the differential force balance equation for any point representing the position of a segment of the threading dislocation can be written as

$$dF''_{\ell} \pm dF''_{p} = dF''_{\varepsilon}.$$

The superscript in the above equation indicates that forces are resolved in the glide direction in the appropriate glide plane.

2. Application to $In_{0.2}Ga_{0.8}As$/GaAs MQW's

A TDC model has been applied to $In_{0.2}Ga_{0.8}As$/GaAs MQW's in the (111) plane with Burgers vector $\vec{b} = a(10\bar{1})/2$, misfit dislocation $\langle\bar{1}10\rangle$ and $\text{Peierls stress} = 2.164\times10^{-3}\mu$ [5]. Here a is the lattice constant and μ is the shear modulus. The bi-layer thickness of the strained layer is $2.9039\,\mathring{A}$ and the critical thickness h_c for a single strained layer was found to be 24-bilayers ($69.6936\,\mathring{A}$) [3]. Figure 1 shows the equilibrium configuration of a threading dislocation with two and four periods of $In_{0.2}Ga_{0.8}As$ of thickness $h = 0.5h_c$ separated by an unstrained GaAs barrier with a thicknesses of 300 bi-layers. In figure 1(a), the two strained layers are decoupled with no interaction where as in figure 1(b) the strained layers begin to feel the influence of each other and act collectively to induce a maximum impact at the lowest strained layers.

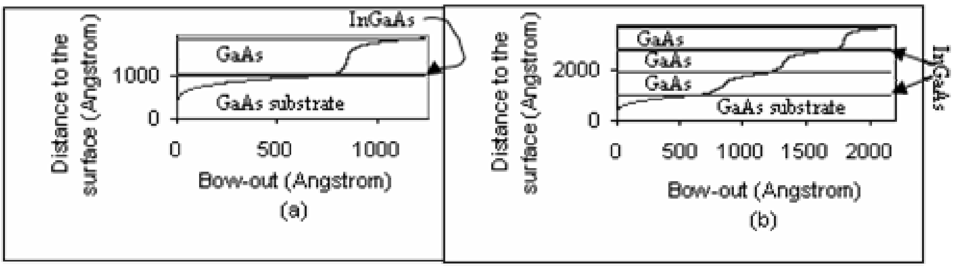
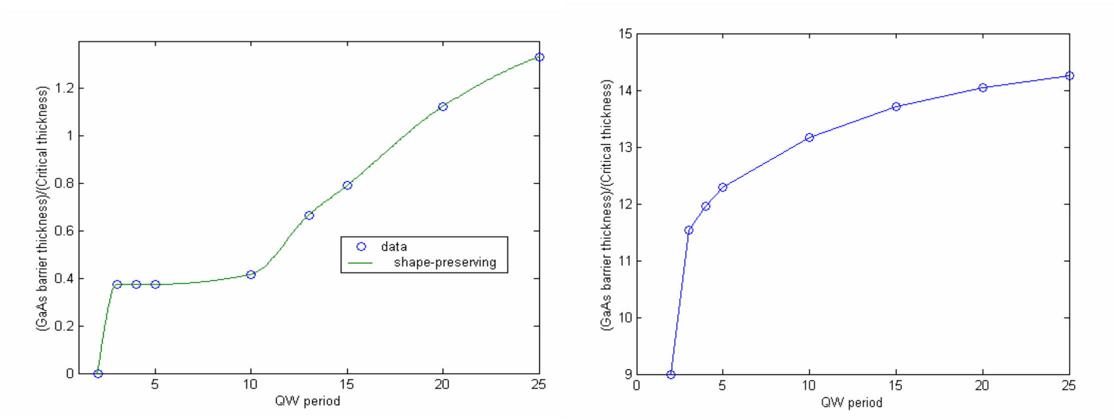


Fig.1. A threading dislocation's configuration in $In_{0.2}Ga_{0.8}As$ (12 bi-layers)/GaAs (300 bi-layers) MQW with (a) two and (b) four periods. In (a) the strained layers are decoupled and in (b) they interact with each other, the lowest layer experiencing the maximum effect.

Figure 2 shows critical thickness criteria for two structures with single strained layer thicknesses $0.5h_c$ and h_c. In each case, the normalized GaAs barrier thickness (GaAs barrier thickness divided by single-strained layer critical thickness) versus the number of quantum well periods is shown. In figure 2(a), the barrier thickness needed to avoid misfit dislocation for periods 3, 4 and 5 is $0.375h_c$, which is 9 bi-layers of GaAs. Although these periods appear to have the same minimum GaAs barrier thickness, a structure with five periods is relatively less stable than 3 or 4 periods. The figure also shows that no barrier thickness is needed for a structure containing two periods to avoid the formation of a misfit dislocation. This is because two layers without any barrier between them constitute a single strained layer at its critical thickness.



(a) (b)

Fig. 2. GaAs barrier thickness/critical thickness vs. QW period for an $In_{0.2}Ga_{0.8}As$/GaAs MQW with strained layer thickness (a) $0.5h_c$ and (b) h_c.

In figure 2(b) each strained layer is at its critical thickness and is about to form a misfit dislocation. One additional strained bi-layer will create a misfit dislocation at the interface of each layer. From the figure we see that the barrier thickness required to isolate the two strained layers in a two-period structure is about nine times the single strained layer critical thickness. As the number of periods increases so does the barrier thickness required to avoid misfit dislocation formation.

3. Conclusion

Comparing figures 2(a) and 2(b), one can conclude that plots of the barrier thickness, scaled by the critical thickness, versus the number of quantum well periods follow a logarithmic form for thicker strained layers and higher period numbers. If the barrier thickness is sufficiently large, strained layers would be totally separated from each other and there will be no limit to the number of periods for the quantum well. For smaller barrier thicknesses, however, there will be a limit on the size of the quantum well due to the interaction of the successive layers with each other.

References

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