IN-SITU GROWTH OF THREE-DIMENSIONALLY CONFINED STRUCTURES ON PATTERNED GaAs (111)B SUBSTRATES

K. C. Rajkumar, K. Kaviani, J. Chen, P. Chen, A. Madhukar, and D. H. Rich.
Photonic Materials and Devices Laboratory, University of Southern California,
Los Angeles, CA90089.

The potential of realizing quantum box structures via in-situ molecular beam epitaxical growth on the (111)B face of GaAs is explored. Growth is carried out on patterned (111)B substrates with an array of truncated triangular pyramidal mesas. The mesa tops with arbitrarily small areal dimensions are used as templates for quantum box realization. Under appropriate conditions of growth along with the attendant interfacet migration, a mesa top growth profile characterized by monotonically shrinking lateral dimensions resulting in 'pinch-off' is achieved.

Thin film growth techniques with the capability of thickness control in the growth direction within an atomic monolayer have led to the routine fabrication of quantum wells with their electronic states confined along the growth direction. Preliminary work [1] on lower dimensional structures - the quantum wires (2-D confinement) and quantum boxes (3-D confinement), has yielded the twin promises of exciting new physics and novel applications. Much of the work in this emerging field has been directed towards the fabrication of such structures by limiting the lateral dimensions (i. e. perpendicular to the growth direction) of an as-grown 1D confined structure via some post-growth patterning technique [2-7] to achieve confinement in 2D or 3D. Such approaches are faced with issues relating to the deleterious effects of the damage resulting from the pattern transfer and/or etching processes. An alternative conceptual approach which largely circumvents these issues is one of growth on substrates with special geometrical features which can act as templates for *in situ* realization of low dimensional structures via purely growth control. Use of vicinal surfaces [8] and substrates containing appropriate pre-patterned mesas of dimensions significantly larger than the nanostructure [9-13] regime belong to this category. The burden now, however, is one of a deeper understanding of a more complicated growth process with its attendant surface and interfacet kinetics and a much tighter control of such processes. Essentially all the work reported to date following this approach has been restricted to the realization of structures with confinement in the growth plus one lateral direction i. e. quantum wires. This is a consequence of the use of (001) substrates (singular or vicinal). In the III-V zincblende system, quantum well wires(i.e. 2D confined structures) have been fabricated along the $[1\bar{1}0]$ direction by exploiting the mirror symmetry about {110} planes [9,10]; size reduction on the (001) plane along the [110] direction is brought about by symmetric {hhl} planes belonging to the $[1\bar{1}0]$ zone. However, due to the lack of a higher order symmetry element perpendicular to (001), simultaneous size reduction along more than one lateral direction required for the fabrication of quantum boxes (i.e.3D confined structures) appears, at best, to be difficult on the (001) orientation, although there has been at least a report [13] of having overcome the symmetry problem.

The {111} surface on the other hand, has a 3-fold axis of symmetry perpendicular to the surface. As such, etched mesas are expected to have this 3-fold symmetry. Fig. 1(a) is a scanning electron microscope (SEM) image of an array of mesas on an As terminated GaAs (111)B (±0.1°) substrate. The array was created by photolithographically defining an array of 5 μm square resist patterns aligned along a $<1\bar{1}0>$ direction followed by wet chemical etching [14]. Fig. 1(b) is a magnified view of a typical mesa. Each mesa is a truncated triangular pyramid (in keeping with the 3-fold symmetry of the surface). The mesa top is (111)B and the three side facets are of the {100} type. The sides of the mesa top can

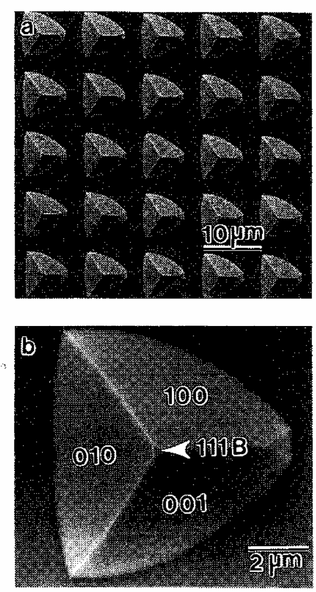

Fig. 1

be decreased from the initial pattern size all the way down to practically zero depending only on the duration of etching. Templates with arbitrarily small areal dimension can thus be created. If during subsequent growth lateral size reduction is at all possible, then simultaneous size reduction along three lateral directions becomes possible. This makes usage of {111} substrates attractive for realization of quantum boxes. The aim of this paper is to report our findings on the growth of GaAs/AlGaAs quantum well structures on such pyramidal mesas with a view to obtaining growth conditions suitable for achieving laterally confined structures. This work follows our recent work [14] on realization of quantum boxes via *ex-situ* patterning and etching of as-grown 1D confined quantum well structures on GaAs (111)B.

THE IN-SITU APPROACH :

The *in-situ* approach places the burden of achieving lateral sizes in the quantum confinement regime on growth itself and not on pre-growth processing. Consequently, the burden is to find growth conditions with attendant growth kinetics such as to create a growth profile in which successive layers growing on the templates have monotonically decreasing lateral areal dimensions, ultimately resulting in the mesas pinching-off. Schematic of such a growth profile on the ($\bar{1}\bar{1}1$)B mesas is shown in fig. 2. If a nominal SQW is grown sufficiently close to the pinch-off point, due to the expected 3-fold symmetry of the growth profile, the lateral dimensions of the SQW in all lateral directions can be made to be within the quantum confinement regime thus resulting in a quantum box. For the shrinkage of the lateral dimensions of the layers growing on the mesa top, the requirement is that there be a net migration of atoms during growth from the side facets to the mesa top. During their studies of growth on patterned (001) GaAs, Guha *et al* demonstrated [10,15] a growth condition dependent tendency for lateral shrinkage on the (001) mesa tops and the (111) sidewalls caused by interfacet migration from the thermodynamically driven tendency for the appearance of continually curved facets between the singular surfaces. Such interfacet has been proposed [16] to be a consequence of ledge-ledge interactions occuring on the continually curved sidefacets causing the adatoms to migrate to the singular surfaces. Thus, in the present case of as-patterned (111)B mesa tops with {001} type sidewalls also one can reasonably expect to achieve interfacet migration such as to cause lateral shrinkage of the (111)B mesa tops provided the growth conditions were appropriate. In the remainder of the paper we present illustrative results which demonstrate this to be indeed true. Three-dimensionally lateral confined structures with dimensions down to ~ 2500 Å have been realized.

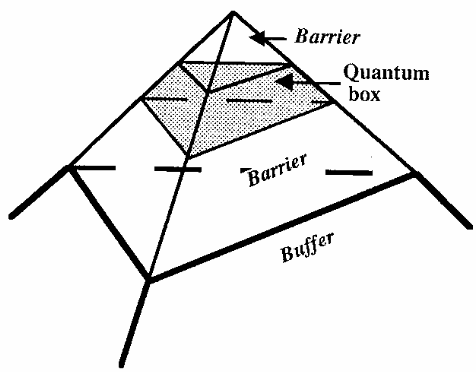

Fig. 2

The first sample we discuss is comprised of a 5 period multiple quantum well buffer made of 10 ML $Al_{0.3}Ga_{0.7}As$ / 40 ML GaAs, a nominal 60 ML $Al_{0.3}Ga_{0.7}As$ / 40 ML GaAs / 60 ML $Al_{0.3}Ga_{0.7}As$ single quantum well (SQW), and finally a GaAs cap. The structure was growth under an Arsenic pressure of 2 E-6 torr, at a substrate temperature of 635 °C and a GaAs growth rate corresponding to 2 sec/ML. Fig. 3(a) is a {200} dark field TEM image of the growth on a typical mesa top. Along the <1$\bar{1}$0> azimuth of observation, the mesa top layers and the layers growing on only one sidefacet can be imaged edge-on. The other two sidefacets do not belong to the same <1$\bar{1}$0> azimuth and thus cannot be imaged in this azimuth. The image clearly demonstrates the lateral finiteness of all layers on the mesa top.

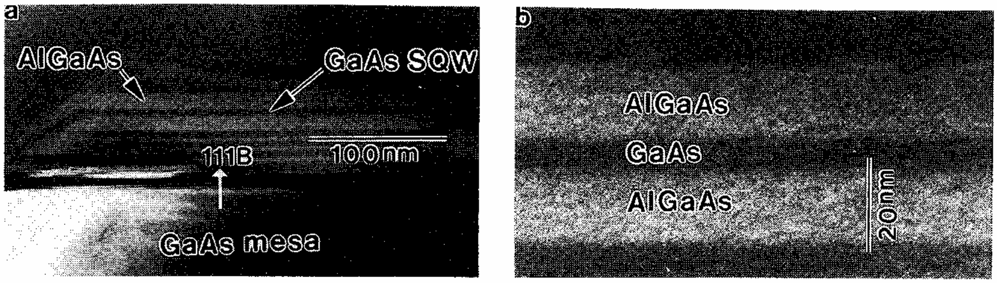

Fig. 3

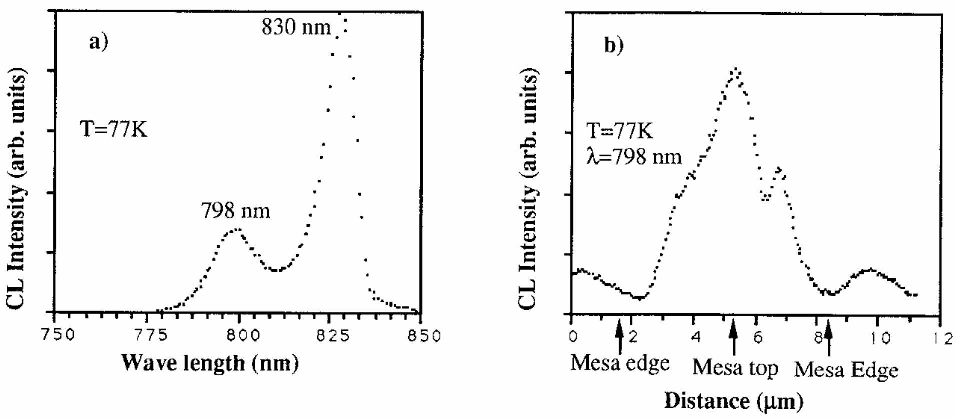

Fig. 4 : (a) CL spectral scan taken from mesa top. (b) CL line scan at λ=798 nm taken across mesa

The mesa SQW lying along (111)B has a lateral dimension of approximately 2500Å. Fig. 3(b) is a magnified image of the quantum well showing its high structural perfection. As the laterally finite SQW was realized *in-situ*, the adverse influence of surface contamination faced in *ex-situ* patterning approaches is not expected to be faced here. This is evidenced by the cathodo-luminescence (CL) results in fig. 4. Fig. 4(a) is a spectral scan taken from a typical mesa top . The 8300 Å peak is attributed to bulk GaAs. The 7980 Å peak is from the SQW. Fig. 4(b) is a line scan at 7980 Å taken across the mesa. The 7980 Å intensity peaks at the mesa top indicating that the signal is coming primarily from the layers on the mesa top. Further CL investigations are underway.

Fig. 5 is a {200} dark field TEM image (<1$\bar{1}$0> azimuth) of a 13 period superlattice consisting nominally of 10 ML $Al_{0.3}Ga_{0.7}As$ / 40 ML GaAs layers. The structure was grown under an Arsenic pressure of 2 E-6 torr, at a substrate temperature of 580 °C and at a GaAs growth rate corresponding to 3.45 sec/ML. The compositional contrast in the image graphically illustrates the temporal evolution of the growth front. For the first ten periods, the lateral size of successive layers increases, indicating a net migration of atoms from the mesa top to the {100} side walls. Starting from the eleventh period, inexplicably,

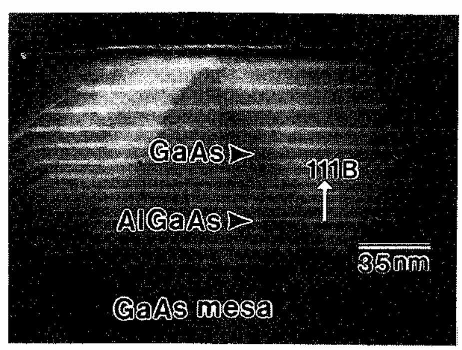

Fig. 5

migration occurs in the opposite direction as evidenced in the shrinking lateral size of the layers. Had growth been allowed to progress, the mesa might have pinched off. As the exact stage of the turn over is, at this stage, practically impossible to predict and equally hard to reproduce, the growth conditions employed are deemed unsuitable for in-situ quantum box realization.

Under appropriate conditions of growth, a monotonically shrinking growth profile has been realized. The 13 period superlattice was grown under an Arsenic pressure of 2 E-6 torr, substrate temperature of 560 °C and a GaAs growth rate corresponding to 2.7 sec/ML. SEM images of the patterned substrate before and after growth clearly indicated that the growth caused the mesas to pinch-off. Fig. 6(a) is a {200} dark field TEM image (<1$\bar{1}$0> azimuth) of a typical mesa . Starting from a 0.6 μm as-patterned mesa top, the lateral size of successive layers growing on the mesa top are seen to decrease. A new facet identified to be of the {211} type has emerged during growth and is contiguous with the (111)B mesa top. Shrinkage of the (111)B layers is due to a net migration of atoms from the {211} facet to the (111)B mesa top. This inter-facet migration also ensures that the {211} layers are thinner than the (111)B mesa top layers. The (111)B GaAs layers are thus surrounded from all lateral directions by the thinner and thus higher band gap GaAs quantum wells growing on the {211} side facets. It is this difference in band gap that provides the lateral electronic confinement in such a situation. Interfacet migration thus performs the twin functions of lateral size reduction and lateral electronic confinement and is thus of prime importance in quantum box realization.

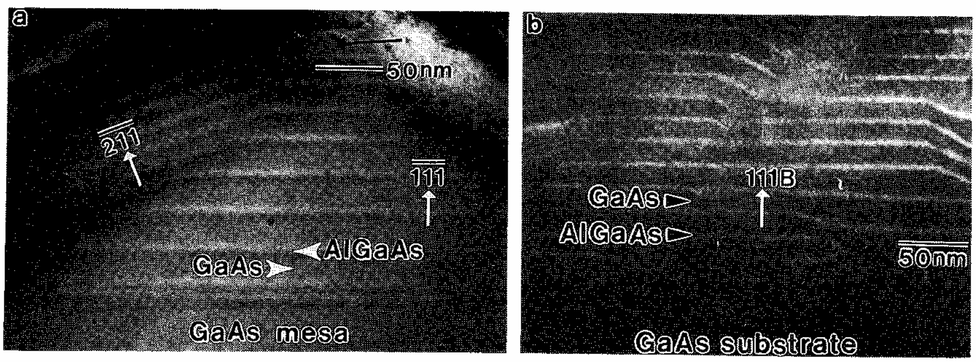

Fig. 6

Migration to the mesa top also makes the mesa top layers thicker than those growing on a non-patterned (111)B GaAs substrate. Fig. 6(b) shows a {200} dark field TEM image of the layers on a non-patterned GaAs (111)B substrate grown simultaneously with the growth on the pyramidal mesas (fig. 6(a)). Interestingly, the layers on the non-patterned substrate are not continuous, indicating that conditions of growth yielding optimal layering on the mesa top are not necessarily the same that yield optimized non-patterned growth.

The continuous shrinkage of the mesa top layers (fig. 6(a)) results in the mesa pinching off at the 8th period (indicated by a black arrow). The 8th GaAs well at the tip of this *in-situ* created pyramid has a base dimension of about 500Å, height of 130Å and its top vanishes into an apex. Vertical confinement is provided by the AlGaAs layers and the lateral confinement by the thinner {211} GaAs layers. This GaAs well has its physical dimension within that required for a quantum box. However to obtain an observable electronic/optical signature of 3D confinement of the electronic states, the well probably requires better confining barriers. The AlGaAs barriers, 30Å thick, need to be made thicker (a trivial

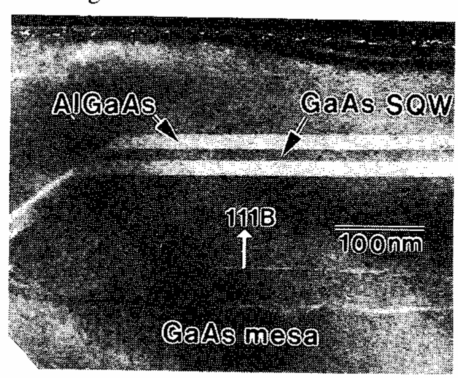

Fig. 7

matter) and the {211} GaAs layers need to be made thinner or preferably nonexistent, a far harder growth problem.

Work towards this end is proceeding and preliminary results are shown in fig. 7. Starting from a 0.6 μm mesa top, growth of a buffer layer was used to create a template of size 0.45 μm for the subsequent deposition of a SQW. The 50 ML AlGaAs barriers provide improved vertical confinement. More significantly, there is no observable GaAs growth on the sidefacets resulting in vastly improved lateral confinement.

In conclusion, we have explored the potential of the *in-situ* growth control approach to realizing 3D confined structures, including quantum boxes, on pyramidal mesas obtained via etching of the (111)B face of GaAs. We have directly imaged the resulting structures via TEM. SQW's having good structural and optical properties with lateral dimensions down to 2500Å have been demonstrated. Through judicious choice of growth conditions, the desired interfacet migration is achieved, yielding a monotonically shrinking lateral areal dimension of successive layers growing on the mesa top and resulting in the mesas pinching off. GaAs wells with physical dimensions ≤ 500Å in all 3 dimensions have been realized and imaged. Work towards converting such mesoscopic volumes into structures with better confining barriers and optical properties is proceeding.

This work was supported by the Army Research Office, the Office of Naval Research, and the Air Force Office of Scientific Research.

References:

1. See, for example, *Science and Engineering of One- and Zero-Dimensional Semiconductors*, edited by S. P. Beaumont and C. V. Sotomayor Torres (Plenum, New York, 1989); *Localization and Confinement of Electrons in Semiconductors*, edited by F. Kuchar, H. Heinrich, and G. Bauer (Springer-Verlag, Berlin, 1990)
2. K. Kash, A. Scherer, J. M. Worlock, H. G. Craighead, and M. C. Tamargo, Appl. Phys. Lett., **49**, 1043 (1986)
3. J. Cibert, P. M. Petroff, G. J. Dolan, S. J. Pearton, A. C. Gossard, and J. H. English, Appl. Phys. Lett., **49**, 1275 (1986)
4. H. Temkin, G. J. Dolan, M. B. Panish,and S. N. G. Chu, Appl. Phys. Lett., **53**, 995 (1988)
5. M. A. Reed, J. N. Randall, R. J. Aggarwal, R. J. Matyi, T. M. Moore, and A. E. Wetsel, Phys. Rev. Lett., **60**, 535 (1988)
6. B. I. Miller, A. Shahar, U. Koren, and P. J. Corvini, Appl. Phys. Lett., **54**, 188 (1989)
7. K. Kash, R. Bhat, D. D. Mahoney, P. S. D. Lin, A. Scherer, J. M. Worlock, B. P. Van der Gaag, M. Koza, and P. Grabbe, Appl. Phys. Lett., **55**, 681 (1989)
8. M. Tsuchiya, J. M. Gaines, R. H. Yan, R. J. Simes, P. O. Holtz, L. A. Coldren, and P. M. Petroff, Phys. Rev. Lett., **62**, 466 (1989)
9. E. Kapon, M. C. Tamargo, and D. M. Hwang, Appl. Phys. Lett., **50**, 347 (1987)
10. S. Guha, A. Madhukar, K. Kaviani, L. Chen, R. Kuchibotla, R. Kapre, M. Hyugaji, and Z. Xie in *III/V Heterostructures for Electronic/Photonic Applications* edited by C. W. Tu, A. C. Gossard, and V. D. Matera (Mater. Res. Soc. Proc. 147, Pittsburgh, PA, 1989) p27
11. J. A. Lebens, C. S. Tsai, K. J. Vahalla, and T. K. Kuech, Appl. Phys. Lett., **56**, 2642 (1990)
12. T. Fukui, S. Ando, Y. Tokura, and T. Toriyama, Appl. Phys. Lett., **58**, 2018 (1991)
13. Y. D. Galeuchet, H. Rothuizen, and P. Roentgen, Appl. Phys. Lett., **58**, 2423 (1991)
14. K. C. Rajkumar, K. Kaviani, J. Chen, P. Chen, and A. Madhukar, Appl. Phys. Lett., **60**, 850 (1992)
15. S. Guha, A. Madhukar, Li Chen, K. C. Rajkumar, and R. Kapre in SPIE Proceedings on *Growth of Semiconductor Structures and High T_c Superconductors* edited by A. Madhukar, Vol. 1285, p 160 (1990)
16. S. Guha, Ph.D dissertation (University of Southern California, 1990) ; S. Guha and A. Madhukar (to be published)