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Strain relaxation behavior of $In_xGa_{1-x}As$ quantum wells on vicinal GaAs (111)*B* substrates

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A number of reports have suggested that InGaAs/GaAs (111)*B* strained layer epitaxy has the prospect of reaching a higher critical layer thickness than that which can be achieved for (001) substrates. This has motivated a study of the relaxation mechanism of InGaAs/GaAs (111)*B* quantum wells with high In content ($0.12<x<0.35$). Transmission electron microscopy has revealed the existence of a different misfit dislocation (MD) configuration for high In contents ($x>0.25$), which, we believe, has not been reported until now. For such compositions, plastic relaxation takes place through a polygonal network of MDs, which have Burgers vectors in the interface plane. The origin of this network is an unusual dislocation source that occurs through the formation of a three-pointed star-shaped configuration. The characteristics of this misfit dislocation network, which has a higher misfit relieving component and a glide plane coincident with the interface plane, imply a reduction of the previous critical layer thickness estimates for high In content InGaAs/GaAs (111)*B* heterostructures. However, we observe that none of the (111)*B* samples shows evidence of a transition to a three-dimensional growth mode, which represents a significant advantage compared to the behavior of high In content quantum wells on (001) substrates. [DOI: 10.1063/1.1455691]

There is considerable interest in the InGaAs/GaAs system due to its potential to cover the wavelength region between AlGaAs/GaAs and InGaAsP/InP systems. InGaAs quantum well (QW) devices have already been successfully developed as pump lasers for rare earth-doped optical fiber amplifiers (0.98–1.02 μm). However, to obtain technologically important longer wavelengths like those required in next generation wavelength multiplexing systems higher In contents are required. The critical layer thickness (CLT) for strain relaxation in InGaAs/GaAs for usual (001) orientation is rapidly exceeded for QW emission wavelengths greater than 1 μm. In this case, the limiting In content (x) is around 0.23–0.25, due to the growth mode evolving towards Stranski–Krastanov (SK) type. To overcome these problems, a number of reports have suggested that InGaAs/GaAs (111)*B* strained layer epitaxy may be able to reach a higher CLT than that which can be achieved for (001) substrates.[1,2] In addition, it is both theoretically predicted and experimentally demonstrated that no equivalent SK mode exists in (111) orientation.[3,4] The higher CLT would allow an increase in the In content of strained QWs, thereby retaining layer-by-layer growth mode, to access important wavelength ranges at, or greater than 1.1 μm. In addition, $In_xGa_{1-x}As$ QWs in (111) orientation offer a number of interesting properties for potential optoelectronic devices, such as a strain-induced piezoelectric field and an increased optical matrix element that arises from a heavier hole mass.[5] The possibility to externally modulate the piezoelectric field opens up opportunities for enhanced devices such as optical modulators or tunable lasers.[6,7] Optical bistability has been also shown in these structures[8] and recently high efficiency InGaAs/GaAs (111)*B* lasers operating up to a wavelength of 1.08 μm have also been reported.[9]

If strain relaxation close to the (001) orientation is relatively well understood, the same cannot necessarily be said of alternative substrate orientations. At present, no significant experimental work exists on the dislocation characteristics and the CLT of misfit dislocations (MDs) in high In content (111) structures. In this letter, a transmission electron microscopy (TEM) study has revealed the existence of a special MD configuration for high In contents ($x>0.25$), which has not, we believe, been reported until now. The characteristics of this MD network imply a reduction of the previous CLT estimates for high In content InGaAs/GaAs (111)*B* heterostructures. The resulting revised CLT has implications for the maximum reachable wavelength that can be achieved for InGaAs/GaAs (111)*B* optoelectronic devices.

InGaAs/GaAs strained QWs were grown by molecular

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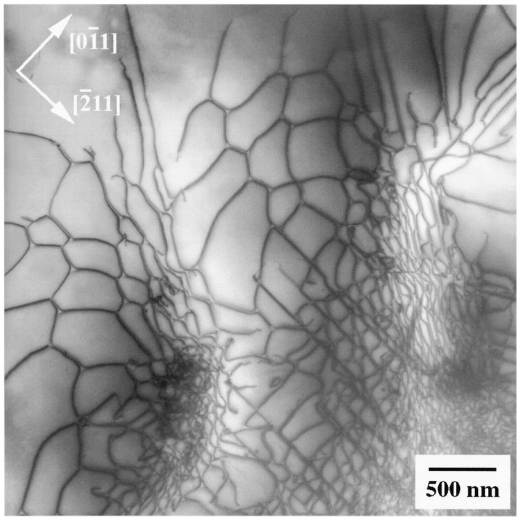

FIG. 1. PVTEM image of an $In_{0.35}Ga_{0.65}As$/GaAs (111)*B* single QW. A polygonal array (type II) with lines parallel to the ⟨110⟩ and ⟨112⟩ directions is shown.

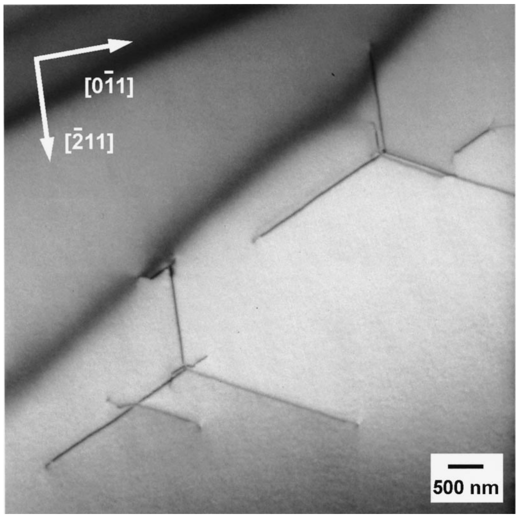

FIG. 2. PVTEM image of an $In_{0.3}Ga_{0.7}As$/GaAs(111)*B* single QW. A three-pointed star MD with its arms parallel to the ⟨112⟩ directions is shown.

beam epitaxy (MBE) on (111)*B* substrates misoriented 2° towards the [211] direction. Suitable conditions exist for high quality growth in this orientation.[10] The growth conditions for the QWs were chosen to obtain a specular surface morphology and to achieve InGaAs growth without significant In desorption. The quantum well heterostructures consisted of 10 nm $In_xGa_{1-x}As$ QWs in the center of a 0.2 μm intrinsic GaAs layer. The intrinsic layer had 0.3 μm p^+ and n^+ GaAs layers above and below it, respectively, with the whole structure comprising a $p-i-n$ diode on an n^+ GaAs substrate. The In content (x) of the quantum wells was varied between 0.10 and 0.35. The TEM observations were performed in a JEOL 1200EX transmission electron microscope. Planar view (PV) TEM specimens were prepared for the dislocation analyses. However, several cross sectional samples were also prepared, which showed in all cases the presence of coherent QWs with no evidence of an equivalent SK growth mode like that which occurs in (001).

For In content, x, less than 0.25, any MDs were described in the form of a triangular array with dislocation lines lying parallel to the ⟨110⟩ directions contained in the growth plane. A **g·b** analysis of these dislocations showed that they were of the 60° mixed type with Burgers vectors that lie outside of the growth plane. This MD array, which we will call type I in the following discussion, has been described thoroughly in the literature[2,11] and has been exclusively used in previous CLT models of (111)*B* substrates.[2,12] However, these studies did not include In compositions higher than about 0.20. For In compositions higher than 0.25, a different MD configuration appears with dislocation lines following the ⟨110⟩ and ⟨112⟩ directions (see Fig. 1). This configuration (type II) shows important differences in both its formation and its character in comparison to the type I case.

A study of the structures with $x=0.30$ has allowed us to determine the mechanism of formation of this polygonal network. This sample showed a MD configuration in the form of a three-pointed star with its arms parallel to the ⟨112⟩ directions and contained in the growth plane. This is called type IIa in the following (see Fig. 2). A PVTEM analysis has revealed that the MDs become invisible when observed with the 224 reflection contained in the [111] pole. This fact allows us to deduce that the Burgers vector is of the $\frac{1}{2}\langle 110\rangle$ type and lies within the growth plane. For $x=0.30$, this configuration was stable and its arms did not extend along the interface. However, as the In content was increased, two modifications were observed: First, new structures formed by several closely separated star dislocations appear. Second, the star branches bend at right angles, following lines parallel to the ⟨110⟩ directions contained in the growth plane (type IIb). The interaction between MDs with ⟨110⟩ and ⟨112⟩ directions generates the dense polygonal network observed for In contents higher than $x=0.30$ (see Fig. 1).

The change in Burgers vector for high In contents presents an important consequence: the misfit-relieving component, $\mathbf{b_r}$, is much larger (see Table I). That is to say, InGaAs/GaAs (111)*B* heterostructures with high lattice misfits are relaxed by forming a type II MD network which has a larger plastic relaxation contribution compared to the type I array reported at low In content. Previous CLT models applied to the (111) growth direction have taken into account only the type I network. For this network, the models predict an increased CLT with respect to the (001) growth direction due to a smaller misfit-relieving component for the type I configuration. In contrast, the type II MD configuration imposes significant modification of this prediction. Here we use Anan's equation,[2] neglecting the surface energy term, which can then be written as

TABLE I. Misfit relieving component, $\mathbf{b_r}$, (the projection of **b** onto a line in the interface at right angles to the misfit dislocation), dislocation line and characteristic angle, θ, of the different MDs observed in InGaAs/GaAs (111)*B* epilayers. The type I array is predominant for $x<0.2$ and the type II for $x>0.25$.

MD configuration type	Misfit relieving component	Dislocation line	θ (deg)
I	$1/\sqrt{12}$b	⟨110⟩	60
IIa	1/2b	⟨112⟩	30
IIb	$3/\sqrt{12}$b	⟨110⟩	60

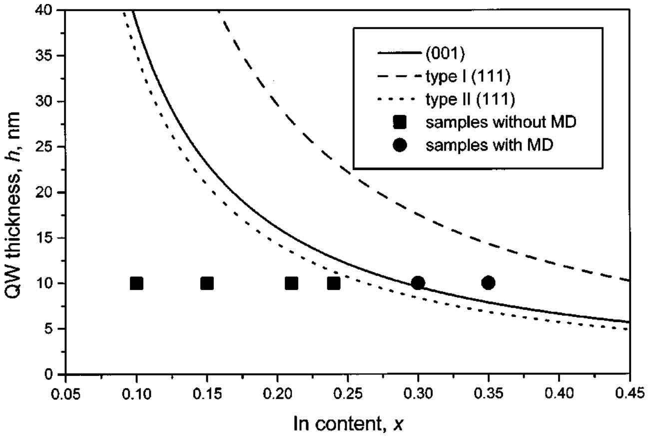

FIG. 3. CLT vs In content for the different MD configurations observed in InGaAs epilayers using Anan's expression. The type II MDs show a remarkable CLT reduction compared with the type I, with the value becoming close to that for (001) substrates.

$$h_c = \frac{G_{111} b^2 (1 - v_{111} \cos^2 \theta)}{4\pi (1 - v_{111}) M_{111} b_r f} \ln\left(\frac{\alpha h_c}{b}\right),$$

where G, v, and M are the shear modulus, Poisson ratio and biaxial Young's modulus and b, θ and α, the modulus of the Burgers vector, the angle between the Burgers vector and the MD line and dislocation core radius, respectively. The term b_r is the misfit-relieving component of the Burgers vector defined as the projection of $\mathbf{b}$ onto a line on the interface plane at right angles to the MD.

Figure 3 shows that the CLT of the type II network is lower than previously predicted using the type I network. The result explains our experimentally observed CLT in high In content QWs and is consistent with the deterioration of optical quality or laser performance in other reports.[9,13] In accordance with these results, significant differences then do not exist between epilayers grown on (111) and (001) substrates in terms of their CLT. This is due to the existence of a separate misfit dislocation mechanism in $(111)B$, which is highly efficient in relieving strain. Although the CLT does not reach the previous theoretical predictions, the absence of a three-dimensional (3D) growth mode does present a considerable advantage for InGaAs QW growth, compared to that on (001) substrates. This allows the growth of quantum wells with In contents up to $x = 0.30$ which are free of crystalline and morphological defects. Further work is in progress to understand the nucleation and evolution of type II MDs in high In content InGaAs/GaAs $(111)B$ structures.

In summary, a study of the relaxation mechanism for $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}(111)B$ QWs shows a change in the MD type with an increase in In content. For high In contents ($x > 0.30$), plastic relaxation takes place through a polygonal MD network, which has its Burgers vector in the interface plane. This network originates through the formation of a three-pointed star-shaped dislocation and operates as a new MD nucleation mechanism. The higher misfit-relieving component of the new network implies a lower CLT for plastic relaxation compared to that previously expected. The CLT we have determined for high In content InGaAs epilayers grown on $(111)B$ is similar to that predicted for the CLT of InGaAs epilayers on (001). However a significant advantage of the (111) orientation is the absence of a 3D growth mode, which allows $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ quantum wells of $x = 0.3$, or higher, to retain a layer-by-layer growth mode.

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[1] T. E. Mitchel and O. Unan, J. Electron. Mater. **20**, 723 (1991).
[2] T. Anan, K. Nishi, and S. Sugou, Appl. Phys. Lett. **60**, 3159 (1992).
[3] H. Yamaguchi, M. R. Fahy, and B. A. Joyce, Appl. Phys. Lett. **69**, 776 (1996).
[4] M. Henini, S. Sanguinetti, L. Brusaferri, E. Grilli, M. Guzzi, M. D. Upward, P. Moriarty, and P. H. Beton, Microelectron. J. **28**, 933 (1997).
[5] D. L. Smith and C. Mailhiot, J. Appl. Phys. **63**, 2717 (1988).
[6] P. Ballet, P. Disseix, J. Leymarie, A. Vasson, A. M. Vasson, and R. Grey, Phys. Rev. B **56**, 56 (1997).
[7] A. S. Pabla, J. Woodhead, E. A. Khoo, R. Grey, J. P. R. David, and G. J. Rees, Appl. Phys. Lett. **68**, 1595 (1996).
[8] E. A. Khoo, J. Woodhead, J. P. R. David, R. Grey, and G. J. Rees, Electron. Lett. **35**, 150 (1999).
[9] T. Fleischmann, M. Moran, M. Hopkinson, H. Meidia, G. J. Rees, A. G. Cullis, J. L. Sánchez-Rojas, and I. Izpura, J. Appl. Phys. **89**, 4689 (2001).
[10] X. Marcadet, A. Fily, S. Collins, J. P. Landesman, M. Larive, J. Olivier, and J. Nagle, J. Cryst. Growth **201/202**, 284 (1999).
[11] A. Sacedón, F. Calle, A. L. Alvarez, E. Calleja, and E. Muñoz, Appl. Phys. Lett. **65**, 1 (1994).
[12] F. Colson and D. Dunstan, J. Appl. Phys. **81**, 2900 (1997).
[13] J. J. Sánchez, M. Hopkinson, M. Gutiérrez, D. González, G. Aragón, I. Izpura, and R. García, J. Cryst. Growth **202**, 1085 (1999).