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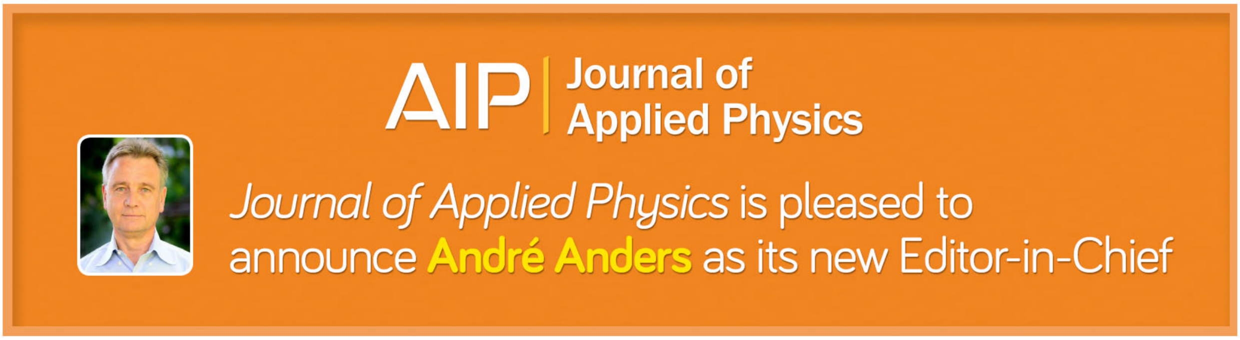

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Periodic index separate confinement heterostructure InGaAs/AlGaAs quantum well lasers grown by temperature modulation molecular beam epitaxy

M. Hong, Y. K. Chen, M. C. Wu, J. M. Vandenberg, S. N. G. Chu, J. P. Mannaerts, and M. A. Chin
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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Solid-source molecular beam epitaxy with substrate temperature modulation has produced periodic index separate confinement heterostructure InGaAs/AlGaAs quantum well lasers with greatly improved performance. These lasers in a broad area geometry are under room-temperature continuous wave operation and have low threshold current density of 300 A/cm^2, high internal quantum efficiency of 91%, low internal waveguide loss of 2.2 cm^{-1}, a reduced transverse beam divergence of 30°, and a high characteristic temperature of 187 K.

Growth of periodic structures consisting of GaAs and AlGaAs such as distributed Bragg reflector (DBR) mirrors requires precision in thickness and composition of the constituent layers. For many optoelectronic device applications, an accuracy within a few percent is required.[1,2] The growth of these multilayers using solid-source molecular beam epitaxy (MBE) usually takes place at substrate temperatures (T_s) near 600 °C, since the growth rates of GaAs and AlAs remain constant and are independent of the substrate temperatures at this temperature range. Above $\sim$640 °C, the GaAs growth rate decreases rapidly with temperature for the same beam flux due to a decreased sticking coefficient of Ga.[3] At the growth temperature of 600 °C, a good crystal quality in GaAs is obtained, while an excellent growth in AlGaAs is usually achieved at higher temperatures around 700 °C.[4] Therefore, it is experimentally difficult to achieve the precision in thickness and composition of these periodic multilayers, and at the same time to obtain optimal growth in both GaAs ($T_s \sim 600$ °C) and AlGaAs ($T_s \sim 700$ °C).

In this work, we have used a novel growth technique to achieve this goal by modulating the substrate temperatures to grow GaAs at 600 °C and AlGaAs at 700 °C. The cell temperatures of Al and Ga were also modulated to achieve shutterless solid-source MBE growth.[5] This new growth technique has been applied to the growth of a recently designed and demonstrated edge-emitting laser in a configuration of periodic index separate confinement heterostructure (PINSCH).[6] We compare the characteristics of the PINSCH lasers grown using constant T_s of 600 °C and modulated T_s between 600 and 700 °C.

The PINSCH laser used *periodic index* (PIN) semiconductor multilayers consisting of GaAs/Al$_{0.4}$Ga$_{0.6}$As as optical confinement layers to simultaneously reduce the transverse beam divergence, achieve carrier confinement, and increase the maximum output power. In comparison, the conventional graded index separate confinement heterostructure (GRINSCH) lasers using optical confinement layers of *constant composition* have produced low threshold currents and high quantum efficiencies.[7] However, due to the tight optical confinement, the GRINSCH lasers have generated large transverse beam divergence of $\sim$50° with a highly elliptical far-field pattern.[8] High power semiconductor lasers with small circular optical beam divergence find applications in fiber optics and optical data storage.

The schematic band diagram of the PINSCH laser is shown in Fig. 1: an active region in the center and eight pairs of PIN confinement layers on either side of the active region. The active region comprises three $\mathrm{In_{0.2}Ga_{0.8}As}$ quantum wells 70 Å thick and four GaAs barriers 200 Å thick. Both Si- and Be-doped PIN layers are identical in composition and thickness: GaAs and $\mathrm{Al_{0.4}Ga_{0.6}As}$ with a nominal thickness of 1250 Å and the two compositionally graded regions 600 Å thick are shown in Fig. 1. The heterointerfaces in the PIN layers are linearly graded such that the energy barrier heights are greatly decreased.[5] This has led to a drastic reduction in the series resistance which is essential for the performance of high output power. The series resistance obtained in the PINSCH laser is no different than that obtained in the GRINSCH laser whose confinement layer has a constant composition without any heterointerfaces. The PIN layers were grown using modulation of the cell temperatures without any shutter operation as discussed earlier.[5] The cell temperatures of Si and Be are also modulated accordingly to generate a prescribed doping profile.

For the growth of the PIN layers, two approaches in substrate temperatures have been used: A constant substrate temperature T_s of $\sim$600 °C was used in the first approach. For the second technique, we have modulated the substrate temperatures. As shown in Fig. 1 of the periodic substrate temperature profile, the T_s remained at 600 °C for GaAs, was then gradually increased to 700 °C during the growth of the graded region, and remained at 700 °C for the $\mathrm{Al_{0.4}Ga_{0.6}As}$. More specifically, the substrate temperature rises after the graded region reaches $\mathrm{Al_{0.1}Ga_{0.9}As}$, goes to 700 °C when the graded region is at $\mathrm{Al_{0.35}Ga_{0.65}As}$, and stays at 700 °C for the growth when the composition is above $\mathrm{Al_{0.35}Ga_{0.65}As}$. For lowering the substrate temperature, the procedure is reversed except using a slower temperature decreasing rate. The growth rate for the entire PIN layers has remained constant of 1.0 μm/h due to the use of cell temperature modulation.[5] The As beam flux was kept at the minimum level for the growth.

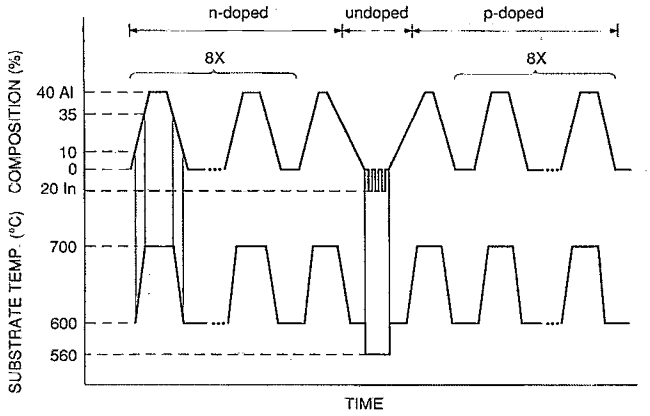

FIG. 1. The schematic band diagram and the substrate temperature modulation of the PINSCH quantum well laser.

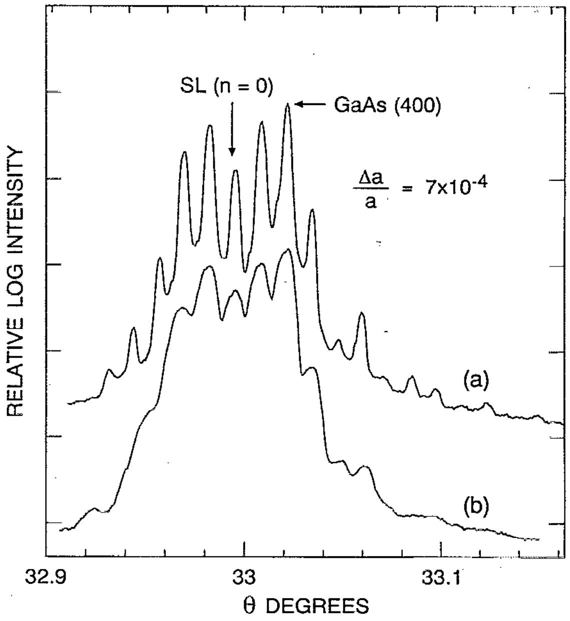

FIG. 3. High-resolution x-ray diffraction θ-2θ scans taken in the vicinity of the (400) reflection of two 8-period $Al_{0.4}Ga_{0.6}As$/GaAs PIN structures grown using constant T_s of 600 °C (a) and modulated T_s between 600 and 700 °C (b).

The substrate temperature modulation follows the cell temperature modulation and the compositional profile accordingly. This is critical, otherwise growth with sausagelike reflection high energy electron diffraction (RHEED) patterns or a Ga-stabilized surface may occur. The growth temperature was lowered to 560 °C for the active layer of InGaAs/GaAs in both the approaches. This has consistently given the structures lasing at 980 nm wavelength.

During the constant T_s PIN growth, the quality of RHEED streaks after the growth of 300 Å in the $Al_{0.4}Ga_{0.6}As$ is not as good as that in the GaAs in terms of elongation, sharpness, and brightness. The characteristic of the RHEED recovers after the growth of 200 Å in the GaAs layer. On the contrast, during the modulated T_s PIN growth, the sharpness, the elongation, and the intensity of the RHEED remain the same everywhere in the entire PIN layer. Moreover, the periodicity of the multilayers is maintained despite the modulation (600–700 °C) of the substrate temperature. This is evidenced by transmission electron microscopy (TEM) cross-section observation (Fig. 2) and high-resolution x-ray diffraction analysis (Fig. 3) on the PIN layers grown using constant and modulated T_s.

X-ray scans of the PIN structures were taken in the vicinity of the GaAs (400) reflection using a previously described five-crystal x-ray diffractometer.[9] The (400) scan [Fig. 3(a)] of the PIN layers grown with constant T_s

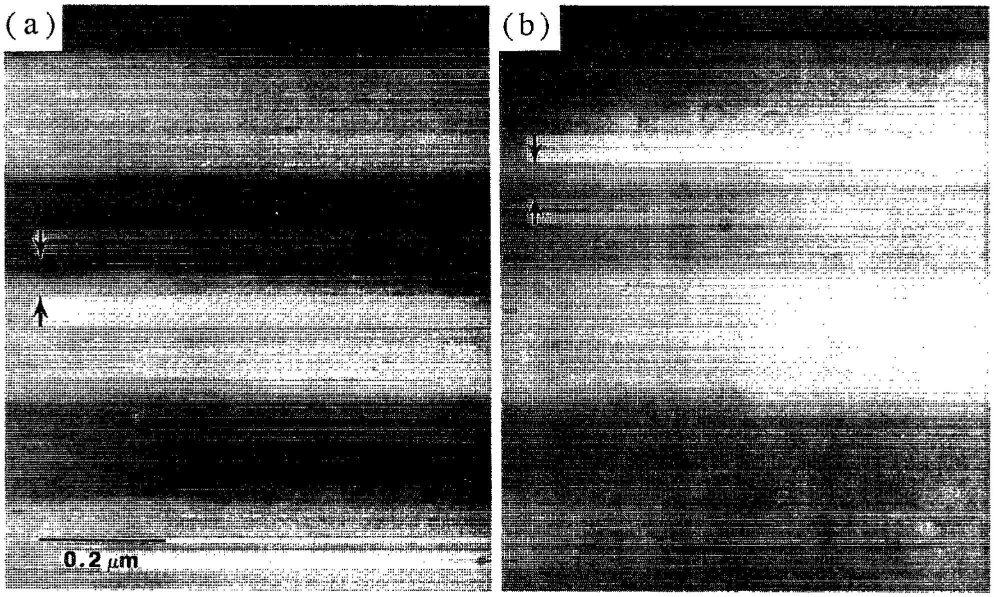

FIG. 2. TEM cross-section micrographs of periodic index (PIN) layers grown using constant T_s of 600 °C (a) and modulated T_s between 600 and 700 °C (b). The interfacial region is indicated by the arrows. The dark region is the GaAs layer, while the light region is the $Al_{0.4}Ga_{0.6}As$ layer.

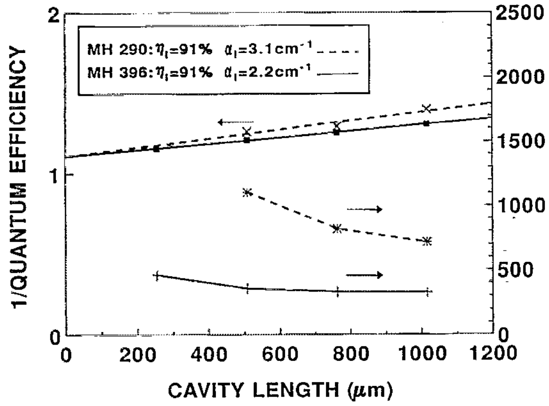

FIG. 4. Cavity length dependence of threshold current densities and quantum efficiencies for PINSCH lasers with PIN layers grown using constant T_s of 600 °C (MH290) and modulated T_s (MH396).

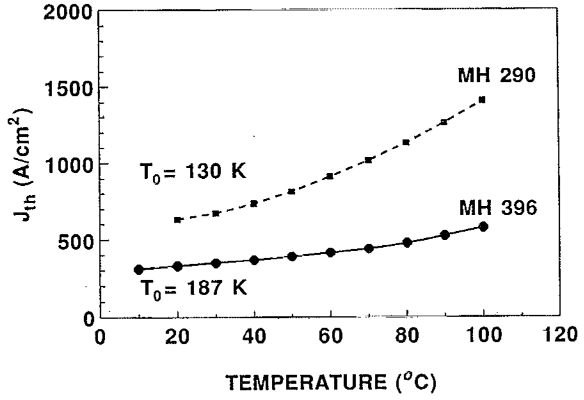

FIG. 5. Temperature dependence of threshold current densities for PINSCH lasers with PIN layers grown using constant T_s of 600 °C (MH290) and modulated T_s (MH396).

shows very sharp satellite peaks, indicating a well-defined periodic structure. The period determined from this diffraction scan is 4050 Å which is to be compared to a nominal thickness of 3700 Å. The period 3960 Å of the modulated T_s grown PIN layer is somewhat smaller, but the relative satellite intensities are the same indicating that the overall periodic structure is similar as the one grown using constant T_s. However, the satellite peaks of the modulated T_s grown PIN layer are much broader. Stronger diffusion due to the high-temperature growth and asymmetry of the interfaces due to the difference in the heating and the cooling rates may attribute to the line broadening.

The substrate temperature modulation technique has also been successfully applied to the growth of distributed Bragg reflectors (DBR) used in the vertical cavity surface emitting lasers (SEL). This is demonstrated by the optical reflectivity measurement on the quarterwave DBR consisting of AlAs/GaAs. The data of reflectivity versus wavelength show that there is no difference between the DBRs grown using the constant and the modulated T_s.

Broad-area lasers with 50 μm wide strips are fabricated with different cavity lengths from 200 to 1000 μm. Figure 4 shows the cavity length dependence of the reciprocal differential quantum efficiency, and the threshold current density. For the modulated T_s grown PINSCH lasers, a low threshold current density of 300 A/cm^2 was achieved for a 1000 μm long laser. A low internal waveguide loss of 2.2 cm^{-1} and a high quantum efficiency of 91% are obtained. In comparison, the PINSCH lasers with the PIN layers grown at constant temperature of 600 °C have a higher threshold at 700 A/cm^2 and a slightly higher internal waveguide loss of 3.1 cm^{-1} as shown in Fig. 4.

Figure 5 shows the temperature dependence of the threshold current density of a 50×750 μm broad area laser. The characteristic temperature (T_0) is 187 K. For comparison, the 600 °C grown PINSCH lasers have a lower T_0 of 130 K. The reduced temperature sensitivity is attributed to the reduction of the threshold current by the substrate temperature modulation MBE growth technique. The transverse beam divergence angle has been reduced to 30° for the modulated T_s grown PINSCH lasers, as compared to 20° achieved in the 600 °C grown PINSCH lasers. However, the former lasers were operated under cw condition at room temperature, while the latter were under pulsed conditions. As observed by the TEM cross-sectional examination and the high-resolution x-ray diffraction analysis, diffusive and asymmetrical interfaces and a slight deviation occurs in the composition and the thickness of the PIN layers may account for the larger transverse beam divergence obtained in the modulated T_s grown PINSCH lasers.

In summary, we have used substrate temperature modulation MBE technique to optimize the growth of the PINSCH laser. Using this new growth technique, we have achieved an excellent growth in GaAs, $Al_{0.4}Ga_{0.6}As$, and the composition-graded region. At the same time, the periodicity of the multilayers is also maintained as measured by the high-resolution x-ray diffraction and TEM cross-sectional analysis. Low threshold current densities, high internal quantum efficiency, low internal waveguide loss, high characteristic temperatures, and a reduced transverse beam divergence in the PINSCH lasers under room-temperature cw operation are obtained.

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