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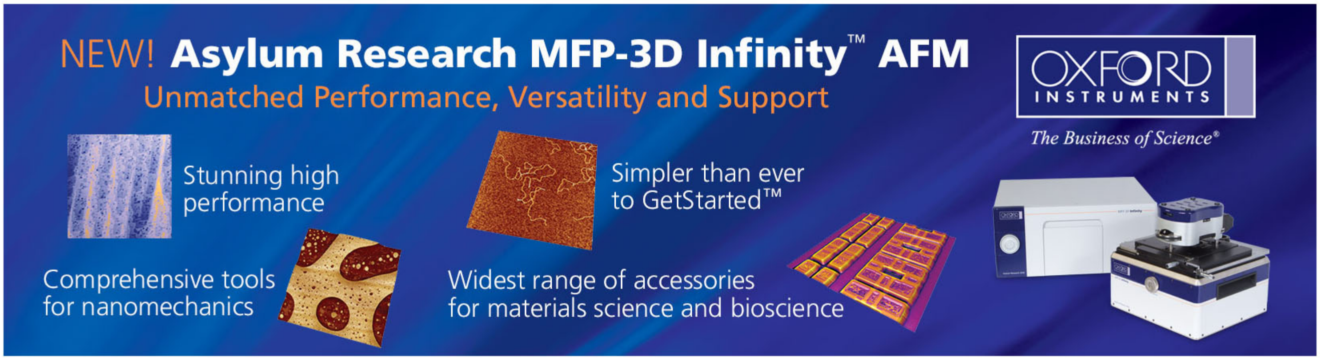

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Real index-guided InGaAlP red lasers with buried tunnel junctions

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Real index-guided buried ridge InGaAlP 650 nm band lasers with p^+-n^+ buried tunnel junctions are demonstrated. Located on top of the buried ridges, the tunnel junctions, made of InGaAs/GaAs superlattices with modulation doping, were introduced as the current injection window areas. The large band gap $In_{0.5}Al_{0.5}P$ layers were directly regrown around the ridges using metalorganic chemical vapor deposition to serve as the current blocking layers. Real index optical waveguiding in the lateral direction was also provided by the smaller refractive index of $In_{0.5}Al_{0.5}P$ layers. The lasers showed lower threshold current and higher slope efficiency compared to conventional complex index-guided InGaAlP lasers with GaAs current blocking layers, and had low internal loss of about 5.4 cm^{-1}. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1459763]

In applications of high density optical storage systems, laser beam printers, and bar code scanners, stabilized fundamental transverse mode operation is the key factor in designing InGaAlP red lasers. The complex index-guided structure is used for conventional InGaAlP red lasers,[1,2] in which lateral mode stabilization and current blocking are achieved by regrown *n*-type GaAs layers. The GaAs layers, with smaller band gaps, offer large modal discrimination to ensure single spatial mode operation but result in higher internal loss and threshold current. As an alternative approach, $In_{0.5}Al_{0.5}P$ with a smaller refractive index can be used instead of GaAs to provide a real index optical waveguide structure in the lateral direction. Real index-guided lasers with lower internal loss have lower threshold current and higher slope efficiency. However, it has been difficult to selectively grow $In_{0.5}Al_{0.5}P$ layers by conventional metalorganic chemical vapor deposition (MOCVD). Kobayashi *et al.* reported real index-guided InGaAlP lasers grown by HCl-assisted MOCVD,[3,4] in which the $In_{0.5}Al_{0.5}P$ layers was selectively regrown. Imafuji *et al.* reported a real refractive index-guided self-aligned structure by regrowning the InGaAlP laser ridges.[5]

In this letter, we demonstrate an alternative way to achieve real index-guided InGaAlP lasers by introducing buried tunnel junctions. Buried tunnel junctions have been applied in many opto-electronic devices, such as in multijunction solar cells,[6] multilayer GaAs lasers,[7–10] vertical cavity surface emitting lasers,[11] and GaN based blue light emitting diodes.[12] Basically, a tunnel junction uses reversed bias to provide hole injection by feeding the electron current. Introducing buried tunnel junctions in InGaAlP lasers has several advantages. First, the buried tunnel junction located on top of the laser ridge region allows selective tunneling current injection and the areas outside the ridge region without the tunnel junction automatically serve as the current blocking function. Second, the regrown $In_{0.5}Al_{0.5}P$ layers with larger band gap form the real index-guiding structure and reduce internal loss. Last, this buried tunnel junction laser requires only one step regrowth compared to the two step regrowth reported by Kobayashi *et al.*[3,4] In the present work, the *n*-type $In_{0.5}Al_{0.5}P$ layers that serve as lateral optical guiding can be regrown directly after the formation of laser ridges by conventional MOCVD. The buried tunnel junctions located on top of the laser ridges serve as window areas and assist current flowing from *p*-type cladding layers to *n*-type $In_{0.5}Al_{0.5}P$ layers and then to top *n*-contact layers. That is, both contacts of the lasers are *n* type, except that the top contact is positively charged and the bottom contact is negatively charged.

The laser structure was grown in a vertical reactor of a low pressure MOCVD system with a rotating disk. All the epitaxial layers were grown on *n*-type GaAs substrates with Si as the *n*-type dopant and Zn as the *p*-type dopant. The InGaAlP laser structure consists of the following layers: a 1 μm *n*-type GaAs buffer layer, a pair of 1.2 μm $(Al_{0.73}Ga_{0.27})_{0.5}In_{0.5}P$ cladding layers ($n,p\sim1\times10^{18}$ cm^{-3}), a pair of 0.07 μm undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ confinement layers with *x* graded from 0.73 to 0.5, and active layers with four compressively strained InGaP quantum wells separated by three $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ barrier layers. Tunnel junction are grown on top of the *p*-type cladding layers. The growth temperature is 700 °C for laser structures, 550 °C for the p^+ region of the tunnel junction, and 600 °C for the n^+ region.

Figure 1 shows a schematic of the device's fabrication steps. The first step, shown in Fig. 1(a), was to grow the InGaAlP laser structure. Instead of growing a *p*-type GaAs contact layer, the p^+-n^+ tunnel junction layer was grown on top of the *p*-cladding layer. The tunnel junction layers consisted of 10 period $In_{0.2}Ga_{0.8}As/GaAs$ (6 nm/6 nm) modulation doped p^+ layers and 10 period $In_{0.2}Ga_{0.8}As/GaAs$ (6 nm/6 nm) modulation doped n^+ layers. The modulation doping can increase the carrier concentration and the InGaAs transition regions can enhance the tunneling probability.[8,9] Then, the as-grown wafer was wet etched to form a laser ridge with bottom width of 5 μm as shown in Fig. 1(b). The wafer was sent back for MOCVD to regrow the *n*-type $In_{0.5}Al_{0.5}P$ layer and *n*-type GaAs layer as shown in Fig. 1(c). The thickness of $In_{0.5}Al_{0.5}P$ and GaAs was 0.6

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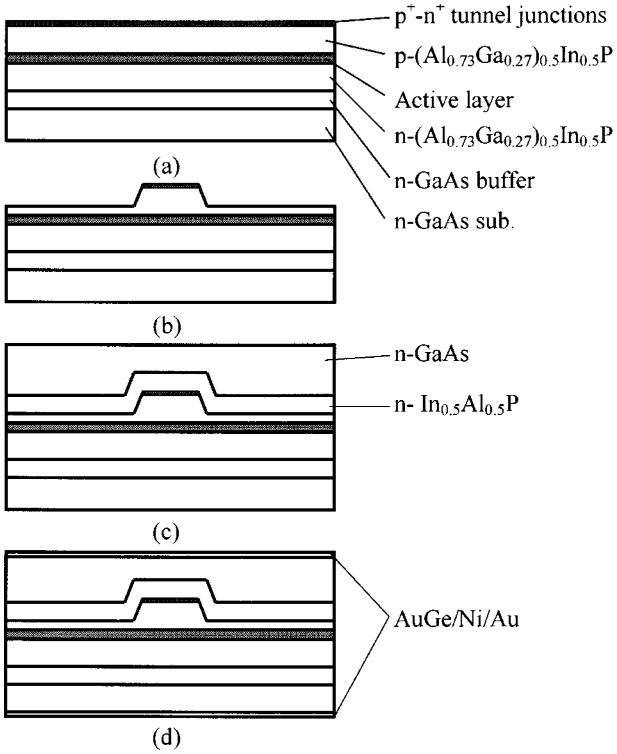

FIG. 1. Schematic representation of the device fabrication steps. (a) Growth of the InGaAlP laser structure with the p^+-n^+ tunnel junction; (b) formation of the laser ridge by wet etching; (c) regrowth of n-type $In_{0.5}Al_{0.5}P$ and GaAs; (d) evaporation of metal contacts.

and 2 μm, respectively. The doping concentration was 5×10^{17} cm^{-3} for $In_{0.5}Al_{0.5}P$ and 1×10^{18} cm^{-3} for GaAs. AuGe/Ni/Au was evaporated on both sides of the wafer in the last step, shown in Fig. 1(d). Finally, the laser diodes were cleaved and diced so they were 300 μm wide and 500 μm long. Meanwhile, the complex index-guided lasers with the same layer structures had been fabricated by the conventional method for comparison. The wafers without the tunnel junctions were wet etched to form a 5 μm wide ridge. Then, n-type GaAs layers were selectively grown on the wafers for the first regrowth and p-type GaAs layers were grown for the second regrowth. The ohmic contact for the p metal was Ti/Pt/Au and for the n metal it was AuGe/Ni/Au. Laser diodes were also cleaved and diced to 300 μm$\times$500 μm. Two types of lasers were mounted (epitaxial layer side) on an In-coated copper heat sink for testing.

Figure 2 shows the laser output power and forward voltage versus current characteristics for two types of lasers under continuous wave (cw) operation at room temperature. For real index-guided lasers with buried tunnel junction, the threshold current is 45 mA and the one end slope efficiency is 0.58 W/A for both facets uncoated. On the other hand, the complex index-guided lasers have threshold current of 50 mA and one end slope efficiency of 0.45 W/A for both facets uncoated. Although the forward voltage for real index-guided lasers is slightly higher due to the buried tunnel junctions, the overall wall-plug efficiency is higher than the complex index-guided lasers.

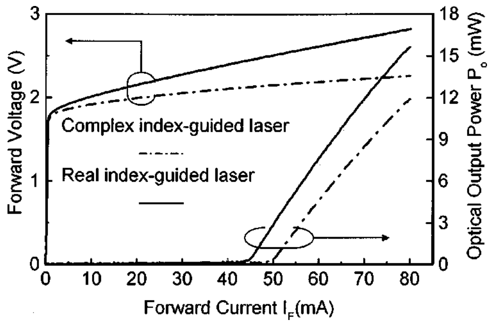

FIG. 2. Optical output power and forward voltage vs current characteristics for real index-guided lasers with buried tunnel junctions and complex index-guided lasers under cw operation at room temperature.

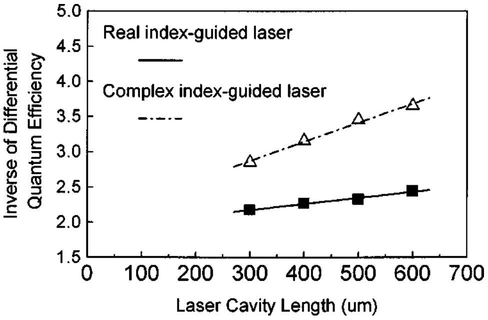

FIG. 3. Inverse of the differential quantum efficiency vs the cavity length characteristics for real index-guided lasers with buried tunnel junctions and complex index-guided lasers.

Laser chips with different cavity lengths were also fabricated and tested under pulsed operation. By examining the relationships between the inverse of the differential quantum efficiency and the cavity length, shown in Fig. 3, the internal loss can be determined. The internal loss is determined to be 5.4 cm^{-1} for real index-guided lasers with buried tunnel junctions and 15 cm^{-1} for conventional complex index-guided lasers. Large internal loss contributes to the high threshold current and low slope efficiency of conventional complex index-guided lasers. It is believed that the relatively low internal loss in our work compared with in previous reports[3,5] could be due to the good material quality of the $In_{0.5}Al_{0.5}P$ regrown layers.

A spectrum for real index-guided lasers with buried tunnel junction is shown in Fig. 4(a). The peak wavelength is 652 nm at 20 °C at output power of 5 mW, and the laser has a fundamental transverse mode with far field angles of 8° and 28° for the directions parallel and perpendicular to the plane of the junction, respectively, as shown in Fig. 4(b).

In summary, real index-guided InGaAlP lasers with buried tunnel junctions on top of p-cladding layers were demonstrated. Due to the real index-guided structure, the threshold current was reduced and the slope efficiency was enhanced compared with conventional complex index-guided lasers. With the assistance of the buried tunnel junction, electron current can flow from the p-type laser ridge to the n-type $In_{0.5}Al_{0.5}P$ layer, which originally served as a current blocking layer and lateral index-guided layer. One step regrowth in a conventional MOCVD reactor not only simplified the laser process procedure but also improved the material's quality. The internal loss of the real index-guided InGaAlP lasers with buried tunnel junctions is measured to be as low as 5.4 cm^{-1}. The threshold current for lasers with 500 μm cavity length is 45 mA and the one end slope efficiency is 0.58 W/A for both facets uncoated. The results

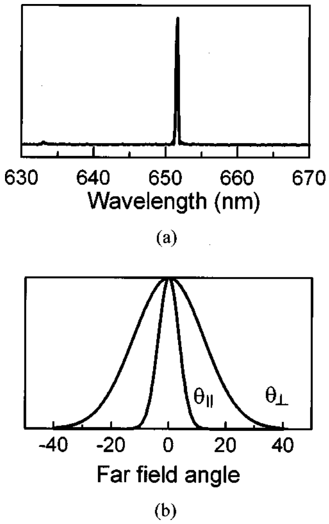

FIG. 4. (a) Laser output spectrum and (b) far field beam patterns at output power of 5 mW at 20 °C for real index-guided lasers with buried tunnel junctions.

suggest that the introduction of buried tunnel junctions for the realization of real index-guided InGaAlP lasers is a viable approach. By further optimizing the laser structures, the growth conditions of tunnel junctions, the thickness of *n*-type $In_{0.5}Al_{0.5}P$ layers, and the bottom width of the laser ridge should be capable of improving the laser characteristics.

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