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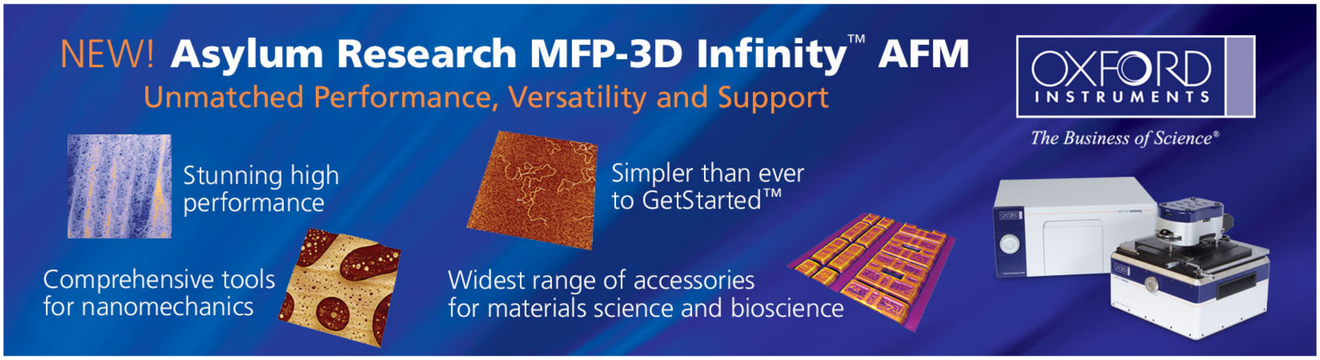
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Characteristics of monolithically integrated two-wavelength laser diodes with aluminum-free active layers

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A two-wavelength integrated laser diode (TWINLD) with aluminum-free active areas (AAA) has been realized by monolithically combining two different laser material structures in a single chip utilizing the metalorganic chemical vapor deposition growth and regrowth techniques. The single TWINLD chip comprises two ridge wave-guide lasers, one is an InGaP/InGaAlP material structure for a 650 nm red laser, and another is an InGaAsP/AlGaAs material structure with AAA for a 780 nm infrared laser. The chip geometry is 300 μm long and 300 μm wide with a separation of 150 μm between two laser emission spots. The ridge widths are 3.5 and 2 μm for the red and IR laser, respectively, and both lasers emit a single transverse mode with a threshold current of 12 mA for a 650 nm laser and 14 mA for a 780 nm laser under continuous wave operation condition. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1347019]

Recently, the digital versatile disk (DVD) has been increasingly prevalent for high-density data storage and readout applications including video systems, personal computers, and car navigation systems. In general the pick-up head for a DVD system requires not only being capable of reading out the DVD signals, but also the ability of backward compatibility to fetch the signals from a compact disk (CD), recordable compact disk, and rewritable compact disk. As a result the conventional DVD pick-up heads are equipped with two separate laser diodes, a 650 nm laser and a 780 nm laser, with two optical paths to read out DVD and CD signals, respectively.[1] It would be desirable and advantageous to have two lasers integrated into one single chip to form a two-wavelength integrated laser diode (TWINLD). This will allow the reduction of the optical components, the dimension of the pick-up heads, the assembling time, and the overall costs.[2] A hybrid TWINLD design was reported earlier[3] by using two distinct laser chips mounted on a single submount. Although the hybrid type design has the advantage of adopting the existing well-developed semiconductor laser chip technology, it has difficulty in precise definition of two laser emission spots that could increase the laser packaging cost.

In this letter we report a monolithically integrated TWINLD that combines two laser diodes in a single chip using a metalorganic chemical vapor deposition (MOCVD) regrowth technique. The TWINLD emits a red wavelength at $\lambda = 650$ nm and an infrared wavelength at $\lambda = 780$ nm with good performance. In comparison with the hybrid TWINLD, the distance between two emission spots of the monolithic TWINLD can be defined exactly by photolithography. Moreover, an aluminum-free active area structure[4,5] was first introduced in the TWINLD that could allow high-power operation.

The epitaxial growth and regrowth of the two different laser structures were carried out in a low-pressure MOCVD system with a multiwafer (7×2 in. wafers) rotating disk. A misoriented (100) n-GaAs substrate ($n = 1-3 \times 10^{18}\,\text{cm}^{-3}$) with 10° off toward the (111) direction was used for the purpose of avoiding the ordering phase of AlGaInP during the epitaxial growth.[6,7] The schematic structure of the TWINLD is shown in Fig. 1. The 650 nm laser structure shown in Fig. 1(a) has been optimized to achieve better carrier and light confinement as reported earlier.[8,9] It has a double quantum well active layer and a pair of cladding layers made of $In_{0.5}Al_{0.5}P$. The 780 nm laser structure as shown in Fig. 1(b) has an active region consisting of two -0.1% tensile strained $In_{0.08}Ga_{0.92}As_{0.83}P_{0.17}$ wells and one $Al_{0.3}Ga_{0.7}As$ barrier. The $Al_{0.7}Ga_{0.3}As$ is adopted as a p- and n-cladding layer with the same thickness as the cladding layers of the 650 nm laser. The Al composition of the confinement layer is graded from 0.7 to 0.3. Two $In_{0.5}Ga_{0.5}P$ etching stop layers are introduced in the structure. The first one is grown under the buffer layer in order to obtain a flat etched surface and to accurately control the depth of the regrowth area.[10] And the second one is amid the p-type cladding layer to ensure the precision of etching depth when making the ridge wave-guide structure.

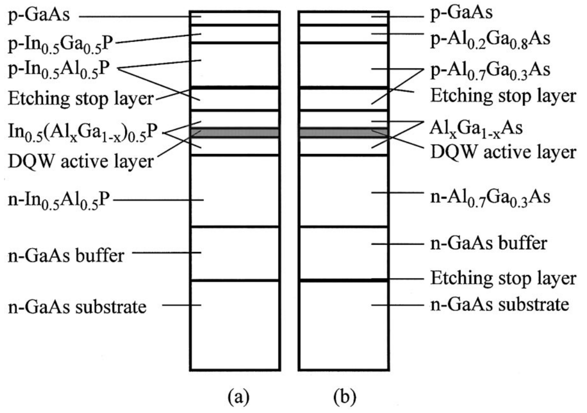

FIG. 1. Schematic layer structures of (a) 650 nm laser and (b) 780 nm laser for the TWINLD.

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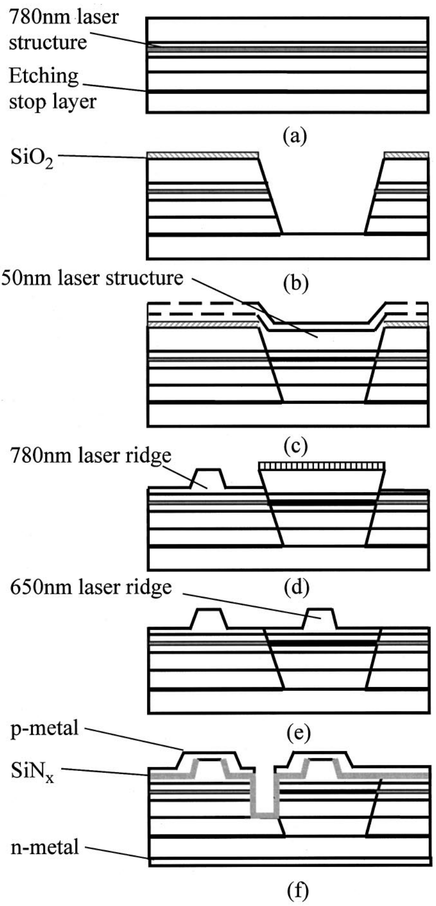

FIG. 2. Schematic representation of the device fabrication steps. (a) Growth of 780 nm laser structure; (b) deposition of SiO_2 and formation of the regrowth area; (c) regrowth of the 650 nm laser structure; (d) formation of the 780 nm laser ridge; (e) formation of the 650 nm laser ridge; and (f) formation of isolation and contacts.

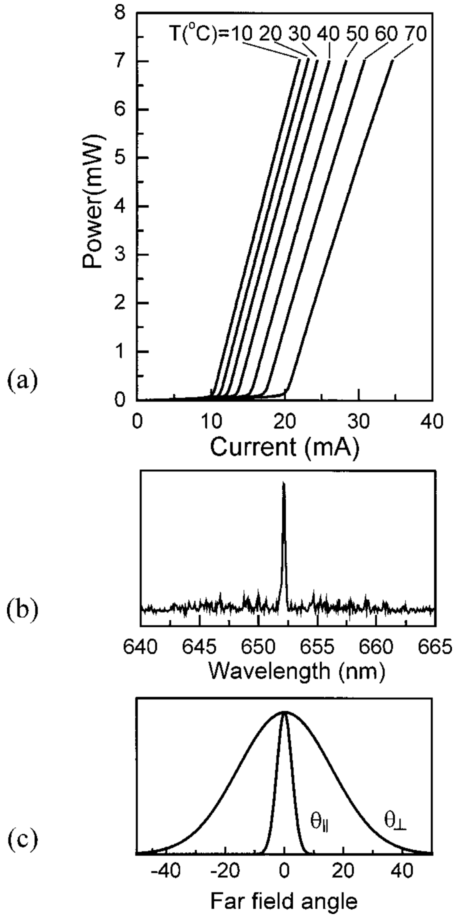

FIG. 3. cw output characteristics of the 650 nm laser. (a) Light output vs current characteristics at various temperature conditions; (b) laser output spectrum, and (c) far field beam patterns at the output power of 5 mW and 20 °C.

Figure 2 shows the schematic of the device fabrication steps. The first step, as shown in Fig. 2(a), was to grow the 780 nm laser structure. The 50 μm wide SiO_2 stripes with 300 μm apart were then deposited on the top of the as-grown wafer along the (0-11) direction. The surface areas without the SiO_2 mask were then wet etched for regrowth purposes. The etching procedure started by using H_2SO_4:H_2O_2:H_2O $=4:1:1$ for removing the cap layer and *p*-cladding layer. The etching rate of the H_2SO_4 based solution would be greatly reduced when it came to the second etching stop layer. The $In_{0.5}Ga_{0.5}P$ stop layer was removed by a HCl:H_3PO_4=3:1 solution. Then, the H_2SO_4 based solution was used again to remove the remaining *p*-cladding layer, confinement layers, active layers, *n*-cladding layer, and buffer layer. The first etching stop layer was etched by a HCl and H_3PO_4 mixed solution, leaving the bottom surface flat and smooth, as shown in Fig. 2(b). The wafer was then sent back to the MOCVD reactor for regrowth of the 650 nm laser structure as shown in Fig. 2(c). Next, the amorphous layers on the top of the SiO_2 mask and the SiO_2 mask itself were removed, and a 2 μm wide ridge for 780 nm laser and a 3.5 μm wide ridge for the 650 nm laser were formed in sequence as shown in Figs. 2(d) and 2(e), with a 150 μm separation between the two emission spots. Next, the trench between the two lasers was formed and the SiN_x films were deposited to provide the isolation protection of the ridges and two laser structures. After the wafer was coated with *p* and *n* metal, the wafer was made into $300\,\mu m \times 300\,\mu m$ TWINLD chips as shown in Fig. 2(f) for device testing.

Figure 3(a) shows the laser output power versus current ($L-I$) characteristics for 650 nm laser under continuous wave (cw) operation at various temperatures. The threshold current is 12 mA at 20 °C and the one end slope efficiency is 0.6 W/A for both facets uncoated. The characteristic temperature was estimated to be 88 K between 10 and 70 °C. The lasing wavelength is 652 nm at 20 °C at the output power of 5 mW, and the laser has a single mode with the far field angles of 6° and 37° for the direction parallel and perpendicular to the junction plane, respectively, as shown in Figs. 3(b) and 3(c).

Similarly, Fig. 4(a) shows the temperature dependence of $L-I$ characteristics for the 780 nm laser under cw operation condition. The threshold current is 14 mA at 20 °C and the one end slope efficiency is 0.4 W/A for both facets uncoated. The characteristic temperature is 104 K between 10 and 70 °C. The peak emission wavelength is 781 nm at 20 °C at the output power of 5 mW, and the laser has a single mode with the far field angles of 17° and 37° at the direction parallel and perpendicular to the junction plane, respectively, as shown in Figs. 4(b) and 4(c). The single ended output power under cw operation can reach up 35 mW for both facets uncoated.

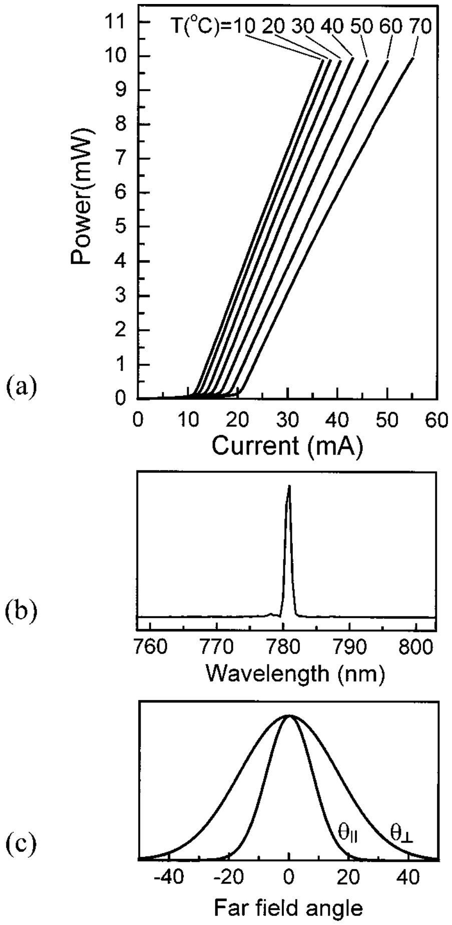

FIG. 4. cw output characteristics of the 780 nm laser. (a) Light output vs current characteristics at various temperature conditions; (b) laser output spectrum, and (c) far field beam patterns at output power of 5 mW and 20 °C.

Laser chips with different cavity lengths were also fabricated and tested. From the relationships between the threshold current density and the inverse of the cavity length, the transparent current density is determined to be 339 A/cm^2 for the 650 nm laser and 546 A/cm^2 for the 780 nm laser. The internal quantum efficiency and internal loss are also estimated from the relationships between the inverse of the differential quantum efficiency and the cavity length to be 0.71 and 2.45 cm^{-1} for the 650 nm laser, and 0.79 and 4.48 cm^{-1} for the 780 nm laser.

In summary, monolithic two-wavelength integrated laser diodes have been fabricated by utilizing the regrowth technique. Due to the well-controlled MOCVD growth technique and the adoption of the etching stop layers, both of the integrated devices still maintain their high performance characteristics. The threshold current of a 650 nm laser is 12 mA and the one end slope efficiency is 0.6 W/A for both facets uncoated. On the other hand, the threshold current of a 780 nm laser is 14 mA and the one end slope efficiency is 0.4 W/A for both facets uncoated. The TWINLDs should be suitable for DVD pick-up head applications. In addition, the monolithic single chip approach may be applicable for the next generation DVD system using a 400 nm blue laser diode, and for the integration of three-wavelength laser diodes.

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