III-N-V: A novel material system for lasers with good high-temperature characteristics

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ABSTRACT

We have obtained GaInNAs/GaAs quantum wells with emission at 1.3 μm at room temperature. We also show that another novel material InNAsP grown on InP is a viable material for long-wavelength lasers. The maximum temperature of operation for an InNAsP/GaInAsP microdisk laser is 70 °C, which is about 120 °C higher than that of a similar laser fabricated from GaInAs/GaInAsP. The characteristic temperature T_o of the former is 97 K, also higher than that of the latter.

Key words: III-V compound semiconductors, nitrogen, GaInNAs, InNAsP, microdisk laser

1. INTRODUCTION

Long-wavelength lasers emitting at 1.3 and 1.55 μm are important for optical-fiber communications and have been intensively investigated. These lasers were commonly realized with the GaInAsP-InP material system, but they have poor performance at high temperature (25 °C to 85 °C) and thermoelectric coolers are often required for their use in optical-fiber communication systems. The high-temperature performance is described by a characteristic temperature T_o where the temperature dependence of the threshold current density is proportional to exp (T/T_o). Obviously a higher the T_o is desirable. In the case of the GaInAsP-InP system, T_o is about 60 K, due to the small conduction band offset resulting in poor electron confinement in the quantum wells (QWs).[1] The hole confinement is less of a problem because of heavier effective hole masses. Materials with a larger conduction band offset and a higher T_o have been reported, e.g., the AlGaInAs/InP system with a T_o of 105-120 K[2] and the AlGaInAs/InAsP system with a T_o of 127-143 K.[3] In 1995 Kondow et al. proposed a novel material system, GaInNAs/GaAs,[4] and they reported a T_o of 126 K for a laser emitting at 1.2 μm[5] and recently they also report edge-emitting and vertical-cavity surface-emitting lasers (VCSELs) emitting at 1.3 μm.[6] In this paper we show some results from our work on GaInNAs/GaAs quantum wells and describe another Al-free material system for long-wavelength lasers at 1.3 and 1.55 μm: InNAsP on InP.[7]

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2. GROWTH AND CHARACTERIZATION OF N-CONTAINING III-V COMPOUNDS: III-N-V

We have grown N-containing III-V ternaries and quaternaries by gas-source molecular beam epitaxy with a RF plasma nitrogen radical beam source, elemental group III sources and cracked arsine and phosphine. Despite the low solubility limits of N in arsenides and phosphides,[8] the highest N composition we have obtained in InNP is 1%,[9] whereas that in GaNP[10] and GaNAs[11] is 16%. These numbers are the highest reported to date. One striking feature of nitrogen incorporation is the resultant large bandgap bowing, which is used to advantage for long-wavelength applications. Because of this bandgap narrowing with nitrogen incorporation, it should be possible to produce 1.3 μm emitting materials on GaAs substrates, as proposed by Kondow et al.[4] Figure 1 shows our 7-period $Ga_{0.7}In_{0.3}N_{0.02}As_{0.98}$ (6.2 nm)/GaAs (16.9 nm) multiple quantum well structure with room-temperature photoluminescence (PL) emission at 1.3 μm[12]. Note, however, that the intensity is lowered by a factor of about 20, compared to the sample without nitrogen. We do not yet know the origins of the decrease in PL intensity with increasing N incorporation.

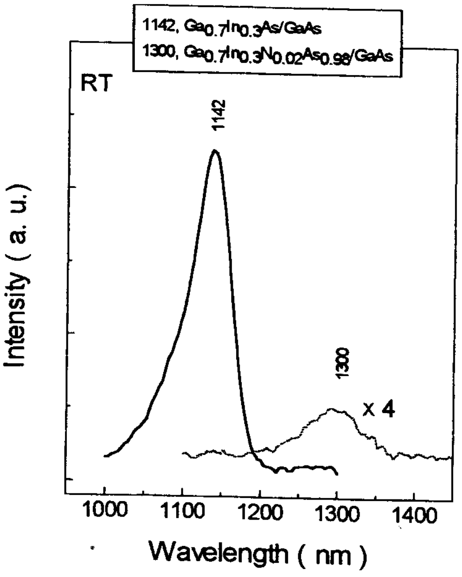

Fig. 1 Room-temperature PL of GaInAs/GaAs and GaInNAs/GaAs MQWs.

Because nitrogen has a large electronegativity[13] and the bandgap bowing, incorporating nitrogen into the conventional III-V materials pulls down the conduction-band edges, resulting in a larger conduction-band offset.[4,7] Based on the band edge positions of the nitrides13, the valence band edge is expected to move down as well. Figure 2(a) shows qualitatively the band edges for GaInAs and GaNAs as a function of strain. Adding In into GaAs increases the lattice constant, resulting in compressive strain ε_1 in the plane parallel to the interface. The bandgap becomes smaller, with the valence band edge moves up and the conduction band edge moves down. On the other hand, adding N to GaAs results in tensile strain ε_2. The bandgap also becomes smaller, but the conduction band edge moves down much faster. Therefore, adding N to GaInAs reduces the strain from ε_1 to ε_1-ε_2 and increases the conduction band offset from ΔE_{c1} to $\Delta E_{c1}+\Delta E_{c2}$, resulting in better electron confinement.[4,12]

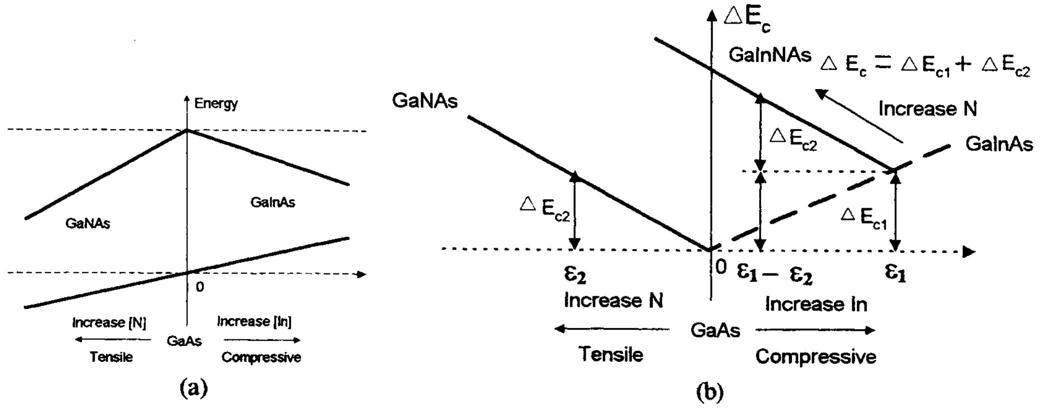

Fig. 2 A schematic diagram of (a) the band edges and (b) the conduction band offset as a function of the strain for Ga(In,N)As/GaAs heterostructures.

Since the GaInNAs/GaAs system has been intensely investigated, we concentrate on another material system, InNAsP on InP. We also expect better high-temperature performance as discussed below. It may be expected that such a material InNAsP, being a quaternary with three different group V elements, would be difficult to control the relative compositions, but it is no more difficult than growing a quaternary with two group III and two group V elements. We have found that because the arsenic vapor pressure is much lower than that of phosphorus on InAsP, if the flux of arsenic is smaller than that of indium, i.e., if the As/In incorporation-rate ratio is less than unity, the As concentration is essentially determined by that ratio.[14] The arsenic and indium incorporation rates, which depend on the substrate temperature, can be determined easily by group III- and group V-induced oscillations of reflection high-energy electron diffraction (RHEED), as shown in Figure 3(a) for InAs at a growth temperature of about 460 °C. The period of oscillations between t_1 and t_2 is determined by the indium incorporation rate. At t_2, by closing the arsenic shutter, we intentionally deposit an excess amount of indium on the surface, which forms indium droplets. At t_3 we re-supply the arsenic flux and close the indium shutter, and the period of RHEED oscillations between t_3 and t_4, indicative of layer-by-layer growth between indium droplets, is determined by the arsenic incorporation rate. Figure 3(b) shows the arsenic concentration in InAsP/InP multiple quantum wells (MQWs), which were determined by X-ray rocking curves and simulations, versus the As/In incorporate rate ratio measured from the experiments as shown in Figure 3(a).[14] The agreement is very good for an arsenic concentration up to 0.5, which is sufficient for 1.3 μm applications, where 0.4 is need for a 10 nm-wide QW. The discrepancy is due to only two or three periods of RHEED oscillations when the As concentration, therefore the strain, is large and lattice relaxation in MQWs. The relative concentrations of N and P in InNAsP were then determined by several growth runs.

By adding different amount of nitrogen, we can obtain different emission wavelengths, e.g., 1.3 μm and 1.5 μm, as shown in Figure 4.[15] In this case the barriers are GaInAsP with a 1.1 μm bandgap, specifically for microdisk lasers.

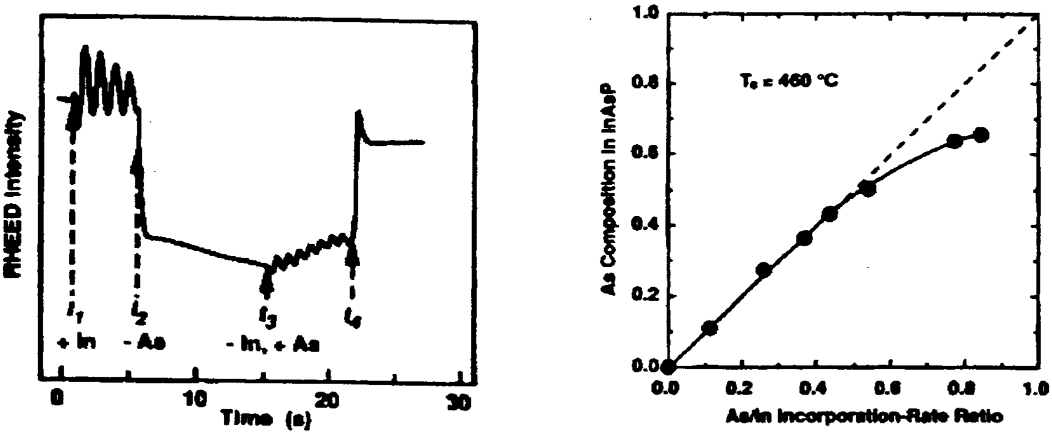

Figure 3 (a) Group III- and group V-induced RHEED oscillations on InAs, and (b) the arsenic concentration determined by X-ray rocking curves and simulations versus the As/In incorporation-rate ratio determined from (a).[14]

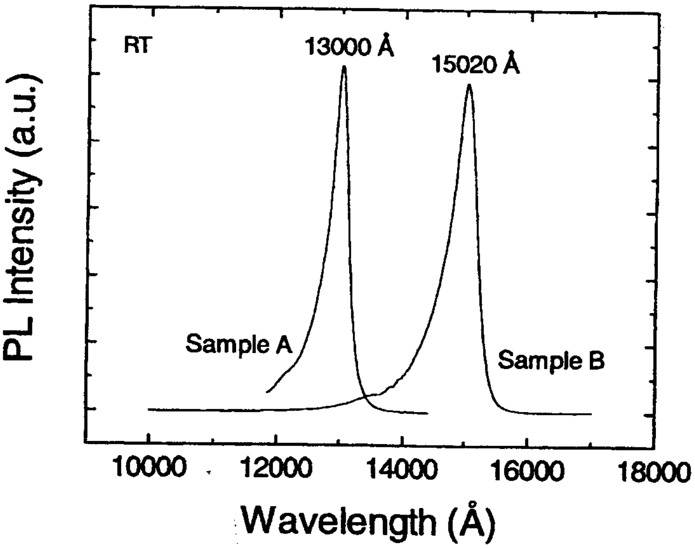

Figure 4 Room-temperature photoluminescence of InNAsP/GaInAsP quantum wells with different N concentrations. The intensities are normalized, with that of Sample B is about half of that of Sample A.[15]

3. MICRODISK LASER RESULTS

To evaluate the usefulness of the novel InNAsP/InP material for laser applications, we fabricate microdisk lasers because only undoped QWs are involved, without the complication of growing n- and p-doped cladding layers in conventional lasers. Furthermore, we can compare the results with those obtained previously on GaInAs/GaInAsP QW microdisk lasers. Figure 5(a) shows the microdisk laser structure, which is just a 1.3 μm single quantum well (SQW) of InNAsP/GaInAsP grown on InP, and Figure 5(b) shows a fabricated microdisk with a diameter of 5 μm.[7] The mesa is first defined by reactive ion etching to the InP layer and followed by wet chemical etching, which is isotropic and etches InP but not GaInAsP. Therefore, the SQW disk sits on top of an InP post as shown in Figure 5(b).

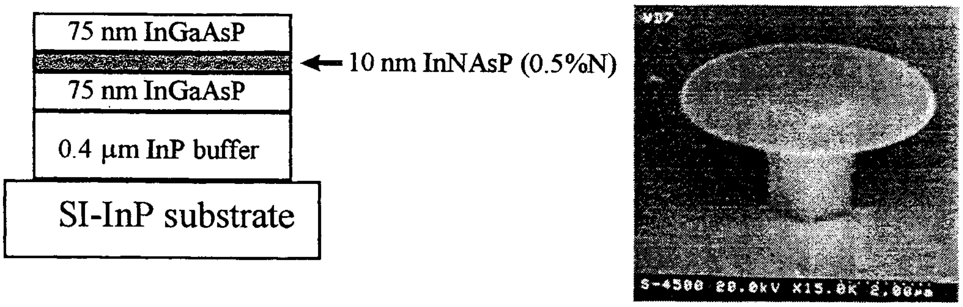

Figure 5 (a) Schematic layer structure of the InNAsP/GaInAsP microdisk laser shown in (b).[7]

Optical pumping, with a 1% duty cycle, at a wavelength of 514 nm from an argon-ion laser was then used to achieve lasing. Figure 6 shows the pump-light intensity plots for (a) InNAsP/GaInAsP and (b) GaInAs/GaInAsP microdisk lasers at 85 K. At this temperature, the threshold pump power of (a) is about 20 µW, compared to the 36 µW of (b). Furthermore, the emission intensity saturates in (b), but not in (a). These results all indicate a larger conduction band offset in the InNAsP/GaInAsP system.

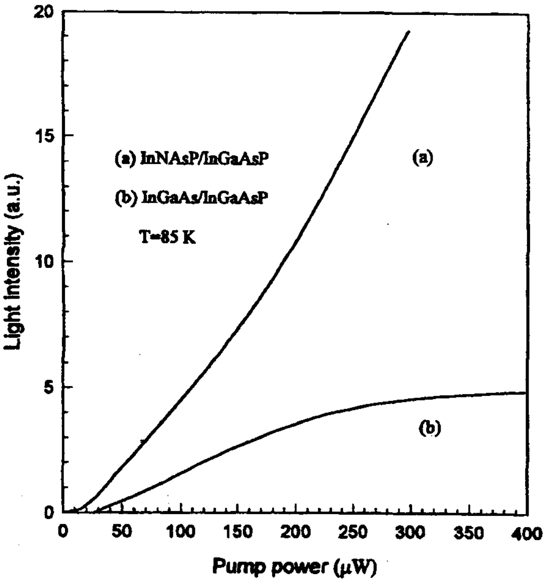

Figure 6 Output light intensity versus pump powr for a 5 mm-diameter (a) InNAsP/GaInAsP and (b) GaInAs/GaInAsP microdisk lasers measured at 85 K.[7]

Figure 6 shows the pump threshold as a function of temperature, indicating a T_o of 97 K, above the 60 K achieved with a GaInAs/GaInAsP microdisk laser. Note also that the maximum temperature of operation is about 330 K, which is higher than the 240 K of a GaInAs/GaInAsP microdisk laser operating at 1.45 µm.[16]

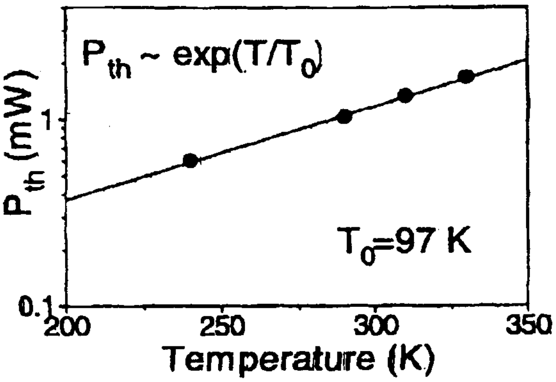

Figure 7 Laser pump threshold as a function of temperature

In summary, the results shown above demonstrate that the InNAsP/GaInAsP is a superior material compared to GaInAs/GaInAsP for long-wavelength microdisk lasers. We expect similar performance advantage for edge-emitting lasers, which are under investigation in our laboratories.

4. ACKNOWLEDGMENT

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