A Novel Material for Long-Wavelength Lasers: InNAsP

Charles W. Tu, W. G. Bi, Y. Ma, J. P. Zhang, L. W. Wang, and S. T. Ho

***Abstract*— We show that a novel material InNAsP grown on InP is superior for long-wavelength microdisk lasers (and so expected for edge-emitting lasers) because of its larger conduction band offset from the addition of a small amount of nitrogen (0.5%–1%). 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.**

***Index Terms*— Bandgap bowing, characteristic temperature, InNAsP, nitrogen incorporation, semiconductor laser.**

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–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 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 (QW's) [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 K–120 K [2] and the AlGaInAs–InAsP system with a T_o of 116 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 (VCSEL's) emitting at 1.3 μm [6]. In this paper, we describe another Al-free material system for long-wavelength lasers at 1.3 and 1.55 μm: InNAsP [7].

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C. W. Tu and W. G. Bi are with the Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093-0407 USA.

Y. Ma, J. P. Zhang, L. W. Wang, and S. T. Ho are with the Department of Electrical and Computer Engineering, The Technological Institute, Northwestern University, Evanston, IL 60208 USA.

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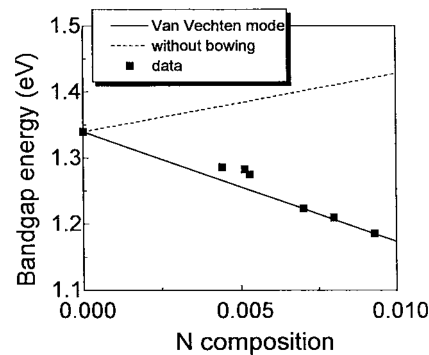

Fig. 1. Bandgap energy of InNP as a function of N concentration. The bandgaps were measured by absorption spectroscopy [9].

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. Fig. 1 shows the bandgap as a function of nitrogen concentration in InNP [9]. The dashed line is a linear interpolation between InP and InN. At small concentration range, the bandgap bowing agrees with the calculations based on the Van Vechten model, which is a perturbation theory.

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]. We find, however, that increasing the nitrogen incorporation decreases photoluminescence (PL) efficiency [12]. Even though we have produced a sample that emits at 1.3 μm at room temperature (RT), the intensity is lowered by a factor of ten, compared to the sample without nitrogen. That is why we concentrate on another material system, InNAsP on InP because in this case we do not have to incorporate as much nitrogen. Although it may not be suitable for VCSEL's, we expect better high-temperature performance as discussed below.

Because nitrogen has a large electronegativity [13], incorporating nitrogen into the conventional III–V materials pulls down both conduction-band and valence-band edges, resulting in a larger conduction-band offset [4], [7]. Fig. 2 shows qualitatively the band edges for InAsP and InNP as

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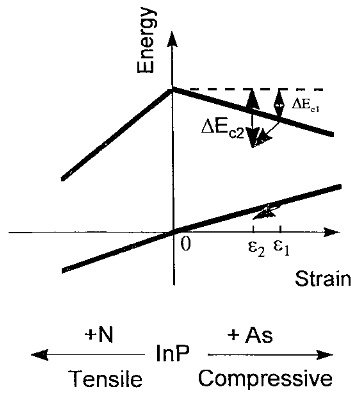
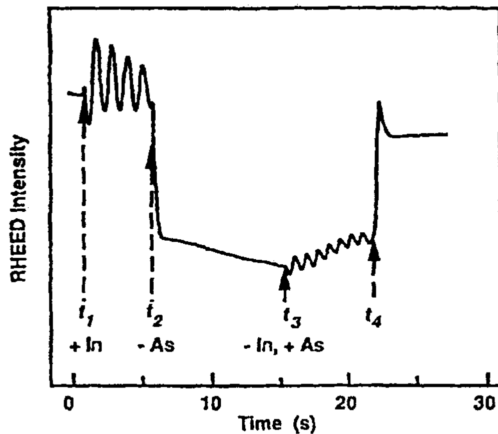
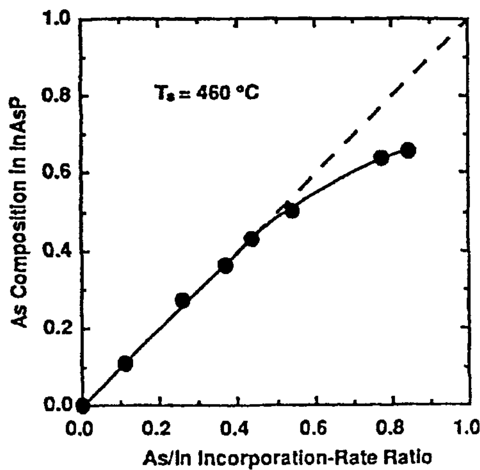


Fig. 2. Conduction band and valence band edges for InAsP and InNP.



(a)



(b)

Fig. 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].

a function of strain. Adding As into InP increases the lattice constant, resulting in compressive strain in the plane parallel to the interface. The bandgap becomes smaller; the valence band edge moves up and the conduction band edge moves down. On the other hand, adding N to InP results in tensile strain. The bandgap also becomes smaller, but both the valence band edge and conduction band edge move down. Therefore, adding

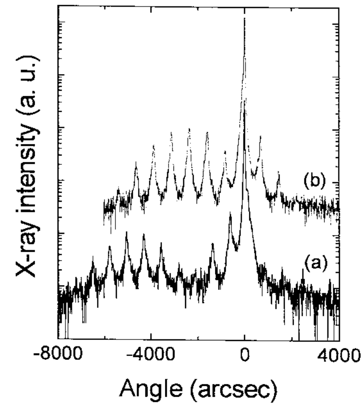


Fig. 4. High-resolution X-ray rocking curves for (a) $InAs_{0.4}P_{0.6}$–InP and (b) $InN_xAs_{0.4}P_{0.6-x}$–InP MQW's.

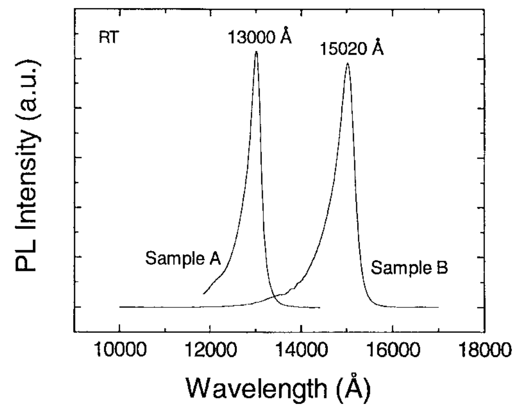
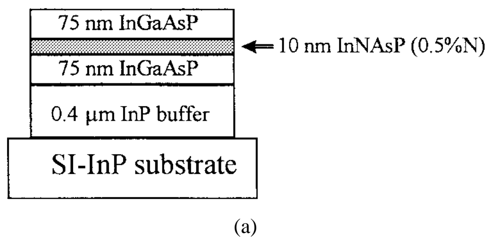


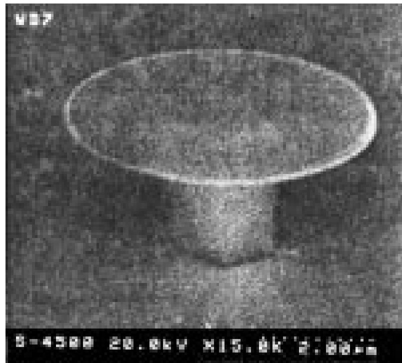
Fig. 5. RT photoluminescence of InNAsP–GaInAsP quantum wells with different N concentrations.

N to InAsP reduces the strain from ε_1 to ε_2 and increases the conduction band offset from ΔE_{c1} to ΔE_{c2}, resulting in better electron confinement.

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 Fig. 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 resupply 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. Fig. 3(b) shows the arsenic concen-



(a)



(b)

Fig. 6. (a) Schematic layer structure of (b) the InNAsP–GaInAsP microdisk laser [7].

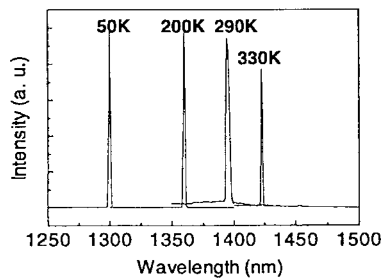


Fig. 7. Lasing spectra as a function of temperature.

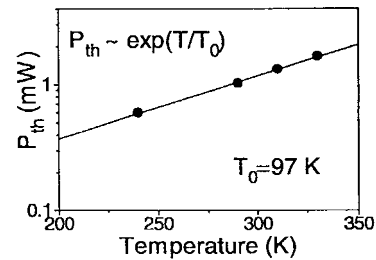


Fig. 8. Laser pump threshold as a function of temperature.

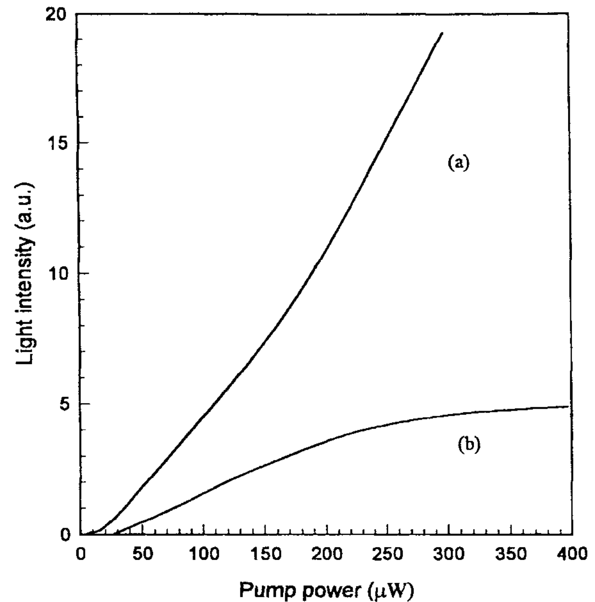


Fig. 9. Output light intensity versus pump power for a 5-μm-diameter (a) InNAsP–GaInAsP and (b) GaInAs–GaInAsP microdisk lasers measured at 85 K [7].

tration in InAsP–InP multiple-quantum wells (MQW's), which were determined by X-ray rocking curves and simulations, versus the As–In incorporate rate ratio measured from the experiments as shown in Fig. 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 needed 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 occurs in the MQW's. The relative concentrations of N and P in InNAsP were then determined by several growth runs.

Fig. 4 shows the effect of N incorporation in InAsP. Curve (a), the bottom one, is a high-resolution X-ray rocking curve for an InAsP–InP MQW, and curve (b) is for a similar sample with some nitrogen incorporation. We see that the superlattice satellite peaks become sharper, indicating better structural quality, but more importantly, the envelope of the satellite peaks shifts toward the substrate peak, indicating less strain. By adding different amounts of nitrogen, we can obtain different emission wavelengths, e.g., 1.3 and 1.5 μm, as shown in Fig. 5. In this case, the barriers are GaInAsP with a 1.1-μm bandgap for microdisk lasers. The nitrogen concentrations are 0.5%–1%, estimated from X-ray rocking curves and simulations.

Fig. 6(a) shows the microdisk laser structure, which is just a 1.3-μm single-quantum well (SQW) of InNAsP–GaInAsP grown on InP, and Fig. 6(b) shows a fabricated microdisk with a diameter of 5 μm [7]. The mesa is first defined by reactive ion etching (RIE) to the InP layer, 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 Fig. 6(b). Optical pumping, with a 1% duty cycle, at a wavelength of 514 nm from an argon–ion laser was then used to achieve lasing. Fig. 7 shows lasing spectra at different temperatures, up to 340 K, above the previously achieved 220 K of a 1.45-μm GaInAs–GaInAsP microdisk laser with a similar structure grown and fabricated by us. More important is Fig. 8, which shows the pump threshold as a function of temperature, indicating a T_o of 97 K, again above the 60 K achieved with a GaInAs–GaInAsP microdisk laser.

Fig. 9 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.

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 advantages for edge-emitting lasers, which are under investigation in our laboratories.

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Charles W. Tu received the B.Sc. (Honors) degree in physics from McGill University, Montreal, PQ, Canada, in 1971, and Ph.D. degree in engineering and applied science from Yale University in 1978.

From 1978 to 1980, he was a Lecturer in the Physics Department, Yale University, and from 1980–1988, a Member of the Technical Staff at AT&T Bell Laboratories, Murray Hill, New Jersey. In 1988 he joined the faculty of University of California, San Diego (UCSD). He is a Professor and Vice Chair in the Department of Electrical and Computer Engineering, UCSD. His fields of research include gas-source (hydrides) molecular beam epitaxy (MBE) and (laser-assisted) metal–organic MBE or chemical beam epitaxy (CBE) of III–V heterostructures for electronic and optoelectronic applications. In 1987, he was awarded as a Distinguished Member of Technical Staff of AT&T Bell Labs; in 1991, a United Nations Development Program Award for a lecture tour in China; in 1993 a National Science Foundation-Japan Center for Global Partnership Fellowship to conduct research in Japan; and in 1997 a JSPS (Japan Society for Promotion of Sciences) Fellow. He is also an Adjunct Professor in the National Kwangju Institute of Science and Technology in Korea. He is active in a number of professional societies and conferences. He has authored or co-authored over 200 publications in refereed journals, over 60 papers in conference proceedings, four book chapters, five edited conference proceedings, and two patents.

W. G. Bi, photograph and biography not available at the time of publication.

Y. Ma, photograph and biography not available at the time of publication.

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