Improved High-Temperature Performance of 1.3–1.5-μm InNAsP–InGaAsP Quantum-Well Microdisk Lasers

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***Abstract*— We report for the first time lasing action in the InNAsP–InGaAsP material system. Dramatic improvement in lasing action in a microdisk cavity was observed at elevated temperature up to 70 °C, which is about 120 °C higher than that of InGaAs–InGaAsP microdisk. This resulted in the first optically pumped InNAsP–InGaAsP microdisk lasers capable of above room-temperature lasing. The improvement of lasing temperature can be attributed to a large conduction band offset between the quantum well and barriers in the InNAsP–InGaAsP material system.**

***Index Terms*— Carrier leakage, characteristics temperature, InNAsP–InGaAsP quantum well, microdisk lasers, optical-fiber windows.**

MUCH effort has been devoted to the studies of the temperature characteristics of long-wavelength lasers emitting at the optical-fiber communication wavelength windows (1.3–1.55 μm) [1]–[3]. These lasers were commonly realized with InGaAsP–InP material system involving InGaAsP quantum wells (QW's). However, these lasers have poor performance at high temperature (25 °C–85 °C) and thermoelectric coolers are often required for their applications in optical-fiber communications systems [4]. Recently Kondow *et al.* proposed and demonstrated that GaInNAs can be a new material for long-wavelength lasers on a GaAs substrate with record-high-temperature performance (T_o = 126 K) [5], [6] but the wavelength is only about 1.2 μm. We have since also grown GaInNAs–GaAs QW's and found decreasing photoluminescence intensity with increasing N concentration for longer wavelength. At 1.3 μm there is no photoluminescence. In this letter, we demonstrate for the first time another material, InNAsP on InP, that improved high-temperature laser performance at about 1.3 μm, compared with conventional InGaAsP QW's, can be achieved. Specifically, we demonstrate that microdisk lasers based on this new material system can lase at high temperature up to 340 K, while microdisk lasers based on InGaAs–InGaAsP QW can lase only up to 220 K. As explained below, this improvement is due to the stronger confinement of electrons resulting from a larger conduction band offset in InNAsP–InGaAsP QW structure compared to that of InGaAs–InGaAsP. The use of high-Q microdisk structure to study lasing properties of new materials is an advantage because the microdisk structure is substantially thinner than the conventional laser structure, and this helps to reduce the thickness of material that has to be grown in our initial experiment.

Up to the present, several mechanisms have been proposed to explain the poor high-temperature performance of InGaAsP QW lasers [1], [2]. One of the main factors is carrier leakage over the QW barrier layer. A large conduction band offset between the QW and the barrier can lead to stronger confinement for electrons in the well. This can help to reduce carrier leakage because the electrons require a stronger confinement than the holes due to their lighter effective mass. Theoretical calculation shows that adding N into conventional III–V's such as InP can pull down the conduction and valence band edges and lead to a larger conduction band offset because of the large electronegativity of nitrogen atoms [7]. Experimentally, we have shown that incorporating N into InP results in a lowering of the bandgap [8]. InAsP–InGaAsP QW structures have been used for 1.3-μm lasers, and the characteristics temperature (T_0) has been improved to ~72 K from ~60 K of the InGaAs–InGaAsP system [9]. We can expect that adding N into InAsP will further improve T_0. In addition, InAsP alloy is compressively strained when grown on InP, and the small lattice constant of nitride can help to reduce the system strain.

Fig. 1 shows qualitatively the band edges (a) and conduction band offset (b) versus strain for InNAsP–InP heterostructures. From Fig. 1(a), we can see that adding As into InP increases the lattice constant, raises the valence band edge, and lowers the conduction band edge. On the other hand, adding N into InP decreases the lattice constant and lowers both the conduction and valence band edges. Fig. 1(b) shows the conduction band offsets of InAsP (solid line), InNP (dashed line) and InNAsP (dotted line) as a function of strain. From Fig. 1(b), we can see that as As concentration in InAsP increases, the strain increases, say, to ε_1 as indicated by point P_1. Adding N into InAsP then moves the strain along the dotted line to ε_2, as indicated by point P_2. Note that the dotted line is parallel to the dashed line and is obtained by

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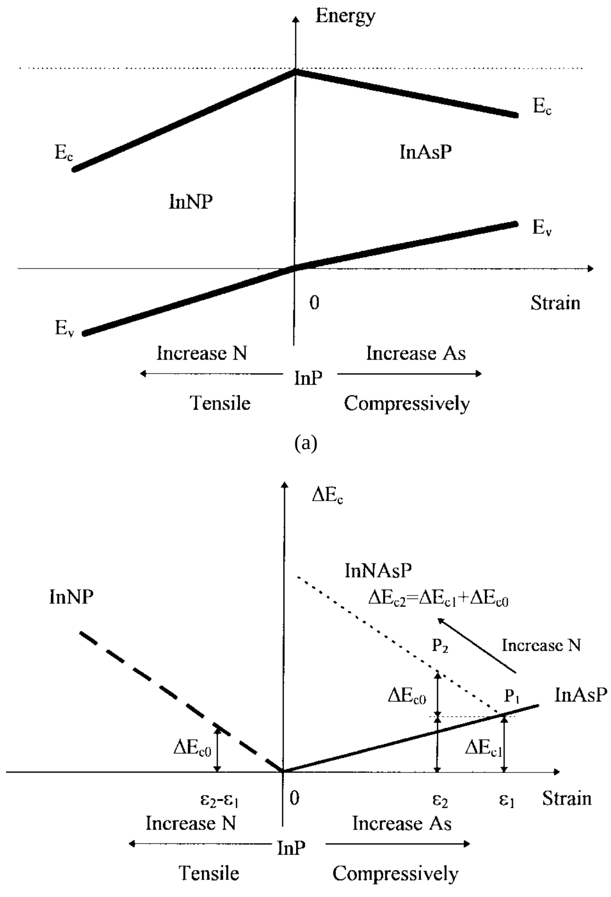

Fig. 1. Schematic diagrams of (a) the band edges and (b) conduction band offsets of InAsP (solid line), InNP (dashed line) and InNAsP (dotted line) versus strain for In (N, As)/InP heterostructures.

transposing the dashed line to point P_1. Fig. 1(b) shows that P_2 corresponds to a larger conduction band offset ($\Delta E_{c2} = \Delta E_{c1} + \Delta E_{c0}$ of InNAsP than ΔE_{c1} of InAsP at P_1. As mentioned above, this larger conduction band offset can help to improve the high-temperature performance of these lasers. We note that the optical emission wavelength of InNAsP material system can be tuned over a wide range covering the window (1.3–1.55 μm), which makes this material system very attractive for applications in optical-fiber communications.

The 0.16-μm-thick InNAsP–InGaAsP single QW disk structure on a 400-nm-thick InP buffer layer was grown by gas-source molecular beam epitaxy on a semi-insulating (100) InP substrate. The disk structure layer is comprised of a 75-nm-thick $In_{0.885}Ga_{0.115}As_{0.25}P_{0.75}$ lower barrier layer, a 10-nm-thick $InN_{0.005}As_{0.45}P_{0.545}$ single QW and a 75-nm-thick $In_{0.885}Ga_{0.115}As_{0.25}P_{0.75}$ upper barrier layer. Rutherford backscattering (RBS) was used to determine the In concentration of the quaternary materials first, and then the thickness of the layers and the compositions of As and P were determined from high-resolution X-ray rocking curves of multiple QW's and simulations based on the dynamical theory. The thickness of the disk structure is chosen to yield a high spontaneous emission coupling factor β value in the microdisk lasers which can help to achieve low-threshold lasing [10].

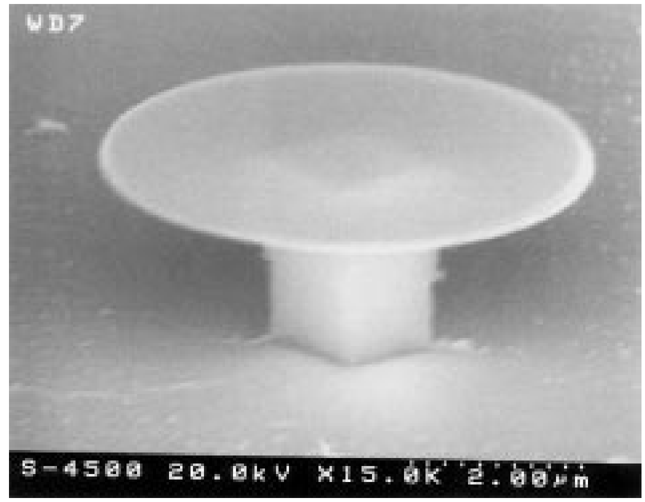

Fig. 2. Scanning electron microscope image of a 5-μm-diameter InNAsP–InGaAsP microdisk laser.

Microfabrication process involving reactive ion etching (RIE) and selective chemical etching were used to fabricate the lasers. First, the circular microdisks with different diameters ranging from 5 to 20 μm were patterned using AZ-1518 positive photoresist by optical lithography. Then RIE was used to etch the disks down vertically through the QW layer into the InP buffer layer in the same way as described in [11]. Finally, a highly selective etchant ($2HCl{:}3H_3PO_4$) was used to etch the InP buffer layer down as well as inward under the disk layer to form the supporting pillar. A scanning electron microscope photo of a resulting disk structure is shown in Fig. 2. Optical pumping at a wavelength of 514 nm from an Argon-ion laser was then used to achieve lasing for 5-μm-diameter mirodisks. The measurement setup is similar to the one we used before with $1 = 100$ pump duty cycle [12]. The ambient temperature of the samples was controlled by a programmable temperature controller.

Photoluminescence measurement shows that the InNAsP–InGaAsP microdisk lasers can lase at up to 340 K (about 70 °C). In Fig. 3, we plot the emission light intensity versus the pump power for a 5-μm-diameter InNAsP–InGaAsP microdisk at 330 K. After taking into account 30% reflection at the sample surface and an estimated absorption of 85% through the 0.16-μm-thick QW, we obtained a low-threshold pump power of about 156 μW. This is the total peak pump power absorbed by the 5-μm microdisk and this threshold pump power corresponds to an incident threshold intensity of 0.8 kW/cm^2. The inset in Fig. 3 shows the single-mode lasing spectra measured at (dotted line) and above threshold (solid line). The peak pump power absorbed by the microdisk is approximately 156 and 400 μW, respectively. The lasing wavelength is at $\lambda = 1.422$ μm.

For comparison, we also measured InGaAs–InGaAsP QW microdisk lasers ($\lambda \sim 1.5$ μm) which were fabricated by the same processes and have the same geometrical configuration as the InNAsP–InGaAsP microdisk lasers. We found that the InGaAs–InGaAsP microdisk lasers ceased to lase at a temperature as low as 220 K. This clearly demonstrates that InNAsP–InGaAsP has an improved performance at high

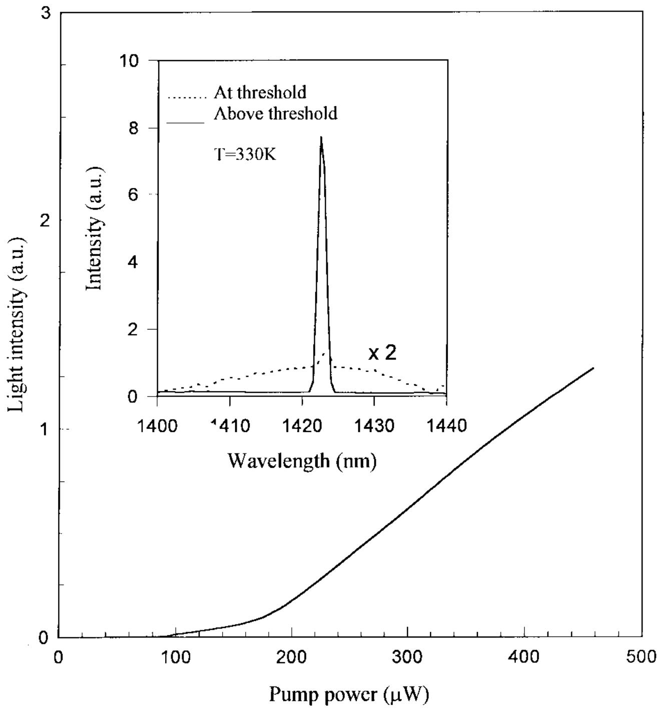

Fig. 3. Measured output light intensity versus pump power for the InNAsP–InGaAsP microdisk lasers with 5-μm diameter at 330 K. The inset shows the emission spectra measured at and above threshold at 330 K. The emission peak wavelength is at $\lambda = 1.422$ μm.

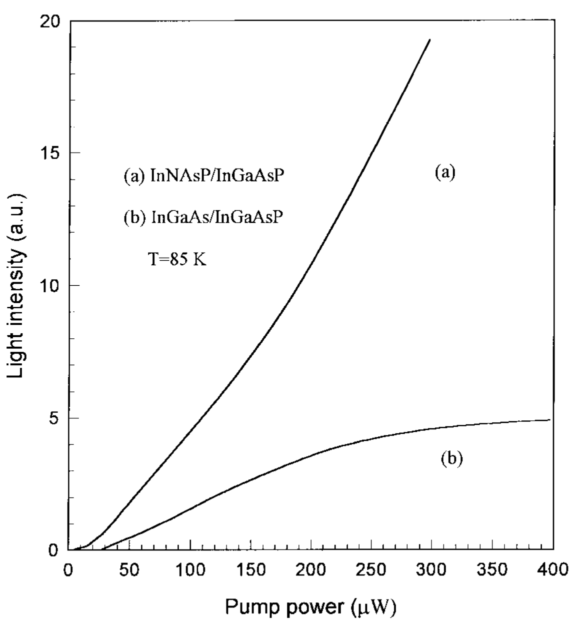

Fig. 4. Output light intensity versus pump power for the 5-μm-diameter InNAsP–InGaAsP and InGaAs–InGaAsP QW microdisk lasers measured at 85 K. Threshold pump power is about 20 and 36 μW, respectively.

temperature compared with InGaAs–InGaAsP. Fig. 4 shows the pump-light intensity plots for InNAsP–InGaAsP and InGaAs–InGaAsP microdisk lasers at 85 K. At this temperature, the threshold pump power of InNAsP–InGaAsP microdisk lasers is about 20 μW, whereas that of InGaAs–InGaAsP microdisk lasers is about 36 μW. It also can be seen from Fig. 4 that there is an emission intensity saturation in InGaAs–InGaAsP microdisk lasers when the pump power is more than 200 μW, whereas there is no saturation in InNAsP–InGaAsP microdisk lasers.

In summary, we have demonstrated lasing at an elevated temperature up to 70 °C under optical pulsed excitation in InNAsP–InGaAsP QW microdisk lasers with very low threshold. Similar experiments done with InGaAs–InGaAsP QW microdisk lasers show that the highest lasing temperature is about −50 °C, 120 °C lower than that of InNAsP–InGaAsP. A larger conduction band offset in the InNAsP–InGaAsP material system, which can provide stronger electron confinement, could explain this difference. Our experimental results demonstrate that InNAsP–InGaAsP, a new material system, can be advantageous for device applications in optical-fiber communications because of its improved high-temperature characteristics compared to that of InGaAsP–InP material system. A detailed study of the characteristic temperature T_0 of InNAsP–InGaAsP microdisk lasers is currently being performed.

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