High-power disk lasers based on dilute nitride heterostructures

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New Journal of Physics 11 (2009) 125019 (13pp)
Received 21 June 2009
Published 17 December 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/12/125019

Abstract. We report the development of InGaAsN-based gain mirrors for high-power optically pumped semiconductor disk lasers with direct emission at wavelengths around 1180 nm. The gain mirrors were fabricated by molecular beam epitaxy. They consist of 10 dilute nitride quantum wells, which were placed within a GaAs micro-cavity on top of a GaAs/AlAs distributed Bragg reflector. We demonstrated laser operation at ~1180 nm with record high output power (~7 W). The differential efficiency was ~30% for operation at 5 °C and ~28% when operating at 15 °C. The lasers exhibited excellent tuning characteristics, delivering an output power of more than 5 W in a narrow spectrum and providing over 30 nm tuning band. These features represent significant progress towards demonstration of practical high-power lasers with frequency-doubled yellow emission required for laser guide stars, life sciences and spectroscopy. At the same time the results emphasize the importance of dilute nitride heterostructures in the development of novel optoelectronic devices.

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1. Introduction

Developed initially for their advantages compared to InP-based heterostructures [1], InGaAsN-heterostructures delivered unexpected development opportunities for a large variety of optoelectronics devices. The possibility to monolithically grow long-wavelength quantum wells (QWs) on GaAs/AlGaAs distributed Bragg reflectors (DBRs) leads to new opportunities for fabricating high-quality vertical-cavity semiconductor structures operating in the 1300–1550 nm wavelength range, which is traditionally covered by the InP material system. This feature has already been exploited for fabricating vertical-cavity semiconductor lasers [2], vertical-cavity semiconductor amplifiers [3] and semiconductor saturable absorber mirrors [4]. Tandem solar cells incorporating dilute nitride junctions hold promise for achieving conversion efficiencies higher than 45% [5]. More recently, dilute nitride heterostructures have secured the leading position in the race for developing frequency-doubled high brightness multi-watt laser sources emitting orange–red radiation [6, 7]. This development was made possible by the use of the semiconductor disk laser (SDL) concept [8], also known as the vertical-external-cavity surface-emitting laser (VECSEL) [9], and technological advances related to fabrication of high-quality dilute nitride gain mirrors with optical emission at 1220–1240 nm [10].

An optically pumped (OP) SDL exhibits many advantageous features, such as wavelength versatility enabled by the use of semiconductor gain materials, capability for multi-watt output power and the possibility to use low-cost multi-mode diode lasers for optical pumping. The laser has excellent output beam quality and allows modulating the output by directly modulating the pump laser. Efficient frequency conversion is also possible by placing a nonlinear crystal inside the laser resonator, where the optical intensity is highest [11]. The principal elements of an OP-SDL are schematically represented in figure 1. A typical gain mirror consists of a QW region and a DBR optimized for operation at the desired laser wavelength. The laser cavity is formed between the gain mirror and one or more external cavity mirrors often arranged in I-, V- or Z-shaped form. High-power laser operation and power scaling depend to a large extent on how efficiently the pump-induced heat can be removed from the gain region. A common way to remove the heat is to use a transparent heat spreader with high-thermal conductance between the semiconductor sample and a metallic heat sink [12, 13]. Common heat spreader materials include for example diamond, SiC and sapphire, diamond being the most frequently used because of superior thermal conduction [14].

The increased interest in developing OP-SDLs has been largely motivated by the potential they hold for generating high-power visible light via frequency conversion. In particular, the OP-SDL platform is poised to become one of the main choices for laser projection and laser display applications, which are in urgent need of compact and high-brightness light sources.
delivering red–green–blue laser beams \[15\]. The generation of green and blue laser radiation using OP-SDL with fundamental emission at 940–1060 nm is straightforward, as fabrication of the high-quality gain materials (InGaAs QWs) and DBRs is a mature semiconductor technology. On the other hand, the development of frequency-converted OP-SDLs emitting in the red region has been hindered by the availability of semiconductor gain materials with emission at 1200–1240 nm, and which can be monolithically grown on GaAs DBRs. The lattice-mismatch between InGaAs and GaAs makes it difficult to reach an emission wavelength beyond 1170 nm \[16\]. However, by alloying a small amount of N with InGaAs the spectral region that can be covered with QWs grown on GaAs can be extended to beyond 1300 nm \[17, 18\]. In addition, dilute nitride QWs provide benefits in terms of strong carrier confinement and the ability to operate at elevated temperatures. On the other hand, we should note that incorporation of N is usually associated with the introduction of structural defects within the structure, which act as non-radiative recombination traps and ultimately decrease the performance of dilute nitride heterostructures. One of the main factors that calls for careful optimization when fabricating InGaAsN heterostructures is the In/N ratio; a higher amount of N is beneficial as it reduces the compressive strain, but leads to degradation of the structural quality. At wavelengths close to 1.3 \(\mu\)m the power emitted by InGaAsN-based SDLs was limited to below 1 W, owing to a relatively high concentration of N and increased strain in the structure \[19\]. Dilute nitride SDLs operating in mode-locking regime at around 1.3 \(\mu\)m exhibited even lower output powers of about 60 mW \[20\]. On the other hand, SDLs with emission wavelengths close to 1220–1240 nm incorporate active regions with lower amount of N and can exhibit multi-watt output powers in both fundamental operation at 1240 nm \[10\] and frequency-doubled operation at 620 nm \[21\]. More recently, dilute nitride gain mirrors have been proposed as a development path for demonstrating SDLs with emission wavelength at \(\sim\)1180 nm \[22\]. This work was motivated by important applications in medicine \[23\] and astrophysics where high power 589.16 nm emission is required for the sodium laser guide star, commonly deployed in

Figure 1. Schematic of an OP-SDL with intra-cavity heat spreader.
Figure 2. Conduction band profile of the SDL structure showing the locations of QWs at the antinodes of the optical field. The design wavelength for the ‘cold’ device (\(\lambda\)) was \(\sim 1170\) nm, to account for the cavity expansion due to heating when the structure is pumped optically.

Telescopes with adaptive optic systems [24]. A frequency-doubled 1178 nm SDL emitting a high-quality beam at 589.16 nm, which matches the D\(_2\)-sodium absorption line, is a promising laser technology that is expected to meet the specifications of future generation laser guide stars.

In this paper, we report a significant advance in terms of output power and efficiency for dilute nitride based 1180 nm SDLs. Compared with the standard approach based on InGaAs/GaAs QWs, which has been used to achieve SDL operation at 1180 nm [16], our approach enables a significant reduction of the strain within a QW. This in turn offers more flexibility in designing and fabricating the gain regions and ultimately is expected to improve the long-term reliability in demanding high-power operation regime.

2. Fabrication of dilute nitride heterostructures

The dilute nitride gain mirror was grown on an n-type GaAs (100) substrate using solid source molecular beam epitaxy (SS-MBE) and a radio frequency (RF) plasma source for incorporating nitrogen into the crystal. The structure, shown in figure 2, consisted of a 27-pair GaAs/AlAs DBR and an active region with 10 InGaAsN QWs having a relatively low nitrogen content of about 0.6\%. The QWs, each having a thickness of 7 nm, were distributed in five identical pairs placed at the standing wave anti-nodes formed within the Fabry–Pérot (FP) cavity defined by the DBR and the semiconductor–air interface. The elements of the gain mirror are also revealed in figure 3, showing a micrograph obtained with a scanning electron microscope (SEM).

The QW groups were embedded within GaAs layers, which absorb the pump radiation and supply the carriers for QW emission. The GaAs layers surrounding the QW group located deeper in the structure are thicker than those surrounding the QW groups placed closer to the surface; this configuration reflects the pump depletion from the top of the structure to the bottom and should ensure a more uniform carrier distribution between the QW groups. The compressive lattice strain associated with In incorporation was partially compensated by 4 nm thick tensile-strained GaAsN layers grown on both sides of each QW, which also has a beneficial effect in terms of red shifting the emission wavelength [25]. A 0.75\(\lambda\) thick Al\(_{0.37}\)Ga\(_{0.63}\)As window layer was grown on top of the active region to confine the photo-generated carriers within the active region and to avoid non-radiative surface recombination. Finally, a 5 nm GaAs cap layer was grown to prevent oxidation of the window layer. The actual settings of the plasma source used during the QW growth were \(\sim 175\) W for the power and 0.18 sccm for the nitrogen
flow. These settings corresponded to a relatively low nitrogen concentration of about 0.6%. The growth temperature, measured by an optical pyrometer, was 450 °C for the QWs, 580 °C for the GaAs barriers and 590 °C for the DBR and the AlGaAs window layer. The structure was in situ post-growth annealed at 680 °C for 5 min. The reflectivity and the photoluminescence (PL) signal corresponding to the as-grown structure at room temperature are shown in figure 4. The structure exhibits a FP resonance at about 1165 nm, which is intentionally shorter than the intended operation wavelength to account for the wavelength shift due to heating during pumping [26].
As expected, post-growth rapid thermal annealing (RTA) revealed an increase of the PL signal and a blue shift of the peak-emission wavelength [27]. The maximum PL signal was reached after an annealing time of 480 and 240 s, corresponding to annealing temperatures of 700 and 750 °C, respectively. The variation of the PL intensity and wavelength for different annealing parameters is shown in figure 5. These measurements were performed on a sample without a DBR to avoid the FP effect on PL intensity. Although the wavelength blue shift is not very large, it can affect the operation of the SDL significantly; this is because the overall gain provided by the structure depends on the detuning between the FP resonant wavelength of the vertical cavity and the wavelength at which the QWs provide the maximum gain (i.e. maximum PL signal) [26]. The wavelength blue shift could explain why the SDL performance was the same for the gain chips having only in situ and those with post-growth RTA at 700 °C; we expect that the improvement of the PL intensity after RTA is counterbalanced by a higher detuning between the maximum PL and the resonant wavelength of the vertical cavity. The x-ray diffraction (XRD) patterns shown in figure 6 are almost identical for the as-grown and post-growth annealed samples. Based on these observations we have concluded that in situ annealing is effective in improving the crystal quality.

3. SDL demonstration and performance

For laser demonstration, gain mirror chips with a \(2.5 \times 2.5\) mm\(^2\) size were cut from the as-grown wafer and were capillary bonded with de-ionized water [13] to a \(3 \times 3 \times 0.3\) mm\(^3\) type IIIa synthetic single-crystal diamond heat spreader to ensure efficient heat removal from the gain region. The diamond was wedged at a 2° angle and antireflection coated to avoid FP cavity effects and minimize pump reflection on the surface. Birefringence of the diamond was specified to be less than \(1 \times 10^{-5}\).

The bonded chip was mechanically clamped to a Peltier cooled copper heat sink, which had a circular aperture to allow for travel of the pump and signal beams. A piece of indium foil was used between the diamond and the heat sink to improve the thermal contact. A small piece of Teflon was added between the semiconductor and the clamp to alleviate mechanical stress.
and to compensate for the wedge. Temperature was measured from the heat sink at a distance less than 1 cm away from the sample.

The laser cavity, shown in figure 7, had a V-shape configuration comprising the gain mirror, a high-reflective curved folding mirror and a planar output coupler. A fibre-coupled 808 nm diode laser was used for optical pumping of the gain. The pump beam was incident at 27° angle relative to the surface normal and was focused to a spot with a diameter of ~300 µm. The cavity was designed to match the diameters of the pump and the fundamental cavity mode size on the gain mirror. A birefringent filter (BF) was used for tuning the laser wavelength. In this particular experiment, the transmission of the output coupler was 2.5%. The laser was characterized at 5 °C and 15 °C temperatures.

When the BF was removed from the cavity the laser emitted about 7 W of output power in the TEM$_{00}$ mode, exhibiting a differential efficiency of ~28% at 15 °C. When the mount
was cooled to 5 °C the threshold decreased and the differential efficiency increased to ∼30%. However, in this case at pump powers greater than 20 W the cooling element could no longer maintain the set temperature and therefore the output power was limited to ∼5 W under fixed temperature. The output characteristics at 5 and 15 °C are shown in figure 8. The emission spectra corresponding to 5 W output power are shown in figure 9. Multiple peaks with about 0.156 nm spacing were observed in the spectra, which were otherwise relatively broad and flat. The peaks originate from the FP effect taking place in the 3 mm thick output coupler, despite the fact that an antireflective coating was present on the back surface. To provide a smooth spectral shape the output coupler should also be wedged.

Narrow spectral band operation was obtained without significant power penalty by introducing a BF in the cavity at the Brewster angle. With the filter tuned to 1178 nm we obtained over 4 W of output power at a fixed temperature of 5 °C (figure 10). With increased pump powers the temperature increased slightly but the output exceeded 5 W. With optimized
cavity alignment a maximum of 5.38 W output power was attained with 26.68 W of incident pump power. The spectrum could be actively tuned by rotating the BF. In the tuning experiments, lasing was observed in the range of 1160–1200 nm (figure 11). It is worth noting that the tuning band has relatively sharp edges and an output power higher than 2 W was obtained over a 34 nm band. The Brewster loss, i.e. the power reflected by the filter, was also recorded and is shown in figure 11. The maximum power of the reflected beam, corresponding to an output of ∼4.2 W, was ∼210 mW.

The beam quality factor $M^2$ was estimated at the wavelength of 1178 nm and 5 W output power using a system consisting of a pyroelectric camera and a corner mirror. The corner mirror was situated on a translation stage. The output beam was collimated with an $f = 1000$ mm lens and focused onto the camera via the corner mirror using an $f = 750$ mm lens. The beam

**Figure 10.** Light output characteristics at 1178 nm, BF inside cavity ($T = 5^\circ C$). Inset: optical spectrum at 5 W output power.

**Figure 11.** Tuning with BF: output power and Brewster loss given as a function of the operation wavelength at $T = 5^\circ C$. 
Figure 12. $M^2$ measurements at 1178 nm for a 5 W output power: beam diameter in vertical and horizontal directions, given as a function of the distance. Inset: output beam profile from the laser without the BF.

Figure 13. Light output characteristics near 589 nm.

diameter was recorded at different positions along the beam waist by adjusting the translation stage. The acquired beam diameters were fitted to Gaussian beam divergence to obtain the value for $M^2$ (figure 12). In order to provide more accurate results, the system was calibrated to knife edge measurement. The measured values were $M^2 = 1.58/1.12$ (horizontal/vertical).

We have also performed preliminary frequency doubling experiments that led to generation of 589.15 nm radiation corresponding to D$_2$-sodium absorption line. The laser cavity had a V-shaped configuration consisting of the gain chip and two curved mirrors providing high reflection at the fundamental frequency and high transmission at the second-harmonic wavelength. A nonlinear crystal (LBO) was placed at the beam waist located between the curved mirrors. The BF was placed between the gain chip and the first curved mirror. The frequency-doubled output characteristics are shown in figure 13. We obtained a total output...
power of more than 2.1 W corresponding to a beam with a narrow linewidth at about 589.15 nm. A photograph of the SDL emitting yellow light is shown in figure 14. We expect that by improving the heat dissipation and optimizing the cavity arrangement to increase the efficiency for nonlinear conversion, we could generate 5 W yellow radiation in fundamental transversal mode.

4. Conclusions

We have demonstrated high-quality InGaAsN-based QW heterostructures with optical emission near 1180 nm wavelength and applicability as gain mirrors in OP-SDLs. The gain mirrors were used to achieve laser operation at ~1180 nm with high-output power of ~7 W in the fundamental transverse mode. The lasers exhibited excellent tuning characteristics, delivering more than 5 W of output power in a narrow spectrum tunable over a 30 nm band. The differential efficiency of the laser was significantly increased compared to state-of-the-art results reported so far; we report a differential efficiency of ~30% compared to 20% reported in [10]. Compared with dilute nitride SDL operating at longer wavelength, i.e. 1.3 μm, the present results are improved remarkably both in terms of output power and efficiency. This is to a large extent due to the use of QWs with a low amount of N.

The results are particularly important for development of the compact high-power lasers with yellow emission required for laser guide star and spectroscopic applications. For these applications, the OP-SDL concept could deliver high-quality and high-power laser beams, at the same time offering a broad tuning range, a small footprint and potentially a lower cost than competing technologies. Based on our recent observations, we expect that in the near future dilute nitride heterostructures will become a reliable choice for the development of practical OP-SDLs with an emission wavelength at 1160–1260 nm.

New Journal of Physics 11 (2009) 125019 (http://www.njp.org/)
Acknowledgments

We acknowledge the passionate support of Ville-Markus Korpijärvi and Janne Puustinen for fabricating and characterizing the gain mirrors. We also express our gratitude to Dr Antti Tukiainen, Teemu Hakkarainen and Jari Nikkinen, for their support concerning material characterization and coating deposition. We thank Dr. Ryan Epstein from Areté Associates for his support with the nonlinear frequency conversion experiment. This work was financially supported by the Academy of Finland, Pirkanmaa TE-center and TEKES.

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