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To cite this article: T Jouhti et al 2003 New J. Phys. 5 84

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Dilute nitride vertical-cavity surface-emitting lasers

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New Journal of Physics 5 (2003) 84.1–84.6 (http://www.njp.org/)
Received 23 April 2003
Published 4 July 2003

Abstract. A novel quaternary compound semiconductor material, Ga$_{1-x}$In$_x$N$_y$As$_{1-y}$ ($0 < x, y < 1$), was successfully used in demonstrating optically pumped continuous-wave vertical-cavity surface-emitting lasers emitting at 1280 nm. The epitaxial heterostructures of each laser wafer were grown in a single nucleation process by conventional molecular beam epitaxy using a nitrogen radio-frequency plasma source. The lasers consist of GaAs/AlAs distributed Bragg reflector mirrors and 6 or 15 Ga$_{0.65}$In$_{0.35}$N$_{0.014}$As$_{0.986}$/GaAs quantum wells with special strain-mediating layers. The laser characterization was carried out by using a fibre pigtailed 980 nm pump laser diode, 980/1300 nm wavelength division multiplexer and an optical spectrum analyser. A high optical output power of 3.5 mW was coupled lenslessly into a standard single-mode fibre.

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1. Introduction

The development of high-performance, cost-effective GaAs-based monolithic vertical-cavity surface-emitting lasers (VCSELs) in the 1.3 µm spectral band for the next-generation fibre-optic metro and access networks is under intensive study worldwide [1]–[3]. Heretofore, InP technology has been used for all these applications but it has serious shortcomings—InP edge-emitting lasers exhibit relatively poor thermal properties and there is a lack of suitable distributed Bragg reflector (DBR) mirror materials required by the monolithic vertical device geometry. This situation is drastically changed by stacking superior GaAs/AlGa1−zAs (0 ≤ z ≤ 1) DBR layers on an inexpensive GaAs substrate and inserting an active region which consists of novel dilute nitride, Ga1−xInxNyAs1−y, quantum wells (QWs) [4]. Similar DBRs together with GaAs QWs are widely used in commercial 850 nm VCSELs which have rapidly conquered the short-range (<550 m) optical data-communication applications.

The GaInNAs/GaAs materials system is indeed a very promising candidate in opening a new era of semiconductor lasers because high-performance and low-cost long-wavelength (1.3–1.6 µm) VCSELs can potentially be realized [1]–[3]. However, the commercialization of these devices has not been as straightforward as initially expected. When adequate yield, lifetime and optical output power can be achieved these VCSELs can finally be brought to the fibre-optic telecommunications market arena.

Generally, VCSELs may be optically pumped [4, 5] or electrically driven [1]–[3]. Optical pumping is traditionally seen as a preliminary to electrical injection. However, this is emphatically not the case with the 1.3 µm range VCSELs as well as with vertical-external-cavity surface-emitting lasers (VECSELs), because they are proving to be of real commercial significance in their own right. The optically pumped device is undoped, which simplifies the layer growth and device processing and minimizes doping-mediated absorption. Second, the formation of heat is small, which improves high-temperature operation. Third, longer mode-matched cavities allowing for a large number of QWs to be inserted into the cavity, and less stringent requirements for DBR reflectivities, can be exploited to achieve high-power single-transverse-mode output, good wavelength control or fast dynamics [6]. These advantages, however, come at the cost of an extra pump laser needed for carrier generation. Here, we report state-of-the-art optically pumped 1280 nm GaAs-based VCSELs consisting of specially designed GaInNAs/GaAs QWs and GaAs/AlAs DBRs.

2. Epitaxial growth and structures

High-quality GaInNAs/GaAs heterostructures and optoelectronic devices can be grown by using molecular beam epitaxy (MBE) [1]–[3] and metalorganic chemical vapour deposition (MOCVD) crystal growth methods [7]. Our GaInNAs VCSEL structures were grown on n-type GaAs (001) substrates by an MBE system equipped with a radio-frequency (RF) nitrogen plasma source. Using an RF source provides a highly efficient, precisely controllable and high-purity source of active atomic nitrogen. Furthermore, the nucleation of layers was monitored by reflected high-energy electron diffraction, the intensity oscillations of which were observed to determine the growth rate to an atomic layer-by-layer accuracy.

Three GaInNAs/GaAs VCSELs (hereafter referred to as VCSEL1, VCSEL2 and VCSEL3) were designed and grown. Their epitaxial structures are shown in figure 1. A low number of undoped GaAs/AlAs DBRs were used in VCSEL1 in order to maximize the output power.
The theoretical reflectivities of the top and bottom DBRs are 99.3 and 99.4%, respectively. In practice, the reflectivities are lower due to several absorption and scattering mechanisms. The optical thickness of a cosine-type GaAs-based microcavity used in VCSEL1 was $3\lambda$. A stack of three 7.2 nm highly strained Ga$_{0.65}$In$_{0.35}$As$_{0.986}$ QWs, separated by 13 nm thick GaAs spacers, was placed at five antinode positions of the standing optical wave within the cavity. Each QW was sandwiched between thin (2 nm) Ga$_{0.73}$In$_{0.27}$As$_{0.013}$As$_{0.987}$ strain-mediating layers (SMLs) which, in turn, were surrounded by GaAs to complete the cavity. Because SMLs had less indium than QWs, they had a lower lattice strain, enabling a desired steplike strain profile in the interfacial region. A similar QW structure has been proved to improve photoluminescence from GaInNAs/GaAs QWs [8, 9]. We believe that the present study represents the first attempt to make use of such an active region structure in actual devices.

Reflectivities of the DBRs of VCSEL2 and VCSEL3 are higher due to the increased number of DBR mirrors. Here, 22 pairs were placed on the top and 28 pairs on the bottom, which corresponds to reflectivities of 99.90 and 99.96%, respectively. The aim was to decrease the threshold pump power by increasing DBRs. The active regions of VCSEL2 and VCSEL3 are similar to VCSEL1 except they have fewer QWs. Only two stacks of three QWs were placed on two antinode positions of the 1.5 $\lambda$ thick cavity.

3. Results

A piece (1 cm$^2$) of each as-grown (unprocessed) VCSEL epiwafer was photopumped at room temperature. A 980 nm continuous wave (cw) fibre pigtailed single-mode diode laser was used for VCSEL excitation through a butt-coupled 980/1300 nm fibre wavelength division multiplexer (WDM). The single-mode fibre (core diameter 6.9 $\mu$m) end was brought very close
to the surface of the sample. Therefore, the fibre end defines the volume of the active region and device aperture. The emission of each VCSEL was coupled lenslessly into the fibre after a careful positioning. The light power as a function of pump power and optical spectra were analysed at the output port of the WDM.

Figures 2(a)–(c) show the output power of VCSEL1, VCSEL2 and VCSEL3, respectively. Due to the fact that VCSEL1 has the largest number of QWs and the lowest number of DBRs the highest output power of 3.5 mW was obtained. The threshold pump power for VCSEL1 was the highest as well, ∼160 mW. The power level increased linearly when the pump power was increased. No output power saturation was observed; in fact, the light power was limited by the capacity of the pump laser used (190 mW). We think this is the highest fibre-coupled single-mode power reported on monolithic GaInNAs/GaAs VCSELS in the 1.3 µm wavelength range. The total power launched into free space was presumably much bigger than that coupled into the fibre. Due to an unknown coupling efficiency and an uncertainty in size of the effective area actually pumped by the diode laser we could not determine the total power, or the threshold power density in a dependable way.

The highest measured output power from the 6QW VCSEL2 reached ∼0.23 mW. The threshold pump power (50 mW) was considerably lower than in VCSEL1 due to higher reflectivity. VCSEL3 had the double-pass pumping geometry which was realized by a growing a gold mirror with metallization equipment. VCSEL3 has almost double output power compared to VCSEL2. Another advantage of the double-pass pumping is decreased threshold which was ∼30 mW here.
Optical spectra for VCSEL1 are shown in figure 3(a). Emission is single-mode throughout the entire range of pump power. The side-mode suppression ratio (SMSR) is greater than 50 dB when pumped with the maximum power. The emission wavelength is between 1281 and 1282 nm, exhibiting a small systematic red-shift, about 0.5 nm, due to the heating effect. The linewidth is narrow: only 0.14 meV (0.2 nm) at half maximum.

Very similar spectral characteristics were obtained for VCSEL2 and VCSEL3. The optical spectrum of VCSEL2 under 190 mW pump power is shown in figure 3(b). The emission wavelength is 1281–1282. The spectrum is highly single-mode (SMSR ~50 dB). Comparing to VCSEL2 no major differences in the spectral properties were observed for VCSEL3.

4. Conclusions

Growing long-wavelength VCSELs based on the GaAs system simplifies the manufacturing process and eliminates the wafer bonding technique which is not preferred for mass production. In particular, optically pumped devices are simpler to make but they require a pump source. Here, we have presented a group of monolithic optically pumped single-mode VCSELs. Their active regions have 6 or 15 Ga0.65In0.35N0.014As0.986 QWs which each have Ga0.71In0.27N0.013As0.987 SMLs placed on both sides. The VCSELs were prepared by the MBE method and their lasing features were characterized at room temperature. A high fibre-coupled light power of 3.5 mW with the SMSR greater than 50 dB was observed. Efficient fibre butt-coupling simplifies the pumping and signal collection scheme. This advantage, combined with the on-wafer testing capability, are key factors for a sharp cost reduction of modules, since testing, mounting and assembly time represent more than half the cost of an optical source. The performance characteristics of our VCSELs, though preliminary, are very promising, indicating that the GaAs-based 1.3 µm VCSELs are potential light sources for low-cost, next-generation transmitters for fibre-optic metro and access networks. The modulation bandwidth of VCSELs is currently under study, and it is expected to be determined by the wide bandwidth of commercial 980 nm pump lasers.
Acknowledgments

This work was supported, in part, by the Academy of Finland (EMMA no 67395) and the Technology Development Centre (COST 268b no 40663/01). LAG’s work was also supported by FCT/PRAXIS XXI.

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