Recent Developments on III-V Heterostructure Laser Diodes

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Recent advances in materials technology and device design now allow the fabrication of laser diodes from the mid-IR to the UV spectral regions. This paper presents some of the latest progresses on the technology of the III-V semiconductor materials and reviews the present status on advanced device concepts, such as vertical cavity surface emitting lasers (VCSELs) and quantum cascade lasers.

Significant developments in wide-gap III-V nitride semiconductors have recently led to the improvement of the lifetime of short-wavelength InGaN multi-quantum-well lasers. An essential step towards higher reliability has been the ELOG technique (epitaxially laterally overgrown GaN), by which the lateral growth of GaN over a masked area produces areas with a reduced number of threading dislocations, above which high-performance heterostructures can be grown [1]. With this method an estimated lifetime of more than 10000 h under cw operation at room temperature has been demonstrated. A further progress is expected by replacing the hitherto used sapphire substrates by epitaxially grown GaN substrates, which are made with the ELOG technique, and the subsequent removal of the sapphire substrate [2]. This also will markedly improve the thermal conductivity, and cleaved mirror facets may easily be achieved. The schematic structure of the corresponding InGaN laser diode for a 400 nm wavelength is shown in Fig. 1.

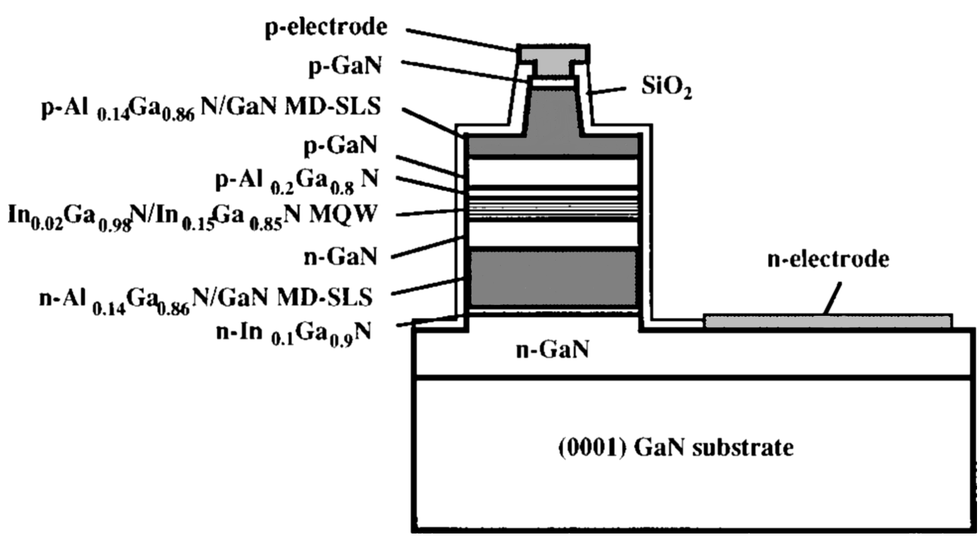

Fig. 1: InGaN laser diode on a GaN substrate (@ *Appl. Phys. Lett.* **72** (1998) 2014).

While the laser diodes made so far with this technique showed a relatively large threshold current density of the order 7 kA/cm^2, the lifetime at cw room-temperature operation is around 800 h being four times longer than for laser diodes made on sapphire substrates with equal threshold current density. The reduction of the threshold current density to below 4 kA/cm^2 is therefore expected to improve the lifetime to above 10000 h [2].

Presently, much effort is being paid to realize vertical cavity surface emitting lasers (VCSEL) for the wavelength range of 1.3 to 1.55 µm. While the Al(Ga)As/GaAs VCSEL shows excellent performance for wavelengths around 0.8 – 1 µm [3], [4], it reveals difficult to fabricate electrically pumped VCSELs for longer wavelengths that operate cw at room temperature. This striking difference with respect to the short-wavelength devices is mainly because the Al(Ga)As/GaAs material system exhibits several features that enable the laser oscillation with gain medium lengths of the order of only 100 nm, which are required in VCSELs. First of all, AlAs and GaAs show a large refractive index contrast around 0.5 for wavelengths around 0.9 µm, so that epitactic Bragg mirrors with a high reflectivity (>99 %) may easily be prepared with a moderate numbers of layer pairs (> 15) yielding total thicknesses of the order 2 – 3 µm with low refraction losses. Secondly, the binary lattice-matched AlAs/GaAs Bragg mirrors exhibit low specific thermal resistivity, which together with the relatively low pair number yields low thermal resistance, which is essential for the cw operation at room temperature. Thirdly, the application of isolating and waveguiding aluminum oxide apertures made by steam oxidation of AlAs layers [5] leads to strong transverse waveguiding in narrow devices with sub-mA threshold currents. On the other hand, InP-based heterostructures for 1.3 to 1.55 µm wavelength consist of quaternary InGaAsP, Al(Ga)AsSb, or AlGaInAs compounds that show an order of magnitude larger specific thermal resistivities [6] and – with the exception of the antimonides [7] – a significantly smaller refractive index contrast (0.25 – 0.3) than AlAs/GaAs [8]. Consequently, higher pair numbers (>30) are required for the Bragg mirrors yielding higher diffraction losses and markedly higher thermal resistances. Finally, the waveguiding oxide apertures have not yet been applied, because no suited compounds exist in the GaInAsP and AlGaInAs material systems that are lattice-matched to InP and can be steam oxidized to form the aperture. However, by the use of AlAsSb, which can be lattice-matched to InP, oxide apertures may be feasible also in long wavelength VCSELs [9].

Besides the investigation of InP-based VCSEL structures, therefore, also the application of GaAs-based VCSEL structures for 1.3 to 1.55 µm is being considered. In the latter case, approaches are investigated to maintain the superior AlAs/GaAs Bragg mirrors and the oxide aperture but to replace the active region with a material of smaller bandgap energy. To this end, InAs and InGaAs quantum dot structures have been developed [10], [11], and a 1.15 µm quantum dot VCSEL on GaAs has been demonstrated [12]. A second approach is the application of the new compound GaInAsN, which principally can be grown lattice-matched to GaAs and should cover the bandgap energy range from 0 to 1.42 eV [13]. The band gap energy versus lattice constant diagram of this compound is displayed in Fig. 2 showing a strong bowing and the possibility to fabricate GaInAsN lattice-matched to GaAs. Also with this concept a VCSEL was demonstrated at 1.18 µm wavelength [14], however, with a rather large threshold current density. Optimum performance at 1.55 µm wavelength has been achieved so far with the wafer-fusing technique [15] by which an InGaAsP/InP active region is being sandwiched between wafer-fused GaAs-AlGaAs Bragg reflectors as shown in Fig. 3. Cw threshold currents are as low as 0.8 mA at room temperature. The maximum cw lasing temperature achieved today with wafer-fused VCSELs at 1.55 µm wavelength is 64 °C, and pulsed operation has been obtained up to 100 °C [16].

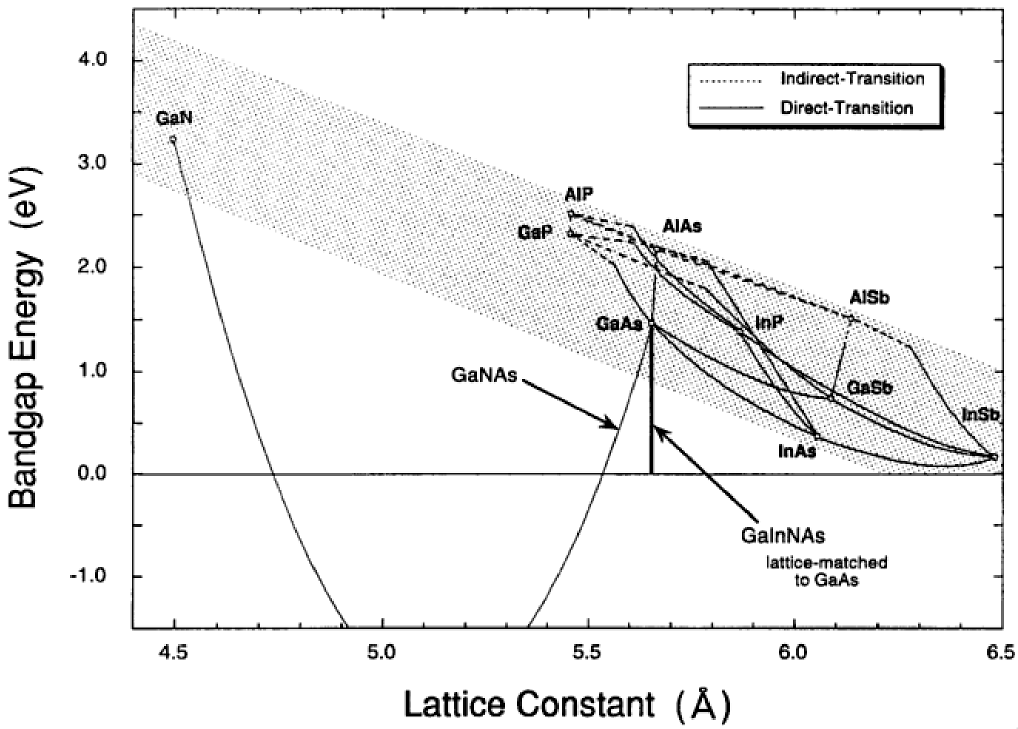

Fig. 2: Band gap energy vs. lattice constant of various III-V compound semiconductors (@ *IEEE J. Sel. Top. Quantum Electron.* **3** (1997) 719).

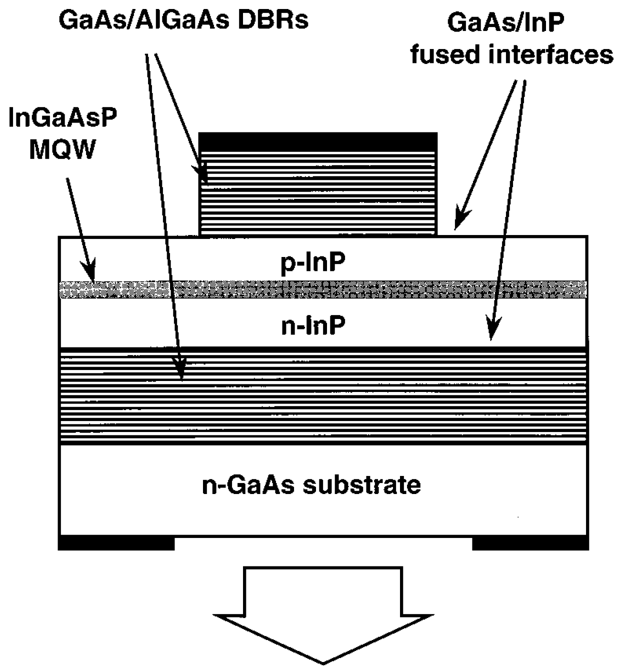

Fig. 3: Wafer-fused InGaAsP VCSEL for 1.55µm wavelength (@*Appl. Phys. Lett.* **72** (1998) 1814).

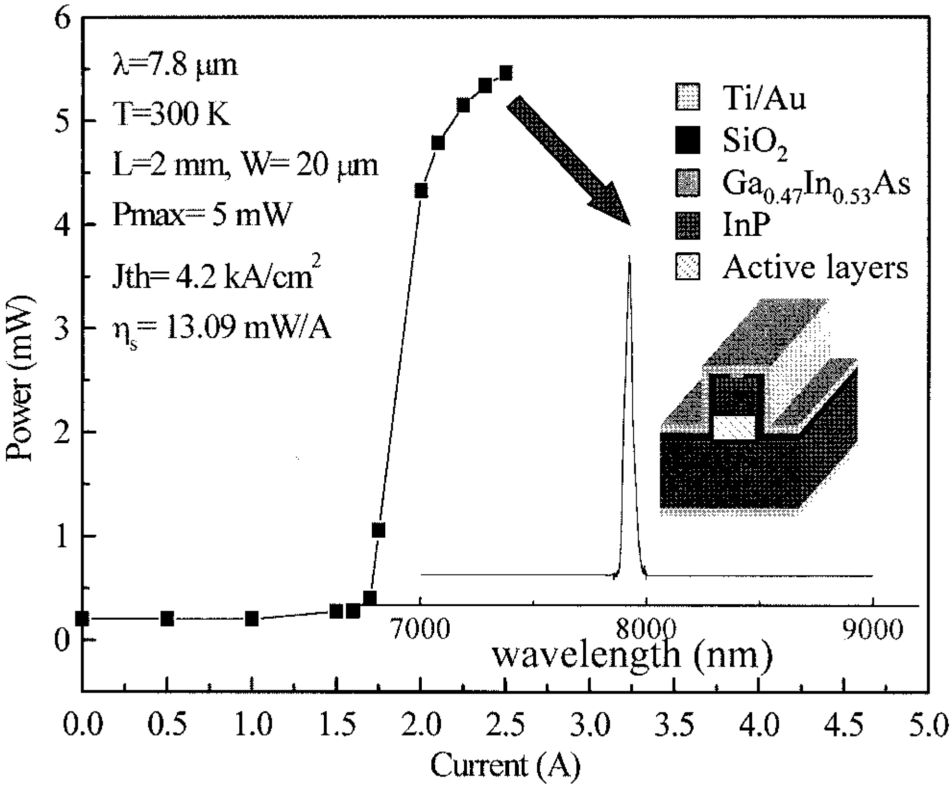

Fig. 4: Room-temperature pulsed operation of a 7.8μm QC laser (@*Appl. Phys. Lett.* **74** (1999) 173).

As spectroscopic and sensing applications become more attractive, particularly with respect to compactness and cost, if semiconductor light sources for wavelengths larger than 2 μm are available, much effort is being paid for developing suited laser diodes. While the well-established InGaAsP/InP material system is still capable for wavelengths just above 2 μm, the wavelength range from 2 to 4 μm will mainly be covered by antimony-based devices. For wavelengths larger than 4 μm novel laser diode concepts, such as the quantum cascade (QC) laser [17], become interesting. The QC laser, which is a unipolar device based on intersubband transitions in the conduction band of multiple quantum well structures, therefore, has intensively been studied worldwide and gained considerable progress. Today InP-based QC lasers are available with wavelengths from about 3.4 μm [18] to 17 μm [19]. At a wavelength of 7.6 μm QC lasers can be operated up to 160 K in cw and 325 K in pulsed mode [20], and first sensing applications have been reported [21]. A recent result on a 7.8 μm QC laser [22] operated in pulsed mode at room temperature is shown in Fig. 4. Also distributed feedback QC lasers have been presented exhibiting single longitudinal mode operation [23], and first devices on GaAs substrates were reported [24], [25]. The performance of the QC laser is strongly affected by the LO phonon relaxation between the intersubband levels, which mainly determines the threshold current and temperature dependence of QC lasers.

A different type of QC lasers, the interband cascade laser (ICL), has also been reported as a promising optical source for wavelengths beyond 2.5 μm, which is based on interband transitions in type II superlattices [26] that particularly occur in antimony-based compounds. A representative conduction and valence band structure of an ICL is shown in Fig. 5. Laser operation at 4 μm was reported up to temperatures of 285 K [27]. Due to the large band offsets in these compounds a considerable degree of freedom principally exists to adjust the wavelength, and the shortest wavelength achieved so far with these lasers is 2.9 µm. Theoretically, the wavelength range between 2.5 and 7 µm should be covered with this approach [27]. Differing from the QC laser, the ICL devices do not suffer from phonon relaxation, however, Auger relaxation is the dominant nonradiative relaxation path. Considering the early stage of development, essential progress can be expected with these novel approaches for long-wavelength semiconductor lasers. In particular, a further increase of the maximum temperature for cw operation at wavelengths beyond 2 µm will greatly enhance the applicability of laser diodes in the future and will lead to new applications in sensing and spectroscopy.

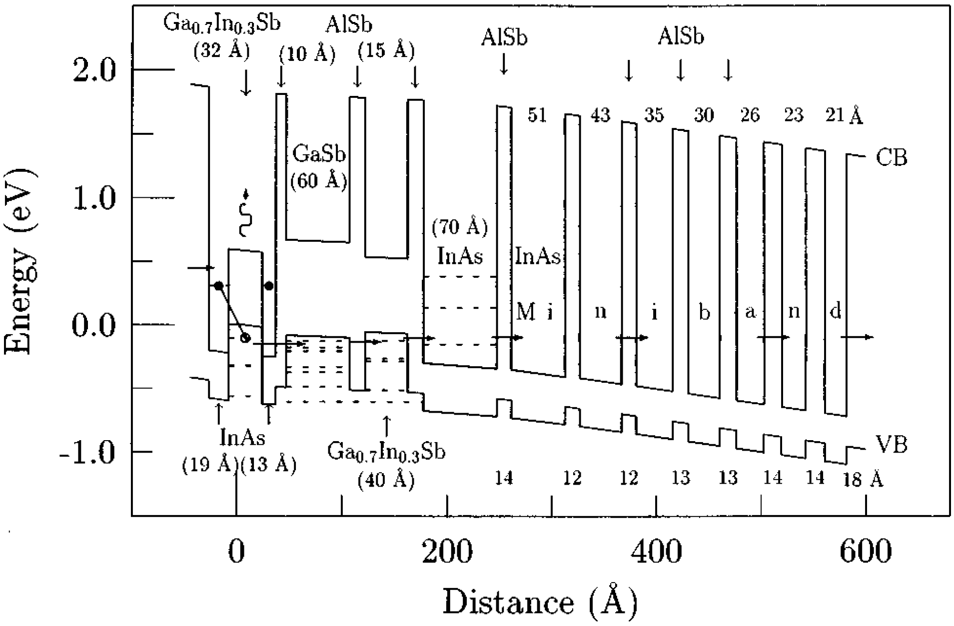

Fig. 5: Interband cascade laser conduction and valence band structure (@ *Appl. Phys. Lett.* **72** (1998) 2370).

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