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Review

A review of energy bandgap engineering in III–V semiconductor alloys for mid-infrared laser applications

Zongyou Yin *, Xiaohong Tang *

Photonics Research Center, Microelectronics Division, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

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Abstract

Semiconductor lasers emitting in mid-infrared (IR) range, 2–5 μm, have many important applications in semiconductor industries, military, environmental protection, telecommunications, molecular spectroscopy, biomedical surgery and researches. Different designs of the reactive regions in mid-IR laser structures have been investigated for achieving high performance devices. In this article, semiconductor mid-IR lasers with double heterostructure, quantum well, quantum cascade, quantum wire, quantum dash and quantum dot active regions have been reviewed. The performance of the lasers with these different active regions and the development of the newly emerging III–V–N materials for mid-IR applications have been discussed in details.

Keyword: Mid-infrared

Contents

* Corresponding authors.
E-mail addresses: ezyyin@pmail.ntu.edu.sg (Z. Yin), exhtang@ntu.edu.sg (X. Tang).

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1. Introduction

Powerful and easy-to-use lasers operating in the mid-infrared (IR) range, 2–5 μm, are very important for a variety of military, biomedical, environmental and industrial applications including range-finding, laser surgery and remote trace-gas sensing. Researchers began to develop III–V semiconductors based lasers working in mid-IR 2–5 μm region over two decades ago [1]. The first successful mid-IR laser was with double hetero-junction (DH) structure active region. But the poor performance, such as high threshold current, low output power and low maximum operating temperature, etc., of such lasers restricted their applications. Using quantum well (QW) in the active region of the laser enhanced the device's performance [2–4]. However, semiconductor lasers based on inter-band transition of QW active region structure are difficult to achieve long wavelength lasing, 3.5 μm $\leqslant \lambda \leqslant$ 5.0 μm. So, mid-IR emission quantum cascade (QC) structures were proposed [5,6] for developing long wavelength mid-IR lasers. Now, quantum wire (QWR) [7], quantum dash (QDH) [8] and quantum dot (QD) [9] have attracted much attention for developing high performance mid-IR lasers. III–V–N materials [10,11] are becoming very attractive for mid-IR laser applications because they can be used for developing mid-IR lasers' active region on GaAs and InP substrates.

This paper gives a detail review of different approaches in III–V semiconductor compound active regions for mid-IR laser structures from early 1960s to present. The performance of the mid-IR lasers with different designs of active region has been analyzed, compared and discussed. In this review, the progress in the active region structures for achieving high performance mid-IR lasers and the recent development of III–V–N based semiconductors for mid-IR applications have been provided.

2. Mid-IR DH lasers

The first successful mid-IR laser was with InGaAsSb DH active structure reported by Caneau et al. [1]. The schematic diagram of the device structure is shown in Fig. 1. The device structure was grown by liquid phase epitaxy (LPE) technique and emitted at 2.2 μm. GaSb based material system has attracted most researchers' interest for

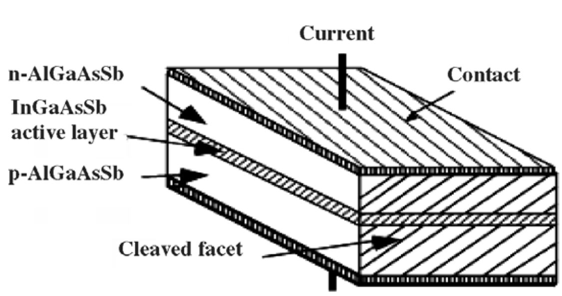

Fig. 1. Schematic diagram of DH laser diode.

developing mid-IR DH devices. This is because InGaAsSb quaternary alloy can be made lattice-matched to GaSb substrate by controlling its composition and at the same time has a room-temperature (RT) direct band gap continuously adjustable from 0.29 eV to 0.73 eV which covers wavelength range between 1.7 μm and 4.3 μm. But because of the very large miscibility gap, the solid composition of $In_xGa_{1-x}As_ySb_{1-y}$ alloy with lattice-matched to GaSb is limited to $x \leqslant 0.22$ [12] or $x \geqslant 0.84$ [13]. The longest RT emission wavelength achievable form this quaternary alloy before encountering the immiscible is only about 2.3 μm. To achieve emission wavelength beyond 2.3 μm, InAs substrate based material system has been investigated. Baranov et al. used the InAsSb(P)/InAsSbP/InAs material system in mid-IR lasers to extend the emission wavelength to 3.9 μm measured at 77 K [14]. But all these mid-IR lasers performed with low differential quantum efficiency and low maximum operating temperature.

The reasons for the poor performance of these mid-IR lasers with DH active region structure are mainly because: First, for LPE growth technology, it is difficult to grow thermally meta-stable materials, such as Al or In contained alloys. LPE is also difficult to grow multiple layer structures with sharp interfaces and control the layer thickness precisely [15,16]. More sophisticated epitaxy growth technologies, such as metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE), have now been widely used for growing laser structures. Using MOCVD and MBE, meta-stable alloys, such as AlGaSb and AlGaAsSb, with good optical quality can be easily grown [17]. InGaAsSb quaternary alloy with compositions in the miscibility gap have also been successfully prepared [18,19]. In 1991, Choi et al. reported the mid-IR laser structure with closely lattice matched GaInAsSb/AlGaAsSb/GaSb DH active region grown by MBE. The laser emitted at 2.2 μm and operated at RT with cw operation. The threshold current density of the laser achieved $J_{th} = 940\ A/cm^2$ [20]. The material quality and hence performance of the lasers have been improved by using advanced MOCVD or MBE epitaxy technologies. Second, DH active region of the mid-IR laser structures limits the device's performance. Using QWs as the active region in mid-IR laser structure improves the laser performance. Compared with DH lasers, QW lasers have lower threshold current density; the temperature performance [21], differential gain [22] and modulation [23] of the mid-IR lasers can also be improved. Since Tsang at the Bell Telephone Laboratory firstly demonstrated the QW lasers with very low threshold current density, $\sim 160\ A/cm^2$ [24], using QW structures as the active region to improve the mid-IR laser's performance has caught more and more researchers' interests. Following sections review the QW mid-IR lasers.

3. Mid-IR QW lasers

In QW lasers, QW structure active region is embedded in two spacer layers (or waveguide layers) in QW laser