Interband Mid-IR Semiconductor Lasers

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Abstract: Significant advances in the room-temperature (RT) continuous-wave (CW) output power of both type-I quantum-well (QW) active-layer lasers and interband cascade lasers have been reported within the 3–4-μm wavelength region in 2009. Recent developments on the growth of highly strained QWs and low-defect-density lattice-mismatched materials also demonstrate potential for realizing high-performance mid-infrared (IR) lasers on conventional substrates such as Si, GaAs, and InP.

Index Terms: Semiconductor lasers, mid-infrared lasers.

Semiconductor lasers employing interband transitions of a quantum-well (QW) active region have made significant strides in terms of output power, wavelength extension, and in the development of lattice-mismatched materials and device structures in 2009. High-performance room-temperature (RT) continuous-wave (CW) operation from devices based on QW interband transitions have now been realized in the important 3–4-μm wavelength region. Interband devices generally exhibit significantly lower operating voltages and lower threshold current densities compared with inter-subband quantum cascade lasers. However, challenges remain to reduce the strong temperature sensitivity of the threshold current and efficiency in such devices, as well as further increasing the CW output powers.

Of all semiconductor lasers, interband devices employing type-I InGaAsSb QWs on a GaSb substrate have demonstrated the highest performance in the 2–3-μm emission wavelength range. High-power (1-cm) arrays have been demonstrated at 2.2 μm with 15-W CW output powers and 23% wallplug efficiency [1]. Ultralow threshold current densities, J_{th}, have also been reported; J_{th} as low as 74 A/cm^2 for a 5-mm cavity length at 2.65 μm [2]. By contrast, extending RT CW operation to wavelengths of 3 μm and beyond has been more difficult, as a result of poor active region carrier confinement (in particular, hole confinement) in the highly (compressively) strained InGaAsSb QW active region. The use of a quinternary AlInGaAsSb separate confinement heterostructure (SCH) region was introduced by Grau *et al.* in 2005, resulting in the first report of type-I QW lasers operating with wavelengths as long as 3.26 μm at 50 °C under pulsed operation [3]. The quinternary SCH results in increased valence band offset leading to improved hole confinement to the QW active region as well as more homogeneous electron injection among the QWs [3]–[9]. In 2008, employing the quinternary SCH approach led to the first report by Hosoda *et al.* of appreciable power levels ($>$ 100 mW) under RT CW operation at 3 μm [4]. In 2009, optimization of the optical waveguide width and composition, as well as a reduction of free-carrier losses, in structures with an AlInGaAsSb SCH region led to significant improvement in the CW output powers; 600 mW at 2.7 μm [5], 310 mW at 3 μm [6], 190 mw at 3.1 μm, 160 mW at 3.2 μm, and 50 mW at 3.32 μm [7].

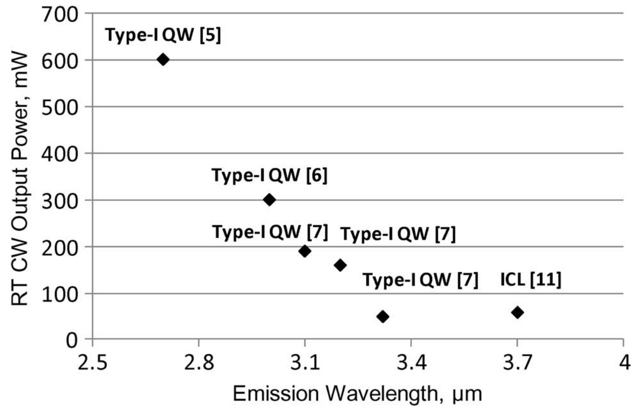

Fig. 1. Maximum RT CW output powers reported in 2009 for interband lasers in the 2.7–4.0-μm range.

A larger range of emission wavelengths in the 3–4-μm spectral region is accessible using a type-II QW, W configuration, interband cascade active region. The first CW operation above RT at 3.75 μm from such devices was reported in 2008 using a 5-stage active region Interband Cascade Laser (ICL) design [10]. Further optimized devices with low internal losses ($\sim$6 cm^{-1}) were reported in 2009, leading to a 50% increase in efficiency at 300 K compared with previous devices, enabling input power densities below 1 KW/cm^2 [11]. Record CW output power (59 mW) at 3.7 μm was reported from such devices with a wallplug efficiency as high as 3.4% [11]. The increased CW output powers (see Fig. 1) now open the door for the practical implementation of both the type-I QW and ICL devices to a variety of applications including medical diagnostics and therapy, gas sensing, and material processing. Further increases in the CW output powers can be expected if thermal management can be improved. For example, a novel approach of using highly doped InAs plasmon waveguides for ICL structures was reported by Tian *et al.* in 2009 and significant reductions in thermal resistance over conventional InAs/AlSb superlattice cladding layers were reported [12].

While highest performance interband lasers in the 2–4-μm wavelength region currently employ GaSb substrates, there is strong motivation to move away from this less mature material system toward a more conventional GaAs or InP platform. Advantages of such a strategy include; significantly lower cost (also larger diameter substrates are available), access to a more mature processing technology, better thermal conductivity and straightforward regrowth of buried-heterostructure-type devices for improved thermal management. Extending the emission wavelengths into the mid-infrared (IR) on an InP substrate by employing highly strained InGaAs(Sb) type-I multiple QWs (MQWs) [13]–[17] encounter difficulties for wavelengths $> \sim 2$ μm. Through the use of the InAs/InGaAs type-I MQW active region grown at very low temperatures to inhibit strain relaxation, the emission wavelength has was extended to 2.33 μm in 2008 [18]–[20]. In 2009, RT PL at 2.52 μm was reported from MOCVD grown highly strained InAs QWs on InP substrates employing tertiary-butylarsine (TBA), an arsenic source which efficiently decomposes at low growth temperatures [21]. Furthermore, recently reported design studies indicate employing a highly strained In(Ga)As/GaAsSb type-II QW holds potential for extending emission wavelengths near 3 μm [22]. The addition of nitrogen into InAs was reported by de la Mare *et al.*, allowing for RT PL emission near 4 μm from InAsN grown by molecular-beam epitaxy (MBE) on GaAs [23]. An alternate approach to employing a highly strained active region is to utilize a *virtual* substrate with a larger lattice constant and low threading dislocation density, allowing for the growth of relaxed lattice-mismatched materials with low dislocation densities. Compositionally graded metamorphic buffer layers (MBLs) or very thick relaxed single composition buffer layers can produce such a virtual substrate. In 2009, Nash *et al.* reported that the use of a MBE grown high-Al-content $Al_zIn_{1-z}Sb$ interface layer and 8-μm-thick $Al_xIn_{1-x}Sb$ cladding layer was effective in defect reduction, allowing 3.3-μm-emitting GaInSb QW lasers on GaAs substrates which operate up to 219 K under pulsed operation [24]. However, there are few reports of employing MBL structures on InP substrates for the realization of mid-IR lasers [25]. In 2009, Kirch *et al.* reported MOCVD-grown QW lasers emitting in the mid-IR spectral region employing $InAs_yP_{1-y}$ MBL structures on InP substrates [24]. Pulsed laser operation was reported near 2.45 μm from InAs QW active region devices with threshold current densities as low as 290 A/cm^2 [26]. Optimized device designs employing InPSb cladding layers and an InAsP SCH increase the active region carrier confinement, potentially allowing for RT operation in the 3-μm wavelength region.

In 2009, significant progress on the use of MBE grown interfacial misfit (IMF) arrays has also been reported to reduce threading dislocations in lattice-mismatched devices grown on both GaAs [27] and Si [28], [29] substrates. Unlike the relatively thick MBL, the dislocations in the IMF self-arrange in a periodic array configuration and the strain is relieved primarily in a very thin interface layer. In 2009, Tatebayashi *et al.*, reported GaSb-based lasers grown on Si substrates employing the IMF growth which demonstrate $J_{th} \sim 2$ KA/cm^2 (77 K) from lasers emitting at 1.62 μm under pulsed operation [28]. Pulsed laser operation near 2.2 μm was also reported by Rodriguez *et al.* in 2009 employing the IMF growth on Si substrates, with threshold current densities in the 4–8-KA/cm^2 range [29]. Employing the IMF growth on GaAs substrates, CW operation at 2.2 μm up to 50 °C was also reported by Rodriguez *et al.* with threshold current densities significantly lower ($J_{th} \sim 1.5$ KA/cm^2 at 20 °C) than the Si substrate based devices [27]. While the threshold current densities of lattice-mismatched devices are still significantly higher than that of state-of-the-art devices grown on a GaSb substrate, significant progress has been made in 2009 to establish the potential for this technology, provided further reduction in defect densities can be achieved through improved material growth.

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