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Midinfrared GaInSb/AlGaInSb quantum well laser diodes grown on GaAs

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The realization of midinfrared GaInSb/AlGaInSb type I quantum well diode lasers grown on GaAs is reported. Lasing was observed up to 95 K, at an emission wavelength of ~3.5 μm, threshold current density of 115 A/cm^2, and with a characteristic temperature T_0~51 K. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2793821]

Midinfrared semiconductor lasers that can operate at or near room temperature would have a wide range of potential applications in health care, environmental monitoring, manufacturing, security, and defense. For example, the favorable atmospheric transmission characteristics at these wavelengths, including low atmospheric scattering and absorption[1] relative to shorter wavelengths, would make them attractive for secure free-space communications in a range of security and military applications, in particular, for communication via low orbit satellites or unmanned aerial vehicles. However, for most of the important 3–4 μm spectral band, there are currently no practical high-temperature semiconductor lasers. Although much progress has been made in the development of "short wavelength" quantum cascade lasers (QCLs), with room temperature pulsed laser emission at a wavelength of 4.1 μm in InGaAs/AlAsSb/InP strain compensated devices,[2] 240 K pulsed laser emission at λ~3.2 μm from InAs/AlSb devices,[3] and low temperature pulsed laser operation at λ~3.1 μm for both InP based strain compensated InGaAs/InAlAs/AlAs (Ref. 4) and lattice matched InGaAs/AlAsSb,[5] only one QCL operating continuous wave (cw) at room temperature and at wavelengths below 4.0 μm has been reported.[6] The longest wavelength for room temperature cw operation for a type I interband diode is ~3.1 μm,[7] whereas maximum cw operating temperatures of 264,[8] 257,[9] and finally 269 K,[10] at emission wavelengths of 3.3, 3.7, and 4.05 μm, respectively, have been achieved recently by interband cascade lasers (ICLs), which have also achieved cw power outputs above 1 W at 78 K.[11]

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The aluminum-indium-gallium-antimonide ($Al_xGa_yIn_{1-x-y}Sb$) material system offers great promise for efficient diode laser operation across the 3–5 μm wavelength range. It offers an excellent compromise between the requirements for good electronic and optical confinement and those for low series resistance, and the use of an active region comprising compressively strained type I quantum wells is predicted to lead to increased gain, which leads to lower threshold current densities and hence reduced nonradiative Auger recombination.[12,13] Although there has been a previous report of optically pumped GaInSb/AlGaInSb multiple quantum well lasers grown onto GaSb substrates,[14] in this paper, we report the growth of GaInSb/AlGaInSb quantum well (QW) diode lasers onto GaAs substrates. Growth onto these substrates not only offers potential benefits in terms of cost and availability but also opens the possibility of the integration of midinfrared diode lasers with GaAs based optoelectronic components, such as electro-optic modulators, for beam steering and beam shaping. In the future, similar growth techniques may enable the growth of these layers onto Si substrates (which have the additional advantage of relatively high thermal conductivity) as, for example, in the recent demonstration of superluminescent emission at room temperature GaSb quantum-well-based light emitting diodes.[15]

GaInSb/AlGaInSb diode lasers were grown by molecular beam epitaxy at QinetiQ Malvern onto on-axis semi-insulating (001) GaAs substrates. The structure of the diodes and associated energy band diagram under zero bias are shown schematically in Fig. 1. The structure consists of a high Al content $Al_zIn_{1-z}Sb$ interfacial layer grown directly onto the GaAs, $Al_{0.25}In_{0.75}Sb$ cladding regions, $Al_{0.12}Ga_{0.12}In_{0.76}Sb$ barriers, and two $Ga_{0.16}In_{0.84}Sb$ QW ac-

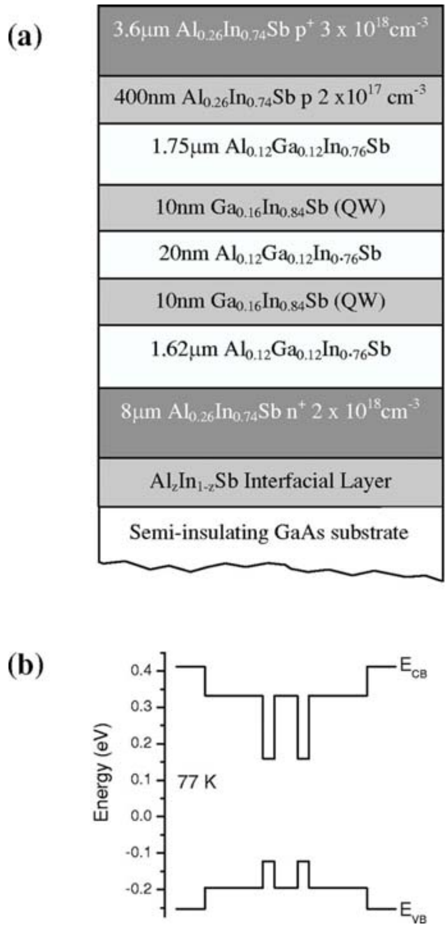

FIG. 1. Schematic cross section (a) showing the structure of the QW laser and (b) the calculated energy band diagram of the diode under zero applied bias.

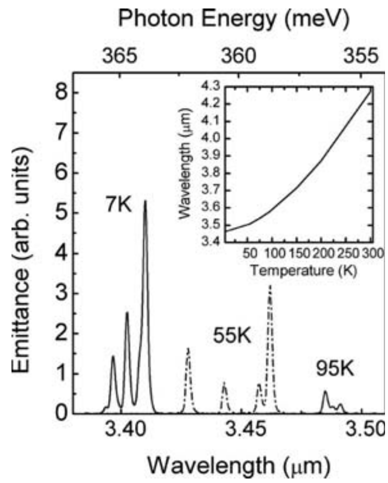

FIG. 2. Measured emission spectra as a function of temperature. The inset shows the predicted emission wavelength as a function of temperature.

tive regions. The $Al_zIn_{1-z}Sb$ layer and bottom $Al_{0.25}In_{0.75}Sb$ cladding region together accommodate the lattice mismatch between the GaAs substrate and the GaInSb quantum wells. Although no measurements of dislocation densities were made on the wafers described here, from atomic force microscopy measurements on similar structures it is expected that the dislocation density will be $\sim 10^8$ cm^{-2}. Further work is underway to investigate both the mechanisms of dislocation propagation and the effect of the dislocations on the laser properties. Beryllium was used to dope the top cladding layers *p* type (to nominal levels of 3×10^{18} and 2×10^{17} cm^{-3}, as shown in Fig. 1), whereas tellurium was used to dope the bottom *n* type to a nominal level of 2×10^{18} cm^{-3}. The composition of the cladding, barrier, and quantum well layers was determined by x-ray diffraction (XRD) measurements on both the full laser structure and also on two calibration layers. The first calibration layer consisted of the bottom buffer (AlInSb) and barrier (AlGaInSb) layers only (i.e., growth up to the bottom of the first QW). XRD measurement of the layer lattice parameters showed the barrier to be well matched to the buffer with the strain in the barrier less than 0.2% (the majority of this strain is due to residual strain in the buffer layer). The second calibration layer consisted of the bottom buffer and barrier layers plus 15 periods of the GaInSb QW and AlGaInSb barriers (no top barrier was present in this layer). XRD analysis showed the compressive strain in the QWs to be approximately 0.6%. Further details of the measurements undertaken on the calibration layers are given in Ref. 16.

Ridges with sloping sidewalls and a width of ~ 31 μm at the active region were defined using contact photolithography and wet chemical etching. Approximately 700 nm of SiO_X was then deposited by plasma enhanced chemical vapor deposition and a window opened by contact lithography and dry etching. Sputtered Ti/Au metallic contacts were then deposited, one on top of the ridge to provide a *p*-type contact and one on top of the etched region adjacent to the ridge to provide a *n*-type contact. Electroplating was used to increase the total metal thickness to ~ 5 μm to aid heat dissipation. The devices were cleaved to cavity lengths of 2 mm and mounted substrate side down onto uncoated copper blocks using a nonmetallic epoxy glue (note that this glue provides a relatively poor thermal path relative to, for example, indium soldering). The facets were neither polished nor coated.

Emission spectra were acquired using a Bentham M300 grating spectrometer, together with a cooled InSb detector, with a resolution of ~ 0.1 nm, with the device mounted on the cold finger of a continuous flow liquid helium cryostat. The device was driven with a 50 kHz square wave with a 5% duty cycle (pulse length ~ 1 μs) and with a peak current of 400 mA (equivalent to a current density of ~ 680 A/cm^2). At temperatures up to 95 K, multimode lasing was observed, as shown in Fig. 2, whereas electroluminescence was observed from 95 K up to room temperature. Figure 2 shows the measured emission spectra taken at 7, 55, and 95 K together with the predicted spontaneous emission wavelengths (e1-hh1), plotted as a function of temperature, calculated using 8×8 $k\cdot p$ theory with strain taken into account.[12]

Figure 3 shows a typical plot of the laser emission *L* versus current density *J* as a function of temperature (note that although characteristics were taken at 5 K intervals, some plots have been omitted to aid clarity). In this case, the device was mounted on the cold finger of a closed cycle cryostat and was driven with a 10 kHz square wave with a 1% duty cycle (pulse length ~ 1 μs). Threshold current densities were extracted from the data shown in Fig. 3 by a linear fit to the points above threshold and are shown on a logarithmic scale as a function of temperature in Fig. 4. At 75 K, the threshold current density is 78 A/cm^2, which is comparable to the value of 40 A/cm^2 we have obtained pre-

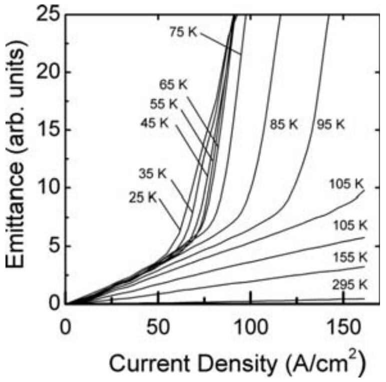

FIG. 3. Typical *L-J* characteristics measured as a function of temperature.

viously from 2 mm GaInSb/AlGaInSb QW diode lasers with a similar composition,[13] and emitting at comparable wavelengths at this temperature, but grown on InSb substrates. There is an indication that there is a change in the characteristic temperature T_0 at approximately 75 K and the two lines shown in Fig. 4 are fits to the data from 25 to 75 K and from 75 to 95 K, yielding T_0 values of 136 and 51 K, respectively. These values are also comparable to the value of 38 K obtained from the lasers previously grown on InSb.[13] Extrapolating the fit to the high-temperature data yields an estimated threshold current density of ~6.5 kA/cm^2 at room temperature. Although this is larger than the value of 660 A/cm^2 obtained recently from an ICL at 269 K,[10] and emitting at 4.05 μm, Andreev *et al.*[12] predicted that the threshold current density will fall by a factor of ~10 at room temperature as the strain in the QW active region of the GaInSb/AlGaInSb lasers is increased to approximately 1.5%. Further experiments are therefore underway examining the effect of strain on the laser performance.

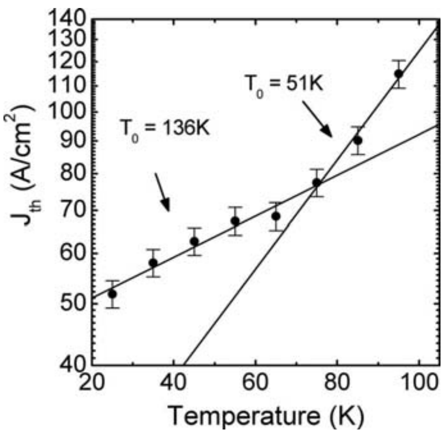

FIG. 4. Threshold current densities J_{th}, extracted from the data shown in Fig. 3 by a linear fit to the points above threshold, as a function of temperature. The two lines are fits to the data from 25 to 75 K and from 75 to 95 K, yielding T_0 values of 136 and 51 K, respectively.

In conclusion, we have investigated the characteristics of GaInSb/AlGaInSb type I quantum well diode lasers grown onto GaAs. Multimode lasing was observed up to a temperature of 95 K, with electroluminescence observed up to room temperature. Further improvements to the diode mounting, facet polishing, and coating, coupled with the realization of quantum wells with higher strain, offer the prospect of relatively low current operation at room temperature.

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