III-V interband 5.2 μm laser operating at 185 K

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We report the operation of a III-V interband laser at a wavelength beyond 5 μm and temperatures above 90 K. The active region consists of a strain compensated broken gap four layer superlattice of InAs/$Ga_{0.6}In_{0.4}Sb$/InAs/$Al_{0.3}Ga_{0.42}In_{0.28}As_{0.5}Sb_{0.5}$ grown by molecular beam epitaxy. The maximum operating temperature under 2.01 μm pulsed optical excitation was 185 K at a wavelength of 5.2 μm. The peak pump intensity at the 80 K threshold was 62 kW/cm^2, and the characteristic temperature (T_0) of the threshold intensity was 37 K. This T_0 is comparable to the best observed values for 3–4.5 μm lasers based on the InAs/GaInSb material system. © *1997 American Institute of Physics.* [S0003-6951(97)04252-6]

The development of III-V semiconductor sources in the mid-infrared has proceeded from both the short-wavelength side of the spectrum, through work on interband lasers,[1–5] and from the long-wavelength side through work on quantum cascade intersubband lasers.[6] The area of the spectrum not dominated by either strategy extends from (roughly) 5 to 10 μm. Within this range a quantum cascade laser at 5.2 μm (Ref. 7) and an InSb-based interband injection laser[8] at 5.1 μm have been developed recently. The quantum cascade laser operated up to 320 K, and the InSb laser operated up to 90 K, both with pulsed injection current. The quantum cascade laser operated cw up to 140 K.

We report here an optically pumped interband laser which operates up to 185 K at 5.2 μm. This is the first laser based on the InAs/InGaSb material system to operate beyond 5 μm. The active region of the design is a four-layer superlattice, 20 Å InAs/35 Å $In_{0.40}Ga_{0.60}Sb$/20 Å InAs/64.8 Å $Al_{0.30}Ga_{0.42}In_{0.28}As_{0.50}Sb_{0.50}$. The band-edge diagram for one period of this superlattice is shown in Fig. 1(a). Variations of this superlattice with different layer thicknesses also have yielded a 2.7 μm diode operating at 180 K and a 3.7 μm structure which operated under optical pumping to 300 K.[9] The presence of large band-edge differences among the constituents of the superlattice allows substantial flexibility for band structure engineering.

The sample was grown by molecular beam epitaxy in a Perkin–Elmer 430P machine on a (nominally undoped) p-type GaSb substrate. A schematic of the structure is shown in Fig. 1(b). X-ray diffraction indicated that the active region of the grown sample has a 145 Å superlattice unit cell. We note that the properties of this structure are not extremely sensitive to small changes in the quinternary region thickness, where most of the discrepancy between the grown structure and intended structure is likely to occur. Since this sample was intended to be an electrically injected laser, 1.8 μm thick superlattice cladding layers composed of alternating layers of 13.4 Å InAs and 13.4 Å AlSb were grown on

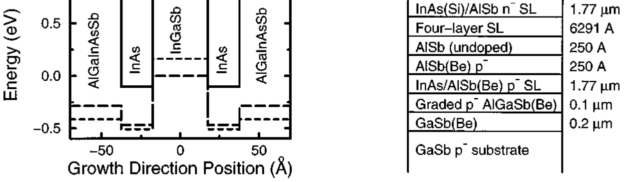

FIG. 1. (a) Conduction (solid), heavy-hole (short dashed), and light-hole (long dashed) band-edge diagram of one superlattice unit cell and (b) schematic of the epitaxial structure.

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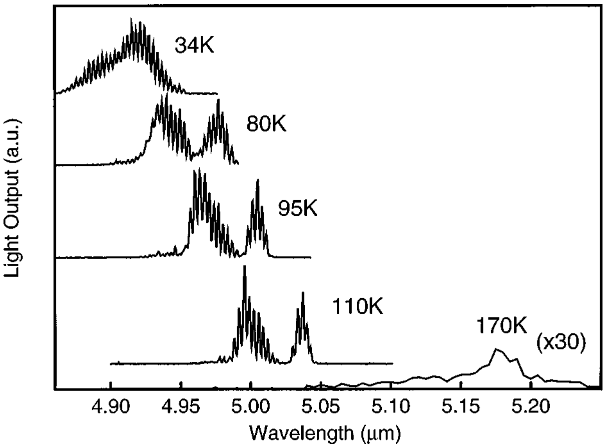

FIG. 2. Measured lasing spectra at maximum pump intensity at five temperatures: 34, 80, 95, 110, and 170 K.

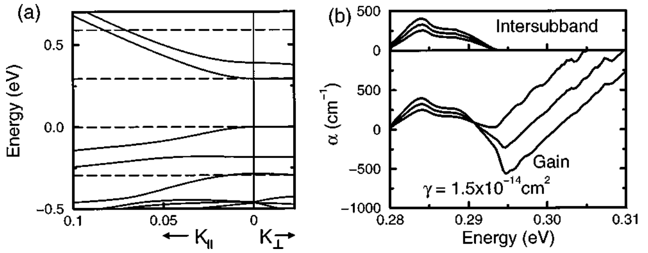

FIG. 3. (a) Band structure in the growth direction ($K_\perp$) and parallel to the interfaces ($K_\parallel$). Dashed lines indicate the band edges and the resonant energies for Auger transitions. (b) Band-edge absorption spectrum indicating gain (lower) and intersubband absorption spectrum (upper) for the active region at 80 K and at densities of 0.8, 1.0, and 1.2×10^{17} cm^{-3}. The differential gain is 1.5×10^{-14} cm^2 near threshold.

either side of the 0.63 μm thick active region, and the sample was capped with 300 Å of heavily doped InAs to facilitate ohmic contact formation. This structure did not lase under electrical injection, so we investigated its properties under optical pumping.

The sample was pumped by a 2.01 μm Tm:YAG laser at a 1 kHz repetition rate with 490 ns pulses. The peak power incident on the sample was 650 W. The pump beam was line focused to roughly 200 μm$\times$4 mm, yielding a peak intensity of 81 kW/cm^2. We calculate that only 22% of the light entering the sample was absorbed. That limited the peak absorbed intensity to 18 kW/cm^2. Light output was measured with an InSb detector after it was passed through a 1/3 m spectrometer. Spectra at five temperatures, from 34 to 170 K, are shown in Fig. 2. The four lower temperature measurements are high-resolution scans, while the 170 K measurement is a low-resolution scan taken during a period where the pump laser operated at higher intensity than 81 kW/cm^2 before the high-resolution scans were taken. The high-frequency oscillations in the high-resolution scans of the light output are due to cavity modes; the 38 GHz mode spacing corresponds within 10% to the 1 mm cavity length.

The unusual spectral ‘‘hole’’ apparent in the spectra from 80 to 110 K is likely due to intersubband absorption. The hole moves with temperature, and thus is not a consequence of atmospheric absorption. We have calculated the band structure, gain, and intersubband absorption for this structure at 80 K, using a multilayer superlattice $\mathbf{K}\cdot\mathbf{p}$ technique.[10] The band structure is shown in Fig. 3(a) while the band-edge absorption (showing a gain region) and intersubband absorption are shown in Fig. 3(b). The measured change in the spectral hole's energy is 3.1 meV from 80 to 110 K, while we calculate the intersubband absorption feature's change in location to be 0.6 meV over the same temperature range. We are unable to calculate the energies of the intersubband absorption feature and the gain region accurately enough to determine their relative location better than about 15 meV, but our calculation and the experimental spectra indicate that they are within 15 meV of each other. The observed width of the spectral hole is much narrower than the calculated width of the intersubband absorption feature, however, the relationship between the loss and the laser output at a given frequency is highly nonlinear.

The band structure of the sample, which was optimized for 300 K operation, is not optimized at 80 K. Features are evident which have previously been identified as degrading laser performance: there are final states in the key energetic regions for Auger recombination[11] within the valence band (shown by dashed lines), and there is a prominent intersubband absorption feature which, as we have already mentioned, interferes with the gain region.[10] In the calculations at 80 K the intersubband absorption feature only overlaps with the peak gain just above threshold. Hence the calculated differential gain in this structure is still quite high: 1.5×10^{-14} cm^2 near threshold. The presence of the spectral hole in the lasing spectra, however, suggests that the intersubband absorption does interfere with the peak gain region above threshold.

Carrier lifetime measurements based on a pump-probe experiment[12] performed on a sample with the same active region, but grown for optical measurements, indicate a Shockley–Read–Hall lifetime of 3.5 ns, which is characteristic of the best InAs/InGaSb superlattice samples grown in this machine. The measured Auger coefficient at 300 K was 2.5×10^{-26} cm^6/s, which is relatively high compared to samples with band gaps in the 3–4.5 μm range. Assuming a required 50 cm^{-1} gain for lasing, we have calculated the threshold carrier density as a function of temperature. Using these threshold carrier densities in conjunction with the measured Auger coefficient leads to an estimate of the threshold pump intensity of 302 W/cm^2 at 80 K and 1704 W/cm^2 at 125 K, as well as a T_0 from 34 to 125 K of 30 K. We note

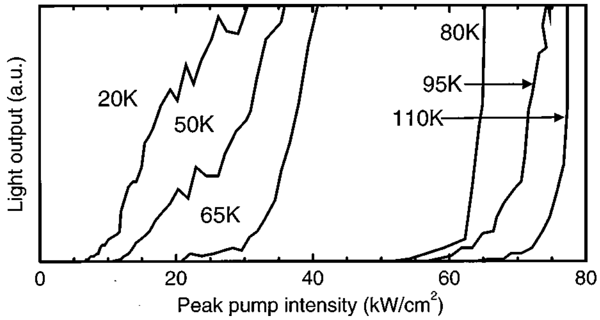

FIG. 4. Light output relative to the pump intensity for the temperatures 20, 50, 65, 80, 95, and 110 K. The noise is principally due to variations in the pump intensity from pulse to pulse.

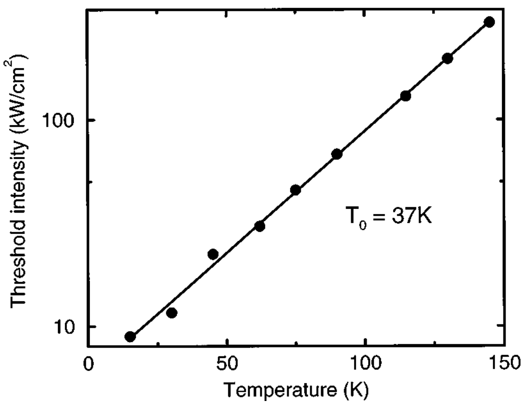

FIG. 5. Threshold pump intensity as a function of temperature, characterized by a $T_0 = 37$ K for temperatures above 34 K.

that this analysis neglects the small confinement factor likely at such long wavelengths, and the estimate of the threshold carrier density for lasing could easily be too low by a factor of 2. This estimate, therefore, should be considered as a lower bound to the threshold pump intensity for lasing.

Figure 4 shows the light output relative to the input pump intensity for six temperatures from 20 to 110 K. The threshold pump intensity as a function of temperature is shown in Fig. 5. Figure 5 includes some results from measurements during a period where the pump laser operated at a higher pump intensity than 81 kW/cm^2, before the results of Fig. 4 were obtained. The temperature dependence of the threshold pump intensity is characterized by a $T_0 = 37$ K, which compares well to optically pumped lasers in the 3–4.5 μm range. The threshold pump intensities estimated from carrier lifetime measurements and theoretical gain calculations differ from the optical pumping thresholds by a factor of 30. Due to the uncertainties in our estimated threshold intensities, we do not consider this a serious discrepancy. For example, if we underestimated the threshold carrier density by a factor of 2, we would underestimate the threshold pump intensity by a factor of 8.

We emphasize that this sample was intended to be an electrical injection laser, hence its performance under optical pumping is even more remarkable. In particular, due to the absence of pump-absorbing regions of the sample near the active region, only about 22% of the pump entering the sample was absorbed by the sample, severely limiting the maximum operating temperature. Although the structure did not lase electrically, the optical pumping results verify the quality of the active region.

In summary we have demonstrated the longest wavelength III-V interband laser to date, operating at 5.2 μm up to 185 K under pulsed optical pumping. The threshold intensity and T_0 are comparable to the best achieved in the 3–4.5 μm range, and the T_0 is more than twice as high as the 16 K value of the 5.1 μm InSb injection laser. Although lasers processed from other pieces of this sample's wafer did not lase electrically at injection currents significantly higher than those induced here optically, we regard this as a tractable problem, which may be associated with hole transport in the active region.

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