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Vertical cavity single quantum well laser

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We have achieved room-temperature pulsed and cw lasing at 980 nm in an optically pumped vertical cavity structure grown by molecular beam epitaxy containing only a single quantum well (SQW) of $In_{0.2}Ga_{0.8}As$. Limited gain due to the extremely short active material length of 80 Å implies that losses due to absorption, scattering, and mirror transmission are extremely low. Using 10 ps pump pulses at 860 or 880 nm, the estimated energy density absorbed in the spacer was ~ 12 fJ/μm^2 at threshold, indicating a carrier density approximately four times that required for transparency. Continuous wave pumping yielded an estimated threshold absorbed intensity of $\sim 7\ \mu$W/μm^2.

Epitaxially grown semiconductor resonators with quantum well (QW) spacers have important potential as optical device structures. Optical gating[1] and optically pumped lasing[2] were early demonstrations of nonlinear applications. A QW Fabry-Perot electrodispersive modulator was demonstrated[3] to have several advantages over electroabsorptive modulators. Energy requirements and speed have both been greatly improved by etching waveguiding microresonators.[4,5] Recently we reported[6] étalon finesse values as high as 160, and predicted that optical gating could be performed with only a *single* quantum well (SQW) as the nonlinear material. In this letter we report room-temperature optically pumped *lasing* in a SQW étalon grown by molecular beam epitaxy (MBE). Pulsed excitation yielded a threshold with an estimated absorbed average energy density in the spacer ~ 12 fJ/μm^2, implying a carrier density in the SQW not greatly above the density for transparency of about 1.3×10^{12} cm^{-2}. In cw experiments the estimated average absorbed power density at threshold was $\sim 7\mu$W/μm^2 and the internal slope efficiency was $\sim 33\%$. The carrier densities per QW are similar to those in previous multiple QW experiments. The very low energy and power densities here are the result of reducing the number of wells to just one, and increasing finesse to a high enough level to permit lasing.

The MBE-grown structure (inset of Fig. 1) has a bottom mirror adjacent to the substrate comprising $24\frac{1}{2}$ pairs of 802 Å AlAs and 670 Å GaAs. The spacer is a 80 Å $In_{0.2}Ga_{0.8}As$ SQW clad on both sides by 1290 Å GaAs barriers for a total thickness of one wavelength in the material. The top mirror with an air interface has 24 pairs of AlAs and GaAs layers of the same thicknesses as the bottom mirror. All layers are nominally undoped. The bottom mirror is designed to be more transmissive so more than half the light should exit into the substrate. The InGaAs SQW should be elastically strained since it is well below the critical thickness[7] of ~ 200 Å. Optical studies of $In_xGa_{1-x}As$/GaAs strained-layer QWs similar to this one have been detailed elsewhere.[8] GaAs/AlAs resonators with $In_xGa_{1-x}As$ QWs are interesting for optical device applications since the typical operating wavelenghts of 950–1000 nm are almost as short as for GaAs QW, yet the GaAs substrates are transparent.[9] This allows, for example, the integration of high-numerical-aperture micro-optic lenses on the backsides of the substrates.[10] Even when InGaAs QWs are grown individually below their critical thickness, growing a large number of them can result in misfit dislocations. It is essential to keep their total thickness below the level at which an unacceptable density of dislocations appears. The present SQW demonstration shows that it is possible to fabricate structures well below this limit.

The unetched wafer was pumped through the top mirror by a synchronously pumped mode-locked dye laser emitting ~ 10 ps pulses tunable from about 800–920 nm. Usually the pulses were incident continually at 82 MHz with no modulation and were focused by a $5\times$ microscope objective. We also used an unmodulated cw dye laser to pump at 860 nm. Pulsed measurements were carried out with the pump wavelength in two regions where the mirror reflectivity was low about 860 (880) nm which is above (below) the GaAs band-gap energy. With the pump photon energy above the GaAs band-gap energy, the top mirror absorbed about 80% of the incident energy. The spacer absorbed $\sim 23\%$ of the

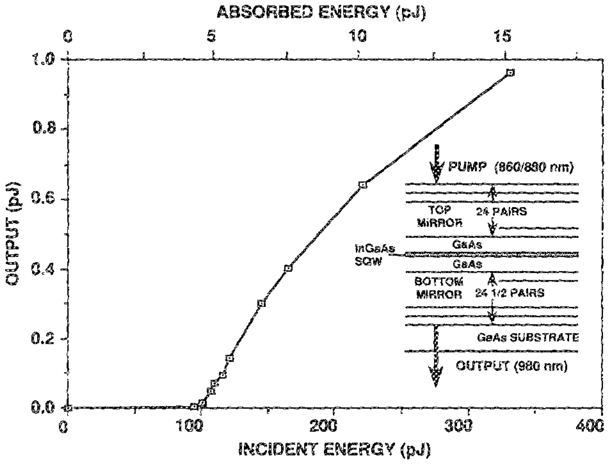

FIG. 1. Output through the bottom mirror vs incident input and estimated absorbed input for pulsed pumping at 860 nm. Inset: schematic of the MBE-grown SQW resonator.

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light which had transmitted through the top mirror and the rest was absorbed in the bottom mirror and substrate. Thus, neglecting reflections, the absorption in the spacer was only ~4.6% of the incident beam as discussed near the end of this letter. The carriers generated must then cool and be trapped in the InGaAs QW. This pumping efficiency is still much larger than a similarly estimated ~1.6% absorption in the QW only due to pumping below the GaAs band gap. The incident energy required for lasing was about 2.7 times larger for below gap than for above gap pumping, thus our calculations are consistent. Both calculations tend to overestimate the carrier density in the lasing region of the QW since many carriers are generated outside the lasing area and a significant number of them will be in the GaAs barriers.[11] For cw operation we use the ~4.6% pump efficiency since the pump is above the GaAs band gap.

Figure 1 shows an output/input characteristic with a threshold of 100 pJ incident or ~4.6 pJ absorbed in the spacer (above the GaAs band gap). Minimizing the threshold required *defocusing* the pump beam from its minimum spot size, due to finesse and area requirements imposed by the small gain and mirror structure. The gain data from Lau *et al.*[12] show a modal gain ~60 cm^{-1} at current densities a few times above the transparency density. Assuming their modal confinement factor[13] is 3% and ours is 100% yields a gain ~2000 cm^{-1} for the SQW. Multiplying by the 80 Å length and an additional factor 2 (the SQW is in the antinode of the standing waves[14]) yields the largest gain-length product, 3×10^{-3}, we can expect from the SQW. Thus, the cavity losses must be smaller than ~0.3%. This is reasonable since both mirrors have many more layers than did the high-finesse étalons previously measured.[6] Their calculated reflectivities are both above 99.9% neglecting diffraction losses. Because there are no waveguiding structures (e.g., microresonators), such small loss cannot be attained in a small diameter. Diffraction formulae show the minimum spot radius (half width at half maximum) varies with wavelength λ, cavity length L, refractive index n, and cavity losses per pass A, as $a^2 \sim L\lambda/nA$. As explained in Ref. 6, the effective cavity length in an étalon with dielectric mirrors is larger than the spacer thickness and is about 1 μm in our case. For $A \sim 0.002$, the SQW étalon needs about 430 μm^2 area which is larger than the diffraction limit of the focused pump beam. Thus, we expect lower thresholds when carriers are directly injected into the optimum area by defocusing. The actual area of the lasing region for Fig. 1 was calculated by measuring the angular divergence of the output beam to be about 400 μm^2 for the whole lasing region. Thus, the absorbed energy density averaged over the lasing area is < 12 fJ/μm^2 creating an average carrier density $\sim 5 \times 10^{12}$ cm^{-2}. Even if all the carriers fell into the SQW, the density was only approximately four times that required for transparency.[15] It is quite possible that less than half this density actually existed inside the SQW.[11] The data indicate a ~14% internal single-face slope efficiency which is higher than for previous lasers pumped by picosecond pulses.[5,16] Pumping below the GaAs band gap at 880 nm yielded a threshold of 270 pJ incident, or ~4.3 pJ absorbed. Our estimates of the absorbed energies for above and below gap pumping are thus consistent. The internal slope efficiency for below gap pumping was much lower however, about 5.4%, possibly due to bleaching of the SQW absorptivity, or reduced carrier lifetimes in the SQW compared to the GaAs barriers.

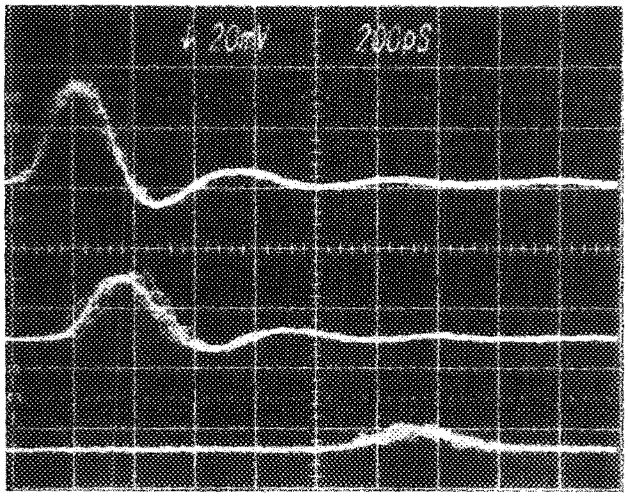

FIG. 2. Triple exposure (all at 200 ps/div) showing the times of the pump pulse (upper), minimum-delay output (middle), greatly delayed and reduced output (lower). The pulse widths on the oscilloscope indicate the response of the avalanche photodiode. The large > 1 ns delay results from focusing the pump beam too tightly.

Other interesting effects were seen when we focused the pump beam more tightly. A high density of carriers is generated in an area too small to permit lasing as discussed above. However, if enough of them are created, over a period of time they will diffuse outward eventually filling a sufficiently large region and if their density is still high enough, lasing should occur. It should have reduced output, however, due to carrier losses during this diffusion time. This is exactly what we see. Figure 2 shows that this delay can be more than 1 ns, which is consistent with the diffusion measurements of Olsson *et al.*[17] It also shows an ~150 ps minimum delay between the pump pulse and the output pulse. Since the cavity buildup time is only ~10 ps and the carriers are trapped[11] in the well in ~6 ps, we attribute this delay to the gain buildup time of the low-gain high-reflectivity cavity. The ~150 ps delay was essentially constant with input energies ranging from ~1.2× to >4× threshold. This could be explained by the fact that our SQW is quite shallow and cannot hold a very large carrier density. Thus, adding more pump energy does not increase the carrier density or the gain enough to cause a noticeable reduction of the delay. The output keeps increasing with pump energy however, which suggests that once the device starts to lase the SQW is continuously resupplied with carriers from the adjacent GaAs barriers until they are depleted.

Continuous pumping yielded results consistent with the pulsed experiments. Figure 3 shows an ~45 mW cw threshold incident on the device, or about 2 mW of the 860 nm pump absorbed. The lasing area $> 300\,\mu\text{m}^2$ so $< 7\,\mu\text{W}/\mu\text{m}^2$ was absorbed. The internal slope efficiency was ~33%, much larger than in the pulsed case. This may be largely due to the fact that the carrier density must be above that of transparency throughout the lasing region. With pulsed

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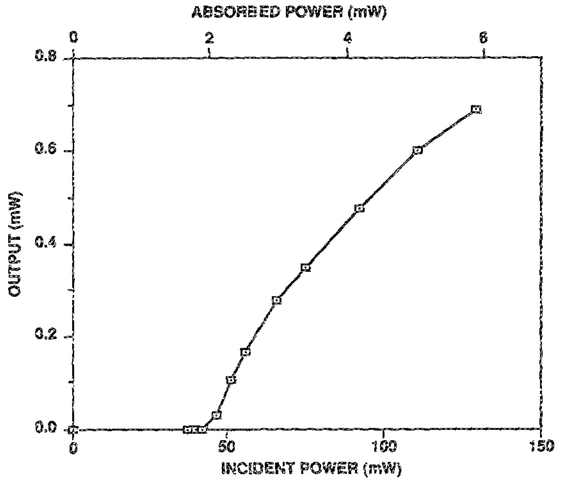

FIG. 3. Output (bottom mirror) vs incident input and estimated absorbed input for cw pumping at 856 nm.

pumping we must create a significant number of carriers outside this region due to the intensity profile of the pump beam. These carriers will mostly be wasted and not contribute to the output. In cw operation we can focus the pump more tightly since the carriers will diffuse outward. The slight delay in the onset of lasing would not be noticed in the cw measurements. While diffusing outward the carriers have a high probability of contributing to stimulated emission, thus fewer are wasted. Other loss mechanisms in the pulsed case, such as recombination during the 150 ps delay, also contributed to its decreased slope efficiency. The SQW laser spectrum in both pulsed and cw operation was a single line of instrument-limited width on our 270 mm spectrometer. We measured coherence lengths of ~20 mm (>50 mm) for pulsed (cw) operation yielding linewidths of ~0.5 Å (<0.2 Å). These values are consistent with the expected instrument width of the SQW étalon of ~1 Å. Since the free-spectral range is on the order of 1000 Å (see Ref. 6), multiple longitudinal mode lasing is extremely unlikely.

The pump absorption calculations assume that no cavity resonance was present which would enhance it absorption. Tuning the wavelength while checking the energy threshold shows fairly constant threshold regions, from ~850–865 nm and from 875–880 nm. Below ~875 nm the threshold decreased, where absorption in the GaAs barriers increased the pump efficiency. Above ~881 nm the mirror became highly reflective and lasing did not occur with the pump >885 nm. These observations coupled with the constistancy of our estimates for thresholds for above and below gap pumping are the basis for our confidence that no such resonances were present. Deviations of the actual structure from its design could cause some nonresonant enhancement of the pump abosrption, but models of such were inconsistent with measurements. The straightforward estimates are fully consistent, thus any error factors should be much less than 2.

Thermal effects did not appear to play any important role, probably because the lasing wavelength is far from the absorption band of GaAs. By using an acousto-optic modulator we were able to observe lasing in the absence of heating. The threshold actually *decreased* slightly, <5%, when the device heated up. This could be due to some thermal lensing created by the temperature gradient, or temperature tuning the SQW luminescence peak closer to the resonator transmission peak. With 40 mW average power incident above the GaAs band gap (10 kW/cm^2), the laser heated enough to change its peak wavelength by ~5 Å.

In conclusion, we have deomonstrated room-temperature lasing in a vertical cavity SQW resonator (80 Å active material length) under both pulsed and cw optical pumping in the strained $In_{0.2}Ga_{0.8}As/(Al,Ga)As$ system where the substrate is transparent at the lasing wavelength of ~980 nm. The large are of ~400 μm^2 can be reduced considerably by forming microresonators, resulting in very low energies. It will be important to determine how small a microresonator can maintain such a high finesse since the required energy (or current for electrical pumping) is proportional to the cross-sectional area divided by finesse. A 1-μm-diam SQW microlaser electrically pumped would have a current threshold <10μA if cavity losses and surface recombination are kept low.

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