GaAsSb/InGaAs Type-II Quantum Wells
for Long-Wavelength Lasers on GaAs Substrates

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Abstract- We have investigated the properties of GaAsSb/InGaAs type-II bilayer quantum well structures grown by molecular beam epitaxy for use in long-wavelength lasers on GaAs substrates. Structures with layers, strains and thicknesses designed to be thermodynamically stable against dislocation formation exhibit room-temperature photoluminescence at wavelengths as long as 1.43 μm . The photoluminescence emission wavelength is significantly affected by growth temperature and the sequence of layer growth (InGaAs/GaAsSb vs. GaAsSb/InGaAs), suggesting that Sb and/or In segregation results in non-ideal interfaces under certain growth conditions. At low injection currents, double heterostructure lasers with GaAsSb/InGaAs bilayer quantum well active regions display electroluminescence at wavelengths comparable to those obtained in photoluminescence, but at higher currents the electroluminescence shifts to shorter wavelengths. Lasers have been obtained with threshold current densities as low as 120 A/cm^2 at 1.17 μm , and 2.1 kA/cm^2 at 1.21 μm .

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I. Introduction

The desire for low-cost, manufacturable 1.3 μm vertical-cavity surface-emitting lasers is currently fueling a number of efforts to develop novel long-wavelength materials which can be grown on GaAs substrates. Among these efforts, the use of highly-strained GaAsSb quantum wells shows great promise, including the demonstration of low-threshold lasers at 1.2-1.3 μm .¹⁻³ A fundamental concern with many of the current approaches, including GaAsSb quantum wells, is that these long wavelengths are achievable only by using quantum well compositions which result in large strains, and that the strain which can be accommodated elastically limits the achievable wavelength. Furthermore, while edge-emitting lasers with reasonable room-temperature characteristics have been demonstrated at 1.3 μm , no lifetime data have been reported for these devices, so that the long-term stability of these highly-strained structures is so far unproven. For these reasons, approaches for further extending the wavelength of the current devices are of interest.

One variation of the simple GaAsSb quantum well which has been suggested is the combination of GaAsSb with InGaAs in a type-II bilayer structure.⁴ In this structure, electrons are confined in the InGaAs layer, and holes are confined in the adjacent GaAsSb layer. A reduction in the effective bandgap relative to GaAs/GaAsSb/GaAs quantum wells is achieved by the lowering of the electron energy, since the position of the InGaAs conduction band edge is below either the GaAs or GaAsSb conduction band. In addition, this structure may also have improved electron confinement relative to the simpler GaAsSb quantum well, since the GaAs/GaAsSb band alignment has also been suggested to be type-II. Because the InGaAs layer is also under a biaxial compressive

stress similar to the GaAsSb, the addition of the InGaAs layer to the highly strained GaAsSb layer necessitates a reduction in the GaAsSb layer thickness in order for the combined bilayer to remain under the Matthews-Blakeslee critical layer thickness.⁵ This reduction in the GaAsSb layer thickness to some extent offsets the advantage gained by the introduction of the InGaAs layer, since the hole confinement energy in the narrower GaAsSb well is increased. However, a previous model of this system suggests that for optimized compositions and layer thicknesses, the bilayer structure will have a ground-state transition energy which is substantially lower than a similarly-strained GaAsSb well of the same thickness.⁴ Currently, only lasers grown on InP have been reported employing the GaAsSb/InGaAs bilayer scheme.⁶ Based on these preliminary reports, we have investigated the molecular beam epitaxial growth and characterization of these structures, and demonstrate the first operation of GaAsSb/InGaAs bilayer quantum well lasers on GaAs substrates.

II. Experimental

Samples were grown on (100)-oriented GaAs substrates by solid-source molecular beam epitaxy (MBE). Substrate temperatures of 450-500°C were used for the growth of GaAsSb and InGaAs layers, while GaAs and AlGaAs layers were grown at 590-615°C. Group V fluxes were obtained from cracking effusion cells with cracking zone temperatures of 600°C and 900°C to give predominantly As₂ and Sb₁ species, respectively. Compositions and thicknesses of the bilayer structures were typically 24-30% GaSb, 30-45 Å for the GaAsSb; and 24-30% ^{InAs} 30-45 Å for the InGaAs. Quantum well samples grown primarily for photoluminescence (PL) characterization consisted of a single bilayer with 0.2-0.5 μm GaAs barrier layers above and below.

Simple double-heterostructure edge-emitting lasers were fabricated from structures consisting of active regions with a bilayer centered in approximately 2300 Å of undoped GaAs waveguide, with lightly-doped ($\sim 1 \times 10^{17} \text{ cm}^{-3}$) 1.5 μm $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ cladding layers and appropriate contact layers. Devices with stripe widths of 25-100 μm and cavity lengths of 500-1250 μm were fabricated. Room-temperature electroluminescence and lasing characteristics were measured using 0.2 μs pulses at a repetition rate of 10 kHz. PL measurements were performed at room temperature using 800 nm excitation at a power density of approximately 10-250 W/cm^2 .

III. Bilayer Quantum Well Structures

Photoluminescence emission for the quantum well samples is significantly affected by growth temperature between 450 and 500°C. As shown in Figure 1, for nominally identical structures, higher growth temperatures produce higher PL intensities, but substantially shorter wavelengths. The increase in PL intensity for higher growth temperature is most likely associated with a decrease in the density of point defects, while the shift in wavelength could be attributable to either compositional differences in the samples due to desorption of Sb flux from the growth surface, or non-ideal compositional profiles associated with the surface segregation of In or Sb.^{7,8} Our experience with the growth of the simpler GaAsSb/GaAs quantum well structures, which exhibit a substantially smaller wavelength shift than shown in Figure 1, suggests that segregation is the dominant factor in this wavelength shift. Further evidence for surface segregation is shown in Figure 2, which compares two bilayer quantum well structures which differ only in the sequence of growth, i.e. GaAsSb/InGaAs vs. InGaAs/GaAsSb. We have found that over the range of 450-500°C, structures with the GaAsSb layer

grown first always exhibit PL at significantly longer wavelengths than the samples with the InGaAs grown first. In addition, the wavelength difference between GaAsSb/InGaAs and InGaAs/GaAsSb samples is reduced at lower growth temperatures, suggesting that lower growth temperatures lead to reduced segregation and improved interfacial abruptness. It is important to reduce this segregation in order to produce structures with the longest possible emission wavelength because, in contrast to the case of In or Sb desorption, the segregated In or Sb does eventually incorporate, and thus contributes to the overall strain of the quantum well structure. Therefore, simply increasing the In or Sb content to produce longer PL wavelengths will result in layers which exceed the critical strain-thickness limits for dislocation formation.

PL linewidths for these structures range from 45-120 meV (full-width at half-maximum), with higher growth temperatures generally resulting in the wider linewidths. Some of this may be attributable to microscopic compositional nonuniformity (clustering) in the GaAsSb layers, which has been previously demonstrated to increase with growth temperature.⁹ In addition, samples grown at higher temperatures frequently show evidence of a second peak at shorter wavelengths (see Figure 1, for substrate temperature 500°C) which may artificially broaden measurement of the long-wavelength peak.

Growing an optimized structure involves choosing a growth temperature which reduces segregation effects sufficiently to achieve the theoretical advantages of the type-II bilayer structure while simultaneously keeping the optical quality of the material at a level suitable for laser active region material. As shown in Figure 3, bilayer structures grown at 475°C (in the configuration where the GaAsSb is grown first) exhibit PL at

wavelengths 30-50 nm longer than GaAsSb-only structures of similar composition and overall thickness, while exhibiting a moderate reduction in intensity.

The peak wavelength of the photoluminescence in these structures is highly dependent on the pump power density. Shown in Figure 4 are PL spectra for a structure which emits at 1.43 μm for a pump power density of 30 W/cm^2 . At 250 W/cm^2 , the emission peak blueshifts to 1.38 μm . Such shifts are commonly associated with material inhomogeneities¹⁰ or, in type-II structures, the presence of bandbending¹¹ near the bilayer interface resulting from the spatial separation of electrons and holes in the InGaAs and GaAsSb layers, respectively. It is likely that a combination of these effects is responsible for the shift exhibited in these structures.

The electroreflectance spectrum from a bilayer structure is shown in Figure 5. The spectrum shows a bandedge feature at 1.31 μm , and additional features at approximately 1.18 and 0.97 μm . This structure was modeled using a tunneling resonance approach, with material parameters and band offsets taken from the literature. We assumed in this calculation that the bowing in the bandgap of the GaAsSb as a function of composition was reflected in the absolute energy of the valence band, while the energy of the conduction band was a linear function of composition. This results in GaAsSb/GaAs band alignments which are strongly type-II. The calculated energies of the transitions between the single bound conduction band state and three bound heavy-hole states are also indicated in the figure and are in good agreement with the electroreflectance features. The position of the long-wavelength feature in the reflectance coincides with the peak wavelength in photoluminescence and electroluminescence (at low excitation powers), demonstrating that the long-wavelength emission from these

structures is close to the actual bandedge, and is not related to the presence of deep impurity levels.

IV. Edge-Emitting Lasers

The pump power vs. emission intensity of electroluminescence from edge-emitting GaAsSb/InGaAs lasers is similar to that obtained in power-dependent photoluminescence. At low injection currents a single long-wavelength peak is present. As the injection current is increased, this long-wavelength peak grows in intensity, and blueshifts substantially. At sufficiently high current, lasing occurs near the electroluminescence peak. Even for the relatively low-threshold lasers demonstrated here, the blueshift results in a significant and undesirable reduction in the lasing wavelength of the device. This effect has been observed in similar GaAsSb/InGaAs lasers on InP substrates⁶, and also occurs in the simpler GaAsSb/GaAs laser designs¹.

Lasers were fabricated from samples grown at various temperatures, and with different bilayer thicknesses and compositions. In general, the lasing wavelengths were substantially shorter than the peak wavelength of the low-current electroluminescence. Excellent characteristics were obtained for a device with the bilayer grown at 475°C. At room temperature, pulsed 1.17 μm laser emission was obtained with a threshold current density as low as 120 A/cm^2 for 75 x 2000 μm^2 stripe dimension. The light output vs. current characteristics of a 75 x 1250 μm^2 device are shown in Figure 6. Output powers in excess of 140 mW per facet were obtained (limited by our current supply), and a slope efficiency of 0.2 W/A per facet was measured. The longest room-temperature lasing wavelength obtained to date is 1.21 μm , obtained in a device grown at 450°C. At that wavelength, a threshold of 2.1 kA/cm^2 was measured, with a much lower slope efficiency

of 0.05 W/A per facet. Low-current electroluminescence was observed in that device at 1.32 μm . The higher threshold current and relatively broad electroluminescence obtained in that device may indicate that higher growth temperatures are necessary for obtaining high-quality laser material in this system. The much larger difference between the low-current electroluminescence and lasing wavelengths may also indicate that this device is lasing on an excited hole state.

Optimization of the growth conditions for lasers containing GaAsSb/InGaAs bilayer quantum well active regions requires a compromise between achieving the highest optical quality of the material and achieving the longest emission wavelength. The longest wavelengths are obtained by growing at low temperatures to reduce segregation effects, but lower growth temperatures result in poorer optical quality. Complicating this situation is the relatively large blueshifts observed for luminescence and lasing, even at relatively low injection levels. Given that further reductions in threshold currents appear unlikely to significantly lessen this shift, it appears that the key to achieving longer-wavelength lasing will be improvements in growth conditions and bilayer design which will result in structures with improved optical quality and low-injection bandedges significantly longer than 1.3 μm . This approach will undoubtedly be highly empirical, given the uncertainties involved in accurately growing such thin structures in the presence of significant surface segregation.

V. Conclusions

GaAsSb/InGaAs bilayer quantum well structures were grown on GaAs substrates by molecular beam epitaxy and characterized by optical techniques. Strong evidence of surface segregation and non-ideal interfaces was demonstrated for growth temperatures

between 450 and 500°C. Higher growth temperatures resulted in higher photoluminescence intensity over this range. Photoluminescence emission exhibited a strong blueshift with increasing pump intensity, which we attribute to a combination of bandfilling in the clustered GaAsSb and the formation of an electric dipole at the GaAsSb/InGaAs interface. Photoluminescence emission as long as 1.43 μm was obtained at room temperature. Lasers utilizing the bilayer quantum well active regions operate at wavelengths significantly shorter than obtained under low injection conditions. Lasers operating under pulsed conditions have been demonstrated at wavelengths as long as 1.21 μm , while devices operating at 1.17 μm have thresholds as low as 120 A/cm².

VII. Acknowledgements

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Figure Captions

Figure 1. Room-temperature photoluminescence for GaAs/GaAs_{0.7}Sb_{0.3}/In_{0.3}Ga_{0.7}As/GaAs structures with the GaAsSb/InGaAs bilayer grown at various temperature.

Figure 2. Room-temperature photoluminescence from bilayer structures which nominally differ only in the sequence of bilayer growth (GaAs_{0.7}Sb_{0.3}/In_{0.3}Ga_{0.7}As vs. In_{0.3}Ga_{0.7}As/GaAs_{0.7}Sb_{0.3}). The growth temperature was 475°C.

Figure 3. A comparison of room-temperature photoluminescence between simple GaAs_{0.76}Sb_{0.24} and GaAs_{0.76}Sb_{0.24}/In_{0.24}Ga_{0.76}As bilayer quantum well structures. The surrounding material was GaAs in both cases, and the total quantum well thickness was approximately 80Å. The growth temperature was 475°C.

Figure 4. Photoluminescence spectra for a GaAs_{0.7}Sb_{0.3}/In_{0.3}Ga_{0.7}As structure at various pump power densities, illustrating a blue shift with increasing power.

Figure 5. Room-temperature electroreflectance for a GaAsSb/InGaAs bilayer structure. Transition energies as calculated in the text are indicated.

Figure 6. Light output vs. current characteristics for a GaAsSb/InGaAs bilayer quantum well laser emitting at room temperature. The pulse width was 0.2 μs, and the pulse repetition frequency was 10 kHz.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.