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The Growth of Mid-Infrared Emitting InAsSb/InAsP Strained-Layer Superlattices Using Metal-Organic Chemical Vapor Deposition

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Abstract. We describe the metal-organic chemical vapor deposition of InAsSb/InAsP strained-layer superlattice (SLS) active regions for use in mid-infrared emitters. These SLSs were grown at 500 °C, and 200 torr in a horizontal quartz reactor using trimethylindium, triethylantimony, AsH₃, and PH₃. By changing the layer thickness and composition we have prepared structures with low temperature (≤ 20 K) photoluminescence wavelengths ranging from 3.2 to 5.0 μ m. Excellent performance was observed for an SLS light emitting diode (LED) and both optically pumped and electrically injected SLS lasers. An InAsSb/InAsP SLS injection laser emitted at 3.3 μ m at 80 K with peak power of 100 mW.

1. Introduction

Chemical sensor and infrared countermeasure technologies would become viable with the availability of high power, mid-infrared (3-6 μ m) lasers and light emitting diodes (LEDs) operating near room temperature. However, the performance of mid-infrared emitters has been limited by nonradiative recombination processes (usually Auger recombination), which overwhelm radiative recombination in narrow bandgap semiconductors. Auger recombination can be suppressed in "band-structure engineered", strained InAsSb heterostructures. In order to reduce Auger recombination in mid-infrared (2-6 μ m) lasers, several narrow bandgap III-V, strained-layer superlattices (SLSs) have been explored using metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) [1-13]. In both type I and type II SLS laser active regions, holes are confined to compressively strained layers, producing a low in-plane, effective mass ($1/2, \pm 3/2 >$) hole ground state. In compressively strained InAsSb SLSs, it is necessary to maximize the light-heavy ($1/2, \pm 1/2 > - 1/2, \pm 3/2 >$) hole splitting to suppress Auger recombination. For example, we have investigated the electronic properties of InGaAs/InAsSb SLSs, and we find that the light-heavy hole splitting (≈ 30 meV) is insufficient to achieve maximum suppression of Auger recombination [1,12-15]. InAsSb SLSs incorporating barrier layers with larger valence band offsets are required to maximize the light-heavy hole splitting through quantum confinement. In this work, we report the properties of InAsSb/InAsP SLS materials and devices. Incorporating InAsP as a barrier layer in the active region will introduce a larger valence band offset than either of the offsets between InAs or InGaAs and InAsSb. Compared with other compressively strained InAsSb devices, initial tests on InAsSb/InAsP SLS lasers and LEDs show state-of-the-art performance. We report on the synthesis of these materials by MOCVD and their use in improved 3-6 μ m, mid-infrared optoelectronic heterojunction emitters.

2. Experimental

This work was carried out in a previously described MOCVD system [16,17]. The InAsSb/InAsP SLSs were grown on n-type InAs substrates at 500 °C, and 200 torr in a horizontal quartz reactor using trimethylindium (TMIn), triethylantimony (TESb), 100 % AsH₃ for the InAsSb layers, 10 % AsH₃ in hydrogen for the InAsP layers, and 100 % PH₃. The InAsSb layers were grown using a V/III ratio of 15 to 21 and an TESb/(AsH₃+TESb) ratio of 0.29 to 0.41 at a growth rate of 2.5 Å/second. A 5 to 15 second purge, with reactants switched in and out of the chamber, was used for different samples. The InAsP layers were grown using a V/III ratio of 217 and an AsH₃/(AsH₃+ PH₃) ratio of 0.02 with an identical

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growth rate of 2.5 Å/second. The strained balanced SLSs were lattice matched to InAs with $\Delta a/a < 0.0004$ with the InAsSb layers in compression and the InAsP layers in tension relative to the InAs substrate. The SLS composition and strain were determined by double crystal x-ray diffraction.

We used ethyldimethylamine alane (EDMAA), TESb and 10% arsine (AsH_3) in hydrogen as the sources for Al, Sb and As respectively, for the growth of $\text{AlAs}_x\text{Sb}_{1-x}$ cladding layers. Triethylgallium (TEGa), arsine and TESb were used to grow a 400 to 2500 Å GaAsSb cap on all samples to keep the $\text{AlAs}_x\text{Sb}_{1-x}$ layer from oxidizing and to serve as a semi-metal electron injector for the emitter structures.[10, 13] Hydrogen was used as the carrier gas at a total flow of 8 slpm.

Infrared photoluminescence (PL) was measured on all samples at 14 K up to 300 K using a double-modulation, Fourier-transform infrared (FTIR) technique which provides high sensitivity, reduces sample heating, and eliminates the blackbody background from infrared emission spectra. Injection devices (both LEDs and lasers) also were characterized with double modulation FTIR.

3. Results And Discussion

The growth rate of the InAsSb/InAsP SLSs was found to be proportional to the TMIn flow into the reaction chamber and independent of the TESb, PH_3 , and AsH_3 flow. The variation of the Sb composition for the InAsSb layer as a function of TESb / ($\text{AsH}_3 + \text{TESb}$) ratio in the vapor is shown in Figure 1. The Sb composition could be varied between 0.12 to 0.23 while maintaining constant layer thickness for both the InAsSb and InAsP layers.

The PL peak wavelength dependence on composition for the SLSs is shown in Figure 2. For a change of composition from $x = 0.12$ to 0.23 the PL peak changes from 3.6 to 5.0 μm . Room temperature photoluminescence, also shown in Figure 2, was observed from 4.2 to 5.8 μm . The variation of PL wavelength versus thickness of the InAsSb well is shown in Figure 3. The wavelength could be varied from 3.2 to 3.8 μm for a change in thickness from 45 to 108 Å. For layers thicker than approximately 90 Å the x-ray diffraction patterns broadened, indicating the presence of dislocations. The crystal quality of the SLSs was excellent with 3 to 4 orders of x-ray diffraction satellite peaks typically observed. The intensity of the PL peak and the surface morphology of the layers was found to be strongly dependent on the purge time between the growth of the layers of the SLS and whether or not AsH_3 was present during the purge. We investigated purge times from 0 to 30 seconds with and without AsH_3 in the reactor during the purges. The optimum growth conditions are a purge of 15 seconds duration with AsH_3 in the reactor.

Figure 1. Incorporation of Sb into the InAsSb layer as a function of TESb / ($\text{AsH}_3 + \text{TESb}$) ratio in the vapor phase for the InAsSb/InAsP SLSs.

Figure 2. Photoluminescence at 300 K and 16 K from 40 period 78-87 Å $\text{InAs}_{1-x}\text{Sb}_x$ / 81-89 Å $\text{InAs}_{.76}\text{P}_{.27}$ SLS's grown on InAs for different Sb contents in the InAsSb layer.

Figure 3. Low temperature PL ($< 20\text{K}$) from 20 period $\text{InAs}_{0.86}\text{Sb}_{0.14}/84\text{\AA}\text{InAs}_{0.76}\text{P}_{0.24}$ SLS's grown on InAs for different InAsSb layer thicknesses.

Figure 4. Electrically injected, pulsed laser emission spectra at 80 and 180 K for a 10 period $\text{InAs}_{0.89}\text{Sb}_{0.11}/\text{InAs}_{0.74}\text{P}_{0.26}$ ($87\text{\AA} / 84\text{\AA}$) SLS active region.

An LED was constructed with a $0.7\text{ }\mu\text{m}$ thick, n-type, $\text{InAs}_{0.88}\text{Sb}_{0.12}/\text{InAs}_{0.75}\text{P}_{0.25}$ ($80\text{\AA} / 82\text{\AA}$) SLS active region. As for the previously published MQW structures, [10] a semi-metal layer consisting of a $500\text{\AA}$ thick GaAsSb (p-type) and a $500\text{\AA}$ thick InAs (n-type) heterojunction provided electrical injection for the LED. A 1 mm^2 piece of the wafer was mounted onto a header with a parabolic collector. The top contact of the LED was a $0.02''$ diameter Ti/Au dot. Operating the device at 1 kHz , 50% duty cycle, 200 mA average current, the average output power of the LED was $80\text{ }\mu\text{W}$ at 300 K . At 80 K the output power of the LED was $24\times$ that observed at 300 K . The output power of our SLS device (300 K) was $5\text{-}6\times$ that measured with the same current for LPE-grown, InAsSb alloy, commercial LEDs [18].

The electrically injected laser structure consisted of $2.5\text{ }\mu\text{m}$ of undoped AlAsSb top and bottom claddings, a p-GaAsSb / n-InAs semi-metal electron injector, and a 10 period InAsSb/InAsP SLS active region separated from the claddings by $3000\text{\AA}$ of InAs. Gain-guided, stripe lasers were fabricated with Ti/Au metallizations. The facets were uncoated. Under pulsed operation, lasing was observed in forward bias with 40×1000 or 80×1000 micron stripes. Devices were tested with 100 nsec pulse widths at 10 kHz (0.1% duty-cycle). Several longitudinal modes were observed in the $3.3\text{-}3.4\text{ }\mu\text{m}$ range, shown in Figure 4 for 80 K and 180 K operation. The wavelength of our laser shifts from $3.31\text{ }\mu\text{m}$ to $3.36\text{ }\mu\text{m}$ due to the decrease in bandgap over the $80\text{-}180\text{ K}$ temperature range. At 80 K , peak powers of 100 mW could be obtained with a maximum average power of 0.5 mW . The temperature dependence of the SLS laser threshold is described by a characteristic temperature, $T_0 = 39\text{ K}$, over the entire temperature range.

An optically pumped laser was grown on an InAs substrate with a $2.5\text{ }\mu\text{m}$ thick $\text{AlAs}_{0.16}\text{Sb}_{0.84}$ lower cladding. The active region was a $1.0\text{ }\mu\text{m}$ thick, $\text{InAs}_{0.89}\text{Sb}_{0.11}/\text{InAs}_{0.77}\text{P}_{0.23}$ ($83\text{\AA} / 87\text{\AA}$) SLS. The SLS laser was pumped with a Q-switched Nd:YAG ($1.06\text{ }\mu\text{m}$, 20 Hz , 10 nsec pulse, focused to a $200\text{ }\mu\text{m}$ wide line), and emission was detected with an FTIR spectrometer operated in a step-scan mode. Due to the low rep-rate of the pump, approximately a 4 hour scan was required to obtain an interferogram with resolution $\geq 2\text{ cm}^{-1}$. Laser emission was observed from cleaved bars, $1000\text{ }\mu\text{m}$ wide, with uncoated facets. A lasing threshold and spectrally narrowed, laser emission was seen from 80 K through 240 K , the maximum temperature where lasing occurred. The PL linewidth is $\approx 25\text{ meV}$ at 80 K , but above threshold, the laser emission narrowed to $3\text{-}5\text{ meV}$ depending on the sample. The laser emission linewidth is limited by inhomogenities in the material and the presence of multiple, unresolved longitudinal modes; similar behavior was observed in optically pumped type II, GaInSb/InAs lasers

[7,9]. The wavelength of our laser shifts from 3.57 μm to 3.85 μm due to the decrease in bandgap over the 80-240K temperature range. At 80 K, peak powers >100 mW could be obtained. The temperature dependence of the SLS laser threshold is described by a characteristic temperature, $T_0 = 33$ K, over the entire range.

4. Conclusions

We have evaluated InAsSb/InAsP SLSs as active regions for MOCVD-grown, mid-infrared lasers and LEDs. X-ray and optical characterization of the SLSs indicate very high crystalline quality for the MOCVD-grown material and electronic properties consistent with our model of the SLS. Excellent performance was observed for an SLS LED, an electrically injected laser, and an optically pumped laser. The semi-metal injected, broadband LED emitted at 4 μm with 80 μW of power at 300K, 200 mA average current. The electrically injected laser emitted at 3.36 μm at 180 K with peak powers of 100 mW at 80 K and a characteristic temperature of 39 K. The optically pumped laser displayed 3.86 μm emission at 240 K, the maximum operating temperature of the laser, and a characteristic temperature of 33 K. InAsSb/InAsP SLS laser operating temperature, characteristic temperature, and threshold power values are state-of-the-art for InAsSb lasers at ≈ 4 μm . With nominal improvements in materials and processing and the further development of multi-stage active regions, MOCVD-grown InAsSb devices should be able to satisfy the system requirements for use in chemical sensor and infrared countermeasure technologies in the near future.

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