Förderschwerpunkt Photonik

Teilvorhaben:	Leucht- und Laserdioden für die optische Kommunikationstechnik bei Wellenlängen oberhalb 2 µm
Zuwendungsempfänger:	Fraunhofer-Gesellschaft Institut für Angewandte Festkörperphysik
Förderkennzeichen:	01 BP 704A
Laufzeit:	01.09.2000 - 31.08.2003
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December 2003

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Wissenschaftlich-technische Ergebnisse

I. GaInAsSb/AlGaAsSb-based type-I diode lasers

1. Introduction

Due to the worldwide interest in infrared LEDs and diode lasers with emission wavelength above 2 µm for the optical free space communication, significant efforts are devoted to investigate new materials as well as new laser structure concepts. Moreover, this application requires robust, compact and reliable infrared laser light sources. On the basis of III-V compound semiconductor quantum structures, such lasers have been realized employing different device concepts. Within the current project antimonide-based III-V semiconductor diode lasers have been developed, with targeted purpose as direct implementation in the free space communication applications for the mid-infrared spectral interval above 2 µm. The III-V (AlGaIn)(AsSb) semiconductor materials system is favorably suitable for the fabrication of this sort of LEDs and diode lasers. Employing quaternary alloys the GaInAsSb semiconductor band gap can be tuned between 0.3 and 0.7 eV, which corresponds to a wavelength range between 1.7 and 4.2 µm. This can be realized simply by varying the alloy composition. Besides, using quaternary compounds the lattice constant can be adjusted as well, so that lattice matched as well as strained layers can be grown on the GaSb substrate.

For the wavelength range spanning from 2 to 3 µm the type-I diode laser concept with GaInAsSb/AlGaAsSb quantum wells (QWs) as active region is employed. In the type-I laser structures the electrical carriers, namely the electrons and holes, are localized in the same epitaxial layer, in this case in the GaInAsSb QW layer, and a spatially direct recombination process takes place generating the desired light emission. For the next longer wavelength interval, 3 to 5 µm, the InAs/GaInSb/AlGaAsSb type-II W-laser concept has been employed. In this configuration the electrons and holes are located in adjacent epitaxial layers, i.e. in the InAs and GaInSb, respectively, resulting in a spatially indirect recombination process for the infrared light emission. The type-II laser is described in details in the second part of the present report.

The growth of the epitaxial layer sequence for both diode laser concepts was realized using two growth techniques, the Molecular Beam Epitaxy (MBE) and the Metal Organic Vapor Deposition (MOCVD), in both cases on GaSb substrates. The research at IAF was accompanied by a study regarding MOCVD growth of group III-(AsNSb) structures, conducted by Prof. Dan Fekete at the Technion-Haifa (Israel) carried out as a subcontract of the current project. In terms of material quality, straight away after growth the epitaxial layers were on wafer-level characterized using ex-situ high resolution X-ray diffraction (HRXRD), secondary ion mass spectroscopy (SIMS) as well as photoluminescence spectroscopy (PL). For the fabrication of the optical active region of the laser structures, GaInAsSb/AlGaAsSb quantum layers and InAs/GaInSb/AlGaAsSb layer sequences have been used for the type-I and type-II lasers respectively. In the type-I layer structures the GaInAsSb QW-layers are separated by lattice matched AlGaAsSb barrier layers with Al-content varying between 20-40%. For the type-II laser structures the InAs/GaInSb/InAs QW triple-layers are separated by low Al-content AlGaAsSb interperiod barriers. For both laser types the active region is embedded between low Al-content AlGaAsSb separate confinement layers resulting in a broadened waveguide design. The waveguide core in turn is sandwiched between high Al-content AlGaAsSb optical cladding layers with Al-content about 85%, again lattice matched to the GaSb substrate. The cladding material alloy has a high energy gap and therefore a low refractive index, condition requested for a good wave guiding.

2. Diode lasers emitting between 1.7 – 2.34 µm

With a first series of samples, GaInAsSb/AlGaAsSb diode lasers with emission wavelengths between 1.7 and 2.34 µm have been investigated. A detailed study related to the temperature dependence of the threshold current as a function of the wavelength has been conducted, by comparing a set of ten different laser structures. Additionally, the laser characteristic parameters, including the characteristic temperature T_0, the internal quantum efficiency η_i, and the internal loss coefficient α_I have been deduced. Electro-optical characterization in cw mode has been performed for the whole set of diode lasers. In addition, pulsed measurements have been carried out to determine the pulsed threshold current, using 5 µs short pulses at 10 kHz repetition rate, in order to avoid self-heating of the devices. The light output power as a function of the drive current was measured at heat sink temperatures between 250 and 360 K for several ridge widths and cavity lengths.

The laser structures under investigation were grown by solid-source MBE on (100) oriented n-type GaSb:Te substrates. The active region of this set of ten lasers consists of three compressively strained 10 nm thick $Ga_{1-x}In_xAs_ySb_{1-y}$ QWs, with $0.16 \le x \le 0.30$ and $0 \le y \le 0.15$, separated by 20 nm thick $Al_{0.29}Ga_{0.71}As_{0.02}Sb_{0.98}$ barriers lattice matched to the GaSb substrate. The QW region is embedded between 400 nm thick $Al_{0.29}Ga_{0.71}As_{0.02}Sb_{0.98}$ separate confinement layers (SCLs) and sandwiched between n- and p-doped 2 µm wide $Al_{0.84}Ga_{0.16}As_{0.06}Sb_{0.94}$ optical cladding layers. The growth is completed by a p^+- GaSb contact layer. All epitaxial layers except the QWs were grown nominally lattice matched to the GaSb buffer layer. Following epitaxial growth the wafers were analyzed by high-resolution X-ray diffraction (HRXRD), photoluminescence (PL) spectroscopy and secondary ion mass spectrometry (SIMS) in order to determine the strains and compositions of the individual layers, the PL emission profile and peak wavelength, as well as the doping concentrations, respectively. Edge-emitting index-guided Fabry-Perot diode lasers with ridge widths varying from 6 to 64 µm have been prepared using standard optical lithography and chemically assisted ion beam etching (CAIBE). Ti/Pt/Au and (AuSn)Au have been deposited for the top p-contact and backside n-contact metallization, respectively. Laser bars with cavity lengths varying between 0.5 and 2 mm were cleaved and soldered either substrate-side down or, for higher output powers, epi-side down onto copper heat sinks. For several laser bars, to maximize single ended output, low-reflectivity, AR (5%), and high-reflectivity, HR (95%), coatings were applied to the cleaved mirror facets.

The 280 K cw lasing spectra corresponding to the ten different diode lasers spanning the 1.7 - 2.34 µm spectral range are shown in Figure 1. These spectra were obtained for 64 µm x 600 µm ridge geometry and cw drive currents slightly above threshold. Several devices exhibited single mode lasing emission, while multi-mode behavior emerged at higher currents. The inset displays the spectrum of the 2.13 µm laser on an expanded wavelength scale, showing well resolved multiple longitudinal modes with ~1 nm mode spacing. The thermal red shift of the emission wavelength amounted to ~1.3 nm/°C due to the shift of the gain peak.

Figure 2 illustrates representative cw power output and total power efficiency plotted versus injection current, recorded at 280 K heat sink temperature for three different diode lasers emitting at 1.94, 2.21 and 2.34 µm, all having a 64 µm x 1000 µm size. As clearly seen in the plot, the light output power drops substantially upon increasing the wavelength, so does the power efficiency, due to the increase of Auger losses and QW heterobarrier carrier leakage with increasing wavelength. The maximum output powers are limited by the onset of thermal rollover due to the substrate-side down mounting of the devices. The maximum output power decreases approximately by a factor of three when proceeding from the shortest to the longest wavelength device, accompanied by a decrease in maximum power efficiency from 29% to 10%.

Higher light output powers have been obtained by applying HR/AR coating with reflectivities of 97% and 6%, respectively, to the mirror facets of the lasers. Figure 3 depicts the cw power output and total power efficiency versus injection current at 280 K of two 64 µm x 1000 µm ridge waveguide lasers with uncoated and HR/AR coated mirror facets, both emitting at 1.94 µm. A cw output power of 388 mW was achieved for the coated laser in comparison with just 173 mW/facet for the laser without coating, at the same drive current of 1.54 A. The maximum total power efficiency (power emitted by both facets of the uncoated device) amounted to 29% for the uncoated laser and a comparable value of 27% for the coated one. The slight difference between these two values is due to the scatter between different devices.

3. Wavelength dependence of the characteristic temperature T_O

A detailed study was carried out regarding the characteristic temperature T_O of the threshold current by characterizing the devices in cw as well as in pulsed operation. Representative results for the temperature dependence of the threshold current I_{th} measured in pulsed mode are depicted in Figure 4, for four different lasers with emission wavelength of 2.34, 2.30, 2.13 and 1.94 µm. For the three diode lasers emitting on the short-wavelength side two distinct temperature intervals are visible showing different T_O values. We found that in the low temperature regime T_O decreases from 179 K to 54 K when proceeding from the 1.94 µm to the 2.34 µm device.