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Semi-insulating InP:Fe for buried-heterostructure strain-compensated quantum-cascade lasers grown by gas-source molecular-beam epitaxy

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ABSTRACT

We describe the realization of buried-heterostructure strain-compensated quantum-cascade lasers that incorporate a very high degree of internal strain and are grown on InP substrates using gas-source molecular-beam epitaxy (GSMBE). The active region of the lasers contains AlAs layers up to 1.6 nm thick with 3.7% tensile strain; restricting any post-growth processing to temperatures below 600 °C to avoid relaxation. We demonstrate that buried-heterostructure devices can be realized by using GSMBE to over-grow the etched laser ridge with insulating InP:Fe at temperatures low enough to preserve the crystal quality of the strain-compensated active region. Two distinct growth techniques are described, both leading to successful device realization: selective regrowth at 550 °C and non-selective regrowth at 470 °C. The resulting buried-heterostructure lasers are compared to a reference laser from the same wafer, but with SiO_2 insulation; all three have very similar threshold current densities, operational thermal stability, and waveguide losses.

1. Introduction

Since their invention in 1994, quantum-cascade lasers (QCLs), [1] have become the ultimate semiconductor laser sources from near-infrared [2] to middle THz [3] spectral range. QCLs are widely used now as sources of infrared laser emission for spectroscopy and chemical sensing. They also have the potential for application in military countermeasures and free-space communication.

Several applications, for example photo-acoustic spectroscopy, require high average output power, which in turn requires efficient heat sinking out of the laser ridge. There has been enormous progress in QCL technology towards the optimization of the heat extraction and the best results are obtained by means of buried-heterostructure (BH) laser fabrication using semi-insulating InP:Fe overgrown by metal-organic vapor phase epitaxy (MOVPE) [4–8].

A successful QCL design for wavelengths between 3 and 5 μm is based on strain compensation with very high degrees of internal strain, including pure 1–2 nm AlAs barriers with 3.7% tensile strain to the InP substrate [9–12]; these structures, however do not withstand the typical MOVPE regrowth temperature of about 650 °C [13]. Thus, the growth of high-resistivity InP at low growth temperatures is required for these strain-compensated QCLs. Gas-source molecular-beam epitaxy (GSMBE) has already been used before to fabricate BH telecom lasers [14] and also BH QCLs with a lattice-matched active zone [13]. However, extending the GSMBE overgrowth technique to strain-compensated QCLs with highly strained alternating $In_{0.73}Ga_{0.27}As$ and AlAs layers is not trivial and has not been demonstrated yet. Contrary to the MOVPE technique, GSMBE leaves the etched side walls of the laser ridge half a time without the group-V flux at elevated temperatures of 500–550 °C before the regrowth process is initiated. The situation arises because with a single gas injector and conventional sample rotation, the ridge shades each etched sidewall from the side-coming surface-stabilizing group-V flux during the half of the sample rotation. This is problematic because it can lead to material intermixing on the sidewalls due to strain-driven surface migration, which can cause electrical shorts. In this paper we describe the successful InP:Fe regrowth of strain-compensated QCLs that include highly strained and relatively thick (up to 1.6 nm) AlAs barriers in the active zone. The regrowth can be done selectively around a dielectric mask, similar to the technique typically used with MOVPE, but at a significantly lower growth temperature of 550 °C. These BH QCLs, when compared to the reference QCLs with SiO_2 insulation of the ridges, show comparable threshold current densities, J_{th}, and T_0; the confinement factor, Γ, is somewhat lower due to the smaller index discontinuity, and the waveguide losses, α_w, are somewhat lower due to a superior interface.

2. QCL active region design

The conduction band edge profile of the single active region cascade and the moduli square of the confined states, wavefunctions are shown in Fig. 1. The active region is designed to emit at the wavelength close to 4 μm at an operation voltage of approximately 13 V for 30 cascades. High values of T_0 and T_1 require the use of high

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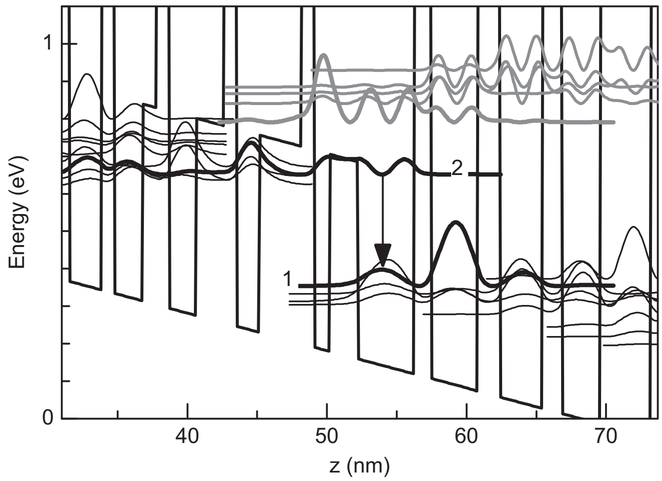

Fig. 1. Conduction band diagram and probability functions calculated within a single period of the active region with a 100 kV/cm electric field. The moduli square of the wavefunctions (***1*** and ***2***) responsible for the laser transition is drawn with the thick lines. The design emission wavelength is approximately 4 μm at an operation voltage of 13 V for 30 cascades.

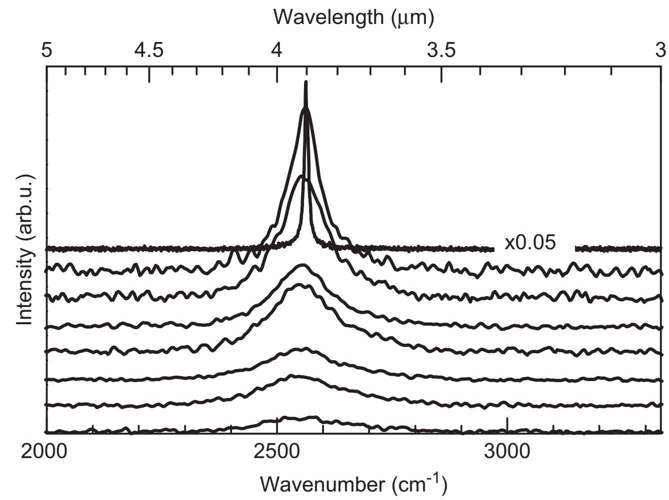

Fig. 2. Development of the emission spectrum of the BH QCL between 1.8 and 3.0 A in pulsed mode at room temperature. The half-width of the low-current electroluminescence spectrum is equal to 29 meV.

barriers within the active region to minimize the thermally activated carrier leakage from the upper laser state 2. For that purpose, we use pure AlAs with very high tensile strain (3.7%) that are grown thinner than the critical thickness for coherent growth on InP. The net strain across the single cascade is compensated by compressively strained $In_{0.7}Ga_{0.3}As$ wells. The lattice-matched InAlAs layers add to the AlAs barriers and allow to tune the tunneling probability across the structure without affecting the strain. The layer thicknesses in nm from left to right, beginning with the thickest injection barrier are ***3.0***/**0.9**/1.1/**0.2**/4.0/**1.2**/3.3/**1.6**/3.0/**1.4**/2.7/**1.2**/2.4/**1.0**/2.3/**0.9**/2.0/***1.0***/**0.9**/1.9/***2.0***/**0.9**/1.6. The AlAs barriers are in bold, the $In_{0.52}Al_{0.48}As$ barrier material layers are in bold italic, and the $In_{0.73}Ga_{0.27}As$ well layers are in roman. Underlined layers are Si-doped to $4\times10^{18}\,cm^{-3}$, which results in an electron sheet density of approximately $2\times10^{12}\,cm^{-2}$ per cascade or 5×10^{17} cm^{-3} in terms of average doping across the cascade.

This particular design uses the thick InAlAs barrier next to the thinnest quantum well instead of the thin and high AlAs barrier, which lowers the interface scattering [12] in the transition region, evidenced by narrow electroluminescence spectrum (Fig. 2).

3. Sample fabrication

Both the primary growth of the laser structure and the second growth (regrowth) for the BH part of the process are carried out in a Riber Compact 21 T GSMBE system, using solid sources for In, Ga, and Al; As and P are supplied by arsine and phosphine that are pre-cracked at 920 °C. Both the Si doping for the active region as well as the Fe doping for the regrown insulator layers are supplied from solid sources. The growth chamber is pumped using a 1600-l/s turbo pump.

The laser structure was grown on a low-doped ($n=2\times 10^{17}$ cm^{-3}) InP:S substrate, which serves as the lower cladding layer. The epitaxy sequence consists of 100 nm InP:Si ($n=1\times 10^{17}$ cm^{-3}); 200 nm of lattice matched InGaAs:Si spacer ($n=7\times10^{16}$ cm^{-3}); then the 1.3 μm (total thickness), 30-period active region; 200 nm of lattice matched InGaAs:Si spacer ($n=7\times10^{16}$ cm^{-3}); then a 2.5 μm ($n=1\times10^{17}$ cm^{-3}) InP:Si plus 1 μm ($n=3\times10^{18}$ cm^{-3}) InP:Si top cladding; and 100 nm of lattice matched InGaAs:Si ($n=8\times10^{18}$ cm^{-3}) contact layer.

One reference laser and two BH lasers were fabricated from the same wafer. The reference QCL was processed into approximately 25-μm-wide deep-etched ridges using optical lithography and wet-chemical etching. The side-wall insulation of the reference QCLs was accomplished by sputtering of a 500 nm thick SiO_2 layer. The two BH QCLs were first wet-etched into stripes of various widths (approximately 10, 14, 20, 29, and 49 μm) then insulated by overgrowth of nominally 6 μm InP:Fe. One BH QCL (BH470) was overgrown non-selectively at 470 °C with subsequent removal of the overgrown material on the top of the stripes to facilitate electrical contacts. The second BH QCL (BH550) was overgrown selectively at 550 °C, using a dielectric mask to define the growth area and with subsequent lift-off of the mask in buffered HF. Thermally evaporated Au/Cr is used for ohmic contacts. Selective regrowth at 550 °C significantly simplifies the further fabrication process and represents an advantageous way to produce buried-heterostructure QCLs compared to the non-selective regrowth at 470 °C. In order to avoid electrical shorts due to surface migration of the atoms at the etched laser side walls, regrowth in sample BH550 was initiated as soon as the temperature had reached the set-point of 550 °C, minimizing the time of detrimental exposure. This step ended up being successful.

Fig. 3 shows the scanning electron microscope image of the cleaved facet of the 14 μm-wide laser ridge of sample BH550. Sample BH550 was processed with metallic contacts evaporated directly onto the InP:Fe and the top of the laser ridge. Sample BH470 includes a 500 nm-thick top SiO_2 insulating layer with the contact windows opened above the laser ridge. Including this top electrical insulation has significantly improved the yield of defect-free lasers across the wafer.

The absence of the insulating SiO_2 layer in sample BH550 allows a direct characterization of the insulating properties of the overgrown InP:Fe material. The electrical resistance of the InP:Fe insulation layer (sample BH550) cleaved next to the laser ridge (the bond pad itself) was measured as a function of temperature. Fig. 4 shows the resistance of the 0.2 mm^2 pad as a function of reciprocal temperature. The room-temperature resistance gives a resistivity of roughly 0.2×10^8 Ω cm, similar to what was measured in Ref. [13]. A fit of the data gives a thermal activation energy of 680 meV. The value of the extracted activation energy is about half of the InP band gap, consistent with the Fe deep acceptor level that results in the insulating properties of the