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Growth initiation for buried-heterostructure quantum-cascade laser regrowth by gas-source molecular-beam epitaxy

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ABSTRACT

We describe an optimized growth sequence for the overgrowth of quantum cascade laser ridge sidewalls with semi-insulating InP:Fe. A thin $In_{0.52}Al_{0.48}As$ spacer layer grown on the laser ridge sidewalls before InP:Fe prevents the formation of void defects at this interface, which appear otherwise. Elimination of these voids at the sidewalls has led to more than a two-fold improvement of the thermal conductivity in a 7 μm wide buried-heterostructure quantum-cascade laser overgrown with InP:Fe by gas-source molecular-beam epitaxy, and has allowed the continuous-wave operation of the laser up to 210 K. The measured thermal conductance is $G_{th} = 500$ W/K cm^2 at 210 K and $G_{th} = 1020$ W/K cm^2 at 127 K, comparable to the state of the art literature values obtained with regrowth by metal-organic vapor-phase epitaxy.

1. Introduction

Almost 20 years after their invention, quantum-cascade lasers (QCLs) [1,2] occupy today an important position in the global infrared optoelectronics. Photoacoustic spectroscopy, environment monitoring, hot objects' simulation, and free-space communication systems are selected examples of the current and potential applications of QCLs, and all profit from QCLs characteristics which distinguish them from other infrared light sources. These characteristics include the generation of high optical powers at a narrow emission spectrum, the ability to tune the emission wavelength of a device by changing the injection conditions, and the possibility to engineer the emission wavelength using the same heterostructure material.

One important challenge of QCL technology is the capability to extract heat out of the laser core in order to reduce current leakage effects and guarantee thermal stability and laser performance. This issue is particularly important in QCLs operating at high duty cycles and in continuous wave (cw)-operation mode, where the difference between the active region and the heat sink temperature achieves values as high as $\Delta T = 60$–100 °C [3,4]. Increased threshold currents, reduced output powers, and reduced maximal operating temperatures are some of the direct consequences of the laser core heating in QCLs [4–7].

In order to provide the thermal conduction necessary for an efficient heat extraction, QCLs are usually fabricated as a buried-heterostructure (BH) with the etched laser ridge overgrown by a semi-insulating semiconductor material. A widely used material here is iron doped indium-phosphide or, shortly, InP:Fe. Most reported BH-QCLs with InP:Fe lateral cladding use the metal-organic vapor-phase epitaxy (MOVPE) technique for growing both the laser core and the semi-insulating material [6,8,9]. Nevertheless, the typical growth temperature of 650 °C required for MOVPE makes this technique unsuitable for regrowing InP:Fe in QCLs with a high degree of internal strain [10]. This is the case of a variety of short-wavelength (3–5 μm) QCL designs based on strain-compensation of $In_xGa_{1-x}As$ ($x = 0.7$–1.0) wells and 1–2 nm-thick AlAs barriers to the InP-substrate. It is expected that the temperatures experienced during an MOVPE overgrowth of strain-compensated QCL structures with very high local strain would cause degradation of the lasers due to strain relaxation and strain-driven interdiffusion [10].

In the previous works we demonstrated the advantages of using gas-source molecular beam epitaxy (GSMBE) to fabricate BH-QCLs using InP:Fe overgrown at temperatures < 600 °C [10,11]. The proposed method has been first demonstrated for a lattice-matched QCL (emission wavelength $\lambda = 10.7$ μm) [10] and then extended to a strain-compensated design ($\lambda = 3.9$ μm) [11]. In none of the cases, leakage currents through the InP:Fe material

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or a deterioration of QCLs-characteristics after the InP:Fe regrowth were observed.

Initiating the InP:Fe regrowth directly on the sides of the laser ridge, however, leads to a number of void defects. These are mostly located at the arsenide–phosphide interface between the active region and the regrown insulating material. The presence of these defects is reproducible and depends only weakly on growth temperature and PH_3 flux. Interestingly, the electrical insulation properties of the regrown material are not affected by the presence of the void defects, i.e., the laser did not short electrically and the laser threshold remained unchanged. However, we expect that the void defects will reduce the lateral heat flow, which is crucial for the heat extraction in narrow laser ridges. As a matter of fact, no cw-operation was previously observed in BH-QCL lasers using GSMBE for the InP:Fe regrowth [10,11].

In this work we describe an improved method for GSMBE regrowth of InP:Fe on strain-compensated QCL ridges. Using a 20 nm-thin InAlAs spacer layer between the laser ridge sidewalls and the InP:Fe insulating layers we improve the crystal quality of the interface, improving heat extraction from the laser core while preserving the high electrical-resistivity of the overgrown material. The optimized regrowth sequence led to cw-operation in the 100–210 K temperature range of a 7 μm–wide BH-QCL with an emission wavelength of $\lambda = 5.4$ μm. The measured thermal conductance at the temperature of 210 K is $G_{th} = 500$ W/K cm^2, which is comparable to the state of the art BH-QCLs regrown using MOVPE.

2. Sample fabrication

Both the primary growth of the laser structure and the secondary growth (re-growth) for the BH part of the process are carried out in a Riber Compact 21T 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 re-grown 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}); 250 nm of lattice matched InGaAs:Si spacer ($n = 7 \times 10^{16}$ cm^{-3}); then the 2.2 μm (total thickness), 40-period active region; 250 nm of lattice matched InGaAs:Si spacer ($n = 7 \times 10^{16}$ cm^{-3}); then a 3 μm ($n = 1 \times 10^{17}$ cm^{-3}) InP:Si plus 1 μm ($n = 3 \times 10^{18}$ cm^{-3}) InP:Si top cladding. The active region itself is based on strain compensated InGaAs–InAlAs material combination with high AlAs highly strained extraction barriers [12–17]. This configuration has proven to be very useful to minimize carriers leakage, contributing to a high temperature performance of QCLs [17–19].

A number of BH-QCLs were fabricated using a 6 μm wide SiO_2 dielectric etch-mask oriented along the $(1\bar{1}0)$ crystallographic direction. The ridges were etched in a HBr:HCl:H_2O_2:H_2O (10:5:1:50) solution, rinsed with deionized water, dried with nitrogen, and loaded into the MBE loadlock. The SiO_2 dielectric etch-mask was left on the QCL ridge after etching in order to protect the top of the ridge from the regrowth by the semi-insulating InP:Fe. After the regrowth this mask was removed in buffered HF and so the access to the top laser contact was achieved. Thermally evaporated Au/Cr was used for ohmic contacts. The lasers with improved overgrowth were also covered with 4–5 μm thick galvanic gold as a heat spreader and soldered epi-down on AlN sub-mount using a close to eutectic Au:Sn (80:20) solder.

3. Morphology of the interface between the QCL side-walls and the regrown InP:Fe material

Fig. 1 shows scanning electron microscope (SEM) images of cleaved facets of QCL ridges overgrown by GSMBE. Panels (a) and (b) are closeups of the overgrown QCL ridge sidewalls in the reference and in the optimized BH-QCL, respectively.

Both lasers were regrown with 6 μm InP:Fe at 500 °C measured by a thermistor at the growth rate of 1 μm/h. In the reference BH-QCL (a), the wafer was heated under a PH_3 flux and the overgrowth of InP:Fe was done directly on the etched sidewall. In the optimized BH-QCL (b), the wafer was heated in an AsH_3 flux, then the regrowth was started with the 20-nm InAlAs spacer layer. Immediately after, the gas flux was switched to PH_3 and the overgrowth has continued with InP:Fe. A significant number of void-like defects in the QCL ridge overgrown without the InAlAs spacer layer are observed (Fig. 1a). These defects are mostly located at the interface between the active zone and the overgrown InP:Fe and are absent in the QCL overgrown using the InAlAs spacer (Fig. 1b). This impact of the InAlAs spacer layer on the interface morphology is consistently observed on a number of samples grown at various temperatures and also different gas fluxes. Furthermore, it is observed for the lattice-matched active zones as well as for the strain-compensated laser designs [10,11].

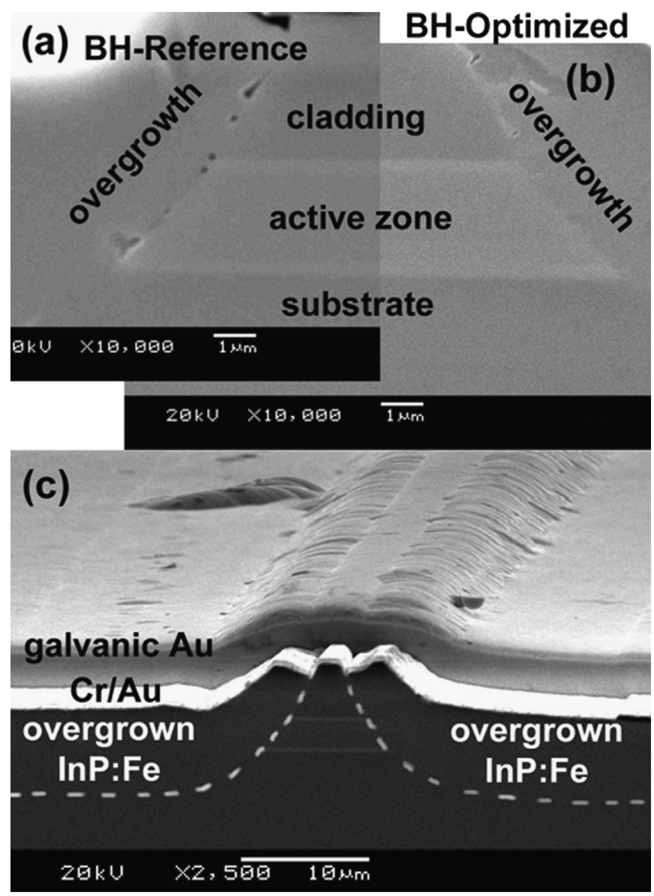

Fig. 1. SEM images of the cleaved facets of overgrown QCL ridges by GSMBE. Panels (a) and (b) are the magnified views of the overgrown QCL ridge sidewalls. In case (a), the overgrowth of InP:Fe is done directly on the etched sidewall. Case (b) shows the optimized BH-QCL. In this case, the overgrowth of InP:Fe is done on the 20 nm-thick InAlAs spacer layer grown previously on the etched sidewall. Panel (c) shows the low-magnification image of the optimized BH-QCL. The shape of the wet-etched laser ridge (highlighted with the white dashed line) and the surface planarization of the regrown structure can be well recognized. The same dashed line marks the location of the InAlAs spacer layer.