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GSMBE growth of GaInAsP/InP 1.3 μm-TM-lasers for monolithic integration with optical waveguide isolator

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Abstract

The GSMBE growth of GaInAsP/InP 1.3-μm-TM active core and highly p-doped contacting layers required for fabricating an integrated optical waveguide isolator is studied in detail. The deposition of a highly doped 1.17-μm-GaInAsP:Be contacting layers provide a good electrical contact between the III–V semiconductor and the ferromagnetic metal is reported. The GSMBE growth of strain-compensated GaInAsP multiple-quantum wells (QWs) allows one to stack up to fifteen 12-nm-thick −1.1% tensile-strained QWs. Broad area TM-lasers with threshold a current density of 0.8 kA/cm^2 and characteristic temperature of 75 K (in the range of 20–80 °C) are obtained for 600 μm-long lasers comprising 6 QWs. The possible wavelength extension of TM lasers to 1.55-μm is also discussed.

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Keywords: A3. Gas source molecular beam epitaxy; B2. Tensile-strained multiple quantum wells; B3. Optical waveguide isolator; B3. TM semiconductor amplifiers

1. Introduction

Reducing the manufacturing cost of laser diodes by developing a planar waveguide-based integrated optical isolator is very attractive. The manufacturing cost of laser diode packages would be significantly reduced by removing the external isolator. This can be done by depositing an electrical contact consisting in a transversely magnetized ferromagnetic metal on a semiconductor optical amplifier (SOA) [1]. The principle operation of such an integrated optical waveguide

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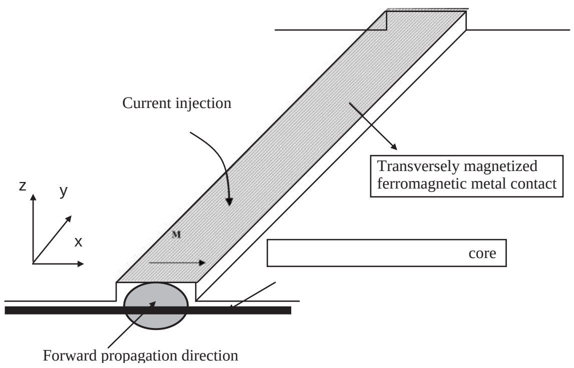

Fig. 1. Schematic illustration of the integrated optical waveguide isolator based on the dependence of the absorption coefficient on the propagation direction along the *y*-axis of the waveguide.

isolator is schematically illustrated in Fig. 1. A transversely magnetized ferromagnetic metal is deposited on the top of an InP-based optical amplifier. The ferromagnetic metal is used both as a magneto-optical (MO) cladding layer and as an electrical contact. The magnetization lies in the plane of the MO layer and perpendicular to the light propagation direction. Therefore, the transverse magneto-optic Kerr effect leads to a non-reciprocal effective index change of guided waveguide modes when a TM mode propagates in the planar MO waveguide. The forward TM mode is then amplified while the backward TM mode is partially absorbed. Electrical pumping of the device can compensate the absorption in the forward propagation direction. The result is a device, which, being transparent in one propagation direction while providing net loss in the other direction, is isolated. The isolation ratio is proportional to the absorption difference between the two propagation directions.

The experimental demonstration of this concept requires an active layer exhibiting a strong TM gain and a good electrical contact between the III–V semiconductor and the ferromagnetic metal. In this contribution, we report the fabrication of such InP-based active core and contacting layers by GSMBE. This novel concept is demonstrated at 1.3 μm and the extension to 1.55 μm is then discussed.

2. III–V semiconductor/ferromagnetic metal contact layers

The usual contact layer suitable for standard GaInAsP/InP heterostructures consists in a highly doped 300-nm-thick ternary layer ($\sim 3 \times 10^{19}\,\mathrm{cm}^{-3}$). This thick InGaAs layer cannot be used in this device due to the strong absorption of the 1.3 μm light in this ternary material. To avoid this absorption, we need to use quaternary layers with bandgap below 1.3-μm, keeping the required high p-doping level. By growing the Be-doped quaternary at low temperature ($T_s = 460\,^{\circ}\mathrm{C}$), we succeeded in fabricating highly doped contacting layers (up to $2 \times 10^{19}\,\mathrm{cm}^{-3}$) with a bandgap of 1.17 μm as illustrated in the electrochemical $C-V$ (ECV) carrier concentration profile of Fig. 2. A 15-nm-thick cap of ternary layer grown on top of a highly doped 100-nm-thick quaternary layer is then sufficient to provide a good electric contact between the III–V semiconductor and ferromagnetic metal.

3. Tensile strained MQWs

In order to observe the non-reciprocal effective index change, the active layer must provide strong gain discrimination between TE and TM polarization. This requires growing tensile-strained multiple-quantum wells (MQWs) instead of the compressive MQWs usually used in optoelectronic devices. Using standard growth conditions, described in detail in

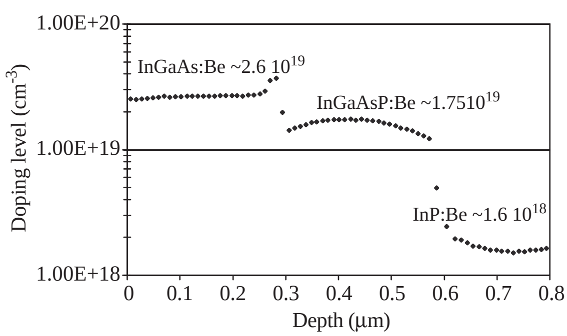

Fig. 2. ECV profile of an III–V hybrid contact comprising ternary and quaternary layers. The 300 nm-thick layers are used for an accurate p-type doping level measurement.

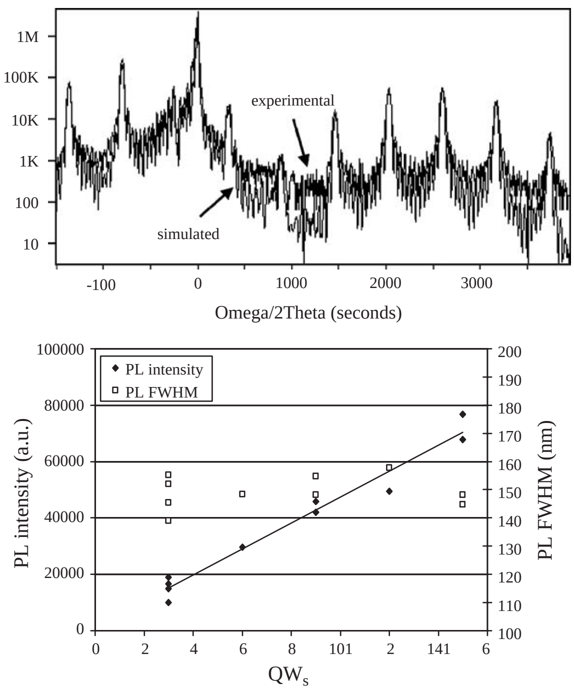

Fig. 3. Top: Experimental and simulated X-ray curves of a MQWs heterostructures comprising twelve –1.1% tensile strained QWs. Bottom : Room temperature photoluminescence intensity and linewidth of –1.1% tensile-strained MQWs as a function of QWs number.

Ref. [2], GSMBE growth of strain-compensated GaInAsP MQWs allows one to stack up to fifteen 12-nm-thick −1.1% tensile-strained QWs. The excellent agreement between experimental and simulated X-ray curves demonstrates the good structural properties of such heterostructures (Fig. 3a). This is confirmed by the room temperature-photoluminescence (RT-PL) properties of the MQWs. As shown in Fig. 3b, the PL intensity increases proportionally with the number of QWs while the RT-PL linewidth remains constant. Transmission electron microscopy (TEM) observation evidences slight undulations of the QWs upper interfaces running along the [1 1 0] direction, whereas the lower interfaces is flat (Fig. 4). The amplitude of the undulations does not increase with the QW number but depends on the Ga content of the well. These undulations are attributed to a complex As/P exchange during the growth interruption used for changing the V-elements flow [3,4],

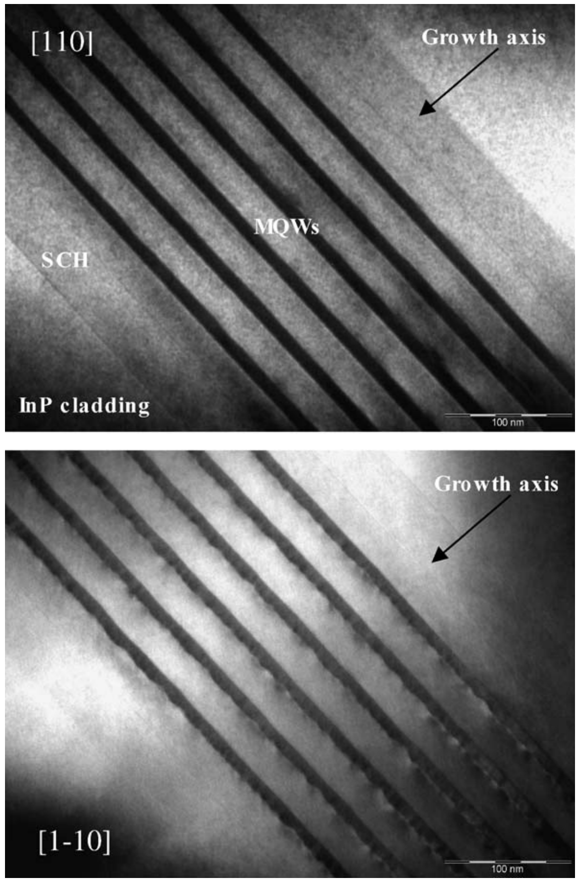

Fig. 4. [1 1 0] and [1 $\bar{1}$ 0] cross-sectional TEM images of a six 12-nm-thick –1.1% tensile-strained QWs heterostructures.

Anan et al. [3] have shown that the deposition of an In monolayer at the upper QW interfaces improves the interface quality, indicating a way to further optimization of the active layer.

4. Devices performances

Broad-area (BA) lasers have been processed on samples with an active core based on −1.1% tensile-strained InGaAsP MQWs confined by +0.3% compressively strained barriers ($\lambda_g = 1.06\,\mu m$) and enclosed within two undoped lattice-matched InGaAsP separate confinement heterostructure layers ($\lambda_g = 1.03\,\mu m$). Samples comprising 3, 6, 9, 12 and 15 QWs have been studied (Fig. 4) and TM lasing was observed for all samples. As expected, the threshold current density (J_{Th}) per QW slightly decreases with the QW number except for the 15 QWs sample for which J_{Th} increases significantly (from 95 to 191 A/cm^2/QW for a cavity length of 600 μm). This degradation of the material quality observed for 15 QWs is likely due to the relatively large strain incorporated in the heterostructure. Nevertheless, active media comprising up to 12 strain compensating QWs with good devices performances can be fabricated, opening the way to a large range of design for the SOA active core of the integrated isolator.

J_{Th} of 0.8 kA/cm^2 and T_0 characteristic temperature of 75 K (in the range of 20–80 °C) are obtained for 600-μm-long lasers comprising 6 QWs (Fig. 5). These performances are comparable to standard compressive-strained GaInAsP/InP 1.3-μm-TE-lasers in agreement with previous publications [5–7]. Lasing at 5 kA/cm^2 is observed for devices with cavity length as low as 100 μm. From the dependence of lasers performances versus cavity length, we derive an external quantum efficiency of 54% and an internal absorption of about 7 cm^{-1}. Isolation strengths of up to 2.0 dB/mm have been observed in the first generation of integrated optical isolator using similar active core, demonstrating the feasibility of the novel concept [8].

5. Wavelength extension

The extension of the isolator to the full range of the telecom window (1.3–1.55 μm) is attractive but not immediate using the GaInAsP material system. Indeed, the bulk lattice-matched ternary is emitted at about 1.66 μm. The change of composition required for a tensile strain and the quantum confinement induced in the QW leads to a strong decrease of the wavelength emission, typically down to 1.5 μm [7]. A good compromise to fabricate 1.55 μm TM lasers consists in growing relatively thick wells with the minimal tensile strain required for TM emission. As shown in Fig. 6, 1.55 μm photoluminescence emission can be achieved for −1% tensile-strained 15-nm-thick MQWs. J_{Th} of about 1.5 kA/cm^2 is obtained for 600-μm-long 6 QWs BA devices with a laser emission at 1.57 μm. These preliminary results

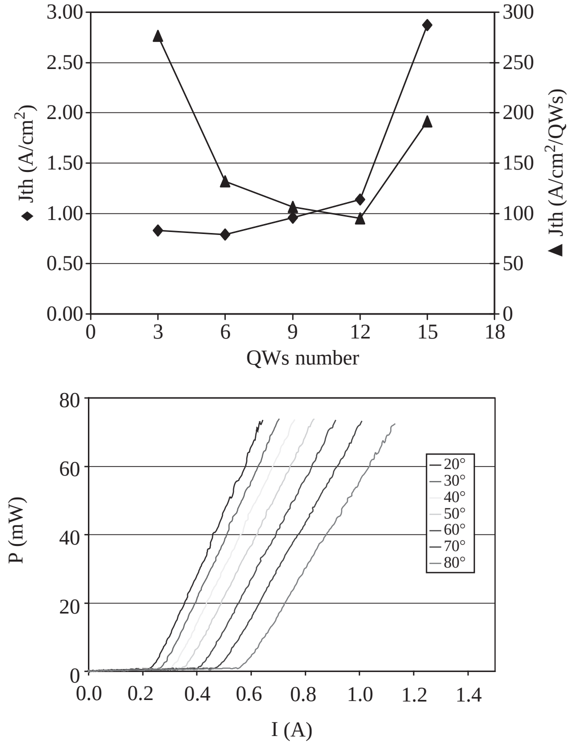

Fig. 5. Top: Threshold current density and threshold current density per QW of 600 μm × 50 μm BA lasers as a function of QWs number. Bottom : P(I) curves of a 600 μm × 50 μm BA laser for the 6 QWs heterostructure in the temperature range of 20–80 °C.

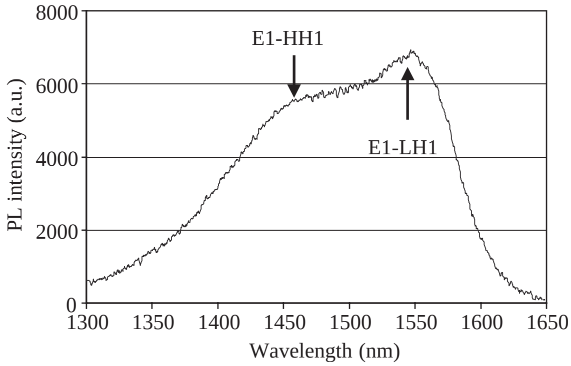

Fig. 6. Photoluminescence spectra of –1% tensile-strained MQWs showing electron/light-hole PL emission at 1.55 μm.

open the way to an extension of the isolator concept to the 1.55 μm telecom window.

6. Conclusion

The structural and electronic properties of GaInAsP/InP 1.3-μm-TM active core and highly p-doped contacting layers grown by GSMBE are reported in detail. By growing the Be-doped quaternary at low temperature, we succeeded in fabricating highly doped quaternary contacting layers with a bandgap of 1.17 μm providing a good electric contact between the III–V semiconductor and the ferromagnetic metal. Broad-area lasers performances such as threshold current density and characteristic temperature comparable to standard compressive strained GaInAsP/InP 1.3-μm-TE-lasers are obtained, opening the way to the fabrication of an integrated optical waveguide isolator. The possible wavelength extension of such devices to 1.55 μm is also introduced.

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