Monolithic Integration of a Spot Size Transformer With a Planar Buried Heterostructure In GaAsP/InP-Laser Using the Shadow Masked Growth Technique

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Abstract—**We present a vertically tapered InGaAsP/InP planar buried heterostructure (PBH) laser for low loss coupling to single-mode fibers. To achieve the vertical tapering we make use of the shadow masked growth technique. Tapered lasers with beam divergences of 15° in both lateral and transverse directions were realized. In comparison with untapered lasers, the coupling losses to cleaved single-mode fibers could be reduced by 4.8 dB down to 5.8 dB.**

I. Introduction

IN OPTICAL COMMUNICATION systems several optical interconnections between opto-electronic devices and single mode fibers are required. Generally there is a big mismatch between the large circular mode in a fiber and the small asymmetric mode in a III–V semiconductor waveguide component, leading to high coupling losses. During the past years many researchers have focused on the integration of mode size converters with passive waveguide components in order to improve the coupling efficiencies [1]–[10]. Less attention has been paid to the integration of mode size converters with active devices [11]–[13]. In this letter, we present the monolithic integration of a 1.55-μm Fabry–Perot InGaAsP/InP laser with a spot size transformer using the shadow masked growth technique.

II. Device Structure and Fabrication

Fig. 1 gives a schematic view of the realized laser with spot size transformer. The laser has a simple double heterostructure active layer (150 nm InGaAsP, $\lambda_g = 1.55$ μm), which is buried by p/n-InP current blocking layers. The cavity length is 600 μm, the width of the active layer is 2.2 μm. In the spot size transformer the thickness of the active layer is reduced to 50 nm over a distance of 200 μm.

To realize the vertical tapering of the active layer, we made use of the shadow masked growth (SMG) technique [14]. SMG uses a monocrystalline mask, that is held by means of a spacer layer at a certain distance above the substrate. During epitaxial growth the deposition on the substrate takes place through the window in the shadow mask. Thickness changes are fully controlled by the lateral dimensions of the shadow mask and the reactor pressure: the smaller the mask window and the higher the reactor pressure, the larger the growth rate reduction relative to the nominal growth rate on a non-masked substrate. The SMG technique is described in detail elsewhere [15].

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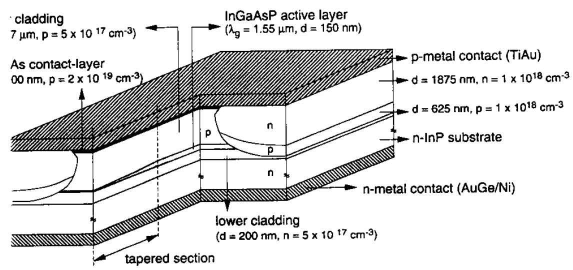

Fig. 1. Schematic drawing of a double heterostructure PBH laser with integrated spot size transformer.

The vertically tapered PBH laser requires four growth steps. All growth steps were done in a low pressure/atmospheric pressure horizontal MOVPE-reactor [16]. In a first run the shadow mask, which consists of a 6-μm InGaAs spacer layer and a 1-μm InP mask layer, was grown on an n-type InP substrate. Then the shadow mask is defined by standard photolithography, non-selective etching through the mask layer and selective etching of the InGaAs spacer layer (see Fig. 2). The shadow mask was designed to achieve adiabatic tapering [17]. The width of the mask window varies exponentially from 150 μm at the start of the taper to 5 μm at the end of the taper over a distance of 200 μm. In this way the thickness decreases more slowly at the end of the taper. The relative growth rate through a 5-μm window is three times lower than that on a non-masked substrate.

In the second run a 200-nm n-InP cladding layer, the 150-nm InGaAsP ($\lambda_g = 1.55$ μm) active layer and a 200-nm p-InP layer (first part of the cladding layer) are grown by the shadow masked growth technique (see Fig. 2). This growth is performed at atmospheric pressure in order to achieve the highest possible thickness reduction [15]. After growth the shadow mask is removed. To do so the deposited layers in the mask window and in the unmasked areas are covered with

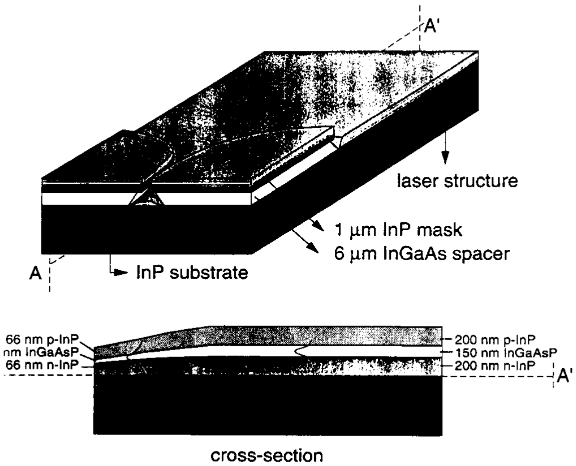

Fig. 2. Schadow masked growth of the laser structure.

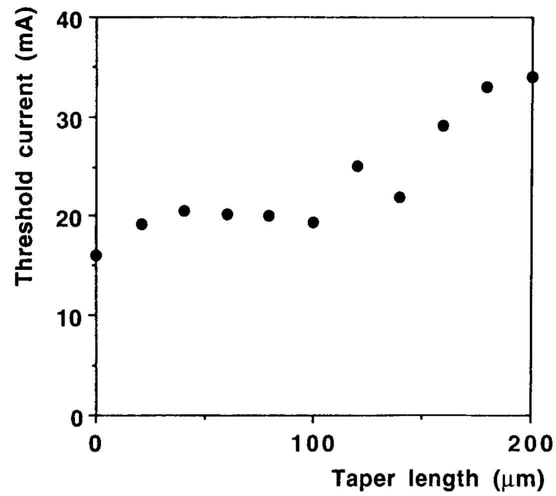

Fig. 3. Threshold current as a function of taper length.

photoresist. The deposited layers on top of the mask, the InP mask and the InGaAs spacerlayer are then selectively removed.

After lift-off of the shadow mask, a 1.5-μm p-InP layer (second part of the cladding layer) and a 100-nm highly p-doped InGaAs contact layer are grown in a third run. Since only a small part of the laser structure is grown with the SMG-technique, the total laser structure is nearly planar. Then 5-μm wide SiO_2-stripes are deposited and 2.5-μm high mesas are etched with a bromine-methanol solution. Finally the p/n-InP current blocking layers are grown.

To achieve the laser device p and n contacts were defined by conventional processing techniques. Current is injected over the whole laser structure (also in the tapered section).

SMG offers some advantages to other techniques for the fabrication of tapered lasers. There are no critical lithographic steps: the smallest dimension (window width) is 5 μm. This is large when compared to lateral tapers realized with e-beam lithography which can have lateral dimensions of only 100 nm [4], [5]. No special or critical etching techniques are required, such as etching with a dynamic etch mask [9]. SMG tapers are defined by growth, not by etching. A disadvantage of SMG might be the additional growth of the shadow mask and the additional lift-off processing step. However, once the lift-off process is finished, conventional growth and processing steps can be used to finish the laser device. The SMG technique is fully compatible with advanced PBH-laser structures.

III. Experimental Results

All lasers had a total cavity length of 600 μm. We cleaved lasers at different positions in the taper, which means that the length of the non-tapered active region varies from 580 to 400 μm and the taper length from 20 to 200 μm. Reference lasers, which had the same growth and processing steps (except the shadow masked growth), have threshold currents of 16 mA and a differential quantum efficiency of 18%.

Fig. 3 shows the threshold current as a function of taper length. For the short tapers ($\leq$100 μm), we only see a slight increase. For tapers longer than 100 μm, the threshold current increases rapidly, which can be explained as follows. During shadow masked growth, there are not only thickness variations, but also compositional variations: InGaAsP-layers become Ga-rich for small mask windows, the As/P ratio remains almost unchanged and therefore the bandgap increases [15]. The compositional changes during SMG can lead to mismatched layers. However, only for small mask windows and thick InGaAs(P) layers, the strain might become too large and introduce misfit-dislocations. The active layer thickness in a laser is generally sufficiently small, especially in the narrow mask windows (where the thickness is reduced by a factor three), to be free of misfit-dislocations. For lasers with a cavity length of 600 μm, the emission wavelength shifts from 1550 nm for an untapered reference laser to 1534 nm for a laser with 200-μm tapered section. To evaluate the impact of the compositional variations in the taper, we also cleaved some lasers with a cavity length of 300 μm. We observed a wavelength shift of 34 nm for a laser with 200-μm taper. This means that the lasing wavelength and the wavelength corresponding to maximal gain do not coincide on all positions along the laser. Due to the compositional variations in the taper, the round trip gain in the laser decreases, resulting in higher threshold currents for lasers with a long tapered section. We expect that the low threshold current can be maintained by only injecting current in a part of the taper. In that case the remainder of the taper forms a transparent window, since the compositional variations lead to a higher bandgap. Unlike the threshold current, the differential quantum efficiency is independent of the taper length.

By integrating a taper with the laser, we aim to decrease the divergence of the laser beam and thus increase the coupling efficiency between the laser and a single mode fiber. Fig. 4 shows the lateral and transverse divergence angle (FWHM) as a function of the taper length. The transverse angle changes from 42° for a reference laser to 15° for a laser with 200-μm taper. The lateral angle decreases from 32 to 15°. This means that we obtain a narrow circular beam (15 × 15°) for

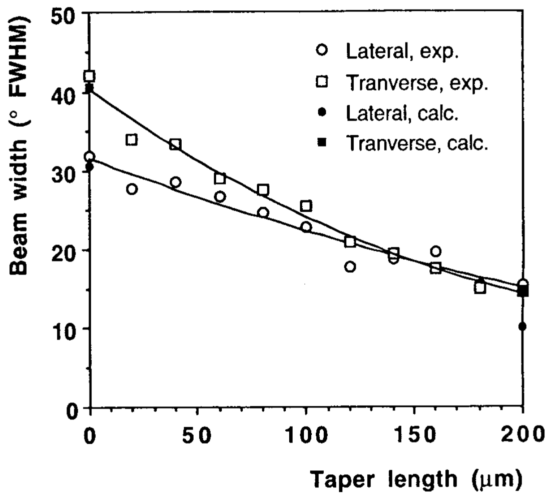

Fig. 4. Experimental (exp.) and calculated (calc.) lateral and tranverse divergences as a function of taper length.

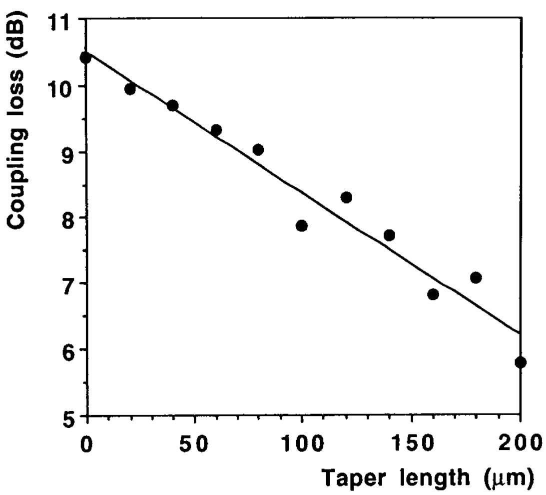

Fig. 5. Coupling loss of laser light coupled into a cleaved monomode fiber as a function of taper length.

the laser with 200-μm taper. The achieved beam divergences correspond well to the predicted values for the divergence of the local normal mode at the facet (see Fig. 4). Finally we measured the coupling loss when coupling laser light into a cleaved single mode fiber (core diameter = 8 μm). The results are presented in Fig. 5. The coupling losses decrease from 10.5 dB for a reference laser to 5.8 dB for a laser with 200-μm taper, which is an improvement of 4.7 dB.

IV. Conclusion

We have realized, for the first time, InGaAsP/InP lasers with an integrated mode size transformer by means of the shadow masked growth technique. We have demonstrated that the SMG-technique is fully compatible with a PBH laser structure. Lasers with a 200-μm taper have a beam divergence of $15 \times 15°$. The coupling loss to a single mode fiber is only 5.8 dB, which is a 4.7 dB improvement compared to non-tapered lasers. A drawback is the increase in threshold current with taper length because of the compositional variations occurring during shadow masked growth. This problem can be solved by using quantum well active regions and by injecting current in only a part of the tapered section. The reduction of the quantum well thickness as well as the compositional variations during SMG will increase the bandgap in the taper, so that the main part of the taper will form a transparent window.

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