Multi-Guide Vertical Integration in InP – A Regrowth-Free PIC Technology for Optical Communications

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Introduction

Monolithic photonic integrated circuits (PICs) provide an automated (optical alignment by means of lithography), robust (no moving parts), small footprint (no bulk-optics assemblies) and volume-scalable (wafer start rather than optical sub-assembly scaled) solution to a component base of fiber-optics communication systems and therefore are an attractive design and manufacturing option for both tele- and datacom. InP-based materials are and will continue to be a natural choice for transmitter, receiver and transceiver components in such systems, since they are the direct bandgap semiconductors perfectly suited for transmission and reception in the most important wavelength ranges around 1.3μm and 1.5μm. At the same time, InP-based compound semiconductors offer a variety of choices for optical guiding and processing of the guided waves. Together, a natural ability to generate / detect optical signals in a required wavelength range and an availability of highly functional passive waveguide circuitry in this range makes InP-based compound semiconductors a perfect material platform for optical communications PICs. Such PICs have been the focus of an intensive research over the last thirty years and now are emerging as an industry accepted technology [1]. Still, their market penetration (as well as that of any other PIC technology, for this matter) is not very significant. Development of a versatile and cost-efficient photonic integration platform in InP remains the key to further advancements in the area. Multi-guide vertical integration (MGVI) is such a platform and, unlike its counterparts, implementable in one-step epitaxial growth process. This not only eliminates yield issues associated with multiple growth steps, but also allows for decoupling of epitaxial growth and wafer fabrication, thereby enabling to outsource each of them to commercial InP foundries (which currently are mostly RF electronics, not photonics, foundries) and practically implement a fabless model (which otherwise is limited to research or in-house photonic fabs). This paper explains the basics of MGVI platform, describes its key building blocks, and reports on exemplary PICs for optical communications.

Multi-guide vertical integration platform

The key to any photonic integration platform is an ability to combine different waveguide devices (and materials they are made from) for different – active and passive – functions onto one substrate. In a case of the InP-based PICs for optical communications, circuit functionality includes, but is not limited to: light emission, amplification, detection and modulation, on the active side, in addition to the guided wave (re)routing, splitting / combining, wavelength division (de)multiplexing (WDM) and mode / spot-size converting (SSC), on the passive side. These functions require different semiconductor materials: waveguide detector typically has its core layer bandgap wavelength λ_G well above, emitter an amplifier – close to, and passive devices – well below the operating wavelength λ. Also, they need different doping and waveguide designs: the active waveguides are doped as a vertical PIN structure and benefit from a strong confinement, while the passive waveguides are preferably not doped at all and often diluted. It is clear that such features cannot be combined in a simple planar waveguide structure with one – common – waveguide for all of them. Basically, there are two distinct approached to this problem: different semiconductor materials either are locally grown, e.g. through an etch and regrowth process, thereby enabling for a planar waveguide structure with butt-coupling between the functional waveguides, or they are vertically stacked in one growth step process, forming a multi-guide vertical waveguide structure with an evanescent-field coupling between the functional waveguides. The MGVI is based on a consistent implementation of the second approach and extends it from a simple twin-guide structure [2] to fairly sophisticated multi-functional PICs [3], in which the functional waveguides are vertically stacked in ascending order of their λ_G, while adiabatic transitions between them are affected by lateral tapers defined at each guiding level [4]. Then, the functional waveguide at each vertical level can be designed and optimized independently, except with the compatibility requirements related to evanescent-field coupling with other waveguides in the vertical stack. This allows for a large variety of materials, doping levels and waveguide configurations, but on expense of sophisticated design (both epitaxial structure and layout), by shifting manufacturing challenges from multiple step epitaxy to many-layer one-step epitaxial growth (typically several tens, in certain cases 70-80 layers) and multiple etch step fabrication process (number of consequitive etches depends on the PIC functionality and may reach 6-7). Both the many-layer epitaxial growth and multiple etch step wafer fabrication process are commercially available, by means of MOCVD and optical stepper lithography, respectively, and hence can be used for outsourcing of MGVI PIC manufacturing. This is exactly that OneChip Photonics does under its fabless model: all the examples in the following Sections represent the devices processed in the commercial foundry, on 4” wafers with epitaxial structure commercially MOCVD grown on semi-insulated Fe:InP substrates, by using I-line optical stepper at each lithography step. The commercial yet customer-refined regrowth-free process also includes dry and wet etching, passivation, planarization and metallization steps.

Design and fabrication building blocks

In addition to decoupling of the epitaxial growth from wafer processing, which enables for outsourcing both to independent commercial foundries, decoupling of the device and circuit designs is the key to a fabless PIC manufacturing. To address the issue, the MGVI platform is based on a building block approach, in which a limited number of devices form a library of pre-verified generic functional elements. On the active device side, these are: a distributed feedback (DFB) laser, an electro-absorption modulator (EAM), a semiconductor optical amplifier (SOA) and a PIN waveguide photodetector (WPD). On the passive device side, the MGVI building block library includes a SSC, a WDM and various elements of passive waveguide circuitry. Different yet inherently compatible combinations of these building blocks allow for a wide range of MGVI PICs featuring functional (e.g. emit *and* detect) or / and parallel (e.g. demultiplex *and* detect) integration. At the same time, limited building block library of relatively few generic functional elements enables for their pre-design and process pre-development, such that a new PIC can reuse them, with a certain adjustment. This reduces design to fabrication time and simplifies new PIC product introduction.

Transceiver PICs for FTTH

Burgeoning fiber to the home (FTTH) deployment created the most massive and cost-sensitive telecom transceiver market to date, which also is a perfect match to the MGVI technology and economics. The key component is the optical network unit (ONU) transceiver and has to transmit in 1310nm / receive in 1490nm, while demultiplexing these two wavelengths (they share the same fiber). The transceiver PIC, which gives an example of a sophisticated functional integration, is shown at the top of Fig. 1. A 4-guide MGVI structure comprises, top to bottom, a WPD for detection in 1490nm range; a DFB laser for emission at 1310nm; a passive waveguide used for on-chip routing and connection to a common optical port; and a diluted (fiber) coupling waveguide at this port, equipped with SSC for low insertion loss connection to / from the functional waveguides. Typical light-current and spectral characteristics of the on-chip transmitter, as well as its eye diagram, are shown in the bottom part of Fig. 1. This and related MGVI PICs, which now are productized, perhaps are the only ones commercially used in FTTH transceivers today.

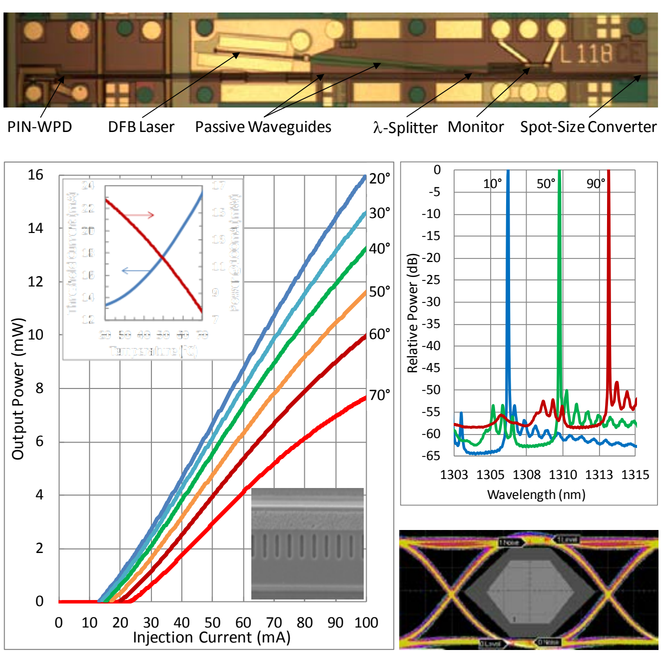

Figure 1 Diplexer PIC for ONU transceiver applications in FTTH networks. Top – optical microscope image; bottom – key performance features of the on-chip DFB laser. Shown in the bottom right corner insert to the light-current characteristic plot on the left is the scanning electron microscope image of the vertically-coupled surface-etched grating, which makes the laser's DFB cavity.

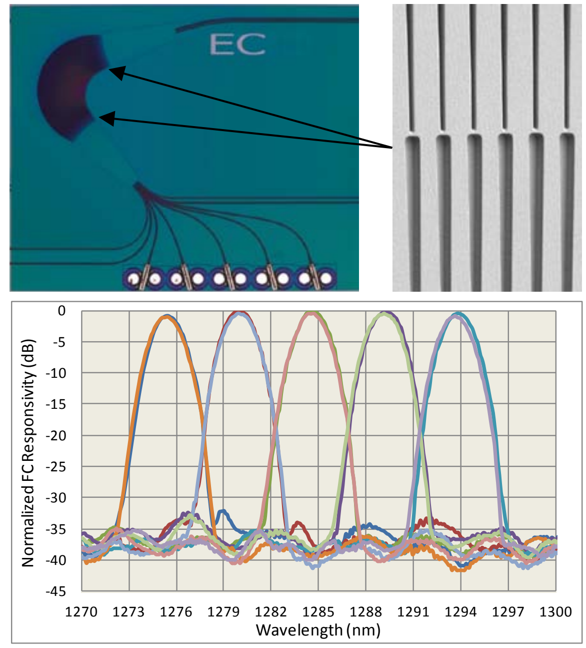

Figure 2 5x25G / 800GHz WDM receiver PIC for high-capacity transport OI. Top – optical microscope image of the die (left) and scanning electron microscope image of the shallow etch – deep etch waveguide junction; bottom – normalized fiber-coupled responsivity spectra in TE and TM polarizations.

Receiver and transmitter PICs for OI

Emerging optical interconnects (OI) provide another example of the massive and cost-sensitive market, which can be well served by the MGVI technology. The key components are the optical transmitter and receiver for high-capacity transport fiber links. The WDM receiver PIC designed for operation at 25Gb/s speed over 800GHz channel spacing is shown in Fig. 2 and illustrates MGVI capabilities for the parallel, along with functional, integration. A 5-channel device (only 4 channels are used in 100Gb/s links) is processed in a 3-guide MGVI structure, which comprises, top to bottom, an array of WPD's, passive and coupling waveguides (with SSC formed between the two), all of which being similar to those used in the FTTH transceiver PIC. Typical passband spectra of the device are given at the bottom of Fig. 2. This and complementary transmitter chips, based on a separate waveguide DFB – EAM design, now are being productized for OI market.

References

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