Realization of Polarization based Integration Scheme (POLIS) for Active and Passive Components

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Abstact: *Polarization based integration scheme (POLIS) combines active and passive components on the same material, using polarization properties of compressively strained InGaAs/InP quantum wells. A first integrated circuit with detectors, polarization converters and waveguides has been fabricated, characterized and reasonable performances have been observed.*

Introduction

The evolution of information transport over optical networks is one of the drivers behind the upcoming information society. This development results in increasing demand for more complex optical functionality at ever-lower prices. The monolithic integration of these functions in an optical integrated chip (IC) opens the possibility for mass production, which will be able to fulfill this demand.

Essential to the success of mass production of these circuits is a cheap, flexible and efficient integration technique. An optical IC will contain a variety of components, such as optical waveguides, light sources, detectors, optical switches etc. These functions put different requirements on the material system used, e.g. waveguides require transparent materials to keep the attenuation low, while on the other hand detectors need absorption of the light. Several solutions have been proposed and demonstrated to reconcile these conflicting requirements. They all have however the disadvantage that additional processing steps are needed, e.g. applying extra material through a regrowth proces.

Here we report the idea of POLIS (POLarization based Integration Scheme) together with experimental results. It is based on the fact that properties of an optical IC are dependent on the polarization state of the signal. In general this is a severe problem, but here we use it to advantage. It is possible to design a layer structure on a substrate of indium phosphide (InP), which can guide light with one polarization, but absorbs light with the opposite polarization. This creates the possibility to integrate lasers and detectors together with waveguides, switches and demultiplexers on one material. The polarization is in this case a parameter that determines the material properties. Thus instead of changing the material via regrowth, the polarization state of the signal is changed to realize active and passive components. With polarization converters it is possible to obtain the required polarization, transparent or absorbing, in each component of the optical circuit.

Previously we have reported [1] that it is possible to realize active (detectors) and passive (waveguides) components on the same layer stack, with efficient device performance. However to integrate active and passive components an additional component, to rotate one polarization to another, is required. An efficient, short polarization converters on a wafer of indium phosphide has also been realized [2,3,4]. For them TE-TM polarization conversion efficiency was more than 95% and the insertion loss was about 1 dB for entire structure of length 125 μm.

Concept

As mentioned earlier, polarization for TE or TM, is the parameter that defines the active or passive part of the circuit. Therefore transparency for one polarization and absorption for the other is required at the same wavelength. This can be achieved through bandgap modification: strain in the

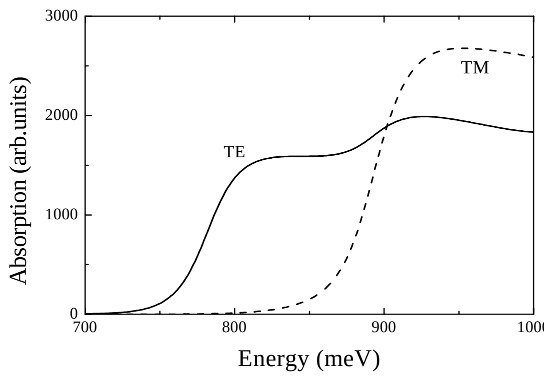


Fig. 1: Calculated absorption spectrum of a 4 nm compressively strained $In_{65}Ga_{35}As$ quantum well with InGaAsP barriers

quantum well splits the heavy hole and the light hole in the valence bandedge, and thus the two transitions give absorption at different wavelengths. At a single wavelength one polarization gives absorption while the other is transparent. Compressive strain, which moves the heavy hole (TE-transition) up in the valence band and light hole (dominantly TM-transition) down, can serve our purpose. For higher strain, the separation between the heavy-hole and light-hole valence bands increases, resulting in an increased wavelength separation between the bandgap for TE and TM polarization. Calculations [5] showed that 4 nm thick $In_{0.65}Ga_{0.35}As$ compressively strained quantum wells have both TE absorption and TM transparency at 1550 nm wavelength as shown in the Fig 1.

Realization

Our material system contains InGaAs compressively strained quantum wells sandwiched between InGaAsP on a semi insulating InP substrate. The designed layer structure consists of a 300 nm $In_{73}Ga_{27}As_{59}P_{0.41}$, a 3 nm compressively stained quantum well of $In_{64}Ga_{36}As$ and again 300 nm $In_{0.73}Ga_{0.27}As_{0.59}P_{0.41}$ as a waveguide layer. The thickness of the quantum well is reduced w.r.t. the calculations, because our first realizations [1] showed POLIS-behaviour at too high wavelengths. A layer of 505 nm InP as a cladding layer and finally a contact layer of 100 nm $In_{0.53}Ga_{0.47}As$ are needed. A layer stack according to this design was grown by MOVPE.

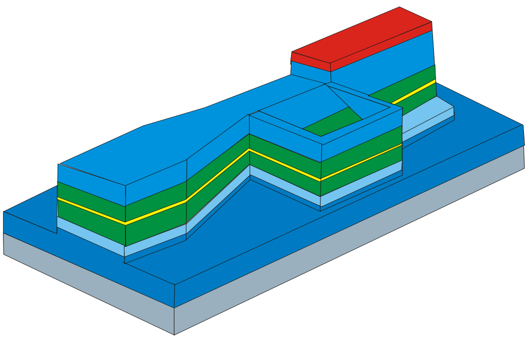
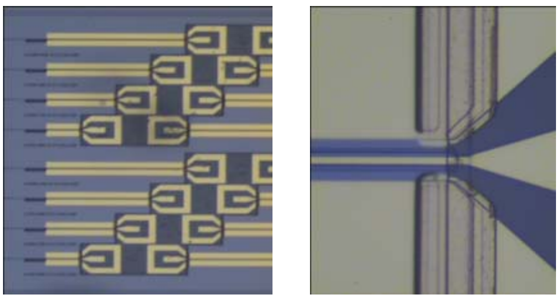


Fig. 2: Integrated waveguide and detector within POLIS (before metal contacts are applied). Form left to right the input waveguide, a taper, the polarization converter (with the sloped side inside a wall that defines the wet etch region) and the detector are shown.

The integrated circuits of input waveguide of 3 µm width, connected to the polarization converter of 0.9 µm width via taper and a small width waveguide of 1.5 µm. Detector is butt coupled to the other end of the polarization converter. Detector with length variations of 250 µm to 2000 µm in steps of 250 µm, for a width of 6 um are implemented. For polarization converter length is 150 um. However highest conversion efficiency of 90% is found for 137 µm. Schematic is shown in Fig. 2.

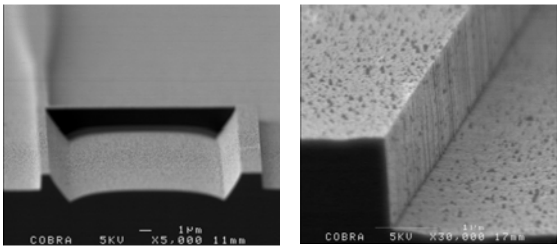
Polarization converter is relatively sensitive to fabrication errors. It needs at least three lithographic steps in order to define the width of the waveguide, then to form the vertical wall and in the end slanted side. The submicron width of the converter with a tolerance of 100 nm is difficult to realize with standard contact optical lithography. Alignment accuracy of protection masks to realize the vertical and slanted sides is also critical. So for these critical exposures high resolution optical lithography was used instead of contact optical lithography. An optical the critical component due 5x reduction wafer stepper is used. It is an ASML PAS5500/100D i-line tool with a variable numerical aperture (NA=0.48-0.60), overlay-accuracy of ≤ 60 nm (99.7% 2-point global alignment) and specified resolution 0.4 µm. Light of wavelength 365 nm is used to expose the wafer through a projection lens. Basically it is a step and repeat system for multiple exposures on four to eight inch wafers. However, we used a quarter of a two-inch wafer. To align and expose on the PAS5500/100D, a special mounting technique is developed. To align the quarters on this system phase grating alignment marks designed by ASML were made with standard optical contact lithography. Detector and waveguides ridges are processed together with the converter.

The vertical wall of the converter, the waveguides and the tapers are deeply etched by reactive ion etching. The slanted wall is realized by non-selective wet chemical etching with bromine methanol. SiN_x and Ti are used as masking materials. Metal pattern for top p-contact and side n-contacts are defined by evaporation and lift off techniques. SiNx is used for passivation of the active structures and for planarization polyimide is used. The top view of these integrated devices are shown in Fig. 3 (a), whereas in (b) the zoom in view of the end of the detector is presented, with 4 µm wide p top contact and 50 µm side n-contacts. Cross- sectional view of converter section and waveguide are shown in Fig. 4.



(a) (b)

Fig. 3: Integrated circuits after complete fabrication are shown, from left to right 3 µm input waveguide of 500 µm length, converter section of 150 µm length, then detectors with varying lengths (a), the edge of the detector is shown in (b).



(a) (b)

Fig. 4: Cross sectional of polarization converter (a) and waveguide (b) are shown.

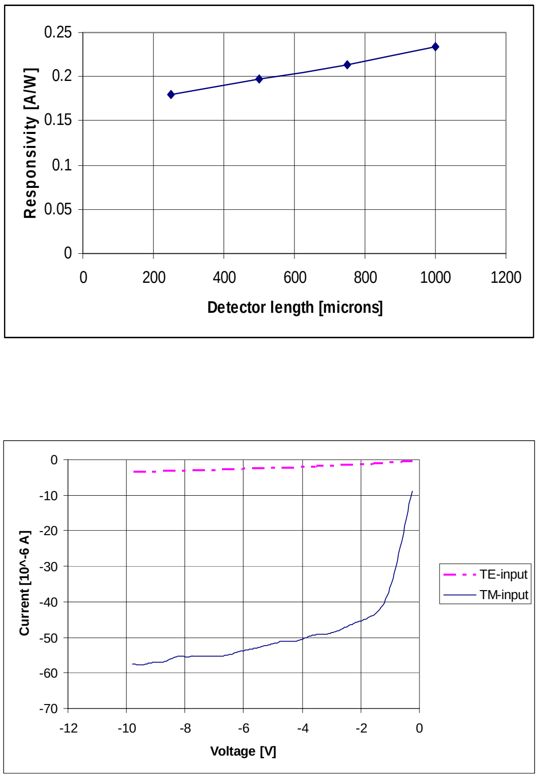


Fig. 5: Experimental results for the integrated waveguide-detector. Top: IV-curve of a 1 mm long detector with -6.1 dBm input power in TE and TM polarization. Bottom: Responsivity as a function of detector length, for TM polarized input power

Results and Discussion

The results are shown in Fig. 6. An external response of 0.234 A/W is measured, corresponding to an external quantum efficiency of 20%. These numbers are uncorrected for coupling losses, around 5 dB, into the waveguide and losses in the structure. Due to an accidental pollution (see fig 4b) high contact resistance was obtained. Therefore not all the photogenerated carriers are collected, as is evident from the linear increase of photocurrent with voltage and with length (which means linear decrease of contact resistance). This implies that much higher responsivities can be expected if both the contact resistance and the coupling losses can be reduced. The dark current is very low, in the order of a few nanoamperes. Because of the high contact resistance high frequency measurements are not relevant. The absorption length is however below 230 µm, which is short enough to allow detection at frequencies above 10 GHz with usual contact resistances. From the response to both the TM- and the TE-input an estimate of the polarization conversion can be made. The polarization converter in this circuit shows around 70% conversion, and the passive waveguide loss is less than 0.5 dB for 1 mm length.

Conclusions

The polarization based integration scheme (POLIS) opens up the possibility to integrate active and passive circuitry without regrowth. It is a simple technique to implement based on the fact that compressively strained quantum well increases the separation between the heavy-hole and light-hole valence bands, resulting in an increased wavelength separation between the bandgap for TE and TM polarization. Experimental results show quite good performance for the first integration of a waveguide with a detector and a compact polarization converter.

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