Optical coupler concept for wafer scale fabrication of adhesively bonded photonic and electronic circuits

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Wafer scale integration of photonics and electronics enables cost-effective realization of high-density and high-performance electro-optical modules. In this paper an optical coupler concept suitable for such integration technology is described by means of numerical simulations. Light from a vertically tapered indium phosphide waveguide is adiabatically expanded into the polymer structure, and subsequently butt-coupled into a standard single mode fiber. With this concept a simulated coupling loss of 0.82 dB can be achieved for a 2.4 mm long device.

Introduction

Internet traffic is continuously growing and will reach the zettabyte threshold at the end of 2016 [1]. Therefore, it is necessary to develop transmitters and receivers with high bandwidths. A standard technique to connect the photonic with the electronic chip is the wire bond but as information capacity and transceiver integration densities increase, the electronic-photonic connections become limiting [2]. Recently we have proposed the wafer scale integration of Silicon electronics and InP photonics at the wafer scale [3]. This concept enables thin membranes containing complete InP PICs to be electronically connected to the electronics during wafer processing. The removal of the InP substrate and the use of low-refractive-index adhesion layers also enables radically new concepts for the optical connections. In this work we propose a new integrated polymer-to-InP mode coupling scheme to enable low-loss, high-tolerance coupling between photonic ICs and fiber optics.

The concept involves the use of a polymer adhesive to connect the InP wafer to the Silicon wafer. The intermediate bonding layer is based on two different polymer materials that connect the two wafers mechanically. Through careful choice of layer thicknesses, a polymer waveguide core can be created using the adhesion layer itself. In combination with careful cladding layer design, the modal cross-section can be expanded from a high confinement InP waveguide to a large cross-sectional area polymer waveguide. The polymer waveguide will be used to couple light in and out of the optical chip. How to achieve this functionality is explained in this publication. Based on the materials used and parameter limitations, an optical coupler is designed to transfer light from the InP wafer into the intermediate bonding layer and later on into a standard single mode fiber (SMF).

The InP waveguide is vertically tapered to couple the light adiabatically into the polymer layers. These layers consist of a waveguide core layer with a slightly higher refractive index compared to the surrounding polymer cladding layers. The polymer waveguide core is structured in the area of the tapered InP waveguide to provide guiding. In this publication we present the concept of the optical coupler and the simulation results.

Coupler design

The layer stack, including the side view of the optical coupler design, is presented in fig. 1. The lowest layer is the Silicon wafer which is covered with 4 µm of SiO_2 to form the lower waveguide cladding. On top is the polymer cladding followed by the polymer core and the vertically tapered InP waveguide. The III-V waveguide is made of Q1.06 (i.e., InGaAsP with a bandgap wavelength of 1.06 µm). In the schematic the Q1.06 layer on the left side is covered with n-doped InP. This layer is the original waveguide cladding and is removed for the tapered section. The top layer is again the polymer cladding.
The layer thicknesses and the refractive indices are given in tab. 1.

Figure 1 - Schematic side view of opt. coupler

layer	height in µm	refractive index
polymer cladding	5	1.5088
InP	1	3.169
Q1.06	1	3.2585
polymer core	4	1.5178
polymer cladding	20	1.5088
SiOx	4	1.46

Table 1 - Layer definition.

The optical coupler is based on two mode transitions. The first one is the change from a mode confined in the Q1.06 waveguide and the InP cladding to a mode that is only located in the Q1.06. Therefore the InP is removed by etching a facet with an angle w.r.t. the propagation direction, to avoid reflections. In figure 2 top view (V1), side view (V3) and selected cross sections (V2) along the taper are shown.
The second part of the optical coupler is the transition of the mode in the Q1.06 shallow etched waveguide into the polymer waveguide mode. The confinement of the Q1.06 mode is obtained with an edged ridge with a height of 200 nm and a width of 2 µm on top of the Q1.06 bulk waveguide material. The Q1.06 waveguide is tapered such that the amount of bulk material is reduced until only the ridge is left. This reduction is shown in V2 of figure 2.

Simulation

The simulation aims at finding a short and effective coupler. Therefore, a bidirectional eigenmode expansion (EME) propagation is used [4]. The structure is divided into cells. The method uses modal decomposition of the electromagnetic fields into a basic sets of eigenmodes in each cell. For every cell the scattering matrices are calculated, taking into

account the boundary conditions. Finally, the solution for each section is propagated bi-directionally through the whole structure to calculate the total transmission and reflection of the device [4].
For an effective simulation the taper is divided in 3 simulation areas along the taper structure. The first simulation area covers the part until the end of the InP waveguide cladding on top of the Q1.06 layer. This area was designed to reduce reflections at the facet of the InP cladding.
Simulation area 2 and 3 describe the taper. The reason to split the taper into two simulation sections is that the actual happens only in the last part of the taper. There a higher numerical accuracy is needed then in the taper section before that.

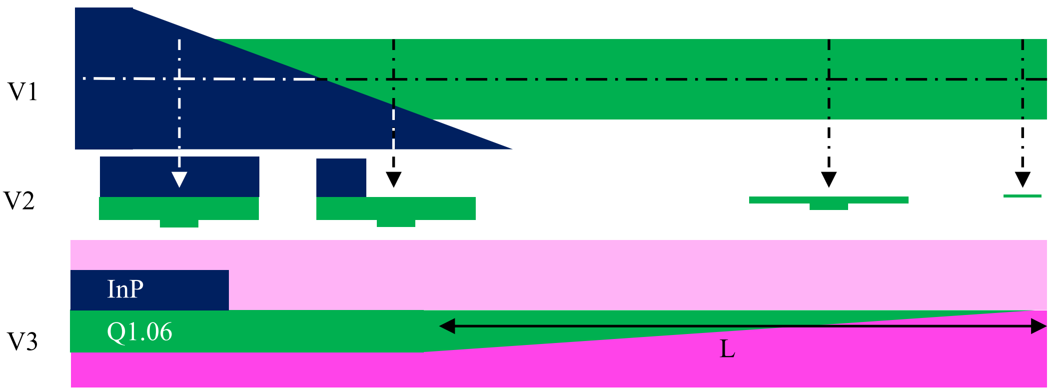

Figure 2 - Detailed schematic view, V1 = top view, V2 = selected cross sections, V3 side view.

Results

The chosen taper structure is 2.42 mm long and has a coupling losses of 0.82 dB before coupling into the single mode fiber. The InP cladding is tapered with an angle of 21 degree. Therefore the reflections are reduced to a value of -40 dB. The tapered section has a length of 2.4 mm.

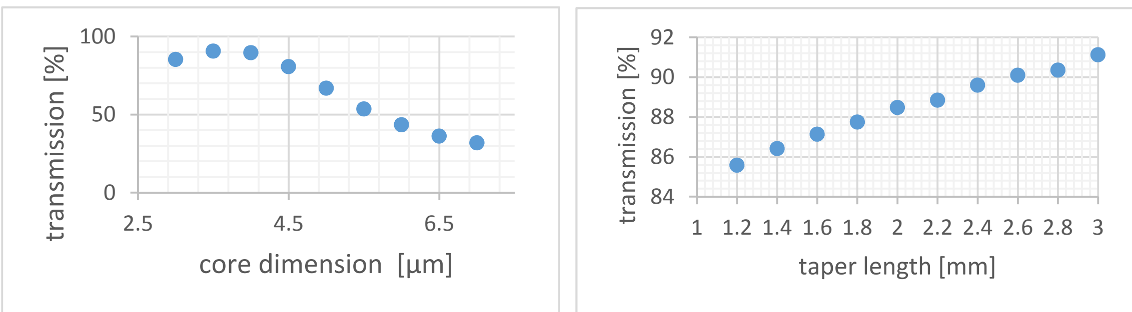

Figure 3 - Transmission for different core dimensions with fixed taper length of 2.4 mm (left) and for different taper length for a fixed core dim. of 4x4 µm (right).

The coupling starts when the waveguide is tapered down to a height of 70 nm. The light is then coupled into the square shaped polymer waveguide core. A smaller core dimension increases the coupling efficiency. This result is presented in the left graph of figure 3. Smaller core dimensions will lead to higher coupling loss when coupling to a single mode fiber. For a core of 8x8 μm^2 these additional coupling losses would be in the order of 0.4

dB [5]. The tradeoff between coupling losses of the taper and the coupling into the fiber resulted in choosing a 4 µm core.
A smaller angle in the coupling area leads to a better coupling efficiency. The only way to achieve this is by an extension of the linear taper length. The results are presented in the right graph of fig. 3. For further optimization it is interesting to use a two slope approach, since the coupling in the region where the Q1.06 layer reduces from 1 µm to 70 nm is negligible. Therefore, a larger taper angle, resulting in a shorter device, can be used there.
Additionally, the impact of the cladding layer was analyzed. We found that the top cladding has to be more than 2.5 µm thick to obtain sufficient coupling. For the lower cladding the best coupling will be achieved by using thicker layers. The best result was found for 20 µm, that is the upper process limit.
The simulated structure didn´t show any polarization dependency. These results show that a coupler is possible with sufficient performance for the planned photonic integration applications.

Summary

We simulate a taper structure for coupling light from an InP photonic integrated circuit, bonded on top of a BiCMOS wafer, into the intermediate photonic bonding layer. The light is guided in the bonding layer and the coupling loss is 0.82 dB for a 2.42 mm long taper. To make this concept more practical the taper length has to be reduced. This can be obtained by using a taper with two linear sloped sections. The taper structure will be fabricated within the WIPE project.

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