Compact and efficient fiber-to-waveguide grating couplers in InP-membrane

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ABSTRACT

Miniaturization and integration are key drivers for future optical communication networks. Nanophotonic components are very interesting for ultra-dense photonic circuits, but the coupling with the outside world remains an important problem. An attractive solution is provided by grating couplers. In this paper, we present the design and fabrication of compact and efficient grating couplers in InP-membrane, for coupling between nanophotonic waveguides and single mode fiber. A high vertical index contrast is achieved by wafer bonding. First components show a coupling efficiency of 30%.

Keywords: grating couplers, wafer bonding, InP-membrane, integrated optics, nanophotonics

1. INTRODUCTION

Today, a large breakthrough of optical communications is compromised by high coupling losses between the chip and the outside world (optical fiber), caused by the large deviation in dimensions between an optical fiber mode and an optical waveguide mode. Several solutions have been proposed to address this issue. By using an inverse taper approach, low loss and broadband operation was demonstrated, but these structures require lensed or special fibers with high numerical aperture [1, 2].

We want to explore the use of grating couplers to tackle the problem. In this approach, light is coupled out-of-plane from fiber to waveguide, by means of a grating (Fig. 1). This makes wafer-scale testing possible, since light can be coupled in and out everywhere on the chip, and not only at the edges of the chip. The use of grating couplers is well known [3, 4]. Traditional couplers often use weak gratings and are therefore rather long and have a narrow bandwidth. By using a high vertical index contrast, strong gratings can be made, resulting in small coupling lengths and compact components. A coupling efficiency of 33% for a 10x10 μm^2 grating coupler in Silicon-on-Insulator (SOI) has been demonstrated in [5]. This type of coupler has a 1dB bandwidth of around 40 nm and good alignment tolerances (+/- 2 μm for 1dB excess loss). A 2D-grating version of this coupler can be used for getting polarization independence through polarization diversity [6].

However, SOI is not suitable for active components (lasers, detectors, etc), which is a major drawback for application in an optical communication network. Other materials can be used for both active and passive components. For telecom applications, InP is the material of interest. However, it is impossible to easily transfer existing designs for SOI-gratings to InP. The vertical index contrast of InP-based heterostructures is too modest for this purpose. A new type of compact coupler in a classical InP-heterostructure was proposed in [7]. The coupler is based on very narrow slots etched at an angle of 45 degrees. Another possibility is modifying the vertical index contrast. In this paper, we successfully use a wafer bonding technique to obtain this high index contrast, and fabricate efficient grating couplers.

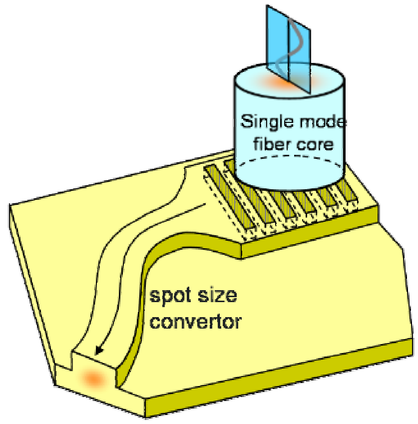

Fig. 1. Principle of a grating coupler for coupling between optical fiber and nanophotonic waveguides.

2. WAFER BONDING

A possible definition of "bonding" is "joining of two materials". We focus on adhesive bonding, where an intermediate spin-on layer is used. In this approach one or both substrates are covered with an adhesive (photoresist, PMMA, SU8, BCB, spin-on-glass …). The adhesive serves as a planarizing layer and therefore a certain degree of non-planarity can be tolerated. We use BCB (BenzoCycloButene) as the intermediate spin-on layer. BCB is widely used in the microelectronics industry and has some interesting properties: low cure temperature (250 C), high degree of planarization, thermal stability, transparency at telecom wavelengths, low dielectric constant, good chemical resistance, low outgassing.

The bonding procedure is shown in Fig. 2. First, the substrates are cleaned. However, structured surfaces or submicron particles can be tolerated. Then, the bonding agent BCB is spun onto a host substrate (e.g. GaAs) (Fig. 2b). The material to be bonded (consisting of an InP-substrate, an InGaAsP etch-stop layer and a thin InP membrane (Fig. 2a)) is placed upside down onto the host-substrate (Fig. 2c). After curing of the BCB, the substrate is removed (Fig. 2d), and also the etch stop layer is removed. The result is a thin InP-membrane on BCB (Fig. 2e). In this way, we achieve a high vertical index contrast.

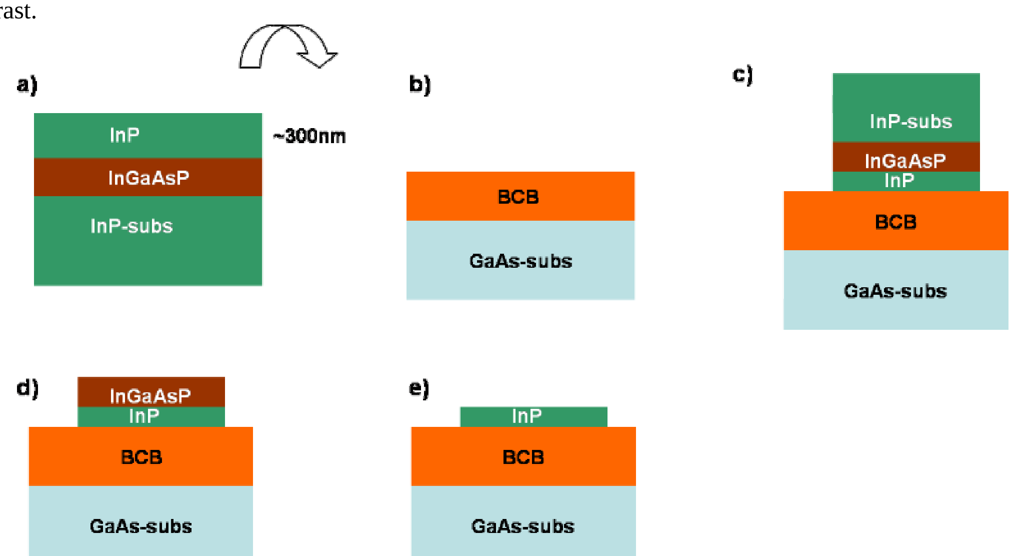

Fig. 2. Schematic view of the bonding principle.

3. DESIGN

For the design of the grating couplers, we use CAMFR [8], an eigenmode expansion tool. All simulations are for TE-polarization. Near vertical coupling at 10 degrees is used to avoid second order reflection. The simulation method is described in detail in [9]. The grating parameters to be determined are the period, etch depth and filling factor. An optimization of these parameters results in: period=660 nm, etch depth=120 nm, filling factor=0.5. The BCB-thickness has a major influence on the ratio between upwards and downwards radiated power, as is shown in Fig. 3. The coupling efficiency is simulated as a function of BCB-thickness. An optimal BCB-thickness is 1.18 μm. The coupling efficiency of this structure is 34%. The up/down ratio can be increased by applying a surface AR-coating. We use an Al_2O_3 layer (n=1.58 at wavelength of 1550 nm) with an optimal thickness of 260 nm. The maximum coupling efficiency is increased to 54% and the 1dB bandwidth is 50 nm. The field profile of an InP-membrane grating coupler with AR-coating is shown in Fig 4. The coupling efficiency curves for the couplers without and with surface AR-coating respectively are shown in Fig. 5. The coupling efficiency is limited by radiation to the substrate. By adding a bottom mirror, the coupling efficiency can be increased to a simulated value of 74%.

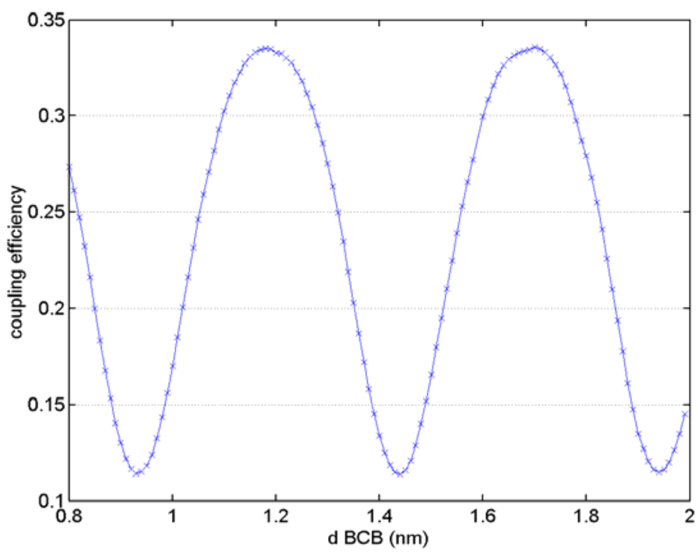

Fig. 3. Determination of the optimal BCB thickness.

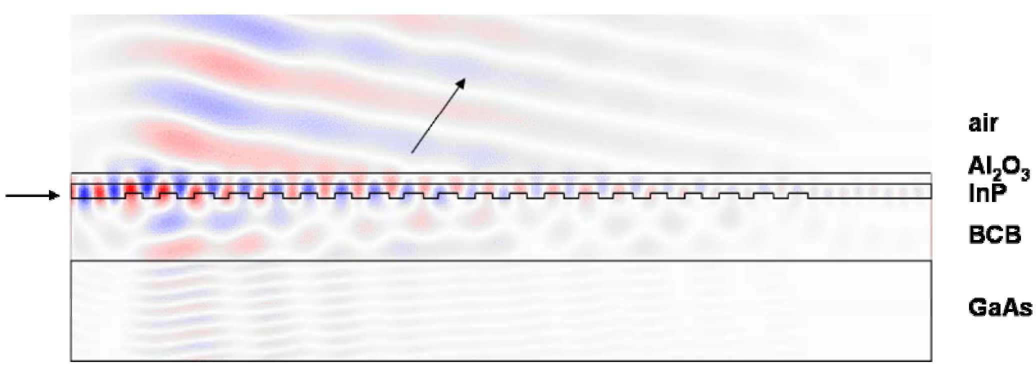

Fig. 4. Field profile of an InP-membrane coupler with AR-coating.

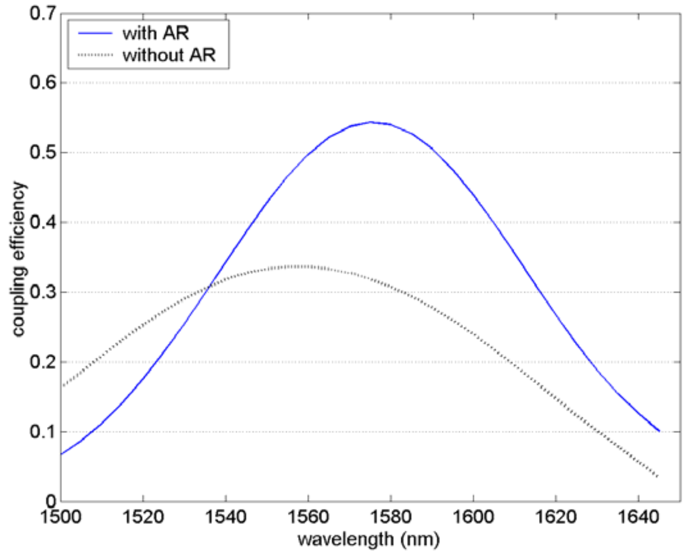

Fig. 5. Coupling efficiency of a 1D-grating coupler with and without AR-coating.

4. FABRICATION

The layer structure used for the devices consists of an InP-substrate, an InGaAsP etch-stop layer and a 300 nm InP-layer, serving as the membrane layer. In a first step, gratings and waveguides are defined by e-beam lithography using PMMA. The waveguides are 10 µm wide and bounded by 5 µm wide trenches. The pattern is then transferred into a Fox-14 (flowable oxide) hard mask by Reactive Ion Etching (RIE) using CHF_3. Finally, the structures are etched into the epistructure by RIE using CH_4/H_2 and the Fox-14 layer is removed with HF. This structure is then bonded onto a host-substrate by means of BCB, with the grating at the bottom side. After curing of the BCB for 1 hour at 250 C in a nitrogen environment, the InP-substrate is removed by lapping and wet etching. Finally the etch stop layer is removed by wet etching. More details about the bonding procedure can be found in [10]. A FIB cross-section of a fabricated structure is shown in Fig. 6.

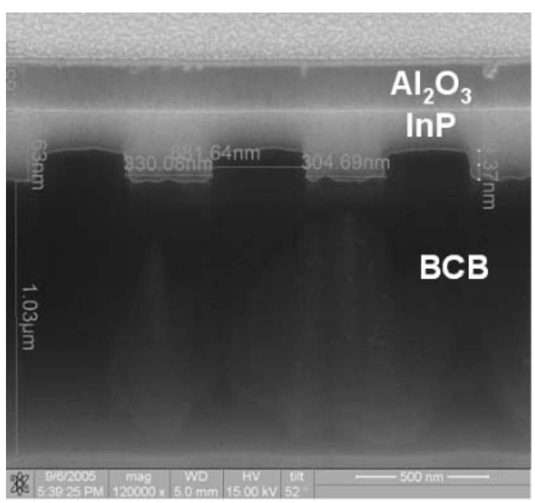

Fig. 6. FIB cross-section of a fabricated 1D-grating coupler.

5. RESULTS

5.1 Measurement setup

The performance of the couplers is determined from a fiber-to-fiber transmission measurement (Fig. 7).

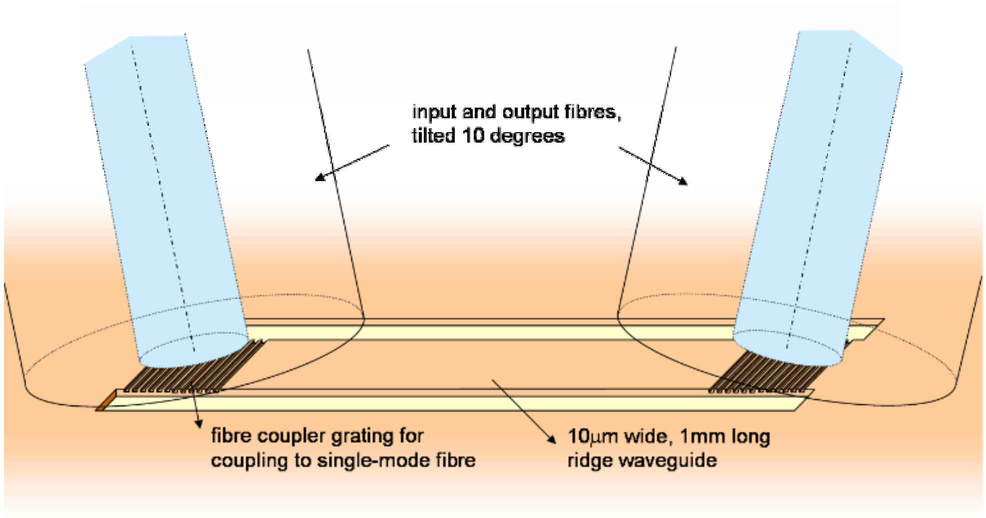

Fig. 7. Schematic drawing of the measurement setup.

A fiber connected to a tunable laser is positioned above the input grating, at an angle of 10 degrees. Another fiber, connected to a power detector is positioned above the output grating coupler, also at 10 degrees. By assuming that input coupler and output coupler are the same, and by characterizing losses in our setup, we can determine the coupling efficiency of a single coupler.

5.2 1D-grating coupler

First measurements are done on a sample without AR-coating. The measured coupling efficiency is 19% per coupler. After applying a surface AR-coating (an Al_2O_3 layer with actual thickness of 240 nm), the coupling efficiency is increased to 30% and the 1dB bandwidth is around 50 nm. There is a discrepancy between simulation and theory. For the case with AR coating, the simulated coupling efficiency is 54%, while we have measured 30%. The main reason is the deviation between targeted structure and fabricated structure. We have simulated the couplers with the parameters (period, etch depth, filling factor, BCB thickness) deduced from a FIB cross-section. The two most important factors are a slightly wrong BCB-thickness (fabricated: 1.3 μm, design: 1.18 μm) and a deviation in refractive index of the AR-coating (fabricated: 1.47, design: 1.58). Other possible factors are roughness induced through the etching and imperfectness of the AR-coating layer and the bonding interface. The measurement results, together with the simulations for the actual fabricated structure are shown in Fig. 8. The discrepancy between theory and experiment has become much smaller.

5.3 2D-grating coupler

We have also fabricated 2D-grating couplers. In this case, the grating lines are replaced by holes. The hole size is optimized in order to get maximal upwards radiation. The optimal hole diameter is 480 nm, and the period is 640 nm, in order to center the coupling efficiency curve at a wavelength of 1550 nm. An SEM top-view picture of the fabricated structure is shown in Fig. 9.

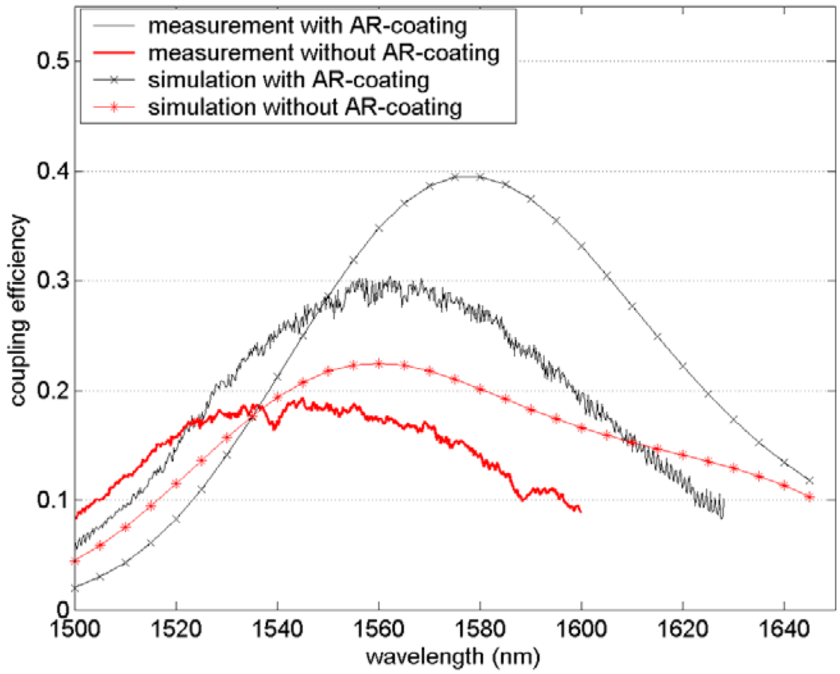

Fig. 8. Measurement result and simulation for the actual fabricated 1D-grating coupler.

The measured coupling efficiency curves are shown in Fig. 10. The coupling efficiency for the case without AR-coating is 23%. By applying an AR-coating, the coupling efficiency is increased to 31%. The 1dB bandwidth is around 40 nm. This coupler is interesting for use in a polarization diversity configuration, in order to get polarization independence.

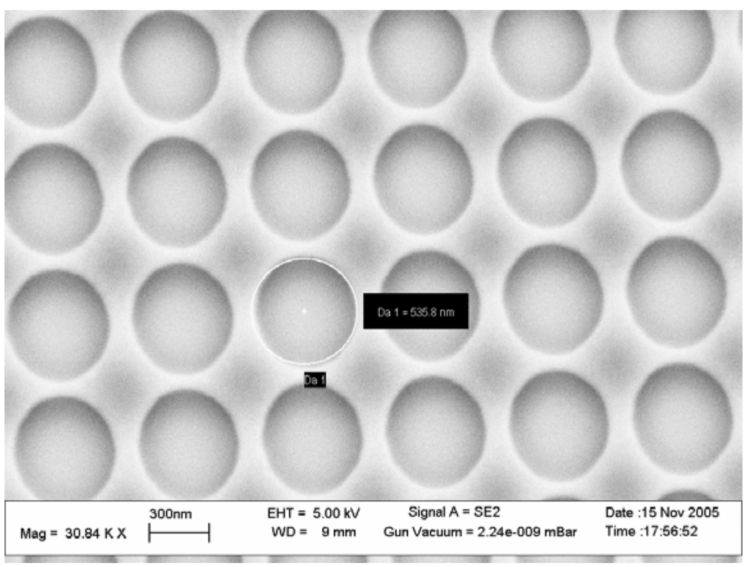

Fig. 9. SEM-top view of a fabricated 2D-grating coupler.

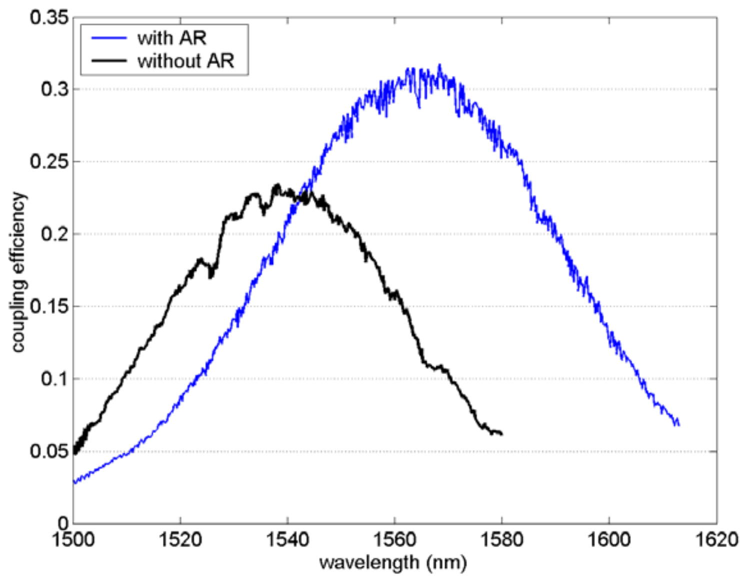

Fig. 10. Measurement result of a 2D-grating coupler.

6. CONCLUSIONS

We have presented the design and fabrication method of compact fiber-to-waveguide couplers in InP-membrane. We have demonstrated around 30% coupling efficiency on first fabricated structures. The wafer bonding approach is very well suited for adding more complexity to the couplers. Work is in progress to fabricate grating couplers with a bottom mirror, which would enhance the coupling efficiency substantially.

ACKNOWLEDGEMENTS

Part of this work was supported by the European Union through the IST-FUNFOX project. F. Van Laere thanks the Flemish Institute for the industrial advancement of scientific and technical Research (IWT) for a specialization grant. J. Schrauwen is acknowledged for making a FIB cross-section of the couplers. Alcatel-Thales III-V lab is acknowledged for providing the InP epi-wafers used in this work.

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