Realization of Fabrication-Tolerant Si₃N₄-Si Mode Transformers

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Abstract—A III-V/Si/Si₃N₄ structure critical in realizing high-performance lasers can be fabricated using microtransfer printing. This approach poses stringent requirements on the Si₃N₄-Si couplers. Accordingly, we realized 174 μm long, fabrication-tolerant Si tapers with simulated losses below 0.8 dB up to 750 nm misalignment.

Keywords—Mode transformer, microtransfer printing, coupled mode theory

I. INTRODUCTION

Heterogeneous integration of III-V semiconductor optical amplifiers (SOA) on an ultra-low loss silicon nitride (Si₃N₄) platform has proven successful in the past using wafer bonding with an intermittent Si layer[1] or microtransfer printing on an intermittent hydrogenated amorphous silicon (a-Si:H) layer[3]. In these approaches, the large refractive-index mismatch between the III-V material and the Si₃N₄ is overcome by transitioning to an intermediate coupling layer. We propose a two-step microtransfer printing approach that can also realize the III-V/Si/Si₃N₄ structure. First, the Si layer is printed on Si₃N₄ covered by a thin oxide and an adhesive benzocyclobutene (BCB) layer. Afterwards, the III-V SOA can be printed on top. This limits the required post-processing on the target Si₃N₄ chip compared to bonding techniques or a-Si:H deposition because it allows processing both the amplifier and the intermediate coupling layer on their native source chips. Moreover, such a two-step microtransfer printing method allows to integrate active devices on generic foundry Si₃N₄ platforms. The bottleneck in the design of a microtransfer printed mode transformer is the lateral displacement between both structures that might occur during the transfer. In order to be useful in practice, a design should be tolerant against such a displacement in addition to ordinary fabrication errors such as width variations. Here, we discuss the design of a mode transformer that meets these requirements without compromising on efficiency or viability. We also explain how the narrow suspended mode transformer can be realized on its native SOI substrate before pick-up. For this, we pay extra attention to protect the structure both from capillary forces in the process flow and from deformations caused by the pick-and-place step during microtransfer printing.

II. ALIGNMENT- AND FABRICATION-TOLERANT TAPER DESIGN

With coupled mode theory, it is possible to find an analytical solution for the mode transformer problem[2], based only on mode calculations. A hurdle that is easily overlooked, is the applicability of such a perturbation theory. For the uncoupled modes to be well-defined, the influence on one another should remain limited. This translates to the following condition for the uncoupled modes: $\iint E_a^* \cdot E_b \, dx \, dy \ll \iint E_a^* \cdot E_a \, dx \, dy$. Here, E_i is the electric field of mode i and the integration spans the full simulation area. The condition typically applies for small index differences and large mode separations. In our case the remaining oxide, along with the BCB layer cause for a sufficient separation which allows to uncouple the problem.

A second important obstacle is the practical use of the resulting design obtained from coupled mode theory. One optimizes the taper to be as short as possible by exploiting regions of high coupling. In practice, both lateral misalignment and process variations need to be taken into account. To circumvent this problem, an uncertainty on the propagation constants of the uncoupled modes should be considered. This way, robustness against possible imperfections appearing in the fabrication is incorporated in the resulting design. By applying this to the critical mode coupling area, we leverage a well-defined trade-off between fabrication tolerance and transformer length. As shown in Fig. 1(a), the resulting transformer structure tapers slowly at the critical width around the phase matching conditions and tapers parabolically away from the phase matched region. Maximal tapering angles are imposed by the coupling strength between the uncoupled modes. The optimized design displays a high coupling efficiency for a misalignment up to 750 nm, as is shown in Fig. 1(b). Commercial microtransfer printers can achieve a consistent 500 nm misalignment accuracy (3σ) which would allow for mode transformers with at most 0.4 dB loss.

Fig. 1. (a) The resulting taper geometry defined by the side profile as a function of its length x , the inset shows a 3D image. (b) Simulated coupling efficiency as a function of the fabrication errors, clearly indicating tolerance against width variations and lateral misalignment. The inset shows a cross section of the layer stack.

III. FABRICATION

Dedicated fabrication methods were developed to guarantee a reliable fabrication of the suspended mode transformer on its native SOI chip before pick-up. Strong capillary forces impinge on the structure during wet underetching with hydrofluoric acid (HF) and subsequent rinsing with deionized water. To suppress these effects, we use a vapour etch approach that achieves a release in which the sample does not come into contact with any liquid anymore. This way, we were able to prevent our suspended structures from collapsing to the surface. The free-hanging Si mode transformer is shown in Fig. 2(a, b). Also the material rigidity of the narrow taper during pick-up and printing is important to prevent fractions. This can be strongly enhanced by shielding the mode transformer with a photoresist encapsulation as shown in Fig. 2(c). Even after a hard bake of the photoresist to survive HF etching, the resulting tapers retain their shape and are protected during handling. As a result, both obstacles of fabrication-tolerant design and manufacturing have been tackled in this work and the developed methods can be applied for efficient mode transformers that can be microtransfer printed in a reliable manner. Subsequently, these can be used to integrate active devices on generic foundry platforms without the need for considerable postprocessing on the low-loss chip.

Fig. 2 (a) Optical microscope image of the vapour etched structure. (b) Shadow-effect-mode image of the same structure. (c) Sample after encapsulation with photoresist and subsequent hard bake, showing no degradation to the shielded mode transformer.

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