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Research paper

Fabrication of photonic integrated circuits in silicon nitride using substrate conformal imprint lithography

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ABSTRACT

The feasibility of nanoimprint lithography as an alternative strategy for the pattern definition of Si_3N_4 based PIC (photonic integrated circuit) is demonstrated in this study. The PICs were patterned by the substrate conformal imprint lithography (SCIL), a variation of UV nanoimprint lithography. The optical quality of the patterned PICs was determined by measuring the optical transmission losses of the fabricated PICs. The quality was then compared with the PICs patterned by an optical stepper. The analysis shows that the optical quality of the patterns fabricated by the SCIL process is similar to the patterns defined by an optical stepper. Our study demonstrates clearly that the SCIL is an alternative to established lithographic approaches in regards to material or pattern resolution.

1. Introduction

Silicon nitride (Si_3N_4) is an interesting core material for photonic integrated circuit (PIC) devices due to its transparency in both the visible and the near infrared wavelength domains and its CMOS process compatibility. These features open opportunities for Si3N4 as the material of choice for future oriented on-chip applications such as sensing and spectroscopy [1,2].

Multitude of parameters have to be considered for the design and the fabrication of a PIC. The width and height of a waveguide for example need to be determined based on the required optical mode profile. Very stringent specifications concerning the fabrication process may arise from the used fiber-to-chip coupling scheme, especially when grating couplers need to be considered. Here, a decrease in waveguide width, aspect ratio or coupler dimensions can rapidly reduce the possible choices for cost effective fabrication of such elements by optical lithographic approaches. Focused beam lithographic techniques like electron beam lithography (EBL), on the other hand, might suffer from charging effects, as Si_3N_4 waveguides typically need a several micrometers thick silicon dioxide buffer layer for optical decoupling from the silicon carrier substrate.

Nanoimprint lithography (NIL) does not suffer from the mentioned drawbacks by using a replication tool termed as stamp. NIL has shown its ability for high-resolution pattern generation down to sub-10 nm regime for the application in photonic devices [3] and is considerably cost effective in compare to conventional optical lithography due to the absence of an expensive optic system [4].

The feasibility of NIL for the fabrication of PICs was already demonstrated with different NIL process variations such as thermal NIL [5,6] utilizing a rigid stamp and soft ultra violet (UV) NIL [7] using a flexible stamp. Although the feasibility was demonstrated by the NIL variations, the potential of the NIL for a successful industrial implementation in the field of PIC application was yet limited by reasons arising from process principles of NIL methods. The thermal NIL lacks in large area contact for a full wafer scale process in a single step due to its high stamp rigidity and the soft UV NIL needs improvement in terms of high pattern resolution due to its low stamp rigidity. Besides, the demonstrated PICs so far were mostly patterned silicon (Si) PIC designs based on silicon on insulator (SOI) substrates.

In this study, we would like to call attention to an optional route for the fabrication of Si_3N_4 PICs by means of substrate conformal imprint lithography (SCIL), a variation of soft UV NIL process utilizing a flexible

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polymer as stamp material that is brought into contact in a very controlled manner. The SCIL process allows full wafer scale pattern definition by avoiding air trapping through incremental local contact between stamp and substrate surface and also enables sub-10 nm pattern resolution that is higher than soft UV NIL by avoiding stamp distortion through low imprint pressure of 20 mbar [8].

2. Experiment

2.1. Pattern definition sequence for the fabrication of Si3N4 PIC by the SCIL process

SCIL process requires a stamp for the pattern definition process that is usually molded from a master template. In our case, a patterned 6-in. Si wafer was used as the master template. Pattern definition of the template was carried out by conventional optical lithography utilizing an i-line stepper (Canon FPA 3000) with subsequent pattern transfer process into a Si wafer using reactive ion etching (RIE) process with Plasma Pro 100 (Oxford Instruments). The patterned master template was treated with an anti-sticking layer for easy stamp demolding afterwards.

The stamp for SCIL process consists of layers by different polymer materials, cushion layer (soft PDMS, Sylgard 184) with lower Young's modulus of 2 MPa and polymer stamp layer (X-PDMS) with higher Young's modulus of 80 MPa respectively [9]. The polymer materials are attached on a thin glass back plane in order to ensure handling and conformal contact over large area with minimal pattern distortion [10]. More information on the stamp composition can be found in [11].

A detailed process flow of the PIC pattern definition by means of SCIL is depicted in Fig. 1. The process was carried out with a MA8 SCIL tool (Suss Microtec).

A 6-in. silicon wafer with 6 μm thick SiO_2 lower cladding layer and a Si_3N_4 layer with a thickness of 100 nm on top was chosen as substrate. The substrate was spin coated with a nanoimprint resist (AMONIL MMS4, AMO GmbH) having an initial layer thickness of 200 nm (1a). The coated substrate was then locally contacted with the SCIL stamp. The first contact between the stamp and the substrate usually occurs at the edge of the substrate as illustrated in Fig. 1b. The contact was controlled by gratings on the stamp holder bending the stamp by over pressure of 20 mbar. When the stamp is fully contacted with the substrate (1c), UV exposure with a 1000 W lamp cures the imprint resist as shown in Fig. 1d. The curing time for the imprint resist in our study was 15 min. The stamp was then locally detached from the cured resist surface (1e) by switching the over pressure in the gratings to vacuum. In the last step, the stamp was fully separated from the cured resist layer leaving the designated patterns on the cured resist surface (1f).

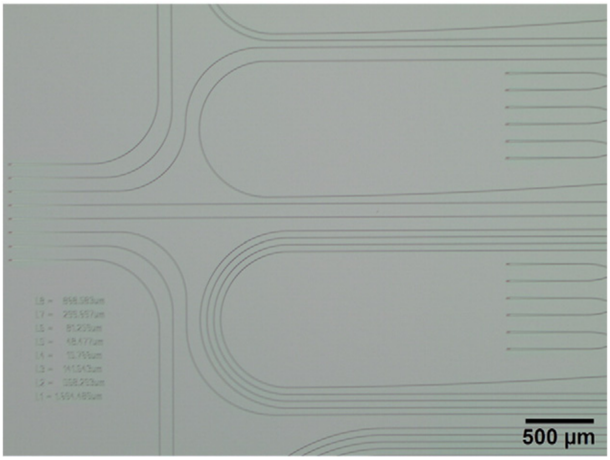

Fig. 2. Optical microscopy of imprinted PIC patterns.

Fig. 2 shows an optical microscope picture of the PIC design defined by the SCIL process. The design consists of a series of waveguides with different lengths between 1.5 cm and 1 m. These waveguides also include grating couples for fiber-to-chip coupling. The wide range of the waveguide lengths was chosen to evaluate the quality of the SCIL process by optical transmission loss measurement of the fabricated Si_3N_4 wave guides.

2.2. Pattern transfer sequence for the fabrication of Si3N4 PIC

Patterns defined by the SCIL process were then transferred into the Si3N4 layer on substrate to fabricate functional PIC structures. Pattern transfer process by means of RIE process with Plasma Pro 100 (Oxford Instruments) was carried out. Residual imprint resist layer underneath the patterns as well as the Si_3N_4 layer were etched in a single RIE process step. The process was conducted with 20 W RF power and 20 sccm of CHF_3 at a pressure of 7 m Torr. In order to determine optimized etch stop at the underlying SiO_2 layer, the process was monitored by a spectrometer (Ocean Optics).

Remaining nanoimprint resist on top of the etched Si_3N_4 PIC structures was removed after the RIE process. In order to strip the resist, the patterned substrate was treated with 25% Tetramethylammonium

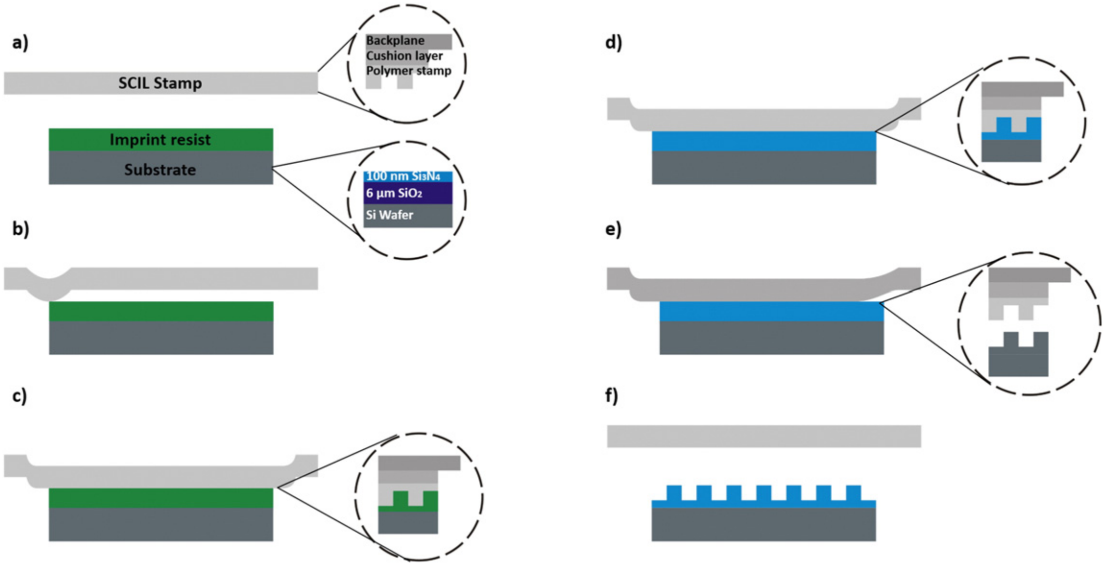

Fig. 1. Process flow of substrate conformal imprint lithography (SCIL).