Heterogeneous Integration of Thin-film Lithium Niobate and Silicon Photonics via Micro-transfer Printing

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ABSTRACT

Micro-transfer printing of thin-film lithium niobate (TFLN), as a backend integration method, enables selective and localized placement of TFLN to silicon photonics platforms, facilitating the creation of complex, multi-material systems that combine lithium niobate with other components. In this study, we investigate the transfer printing technique for TFLN. We present experimental results from hybrid silicon-LN devices created using this method, including micro-transfer printed ring modulators, photonics crystal (PhC) modulators, and Bragg grating modulators, among others.

Keywords: Silicon photonics, micro-transfer printing, thin-film lithium niobate (TFLN), heterogeneous integration, electro-optic modulator (EOM), ring resonator, photonic crystal cavity, Bragg Grating

1. INTRODUCTION

Silicon photonics is compatible with CMOS manufacturing processes, enabling low production costs, high yields, and seamless integration with electronic components. Thin-film lithium niobate (TFLN) is renowned for its excellent electro-optic coefficients and low-loss, high-speed modulation capabilities—features not natively supported by the silicon platform[1,2]. Heterogeneous integration of TFLN can enhance the silicon platform by leveraging the electro-optic properties of LN, incorporating high-performance LN modulators as key building blocks[3,4]. Heterogeneous integration of TFLN through micro-transfer printing overcomes several key challenges[5–10]. Firstly, it enables backend integration of TFLN without disrupting the existing CMOS fabrication process, thus resolving the inherent incompatibility between LN and CMOS fabrication while leveraging the established infrastructure of silicon photonics. This approach also provides flexibility in selecting TFLN thickness, determining precise integration locations, and ensuring easy interfacing with other components. Secondly, by transferring only a thin film, this method reduces fabrication complexity and material usage, making it a cost-effective solution. Moreover, it is a scalable and versatile process, capable of transferring multiple coupons in parallel in a fully automated manner. Versatile materials, devices, and even electronic components can be closely integrated on the same circuits, facilitating the creation of complex, multi-material systems that combine lithium niobate with other components.

To demonstrate the concept, we will detail the micro-transfer printing process of TFLN. We used micro-transfer printing to back-end integrate LN onto silicon waveguide circuits fabricated using standard techniques, as well as onto silicon circuits from a CMOS pilot line. Based on the technique, we demonstrated micro-transfer printed hybrid Si-LN ring modulators, photonics crystal (PhC) modulators, and Bragg grating modulators

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2. MICRO-TRANSFER PRINTING OF THIN-FILM LITHIUM NIOBATE

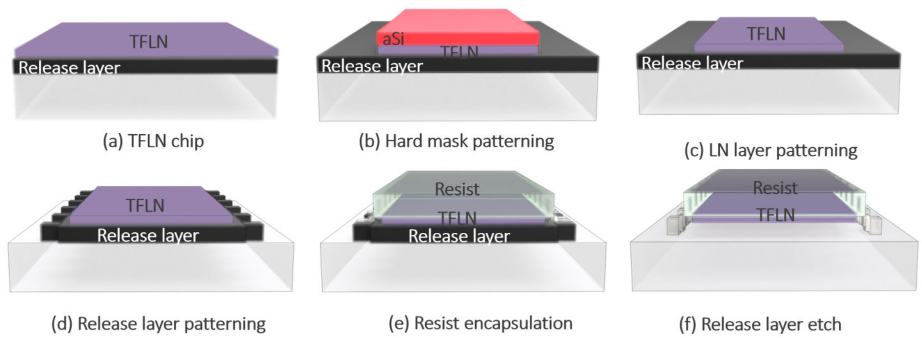

Figure 1 Process flow for preparing the source wafer. (a) TFLN chip; (b) patterning of TFLN coupon with a-Si hard mask; (c) after hard mask removal; (d) patterning of the release layer;(e) patterning of the resist tether system; (f) suspended TFLN coupons after wet etching [images from ref 12].

Micro-transfer printing involves a source wafer (TFLN chip) and a target wafer (silicon chip). Suspended coupons on the source wafer can be picked up using a PDMS stamp on the transfer printer, through the movement of the translation stage, the coupons could be printed over the target wafer. Suspend LN coupons are connected to the source substrate through the resist tethers. The fabrication process is illustrated in Figure 1.The coupons structures are first patterned on the amorphous silicon hard mask and transferred to the TFLN layer. Then the release layer is patterned. A third lithography step is conducted to form the resist tether system for the coupon. A final step of selective wet etching (HF wet etching) is conducted to make the coupon fully suspended. The PDMS is a viscoelastic material, whose adhesion is dependent on the peeling rate. The TFLN coupons can be detached from the substrate by a rapid retrieval process, when the stamp/coupon interface is stronger than the coupon/substrate interface. Subsequently, these coupons can be precisely and slowly transferred onto target silicon circuits, ensuring accurate placement and optimal integration[11].

3. HYBRID SI-LN MODULATORS REALIZED VIA MICRO-TRANSFER PRINTING

Resonant modulators can achieve high modulation efficiency while maintaining a minimal device footprint. However, resonators typically have stringent fabrication requirements regarding the feature size. Heterogeneous integration through micro-transfer printing can leverage the precise lithography capabilities of silicon circuits, enabling seamless integration with other silicon components. The size of the TFLN coupon can match that of the resonator, leading to significant reduction of material usage. We demonstrated a micro-transfer printed thin film lithium niobate (TFLN)-on-silicon ring modulator[12]. Figure 2 (a) illustrates the process of the micro-transfer printing process. Figure 2 (b), (c) and (d) shows the microscopic pictures of the source chip with suspended coupons, printed TFLN coupons over the silicon circuits and after the removal of the resist encapsulation. Figure 2 (d) shows the false-color cross-sectional SEM images of the hybrid Si-LN waveguide. The purple layer is the TFLN film. Figure 2 (f) shows that the device has an insertion loss of ~ -1.5 dB and extinction ratio of -37 dB. Figure 2 (e) shows the high-speed characterization of the modulator. The measured device exhibits an electro-optical bandwidth of 16GHz and supports data rates up to 45Gbits $^{-1}$.

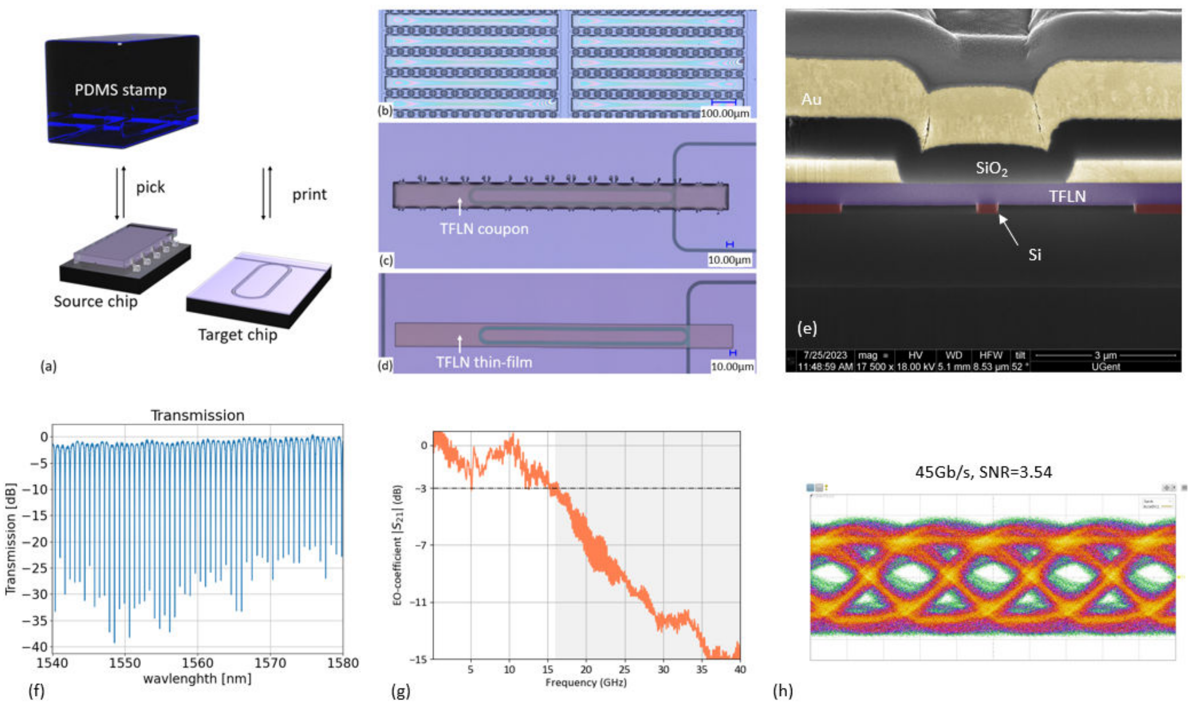

Figure 2 Micro-transfer printed thin film lithium niobate (TFLN)-on-silicon ring modulator. (a) Illustrations of the micro-transfer printing process; (b) the microscopic picture of the suspended TFLN coupons; (c) the microscopic picture of a printed TFLN coupon over the silicon ring resonator; (d) the microscopic picture of a printed TFLN thin film over the silicon circuit; (e) the cross-sectional SEM image of the hybrid Si-LN waveguide; (f) the transmission spectrum of the ring modulator; (g) the electro-optic bandwidth of ring modulator; (h) Eye diagrams of the ring modulator [images from ref 12].

Photonic crystal cavities (PhC) and Bragg Grating structures are resonant structures based on wire waveguides. They have a very compact shape and are easy to integrate with other components. However, they present significant fabrication challenges, requiring precise control within tens of nanometers. In Figure 3 (a)-(d)[13], we demonstrated a hybrid Si-LN photonic crystal modulator realized by micro-transfer printing 300nm-thick TFLN to wafer-scale fabricated silicon photonic crystal structures[14]. The silicon circuit is realized on a 300 mm silicon-on-insulator (SOI) wafer in the CMOS pilot line with 193 nm immersion lithography. Figure 3 (b) shows the microscopic picture of the silicon circuits printed with TFLN coupons. Efficient silicon grating couplers are used for coupling light in/out of the chip. The hybrid Si-LN PhC modulator achieves a single resonance over a wide spectrum from 1540nm to 1600nm. The PhC cavity has an insertion loss of −2.6dB, extinction ratio over 30dB and a quality factor of 150000, as show in Figure 3 (c). VNA measurement results shows that the 3dB electro-optical bandwidth is 3.5GHz. In Figure 3 (e)-(i)[15], we demonstrated a hybrid Si-LN Bragg Grating modulator based on micro-transfer printing of a 600nm-thick TFLN thin film. The Bragg Grating has a period of Λ=360nm and the sidewall corrugation depth is 10nm. The total length of the structure is around 540µm. We measured the device's transmission and observed a band rejection response ranging from 1533 nm to 1552 nm, with a sharp roll-off 60dB/nm around the band edge. The 3 dB electro-optic bandwidth was measured at 26 GHz, as shown in Figure 3 (i).

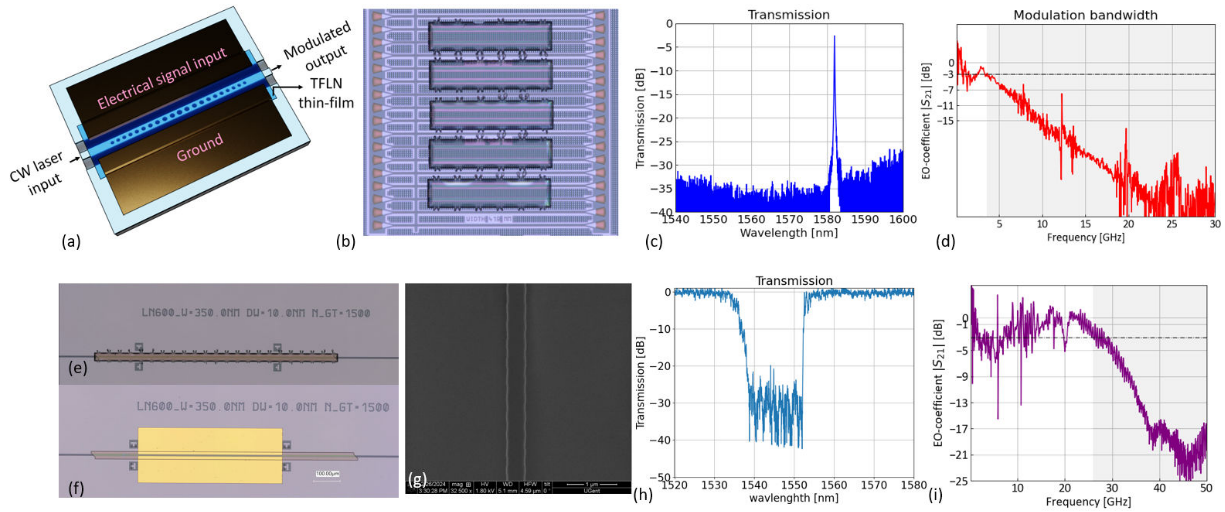

Figure 3 Experimental results of the photonic crystal hybrid Si-LN modulator realized by micro-transfer printing ((a)-(d)) [images from ref 13] and the hybrid Si-LN Bragg Grating modulator realized by micro-transfer printing ((e)-(i)). (a) the schematic image of the photonic crystal hybrid Si-LN modulator; (b) the microscopic image of a CMOS fabricated silicon chip with micro-transfer printed TFLN coupon; (c) the optical transmission of the photonic crystal hybrid Si-LN modulator; (d) the EO bandwidth of the photonic crystal hybrid Si-LN modulator; (e) the microscopic image of a TFLN coupon printed on the silicon Bragg Grating structure; (f) the microscopic image of the hybrid Si-LN Bragg Grating modulator; (g) SEM images of the silicon grating structure of the hybrid Si-LN Bragg Grating modulator; (h) optical transmission of hybrid Si-LN Bragg Grating modulator; (i) EO bandwidth of the hybrid Si-LN Bragg Grating modulator at wavelength λ=1552.36nm.

4. SUMMARY AND OUTLOOK

In summary, we developed a novel process for achieving heterogeneous integration of thin-film lithium niobate (TFLN) through micro-transfer printing. We demonstrated cavity-based modulators utilizing this process. This method provides flexibility and versatility for incorporating lithium niobate into more complex, multi-material systems. By combining TFLN with the CMOS-compatible silicon platform, we anticipate the widespread adoption of lithium niobate in future applications.

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