Printable Optical Nonlinearities: Micro-Transfer Printing of Periodically-Poled Lithium Niobate

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Silicon photonics lacks second order optical nonlinearities, preventing efficient frequency conversion of light on chip. On the contrary, other materials such as lithium niobate excel here and possess large nonlinear coefficients. Through heterogeneous integration, these nonlinearities can be introduced to the silicon photonics platform. We discuss our work on developing micro-transfer printing of periodically-poled lithium niobate onto silicon nitride and obtain efficient second harmonic generation. Additionally, the micro-transfer printing method allows for back-end integration onto the mature silicon photonics platform and enables efficient poling of the lithium niobate before its integration, limiting post-processing on the target wafer. Lastly, we look at how this component can be further improved and consider potential applications.

Introduction

In the last 20 years, silicon photonics (SiPh) has established itself as one of the leading photonic platforms due to its CMOS-compatibility, relying on the established fabrication tools in microelectronics. While large and complex systems can be fabricated in a scalable way, some critical components are still missing. The indirect bandgap of silicon inhibits optical gain, while its centro-symmetry results in a lack of second order optical nonlinear processes, such as the Pockels effect or efficient frequency conversion. While a third-order nonlinearity can be used, two-photon absorption limits the useable powers in silicon, limiting the overall conversion efficiency.

What silicon photonics lacks in nonlinearity, lithium niobate (LN) excels in due to its large $\chi^{(2)}$ coefficient, low losses and broad transparency range [1]. Lithium niobate has been used for many decades already for modulation and frequency conversion and established itself as one of the leading modulator platforms. While the technology started with bulk LN and free-space optics, a push was made towards waveguide-based devices for a much better field confinement, and therefore higher nonlinear efficiencies. In the last decade, thin-film lithium niobate has arisen, where sub-wavelength waveguide dimensions are possible and record efficiencies have been demonstrated [2]. However, in spite of its successes, it lacks the CMOS-compatibility of silicon photonics.

To combine best of both worlds, we demonstrate heterogeneous integration of thin-film lithium niobate on the silicon photonics platform through micro-transfer printing (µTP).

Micro-transfer printing of PPLN

Micro-transfer printing is an integration method that combines advantages from wafer bonding and flip-chip integration [3]. It gives high-throughput integration, high alignment accuracy, pre-testing options and happens at a back-end level. The accessibility of thin-film lithium niobate then enables micro-transfer printing of high-speed modulators and efficient frequency converters without introducing the material in the silicon photonics process flow, solving the CMOS-compatibility problem of lithium niobate [4,5].

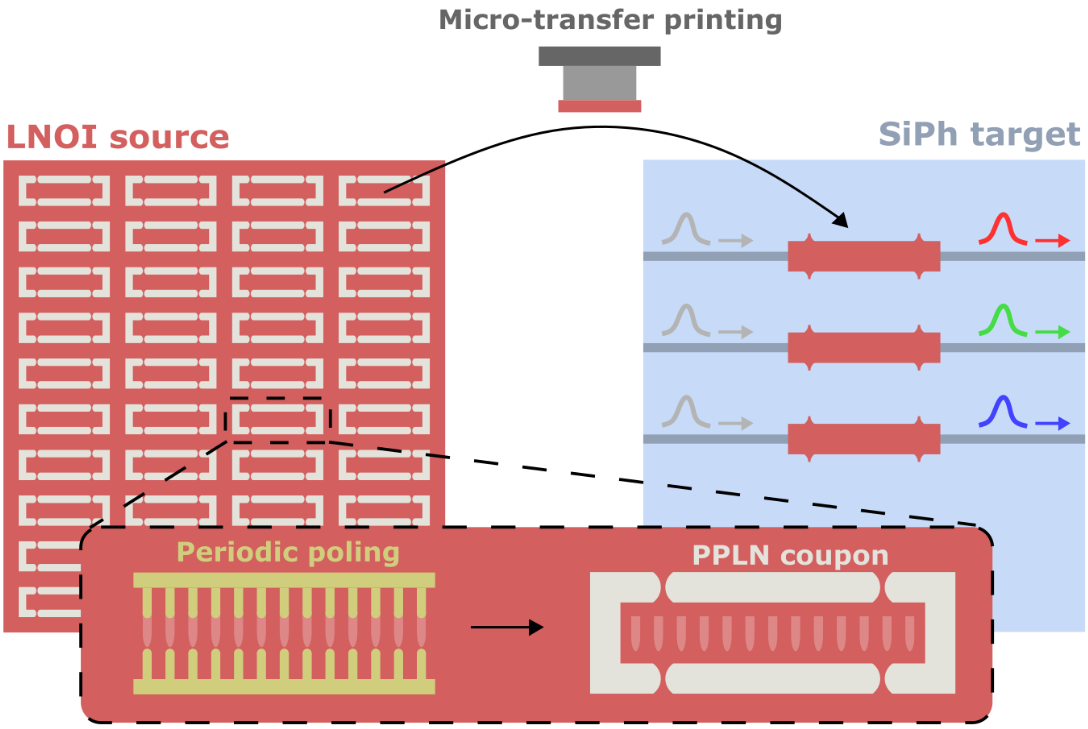

Figure 1: Micro-transfer printing scheme of PPLN onto a silicon photonics target

A sketch of the process flow is given in Figure 1. We start from a lithium-niobate-on-insulator (LNOI) wafer which contains the thin film that needs to be transferred. To be able to use the printed LN for frequency conversion, we opt for quasi-phase-matching, where the lithium niobate is periodically inverted. Therefore, finger electrodes are deposited, followed by electric field poling by applying the correct electric pulses to periodically invert the domains. Next, the electrodes are removed and coupons are fabricated, containing the poled LN. The layer underneath these coupons is selectively etched, resulting in suspended periodically-poled lithium niobate (PPLN). These are picked up with a PDMS stamp and printed onto a prepared silicon photonics target wafer [6]. By controlling the poling period and waveguide dimensions, the phase-matching of the frequency conversion process can be tuned to the required wavelengths, going from infrared to visible.

There are some advantages when considering micro-transfer printing for periodically-poled lithium niobate. The high electric fields which are typically needed for the electric field poling can be avoided on the silicon photonics wafer, where sensitive electronic or active components can be present (e.g. that are also transfer-printed). Additionally, due to the array configuration of all coupons on the LNOI source wafer, the electrodes of neighboring coupons can be connected and many can be poled simultaneously. Lastly, when printing PPLN slabs on top of nitride waveguides, the same PPLN slabs can be used for a large range of phase-matching wavelengths by changing the width of the nitride waveguide. This avoids the need to pole many different poling periods and the fabrication of a single poling period can be optimized, which is beneficial due to the precarious nature of the poling process.

Efficient second harmonic generation

We fabricate the PPLN thin film coupons and print these onto silicon nitride (SiN) waveguide, forming a hybrid PPLN/SiN waveguide. The poling period was taken to be 3.5 µm to aim for a phase-matched second harmonic generation (SHG) process at 1550 nm. Figure 2a shows a microscope picture of a printed PPLN coupon onto a silicon nitride waveguide. The uniform color of the lithium niobate implies a good bonding between coupon and target. The domains can be visualized through piezoresponse force microscopy (PFM) as seen in Figure 2b. The inverted domains are nicely situated above the silicon nitride waveguide, which also confirms they survive the transfer process.

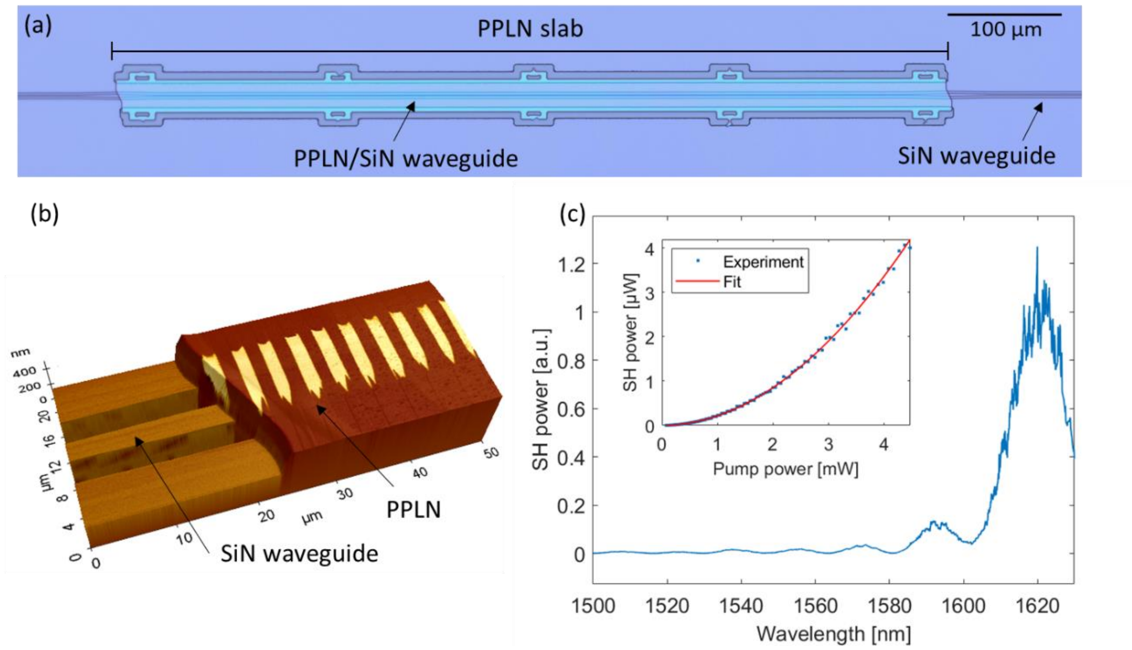

Figure 2: (a) micro-transfer printed PPLN coupon, (b) AFM and PFM measurement of PPLN coupon on nitride, (c) Spectral response of the second harmonic generation, inset: SHG power dependence

The fabricated nonlinear waveguides were optically characterized with the results depicted in Figure 2c. Second harmonic generation is observed with phase-matching situated at 1620 nm with 18 nm bandwidth [5]. The normalized conversion efficiency is measured to be 2500 %/Wcm^2, which is competitive with the LNOI waveguides [7]. The inset shows the quadratic power dependence, confirming the nonlinear behavior of the process. While the phase-matching was designed for 1550 nm, the observed one was situated at 1620 nm. This discrepancy can be fully attributed to the fabrication variation of the nanophotonic waveguide.

Conclusion

Silicon photonics lacks second order optical nonlinearities, and therefore efficient frequency conversion. By micro-transfer printing periodically-poled lithium niobate, we introduced a large $\chi^{(2)}$ coefficient and demonstrate efficient frequency conversion. Additionally, due to the versatility of the transfer-printing process, PPLN can readily be integrated together with transfer-printed lasers for on-chip frequency conversion. In conclusion, this work demonstrates printable nonlinearities in a CMOS-compatible way.

References

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