Silicon Photonics: silicon nitride versus silicon-on-insulator

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Abstract: Silicon photonics typically builds on a silicon-on-insulator based high-index-contrast waveguide system. Silicon nitride provides an alternative moderate-index-contrast system that is manufacturable in the same CMOS environment. This paper discusses the relative benefits of both platforms.

OCIS codes: (130.0130) Integrated Optics; (040.6040) Silicon

1. Introduction

In the past decade silicon photonics has emerged as one of the most prominent technology platforms for photonic integrated circuits (PICs) [1]. It owes its success to two prominent features: high refractive index contrast and CMOS-compatibility. The high index contrast (between a silicon waveguide core and a silicon oxide cladding) enables the fabrication of complex circuits on a small footprint and hence the fabrication of many chips per wafer. Furthermore it allows for the implementation of functions that are simply impossible or more difficult in waveguide technologies with lower index contrast, such as wavelength-sized cavities, photonic crystal structures, high-efficiency grating couplers etc.

The CMOS-compatibility – in the sense of manufacturability by means of the standard process technology in a state-of-the-art CMOS fab – is a key driver for the growth of the field. It allows one to manufacture silicon photonics products, both at moderate and at high volume, in existing CMOS-fabs, loaded primarily with the manufacturing of electronic ICs. This is an enormous asset as compared to those photonic integration platforms that rely completely on photonic ICs to cover the costs of the fab, implying that the investment in such a dedicated fab holds a huge financial risk.

2. Silicon-on-Insulator (SOI)

Today mainstream silicon photonics products are built on silicon-on-insulator (SOI) wafers, in which a crystalline silicon layer – typically 200 to 400 nm thick – resting on a silicon oxide buffer layer forms the core layer from which a large variety of waveguide-based devices can be patterned. The SOI-wafers can be procured commercially in both 200 and 300 mm wafer size for several standardized thicknesses of the silicon top layer. In its most basic form the technology allows to implement passive optical components, such as splitters, filters, (de)multiplexers, polarization-handling components, interferometers, resonators and their combination with coupling structures to optical fibers or to free space optical elements. The addition of electrically driven micro-heaters allows one to induce refractive index changes and with that one can implement low speed tunable or switchable functions. But the main momentum in this field has come from the integration of high speed transmitter and receiver functions for telecommunication or data communication purposes. At the transmitter side the key device is a high speed optical modulator based on refractive index modulation induced by electron or hole density variations in an electrically driven p-n junction built around a waveguide. This approach has proven to be very effective for either amplitude or phase modulation at speeds beyond 40 Gb/s. At the receiver end high speed detection is typically implemented by integrating epitaxially grown germanium PIN or APD detectors with the silicon waveguides. With this approach detectors operating at data speeds beyond 40 Gb/s have been demonstrated. The integration of light sources is typically done with hybrid approaches today but at the research level rapid progress is being made to integrate III-V-based sources by means of wafer-scale processes in the CMOS-fab.

While the SOI-approach has become mainstream in the field of silicon photonics, there is an increasing interest in exploring alternative material combinations that satisfy the same key features as is the case with SOI: high index contrast and CMOS-compatibility. A major driving factor to deviate from SOI is the desire to operate in spectral bands where silicon or silicon oxide are absorbing, but there are many more reasons why SOI is not necessarily the best option for device functionality and performance. An important candidate in this respect is the silicon nitride waveguide system, in which the silicon core of the SOI-system is replaced by a silicon nitride core, while remaining CMOS-compatible [2-4].

3. Silicon nitride

Silicon nitride (SiN) is a common material in CMOS fabs and is typically deposited by either Low Pressure Chemical Vapour Deposition (LPCVD) at high temperature (>700 C) or by Plasma Enhanced Chemical Vapour Deposition (PECVD) at low temperature (<400 C). LPCVD-based SiN is typically close to stoichiometric Si_3N_4, is highly strained and provides an excellent control over the homogeneity of material index and thickness. It has a refractive index of around 2.0 at a wavelength of 1550 nm. PECVD-based nitride has a composition that depends strongly on the deposition conditions and can be silicon-rich (higher refractive index) or nitrogen-rich (lower refractive index). Both types of nitride have been used for photonic ICs. In the telecom band around 1550 nm it is common to use LPCVD nitride to avoid the absorption due to N-H and Si-H bonds around 1520 nm [5]. To this end the LPCVD nitride is annealed at high temperature to drive out the hydrogen. Hereafter we discuss the key properties of a SiN-based PIC-platform in comparison to the SOI-based PIC-platform.

Transparency range: SOI-based waveguides have low absorption losses in the wavelength range from 1.1 µm (band edge of silicon) to about 3.7 µm (onset of mid-IR absorption of silica). For applications requiring shorter wavelengths (e.g. data communication at 850 nm, sensors operating in the therapeutic window etc.) SOI is not an option. Since SiN is transparent throughout most of the visible range – down to at least 500 nm – it is a viable candidate to implement "silicon photonics" at wavelengths below 1.1 µm [6]. This has led to demonstrations of spectroscopic functions [7-8], Raman spectroscopy-on-chip functions [9-11] and integration with colloidal quantum dots emitting in the visible [12].

Index contrast: The index contrast in SOI waveguides (cladded with silica) is very high (3.5 vs 1.5) while that in SiN waveguides (cladded by silica) is moderately high (2 vs 1.5). Very high index contrast is both a blessing and a curse: it allows one to implement unique functionalities on a very compact footprint but at the same time it makes the waveguide prone to scattering losses due to nm-scale roughness of the sidewalls of the waveguide. Even a roughness of only a few nm already leads to a waveguide loss of the order of 1 dB/cm. It also implies high sensitivity of the effective index to the waveguide width. This leads to the harsh rule of thumb that a waveguide width deviation of 1 nm leads to a ~1 nm wavelength error in the spectral transfer function of interferometric components such as Mach-Zehnders or ring resonators. It also leads to less than ideal crosstalk in arrayed waveguide gratings. In SiN waveguides all of this is relaxed to a certain degree, while the compact footprint is largely maintained. One could say that the index contrast in silicon nitride waveguides sits in a nice middle ground.

The lower index contrast of the SiN system as compared to SOI implies that it is harder to make high efficiency grating couplers for out-of-plane optical input/output, a very useful feature that allows for wafer-level testing and alignment-tolerant fiber coupling [13]. Nevertheless grating coupler efficiencies below 3dB have been reported.

Low loss: SOI-based photonic wires – silicon strip waveguides completely surrounded by a silica cladding - have typical waveguide losses of 1 to 2 dB/cm, largely due to the scattering losses associated with sidewall roughness. In SiN photonic wires these losses can in principle be an order of magnitude lower. The losses can be reduced further by using shallow rib waveguides or very thin strip waveguides. Losses down to ~1 dB/m have been reported for such SiN waveguides, but this is obviously at the expense of lateral and/or vertical confinement [14-15].

Manufacturing flexibility: SiN is deposited by LPCVD or PECVD and that implies that there is a lot more flexibility to combine the SiN waveguide with other photonic structures than is the case for SOI. As an example, one can deposit the waveguide layer on top of a DBR-mirror or metal mirror and thereby boost the efficiency of grating couplers [16-17]. Also, one can deposit the waveguide layer in two steps and add luminescent quantum dots to the waveguide core in between both steps [12]. This flexibility also means that one can combine SiN waveguides with SOI waveguides on a single platform, thereby combining the unique features of both platforms in a single chip [3,18].

Third order nonlinearity: The Kerr nonlinearity of silicon is huge but unfortunately it is useless in the 1300/1550 telecom bands because of two-photon absorption (TPA). TPA is a problem in its own right because it induces extra waveguide losses at high power. Already at a continuous wave power of a few tens of mW the penalty sets in. Silicon nitride has a weaker Kerr nonlinearity but the TPA is virtually zero in view of the material's large bandgap. Therefore it has been possible to demonstrate frequency comb generation as well as supercontinuum generation in SiN photonic wires [19-23].

Second order nonlinearity and Pockels effect: In principle both silicon and silicon nitride have negligible second order nonlinearity and Pockels effect in view of the centrosymmetry of both materials (after averaging in the case of the amorphous SiN). Therefore electro-optic modulation is not possible. In the SOI-case one can resort to free carrier induced electro-refraction, but the resulting modulators have a large footprint (several mm long) and consume a lot of power at high modulation speed. Therefore the hunt is open for a more compact high speed modulator. In recent years strong electro-refraction has been reported in SOI waveguides in which a strain gradient was induced by means of a strained silicon nitride overlayer. The precise mechanism for this phenomenon is still a matter of debate, but one recent report attributes the effect to a strain gradient in the silicon nitride rather than that in the silicon [24]. This may open the door to strained SiN-based Pockels-modulators. An alternative route – applicable to both SOI and SiN – is to overlay the waveguide with a strong electro-refractive or electro-absorptive cladding layer. Results have been reported for graphene [25], for poled polymers, for ferro-electric materials and for ABC-metamaterials [26].

4. Conclusion

SOI-based silicon photonics has evolved to being a mature PIC-platform that is used in commercial products. But it is not the only option for high-index-contrast waveguide circuits manufactured in a CMOS-fab. Silicon nitride is emerging as an alternative silicon photonics platform, with complementary features and strengths.

5. References

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