Electro-Optic Modulation in Silicon Nitride Photonic Integrated Circuits by means of ALD ZnO Overlays

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Second-order nonlinear optical ($\chi^{(2)}$) effects are at the basis of many applications such as fast electro-optic modulators (EOMs) and optical parametric oscillators. But most of these $\chi^{(2)}$ devices make use of bulk materials or low-contrast waveguides. By integrating $\chi^{(2)}$ effects on a chip and exploiting the advancements in nanophotonic circuit design, cheaper, smaller and more efficient $\chi^{(2)}$ devices could be realized. The CMOS-compatible Si and SiN platform have proven to be well-suited for photonic integration, however, they lack significant $\chi^{(2)}$ nonlinearity. We propose using atomic layer deposited (ALD) zinc oxide to fill this need. ALD lends itself well to photonic integration as it is a low-temperature, conformal deposition technique that provides thickness precision at the monolayer level. ZnO is a wide band gap material (~3.3 eV) that crystallizes preferably in the hexagonal wurtzite structure, point group 6mm [1]. We report on strong second-harmonic generation (SHG) in polycrystalline plasma-enhanced ALD (PE-ALD) ZnO thin films deposited on glass substrates. Furthermore, we have observed the linear electro-optic (EO) effect in SiN waveguides coated with PE-ALD ZnO. To the best of our knowledge, this is the first demonstration of the linear EO effect in a waveguide with a $\chi^{(2)}$ active ALD overlay.

For thin film deposition a homebuilt ALD reactor with a base pressure of 10$^{-6}$ mbar is used. In the SHG experiments we have studied two samples: (I) 39.1 nm ZnO on glass, and (II) 36.7 nm ZnO on 6 nm Al$_2$O$_3$ on glass. An Al$_2$O$_3$ seed layer is used in sample (II) because it has been shown to promote (002) orientation of the ZnO crystallites and therefore improve $\chi^{(2)}$ nonlinearity [2]. The Al$_2$O$_3$ layer is deposited via thermal ALD at a substrate temperature of 120°C (from trimethylaluminium and H$_2$O, both for 5 s at 5×10$^{-3}$ mbar). ZnO deposition is done at 300°C by PE-ALD (5 s diethyl zinc at 5×10$^{-3}$ mbar and 10 s O$_2$ plasma at 10$^{-2}$ mbar). For the EOM, we started from air-cladded SiN waveguides fabricated in a CMOS-fab on which we deposited 87 nm ZnO (there is no Al$_2$O$_3$ seed layer in this first sample). This was followed by spin coating of a 3 μm SU-8 cladding and electrode fabrication. A cross-section of the structure is depicted in Fig. 1a. The electric field is applied vertically. This allows to access $\chi_{zzz}$ and $\chi_{xxz}$ (or $r_{333}$ and $r_{113}$) in the ZnO layer on top using the TM$_{00}$ and TE$_{00}$ mode respectively. The chip is cleaved at both waveguide ends for edge coupling.
For the SHG experiments we use a femtosecond laser at a wavelength of 980 nm. The laser light (p-polarized) is focused onto the samples and the transmitted SH power is measured as a function of the angle of incidence. More details about the setup and modeling can be found in [3]. The results for both samples are shown in Fig. 1b/c. Using an Al₂O₃ seed layer increases the main tensor element |χzzz| from 4 pm/V to 14 pm/V.

The EOM measurements are done with a fiber-coupled tunable CW laser (890-910 nm). A fiber polarization controller is used to select TE or TM polarization. As the waveguide with cleaved facets forms a Fabry-Pérot cavity, the phase modulation will be converted into amplitude modulation. This makes the EO effect observable by measuring the transmitted power while applying a voltage. Fig. 2a shows the Fabry-Pérot fringes in a transmission measurement (for a waveguide length of 7.5 mm). For the EOM measurement we set the wavelength to a slope of 0.4098x + 0.0289, which corresponds to a waveguide length of 7.5 mm. The fringes are shown in Fig. 2b/c. From these measurements, we estimate χzzz and χxxx of ZnO to be of the order of a pm/V.

In conclusion, by SHG measurements in PE-ALD ZnO thin films we find χ(2) values up to 14 pm/V in line with bulk ZnO crystals (χzzz = -14.31 pm/V) [1] and larger than what has been reported before in ALD ZnO (χzzz = -4.0 pm/V) [2]. Furthermore, we have observed the linear EO effect in SiN waveguides with a PE-ALD ZnO overlay. Using an Al₂O₃ seed layer can improve χ(2) in future EOMs. Considering the SHG results, we expect high-speed modulation to be possible with an appropriate electrode design.