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

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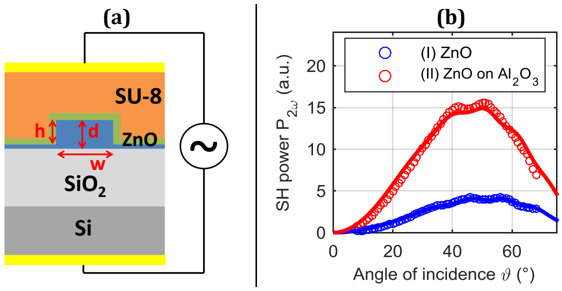
Second-order nonlinear optical ($\chi^{(2)}$) effects are at the basis of many applications such as fast electro-optic modulators (EOMs) and optical parametric oscillators. But most of these $\chi^{(2)}$ devices make use of bulk materials or low-contrast waveguides. By integrating $\chi^{(2)}$ effects 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_2O_3 on glass. An Al_2O_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_2O_3 layer is deposited via thermal ALD at a substrate temperature of 120°C (from trimethylaluminium and H_2O, 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_2O_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 χ_{zzz} and χ_{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.



(c)

$\chi^{(2)}$ values obtained from fitting SHG data		
	(I) ZnO	(II) ZnO on Al_2O_3
χ_{zzz} (pm/V)	-4 ± 2	-14 ± 5
$2\chi_{xxz}+\chi_{zxx}$ (pm/V)	5.9 ± 0.5	13.1 ± 0.9

Fig. 1. (a) Schematic device cross-section of EOM (d = 300 nm, h = 270 nm, w = 650 nm). (b) SHG measurements (circles) and fitted curves (full lines). (c) $\chi^{(2)}$ fitting results.

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 modelling can be found in [3]. The results for both samples are shown in Fig. 1b/c. Using an Al_2O_3 seed layer increases the main tensor element $|\chi_{zzz}|$ 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 the fringes to maximize modulation. Then, an AC voltage is applied and the RF output of the photodetector is connected to an electrical spectrum analyzer. In the RF spectrum a peak appears at the frequency of the applied voltage indicating a linear EO effect (not Kerr or thermal). As expected the peak height varies linearly with the amplitude of the applied voltage (Fig. 2b). From these measurements, we estimate χ_{zzz} and χ_{xxz} of ZnO to be of the order of a pm/V.

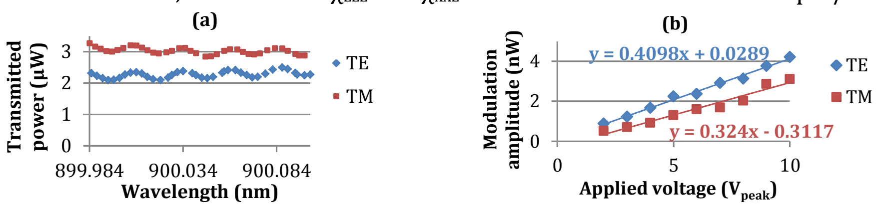


Fig. 2. (a) Transmission measurement. (b) EOM measurement (frequency 100 kHz).

In conclusion, by SHG measurements in PE-ALD ZnO thin films we find $\chi^{(2)}$ values up to 14 pm/V in line with bulk ZnO crystals (χ_{zzz} = -14.31 pm/V) [1] and larger than what has been reported before in ALD ZnO (χ_{zzz} = -4.0 pm/V) [2]. Furthermore, we have observed the linear EO effect in SiN waveguides with a PE-ALD ZnO overlay. Using an Al_2O_3 seed layer can improve $\chi^{(2)}$ in future EOMs. Considering the SHG results, we expect high-speed modulation to be possible with an appropriate electrode design.

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