Engineered Second-Order Nonlinearity in Silicon Nitride

CNF Project Number: 2524-17
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Primary Source(s) of Research Funding: National Science Foundation
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Primary CNF Tools Used: JEOL 9500, ASML PAS 5500/300C DUV Stepper, Oxford PECVD, AJA Sputter Deposition, LPCVD Furnace, Oxford 100 Etcher, Unaxis 770 Deep Silicon Etcher, Xactix Xenon Difluoride Etcher

Abstract:

We induce a permanent second order nonlinearity of 0.24 pm/V in silicon nitride via electrical poling at a high temperature. We demonstrate electro-optic response usable for modulation in the engineered silicon nitride device up to 15 GHz.

Summary of Research:

Silicon nitride (Si_3N_4) is as a high-performance platform for versatile on-chip photonic devices [1,2] because of its low propagation loss, broad transparency window (400-6700 nm [3]) and good compatibility with complementary metal-oxide semiconductor (CMOS) processing. However, Si_3N_4 lacks an intrinsic second-order nonlinearity ($\chi^{(2)}$) due to its centrosymmetric structure [4]. Building an intrinsic $\chi^{(2)}$ that allows high-speed (gigahertz level) EO response in Si_3N_4 will create a new photonic platform with great potential in integrated photonics.

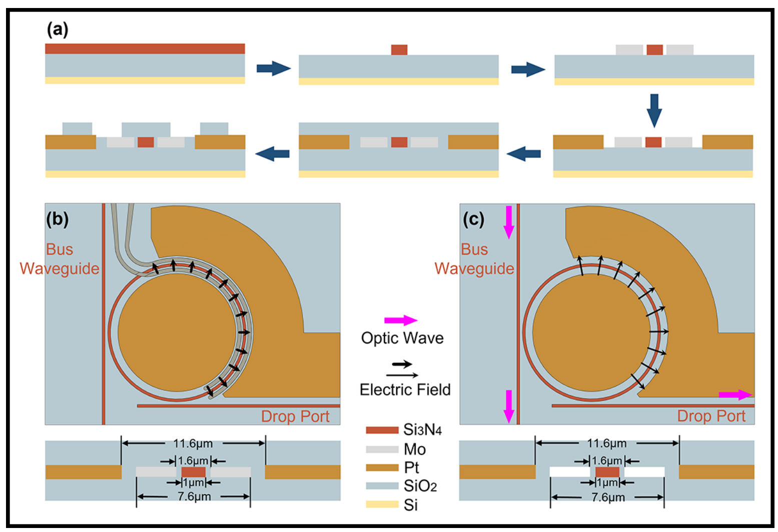

Figure 1: (a) Fabrication procedures of our device. (b) Ring resonator under poling. (c) Ring resonator under high-speed test (Mo removed).

We demonstrate induction of a second-order nonlinearity in Si_3N_4 by electrically poling the film and aligning the Si-N bonds. Khurgin, et al. [5] hypothesized that the Si-N bonds in Si_3N_4 possess a second-order hyperpolarizability comparable to Ga-As bonds in GaAs, whose $\chi^{(2)}$ is as large as 300 pm/V. The centrosymmetric orientation of the Si-N bonds causes their contribution to cancel each other and leads to a bulk $\chi^{(2)}$ of zero. However, by aligning these bonds and breaking the symmetry, even slightly, a non-trivial intrinsic $\chi^{(2)}$ will naturally emerge and thus induce a high-speed EO response in Si_3N_4.

We use an Si_3N_4 ring resonator (1μm*300nm) with electrodes to study the EO response in poled and non-poled Si_3N_4. Fabrication procedures are shown in Figure 1(a). We deposit 300 nm LPCVD nitride over 4 μm thermally-grown oxide on a silicon wafer. The waveguide is patterned using e-beam lithography and etched using reactive-ion etching (RIE). We then pattern a pair of Mo electrodes using DUV lithography and deposit the metal through sputter-liftoff process. This pair of electrodes is placed 300 nm away from the waveguide (edge to edge) to generate a strong electric field to pole the Si_3N_4 ring (Figure 1(b)).

We choose Mo as the material since it can be removed using XeF_2 after poling to eliminate the huge loss it introduces to the ring, which we need for characterization of the EO response, which has a high selectivity to all the other materials used in the device.

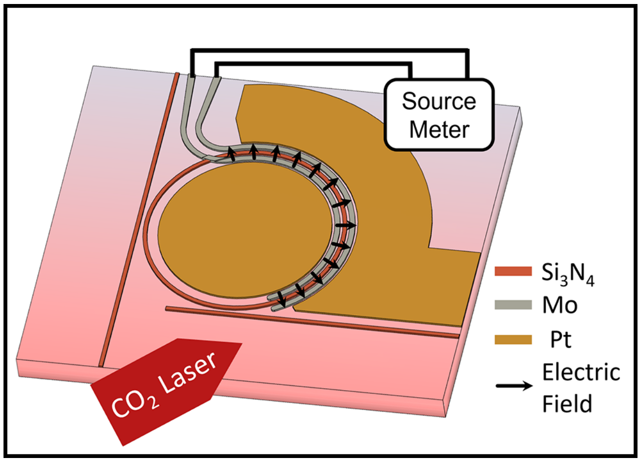

Figure 2: Poling of Si_3N_4 ring resonator heated by CO_2 laser beam.

Another pair of platinum (Pt) electrodes is then patterned and deposited in the same way outside the Mo ones for EO modulation after the removal of Mo (Figure 1(c)). Afterwards, we clad the waveguide and electrodes with 2 µm PECVD oxide and open vias for probe contact and XeF_2 etching.

We heat up the device to facilitate the poling process [6] by focusing a 10W CO_2 laser beam beside the ring (Figure 2). We limit the heating to 700°C as we observe rapid dropping of the arcing threshold between the electrodes, which limits the field strength we can apply, when going to higher temperature. After reaching this desired temperature, we apply a high voltage to the Mo electrodes for poling. The maximum voltage we manage to apply without arcing is 160V and it corresponds to a horizontal poling field of 0.68 MV/cm in Si_3N_4 according to simulation. The device sinks in the high temperature poling for five minutes before we disable the heating laser. The poling field is maintained until the device cools down to room temperature (in a few seconds). Such rapid cooling helps to freeze the aligned bonds in their new positions and prevent them from rolling back (as the poling field still remains).

We quantitively characterize the r_{33} and r_{31} EO coefficients of the Si_3N_4 resonator (Figure 3(a)). The measured values at different working frequencies for the poled device (red lines, various time after poling) and non-poled reference (green line) are shown in Figure 3 (b-c). We observe that the poled device demonstrates an enhancement of the r_{33} component to 30 fm/V (effective $\chi^{(2)}$ 240 fm/V [4]). After the poling the speed of the measured EO response increases. The reference device shows a 3dB cutoff frequency of 3 GHz (data points at high frequencies have their lower error bar set to zero since they are hardly distinguishable from the background noise), while this number improves to at least 15 GHz for the poled device, for both r_{33} and r_{31} component. The *slow response* measured in the non-poled device is a result of carrier-related effects in Si_3N_4 as previously reported [7], which has a speed limit of approximately 1 GHz [8]. The *fast response* of the poled device, on the other hand, confirms our induction of a second-order nonlinearity in the poled Si_3N_4 as no other mechanism can enable EO response of such high speed. We track the EO response in the poled device for one week and observe no significant decay, suggesting our induction is long-lasting and permanent.

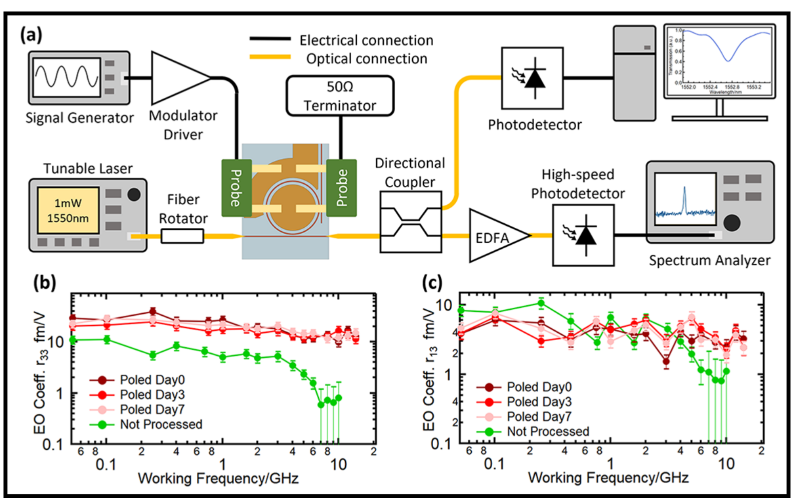

Figure 3: (a) Schematic of apparatus of EO response characterization. (b-c) Measured EO coefficient r_{33}(b) and r_{13}(b) at various frequencies of both poled and non-poled device.

Conclusions and Future Steps:

In conclusion, we demonstrate a permanent second-order nonlinearity of 0.24 pm/V and corresponding electro-optic response as fast as 15 GHz built in silicon nitride through electrical poling. This work paves the way to enabling high-speed active functions on the Si_3N_4 platform, substantially expanding its potential applications.

References:

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