Engineered Second-Order Nonlinearity in Silicon Nitride

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Primary CNF Tools Used: JEOL 9500, ASML PAS 5500/300C DUV stepper, Oxford PECVD, Oxford 100 etcher

Abstract:

We induce a permanent second order nonlinearity up to 26 fm/V in silicon nitride via electrical poling at a high temperature. We demonstrate electro-optic modulation on the engineered silicon nitride device up to 15 GHz.

Summary of Research:

Silicon nitride (Si_3N_4) is a low loss, CMOS-compatible material that has revolutionized many fields including integrated photonics and nonlinear optics, but the lack of a significant electro-optic response limits its applications. Second harmonic generation (SHG) [1-3] is promising; however, these platforms do not show feasible signal modulation at gigahertz or higher speed. Building an electro-optic response available for gigahertz (GHz) modulation in Si_3N_4 will create a new photonic platform with great potential in silicon photonics and quantum optics.

We propose to align the Si-N bonds in Si_3N_4 and induce an electro-optic effect by electrically poling the Si_3N_4 device. Khurgin hypothesized that the Si-N bonds in Si_3N_4 possess a second-order hyperpolarizability comparable to Ga-As bonds in gallium arsenide (GaAs) [4], whose $\chi^{(2)}$ is as large as 300 pm/V. However, the centro-symmetric structure of Si_3N_4 — meaning the bonds are oriented isotropically — leads to the absence of a second-order nonlinearity ($\chi^{(2)}$) and Pockels effect. A non-trivial $\chi^{(2)}$ will naturally emerge in Si_3N_4 if an applied force can align the bonds towards a certain direction, even by just a few degrees, and thus break the structural symmetry of the material.

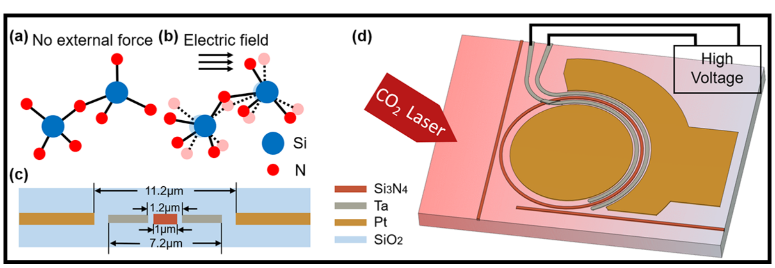

Figure 1: (a-b) Si_3N_4 lattice without (a) and with (b) an electric field applied. (c) Schematic of poling the Si_3N_4 ring with device heated by CO_2 laser. (d) Cross section of the device.

The Si-N bonds are electrically asymmetric and behave as dipoles (Figure 1(a-b)). We place a pair of tantalum (Ta) electrodes 100 nm (edge-to-edge) away from the waveguide (cross section 1 μm × 300 nm) to provide a horizontal electric field strong enough to efficiently align the Si-N bonds (Figure 1(d)). The maximum bias we can apply before arcing happens is 200V, generating a field 1 MV/cm in the Si_3N_4, very close to its electrical breakdown threshold.

To further enhance the poling process, we heat up the Si_3N_4 ring by focusing a 10W CO_2 laser beam at the device (Figure 1(d)) as the poling begins. The temperature reached is approximately 700°C, estimated based on the incandescent color of the device. Such high temperature makes the Si-N bonds more susceptible to the applied field. The poling lasts for five minutes before the heating laser is switched off, and the sample cools down while the poling field stays on. The rapid cooling prevents the aligned bonds from a complete reversal and 'freezes' them at their new positions permanently even after the removal of the poling field.

The fabrication of our device starts from depositing 300 nm of Si_3N_4 using low pressure chemical vapor deposition (LPCVD) over 4 μm thermally grown SiO_2 on a 4-inch silicon wafer. We pattern the ring resonator using electron-beam lithography and inductively coupled plasma reactive-ion etching (ICP-RIE). The temporary Ta electrodes and another pair of permanent platinum (Pt) electrodes for high-speed modulation (Figure 1(c)) are then separately patterned using DUV photolithography and deposited by sputtering.

We examine the induced electro-optic coefficient (EOC) in our device by applying a modulation

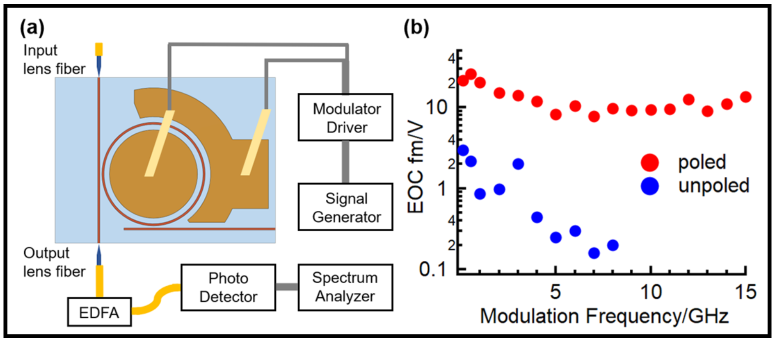

Figure 2: (a) Schematic of measuring the introduced second order nonlinearity in the Si_3N_4 ring resonator. (b) Measured r_{zzz} versus modulation frequency.

signal on it and examine its performance. As shown in Figure 2(a), a signal generator sends modulation signal, amplified by a modulator driver, to the Pt electrodes sandwiching the ring (Ta electrodes removed by XeF_2 etching) through a pair of micro probes. We set the working wavelength properly so that the modulation efficiency is optimized.

A photodetector converts the output optic signal, pre-amplified by an erbium-doped fiber amplifier (EDFA), into electric signal and the following spectrum analyzer extracts the high-frequency component $P(\omega)$ of interest. The EOC (r_{zzz}) of the poled Si_3N_4 can be derived from [5]:

$$P(\omega) = \eta[G(\frac{\partial P}{\partial \lambda})|_{\lambda=\lambda_0} \frac{\lambda_0 L}{2n_{\text{eff}} L_{tot}} n_{SiN}{}^3 r_{zzz} E_Z(\omega)]^2$$

where $\partial P/\partial \lambda$ is the slope of transmitted power spectrum of the device at λ_0, n_{eff} is the effective index of the working mode of our device, n_{SiN} is the refractive index of Si_3N_4, L_{tot} is the total length of the ring and L the length of where modulation field is applied, η is the power conversion efficiency of the photodetector, G is the gain of EDFA and $E_Z(\omega)$ is applied modulation field.

What we derive is the ZZZ component of EOC since the working mode is polarized in the same direction as the poling field as well as the modulation field.

We measure the r_{zzz} to be up to 26 fm/V in the device we engineered using this method, and we present non-decaying electro-optic modulation up to 15 GHz (Figure 2(b)). Compared to the pre-poling value, our engineering induces a > 50X enhancement at high frequency regime (> 4 GHz). Furthermore, we track the quantity of the induced r_{zzz} for 120 hours and no decay is observed.

Conclusions and Future Steps:

In conclusion, we demonstrate a permanent second order nonlinearity, up to 26 fm/V, built in silicon nitride available for modulation as fast as 15 GHz. We are working on fabrication of high-performance Si_3N_4 modulator based on this technique.

References:

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