Electrical and Optical Characterization of Thin Film Silicon-Rich Nitride

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Primary CNF Tools Used: Oxford 100 PECVD, E-Beam Evaporator, Woollam RC2 Spectroscopic Ellipsometer, Metricon 2010/M Prism Coupler

Abstract:

Silicon-rich silicon nitride (SRN) has recently attracted attention for its promise to enable high-power nonlinear optical information processing. The same qualities that make SRN promising for this application—a large optical nonlinearity and high dielectric strength—also make SRN a promising material for programmable integrated photonics. To demonstrate this potential, we fabricated low loss SRN films with a large electro-optic effect and show that the material's electrical properties are extremely versatile and can be optically controlled.

Summary of Research:

We characterized electrical and optical properties of thin silicon-rich silicon nitride (SRN) PECVD films with different silicon and nitrogen contents. SRN is a class of materials with a bandgap ranging between that of stoichiometric silicon nitride (SiN) and amorphous silicon. This makes SRN generally more electrically insulating than silicon but more conductive than SiN. Its optical properties similarly range between those of silicon and SiN, with a refractive index from about 2 to 3.5 at 1550 nm, increasing with higher silicon content, and a large Kerr nonlinearity.

We measured the electrical conductivity of different SRN films by measuring the I-V characteristics under different conditions and we measured the propagation loss of light at 1550 nm in SRN slab waveguides using prism coupling, as well as the electro-optic effect at 1550 nm.

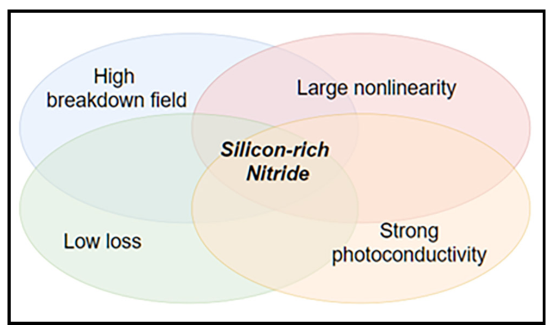

Figure 1: Silicon-rich nitride combines several desirable material properties for programmable photonic circuits. The combination of a high breakdown field [2] and large nonlinear coefficients allows large refractive index modulations [1,3]. A strong photoconductivity allows modulating the electro-optic effect with visible light while low losses [4] are a prerequisite for deep photonic circuitry.

Electrical Conductivity. To measure the electrical conductivity, we deposited around 500 nm thick SRN layers of different silicon content using PECVD on strongly p-type Si wafers. The gas flow ratios for the different materials were varied from 40 sccm SiH_4, 10 sccm NH_3 and 1425 sccm N_2 for the material closest to SiN (lowest refractive index and lowest conductivity) to 25 sccm SiH_4 and no NH_3 or N_2 for the material closest too amorphous silicon (highest index and most conductive). We then deposited 15 nm titanium and 15 nm gold electrodes on top of the SRN layer. We inferred the conductivity from the current flowing when applying a negative bias to the gold electrode and keeping the substrate at ground. We repeated the measured while illuminating the chips with approximately 100 mW/cm^2 at 530 nm.

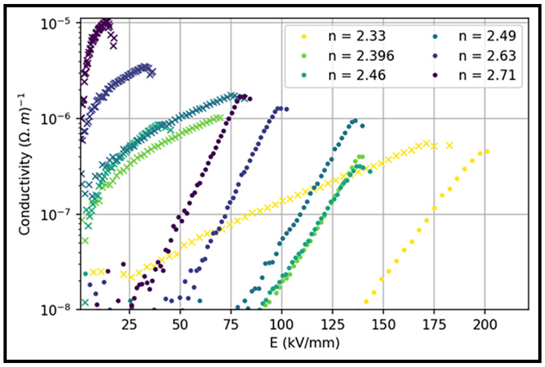

Figure 2: Conductivity of different silicon-rich nitrides as a function of electric field and illumination. Different colors correspond to different gas flow rates of SiH_4 and NH_3, ranging from 4:1 (n=2.33) to >10:1 (n=2.71). Different markers correspond to different illuminations: Dots mark the conductivity in the dark state, "x"s mark the conductivity in the bright state under approximately 100 mW/cm^2 of 530 nm light. The saturation at the top of each conductivity curve is an artifact from the compliance current of our high voltage amplifier.

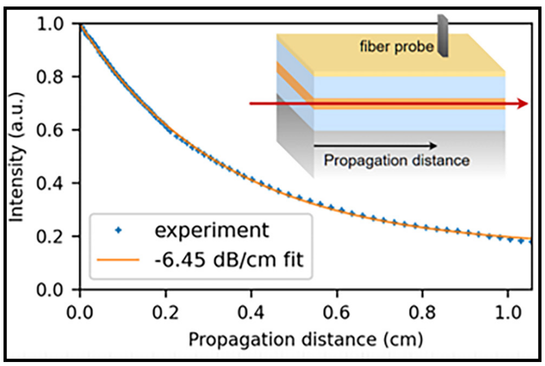

Figure 3: Measurement of optical propagation loss in SRN slab waveguide. The waveguide consists of a 500 nm thick SRN core with refractive index of 2.45 at 1550 nm (SiH_4:NH_3 gas ratio of 6) and 700 nm thick SiO_2 claddings on each side. The loss is estimated by measuring scattered light on top of the waveguide as a function of propagation distance using the Metricon 2010/M prism coupler. An exponential fit yields a loss of 6.45 dB/cm.

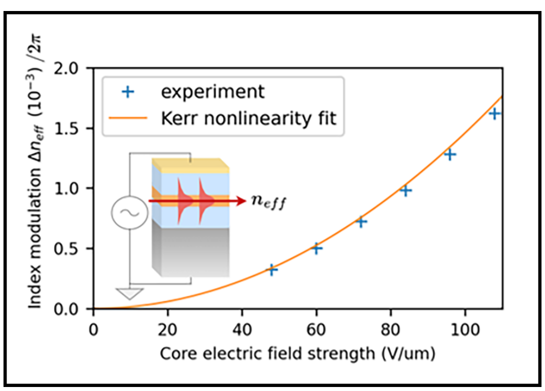

Figure 4: Measurement of the electro-optic response of the SRN waveguide from Figure 3 at 1550 nm. We applied a 10 Hz AC voltage across the waveguide stack. The electric field strength in the core was estimated using the conductivity measurements from Figure 2. The refractive index modulations were measured using an interferometer. A part of the 1550 nm beam was splitted off before entering the waveguide, routed around the waveguide and then recombined with the beam going through the waveguide. We established the refractive index modulations of the waveguide from the resulting interference fringes. The measured index modulations are consistent with a Kerr nonlinearity.

The results are shown in Figure 2. SRN is generally very resistive with conductivities ranging from 10.8 to 10.5Ω cm, but the conductivity is very sensitive to the silicon content (as evident from the refractive index), applied voltage, and can change more than three orders of magnitude from bright to dark state.

Optical Properties. We measured the refractive index of SRNs with different silicon content. Representatively shown in Figure 3 is a measurement of the optical propagation loss of a 1550 nm beam in a 500 nm thick slab of SRN with 700 nm SiO_2 claddings. The loss was much higher than expected from ellipsometer measurements of the extinction coefficient, so we believe the loss is largely due to surface roughness. We also observed a photo-induced loss of yet unknown origin when illuminating the waveguide with visible light. This loss is about 3 dB/cm and might be due to the photoconductivity shown in Figure 2.

We measured the electro-optic modulation by measuring the change in effective refractive index when applying an electric field across the waveguide. As seen in Figure 4, the relation between refractive index and applied field is quadratic, suggesting a Kerr nonlinearity.

Conclusions and Outlook:

We have characterized silicon-rich silicon nitride films for its applications as a controllable electro-optic material. While lower losses (e.g. [4]) and stronger optical nonlinearities (e.g. [3]) in SRN have been demonstrated before, we also show strong photoconductivity. Although our work is preliminary and should not be treated as definitive, we believe SRN is a promising material for optically programmable photonics.

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