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A linear electrooptic effect in silicon, induced by use of strain

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Abstract: The crystal structure in a silicon waveguide can be distorted by application of strain. Thereby, the otherwise forbidden linear electrooptic (Pockels) effect is induced, opening a new route for optical modulation in silicon.

1. Introduction

Silicon photonics is undergoing a spectacular development these years, driven by short-reach interconnection demands (from several μm to a few m) and the pushing need for low-cost electronic-photonic integration at high bit rates. In these systems, the electrooptic modulator is a key component. Most commercial modulators, such as those made in $LiNbO_3$, make use of the linear electrooptic (Pockels) effect. However, this effect is intrinsically zero in single-crystalline Si due to the inversion-symmetry of the crystal structure [1]. We demonstrate [2] that a straining layer can be employed to efficiently break the crystal symmetry in a silicon waveguide, such that a finite Pockels coefficient is generated. This method represents a new method for making electrooptic modulation in Si. Whereas the far majority of proposed silicon modulators [3,4] use the plasma-dispersion effect, the Pockels effect offers advantages of requiring no change of carrier concentration and no current flow for modulation. Therefore it is expected to have very low power consumption and an operation speed which is limited primarily by electrode design.
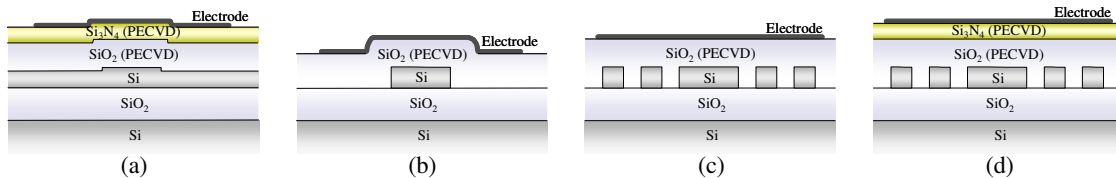

Figure 1. Cross-sectional schematics of waveguides with glass cladding: (a) Shallowly etched ridge, (b) photonic wire, (c) and (d) PCWs. The PECVD glass layers exert stress on the Si waveguide layer. The PECVD glass only partially fills the holes of the PCWs.

2. Method

Different batches of waveguides were investigated. They are shown with cross-sectional schematics in Fig. 1. The waveguides were fabricated in silicon-on-insulator (SOI) having a 1 or 1.2-μm thick buried oxide and a Si device layer with a thickness between 220 and 340 nm. The substrate and device layers are p-type with resistivities ~ 15 and 10 Ω-cm, respectively (Fig. 1[a,d]), or ~ 30 and 30 Ω-cm, respectively (1[b,c]). Photonic wires of width 430 nm and photonic-crystal waveguides (PCWs) were defined with either deep-UV or electron-beam lithography, and plasma etched. On all batches, a top cladding layer of silica glass (SiO_2) with a thickness between 1.2 and 1.5 μm was deposited with plasma-enhanced chemical vapour deposition (PECVD). The strain of this layer can be made either compressive or tensile, with a typical value around ~ 0.3 GPa. In two batches, a 0.75-μm thick layer of silicon nitride glass (approximate stoichiometry: Si_3N_4) with a high, compressive strain of ~ 1 GPa was also deposited. Finally, metal electrodes were formed on the top surface. Electrooptic (EO) measurements were performed by applying an a.c. modulation voltage to the top electrode, keeping the Si substrate at ground potential. While modulating, the optical transmission was monitored either through an on-chip Mach-Zehnder interferometer (MZI) having an electrode over one of the arms, or through a fibre-based MZI

setup with a waveguide placed in one arm and a calibrated LiNbO$_3$ modulator in the other arm, balancing the modulation of the two arms. The measurements were made with transverse-electric (TE) polarisation at modulation frequencies between 70 and 500 kHz, avoiding thermal effects that are generally observed below ~ 10 kHz.

3. Results and analysis

For a ridge waveguide with very shallow etch (~ 30 nm) and PECVD upper cladding glasses, as shown in Fig. 1(a), the EO nonlinearity is below the detection limit. This is so even though a straining layer of Si$_3$N$_4$ has been applied on top. In contrast, a finite nonlinearity is found in waveguides that have been etched through the whole silicon layer and covered with a straining PECVD oxide, shown in Figs. 1(b) and 1(c). These observations suggest that the silicon waveguide core must be allowed to deform to the sides (the waveguide must be fully etched) in order to achieve a breaking of the crystal symmetry sufficient to induce a measurable Pockels effect. In the structure of Fig. 1(d), a Si$_3$N$_4$ straining layer has been deposited on top of the upper silica cladding. This structure exhibits a dramatically enhanced nonlinearity compared to the structures of Figs. 1(b) and 1(c), even though the optical field has no overlap with the Si$_3$N$_4$ layer. This demonstrates that the cause of the nonlinearity is the large strain field, induced by the Si$_3$N$_4$ layer and acting on the silicon waveguide through the silica cladding: With tensile strained SiO$_2$, the second-order nonlinear susceptibility $\chi^{(2)}$ is of the order ~ 0, ~ 1, and ~ 15 pm/V for the configurations of Fig. 1(a), 1(c), and 1(d), respectively. With compressively strained SiO$_2$, $\chi^{(2)}$ ~ 5-10 pm/V for configurations 1(b) and 1(c).

For ease of comparison, these $\chi^{(2)}$ values were obtained after scaling linearly down from the values obtained at the actual group index n_g of the particular waveguide, to those expected at the bulk index, assumed for simplicity to be 3.5. For the highest strain, the electrode length L times the electrical bias V_π required for a phase shift of π is a couple of hundred V-cm, which should be improved by at least an order of magnitude for practical exploitation. However, the values reported here are first results, and large improvement is expected with refined waveguide design, optimised strain, and reduced electrode distance, possibly in combination with utilisation of slow light, as shown further below.
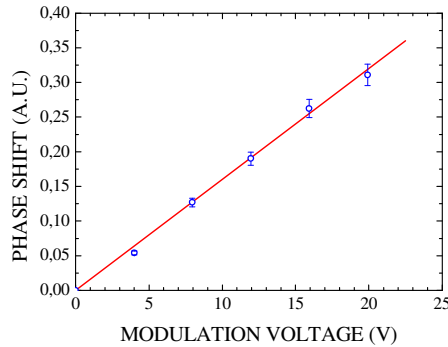

Figure 2. Measured phase shift (arbitrary units) as a function of modulation voltage, measured with 70-kHz modulation at a wavelength of 1530 nm. The straight line is a linear fit.

Fig. 2 demonstrates that the measured phase shift is directly proportional to the applied modulation voltage (4-20 V). This corroborates that the effect is indeed a linear electrooptic (Pockels) effect. No alternative effect was found to be a likely cause of the optical modulation, as discussed in ref. [2]. In particular, the effect is not related to the presence of charge carriers since the a.c. modulation is unaffected by a simultaneous application of a high d.c. voltage that depletes the structure efficiently.

Since the strain-induced nonlinearity is easily induced in a PCW, one can take advantage of slow-light enhancement of the light-matter interaction. In Fig. 3(a) we show the output spectrum of an on-chip MZI with a PCW in one arm, covered by an electrode. The rapidly increasing oscillations are a clear sign

of an increasing group index in the PCW when approaching the cut-off at 1564 nm of the in-gap guided mode [5]. Fig. 3(b) shows that the measured phase shift in the PCW for a given modulation voltage (i.e., the nonlinearity) is enhanced with increasing n_g, being approximately proportional to n_g up to at least $n_g \approx$ 35. In ref [2] we demonstrate phase-shift enhancements with n_g values up to a couple of hundred.
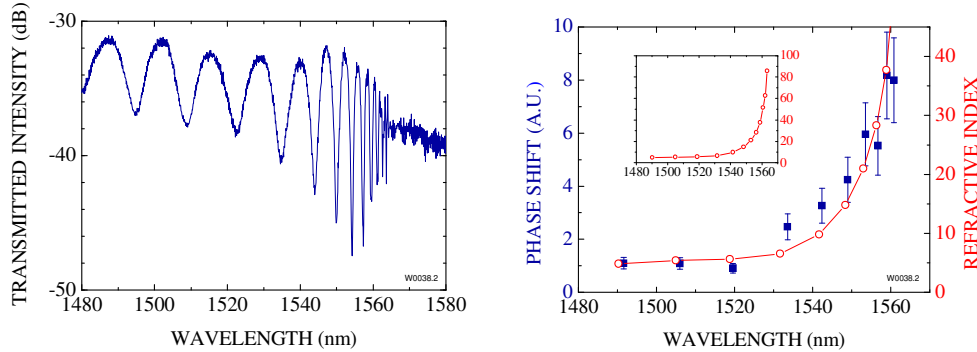

Figure 3. Left: Output power as a function of wavelength for an on-chip MZI with a 30-μm long PCW, covered by an electrode, in one arm (device cross section as in Fig. 1[b, c]). Right: Measured phase shift (■) and effective group index ( ) in the PCW.

Let us finally point out that a $\chi^{(2)}$ nonlinearity arising from distortion of a Si crystal under a straining SiO_2 layer has previously been evidenced by second-harmonic generation (SHG) [6,7]. We believe that the present investigations, performed in waveguides, are the first ones that point to an EO strain-induced $\chi^{(2)}$. In contrast to the SHG experiments, we were not able to detect the EO effect in those samples where the silicon layer is almost flat (Fig. 1[a]). Let us also note that for traditional Si waveguides, having cross-sectional dimensions of several μm, we expect that the strain effect will be rather small. The reason is that for large waveguides, much less lattice deformation is expected in the centre region where the optical field is maximum.

4. Conclusion

Distortion of the crystal symmetry is an attractive new route to enable optical modulation in Si. A Pockels effect can be induced by straining the waveguide core by application of a highly straining layer (e.g. Si_3N_4). The method has high potential due to the expected low power consumption and ultra-high speed operation that is foreseen, and due to the use of standard CMOS processes in the fabrication. Furthermore, the method can be exploited in a slow-light PCW for increased, effective nonlinearity.

5. References

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