Pockels effect based fully integrated, strained silicon electro-optic modulator

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Abstract: We demonstrate for the first time a fully integrated electro-optic modulator based on locally strained silicon rib-waveguides. By depositing a Si$_3$N$_4$ strain layer directly on top of the silicon waveguide the silicon crystal is asymmetrically distorted. Thus its inversion symmetry is broken and a linear electro-optic effect is induced. Electro-optic characterization yields a record high value $\chi^{(2)}_{yz} = 122$ pm/V for the second-order susceptibility of the strained silicon waveguide and a strict linear dependence between the applied modulation voltage $V_{\text{mod}}$ and the resulting effective index change $\Delta n_{\text{eff}}$. Spatially resolved micro-Raman and terahertz (THz) difference frequency generation (DFG) experiments provide in-depth insight into the origin of the electro-optic effect by correlating the local strain distribution with the observed second-order optical activity.

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In 2006 Jacobsen et al. [14,15] proposed and realized an all-silicon electro-optic modulator based on a strain induced Pockels effect in silicon. A second-order susceptibility of $\chi^{(2)}$ was demonstrated using a Si$_3$N$_4$ strain layer deposited on a SiO$_2$ cladged silicon photonic crystal waveguide structure. Also theoretical studies on the generation and application of stress induced $\chi^{(2)}$ in silicon have been conducted [16,17]. However, to further advance the strained silicon modulator technology and ultimately make it competitive with the established LiNbO$_3$ technology an in-depth understanding of the intricate working of the structure is essential.

In this work we report on a substantial progress of the strained silicon modulator concept. For the first time, a fully integrated electro-optic Mach-Zehnder modulator based on a locally strained rib-waveguide structure is presented. Contrary to the approach mentioned above we use a Si$_3$N$_4$ strain layer deposited directly on top of the silicon rib-waveguide and perform a subsequent high temperature rapid thermal annealing process to increase the magnitude and

1. Introduction

Today’s state-of-the-art technology for electro-optical modulation in the telecom and datacom sector is based on lithium niobate (LiNbO$_3$) [1]. In LiNbO$_3$ modulators the linear electro-optic effect (Pockels effect) is utilized, which provides both high-speed and strict linear phase modulation. Especially the phase modulation linearity is a most important feature, because it is a primary requirement for optical modulation in analog systems [2], e.g. cable television (CATV) for fiber-to-the-home broadcast applications. Also advanced digital data transmission concepts, like quadrature amplitude modulation, which use a multi-bit per symbol coding scheme require a linear modulation characteristic.

One of the major limitations of the LiNbO$_3$ modulator technology is the high cost per component due to expensive substrates and a large footprint area on the die, as well as the missing ability to monolithically integrate modulators with other photonic components, e.g. monitor photodiodes.

Silicon Photonics is a potential cost-efficient alternative for LiNbO$_3$, which circumvents the aforementioned limitations. Despite the absence of the Pockels effect in silicon ($\chi^{(2)} = 0$) a multitude of different approaches for silicon based electro-optic modulators have been investigated [3–13]. Unfortunately none of the present concepts fulfills all demands of telecom and datacom applications. Plasma dispersion based modulators for example provide high modulation speeds [5,6] and small footprints [8] but exhibit an intrinsic nonlinear phase modulation characteristic due to the included p-n or p-i-n junctions. Recently a theoretical study on linearizing such modulators has been reported [9]. Silicon-organic hybrid modulators [11–13] utilize the Pockels effect in electro-optic polymers but have a limited temperature budget that makes monolithic integration with other silicon photonic components very difficult.

In 2006 Jacobsen et al. [14,15] proposed and realized an all-silicon electro-optic modulator based on a strain induced Pockels effect in silicon. A second-order susceptibility of the silicon waveguide $\chi^{(2)}_{\text{SiC}} = 15 \text{ pm/V}$ was demonstrated using a Si$_3$N$_4$ strain layer deposited on a SiO$_2$ cladged silicon photonic crystal waveguide structure. Also theoretical studies on the generation and application of stress induced $\chi^{(2)}$ in silicon have been conducted [16,17]. However, to further advance the strained silicon modulator technology and ultimately make it competitive with the established LiNbO$_3$ technology an in-depth understanding of the intricate working of the structure is essential.

In this work we report on a substantial progress of the strained silicon modulator concept. For the first time, a fully integrated electro-optic Mach-Zehnder modulator based on a locally strained rib-waveguide structure is presented. Contrary to the approach mentioned above we use a Si$_3$N$_4$ strain layer deposited directly on top of the silicon rib-waveguide and perform a subsequent high temperature rapid thermal annealing process to increase the magnitude and
asymmetry of the strain induced. In linear electro-optic modulation experiments a $\chi^{(2)}_{yz}$ of 122 pm/V is observed, which is the highest reported value to date for an all-silicon device and a significant step towards the $\chi^{(2)}$ values reported for LiNbO$_3$ ($\chi^{(2)} = 360$ pm/V [2]).

Furthermore, to gain insight into the observed Pockels effect spatially resolved micro-Raman and THz DFG experiments were conducted on strained waveguide structures. These independent measurement techniques provide information about the local strain distribution and the local second-order optical activity. By correlating both methods the vertical waveguide edges are identified as regions of pronounced strain asymmetry and dominant second-order optical activity.

2. Device fabrication

The starting point for the fabrication of the strained rib-waveguide structures is a silicon-on-insulator substrate with a 220 nm thick (100)-orientated top silicon layer on a 3 $\mu$m thick buried oxide. Waveguides are defined using electron-beam lithography and structured in a HBr-based reactive ion etching process. After etching the remaining slab thickness is 45 nm. The width of the single-mode waveguides used in the electro-optic modulator is 400 nm and 450 nm. Additionally 12 $\mu$m wide multi-mode waveguides were fabricated for spatially resolved micro-Raman and THz DFG measurements. On the waveguide templates a 350 nm thick Si$_3$N$_4$ layer is deposited using remote plasma-enhanced chemical vapor deposition (RPECVD). Subsequently the samples are annealed in nitrogen atmosphere with a two-step process. In the first step the samples are heated to moderate temperatures to remove hydrogen remains inside the Si$_3$N$_4$-layer that could cause blistering when the samples are exposed to higher temperatures. The second step is a high temperature annealing process with a subsequent rapid cooling.

During this step thermal stress is generated inside the structure due to the different thermal expansion coefficients of the materials involved. The SiO$_2$ cladding layer is again deposited via RPECVD and has a thickness of 850 nm. Finally Ti/Au-electrodes (20 nm/100 nm) are fabricated using optical lithography, physical vapor deposition and lift-off.

Figure 1 shows a schematic illustration and a cross section scanning electron microscope (SEM) picture of the structure. The diagonal cracks are caused by the cleaving of the sample for SEM inspection.

![Fig. 1. (a) Schematic cross sectional view of a SOI rib-waveguide with a Si$_3$N$_4$ strain layer and a SiO$_2$ cladding. Both the top surface and the vertical sidewalls are subject to strain generation. Here the core of the waveguide features an asymmetric compressive strain. The dots symbolize the induced lattice distortion, not the wall geometry. (b) A corresponding scanning electron microscope (SEM) picture of the structure. The diagonal cracks are caused by the cleaving of the sample for SEM inspection.](image)

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Figure 1 shows a schematic illustration and a cross section scanning electron microscope (SEM) image of the investigated waveguide structure. The silicon rib-waveguide is enfolded by the Si$_3$N$_4$ strain layer resulting in three interfaces, which are particularly subject to strain generation. The x-, y- and z-axis coincide with the [001], [110] and [1–10] lattice direction of the silicon waveguide.
3. Electro-optic characterization

The electro-optic functionality of the strained waveguide design is tested within a fully integrated Mach-Zehnder interferometer (MZI) device. An asymmetric layout with a difference $\Delta L = 50 \, \mu m$ between the two arm lengths is applied to enhance sensitivity for the detection of an effective index change $n_{\text{eff}}$ within the electric field modulated waveguide sections. Figure 2(a) displays a schematic cross section of the electrodes introducing an electric field vector $E_{\text{mod}}$ in $z$-direction inside the waveguide. A push-pull configuration is implemented for the electrode design (Fig. 2(b)) with opposite polarity of the applied modulation field $E_{\text{mod}}$ in each MZI arm. For the given structure an average electric field strength of $E_{\text{mod},z} = 2.33 \cdot 10^4 \, m^{-1}$ within the core of the silicon waveguide is calculated, with $V_{\text{mod}}$ being the applied modulation voltage. No leakage currents could be observed at $V_{\text{mod}} = \pm 30 \, V$ for a detection limit of 1 nA.

For the electro-optic measurements transverse electric polarized light from a tunable continuous-wave laser source is coupled to the device via grating couplers in order to probe the effective $\chi^{(2)}_{yz}$ component of the strained silicon waveguides. The measured spectral transfer function (STF) of the MZI device (excluding grating coupler loss) at different modulation voltages $V_{\text{mod}}$ is plotted in Fig. 3(a). Typical transfer functions for an asymmetric MZI can be clearly identified. The black curve displays the STF at $V_{\text{mod}} = 0 \, V$. Under varying modulation voltages polarity sensitive spectral shifts of the STF in linear dependence to $V_{\text{mod}}$ are observed. Furthermore, the insertion loss of the modulator remains insensitive to $V_{\text{mod}}$. This behavior indicates conclusively that the modulation is caused by a Pockels effect excluding thermal, carrier based or third-order nonlinear Kerr effects.

To support this conclusion in Fig. 3(b) the spectral shift of the STF and the extracted effective waveguide index change $\Delta n_{\text{eff}}$ are plotted as a function of $V_{\text{mod}}$. The strict linear behavior confirms the existence of a linear electro-optic (Pockels) effect. Taking into account linear waveguide dispersion and the confinement factor of $\Gamma = 66\%$ of the strained silicon waveguide a Pockels effect induced effective index change of $\Delta n_{\text{Si}} = 2.4 \cdot 10^{-5}$ is deduced at $V_{\text{mod}} = 30 \, V$, leading to a $\chi^{(2)}_{yz} = 122 \, pm/V$ for the strained silicon waveguide. This experimentally determined value of the second-order susceptibility is about one order of magnitude higher than the highest value $\chi^{(2)}_{yz} = 15 \, pm/V$ reported in silicon so far, taking a significant step towards the state-of-the-art material LiNbO$_3$. 

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Fig. 3. Electro-optic characterization of the MZI device. (a) Spectral transfer functions measured at different modulation voltages \( V_{\text{mod}} \). The spectral shift is extracted by fitting parabolic curves to the STF maximum around \( \lambda_{\text{Peak}} = 1575 \) nm. The corresponding \( E_{\text{mod}} \) und \( \Delta n_{\text{eff}} \) are included on the upper axis and the right axis, respectively.

To validate the measured electro-optic properties and to further explore the potential of the strained silicon modulator device we have performed a wide variety of parameter studies. For reference a MZI modulator without Si\(_3\)N\(_4\)-strain layer was fabricated and characterized. This device did not show any measurable shift. Furthermore, strained MZI devices with a Spin on Glass cladding instead of the SiO\(_2\) cladding displayed identical behavior to the above described strained silicon modulator device. This rules out any parasitic effects that might originate from the surrounding materials and evidently identifies the Si\(_3\)N\(_4\)-strained waveguide as the source of the electro-optic effect. Complementary measurements of push-pull and single-ended electrode configurations with varied \( \Delta L \) give consistent data for the \( \chi^{(2)} \) value.

During these extensive parameter studies it was observed that the \( \chi^{(2)} \) value measured depends strongly on the width of the waveguide geometry. The strain induced second-order nonlinearity increases with decreasing width. For example reducing the width from 450 nm down to 400 nm increases the \( \chi^{(2)} \) value from 71.5 pm/V to 122 pm/V. This striking dependence on the geometry of the waveguide points towards an inhomogeneous strain distribution within the waveguide, e.g. strong enhancement of nonlinearity at the vertical edges of the waveguide. To further investigate the strain distribution spatially resolved nonlinear optical measurement techniques have been employed.

4. Spatially resolved nonlinear optical mappings

The first investigations focus on the characterization of the locally induced strain within the silicon waveguide using micro-Raman spectroscopy (MRS). MRS allows to probe the type (tensile or compressive) and relative strength of the local mechanical strain within the crystalline silicon with a spatial resolution of approximately 1 \( \mu \)m. An unstrained (100)-oriented silicon surface excited in vertical direction exhibits a characteristic peak at \( \omega_c = 520.4 \) cm\(^{-1} \) within the Raman spectrum caused by the Si-Si LO phonon mode vibration [18]. Deviations of this spectral feature are directly related to the material strain within the probed region. Figure 4 displays a comparison of three micro-Raman spectra probed at the (100)-surfaces of an unstrained silicon bulk sample (black), a rib-waveguide strained by a Si\(_3\)N\(_4\)-layer (blue) and an unstrained one without Si\(_3\)N\(_4\) (red). The lateral width of the waveguides is 450 nm. The reference curve of the bulk sample is showing the expected response of unstrained crystalline silicon with a Raman peak located at \( \omega_c = 520.4 \) cm\(^{-1} \). The unstrained waveguide deviates only slightly from this behavior (\( \omega_c = 520.45 \) cm\(^{-1} \)) indicating only marginal strain. In striking contrast, however, a considerably red-shifted peak (\( \omega_c = 521.6 \) cm\(^{-1} \)) is observed at
the strained waveguide revealing dominantly compressive strain within the probed waveguide.

Fig. 4. Micro-Raman investigation of the strain distribution in silicon structures. The MRS measurements were conducted on a bulk silicon reference sample (black), an unstrained (red) and a strained (blue) rib-waveguide. The solid lines are the corresponding fitting curves with a Lorentzian profile.

Furthermore, a distinct spectral line broadening is measured at the strained waveguide, which is a clear indication that the spatial strain distribution within the probed waveguide volume is not homogeneous and must be following considerable spatial gradients. In homogeneously strained silicon a broadening of the Raman peak is usually not observed [19]. However, in the case of deviating strain within the probed volume a line broadening is induced by the superposition of differently shifted Raman lines. In this comparison the line broadening is the most important observation as the presence of an inhomogeneous strain profile is the basic requirement for the existence of second-order electro-optic activity and therefore confirms the Pockels effect as source of modulation in the strained silicon modulator.

In order to resolve the spatial distribution of the asymmetric strain MRS mappings across the edge of a 12 µm wide strained waveguide have been conducted (Fig. 5(a)). Close to the vertical waveguide edge a prominent broadening of the Raman line can be identified indicating strong asymmetric strain in this region.

Fig. 5. Micro-Raman and THz mappings across a 12 µm wide strained rib-waveguide. The black dashed lines mark the edge regions of the waveguide. (a) Measurement of the Raman line width across one half of the waveguide. (b) Near field measurement of the THz amplitude across the whole waveguide.

Complementary to the spatial analysis of the strain profile the local electro-optic activity within the strained silicon waveguides is studied using spatially resolved DFG measurements.
With a novel THz probing technique [20] the strength of the emitted THz field is measured across the waveguide. For THz DFG ultra-short laser-pulses with a duration of 100 fs and a centre wavelength of 1550 nm are used. The THz signal generated in the silicon waveguide is detected using a near-field probe with a spatial resolution of approximately 2 µm. The probe tip is designed to sample the THz field polarized along the z-axis. Therefore this measurement is sensitive to the same tensor component \( \chi^{(2)}_{xyz} \) probed in the electro-optic modulator experiments.

To allow a spatial resolution of both edge regions of the waveguide again 12 µm wide rib-waveguides are investigated in this experiment. Figure 5(b) shows the generated THz field amplitude obtained from a line-scan perpendicular to the waveguide (red curve) at the sample surface. The positions of the vertical waveguide edges are marked by the dashed black lines. Two distinct maxima of the generated THz field located at the edges of the investigated waveguide can be observed. In the centre of the waveguide the THz amplitude exhibits a local minimum. This identifies the waveguide edges as dominant regions of second-order nonlinear activity. Moreover this is in agreement with the observed Raman line broadening and directly correlates the asymmetric strain with the optical nonlinearity.

5. Discussion

Compared to the published \( \chi^{(2)} \) in a strained silicon modulator structure [14] we have reached a considerable gain in performance. This is attributed to fundamental differences in the sample design and processing.

First, the rib-waveguide geometry we use is highly beneficial for the formation of an asymmetric strain field by pinning the bottom part of the waveguide close to the waveguide edges. Additionally it allows the waveguide to deform more freely than in a photonic crystal. This is supported by preliminary strain simulations, which show a much stronger strain asymmetry inside rib-waveguides than in strip-waveguides of comparable size. (Details are subject to further studies.)

Second, in our device the Si\(_3\)N\(_4\) strain layer is deposited directly on top of the silicon waveguide structure. This direct straining scheme has a significant advantage compared to a separated strain-layer with a SiO\(_2\) interlayer, since not only the top-portion of the waveguide is strained but also the vertical edges.

Third, the high temperature annealing step with the successive rapid cool down induces significant thermal stress to the layer stack due to the different thermal expansion coefficients of the materials involved.

6. Conclusion

In summary we have presented unambiguous proof for the existence of a Pockels effect induced by a gradient strain profile. We could demonstrate a \( \chi^{(2)} \) value as high as 122 pm/V in a fully integrated MZI modulator device. This is the highest \( \chi^{(2)} \) ever reported for silicon. Also a strict linear phase modulation behavior was observed.

Complementary Raman and THz DFG measurements gave for the first time an in depth view of the origin of the observed nonlinearity. This novel nonlinear optical analysis approach revealed a direct correlation of the asymmetric strain profile with the \( \chi^{(2)} \) value and a predominant localization of the nonlinearity at the edges of the silicon waveguide.

The investigations also made it obvious that the key to further enhance the electro-optic effect in the strained silicon modulator and thus reduce the modulation voltage \( V_{mod} \) is to increase the asymmetric strain profile inside the silicon waveguide. As mentioned before a reduction of the waveguide width seems to be a suitable method to achieve this goal. However, decreasing the waveguide width also implies the reduction of the mode confinement factor inside the silicon waveguide and eventually reduces the effective electro-optic coefficient of the whole waveguide structure. Additionally, an increase in transmission losses can be expected for smaller waveguide widths. Finding an optimum configuration is subject to further studies.
To conclude we point out that the presented device concept could pave the way towards a new class of highly efficient and fully silicon process compatible electro-optical modulators.

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