Dispersion of silicon nonlinearities in the near infrared region

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The authors present the detailed characterization of the wavelength dependence of two-photon absorption and the Kerr nonlinearity in silicon over a spectral range extending from 1.2 to 2.4 μm. They show that silicon exhibits a significant increase in its nonlinear figure of merit with increasing wavelengths beyond the two telecommunication bands. They expect their results to provide guidance for extending nonlinear silicon photonics into new spectral regimes. © *2007 American Institute of Physics*.
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Silicon photonics has attracted much attention recently because of its potential for providing a monolithically integrated platform for optical interconnects.[1] Silicon exhibits a significant third-order nonlinearity. This feature, together with the tight mode confinement provided by silicon-on-insulator (SOI) waveguides, makes it possible to realize a variety of optical functions at relatively low power levels through complementary metal-oxide semiconductor-compatible technology. Indeed, nonlinear optical phenomena such as optical modulation,[2] Raman amplification and lasing,[3,4] wavelength conversion,[5–7] and self- and cross-phase modulation,[8,9] have already been demonstrated in SOI waveguides. An accurate knowledge of silicon's nonlinear parameters is essential for all these applications. Current knowledge of these parameters is limited to the two telecommunication bands located around 1.3 and 1.5 μm.[3,5,8,10–12] It has been shown recently that silicon exhibits potential for applications far beyond these two narrow bands in the entire near and midinfrared spectral regions.[1,13] In this letter, we report the complete experimental characterization of the third-order nonlinearity of silicon over a broad and most commonly used spectral range extending from 1.2 μm (below but near the indirect band gap) to 2.4 μm (well below the half band gap).

We employ the z-scan technique[14] to characterize both the Kerr coefficient n_2 and the two-photon absorption (TPA) coefficient β_T of crystalline silicon, related to the real and imaginary parts of the third-order susceptibility $\chi^{(3)}$, respectively. Figure 1 shows our experimental setup. An optical parametric amplifier (Spectra Physics, OPA-800FC) provides linearly polarized pulses whose carrier wavelength is tunable between 1.2 and 2.4 μm. The full width at half maximum (FWHM) of the pulses (assumed to have a Gaussian shape) is measured to be 90–150 fs, depending on the carrier wavelength. For such short pulses, free-carrier effects in the silicon sample are estimated to be small. The input pulse train is maintained at a low repetition rate of 500 Hz to prevent thermal effects. A lens with 10 cm focal length focuses the pulses onto a 500-μm-thick silicon sample. The focused beam waist is characterized over the entire spectral range from 1.2 to 2.4 μm by the knife-edge beam-profiling technique[15] to take into account the spectral dependence of the beam size and chromatic aberration of the focal lens. The waist radius w_0 varies between 29 and 71 μm, depending on the carrier wavelength.

The silicon wafer under test has a resistivity of 20 Ω cm (p-doped). It is polished on both sides to reduce light scattering from the two surfaces. The (100) wafer is oriented such that the incident light is polarized along the [010] direction. As a result, we measure the susceptibility component $\chi^{(3)}_{1111}$. The transmitted beam is filtered by an aperture and focused onto an InGaAs detector (Thorlabs, DET10D) whose output is amplified by a lock-in amplifier. We split a small portion of the input beam to monitor energy fluctuations of the incident pulses. It is detected by an identical detector and amplified by a second lock-in amplifier. Because of the high-sensitivity lock-in amplification, the impact

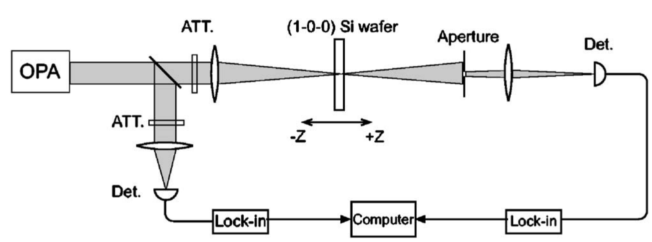

FIG. 1. Experimental setup used for z-scan measurements. OPA: optical parametric amplifier. ATT: attenuator. Det: detector.

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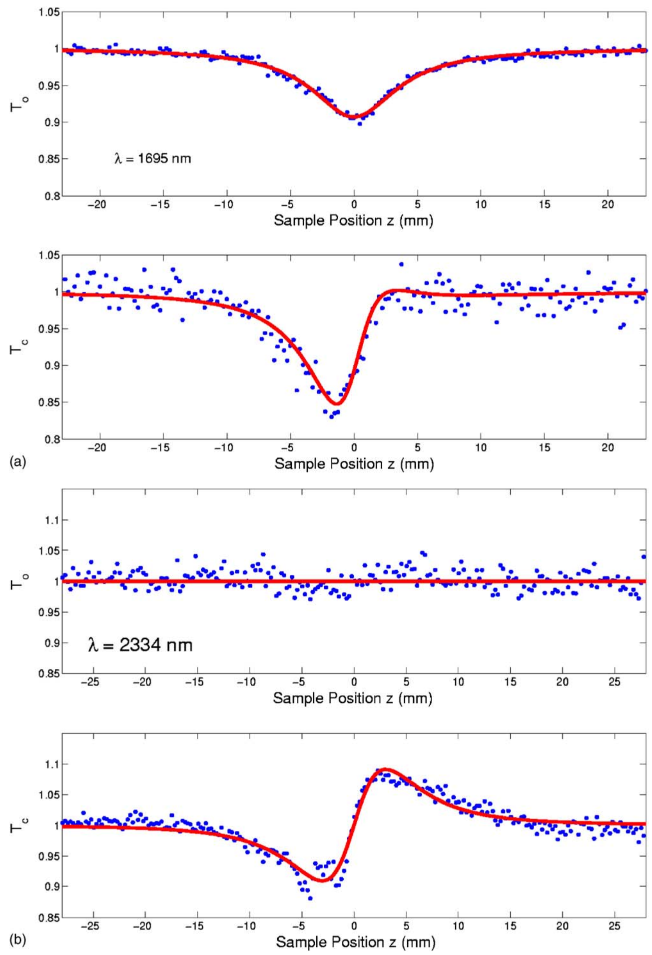

FIG. 2. Z-scan traces at (a) 1695 nm and (b) 2334 nm with open and closed apertures, with pulse energies of 57 and 246 nJ (corresponding peak intensities of 10.1 and 47.3 GW/cm^2), respectively. In each case, solid dots show the experimental data and solid curves show a theoretical fit.

of both the dark current of detectors and the background radiation is estimated to be negligible; the noise in our measurement is primarily dominated by energy fluctuations of incident pulses, measured to be ~10%. We divide the transmitted signal by the reference one to mitigate the impact of such energy fluctuations.[14] The sample is scanned across the focal point by a motorized linear stage to collect multiple scanning traces.

We record scanning traces at wavelengths about 100 nm apart in the range of 1.2–2.4 μm. Figure 2 shows typical z-scan traces at two wavelengths. At 1695 nm, the open-aperture trace exhibits a clear dip, indicating the TPA effect. As TPA is relatively large at this wavelength, the close-aperture trace still exhibits a dip; its asymmetry is a consequence of self-focusing.[14] In contrast, TPA disappears at 2334 nm, a wavelength well below the half band gap of silicon. The open-aperture trace thus shows only a flat background. The close-aperture trace exhibits a peak and a dip of the same relative magnitude. A comparison of the z-scan traces for these two wavelengths shows clearly a considerable dispersion in silicon nonlinearity.

To deduce the magnitude of the Kerr and TPA coefficients, the open- and close-aperture traces are fitted by the standard theory[14] to obtain β_T and n_2, respectively. In the case of an open aperture, the sample transmittance is only affected by TPA and is governed by the simple formula

$$T_o(z) = 1 - \frac{\beta_T I_0 L}{2\sqrt{2}(1+\eta^2)}, \tag{1}$$

where L is the sample thickness and $\eta \equiv z/z_0$ is the location of the sample with respect to the focal point, normalized by the Rayleigh range, $z_0 = \pi w_0^2/\lambda$, of a focused Gaussian beam with the waist radius w_0 at wavelength λ. For a Gaussian pulse with a Gaussian-beam profile, the peak intensity is related to the pulse energy E as $I_0 = 4\sqrt{\ln 2}E/(\pi^{3/2}w_0^2 T_p)$, where T_p is the FWHM of incident pulses. Equation (1) shows clearly that the depth of the absorption dip is linearly proportional to the TPA coefficient β_T, but the shape of the trace is primarily determined by the Rayleigh range of the focused Gaussian beam. As a result, by fitting the trace, we can obtain both the beam waist and β_T. The fitted value of the beam waist agrees well with the independent measurements of the beam waist discussed previously, and thus confirms the fitting accuracy.

In the case of a partially closed aperture, self-focusing induced by the Kerr nonlinearity starts to affect the transmittance. The sample transmittance is then given by[14]

$$T_c(z) = 1 - \frac{I_0 L(\beta_T D_r - 2kn_2 D_i)}{2\sqrt{2}S(1+\eta^2)}, \tag{2}$$

where $k = 2\pi/\lambda$ is the propagation constant in vacuum, S is the aperture transmittance, and D_r and D_i are quantities related to the filtered beam profile. To go beyond the commonly used on-axis transmittance,[14,16] we derive the following form for D_r and D_i:

$$D_r + iD_i = 1 - \exp\left[\frac{2(\eta - i)(\eta + 3i)}{\eta^2 + 9}\ln(1-S)\right], \tag{3}$$

a relation valid for arbitrary values of S between 0 and 1. When $S=1$, Eq. (3) reduces to $D_r=1$ and $D_i=0$ and Eq. (2) becomes Eq. (1). For a small aperture with $S \ll 1$, Eq. (3) can be approximated by $D_r + iD_i \approx 2S(\eta - i)(\eta + 3i)/(\eta^2+9)$, and Eq. (2) reduces to the on-axis transmittance.[14,16] In our experiments, we use an aperture transmittance of $S=0.5$. By using the previously deduced values of β_T and w_0 in Eqs. (2) and (3), and fitting the close-aperture trace, we obtain the value of n_2. Our measurement accuracy is limited by the uncertainties in the pulse and beam shape and fluctuations of pulse energy. It is estimated to be about 30%.

Figure 3 shows the measured values of β_T and n_2 as a function of wavelength. The results show that β_T remains nearly constant for wavelength up to 1.7 μm. At the two telecom wavelengths of 1315 and 1501 nm, we measure the TPA coefficient to be $\beta_T = 0.57 \pm 0.17$ and 0.48 ± 0.14 cm/GW, respectively. These values agree well with previous results in these spectral regions.[3,10,11] Figure 3(a) shows clearly that TPA drops quickly when the wavelength is tuned beyond 1.7 μm. It decreases to 0.24 cm/GW at 1892 nm, and becomes zero when the wavelength is tuned beyond 2.2 μm (corresponding to the half band gap of silicon). A slight nonzero value of TPA (0.012 cm/GW) at 2200 nm is probably due to the broad bandwidth of input pulses: a portion of the spectrum falls below 2.2 μm and induces a small amount of TPA. Figure 3(b) shows that n_2 increases considerably over the spectral region from 1.2 to 1.9 μm. This observation explains the recent experiment in which spectral broadening induced by self-phase modulation was found to increase with

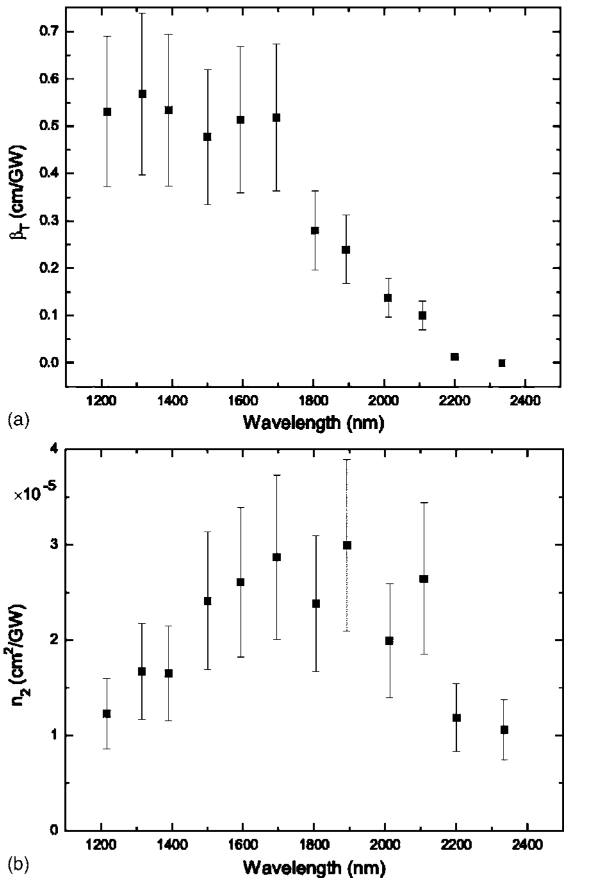

FIG. 3. Measured wavelength dependence of (a) TPA coefficient β_T and (b) Kerr coefficient n_2. Error bars are plotted as ±30% of the experimental data.

increasing carrier wavelength.[8] The Kerr nonlinearity peaks near 1.9 μm and decreases with a further increase in wavelength. It becomes nearly constant when wavelength is beyond the half band gap of 2.2 μm. This observation confirms qualitatively a recent theoretical prediction based on a simple two-band model.[17]

Although TPA can sometimes be utilized for a specific purpose,[2] it is detrimental for most applications of silicon nonlinearity because it creates considerable population of free carriers which, in turn, introduce severe absorption and change the mode index. Indeed, TPA-induced free-carrier absorption has been shown to be an obstacle to practical applications of silicon nonlinear devices.[3–6] It is common to introduce a nonlinear figure of merit (NFOM) as $F_n = n_2/(\lambda\beta_T)$.[18] Figure 4 shows the NFOM as a function of wavelength using the measured data from Fig. 3. For wavelengths between 1.2 and 1.7 μm, NFOM has a relatively low value of around 0.2–0.4. However, it increases rapidly at wavelengths beyond 1.7 μm. It is about 0.66 at 1892 nm, nearly doubles ($F_n = 1.25$) at 2109 nm, and increases to 4.4 when the wavelength reaches the half band gap at 2200 nm. These results suggest strongly that silicon exhibits great potential for nonlinear applications in the spectral region lying beyond the telecom wavelength of 1.6 μm, particularly in the spectral region beyond the half band gap of 2.2 μm.

In conclusion, we have characterized the third-order nonlinearity of silicon by measuring the TPA and Kerr coefficients with the z-scan technique over a broad spectral range between 1.2 and 2.4 μm. Our results explain some recent

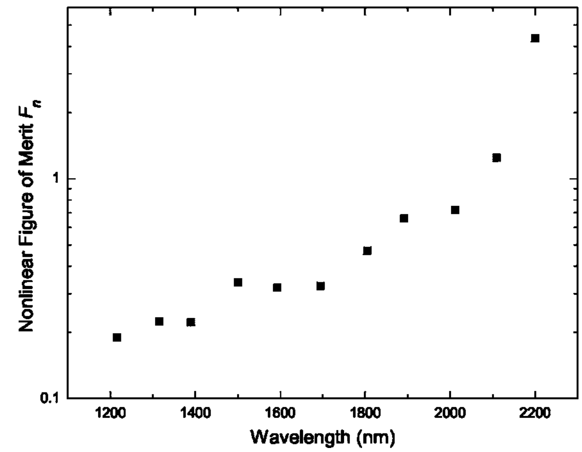

FIG. 4. Nonlinear figure of merit of silicon as a function of wavelength based on the measurements.

experiments on the nonlinear effects in SOI waveguides. They also provide a qualitative confirmation of a recent theory. We expect that our results would provide guidance to extend applications of silicon photonics into new spectral regions beyond the telecom bands. Moreover, further comparison of our experimental results with appropriate theories would help provide physical insights into the complicated relationship between an indirect band structure and optical nonlinearities.[19]

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