Silicon photonics in midwave and longwave infrared

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BIOGRAPHY

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TECHNICAL ABSTRACT

Optical data communication is not the only area where silicon photonics will have an impact. Silicon and related group 4 crystals have excellent linear and nonlinear optical properties in the midwave and longwave infrared spectrum [1-6]. These properties, along with silicon's excellent thermal conductivity and optical damage threshold, open up the possibility for a new class of midwave and longwave infrared photonic devices. As potential platforms for this new regime, a wide range of applications from gas detection, sensing to free space communications can be realized on low cost, chip-level integration. To transfer the knowledge from near infrared and apply them in this new regime, detailed understanding of the material properties is essential. For passive devices, the optical transparency of the materials used for waveguide design has to be well chosen and studied. In the midwave infrared range, the waveguides are likely to be built on silicon-on-insulator (SOI), silicon-on-sapphire (SOS), silicon-on-nitride (SON) and germanium-on-SOI (Ge/SOI), whose low-loss transmission range extends out to the wavelength of 3.7 μm for SOI, 4.4 μm for SOS, 6.7 μm for SON and 14.7 μm for Ge/SOI. The SOI waveguide has a propagation loss of less than 2 dB/cm over the 1.1 to 2.5 μm and 2.9 to 3.6 μm bands, with fairly high loss over 2.5 to 2.9 μm. Except for SOS, these longwave waveguides are untested at present. For active devices, it is known that group 4 materials lack second-order optical nonlinearity due to the centrosymmetric atomic arrangements. Thus, the lowest-order nonlinearity – third-order susceptibility $\chi^{(3)}$, which gives rise to the Kerr and Raman effects, is the key. For nonlinear optical processes at longer wavelengths, there has been experimental realization for applications recently such as Raman amplification [7], wavelength conversion, optical parametric waveguide gain, and cascaded four-wave mixing for multi-line infrared sources [8-10].

Silicon (Si) and Germanium (Ge) are the two most common group 4 materials. Both Si and Ge possess strong third-order nonlinear optical (NLO) coefficients. Also, two-photon absorption (TPA) which is a limiting factor for nonlinear optical processes in the near infrared vanishes at longer wavelengths as the energy of two photons is not enough for a band-to-band transition [4]. Therefore, efficient nonlinear processes at longer wavelengths are expected and we can project a bright future for third-order NLO effects and devices in the midwave and longwave infrared. Designers of the new NLO devices will surely rely upon knowledge of the relevant third-order NLO coefficients. Detailed knowledge is needed because these coefficients may have strong wavelength dependences over the midwave region (a little-known fact). Unfortunately, there are longwave regions or spectral "gaps" over which knowledge of the coefficients (as revealed in the scientific literature) is missing and an examination of the literature shows some inconsistencies in experimental data. To assist NLO designers, we have compiled the important NLO data and filled in the knowledge gaps using semiconductor nonlinear optical theory using the results from the scientific literature recently [6]. The resulting combination of experimental data and model predictions will, we believe, give the community a comprehensive picture of the nonlinear properties (the third-order nonlinear susceptibility, actually the real part of it denoted by $\chi^{(3)\prime}$ and the Raman gain coefficient (g_R)) of un-doped crystalline Si and Ge over the 1.5 to 14.7 μm wavelength range. The experimental data found in literature and modeling predictions of $\chi^{(3)\prime}$ and g_R are shown in figure 1. More details can be referred to ref. 6. The averaged theoretical curves in figure 1 (a) and (b) show the $\chi^{(3)\prime}$ predication for Si and Ge in the mid-wave and long-wave infrared respectively. The g_R predictions of Si and Ge are shown in figure 1 (c).

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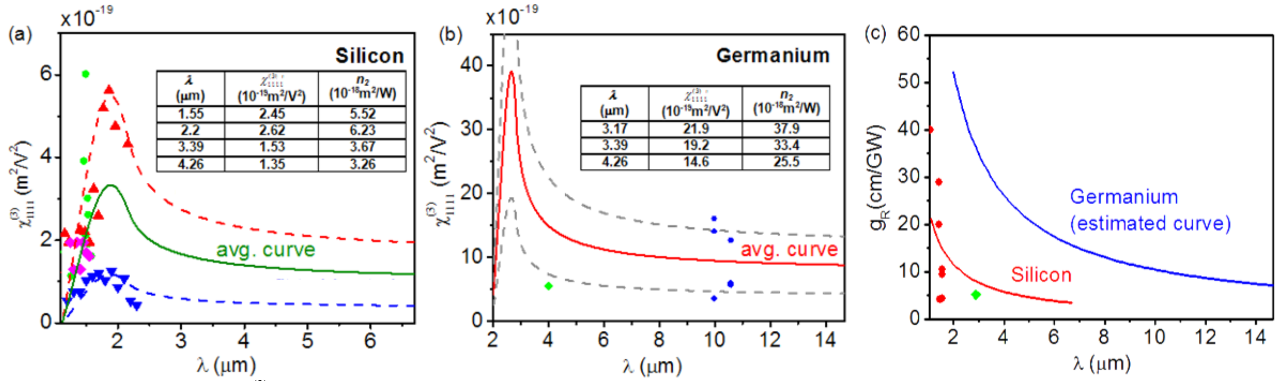

Fig. 1. (a) Experimental $\chi_{1111}^{(3)\prime}$ of Si in the literature as a function of wavelength are shown by the data points. Two theoretical dispersion curves are fitted to set the upper and lower bound of the experimental data. A resulting average dispersion curve is shown which act as a reference for designers dealing with Si. Inset lists the $\chi_{1111}^{(3)\prime}$ and n_2 at 1.55 μm (telecommunication wavelength), 2.2 μm (TPA cutoff), 3.39 μm (HeNe laser) and 4.26 μm (a CO_2 absorption band). (b) Experimental $\chi_{1111}^{(3)\prime}$ of Ge in the literature as a function of wavelength are shown by the data points. The resulting average dispersion curve is shown which act as a reference for designers dealing with Ge. Inset lists the $\chi_{1111}^{(3)\prime}$ and n_2 at 3.17 μm (TPA cutoff), 3.39 μm (HeNe laser), and 4.26 μm (a CO2 absorption band). (c) Experimental g_R data points of Si in literature as a function of the Stoke's wavelength. A theoretical dispersion curve is fitted to the data points for Si. An estimated dispersion curve for Ge is also shown. Adopted from ref. 6.

Besides bulk crystalline, alloying group 4 materials is a way to expand their capability. SiGe alloy has long been investigated due to its high mobility of charge carriers. Also, the use of Si-rich SiGe alloy for the Raman laser has also been demonstrated. This gives a tuned Si-Si Raman mode and thus different Raman emissions for same pump wavelength [11]. Although second-order nonlinearity exists in this alloy due to the break of inversion symmetry, it is seldom considered as there are lots of other choices (e.g. LiNbO3) with stronger second-order effects. We can use the same theory to predict the $\chi^{(3)\prime}$ and g_R of SiGe alloy and the results can be found in ref. 6 . By alloying Si and Ge, device designers can gain flexibility in tuning desired optical coefficients in between the two fundamental components based upon their application requirements. In other words, alloying of group 4 materials gives us an additional tuning parameter to engineer the bandgap and thus the magnitude of $\chi^{(3)\prime}$, TPA as well as the TPA cut-off regime. Moreover, the Raman line can be adjusted which gives flexibility in Raman-based device design.

Indeed, there are a number of rarely explored applications for silicon based midwave and longwave infrared photonics. One of them is generation of high intensity beams with good beam quality for sensing and imaging. Many high power lasers have poor beam quality resulting in excess beam divergence and low intensity when incident on a target. Beam cleanup can be accomplished using stimulated Raman scattering to convert a high power, low beam quality source to high power, high beam quality one with higher far-field intensity. This process has already been demonstrated in silicon [12].

This talk will review the fundamentals of silicon photonics in the mid-wave and long-wave infrared as well as applications that can benefit from such a technology.

Keywords: silicon photonics, mid infrared, midwave infrared, longwave infrared, nonlinear optics, silicon, germanium.

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