Raman Scattering in Silicon

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***Abstract*—This paper is about Raman scattering in silicon, which is used to make silicon optical waveguides and lasers. It focuses on the $1300nm$ - $1500nm$ range, which is mainly used for optical transmission. Wavelength conversion into this wavelength range is demonstrated by Raman four-wave mixing. With the Raman laser, an application example is described in which Raman excitation can be used.**

I. Introduction

USING silicon as waveguide material includes specific nonlinear effects such as Raman scattering. Silicon photonic can be identified with two motives. It can be reduce the cost of photonic devices and can solve important problems in today's computing systems.

Raman scattering was proposed and demonstrated in 2002 to mean to bypass the unfavorable physical properties and to creat optical ampflifiers and lasers in silicon. Unfavorable properties of passive silicon devices are for example the lack of efficient optical transition due to the indirect band structure an the near-absence of Pockel's effect caused by symmetric crystal structure. However, this made the creation of active components much more difficult. The approach was motivated bu the fact that the stimulated Raman gain coefficient in silicon lager than in the fiber. The optical intensity increase proportional because the modal area in a silicon waveguide is about 100 times smaller than in a fibre. This combination makes it possible to realise chip-scale Raman devices that normally require kilometres of optical fibre to operate. The first demonstration of spontaneous Raman emission from silicon waveguides in 2002 was followed by the demonstration of stimulated Raman scattering in 2003, which laid the foundation for Raman lasers and Raman fibre amplifiers that play a major role in modern optical communications. Other advantages of the Raman effect are that the spectrum is widely tunable by the wavelength of the pump laser and that it occurs in pure silicon and therefore does not require rare earth dopants.

Since the Raman effect has been used as a mechanism for making amplifiers, lasers and wavelength converters, the prospects for active optical functionality in silicon have improved dramatically. In 2005 the first silicon laser has been demonstrated. In early 2005, direct electrical modulation of the Raman laser was already demonstrated and the first continuously operating silicon Raman laser was reported. [1]

II. Stimulated Raman Scattering

The Raman scattering process can be described as an intuitive macroscopic from classical electrodynamics. In the spontaneous scattering thermal vibrations of a lattice produce a sinusoidal modulation of the susceptibility. The susceptibility describes the magnetic flux within the crystal lattice. In silicon the frequence is 15.6THz. An electric polarisation is induced which is given by the product of the susceptibility and the pump field. The pump field describes the incident light. The beating of the incident field oscillation ω_p with oscillation of the susceptibility ω_v produces induced polarizations at the sum frequency $\omega_p+\omega_v$, and at the difference frequency $\omega_p-\omega_v$. The radiation produced is called an anti-Stokes (sum frequency) or Stokes wave (different frequency).

To describe the Stimulated Raman scattering the model to describe the scattering process can be extended. It is assumed that the pump and Stokes fields are present. The frequency difference between the two fields is equal to the frequency of oscillation caused by spontaneous emission. The pump and Stokes fields generate a force that stimulates the atomic vibrations. This force amplifies the atomic oscillations, which in turn increase the amplitude of the Stokes field. This phenomenon of positive feedback is called stimulated Raman scattering and leads to an amplification of the Stokes field.

The previous description provide an intuitively appealing description of Raman scattering but does not descried the detailed processes responsible for Raman scattering in silicon. Electrons mediate the Raman scattering process in silicon because the direct coupling in semiconductors is the direct coupling of light with atomic vibrations is very low. Microscopically, the scattering take place in three steps. In the first step, an electron-hole pair is created by the incident photon by exciting the semiconductor into an intermediate stage.This photons are the quanta of energy described for electromagnetic waves. A photon The incident photon has an energy of $\hbar\omega_P$. In the second step, the electron-hole pair is scattered into another state by emitting a phonon via the electron-phonon interaction. A photon is a quantum of energy of the lattice vibrations. The emitted phonon has an energy of $\hbar\omega_V$. In the third step, the electron-hole pair recombines in the intermediate stage, emitting a scattered photon. The scattered photon has an energy of $\hbar\omega_S = \hbar\omega_P - \hbar\omega_V$. In Fig. 1 the Feynman diagram for the Stokes Raman scattering process is shown [1]. The schematic representation is shown in Fig. 2. The Raman scattering process involves the optical phonon branches of atomic vibrations as opposed to Brillouin scattering, which describes scattering involving acoustic phonons. In the first-order scattering, only one phonon is involved. Higher order Raman scattering is not discussed here.

III. General formalisi

Crystal symmetry imposes a selection rule that dictates which scattering geometries are allowed. The spontaneous scattering efficiency (percentage of incident power scattered

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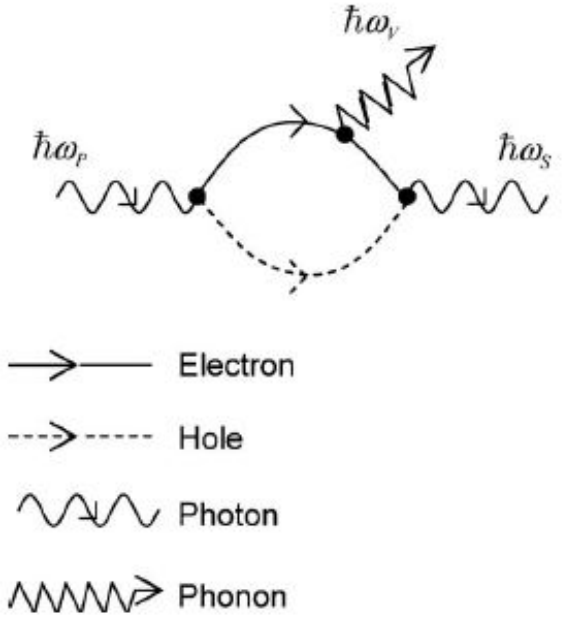

Fig. 1. Characterized Stokes Raman scattering process by emission one photon [1]

per unit length of the material per unit solid angle) S is given buy

$$S = S_0 \sum_{k=1,2,3} \mid e_s \cdot R_k \cdot e_p \mid^2$$

The vectors e_s and e_p are unit vector and denote the polarization of the pump and the Stokes electromagnetic fields. The sum runs over the three Raman matrices. The phonon shifts can be chosen parallel to the crystallographic axes corresponding to those along one of the three principal axes of the crystal.

$$R_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} R_2 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} R_3 = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

S_0 contains intrinsic microscopic property of silicon including derivatives of the polarizability, and the absolute amplitude of the displacement of the zone-center optical phonons. For a wavelength of $\lambda = 1064nm$ the value of $S = 3.05 \cdot 10^{-6}/cmSr$ is obtained. Therefore, we get the scattering efficiency at the wavelength $\lambda = 1434nm$ due the extrapolating the measured values. This gives us $S = 8.4 \cdot 10^{-7}$/cmSr.

The stimulated Raman Scattering is nonlinear. The incident and the Stokes radiation produced act as a driving force for the lattice vibrations. The resultant polarization at the Stokes frequency is proportional to the Stokes field and the square of the incident field. The gain coefficient can be calculated for bulk scattering by the spontaneous efficiency by detailed balancing [3]

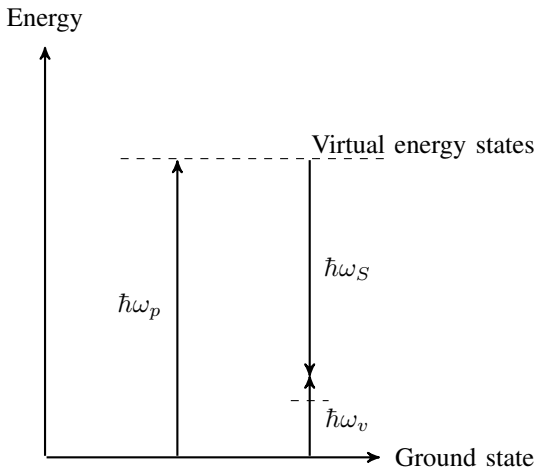

Fig. 2. Schematica Stokes scattering process [2]

$$g_R = \frac{8\pi c^2 \omega_P}{\hbar\omega_s^4 n^2(\omega_s)(N+1)\Delta\omega} S,$$

where N is the Bose occupancy factor, and has a value of 0.1 for silicon at room temperature. A gain coefficient of $g_R = 76$cm/GW is obtained when the corresponding values are inserted. The scattering efficiency of $S = 8.4 \cdot 10^{-7}$/cmSr is used. This is of the same order of magnitude, but several times larger than the values obtained from Raman gain measurements, which is about 20cm/GW at wavelength of 1.55m. Nevertheless, compared to silicon dioxide, which is $0.93 \cdot 10 - 2$cm/GW, the Raman gain in silicon is however $10^3 - 10^4$ times larger. Such a large difference originates from the much narrower linewidth of the Raman spectrum in crystalline silicon compared to amorphous fibre [1].

IV. Raman susceptibility

As silicon crystals exhibit an inversion symmetry, the lowest-order nonlinear effects system from the third-order susceptibility $\chi^{(3)}$. When an optical field $E(r,t)$ propagates inside a silicon crystal or waveguide, the induced nonlinear polarization can be written in the frequency domain in the general form

$$\tilde{P}_i^{(3)}(r,\omega_i) = \frac{3\epsilon_0}{4(2\pi)^2} \int\int \chi_{ijkl}^{(3)}(-\omega_i;\omega_j,\omega_k,\omega_l) \tilde{E}_j(r,\omega_j)\tilde{E}_k(r,\omega_k)\tilde{E}_l(r,\omega_l)d\omega_j d\omega_k$$

where $\omega_l \equiv \omega_i + \omega_k - \omega_j$. This frequency concentration is due to the four-wave-mixing. The third-order susceptibility of silicon has two dominant contributions, one from bound electrons and the other from optical phonons. It is write as $\chi_{ijkl}^{(3)} = \chi_{ijkl}^{R} + \chi_{ijkl}^{R}$. i,j,k ans l take the values $1,2$ and 3. These two terms have quite different dispersion and polarisation properties. The second term represents the Raman contribution of optical phonons [4].

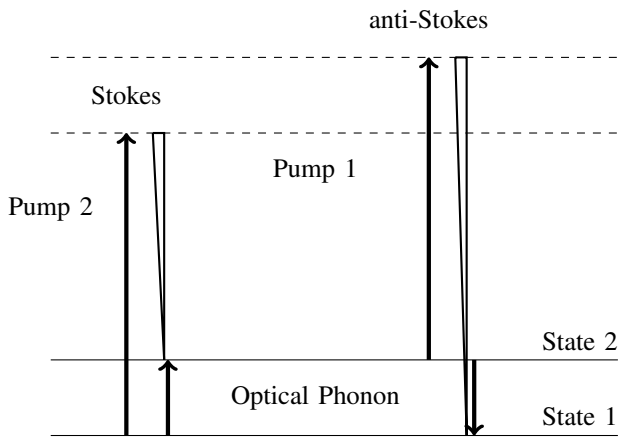

Fig. 3. Process to create of the anti-Stokes photon and annihilation. The arrows represent the virtual transitions [1]

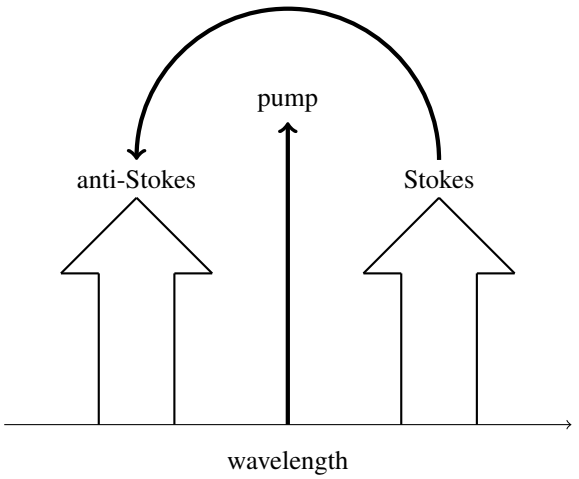

Fig. 4. Wavelength process between pump-, Stokes and anti-Stokes wavelength [1]

By comparing the induced polarisation suggested by the shift and with previous definitions, one arrives at the following expression for the induced Raman susceptibility:

$$\chi^{(3)}_{ijkl} = 2\Gamma\omega_V \frac{2ncg_R}{\omega_s\sqrt{\frac{\mu_0}{\epsilon_o}}} \cdot \frac{\sum_{k=1,2,3}(R_{ij})_k(R_{mn})_k}{\omega_v^2 - (\omega_p - \omega_s)^2 - 2i\Gamma(\omega_p - \omega_s)}.$$

Ω is the disspiative term in the harmonic oscillator equation and n the refraction index. R describes the crystal symmetry. Considering the symmetry, there are 12 equal non-vanishing components. These have the indices of the form

$$1221 = 1212 = 2121 = 2112 = 1331 = 1313 = 3131 = 3113 = 2332 = 2323 = 3232 = 3223$$

[1]

V. Raman scattering generated trough four-wave mixing

The phase mismatch between the pump, Stokes and anti-Stokes fields determines the nature of the Raman scattering process in the medium. The total phase mismatch is defined as

$$\Delta\beta = 2\beta_p - \beta_S - \beta_{aS}$$

where $\beta = 2\pi/\lambda$ is the wave vector for the given wavelength and the polarisation mode must also be considered. Section II has already dealt with the case where only the stimulated Raman scattering process is used. This happens when the phase mismatch is larger. In this case, the gain coefficient for the anti-Stokes wave has a negative sign, indicating that an incident anti-Stokes wave is attenuated.

If the phase mismatch is very small, the anti-Stokes signal can be generated by four-wave four-wave mixing (FWM) induced by Raman susceptibility, which happens in the same way as conventional FWM by 3rd order electronic nonlinear susceptibility.

There is a coherent interaction between pump, Stokes and anti-Stokes waves, since the conservation of energy and momentum must be fulfilled by phase matching. The process to generate the anti-Stokes photon is accompanied by generation of an annihilation, schematically shown in Fig. 3. This process can be used for a typical application to perform a wavelength conversion from the Stokes to the anti-Stokes bands. It is used as an interface between the technologically important telecommunication bands, the 1300nm and 1550nm bands, when pumping at 1400nm (Fig. 4)[1].

VI. Raman laser

Stimulated Raman scattering makes it possible to build a silicon laser or silicon optical amplifier. This was not possible before, as silicon is a semiconductor with an indirect band gap and thus has a very low light emission efficiency. Here we demonstrate a continuously operating silicon Raman laser. The laser resonator is formed by coating the facets of the silicon waveguide with multilayer dielectric films. The continuous-wave silicon Raman laser is constructed from a low-loss silicon-on-insulator rib waveguide whose facets are coated with multilayer dielectric films. The facet coatings have different reflectivities for the Stokes and pump wavelengths. The front facet coating has a reflectivity of $\approx 71\%$ for the Stokes wavelength $(1,686nm)$ and $\approx 24\%$ for the pump wavelength $(1,550nm)$. The backside facet has a broadband highly reflective coating for both pump and Raman wavelengths of $\approx 90\%$. These reflectivities of the waveguide facets were determined using a Fabry-Perot resonance technique. Only emitted photons are reflected in the resonator. The reflected emitted photons are Stokes photons, which can only be reflected if they have the resonance frequency. Other frequencies cannot be amplified by the resonator. The schematic layout of a silicon waveguide laser is shown in Fig. 5 [5].

VII. Conclusion

In this work, we have studied Raman scattering in silicon. Raman scattering is a 3rd order non-linear fibre effect. There is an energy transfer between the light and the crystal. The scattered photon has a higher or lower frequency than the

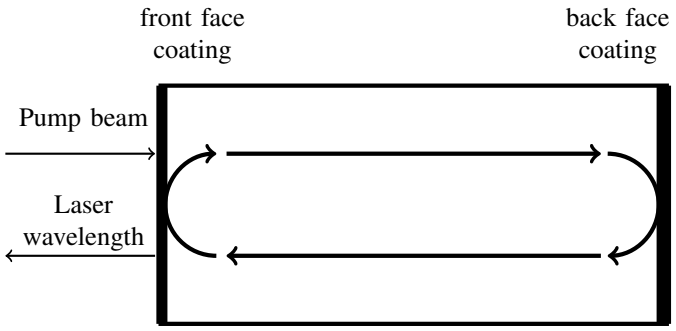

Fig. 5. Schematic layout of the silicon waveguide laser [5]

incident photon and a phonon is produced. Stimulated Raman scattering can be used to create lasers, amplifiers or even waveguides made of silicon. Silicon is a very useful semiconductor raw material, but due to its structure it cannot be used as a waveguide or laser because it has an indirect band gap. Stimulated Raman scattering can be generated by significantly increasing the number of already existing Stokes phontons. This effectively amplifies the Stokes light in the presence of the pump light, which is exploited in Raman amplifiers and Raman lasers. A distinction can be made between Stokes and anti-Stokes waves. In Stokes waves, the scattered photons have a smaller energy and frequency than the pump photons. The anti-Stokes photons have a higher energy and frequency than the incident photons. The scattering geometry in the crystal is determined by your symmetry. The third order nonlinear effects can be described by the Raman susceptibility $\chi^{(3)}_{ijkl}$. The crystal structure simplifies the susceptibility, since no oscillations can occur in certain crystal directions.

Four-wave mixing is used to obtain the important telecommunication bands at 1300nm and 1550nm. The anti-Stokes wave uses the generated optical phonon to get a smaller wavelength and higher frequency than the pump wave. The optical photon is generated by the Stokes wave, which has a larger wavelength. Pumping takes place at a wavelength of about 1400nm.

The Raman laser is an exemplary application for Raman scattering in silicone. By optimising the mirrors and cavity length, the laser can be switched to an integrated photonic chip [5].

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