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2006 J. Opt. A: Pure Appl. Opt. 8 S574

(http://iopscience.iop.org/1464-4258/8/7/S43)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF OPTICS A: PURE AND APPLIED OPTICS

J. Opt. A: Pure Appl. Opt. **8** (2006) S574–S577 doi:10.1088/1464-4258/8/7/S43

Spontaneous Raman emission in porous silicon at 1.5 μm and prospects for a Raman amplifier

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Received 13 March 2006, accepted for publication 2 May 2006
Published 12 June 2006
Online at stacks.iop.org/JOptA/8/S574

Abstract
In the last three years, the possibility of light generation and/or amplification in silicon, based on Raman emission, has achieved significant results. However, limitations inherent to the physics of silicon have also been pointed out. One possible option to overcome these limitations is to consider low dimensional silicon.

In this paper, an approach based on Raman scattering in porous silicon is theoretically and experimentally investigated. We prove two significant advantages with respect to silicon: the broadening of the spontaneous Raman emission and the tuning of the Stokes shift. Finally, we discuss the prospect of a Raman amplifier in porous silicon.

Keywords: Raman effect, porous silicon, nonlinear optics, Raman amplifiers

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The base phenomenon governing Raman amplification is stimulated Raman scattering (SRS), which generates vibrations in the lattice of the medium (optical phonons) and transforms the photons of the pump radiation, turning them into lower energy ones. This process allows a gain on an optical signal to be created, provided that the signal is propagated at the frequency of the diffused light. The Raman effect in silicon is more than 10 000 times stronger than in glass fibre, making silicon an advantageous material. Instead of kilometres of fibre, only centimetres of silicon are required. However, Raman amplification is a small effect, and to build a laser with it one needs very high power intensity and very low absorption losses [1]. Such conditions have already been achieved in optical devices made in silica (SiO_2) [2], whereas Raman amplification in silicon on insulator structures was limited to very short pulses of a few nanoseconds at most [3]. The problem is that an unwanted nonlinear side effect—two photon absorption—creates pairs of electrons and holes that remain in the sample for a long time and absorb both the pump light and signal light, and so quickly turn off the Raman amplification. Rong *et al* [4] solved this problem by embedding the silicon waveguide within a reverse-biased p–i–n junction diode, designed to extract electrons and holes away from the waveguide. With this design, they demonstrated a silicon laser with continuous operation.

However, spectral limitation of the Raman effect in silicon is unavoidable in the SOI platform. In the case of Raman amplification, the limited bandwidth of the spontaneous Raman signal from silicon (105 GHz) makes it unsuitable for use in broad band WDM applications, unless the multi-pump schemes are implemented.

In this paper, an approach based on Raman scattering in porous silicon is presented. Our experimental results prove that a spectral broadening of spontaneous Raman scattering with respect to silicon is achieved. Moreover, in order to provide a theoretical basis for these results, we briefly introduce a

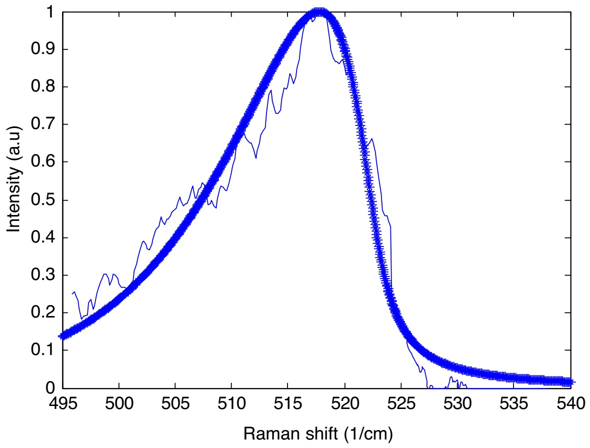

Figure 1. Raman spectra measured in porous silicon compared with the Raman spectrum calculated for a sphere with diameter $L = 4.5$ nm.

phonon confinement model and prove that it is suitable to fit the experimental results. Next, according to this model, we discuss two significant improvements of this approach: broadening of Raman scattering and tuning of Stokes shift in porous silicon with respect to silicon. Finally, we discuss the possibility of simultaneously enhancing the Raman gain coefficient and reducing two-photon absorption in porous silicon.

2. Spontaneous Raman emission in porous silicon

The real structure of porous silicon (PS) may be sponge like, i.e. it is composed of wires and/or dots of no uniform dimensions. When the size of the particle reduces to the nanometre order, the wavefunction of optical phonons will no longer be a plane wave. The localization of wavefunction leads to a relaxation in the selection rule of wavevector conservation. Not only the phonons with zero wavevector $q = 0$, but also those with $q > 0$ take part in the Raman scattering process, resulting in a red shift of the peak position and a broadening of the peak width [5–14].

PS can be modelled as an assembly of quantum dots and the phonon confinement is three dimensional. The weight factor of the phonon wavefunction is chosen to be a Gaussian function as follows:

$$W(r, L) = \exp\left(-\frac{8\pi^2 r^2}{L^2}\right) \tag{1}$$

where L is the average size of the dots. The square of the Fourier transform is given by:

$$|C(q)|^2 = \exp\left(-\frac{q^2 L^2}{16\pi^2}\right). \tag{2}$$

The first-order Raman spectrum $I(\omega)$ is thus given by:

$$I(\omega) \cong \int \exp\left(-\frac{q^2 L^2}{16\pi^2}\right) \frac{\mathrm{d}^3 q}{[\omega - \omega(q)]^2 + \left(\frac{\Gamma}{2}\right)^2} \tag{3}$$

where q is expressed in units of $\frac{2\pi}{a}$ and $a = 0.54$ nm is the lattice constant of silicon, Γ is the natural line width for c-Si at room temperature (3.5 cm^{-1}) and $\omega(q)$ is the dispersion relation for optical phonons in c-Si which can be taken according to:

$$\omega(q) = \omega_0 - 120\left(\frac{q}{q_0}\right)^2 \tag{4}$$

where $\omega_0 = 520\ \mathrm{cm}^{-1}$ and $q_0 = 2\pi/a_0$.

In our experiment, measurements are made on a porous silicon sample. The monolayer realized has a porosity $p = 0.7$ and a thickness $d = 3\ \mu$m. The measurements are carried out in backscattering configuration using a high power fibre laser, delivering a CW light at 1427 nm. In figure 1, we report the experimental results and the fitting by the theoretical curve obtained according to the phonon confinement model. We note that a red shift of the peak position and a broadening of the peak are observed. The Raman peak is at about 517 cm^{-1}, the bandwidth is about 15 cm^{-1} and the estimated size L is about 4.5 nm.

According to the phonon confinement model in figures 2(a) and (b) the peak width and the peak shift of spontaneous

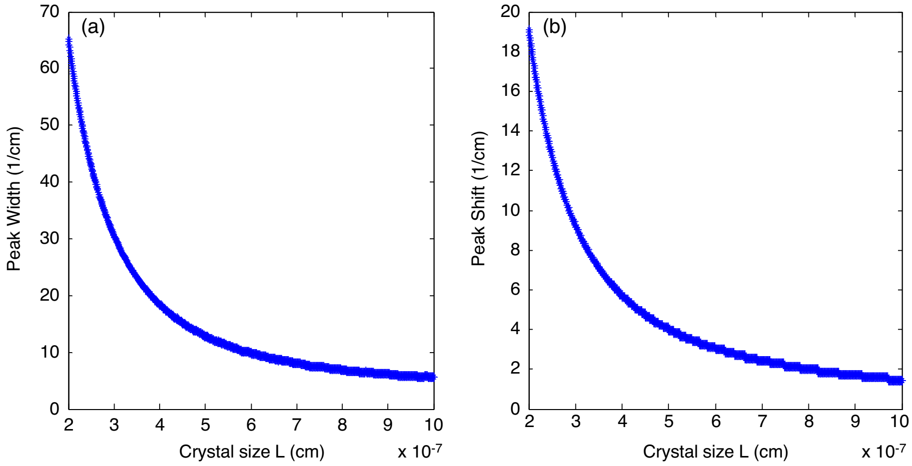

Figure 2. (a) Calculated relationship between Raman peak width and nanocrystal size. (b) Calculated relationship between Raman peak shift and nanocrystal size.

Raman emission as a function of nanocrystal size are, respectively, reported. We note that both peak width and peak shift have an inverse dependence on crystal size. As we can see from figures 2(a) and (b), considering a porous silicon sample with a crystal size of 2 nm, a significant broadening of about 65 cm^{-1} and a peak shift of about 19 cm^{-1} can be obtained. Because the width of C-band telecommunication is 146 cm^{-1}, taking into account the broadening and the shift of spontaneous Raman emission, more than half of the C-band could be covered using porous silicon, without implementing the multi-pump scheme.

3. Prospect for a porous silicon amplifier

The main difficulty in trying to increase the efficiency of Raman laser in silicon, is the presence of two photon absorption (TPA), which reduces the efficiency of SRS. Taking advantage of porous silicon's optical properties, we investigate the possibility of reducing TPA and, at the same time, enhancing SRS.

The TPA process vanishes for $\hbar\omega < 1/2E_g$, $\hbar\omega$ being the photon energy and E_g the band-gap. In PS, due to quantum confinement, an increase of the band-gap with respect to silicon is obtained. The band-gap increases upon reducing the dot (wires) dimensions. Therefore, considering a suitable porosity for which the relation $\hbar\omega < 1/2E_g$ is satisfied, a reduction of TPA is obtained [15].

It is well known that SRS is dependent on the pump intensity and on a gain coefficient g, which depends on the material. As a general rule, there is a trade-off between gain and bandwidth in all laser gain materials. Line width may be increased at the expense of peak gain. While this is true for bulk solids, this trade-off can be overcome for low dimensional materials.

The gain coefficient depends on scattering efficiency, the larger the spontaneous scattering efficiency of materials is, the higher the Raman gain for a given intensity. In porous silicon, Raman scattering efficiency should be stronger than in crystalline silicon [9], as a consequence a stronger gain is expected. Another possibility, in order to enhance the spontaneous scattering efficiency, is to take advantage of the optical confinement effect present in microcavities. A simple optical microcavity can be a $\lambda/2$ Fabry–Perot resonator confined between two $\lambda/4$ distributed Bragg reflectors (DBRs) showing high reflectivity in the wavelength range of interest. The optical characteristic of such an optical microcavity is the presence of a well-defined, high reflectivity stop band with a peak of transmission at the wavelength λ. Moreover, the electric field amplitude within such a cavity is enhanced throughout the whole structure, displaying a maximum at its centre. High reflectivity mirrors in a large range of wavelengths are a problem for Raman experiments where photons having different energy (excitation and Stokes field) must get into, or out of the microcavity. However, both excitation and Stokes fields can be coupled simultaneously into the cavity by tuning their propagation angle with respect to the cavity axis, their fields being strongly amplified [16]. We note that Raman efficiency contains two (squared) matrix elements of light–matter interaction proportional to electric field amplitude, due to incoming and outgoing field amplitudes. Therefore, if these amplitudes are enhanced, the Raman efficiency should be fourth order in the enhancement factor.

Finally, a further possibility is to take advantage of optical confinement in a PS waveguide. In [17] a method to produce porous-silicon waveguides by means of a local laser oxidation process was reported. The estimated losses of the waveguides were below 1 dB cm^{-1}. Because the PS refractive index decreases when the porosity increases, the vertical confinement of the waveguide was obtained by a multilayer structure realized by varying layer porosity while the lateral confinement was obtained by a local laser oxidation. Starting from this waveguide configuration, the optical gain as a function of pump power can be calculated. In order to perform this calculation we have to take into account two important parameters: the effective area $A_{\text{eff}} = \frac{[\int\int|\psi(\omega_p)|^2\,\text{d}x\,\text{d}y]^2}{\int\int|\psi(\omega_p)|^4\,\text{d}x\,\text{d}y}$, where ψ is the mode inside the waveguide, and the value of Raman gain. Regarding the first parameter, with PS being a mixture of air and Si, the PS refractive index is expected to be lower than that of bulk Si, therefore, the effective area of a mode inside a PS waveguide is greater than that of a mode in an SOI waveguide with the same geometrical dimensions. On the other hand, the Raman gain in PS should be greater than in silicon. Therefore, in order to obtain an optical gain of 10 dB, a significant reduction of pump power should be obtained.

On the other hand, it is well known that one way to enhance the cubic nonlinearities in materials is to artificially 'shrink' the electrons in regions much shorter than their natural delocalization length in the bulk. In fact, an enhancement of the real part of the third-order nonlinear susceptibility in porous silicon, due to quantum confinement, in the transparency range has already been proved [15].

Therefore, even if SRS in low dimensional silicon has never been studied, an enhancement of the imaginary part of the third-order nonlinear susceptibility is also expected. The existence of disorder could be of key importance for the SRS of PS. In a binary system with components of refractive indexes n_1 and n_2, the efficiency of light scattering depends on how these components are organized in the system, on the dimensions of the components, and on the refractive index ratio $n_1/n_2 = m$. In a specific regime, light propagation can be inhibited due to interference and the field intensity in localized regions can be significantly larger than in the surroundings [18]. As a consequence the nonlinear optical properties of the disordered material should be enhanced. This issue is currently under investigation.

4. Conclusions

In this paper, with the aim of overcoming some limitations of the Raman approach in silicon, low dimensional silicon is investigated. We prove that two important improvements are achieved: a broadening of the spontaneous Raman emission and a tuning of the Stokes shift. Finally, the encouraging prospects regarding a porous silicon amplifier, based on Raman scattering, are discussed.

Acknowledgments

The authors are very grateful to Professor F Capasso from Harvard University (USA) and Professor E Santamato from

Università 'Federico II' di Napoli (Italy) for very helpful discussions.

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