Raman Approach in Silicon Nanostructure at 1.5 micron

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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 been pointed out, too. In order to overcome these limitations, a possible option 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 about the prospect of Raman amplifier in porous silicon.

Keywords: Raman effect, Porous Silicon, Nonlinear Optics, Raman amplifiers.

I. 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 fiber, making silicon an advantageous material. Instead of kilometres of fiber, 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 [3,4]. The problem is that an unwanted nonlinear side effect - two photon absorption - creates pairs of electrons and holes that remain for a long time in the sample and absorb both the pump light and signal light, and so quickly turn off the Raman amplification. Rong et al. [5] solve 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 demonstrate 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 its use in broad band WDM applications, unless the multi-pump schemes are implemented.

Nanostructured porous silicon could be useful in realising a variety of optoelectronic devices. In 1990, visible luminescence from porous silicon (PS) was demonstrated by Canham. The light emission could potentially be used for a light emitting diode forming the heart of integrated on-chip optical interconnects. The efficiency of porous silicon LED's has risen by 5 orders of magnitude over the last decade to 1% but remains quite inadequate for optical interconnect. The radiative atomic-like transition at 1.54 micron from Er is very important because it matches the window for maximum transmission in silica based optical fibres. Regarding porous silicon, the very large surfaces area to volume ratio makes it very accessible for Er-doping, as well as a host for large concentration of oxygen necessary for erbium emission. Doping of PS has been achieved by ion implantation, diffusion and electrochemical deposition. The maximum external quantum efficiency obtained by Er-doped porous silicon LED's is low. (0.001%) [6]

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In this paper, some advantages of Raman approach in porous silicon with respect to silicon are proved. In our previous paper [7], only experimental results proving spontaneous Raman emission in porous silicon at 1.54 nm were reported. In this paper, we prove that phonon confinement model is suitable to fit the experimental results. After that, according to this model, we discuss two significant improvement of this approach: the broadening of Raman scattering and the tuning of Stokes shift in porous silicon with respect to silicon. Finally, the prospects of Raman amplifier in porous silicon are introduced and discussed. We point out the possibility to enhance the Raman gain coefficient and to reduce two-photon absorption, at the same time, in porous silicon

II. SPONTANEOUS RAMAN EMISSION IN POROUS SILICON

The real structure of Porous Silicon (PS) may be spongelike, i.e. it is composed of wires and/or dots of nonuniform dimensions. When the size of the particle reduce to the order of nm, the wave function of optical phonons will non longer be a plane wave. The localization of wave function leads a relaxation in the selection rule of wave vector conservation. Not only the phonons with zero wave vector **q**=0, but also those with **q**>0 take part in the Raman scattering process, resulting in the red shift of the peak position and the broadening of the peak width [8,9].

PS can be modelled as an assembly of quantum dots and the phonon confinement is three dimensional. The weight factor of the phonon wave function 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 dots. Square of Fourier transform is given by:

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

The first-order Raman spectrum I(ω) is thus given by:

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

where q is expressed in units of $2\pi/a$ 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 $\omega_0 = 520 cm^{-1}$ and $q_0 = 2\pi/a_0$.

In our previous paper [7], spontaneous Raman emission was measured in PS monolayer in backscattering configuration using a high power fiber laser, delivering a CW light at 1427 nm. In figure 1, we report the experimental results and the fitting of experimental results [7] by theoretical curve obtained according to phonon confinement model (Eq. (3)). We note that a red shift of the peak position and a broadening with of the peak width are observed. The Raman peak is at about 517 cm^{-1}, the bandwidth is about 15 cm^{-1} and the estimate size L is about 4.5 nm.

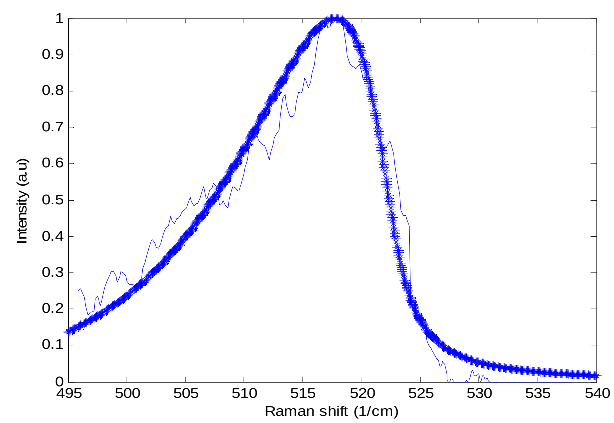

Figure 1 Raman Spectra measured in porous silicon compared with the Raman spectrum calculated for a sphere with diameter L =4.5 nm.

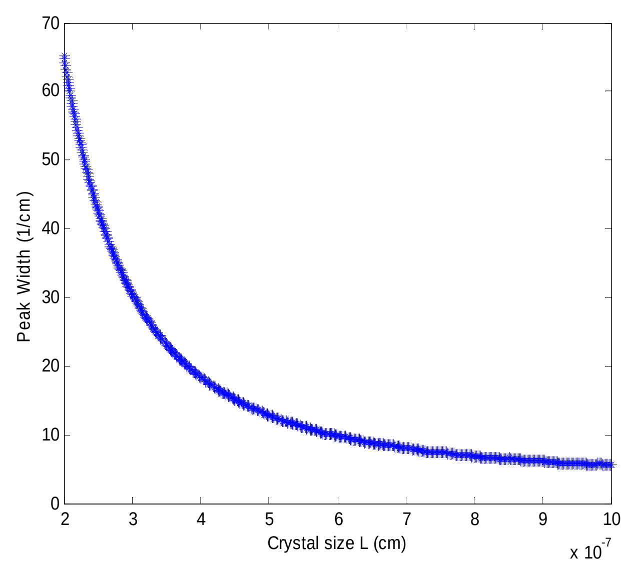

Figure 2 Calculated relationship between Raman peak width and nanocrystal size.

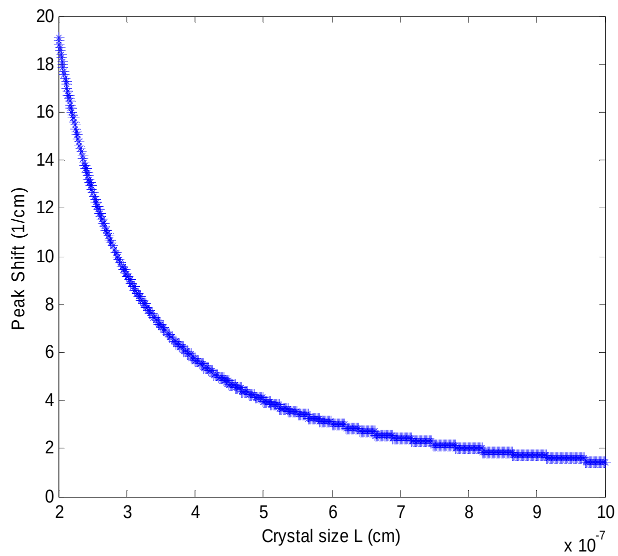

Figure 3 Calculated relationship between Raman peak shift and nanocrystal size.

According to the phonon confinement model in fig. 2 and in fig. 3 the peak width and the peak shift of spontaneous 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 fig. 2 and 3, considering a porous silicon sample having 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.

III. PROSPECT FOR POROUS SILICON AMPLIFIER

In order to increase the efficiency of Raman laser in silicon, the main difficulty was due to the presence of two photon absorption (TPA), which reduces the efficiency of SRS. Taking advantage of porous silicon optical properties, we investigate the possibility to reduce TPA and, at the same time, to enhance SRS.

The TPA process vanishes for $\hbar\omega < 1/2E_g$, hω 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, the reduction of TPA is obtained [10].

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. However this is true for bulk solids, but for low dimensional materials this trade-off can be overcome.
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 is obtained. In porous silicon, Raman scattering efficiency should be stronger than in crystalline silicon [11] 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 λ/2 Fabry-Perot resonator confined between two λ/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 center. 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 go out from 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 [12]. 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 reference [13] 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. Because of 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 $A_{eff} = \frac{\left[\int\int\left|\psi\left(\omega_p\right)\right|^2 dxdy\right]^2}{\int\int\left|\psi\left(\omega_p\right)\right|^4 dxdy}$, where ψ is the mode inside the waveguide, and the value of Raman gain. Regarding the first parameter, being PS 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 the one of a mode in an SOI waveguide having 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 a 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 [10].

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 [14]. As a consequence the nonlinear optical properties of the disordered material should be enhanced. This issue is right now under investigation.

IV. CONCLUSIONS

In this paper, with the aim to overcome some limitations of 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 porous silicon amplifier, based on Raman scattering, are discussed.

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