Raman emission in porous silicon at 1.54 μm

L. Sirleto, V. Raghunatan, A. Rossi and B. Jalali

There have been many reports regarding visible luminescence and light emission at 1.54 μm, at room temperature, from porous silicon and from Er-doped porous silicon, respectively. Described is a different approach, based on Raman scattering in porous silicon, to generate radiation at 1.54 μm. Preliminary experimental results regarding Raman emission in porous silicon samples at 1.54 μm are also reported.

Introduction: 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 LEDs has risen by five orders of magnitude over the last decade to 1% but remains quite inadequate for optical interconnect.

The radiative atomic-like transition at 1.54 μm from Er is very important because it matches the window for maximum transmission in silica based optical fibres. Regarding porous silicon, the very large surface area to volume ratio makes it very accessible for Er-doping, as well as a host for the 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 LEDs is low (0.001%) [1].

According to the Raman approach, the natural atomic vibrations of material can be used to create or amplify light. The Raman effect is used in optical fibres for light generation and amplification, however several kilometres of fibre are required to make a useful device. Typical dimensions on a chip are millimetres and, because of this, the Raman effect was not considered as a candidate for creating silicon optical devices. Interestingly, the Raman effect in silicon is nearly 10 000 times larger than that in the glass fibre. Exploiting these properties, Raman emission at 1542 nm, stimulated Raman scattering (SRS) and coherent anti-Stokes Raman scattering (CARS) have been demonstrated by the authors in silicon waveguides [2].

In this Letter, on the same line of argument, an approach based on Raman scattering in porous silicon is proposed. It has important advantages: to obtain light emission at 1.54 μm no special impurity is required, so the production of samples is simple and cheap; moreover it is possible to take advantage of enhancement of Raman scattering [3] and nonlinear effects in porous silicon [4].

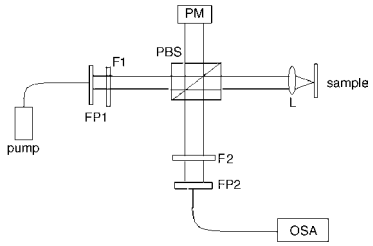

Fig. 1 *Experimental setup for measurement of spontaneous Raman scattering from silicon and porous silicon sample*

Pump: CRC fibre laser; FP1: fibre port; F1: bandpass filter at 1427; PBS: polarising beam splitter; PM: power meter; L = microscope objective lens; F2: longpass filter at 1500 nm; lens; FP2: fibre port; OSA: optical spectrum analyser

Raman emission: In a material the induced polarisation, oscillating at the frequency of the incident light, interacts with the molecular vibration to create a polarisation oscillating at frequencies shifted by the frequency of the vibrations, which then can radiate at the shifted frequency. This is called spontaneous Raman effect. A spectral analysis of the scattered radiation reveals the existence of frequencies that are shifted down by increments equal to vibrational frequencies of the material irradiated. This type of scattering is referred to as Stokes scattering. Frequencies equal to the sum of the incident wave frequency and the vibrational frequencies are also present in the scattered radiation. This is the so-called anti-Stokes scattering.

In Raman scattering both energy and momentum had to be conserved. Ideal crystal translation symmetry leads to plane wave phonon eigenstates and due to the small wavevector of the optical photons, the phonons in the Raman scattering of crystals have very small momentum compared with the Brillouin zone. So one-phonon Raman scattering probes only zone centre phonons. In crystalline silicon the first-order Raman peak is symmetric and shifted by 520 cm^{-1}.

Disorder finite size effects or when the crystalline size becomes very small, quantum confinement relaxes the q = o rule, and phonons at q#O become Raman active leading to a downshift and broadening of the Raman peak. The phonon peak broadens towards lower energy and shifts slightly. The line-shape asymmetry increases as the incident photon energy is increased. In porous silicon Raman scattering should be 10 times stronger than crystalline silicon, perhaps due to the surface enhancement or resonance effect, which is under further investigation [3].

In this Letter experimental results, proving Raman emission at 1.54 μm in porous silicon, are reported. The experimental setup is shown in Fig. 1. The pump laser is a high power cascaded-Raman-cavity (CRC) fibre laser (Streamline-RL from Spectra-Physics). The laser delivers a CW randomly polarised light at 1427 nm. The fibre is connected to a fibre port (FP1) to obtain a collimated beam. The fibre port is a miniature micropositioner, enabling active alignment of an aspheric lens for collimating or free beam to fibre coupling. A 2 nm linewidth is obtained because the beam crosses a bandpass filter (F1) put later on the FP1. A polarisation cube beam splitter (PBS) is used to split the pump beam into two orthogonal linearly polarised components. In particular P-polarised light is transmitted and S-polarised light is reflected. Measuring the S-reflected polarised beam, by a power meter, the power incident on the sample can be monitored. The P-polarised beam, acting as the Raman pump, crosses a microscope objective lens (M = 20X) and it impinges onto the sample. The microscope objective lens is also useful in order to collect the signal constituted by the reflected beam and the Raman signal backscattering. To maximise the power of the collected signal, the microscope objective lens is mounted on a stage with three degrees of freedom. The collected signal, impinging on the PBS, is splitting in two linearly polarised lights. The S-polarised light, reflected by the PBS, crosses a longpass filter at 1500 nm, so that the pump signal (at 1427 nm) is removed, whereas the S-backscattering Raman, going through it, impinges onto FP2. In this case the fibre port is used to couple the free beam in the fibre. Finally the signal is sent to an optical spectrum analyser (OSA) for analysis.

In our experiment silicon and porous silicon samples are measured. The porous silicon sample is constituted by a monolayer having a porosity $p = 0.7$ and a thickness $d = 3$ μm. The sample is obtained by an electrochemical etching starting from $p+$ silicon wafer. The measurements are carried out at room temperature.

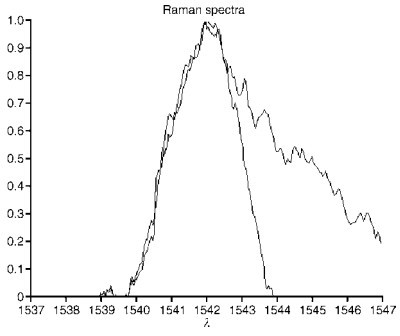

Fig. 2 *Comparison of Raman spectra measured in silicon and porous silicon sample*

Because the characteristic of Raman scattering in a silicon sample is well known, to test our experimental setup we carry out some preliminary measures on silicon. The sample is put on a rotating stage and the value of angle is 45° with respect to the plane of incidence. The Raman spectra measured in the silicon sample is shown in Fig. 2. It is symmetric and is in excellent agreement with the value of the optical phonon frequency in silicon. In fact it has a peak at 1542 nm, corresponding at 15.7 THz red-shifted from the pump wavelength.

To point out the principal difference with respect to the silicon sample, the Raman spectra measured in the porous silicon sample is also shown in Fig. 2. We note that also in the case of the porous silicon the observations are in excellent agreement with the behaviour described by the theory. Because of the small crystalline size, quantum confinement relaxes the q = o rule and phonons at q#O become Raman active, as a consequence the phonon peak broadens towards lower energy.

Fig. 3 shows the measured spontaneous Raman back scattering from the porous silicon sample at increased incident power. The incident powers onto the sample are 0.5 and 1W, respectively. It is important to point out that as expected from theory the spontaneous Raman is a linear effect. Because the thickness of the sample is very small, a measured low signal is justified. Of course, increasing the thickness, an increase of Raman signal is expected. Moreover a greater improvement could be obtained exploring planar optical microcavities.

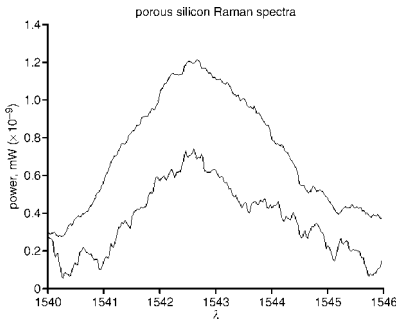

Fig. 3 *Spontaneous Raman scattering measured in porous silicon sample for different value of pump power*

To realise optical active devices, at present the problem to be overcome is one of materials. They exhibit nonlinearities, which are still too low for realistic high speed devices performing at low optical power. A way to enhance the cubic nonlinearities in materials is to artificially 'shrink' the electrons in regions much shorter than their natural delocalisation length in the bulk. In such morphologies, size related optical resonances will usually appear, resulting from dielectric or quantum confinement, the former prevailing in metal nanocrystals, the latter prevailing in semiconductor nanocrystals. High porosity silicon has a pillar-like structure (1-D) while a low porosity must be regarded as an interconnected nanocrystals structure (0-D). In porous silicon an enhancement of third-order nonlinearities has already been demonstrated [4].

The imaginary part of third-order nonlinearities describes nonlinear effects such as stimulated Raman scattering (SRS) and coherent anti-Stokes Raman scattering (CARS). Early interest in SRS and in CARS arose because they could provide intense coherent radiation at new frequencies. Starting from Raman emission in porous silicon and exploiting stimulated Raman scattering a different approach with respect to Er-doped porous silicon could be experienced concerning the amplification of light in porous silicon at 1.54 μm.

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