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Phys. Status Solidi C **8**, No. 9, 2880–2884 (2011) / **DOI** 10.1002/pssc.201084114

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Nanosilicon: a new platform for photonics

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Received 3 October 2010, accepted 4 February 2011
Published online 1 June 2011

Keywords silicon, photonics, nanotechnology

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Silicon photonics has produced the first all-optical components intergrated into systems available already on the market. Nanosilicon, where low dimensional silicon allows new phenomena and devices, is a way to expand the reach of silicon photonics. In this article we review some of our past research activities focused on the demonstration of innovative photonic integrated circuits building blocks.

1 Introduction The extremely fast development of integration and performances of electronic devices in the last two decades pushed this technology to its physical limits: new alternative technologies have to be envisioned to keep pace with the electronic evolution. The problems are dramatic especially for interconnections where both bandwidth and span cannot be satisfied by pure electronics components [1]. Photonics and, in particular, silicon photonics is the natural solution to this problem since photonics enables both the substitution of basic electronic functions with faster optical analogies and the development of new kind of devices with more complex functionalities. In particular, silicon photonics is a platform which has a number of advantages compared to other platforms based on III-V semiconductors or polymers. It is the only one which guarantees full compatibility with the already existing CMOS infrastructures. This is the key to enable an incremental progress where optical functionalities are integrated into electronic based devices and, eventually, in all-optical systems [2]. The integration of electrical and optical functionalities on the same chip creates a synergy that exploit both the high computation capabilities of electronics and the high communication bandwidth of photonics. In addition, with silicon photonics, the microelectronic paradigms (“faster, smaller, cheaper”) become the technology drivers for the evolution of photonic integrated systems.

Besides than simply replacing electronic in semiconductor devices, photonics has a much broader application range that span from health to renewable energy. In this article we review some of the most important results recently achieved in our laboratory. Our research in silicon photonics is aimed at exploit nanotechnology to enable functionalities otherwise not or poorly provided by silicon. With nanotechnology we can confine both electrons in low dimensional silicon and photons in micrometer sized cavities. These confinements permit to demonstrate few innovative building blocks of photonic integrated circuits (PICs) as well as other application of silicon based photonic devices. In Section 2 we will describe three PICs fundamental building blocks, namely: a light emitting diode (LED) structure, an all-optical switch and an ultra dense wavelength division multiplexer (UDWM). In Section 3, two applications in sensing and photovoltaics will be addressed to demonstrate the wide span of silicon photonics.

2 Essential elements of a Si-based PICs

2.1 LED structures The main drawback of silicon as a material for photonic applications relies on its low efficiency as light emitter, and it is due to the indirect nature of its electronic band gap [3]. To overcome this limit, nanoscale structuring of bulk silicon is used to exploit quantum confinement effects that strongly enhance the light emission efficiency [4]. Our vision concentrates on multilayered structures composed by alternating layers of insulating SiO_2 and of Si-nc nucleated into a silicon rich oxide matrix, after a suitable annealing treatment. In particular, we experimented the band gap engineering of Si-nc by growing a graded structure where the Si-nc sizes depend on their position along the multilayer structure, as depicted in Fig. 1.

Figure 1a reports a scheme of a multilayered LED device and a sketch of the graded gap active layer with its energy level sequence. On top of the panel it is shown an idealistic view of the layered structure composed by Si-nc having different sizes: the layers facing the silicon p- or n-type electrodes contain large nanostructures in order to promote an efficient carrier injection by decreasing the quantum jump between SiO_2 and the nanocrystals. Moving towards the center of the active layer, small Si-nc are placed to yield an efficient light emission. Figure 1b compares the power efficiency of the graded gap LED with two different periodic multilayers: the optimized LED shows a systematically greater efficiency. Other figures of merit, such as optical power density, show the same trend (data not shown here). This approach has achieved the highest reported power efficiency (maximum value of 0.2 % for silicon-based LED) together with the lower onset voltage (around 1.4 V) for this class of LEDs [5, 6].

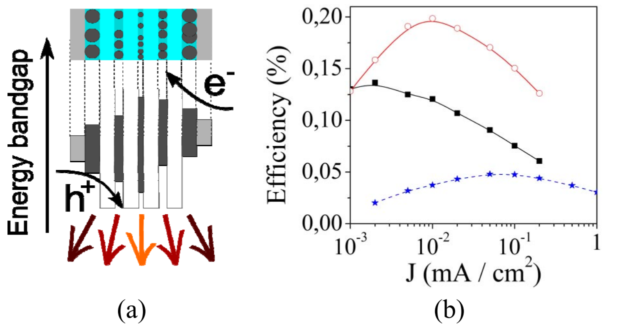

Figure 1 a) Sketch of LED device. On top an idealistic view of the layered structure. It consists in a sequence of 2nm/4nm/2nm/3nm/2nm/2nm/3nm/2nm/4nm/2nm SiO_2 and Si-nc layers, respectively. On the bottom the sequence of energy levels with indication of the carriers injection directions. b) LED performance: power efficiency of the band-gap engineered structure (red line, white circles) and of two period multilayers (blue stars: 3nm/2nm SiO_2 and Si-nc layers and black squares: 4nm/2nm SiO_2 and Si-nc layers, each with 5 periods).

2.2 Si-nc ultrafast switch Silicon, because of its cubic symmetry, does not possess 2nd order optical nonlinearities. Nanocrystalline silicon is known to have quite strong optical nonlinearities (NL). Various effects contribute to the nonlinearity: thermal effects (negative sign, time scale of ms), excited carrier refraction (negative sign, time scale of ns) and Kerr (bound electron) response (positive sign, time scale of <ps) [7]: While the first two mechanisms have a quite slow time responses due to the multiple resonant processes involved, the third one, based on a 3rd order non-resonant mechanism, is extremely fast and has the potential for fast all-optical switches.

Given a certain NL material, the key factor to achieve good efficiency in the switching process is the maximization of the overlap between the propagating optical mode field profile and the active material. Our approach uses a slot waveguide (WG) geometry [8] realized on a SOI wafer, with the slot trench filled with a silicon rich oxide matrix with Si-nc nucleated within it.

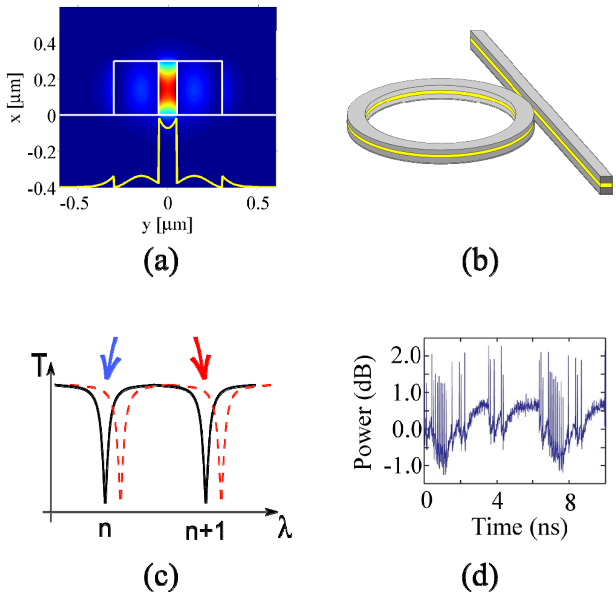

Figure 2 a) Colour map of the fundamental quasi-TE mode of a slot WG. The white lines show the dielectric interfaces, while the yellow line is the field profile (Ex component). b) Sketch of the switch composed by a ring resonator coupled to a straight waveguide. c) Transmission of the bus waveguide for two pumping condition: dark line only the signal is present; red dashed line, transmission of the switch when a pulsed laser centred at the red wavelength copropagates with the signal. The blue arrow indicates the CW probe beam used in the switching experiment reported in (d). d) Time dependence of the transmission of the probe signal when a fast pump beam is present. The time response of the switch is of the order of 10 ps.

Figure 2 reports the basic mechanism of the optical switch and the time resolved characterization that demonstrates the fast switching capability. Figure 2a reports a simulation of the fundamental quasi-TE mode of the slot WG. A large field enhancement in the slot region is observed with a very good overlap between the field maxima and the region filled with the Si-nc. Figure 2b is a drawing of the fabricated structure, composed by a ring resonator coupled to a bus WG. A signal beam and a pump beam are copropagating in the bus WG. Figure 2c illustrates the wavelength dependence of the transmission of the bus waveguide for two pump power condition. Two laser beams are sent along the WG; one is a continuous, low power beam (probe) resonant with the-*n* order of the ring (blue arrow on the left of Fig. 2c), the other is a high power pulsed beam (pump) resonant with the *n+1* ring mode (red arrow on the right). When only the probe beam is present, the transmission is low because of the ring losses. If the pump is switched on, each pump pulse load the cavity with its electromagnetic field inducing a nearly istantaneous NL shift in the cavity refractive index, with a conseguent red shift of the ring resonances. This, in turn, brings the probe beam temporarily in a state of high transmission, detected at the output as a pulsed peak. In this way it is possible to encode a sequence of optical “bits”, determined by the modulation of the pump beam, as shown in Fig. 2d. The slow time response of the baseline is due to other NL process. Time response in the order of 10 ps were achieved and improved performances are expected in more carefully optimized structures [9]:

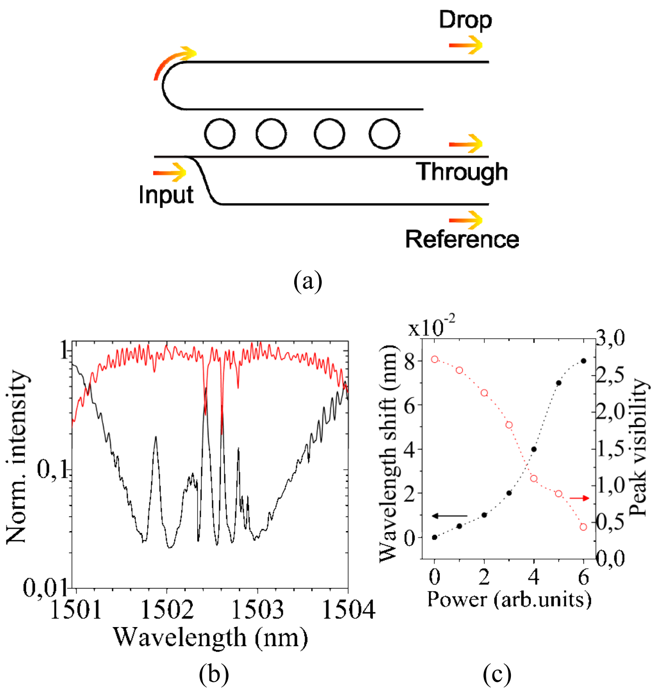

Figure 3 a) Sketch of a SCISSOR device. The structure has one input and two output channels (through and drop ports). Actual devices are composed by 8 rings, realized on a SOI wafer. b) Spectra of a CRIT multiplet: black lines (bottom) through port output, red lines (top) drop port. The small visibility in the drop port of some peaks is due to sample imperfections that strongly enhance out of plane scattering processes. c) All optical tuning effect: black filled circles show the single peak shift under different light intensities, red open circles shows the reduction in peak visibility.

2.3 SCISSOR based UDWM One of the most fascinating advantage of photonics over electronics relies on the non interacting nature of the photons. This allows the transmission of a number of different signals along a single channel (wavelength multiplexing). Besides the different approaches reported in literature [10]; we study a novel structure based on a side coupled integrated spaced sequence of optical resonator (SCISSOR) that enables the achievement of ultra dense multiplexing (channel spacing smaller than 25 GHz) with the further possibility of external tuning/switching of each individual channel.

Figure 3a depict a SCISSOR device. It is composed by one input and two output ports (drop and through) that surround a chain of resonators indirectly coupled together by the WG sections (no direct coupling) [11]: Figure 3b shows the spectra of one ring resonance with the appearance of a coupled resonators induced transparency (CRIT) multiplet. This phenomenon is associate with the constructive interference of the light with a wavelength which satisfies at the same time the single ring resonance condition and the Bragg condition imposed by the ring sequence. Five peaks can be clearly recognized in a bandwidth of 0.6 nm (80 GHZ), resulting in peaks separation of about 16 GHz. Figure 3b reports the tuning and switching possibility on a single resonance caused by a NL resonance shift induced by focusing a laser onto a single microring. It is observed that the resonance frequency is proportional to the laser power up to a shift of 50 % of the separation between nearby resonances. At the same time, the peak visibility is strongly reduced (peak visibility is arbitrarily defined as: $1000[I_{max}-I_{min}]$). This kind of effect allows a great number of resonances to be engineered in a very narrow stop-band and all-optical individual tuning of each single resonance. This has great potential for UDWDM or dynamical routers if integrated into an appropriate topologically optimized PIC.

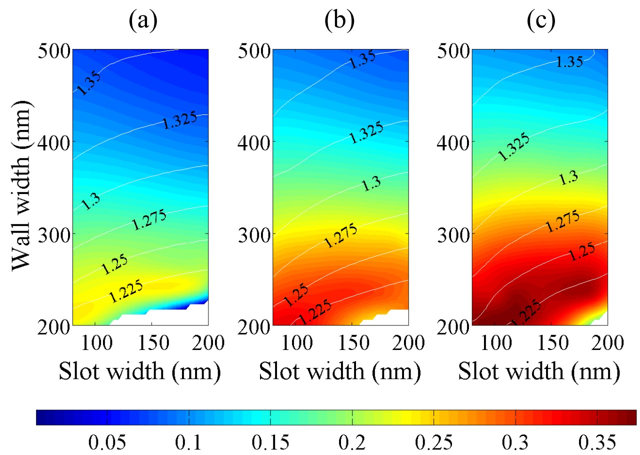

Figure 4 Contour map showing field confinement inside a) single, b) double and c) triple slot WG. Label indicates the refractive index of the fundamental quasi-TE mode.

3. Other photonic applications of silicon nanostructures

3.1 Optical sensing in hybrid materials Silicon has very diverse applications. In this paragraph we describe a recent result in the design of slot waveguide based sensor realized in hybrid materials. Slot waveguides recently came into limelight because of their peculiar field distribution that can be used to enhance the interaction strength in optical sensors. In our simulations a layer of oxidized porous silicon is used as a bottom cladding material, because of its extremely low refractive index (down to 1.16, few micron thick), whereas the guiding layer is composed by a poly(methylmethacrylate) (PMMA) electron beam resist (n=15, thickness 500 nm).

Figure 4 reports contour maps of single (Fig. 4a), double (Fig. 4b) and triple (Fig. 4c) slot WG realized on this hybrid system. It is interesting to note that, while the effective index of the fundamental TE mode (labels inside the maps) is quite low, the field confinement inside the slot region reaches values up to 35 %. These values are only a factor of two smaller to what reported in literature for SOI based slot WG. This is not an intuitive result. In fact, as a sensitivity figure of merit, it is often assumed the ratio of the refractive indexes squared, without a careful analysis of the field integral value that is, instead, the key parameter to consider [12]:

Slot WGs realized in polymeric material enlarge the application fields of integrated optical sensing devices, because of both the transparencies of polymers in the visible and of their great flexibility in chemical functionalization and fabrication processes.

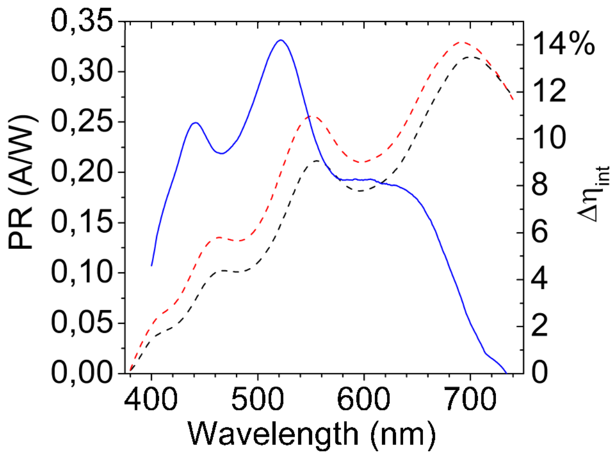

Figure 5 Photoresponsivity of a Si-nc containing PV cell (red dashed line) and of a model of the same cell when the Si-nc plays simply the role of antireflection coating (black dashed line). The blue line indicates the enhancement in internal quantum efficiency due to the photoluminescence of the Si-nc (right axis, percentage).

3.2 Si-nc as a downshifter in 3rd generation photovoltaics cells Photovoltaics (PV) is probably the greatest opportunity to reduce pollution down to sustainable values in a short period of time. The most performing Si cells have an external efficiency lower than 30%. Most of the solar energy absorbed by the cell is wasted as heat since it has an energy larger than the silicon band-gap.

To improve the cell efficiency, an approach consists in shifting the solar photon energy from a wavelength region where they are poorly efficiently converted by the bulk Si cell into a region where they can be readily converted. For silicon this means convert photons from the blue to the red part of the visible spectrum. Si-nc can be used to coat a standard silicon cell with a down-shifting layer. Indeed Si-nc absorb blue photons and emit red photons with an efficiency of the order of 30 %.

Figure 5 shows the effect of a Si-nc downshifting layer on a standard silicon cell. To work out the role of the down shifting, we have measured carefully the photoresponsivity (PR) of the cell and its optical functions (reflectance and transmittance of the Si-nc layer). Then by measuring the internal quantum efficiency of a standard silicon cell, we have estimate the PR of a Si-nc coated cell, where the Si-nc play the role of a simple antireflection coating, i. e. no photoluminescence is considered. Finally the difference between the measured and the modelled PR, normalized by the transmittance of the cell, gives the variation to the cell internal quantum efficiency due to the active role of the Si-nc. The red dashed line in Fig. 5 is the measured photoresponsivity (PR), the black dashed line is the modelled PR and the blue line is the variation in the internal quantum efficiency [13]. An increased conversion efficiency is observed in the spectral region where Si-nc absorbs. These data demonstrate that a thin Si-nc layer deposited on top of a PV cell is effective in downshifting of the solar light yielding an increase the cell internal quantum efficiency of up to 14 %. Even greater increases are expected by carefully choosing the thickness of the layer, to minimize reflection losses.

4 Conclusions

In this paper we have reviewed some recent results in silicon nanophotonics. We have shown that nanostructuring either the electronic properties or the photonic mode density of states change the phenomenological landscape of silicon and enable new functionalities in silicon photonics. These can be further engineered to widen the scope of silicon photonics so that both cheaper and high performences integrated silicon photonics devices can be developed further.

Acknowledgements We acknowledge supports by a number of projects (FP7-ICT 224312 HELIOS, FP7-ICT 216405WADIMOS, FP7-ICT 248909 LIMA, FP6-IST-NMP-017158, PAT- GOPSI) and collaboration with a number of co-workers whose name can be found in the relevant publications.

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