Er doped-Si nanostructures coupled with photonic crystals for high enhancement of light extraction

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Silicon nanophotonics is emerging as a new platform for the integration of photonic and electronic devices. Several examples on our recent efforts on monolithic light sources based on silicon nanostructures will be presented and discussed. In particular it will be shown that silicon-on-insulator (SOI) is emerging as an interesting photonic material.
A first example of a photonic nanostructure on SOI for the control of light emission has been a "slot" waveguide. It is a slab waveguide having a very thin layer (slot) of low refractive index material (SiO_2) embedded within a high refractive index one (Si), the core. It gives rise to a strong enhancement of the electromagnetic field in the slot. Then when Er-doped Si nanoclusters are embedded in the silica thin layer a very strong enhancement of guided photoluminescence is observed. Also the enhancement in the spontaneous emission rate is involved, similar to the Purcell effect of an emitter in an optical cavity, as demonstrated by calculations [1].
Another promising approach is represented by the integration of this singular slot waveguide to a photonic crystal (PhC), that permits to accurately tailor the light propagation and confinement by a periodic modulation of the dielectric constant. Simultaneous inhibition and redistribution of light emission in these systems have permitted to obtain an enhancement of the Er^{3+} near-normal emission when the involved transition is in resonance with an appropriate mode of the PhC slab both under optical and electrical excitation.
Therefore the realized electroluminescent devices on SOI platform (see an image in Fig.1) based on the coupling of efficient emitters, such as Er-doped Si nanoclusters, and the photonic modes of a proper photonic structure have permitted to obtain very high external efficiency, by making these devices very promising.

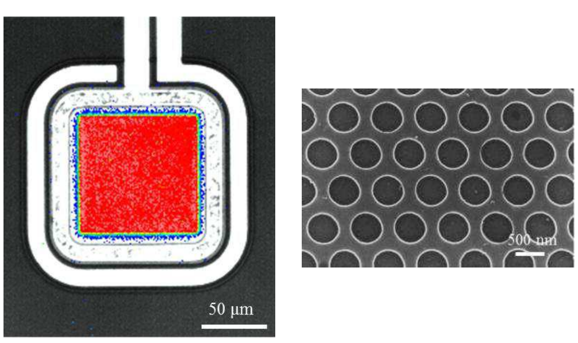

Fig. 1 Emission microscopy of electroluminescent devices based on an active slot waveguide, containing Er-doped Si-nc, coupled to a photonic crystal. The image is in false color. (b) Scanning electron microscopy image in plan view of the active area.

Moreover Er-based rare earth compounds have been proposed since they permit to dilute very high number of emitters, upto 10^{22} Er/cm^3, in a dielectric media totally compatible with Si platform. In particular, Y-Er and Yb-Er disilicate ($Y_{2-x}Er_xSi_2O_7$ and $Yb_{2-x}Er_xSi_2O_7$, $0 < x \leq 2$) will be discussed as good host candidates since they afford a maximum solubility of 10^{22} cm^{-3}. This high solubility is due to the fact that both constituent materials ($Er_2Si_2O_7$, and $Y_2Si_2O_7$, or $Yb_2Si_2O_7$) have the same crystalline structure with very similar lattice parameters, and both Er and Y, or Yb, atoms occupy the same atomic sites [2]. In addition Y is optically inactive and then the optical properties of the compounds depend entirely on Er, therefore an accurate control of Er-Er interactions is reached. Instead when Yb is present a further increase of the Er excited population is observed thanks to the 10-times higher absorption cross section due to the efficient Yb-Er coupling, without deleterious influences on the Er emission. Through the control of Er-Er interactions and excitation processes, high inverted population is reached.
Finally we have successfully demonstrated the coupling between Er atoms in such compounds and the optical modes of a photonic crystal cavity realized in crystalline silicon, as shown in Fig. 2. The photoluminescence of Er atoms in the cavity region is enhanced by the increased extraction efficiency and the Purcell effect, the extraction efficiency being maximized using far-field optimization [3]. Inverted population has been estimated, by making the material very promising as high gain medium. And since our photonic structure is fully fabricated in crystalline silicon and since Er atoms can be excited through an impact excitation mechanisms, also efficient electroluminescent devices can be realized.

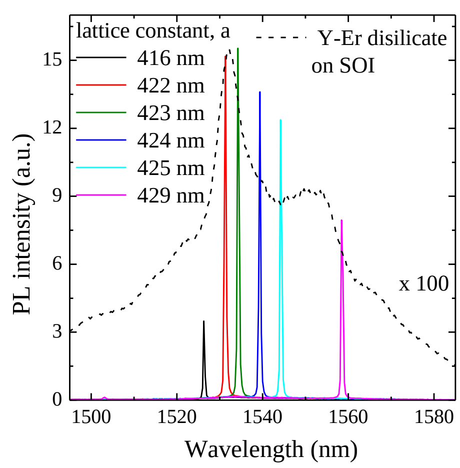

Fig. 2 PL emission from Er in Y-Er silicate on SOI (dashed curve) and when coupled to a photonic structure with different lattice parameters.

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[2] M. Miritello, R. Lo Savio, P. Cardile, and F. Priolo, Phys. Rev. B **81**, 041411(R) (2010).
[3] R. Lo Savio, M. Miritello, M. Galli, L. O' Faolain, T. Krauss, F. Priolo, submitted