

# Multi-photon processes in silicon nano-optics

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## ABSTRACT

Intrinsically silicon is a linear optical material, since its cubic symmetry and indirect band-gap prevent the existence of second-order non-linear optical effects to a good approximation. However, upon closer inspection there are still some possibilities for inducing non-linear functionality. For instance the restrictions imposed by the indirect band-gap may be lifted by dividing the bulk silicon into small segments, e.g. in the form of nano-clusters. Another possibility is to strain the silicon in one or two crystal directions. This will break the symmetry, and thereby allow several types of non-linear effects. Even an isotropic stress may have a small effect, since it will slightly change the size of the (indirect) band-gap and change the carrier concentrations. However, this effect is usually exceedingly small for silicon. On the other hand carriers may more effectively be introduced electrically or by doping, and these methods are very effective. A special case is the use of germanium as doping material. Germanium is chemically very similar to silicon, but it has around 4% lattice mismatch and (in theory) a higher non-linearity. Finally one should not forget, that silicon has a significant third-order non-linearity ( $\chi^{(3)}$ ), which is about 100 times larger than that for silica.

The key obstacle for implementing silicon-based photonics in most integrated optical systems is the difficulties associated with obtaining active and non-linear optical functionality in silicon waveguides. If these effects could be realized with an efficient, cheap and simple method, the way would be open for complete monolithic integration of optics and electronics on the silicon platform. Therefore there is great scientific and commercial interest in multi-photon processes in silicon-based optics. Within the last three years the field has seen a number of breakthroughs, such as the realization of a carrier-based electro-optic modulator [1], silicon Raman lasers [2], integration of III-V material on silicon [3] and stress-assisted electro-optic modulation in silicon-based waveguides [4]. Most of these effects can be enhanced by orders of magnitude in photonic crystal waveguides with photonic band-gap effects due to the large and very flexible dispersion, which allows group refractive indices approaching 1000.

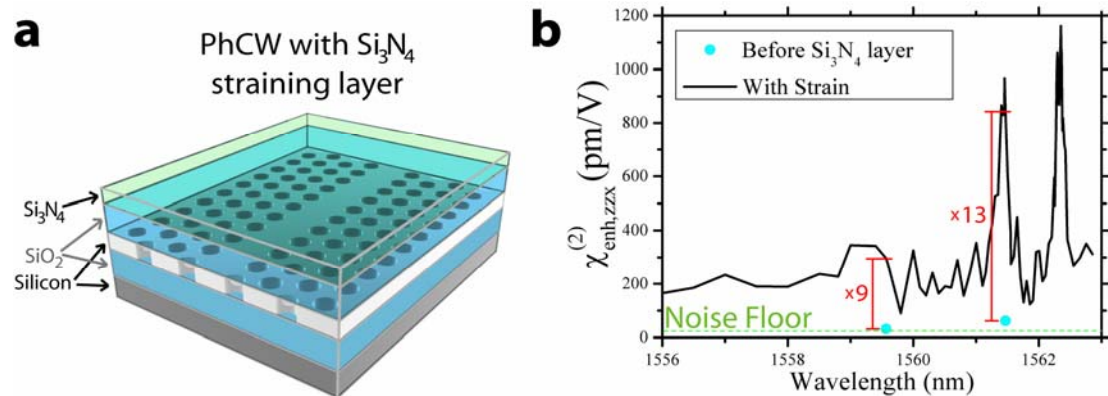


Figure 1: Effect of straining the silicon structure in a photonic crystal waveguide: **a**, Schematic of the investigated photonic crystal

waveguide (PhCW). **b**, Enhanced non-linearity  $\chi^{(2)}_{enh,zzx}$  measured before (blue points) and after (black line) applying the straining layer. A strain-induced increase in  $\chi^{(2)}_{enh,zzx}$  by one order of magnitude is observed compared to the weakly strained structure before deposition of  $\text{Si}_3\text{N}_4$ . The noise-floor is shown as the dotted green line. The peaks are due to dispersion effects.

A significant amount of research is also devoted to the study of silicon nano-clusters and silicon-germanium materials. Due to Heisenberg's uncertainty principle the tight confinement in a nano-cluster leads to a large uncertainty in the momentum, whereby the effects of the indirect electronic band-gap are effectively lifted, since the momentum uncertainty becomes comparable to the k-vector difference to the indirect electronic band-gap.

Doping with germanium is primarily studied because it has around 4% lattice mismatch (leading to a large and controllable stress), while it is still chemically similar to silicon. In addition theoretical predictions point towards much higher intrinsic non-linear coefficients for germanium than for silicon. Finally, germanium may be turned into a direct band-gap material by moderate stress, since the difference between its indirect and direct electronic band-gap is quite small and the stress-induced electronic band-gap shift is relatively large.

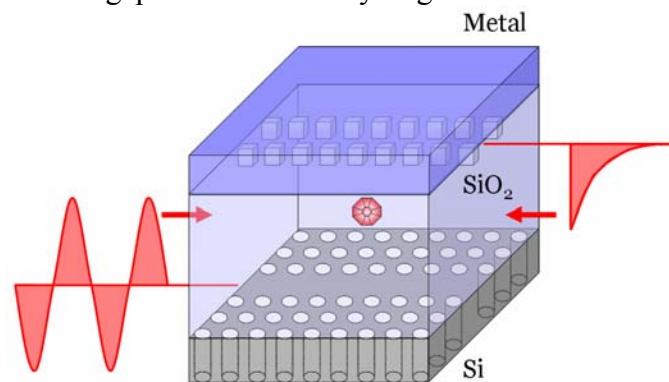


Figure 2: The artist's impression of a silicon-based optical component using several basic interactions. A nano-cluster embedded in silica ( $\text{SiO}_2$ ) mediates interaction between an optical wave in a silicon band-gap structure (Si) and a plasmon wave running at the interface between the silica and a patterned metal layer.

In the lecture I will initially give an extensive introduction to planar photonic band-gap components (crystal waveguides), their design and fabrication, followed by a brief overview of some of the large discoveries in silicon photonics obtained across the world during the last three years. Finally, I will focus on results from stress-induced electro-optic modulation in crystal waveguides and give an outlook on future applications of non-linear processes and multi-photon effects in silicon.

## References

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