The nano-optics of plasmonic optical tweezers, SERS substrates and multi-colored silicon nanowires

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Plasmonic and photonic nanostructures present opportunities for the optical manipulation of micro- and nanoparticles. Compared to traditional optical tweezers based on fields focused by microscope objective lenses, they offer a number of advantages. They enable the generation of optical fields confined to sub-wavelength dimensions, permitting large gradient forces to be generated. Trapped particles can be sensed, due to the fact that they modify the resonance frequency of the nanostructure that performs the trapping. Lastly, plasmonic and photonic nanostructures are suitable for integration into microfluidic chips, thereby enabling optical trapping platforms with reduced footprint. In this presentation, I discuss the trapping of nanoparticles (polystyrene, 110 nm diameter) with localized surface plasmons (LSPs) excited on a gold nanopillar[1].

LSPs on pairs of particles separated by small gaps, termed optical antennas, enable the generation of intense fields for SERS. We demonstrate[2] a lithographic method yielding optical antennas with gaps as small as 3 nm (Fig. 1a]). SERS measurements performed on benzenethiol monolayers formed on these antennas reveal significantly stronger signals for those with 3 nm gaps (Fig. 1b), compared to those with 12 nm gaps (Fig. 1c). This behavior is in agreement with the predictions of numerical electromagnetic simulations (Fig. 1d-e).

We demonstrate that vertical silicon nanowires take on a surprising variety of colors covering the entire visible spectrum, in marked contrast to the gray color of bulk silicon[3]. The vivid colors arise from the guided mode properties of the individual nanowires. The nanowires are fabricated from silicon wafers by electron-beam lithography and dry etching. In Fig. 2a, an SEM of a nanowire array is shown. The letters S (left), E, A, and S (right) each comprise nanowires with radii of 70 nm, 60 nm, 50 nm and 40 nm, respectively. The nanowires are all ~1 μm long. Optical microscope images of the structure of Fig. 2a reveal the strong dependence of color upon the nanowire radius (Figs. 2b-c). In Fig. 2d, an SEM of an array of nanowires of different radii is shown. The optical microscope image of Fig. 2e reveals that the wires appear red, green and blue.

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[1] K. Wang, E. Schonbrun, P. Steinvurzel & K. B. Crozier, Nature Comms **2**, 469 (2011)

[2] W. Zhu , M.G. Banaee , D. Wang , Y. Chu , and K. B. Crozier, Small **7**, 1761 (2011)

[3] K. Seo, M. Wober, P. Steinvurzel, E. Schonbrun, Y. Dan, T.Ellenbogen, and K.B. Crozier, Nano Letters **11**, 1851 (2011)

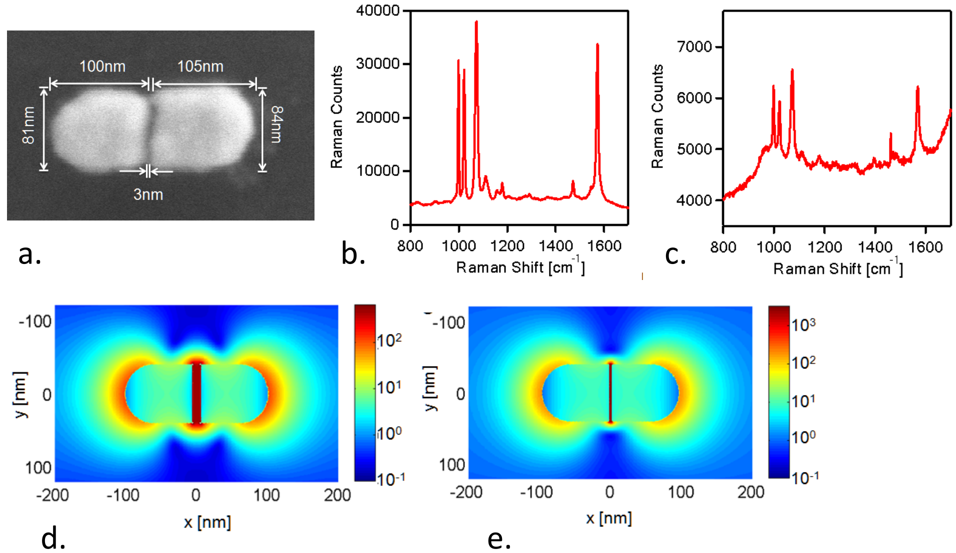

Figure 1 Optical antennas for SERS. (a). Scanning electron micrograph (SEM) of lithographically-fabricated optical antenna, consisting of two gold sections, separated by gap that is 3 nm at position of closest approach. b). SERS spectrum of benzenethiol monolayers formed on optical antennas with gaps of 3 nm. Laser λ=784nm, power = 0.82 mW. Integration time = 5 s. c). SERS spectrum of benzenethiol monolayer formed on optical antennas with 12 nm gaps. Laser λ=750 nm, power = 1.14 mW. Integration time = 5 s. d). Simulated steady-state field intensity distribution ($|E|^2$) for optical antenna with 12 nm gap. Illumination is a plane wave polarized along antenna, at λ = 776 nm. e). Simulated steady-state field intensity distribution ($|E|^2$) for optical antenna with 3 nm gap. Illumination is a plane wave polarized along antenna, at λ = 821 nm.

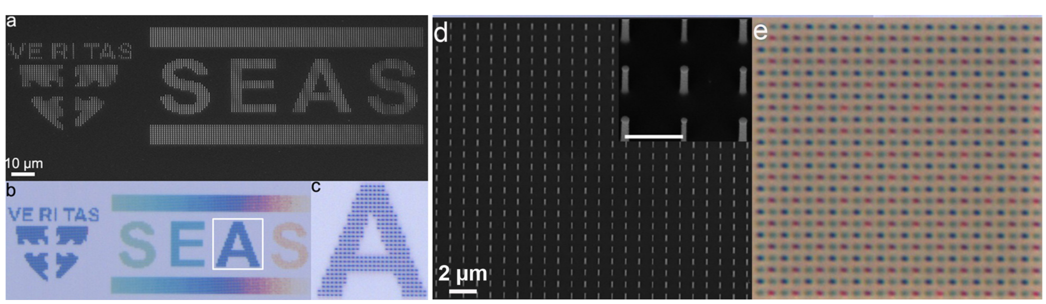

Figure 2 Multicolored vertical silicon nanowires (a) SEM of vertical silicon nanowire array. (b) Bright-field optical microscope image of pattern. (c) Magnified image of the selected area indicated by the white square of panel b. (d) SEM image of pattern consisting of vertical silicon nanowires with radii of 45 nm, 50 nm, and 65 nm representing red, blue, and green colors, respectively. Inset: magnified SEM image. Scale bar is 1 µm. (e) Bright-field optical microscope image of pattern.