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Fabry-Perot Plasmonic Resonances in Silver Nanowire Antennas Imaged with a Sub-Nanometer Electron Probe

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Surface plasmons in metallic nanostructures enhance the conversion of optical radiation into localized electromagnetic energy at the nanoscale. Surface plasmon supporting nanostructures have attracted recent attention due to their potential applications in nanodevices, including their use in sub-wavelength photonic circuits, data storage, solar cells and bio-sensors [1]. In one-dimensional nanoantenna structures, electromagnetic radiation readily excites counter propagating short-range surface plasmon-polariton (SPP) waves which set up Fabry-Perot type resonances [2]. Here, we scan a sub-nanometer electron probe over individual silver nanoantennas and simultaneously collect structural information and excitation spectra through annular dark field imaging and electron energy loss spectroscopy respectively. We detect both odd and even multi-polar resonant SPP modes and measure their spatial distribution in relation to the underlying nanoantenna structure.

Experimental data were acquired on a monochromated FEI Titan 80-300 Cubed electron microscope at 0.1eV energy resolution (FWHM). This instrument is equipped with a high-brightness source. A focused, sub-nanometer electron probe was scanned in a raster over two dimensional regions of interest enclosing individual, high aspect ratio silver rods. At each pixel in a scan, an integrated annular dark-field intensity and an electron energy loss spectrum is acquired. Energy-filtered images, extracted at energy loss peaks in the recorded spectra, reveal the two dimensional spatial variation of various resonance modes (m = 1 to 6) as shown in Fig. 1. The detected resonance energies range from near-infrared to ultraviolet photon energies. The filtered images are in good agreement with simulated near-field distributions, calculated at resonant energies and averaged over all in plane wavevector orientations as discussed in details elsewhere [3].

The direct measure of the SPP intensity profile at resonance, carried out on multiple rods and mode orders, enabled the measurement of the SPP wavelength and phase relative to the nanoantenna structure as shown in Fig. 2. The phase shift of the SPP, acquired upon reflection from the rod terminals as the traveling wave travels back and forth, was calculated according to the Fabry-Perot resonance condition, where the round trip phase must be equal to an integer multiple of 2π. A trend in phase shift with resonance mode order is established [4].

References

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[3] D. Rossouw, M. Couillard, J. Vickery, E. Kumacheva, G.A. Botton, submitted.
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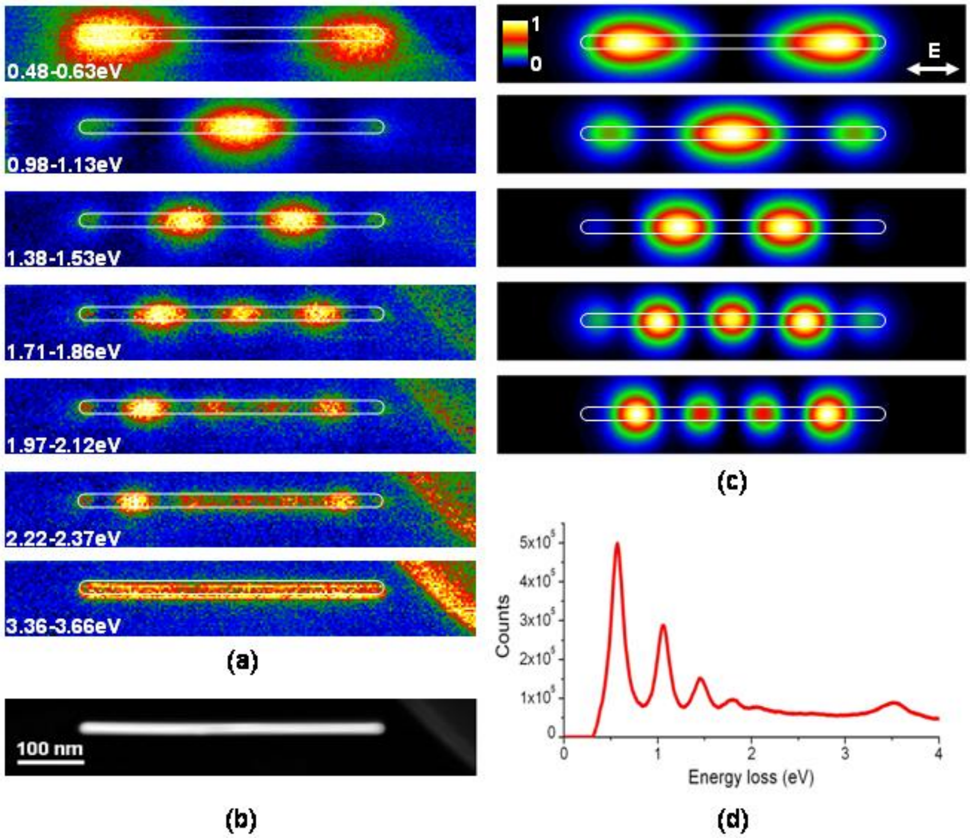

FIG. 1. (a) Energy filtered EELS maps extracted reveal the spatial variation of various plasmon resonant modes in a silver nanoantenna 465nm x 26nm in size. (b) SPP multipolar resonances (m=1 to 6) are resolved. (c) Calculated near field enhancements using the discrete dipole approximation (DDA) method for a silver hemispherical capped cylinder geometry are in good agreement with experiment. (d) Multiple plasmon resonance peaks are resolved in the summed experimental energy loss spectrum after zero loss peak alignment and subtraction (no deconvolution of data is carried out). The plasmon peaks range from the infrared (0.55eV) to the ultraviolet (3.55eV) region of the electromagnetic spectrum.

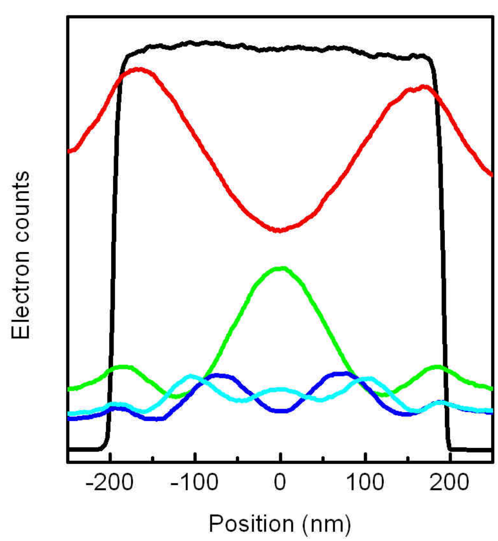

FIG. 2. Experimental line profiles of plasmon mode orders m = 1 to 4 (red, green, blue, cyan respectively). Near-field intensity maxima locations can be compared directly to the dimensions of the antenna structure (black line: HAADF signal recorded simultaneously).

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