Plasmonics On Lithographically-Defined Nanostructures As Studied In Electron Energy-Loss Spectroscopy

Huigao Duan, Michel Bosman, Xiong Yeu Chew, Joel K.W. Yang*
Institute of Materials Research and Engineering, 3 Research Link, Singapore
yangkwj@imre.a-star.edu.sg
Ai Leen Koh
Stanford Nanocharacterization Laboratory, Stanford University, Stanford CA 94305
Antonio I. Fernandez-Dominguez, David W. McComb, Stefan A. Maier
Imperial College London, London SW7 2AZ, United Kingdom

The strong confinement of optical energy into nanoscopic volumes is scientifically important and can be realized by plasmonic effects on metal nanostructures. This phenomenon has been demonstrated useful in high-density magnetic recording, plasmonic lithography, and surface-enhanced spectroscopies. The plasmonic resonances in nanostructures show a strong dependence on material, geometry, and size, with significant (hundreds of meV) resonance shifts resulting from nanometer-scale variations. To probe and manipulate such effects, a combination of high-resolution fabrication and plasmon mapping is required.

Electron energy-loss spectroscopy (EELS) can image the plasmon modes on metal nanostructures with unrivalled spatial resolution.[1] In this method, the energy lost by electrons as they excite plasmon modes is detected in a transmission electron microscope (TEM) equipped with an electron spectrometer. But so far, EELS plasmon mapping has been limited to chemically-synthesized nanoparticles deposited onto TEM membranes. In achieving freedom in nanostructure design and control of spatial dimensions, we turned to high-resolution electron-beam lithography (EBL) to fabricate gold nanostructures directly onto 30-nm-thick TEM membranes.[2] Figure 1 shows examples of these structures. The corresponding EELS plasmon maps in Fig. 1B show bright locations where the electric fields of the given plasmon modes are highest.

To demonstrate the versatility of our method, we look also at split-ring resonators and rods, shown in Fig. 2. Modes that are reminiscent of standing-wave oscillations are observed where integer multiples of half wavelengths fit around the circumference of the split-ring or along the rods. In addition, by combination of EBL and in-situ electron-beam nanosculpting, we were able to fabricate constrictions and gaps of sub-5-nm between larger metal structures. The plasmonic studies of these systems in EELS could shed light on the transport properties in metal constrictions. Furthermore, with the intense electric fields due to the plasmonic focusing effects, electron tunneling at the nano-sized gaps is anticipated, giving rise to novel plasmonic phenomena.

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[1] A. L. Koh, K. Bao, I. Khan, W. E. Smith, G. Kothleitner, P. Nordlander, S. A. Maier and D. W. McComb, ACS Nano **3** (10), 3015-3022 (2009).
[2] A. L. Koh, D. W. McComb, S. A. Maier, H. Y. Low and J. K. W. Yang, Journal of Vacuum Science & Technology B 28, C6O45 (2010).

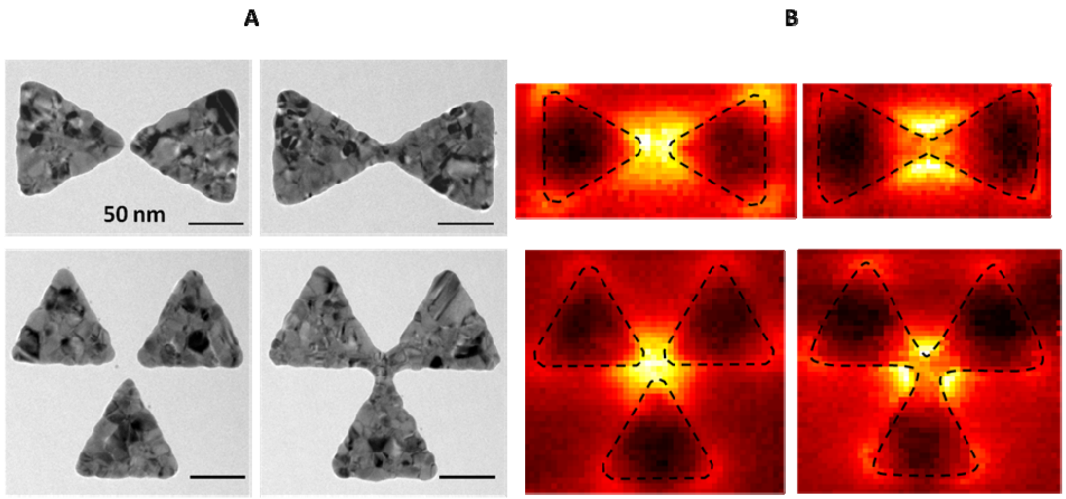

Figure 1: (A) Bright-field TEM images of gold nanotriangles fabricated on 30-nm-thick silicon nitride membrane in various configurations. Scale-bars denote 50-nm length. (B) EELS plasmon maps of the corresponding nanostructures showing strong field localization for the resonant mode at ~1.6 eV.

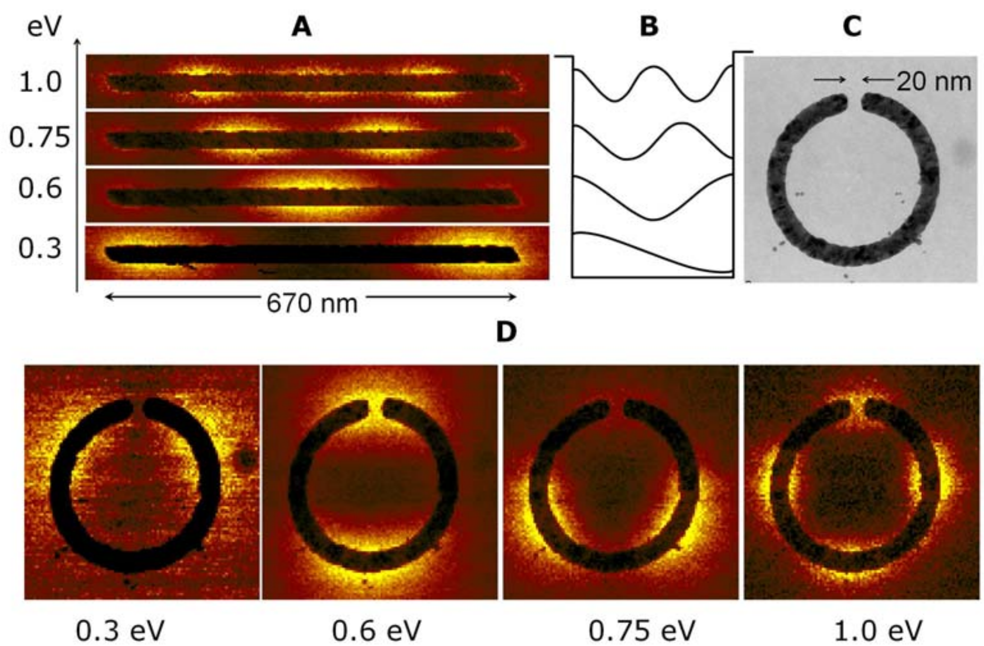

Figure 2: (A) Plasmon maps at different energies for a gold rod. (B) Illustration of charge-density waves of integer half wavelengths corresponding to the plasmon maps in A. (C) Bright-field TEM of a gold split ring resonator; if straightened will have the same length as the rod. (D) Plasmon maps of the split-ring at the same energies as in A. Bending a rod into a split ring appear to surprisingly have little effect on its plasmon resonances.