Plasmonic Antennas: From Optics to THz

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Abstract

Light scattering by nanoscale objects - such as atoms, molecules or nanoparticles - provides a valuable tool to obtain spectroscopic information on the electronic, optical and chemical properties of the object. This is possible because the incident light is converted into nanoscale confined and strongly enhanced optical fields ("hot spots"), thus acting as the optical analog of an antenna [1]. This considerable field enhancement and concentration is sensitive to changes in the geometrical and physical properties of the nanostructure, thus they can be widely exploited in many applications ranging from field-enhanced spectroscopy (SERS or SEIRA) to highly sensitive sensors in the THz [2,3].

In this contribution we study both optical and THz plasmonic antennas reporting on the performance of metallic antenna arrays as well as on semiconductor THz antennas for gas sensing. We first tackle the field-enhanced spectroscopy techniques such as SERS or SEIRA, aiming at optimizing the resonant nanostructures. The interaction between particles in multimers and arrays of nanoantennas need to be carefully considered because it modifies and influences the optical response of the system. The properties derived from the interaction depend on the separation distances to adjacent neighboring antennas as well as on the distribution of the antennas within the array. Although, these effects have been broadly analyzed experimentally and theoretically in the visible spectral range for many different arrangements of particles [4], only few studies have analyzed the IR range [5], where retardation is especially important. In order to get a systematic knowledge on the relationship between infrared plasmonic resonances and longitudinal (d_x) and transversal (d_y) separation distances, we theoretically (by means of FDTD calculations) and experimentally (far-field extinction spectroscopy and near-field optical microscopy) studied the optical extinction spectra of rectangular ordered gold nanorod arrays on silicon wafers [6].

We also analyzed the role of a plasmonic antenna in the enhancement of spectroscopic signals. By means of a combined experimental and theoretical study of the signal scattered by a dielectric tip (probing object) in the proximity of a plasmonic linear antenna, we are able to reveal the double role of the antenna in the scattering, in both, incoming as well as outgoing radiation from the object. For the first time, dependence of the far field scattering on the fourth power of the field enhancement at the object positions, is quantitatively proven. This effect, commonly assumed in SERS is now evaluated by S-NOM. Furthermore, the double phase shift of the scattered radiation corroborates the double role of the antenna.

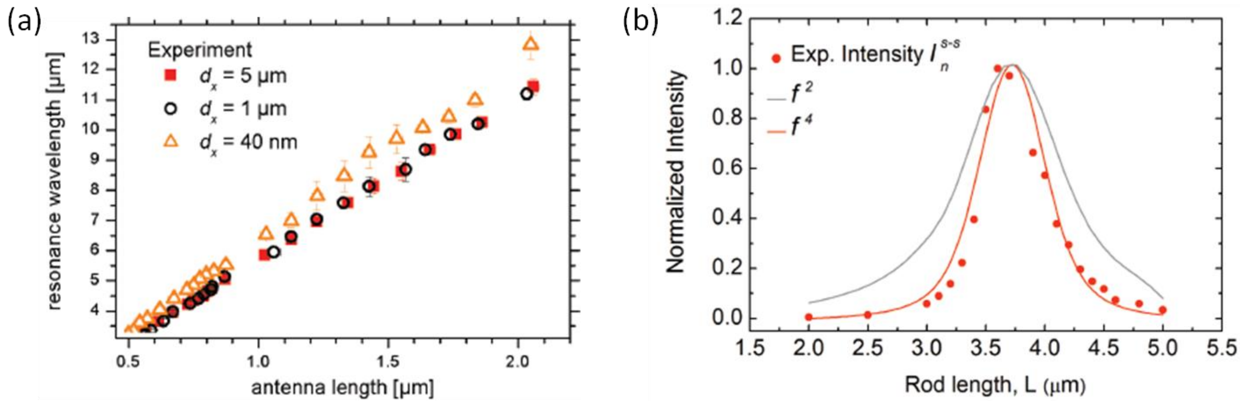

Figure 1.a) resonance wavelength vs rod length for different longitudinal rod separation distances. b) Measured intensity $I_n \propto E_n^2$ (red symbols) and calculated field enhancement f^2 *and* f^4 (black and red solid lines, respectively) at the hot spot as a function of the antenna length L.

Plasmonic antennas also show enhancing capabilities in the THz range of the spectrum and have a widely recognized potential for sensing owing to its capability to couple to various low-energy resonances of matter, including rotational and vibrational motion of molecules, as well as charge carriers and quasi-particles, such as plasmons, in semiconductors [7]. This ability to interrogate specific fingerprints of particular materials appears promising for the detection and recognition of strategic substances such as metals, explosives, gases, organic or biological substances. However, the wavelength of the THz radiation, *e.g.*, 375 µm at 0.8 THz, makes the access to nanometric sensing volumes challenging. Conventional THz spectroscopy makes use of large amounts of matter (requiring flow cells of the order of 1 m for gas spectroscopy). The quest for finding mechanisms that enhance the signal of terahertz radiation in small volumes, hence reducing the amount of matter needed for THz spectroscopy, is therefore a natural drive in this field.

Here, we show that bowtie antennas made of doped silicon operating as plasmonic resonators at THz frequencies are a versatile platform for thin film detection. Compared to metallic resonators, semiconductor-based structures are easily tunable and operate in a regime where the skin depth of the material is larger, *i.e.*, the impedance is lower, and hence the coupling to surface plasmons is more pronounced. A structure such as a bowtie made of doped silicon provides large field confinement and enhancement in the region of its gap at THz frequencies [8]. When an inorganic thin film is deposited on top of the bowtie antenna, the area around the gap of the antenna thus provides an enhanced THz field that results in an enhanced interaction of the terahertz radiation with the deposited ultrathin inorganic films, allowing for THz spectroscopy in very small volumes. We experimentally demonstrate the *in-situ* detection of films that are orders of magnitude thinner than the wavelength using doped silicon bowtie antennas. In particular, we show that semiconductor bowtie antennas operating at THz frequencies allow the sensing of thin inorganic films with a layer thickness as small as λ/3750 in agreement with theoretical FDTD calculations.

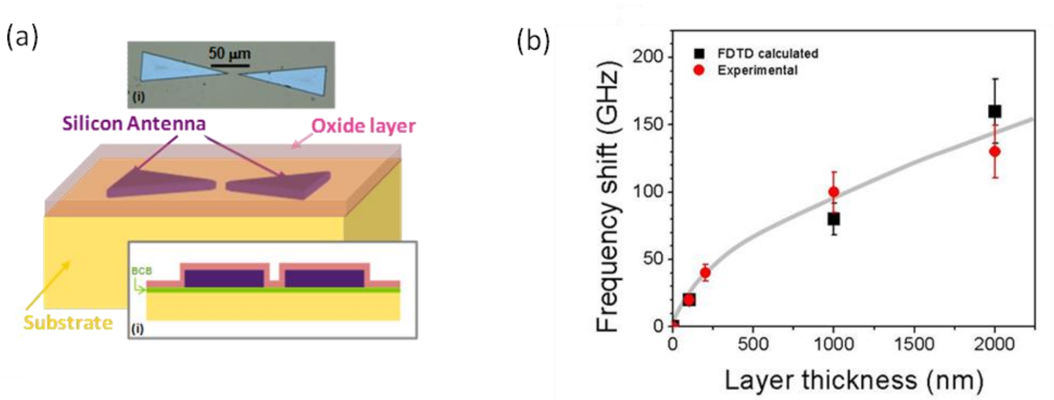

Figure 2.a) Schematic drawing of a silicon bowtie antenna covered with a TiO_2 conformal layer. b) Resonance frequency shift induced by the presence of a SiO_2 layer covering a doped silicon bowtie antenna as a function of the layer thickness (experiment (red circles) and FDTD calculations (black squares). The grey line is a guide to the eye.

The examples and results presented above show the importance of plasmonic antennas as versatile platforms for electromagnetic sensing in a broad range of the spectrum.

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