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Received 16 November 2007, revised 21 May 2008, accepted 26 May 2008
Published online 16 September 2008

PACS 42.25.Bs, 42.70.Qs

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phys. stat. sol. (c) **5**, No. 12, 3701–3703 (2008) / **DOI** 10.1002/pssc.200780127

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REPRINT

phys. stat. sol. (c) 5, No. 12, 3701–3703 (2008) / DOI 10.1002/pssc.200780127

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We report a theoretical study of two-dimensional periodic arrays of composite particles, consisting of two metallic nanodisks separated by a dielectric spacer, using an efficient and accurate multiple-scattering method, which was originally developed for systems of spherical particles and recently extended to non-spherical shapes. In particular, we discuss the plasmonic excitations in such isolated nanosandwiches and study the influence of geometrical parameters like the thickness of the dielectric spacer. Moreover, we investigate the interaction between such composite particles as they approach each other in a two-dimensional periodic lattice.

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1 Introduction The excitation of surface plasmons in metallodielectric nanostructures is associated with intriguing optical properties like negative refraction [1] and extraordinary transmission though subwavelength hole arrays [2]. Moreover, the localization and enhancement of the electromagnetic field at the plasmon resonances offers possibilities for practical applications in chemical and biological sensors of increased sensitivity.

There are several studies which focus on the properties of the plasmon excitation of single metallic nanoparticles, with a variety of shapes like spheres, prisms, nanorings, nanostars, nanoshells, etc., where the plasmon frequency is mainly determined by the particle shape and size. The study of the interaction of surface plasmons in complex metal-dielectric environments is also of considerable importance since a physical understanding can lead to the design of novel structures with exciting optical properties. For example, plasmon interaction can be controlled in periodic arrays of metallic nanoparticles [3].

Recently, composite nanoparticles consisting of a dielectric disk sandwiched between two metallic disks were fabricated using modern lithographic techniques and attracted considerable attention. Typically, the metallic disks have a diameter of the order of 100 nm and a thickness of a few tens of nm, and the dielectric spacer has similar dimensions. Interesting hybridization phenomena were demonstrated on such isolated nanosandwiches [4, 5]. In this work we report on a theoretical study of two-dimensional (2D) arrays of Au/SiO_2/Au nanosandwiches and study the influence of the thickness of the dielectric spacer and of the lattice constant of the structure. Our aim is to provide, by means of full electrodynamic calculations, quantitative description of the hybridization between particle plasmons of the metallic nanodisks in the individual nanosandwiches and, also, between neighboring nanosandwiches as they approach close to each other in a 2D lattice. The latter effect was not investigated up to now and is important towards the design of novel metamaterial structures.

2 Theoretical method In this work, we shall be concerned with 2D periodic arrays of Au/SiO_2/Au nanosandwiches in air. We calculated the extinction spectra of such structures using a layer-multiple-scattering method, which was originally developed for systems of spherical scatterers (see, e.g., Ref. [6] and references therein) and recently extended to non-spherical shapes [7]. The method employs a full multipole expansion of the wavefield to take into account all multiple-scattering processes in a 2D periodic array of particles and, subsequently, deduces the scattering matrices of this layer in a plane-wave representation. A periodic array of nanosandwiches is built from consecutive layers of appropriate nanodisks, through the proper combi-

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nation of the scattering matrices of the component layers. The details of the method can be found elsewhere [7]. Here, we restrict ourselves to note that, metallic particles in close proximity to each other cause slow convergence of the method. This becomes even more pronounced in the case of particles with sharp edges and/or large deviations from the spherical shape, such as those considered in the present work. In order to ensure adequate convergence in our calculations, we truncated the spherical-wave expansions at l_{max}=13 and took into account 137 2D reciprocal-lattice vectors in the relevant plane-wave expansions, while the scattering T matrix of the single nanodisk was calculated with l_{cut}=16 and a Gaussian quadrature integration formula with 4000 points [7]. In the numerical calculations we used the experimental dielectric function of Au [8] and a permittivity of 2.1 for SiO_2.

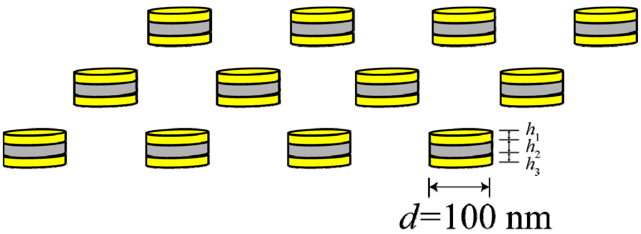

Figure 1 A 2D square array of metal/dielectric/metal nanosandwiches. Light is incident normal to the plane of particles.

3 Results and discussion The structure studied in this work is schematically shown in Fig. 1. We consider $Au/SiO_2/Au$ nanosandwiches of diameter 100 nm and typical thickness h_1=20 nm Au, h_2=20 nm SiO_2 and h_3=20 nm Au. The nanosandwiches are arranged on a square lattice with lattice constant 300 nm. Such large interparticle separations essentially correspond to isolated particles as we discuss below. In order to study the hybridization between the particle plasmons of the two metallic nanodisks, we keep their thickness fixed (h_1=h_3=20 nm) and vary the thickness of the dielectric spacer, h_2. Corresponding extinction spectra at normal incidence are depicted in the lower panel of Fig. 2. It can be seen that, for very thin dielectric spacers, we obtain a single peak, which is essentially the single particle plasmon resonance in the corresponding array of simple Au disks 40 nm-thick (see upper panel of Fig. 2). On the other hand, when the separation between Au disks in the nanosandwich is large enough and consequently their interaction is small, the spectra are close to that of the corresponding array of simple Au disks 20 nm-thick. For intermediate thickness of the dielectric spacer the spectra exhibit two distinct peaks. The high-frequency (short-wavelength) peak is stronger and broader, and shifts to the red with increasing thickness of the dielectric spacer. The low-frequency (long-wavelength) peak is smaller and shifts to the blue as the thickness of the spacer increases, until it merges with the high-frequency peak for h_2=90 nm. These results can be understood as follows. The optical response of the single Au nanodisk is dominated by a particle plasmon resonance which is predominantly of dipole electric type. The interaction between these modes of the constituent Au nanodisks in the nanosandwich results into a symmetric high-frequency hybrid mode (the electric field oscillates in phase in the two Au nanodisks normal to their axis) and an antisymmetric low-frequency hybrid mode (the electric field oscillates with opposite phase in the two Au nanodisks normal to their axis). The double-peak structure in the calculated extinction spectra results from the excitation of theses modes. Interestingly, when the separation between Au disks is small (<10 nm) the low-frequency peak is not observed. For relatively thick dielectric spacers, the high-frequency peak becomes broader, in agreement with the corresponding results for an array of simple Au disks 20 nm-thick. Our results are in good agreement with existing experimental data on isolated nanosandwiches [4, 5].

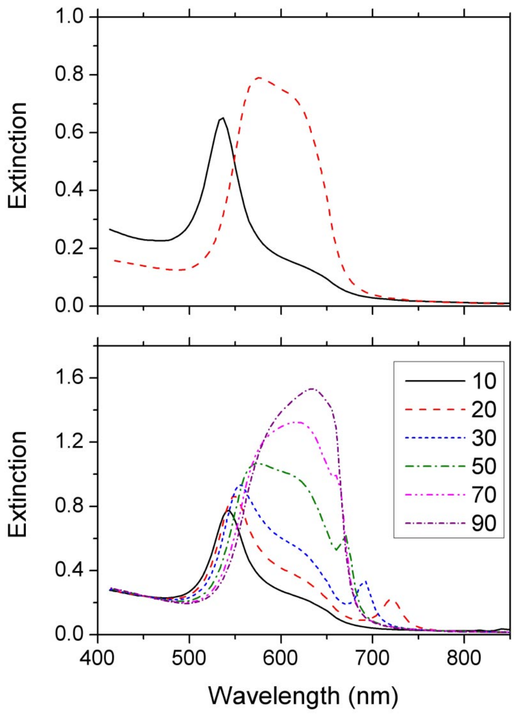

Figure 2 Upper panel: Extinction at normal incidence of a periodic plane of Au disks of diameter 100 nm, and thickness 40 nm (solid line) and 20 nm (dashed line). The disks are arranged on a square lattice with lattice constant 300 nm in air. Lower panel: Extinction at normal incidence of square arrays, with lattice constant 300 nm, of $Au/SiO_2/Au$ nanosandwiches with diameter 100 nm. The Au disks have a thickness of 20 nm and the different spectra correspond to thickness of the SiO_2 spacer varying from 10 to 90 nm.

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Previous work on the subject was restricted to isolated nanosandwiches [4, 5]. Here we investigate, in addition, the interaction between nanosandwiches as we reduce the lattice constant of the square lattice. The extinction spectra of square arrays of 20 nm Au/20 nm SiO_2/20 nm Au nanosandwiches with diameter 100 nm, for different lattice constants, in air are shown in Fig. 3. It can be seen that the symmetric high-frequency resonance remains practically unaffected by the change in the lattice constant. The increase of the interaction between nanosandwiches has an influence on the antisymmetric resonance, which shows a significant redshift for lattice constants smaller than 250 nm. From these results it is clear that, for lattice constants larger than 250 nm, the optical properties of the 2D nanosandanwich arrays are due to the single nanosandanwiches with no significant interaction between them, at least at normal incidence.

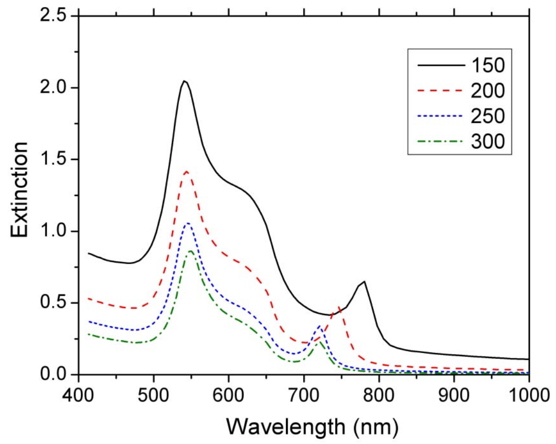

Figure 3 Extinction at normal incidence of square arrays of 20 nm Au/20 nm SiO_2/20 nm Au nanosandwiches with diameter 100 nm in air. The different spectra correspond to lattice constants varying from 150 to 300 nm.

4 Conclusion In summary, we have studied the optical properties of 2D periodic arrays of metal/dielectric/metal nanosandwiches by means of full electrodynamic calculations using the extended layer-multiple-scattering method. Our results show that plasmon hybridization leads to a double-peak structure in corresponding extinction spectra, with a symmetric and an antisymmetric resonance. The latter is more sensitive to the interaction between nanosandwiches. Our results corroborate that such structures, with a tailored optical response, can be useful in the way of practical applications, e.g., as chemical and biological sensors. Moreover, because of the presence of an antisymmetric resonance, metallodielectric nanosandwiches can be potential candidates as building units in the design of novel negative-index metamaterials.

Acknowledgments This work was supported by NCSR “Demokritos” under “Demoerevna” E-1437 and by the research program “Kapodistrias” of the University of Athens.

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