Current Applied Physics 15 (2015) 844–849

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

Magnetic resonance absorption in isolated metal/insulator/metal nanodot arrays with transmission geometry

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ARTICLE INFO

Article history:
Received 17 February 2015
Accepted 6 April 2015
Available online 13 April 2015

Keywords:
Metal/insulator/metal structure
Magnetic absorption
Magnetic permeability
Magnetic resonance
Nanodot arrays

ABSTRACT

In this study, we have systematically investigated a magnetic resonance absorption and tunability of absorption wavelength in isolated metal-insulator-metal (MIM) nanodot arrays with transmission geometry. The elemental electromagnetic resonances and their hybridizations are studied using 3-dimensional finite-difference time-domain (FDTD) calculation and resonance properties including the resonance peak tunability, magnetic permeability and quality (Q) factor are characterized with respect to the coupling strength. We have found the existence of electric and magnetic resonance mode in the MIM ($Au/MgF_2/Au$) structure and the magnetic resonance has larger wavelength tunability than the electric resonance. The absorption cross section calculation revealed that absorption is the dominant extinction process at the magnetic resonance only. Magnetic permeability (μ) calculations for the various MIM parameters showed the maximum value of the imaginary part of μ is 16.1 with Q factor of 9.2 when the size of nanodot is 200 nm and the inter-dot distance is 300 nm. The presented calculations can be used to tune the response of the magnetic resonance absorption with a variable resonance wavelength and Q factor by using the simple MIM structures with transmission geometry.

1. Introduction

Microwave absorption capability of magnetic materials which exploits ferromagnetic resonance (FMR) phenomena is widely utilized in various high frequency wireless communication devices [1,2]. Generally, a high magnetic permeability (μ_r) and a high FMR frequency (f_r) is required for these magnetic materials in order to develop the high-performance miniaturized devices. However there is a trade-off between μ_r and f_r due to the Snoek's limit and the maximum applicable frequency is limited by f_r which usually ranges from 1 GHz to 100 GHz for naturally occurring magnetic materials [3–6]. Nowadays, artificially structured materials that exhibit magnetic properties have received much attention since their resonant frequency can be extended to THz and optical range, which are not available in naturally occurring materials, with the development of advanced fabrication techniques [7–11]. In these materials, the manipulation of magnetic permeability is one of the key factors for the study of the exotic electromagnetic properties including the negative refractive index. The artificially structured materials also have been received much attention in the spectroscopy applications due to their unusual optical absorption characteristics such as perfect absorption and dominant magnetic absorption [12,13].

Among the various artificial structures, metal-insulator-metal (MIM) structures has attracted considerable attention due to their unique optical properties including the polarization and angle independent resonant absorption [14]. In general, the MIM structure consists of a dielectric layer sandwiched between a metal nanopattern and a continuous metal layer. Even though the continuous metal layer based MIM structure is simple and easy to fabricate lithographically, only specific modes are excited in the structure due to the parity of image interaction and also transmission measurement is not possible because of the presence of the metal film [15,16]. However recent progress in nanolithography allows fabricating large area stratified isolated nanodot arrays with a minimum feature size below 100 nm [7]. In this study, we have investigated the isolated MIM nanodot array with transmission geometry and

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http://dx.doi.org/10.1016/j.cap.2015.04.007
1567-1739/

their optical range magnetic resonance absorption characteristics. Geometric and structural dependence of resonance properties including the plasmon hybridization, resonance wavelength, magnetic permeability and quality (Q) factor were systematically investigated to elucidate the magnetic resonance absorption phenomena in nano-sized MIM structures using finite-difference time-domain (FDTD) calculation.

2. Simulation setup

Fig. 1 shows the schematic illustration for the unit cell of the calculation structure composed of MIM (Au/MgF_2/Au) multilayered nanodot array on glass substrate. The dimensions of unit cell (periodicity) along the *x* and *y* directions are s_x and s_y, the diameter of the nanodot is *d*, the thickness of metal layer and dielectric layer is T_g, T_d respectively. FDTD Maxwell's equation solver is used to calculate the electromagnetic properties of the structure. In this simulation, the periodic boundary conditions are applied along the *x, y* directions and perfectly matched layer (PML) boundary condition along the *z* direction was used. The nanodot arrays are illuminated with a linearly polarized plane wave, which propagates in the $k = -z$ direction. The Drude model is used to describe the complex permittivity of Au layer:

$$\varepsilon(w) = 1 - \frac{w_p^2}{w(w + iw_c)}$$

where w_p is the plasma frequency ($2\pi \times 2.175 \times 10^{15}$ s^{-1}) and w_c ($2\pi \times 6.5 \times 10^{12}$ s^{-1}) is the collision frequency [17]. The index of the glass substrate is taken as 1.5 and MgF_2 insulating layer as 1.38 [16].

3. Results and discussion

Fig. 2 demonstrates that calculated *S* parameters as well as retrieved effective permittivity ε' and permeability μ' for the structure of $d = 200$ nm, $s_x = s_y = 500$ nm, $T_d = T_g = 40$ nm circular nanodot array. The effective constitutive parameters of the MIM structures are retrieved by using the previously reported *S* parameter method [18–20]. The corresponding results of effective ε', μ' calculated from Fig. 2a are plotted in Fig. 2b, c. The retrieved results are clearly indicate the electric and magnetic mode excitation at $p_1 = 740$ nm and $p_2 = 858$ nm. The electric and magnetic resonance is related to the plasmon coupling of the top and bottom metallic layers [15,21–23]. The two adjacent metallic layers in the Au/MgF_2/Au nanodots are coupled and it results in the formation of two plasmon modes: the symmetric plasmon mode and the antisymmetric plasmon mode [24]. Fig. 3 shows the electric field (***E***) and magnetic field (***H***) distribution in the metallic and dielectric layers at each resonance frequencies in metal and dielectric layers. The symmetric ($p_1 = 740$ nm) and antisymmetric ($p_2 = 858$ nm) alignments of electric field can be identified in top and bottom metallic layers as shown in Fig. 3a, b. The in phase and out of phase charge oscillations inside the two Au layers at p_1 and p_2 suggesting a symmetric and antisymmetric plasmon mode referred to as an electric and magnetic resonance, respectively. For the magnetic resonance, it is noteworthy that the circular current loop formed in between the top and bottom Au layers creates the strong induced magnetic moment in the dielectric spacer layer. The magnetic field distribution in the dielectric layer for the magnetic resonance shown in Fig. 3b clearly suggests the induced magnetic field in -*y* direction.

In order to elucidate the resonance absorption of the nanodot array, the absorption cross section and the extinction of the nanodot arrays are calculated. Fig. 4 shows the calculated absorption cross section and extinction for the structure given in Fig. 1. Two clear extinction peaks at the resonance wavelengths (p_1, p_2) can be observed in Fig. 4a. However the absorption cross section spectrum as shown in Fig. 4b indicates that absorption is the dominant extinction process at the magnetic resonance wavelength p_2 only [12,13]. To verify the magnetic resonance absorption, the electric field intensity distributions for the nanodot arrays at p_1 and p_2 are plotted in Fig. 4c, d. Compared to Fig. 4c, the localized nature of the electric field energy can be found in Fig. 4d, which implies that the absorption is the dominant process for the magnetic resonance mode at p_2.

In the MIM structure, the dielectric spacer layer plays decisive role to the resonance absorption between the top and bottom metal layers. To investigate the effect of dielectric thickness on the magnetic resonance absorption, we varied the dielectric layer

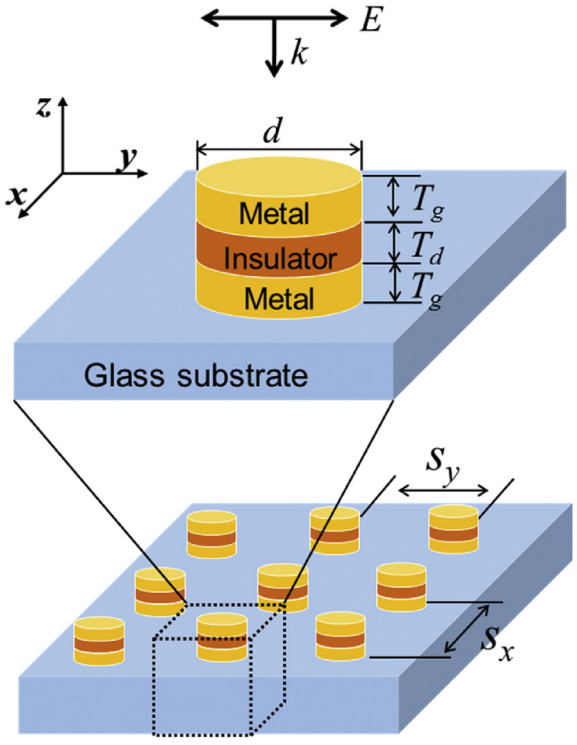

Fig. 1. Schematic illustration of the MIM nanodot array and enlarged view of a single unit cell used for the simulation of the MIM structures.

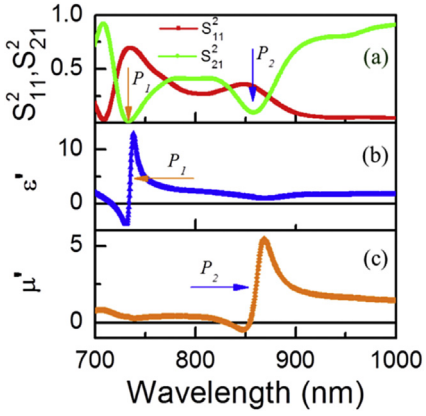

Fig. 2. (a) Reflectance and transmittance spectra, (b) the retrieved effective electric permittivity (ε') and (c) magnetic permeability (μ') for the simulated structure of $d = 200$ nm, $s_x = s_y = 500$ nm, $T_d = T_g = 40$ nm circular nanodot array.