Polarization – Selective Optical Darkness in Metamaterials built from Nano-Bismuth

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Abstract- We extend the concept of polarization – selective optical darkness to metamaterials based on bismuth nanostructures (nano-Bi). It will be shown that in nano-Bi based metamaterials, this phenomenon can be achieved due to the near UV – visible polaritonic resonances permitted by the near IR interband transitions of Bi.

1. Introduction. Polarization - selective optical darkness has been evidenced recently in metamaterials based on noble metal (Ag and Au) nanostructures and linked to their plasmonic resonances. It has been demonstrated that the parallel-polarized reflectance R_p of the metamaterial cancels for specific values of the photon energy and angle of incidence [1,2]. This has an important effect in ellipsometry measurements, since upon cancelation of R_p, the intensity – related ellipsometric angle (Ψ) also cancels and an abrupt jump is observed for the phase – related ellipsometric angle (Δ) in the photon energy space. The Δ value in the vicinity of the jump varies strongly upon very small changes in the plasmonic response of the metal nanostructures, such as those induced by the presence, in their local environment, of molecules or gases. It has been shown that optical sensing schemes based on the measurement of phase signal variations in the metamaterials response can greatly profit from this phenomenon [1,3]. Indeed, enhanced accuracy and lower detection thresholds have been reported compared to conventional detection schemes (transmittance or reflectance measurement of environment-induced plasmon resonance shifts). Although reported so far in metamaterials based on noble metal nanostructures, polarization – selective optical darkness is a general phenomenon that can be found for a broad range of metamaterials provided their effective properties fulfil minimum specific constraints [1]. Therefore, the correlation of polarization - selective optical darkness with spectral resonances has no reason to be restricted to plasmon resonances in noble metals. Plasmonic effects have been reported also for transition metals, alkaline metals, and doped semi-conductors among others [4]. Furthermore, plasmonic-like resonances have been evidenced in the case of nano-Bi [5]. In this work we show how the observed resonances in nano-Bi can be exploited to design metamaterial structures that evidence polarization - selective optical darkness.

2. Results and discussion. Figure 1 shows the typical effective dielectric function of a medium consisting of nano-bismuth embedded in a dielectric matrix (amorphous aluminium oxide, a-Al_2O_3), showing a resonance centered at a photon energy E ~ 3.6 eV. This plasmonic – like resonance has a polaritonic origin due to the near IR interband transitions of Bi [6]. The dielectric function of the matrix is also shown for reference. Figure 2a and 2b show the corresponding spectra of the ellipsometric angles Ψ and Δ of a thin film (100 nm thick) with the previous effective dielectric function on a silicon substrate, at the angle of incidence of 70.1º. The ellipsometric spectra of a pure dielectric a-Al_2O_3 film with the same thickness are also shown. The dielectric film shows smooth spectra. In contrast, for the nanocomposite film, the excitation of the Bi-related polaritonic resonance drastically alters the Ψ and Δ spectra in the near UV and visible spectral regions. This alteration induces the cancelation of Ψ at the photon energy E ~ 3.6 eV, and a large correlated jump in the Δ values of about 175º. As seen in figure 2c, these effects are indeed linked with the cancelation of R_p at E ~ 3.6 eV while R_s remains high.

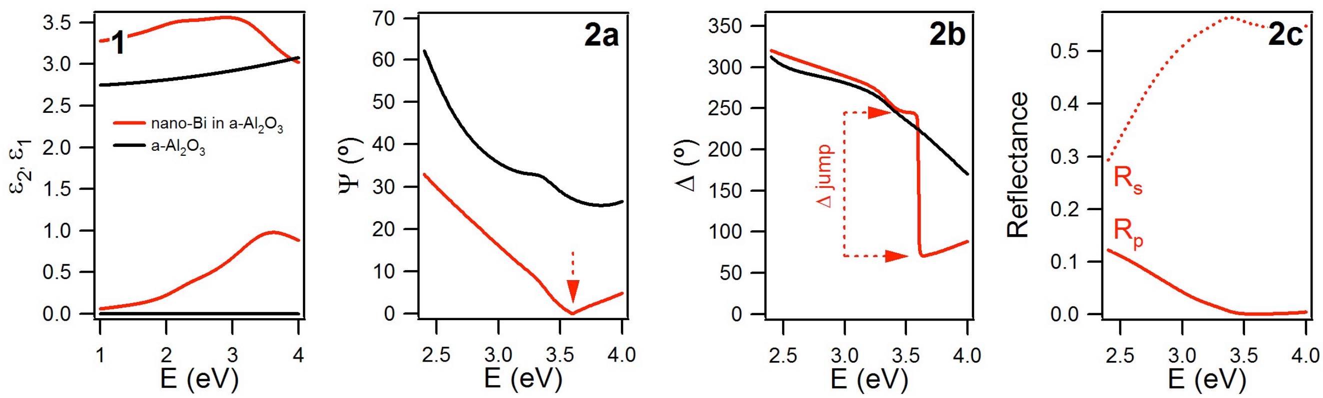

Figure 1: Red lines: Real and imaginary part (ε_1 and ε_2) of the Maxwell-Garnett effective dielectric function of a medium consisting of spherical Bi nanoparticles (volume fraction 6%) embedded in an a-Al_2O_3 matrix. Black lines: Dielectric function of the a-Al_2O_3 matrix. **Figure 2:** Spectra of the ellipsometric angles Ψ (2a), Δ (2b) at an angle of incidence of 70.1º for a 100 nm thin film on a silicon substrate. Red lines: nano-Bi based film; Black lines: a-Al_2O_3 film. The corresponding dielectric functions are those shown in figure 1. (c) R_p and R_s reflectance spectra at 70.1º of the nano-Bi based thin film on a silicon substrate.

3. Conclusion. The concept of polarization – selective optical darkness, reported so far in plasmonic metamaterials, can be extended to non-plasmonic media, such as metamaterials based on nano-Bi. We model the response of a nano-Bi based metamaterial layer that shows a jump in the Δ value as large as 175º. This opens the way to the design of metamaterials based on building blocks with specific spectral response that can provide a strong environmental sensitivity based on optical phase measurements.

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