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Ultrathin broadband antireflection structure composed of multilayer hollow nanopillar arrays of c-Si and Ag shells embedded in a GaAs substrate

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ABSTRACT

In this study, we investigated the spectral response and properties of compositional multilayer hollow nanopillars in the certain arrays that are embedded in a GaAs substrate to design a broadband antireflection subwavelength structure. Considering the arrays of multilayer hollow nanopillars (crystalline-Si/Ag/air) with the appropriate geometrical sizes, three kinds of optical modes at the absorption profile in the wide range of the spectrum are reported. Fabry–Perot (FP), hybrid, and plasmon resonance modes are the three appeared optical modes at the calculated absorption cross-sectional profile using numerical method. Quantifying the reflectance of the subwavelength structure, this parameter is measured as approximately 6.69% in the range of $\lambda \sim 400$–2900 nm. We proved that proposed nanostructure is able to provide high ratio of optical energy absorption due to the existence of GaAs, c-Si and Ag substances that play fundamental role in this enhancement as the absorber materials.

1. Introduction

Broadband antireflective nanostructures in various structural and compositional orientations have extensively been studied numerically and experimentally in designing solar cells and associated photovoltaic (PV) devices in nanoscale [1,2]. It is well accepted that these subwavelength structures have strong potentials to be employed in designing enhanced PV devices, light sensors, and transparent glasses [2,3]. Recently, numerous techniques have been proposed and applied to design antireflective nanostructures with high efficiencies and lower reflectance ratio based on optical materials and components [2–4]. For instance, several shapes of nanoparticles (NPs) such as nanopyramids, nanotips, nanopillars, nanocones, and nanorods in grating orientations are some of the particles that have been used widely in fabricating antireflective structures. From the technical point of view, it is shown that to suppress the "Fresnel reflection" at the air–material interface, a tapered configuration can be employed as subwavelength structure [4,5]. To improve the light absorption coefficient and enhance the broadband antireflection property, the effect of structural and chemical parameters must be considered and applied in numerical computations and fabrication processes. For example, NPs with taller heights and in compact forms are desirable structures in designing PV structures. It is strongly verified that NPs with the height of near or beyond 1 μm and in certain arrays provide remarkable absorption of optical energy in the wide range of spectrum (e.g. nanotips) [6]. In contrast, fabricating of compact gratings with larger heights is highly difficult and needs for complex laboratory processes. Therefore, there is a strong desire to reduce the height of employed NPs while the optical energy absorption ratio remains constant or becomes higher. Recently, parabola and truncate nanocones in pure and multilayer structural conditions have been investigated and applied to realize this goal [4,7]. On the other hand, utilizing noble metal NPs that are oriented in arrays, the light–matter interaction has been characterized by plasmonic notion of optical physics [8–10]. It is shown that this opportunity yields promising ways toward the enhancements in the quality of the PV structures. As we mentioned earlier, numerous shapes of NPs with noble metallic substances (e.g. Ag) can be utilized to enhance the optical absorption. Introducing noble metallic NPs arrays with diverse structural properties, a great localization in excited surface plasmon resonances can be formed between these proximal particles. Appearing of more optical modes such as plasmon resonance modes along the absorption spectral response can help to enhance the broadband absorption property of the examined subwavelength structure [7,11].

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In this study, we use compositional multilayer hollow nanopillar arrays rather than tall NPs to design efficient broadband antireflective structure. We show that multilayer nanopillar arrays composed of crystalline-silicon (c-Si) and Ag shell-like layers inside the GaAs layer as a substrate yield strong absorption of optical energy at the nanoscale from visible to the mid infrared spectrum. Characterizing the optical features of the proposed subwavelength structure, c-Si is considered as an active substance in PV applications, and also, has a weak absorption property at the same time. In addition, Ag is the strong light absorber with low ohmic loss [12]. We proved that employing recommended nanopillars array, we would be able to afford the associate problems with the tall NPs fabrication, while the performance of the structure is improved. Herein, we try to design a structure with noticeable absorption enhancement coefficient which is near to Yablonovitch limit ($4n^2$ limit) [13,14].

2. Results and discussion

Multilayer NPs composed of plasmonic noble metals and dielectric materials have extensively been employed in designing PV structures and devices [7,15]. On the other hand, nanopillars in various formations and sizes have been employed in these purposes as well [16,17]. Herein, we employed and combined two different absorption mechanisms of incident light by a semiconductor material (c-Si) and a plasmonic substance (Ag) to design a novel nanostructure based on hollow nanopillars that has a strong potential to employ in fabrication of PV devices. The influence of the refractive index of utilized substances has extensively been described and analyzed in various publications [12,18]. It is proved that the imaginary part of the refractive index plays fundamental role in determining the absorption coefficient of a substance. To evaluate the potential absorption quality of the employed substances in spite of their formations and orientations, we plotted the real and imaginary parts of the refractive index over the wavelength variations from $\lambda \sim 250$–3000 nm. Fig. 1(a) and (b) illustrates these variations for Ag (with Johnson–Christy constants) and c-Si substances separately. According to the imaginary part of the refractive index (n), Ag with Johnson–Christy constants shows a dramatic absorption at the considered bandwidths and this coefficient is higher at longer spectrum which has a significant impact in enhancing the absorption ratio of the incident light. On the other hand, c-Si as a weak absorber shows a low absorption ratio at longer wavelengths and actually acts as an active material [19]. From the technical point of view, considering the c-Si shell layer in the hollow nanopillar structure, when the plasmon resonance modes excited at the interface of the metal (Ag) and semiconductor (c-Si) shells, the incident electromagnetic (EM) field is confined and localized strongly (localization of surface plasmon resonance modes), and as a result, the resonance modes decayed away from the declared interface. Therefore, considered thickness for the semiconductor shell layer is suitable to support strong plasmon resonance modes excitations which causes to enhancement in the absorption of EM fields inside the investigated compositional hollow nanopillar. Fig. 1(c) illustrates a three-dimensional schematic art of the proposed antireflective structure composed of c-Si/Ag shell/air configurations as hollow nanopillar arrays that are embedded in a GaAs substrate with a certain thickness (h_s). Fig. 1(d) is the cross-sectional outlook of the structure, which shows the quality of hollow nanopillars orientation inside the host material and the height of the nanopillars is indicated by h_p. Fig. 1(e) exhibits the structural characteristics of the utilized hollow compositional nanopillars by a top view. Probing for the appropriate geometrical sizes for the proposed hollow nanopillar, we utilized finite-difference time-domain (FDTD) method as numerical model to extract the optical properties of the proposed nanostructure.

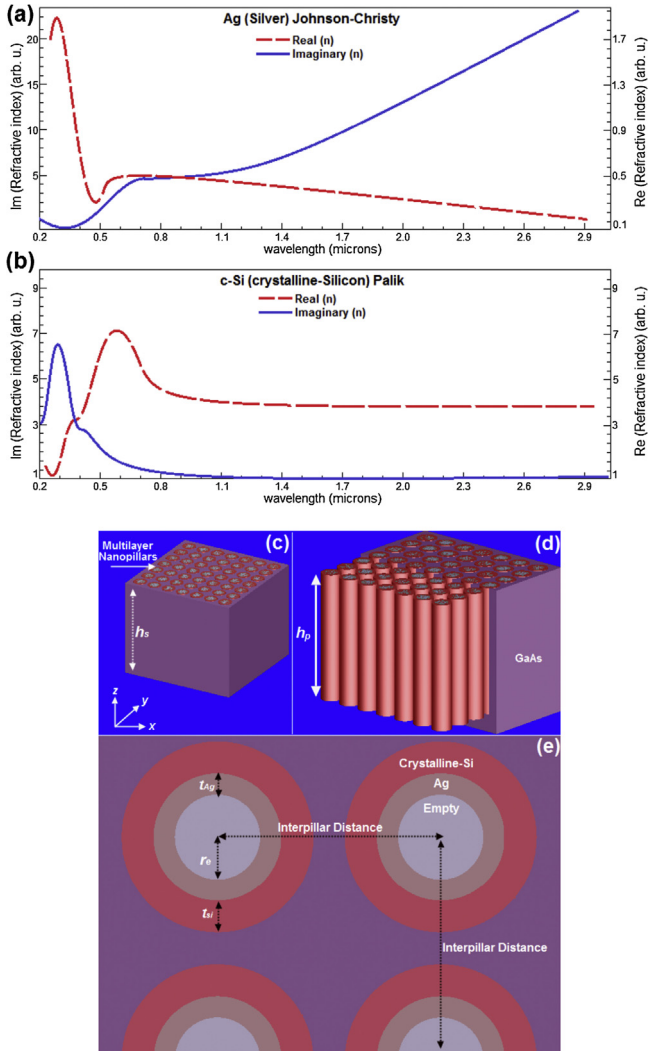

Fig. 1. (a) A three-dimensional schematic diagram of the proposed antireflective structure composed of multilayer hollow nanopillars with the total height of h_s, (b) a cross-sectional view of the arrayed multilayer hollow nanopillars with the height of h_p inside the GaAs substrates, (c) a top view of the multilayer nanopillar composed of c-Si/Ag shells/air with the thicknesses of t_{si} and t_{Ag}, respectively. The radius of the empty space inside the hole or empty space is r_e.

To do this, we considered an isolated hollow nanopillar inside an infinite GaAs host substance. Calculating the absorption cross-sectional diagram for an infinite hollow nanopillar, we determined the appropriate geometrical sizes for the compositional multilayer structure by repeating numbers of simulation steps. As a result, we measured the pillar parameters as following: the total radius of the nanopillar component is $r_t = 50$ nm, the thickness of the c-Si layer is $t_{si} = 20$ nm (to support surface plasmon resonance excitation >10 nm) [7,20], the thickness of the Ag layer is $t_{Ag} = 12$ nm, and the radius of the empty space is $r_e = 18$ nm. All of the nanopillars are oriented in straight chains with an 115 nm interpillar distances. Finally, to determine the height and thickness of the antireflective subwavelength structure, we considered the effect of height of the pillars and structure individually. Thus, the thickness or height of the GaAs substrate is $h_s = 975$ nm and the height of the multilayer pillars is $h_h = 850$ nm. Calculated structural sizes for the structure have been obtained numerically based on FDTD method. Table 1 includes the FDTD parameters and setting regarding to the numerical simulations of the examined nanostructure. Fig. 2 and its subsequent diagrams depict the absorption cross-sectional profile that has been drawn numerically. The absorption spectra