Perfect Absorber at Visible Frequencies Using TiN-based Refractory Plasmonic Metamaterials

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Abstract

Refractory titanium nitride (TiN) was proposed as unit component for metamaterial perfect absorber in visible frequencies. Combining both the intrinsic loss of the TiN material in short wavelength (<500 nm) and the plasmonic resonance absorption in long wavelength (>500 nm), the metamaterial perfect absorber based TiN can be a broadband perfect absorber in whole visible region. The structure is directly applicable to all kinds of opaque substrates without metallic bottom.

I. INTRODUCTION

Metamaterial perfect absorber (MPA) at visible frequencies can be used to manipulate the propagation of light and tailor the visible spectrum purposefully and selectively, it has extensive application prospects in new energy, sensor, spectrum detection, stray light prevention, photonic device and nanolocalized photo-thermal manipulation, et al [1], which makes it a research hotspot in recent years.

Traditionally, MPA at visible frequencies consists of a metal-insulator-nanostructured metal (MIM) made of noble metals such as Au, Ag and Cu. However, their absorbance is limited to a narrow spectral range due to the resonant nature of the plasmon excitation [2]. It must elaborately construct complex nanostructured unit cell to obtain broadband absorption [3]. Moreover, MPA based on noble metals suffers from severe problem of low melting points, which is not suitable for applications in high temperature environments such as solar thermophotovoltaics (STPV), solar thermoelectric generators (STEG) and nanoscale heat transfer systems [4,5]. Besides, most of the reported MPAs need optically thick metallic light blocking layers on the bottom, which might lead to weak adhesive ability when fabricated on insulated surface.

The large free carrier concentrations ($10^{22}\,cm^{-3}$) of TiN make it exhibit metallic properties and a plasmonic material comparable to Au in the visible-NIR range. It's melting point is about 3000 ℃ and has good high-temperature durability [6]. Conductivity and permittivity of TiN only marginally change with temperature. Here, we employ titanium nitride (TiN) as alternative plasmonic material for MPA at visible wavelengths, a novel MPA structure based on TiN is designed and studied by numerical simulation. The influence of the structure parameters on absorption spectrum and electromagnetic field is analyzed.

II. SIMULATION MODELS AND DEVICE STRUCTURE

In this paper, a MPA structure different from the conventional MIM sandwiched structure is proposedas shown in figure 1. The substrate can be any opaque materials in visible region, including various semiconductor and metal. On the substrate is a periodic array of TiN nanoellipsoid which is embedded in AlN dielectric matrix. The height (long axis) of the nanoellipsoid is *H*, the minor axis of the nanoellipsoid is *R*, and the gap between two adjacent nanoellipsoids is Δd. The thickness of AlN dielectric matrix is the same as the height of the nanoellipsoid. A TiO_2 and SiO_2 layer with thickness of 20 nm and 80 nm is located on the top of the MPA structure, as impedance matching layers.

In our simulation, 3D finite-difference time-domain (FDTD) method is employed. Periodic boundary conditions imposed on x and y axis and finite structure are used on z axis. Perfect matched layers are imposed at the top and bottom surfaces. To ensure the accuracy the grid size is carefully chosen. The reflection spectra, transmission spectra and electromagnetic field distribution are calculated to analyze the absorption characteristics and mechanism of the structure.

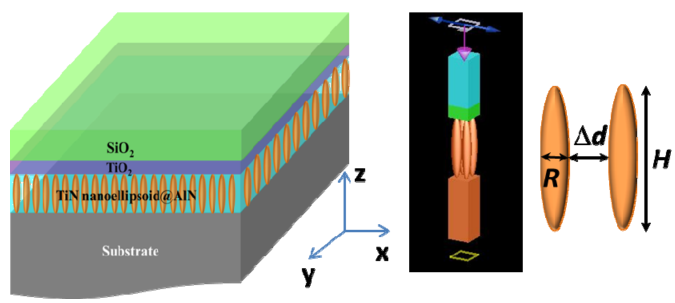

Figure 1 (Color online) Schematic diagram of the MPA structure based on TiN.

III. RESULT AND DISCUSSION

In order to obtain the optimum structure of MPA at visible wavelengths, the influence of the structure parameters on absorption spectrum is firstly studied. A 200 nm TiN layer is employed on the bottom as substrate, and the initialization parameters of the structure is set as Δd=6 nm, *R*=10 nm, *H*=100 nm. Then controlling variables method is used to study the influence of the structure parameters on absorption spectrum from 300 nm to 1000 nm as shown in figure 2. The results show that the simulated absorption of MPA based on TiN spans abroad range of frequencies from ultraviolet to the near-infrared. Near unity absorbance is achieved in whole visible wavelength band from 400 nm to750 nm. Figure 2(a)

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shows that the absorbance in visible region increases with the gap Δd between the TiN nanoellipsoid, while the absorbance in NIR region decreases. Figure 2(b) shows that the absorption bandwidth increases with the minor axis of the nanoellipsoid *R*. Both the Δd and *R* have almost no influence on the absorbance in ultraviolet region (300-400 nm). Figure 2(c) shows that the absorbance in visible region increases firstly and then decreases with the height (long axis) of the nanoellipsoid (*H*), and the maximum absorbance can be obtained when H=100 nm.

After getting the optimal parameter, we calculate the absorption spectra of the optimum structure on different substrates, including Ag, Si, Ge and GaAs, as shown in figure 2(d). The optimum MPA structure shows more that 90% absorbance in whole visible region on all of the substrates, which demonstrates that our MPA based TiN is applicable to various opaque substrates. It can be found that the absorption spectra are almost the same for Si, Ge and GaAs substrates. It shows almost unity absorbance in visible region for TiN and Ag substrates. However, the absorbance in ultraviolet region is much higher for TiN substrate since the intrinsic loss of the TiN material in short wavelength (<500 nm).

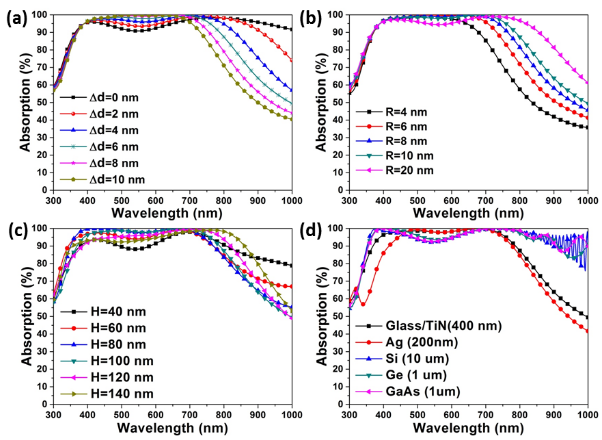

Figure 2 (Color online) The influence of the structure parameters on absorption spectrum of MPA.

To further understand the broadband absorption mechanism of TiN based MPA, the electromagnetic field distribution in the structure is calculated at wavelengths of 400 nm, 500 nm, 600 nm, 700nm and 800 nm. The figure 3(a) and 3(b) show the electric field intensity distribution in the xOy and xOz plane. The electric field is localized near the surface of the TiN nanoellipsoid and incident light is trapped in the gap between the TiN nanoellipsoid at wavelengths of 600 nm, 700nm and 800 nm. The location of the localized field moves to the middle of the nanoellipsoid from the top with the increase of wavelength. These field localizations indicate that localized surface plasmon resonances (LSPR) are excited at these frequencies. The amplitude of the electric field is enhanced many times so that the loss caused by localized surface plasmon resonances lead to high absorption at long wavelengths. What's more, the electric field enters into the TiN nanoellipsoid at wavelengths of 400 nm and 500 nm, because TiN behaves like a lossy dielectric at short wavelength due to an interband transition and large imaginary part of the permittivity [7].

From the analyses of electromagnetic field distribution, it can be concluded that different absorption mechanism at short and long wavelengths lead to a broadband absorption for the TiN based MPA.

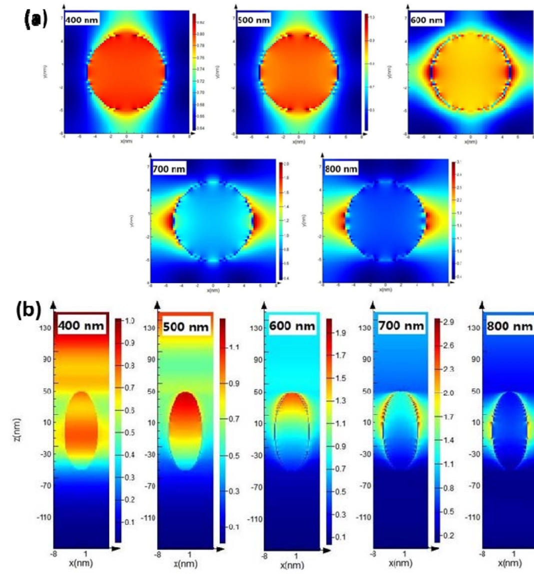

Figure 3 (Color online) The electromagnetic field distribution in the MPA structure at different wavelength along xOy and xOz plane.

IV. Conclusion

In this paper, perfect absorber at visible frequencies was designed and demonstrated using TiN-based refractory plasmonic metamaterial. It showed near unity absorptance in the whole visible region (400 nm-750 nm) due to the intrinsic loss in short wavelength and the plasmonic resonance absorption in long wavelength. The structure was directly applicable to all kinds of opaque substrates without metallic bottom, which is a perfect candidate for the applications in new energy, stray light prevention, photonic device and nanolocalized photo-thermal manipulation.

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