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Ultra-broadband and wide-angle perfect absorber based on composite metal–semiconductor grating

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ABSTRACT

In this letter, we present an ultra-broadband and wide-angle perfect absorber based on composite Ge–Ni grating. Near perfect absorption above 90% is achieved in a wide frequency range from 150 nm to 4200 nm, which covers almost the full spectrum of solar radiation. The absorption keeps robust in a wide range of incident angle from 0° to 60°. The upper triangle Ge grating works as an antireflection coating. The lower Ni grating works as a reflector and an effective energy trapper. The guided modes inside Ge grating are excited due to reflection of the lower Ni grating surface. In longer wavelength band, gap surface plasmons (GSPs) in the Ni grating are excited and couple with the guided modes inside the Ge grating. The coupled modes extend the perfect absorption band to the near-infrared region (150 nm–4200 nm). This design has potential application in photovoltaic devices and thermal emitters.

1. Introduction

In energy harvesting field, it has attracted great interest to realize broadband and angle-insensitive perfect absorbers, which can effectively enhance the conversion efficiency of energy [1–5]. Many methods have been proposed to realize near-perfect absorption including antireflection coating [6], photonic crystals [7], multilayer nanowires [8], metamaterials [9], nanoparticles [10,11] and metal–dielectric slab gratings [12,13]. However, these efforts are limited by their narrow working bandwidth. In order to broaden the absorption band, researchers have combined resonators of different sizes in a unit cell and obtained multi-peaks or broadband absorption [14,15]. This method is often limited by the number of resonators utilized in one period and the absorption efficiency decreases in general when the period of one unit cell increases. Besides, some broadband absorbers have also been proposed based on the slow light mode [16–19], plasmon Brewster metasurface [20], optimized metallic taper arrays [21,22], ultrathin metal–dielectric layers [23,24], and multi-ordered diffraction [25]. Few researches have been focused on the synergistic effect of different absorption mechanisms so far.

Semiconductor nanostructures including nanowire [26], nanocube [27], nanopillar and so on have been demonstrated to be able to effectively enhance light absorption by the leaky mode resonances (LMRs) [28–33]. Semiconductor nanocone gratings have been shown to have broadband absorption of light [34–36] and have been verified in experiments [37]. Besides, metallic subwavelength grating with nanogrooves can absorb light due to the interference of counter-propagating gap surface plasmon (GSP) modes, bouncing between the groove bottom and opening [38,39]. However, this method suffers from the disadvantage of low absorption and narrow band [40]. In this research, by combining a semiconductor grating of Ge and a metallic nanogroove grating of Ni together, we realized ultra-broadband and wide angle perfect absorption in the solar spectrum (Fig. 1(a)). Absorption higher than 90% is achieved in a wide frequency range from 150 nm to 4200 nm (Fig. 1(b)) and the performance of the structure keeps stable in a wide angle range from 0 to 60° (Fig. 1(c)). In our structure, the upper triangle Ge grating works as an antireflection coating. The guided modes in the air gap of Ge grating are excited to absorb the incident energy in the short wavelength range. In addition, intrinsic absorption of Ge itself plays a certain role. The lower Ni grating works as a reflector and an effective energy trapper. The guided modes inside Ge grating are excited due to reflection of the lower Ni grating surface. In longer wavelength band, gap surface plasmons (GSPs) in the Ni grating are excited and couple with the guided modes inside the Ge grating. The coupled modes further extend the flat and high absorption band to the near-infrared region (150–4200 nm).

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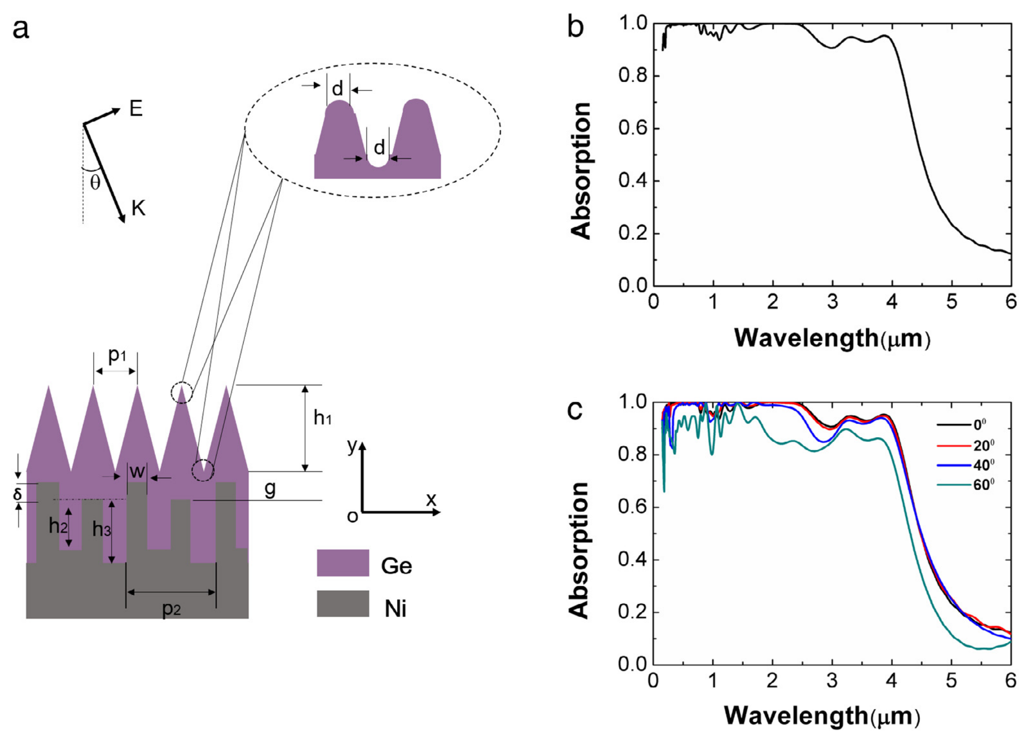

Fig. 1. (a) Schematic illustration of the composite Ni–Ge grating. (b) Absorption spectrum of the proposed structure under normal incidence (p_1 = 200 nm, p_2 = 400 nm, h_1 = 500 nm, h_2 = 400 nm, h_3 = 300 nm, w = 100 nm, g = 100 nm, d = 20 nm). (c) Absorption spectrum of the proposed structure under oblique incidence with angles $\theta = 0°$ 20° 40° and 60°.

2. Structure and methods

Fig. 1(a) schematically shows our proposed structure, consisting of a triangle Ge grating on the top and a Ni nanogroove grating with binary depths on the bottom. The period and height of the Ge grating is p_1 and h_1. The gap between the bottom surface of the triangle Ge grating and the lower Ni surface is g. The period of Ni grating is p_2, twice the value of p_1. The width of nanogroove is w and the binary depths are h_2 and h_3. The difference of height between adjacent Ni surfaces is δ. We use Finite-Difference Time Domain (FDTD) method for the 2D numerical simulation of our proposed structure. In our simulation, all corners are rounded with a round diameter of d to mimic the experimental situation. The permittivity of nickel (ε_{Ni}) and germanium (ε_{Ge}) are taken from Ref. [41]. Periodic boundary condition is used in the x direction and PML boundary condition is used in the y direction. Light with electric field polarized in the xoy surface (TM) is used as the excitation source. The incident angle between the light normal and y direction is θ. The absorptivity is calculated by A=1-R-T, where A, R, T are the normalized absorption, reflection and transmission efficiencies of the structure.

3. Results and discussion

The absorption result given in Fig. 1(b) corresponds to structure parameters as follows: p_1 = 200 nm, p_2 = 400 nm, h_1 = 500 nm, h_2 = 400 nm, h_3 = 300 nm, w = 100 nm, δ = 100 nm, g = 100 nm and d = 20 nm. Simulation at normal incidence shows an absorption spectrum with absorptivity higher than 90% from 150 nm to 4200 nm and a total absorbed energy efficiency Δ = 95% from 150 nm to 6000 nm calculated with $\Delta = \int_{\omega_1}^{\omega_2} \eta(\omega)\, d\omega / \left(\omega_2 - \omega_1\right)$ (Fig. 1(b)). This absorption of this structure also keeps stable and perfect when the incident angle θ changes (Fig. 1(c)). The increase of incident angle only leads to slightly decrease in absorption in the whole band. When θ is smaller than 60°, energy absorption efficiency Δ higher than 90% can still be achieved in the range from 400 nm to 4200 nm. The angle-insensitivity of absorption arises from the angle-insensitivity of the excited modes in our proposed structure (Appendices Fig. A1).

In our proposed structure, the top triangle Ge grating serves as an antireflection coating. It provides an averaged, graded index from air to Ge as the length of its cross section increases from zero to its maximum at the bottom of the grating [36]. A periodic triangle Ge grating can sufficiently suppress the reflection and enhance the absorption of light in the short wavelength band with the guided modes in the grating. In 3D condition, a periodic Ge nanopyramid array has proven to have perfect broadband absorption from 500 nm to 800 nm in experiment by Qi Han etc. [37]. In order to extend the perfect absorption band to the NIR region and utilize the energy in this band, one can add different substrates at the bottom which may serve as reflectors and light trappers. Different substrates such as double-sided grating [36], nanocone and nanohemisphere arrays [42] have been researched previously and show good performance in trapping the incident energy. In our structure, an optimized Ni grating is added under the Ge grating and the whole structure is a composite Ge–Ni grating. In Figs. 2(a) and (b), we show the schematic diagram of two different structures: triangle Ge grating with Ni substrate and our proposed composite Ge–Ni grating. The absorption and reflection of these two structures are shown in Fig. 2(c). The solid lines represent the absorption and the dashed dotted lines represent the reflection. From the black lines, we can see that both the absorption and reflection of the Ge grating with Ni substrate are high in the near-infrared range. While from the red lines, we can see that our proposed structure efficiently absorb the transmitted energy from the Ge grating without increasing the total reflection. The Ni grating at the bottom serves not only as a reflector but also as an energy trapper. The absorption band of absorptivity higher than 90% is extended to the NIR range (150–4200 nm) in our proposed structure. The Ni grating in this structure serves as a perfect energy trapper and the whole structure is a high-efficient energy absorber.

To further illustrate the detailed energy absorption mechanism in our structure, we divided the whole absorption spectrum into three parts and analyzed their physical mechanisms respectively. (1) Part 1 covers from 150 nm to 570 nm, in which light is absorbed by the guided modes in the air gap of Ge grating and the intrinsic loss of Ge. (2) Part 2 covers from 570 nm to 1700 nm. In this spectrum band, light is reflected at