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VO_2 Tungsten Doped Film IR Perfect Absorber

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Abstract. We investigated infrared reflectivity of undoped and Tungsten (W) doped Vanadium dioxide (VO_2) films at varying temperatures. Undoped VO_2 exhibited a clear phase transition at 100°C, achieving near 0% reflectivity, or perfect light absorption. As W doping concentration increased, the phase-transition temperature decreased, maintaining the zero-reflectivity condition. Only a 0.75% W doping enabled room temperature perfect absorption without heating the film.

1 Intro

In recent years, the study of perfect light absorption has gained significant attention due to its potential applications in thermal emitters, optical modulators, and biosensors.

Since the introduction of radar devices, the first perfect absorbers, known as Salisbury screens [1], were proposed. These screens feature an absorbing layer on a thick metal plane, separated by a dielectric spacer. Perfect absorption is achieved through destructive interference of reflected light between the absorbing layer and the reflective metal background.

Nanophotonics advancements have sparked interest in perfect absorbing devices, with developments in systems such as metamaterials, metasurfaces, and multilayer or single-layer devices.[2-5]

Plasmonic metasurfaces, which have absorption values ranging from 90% to as high as 99%, have been studied intensively to achieve perfect absorption [6]. Epsilon-near-zero (ENZ) materials, a new class of low-index materials, have also attracted attention due to their perfect absorption capabilities[7-8]. Examples of ENZ materials include indium tin oxide and aluminum-doped zinc oxide.

Tunable perfect absorption has been explored in systems such as phase-change materials (PCM). PCMs like VO_2 undergo a phase transition at a specific temperature, altering its optical, electrical, and magnetic properties.

In this work, we investigate a tunable perfect absorber made of an ultra-thin VO_2 film on a sapphire substrate. By varying the amount of W dopants in the VO_2 films, the absorption enhancement can be reduced to room temperature. This simple thin-film architecture may advance applications in areas such as modulators, thermal radiation control, tunable radiative cooling, thermoregulating layers, thermal emitters, and bolometers.

The W-doped VO_2 thin films were grown using pulsed laser deposition (PLD), with doping concentration ranging from 0.1% to 10%.

2 Discussion

Infrared (IR) reflectivity measurements were carried out using an Fourier-Transform Infrared Spectroscopy (FT-IR) interferometer in the 4-14 μm spectral range.

The FT-IR setup included a reflectance unit for setting incident and reflectance angles between near-normal and grazing angles.

We conducted measurements at the minimum incidence angle of 13° for each sample under varying temperatures. Before each measurement, reflectance spectra were recorded at room temperature using two distinct crossed, linear polarization states. No differences were found between the s- and p-polarization at near-normal incidence, indicating no optical anisotropy in the films. We gathered FT-IR reflection mode spectra for each sample as temperature changed, using a portable heating stage capable of reaching 100°C.

The undoped VO_2 films' optical IR reflection spectra reveal a clear phase transition when the temperature reaches 100°C, along with a significant, reversible tunability of IR reflectivity spectra. We observed a near zero-reflectivity dip around VO_2's nominal phase transition temperature, consistent with previous findings. As the phase transition occurs, the coexistence of two phases is evident in the FT-IR spectral features. Around the phase transition temperature, VO_2 can be modeled as an effective medium comprising a semiconductor matrix with randomly dispersed metallic inclusions [9-10]. Their filling factor ranges from 0 (pure semiconductor phase at

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low temperatures) to 1 (pure metallic phase after phase transition). We numerically reconstructed experimental spectra for different temperatures (filling factors) using a transfer-matrix method and Looyenga's effective medium mixing rules [11-12]. This resulted in a mixed phase with refractive index matching to the substrate, where the VO_2 layer acts as an antireflection coating, minimizing the reflected signal with near 0% reflectivity. Zero-reflectivity implies perfect light absorption through the substrate.
We then measured IR reflectivity spectra from various VO_2 film samples with different W doping concentrations under similar temperature conditions.
Our experiments show that as W doping concentration increases, the phase-transition temperature decreases.
To better understand the phase transition modifications when W is introduced into the VO_2 lattice, we measured reflectivity spectra as a function of temperature for each sample. The semiconductor-to-metal transition is evident up to approximately 1% W. Further increase of doping content results in films displaying pure metallic behavior, making the phase transition unobservable. Nevertheless, the zero-reflectivity condition still appears in each set of measurements, shifting towards lower temperatures as W concentration increases.
The largest dynamic range of reflectivity values is obtained around λ=11.8 μm at temperatures of 62°C, 32°C, and 30°C for 0.1%, 0.5%, and 0.75% tungsten content, respectively.
The 0.75% W doping amount allows zero-reflectivity, or perfect absorption, to be achieved at room temperature without heating the film.

3 Conclusion

We have experimentally studied W-doped VO_2 films, fabricated using pulsed laser deposition, to control and adjust their spectral characteristics over a range of temperatures. The phase transition of VO_2 from a monoclinic (semiconductor) to a tetragonal (metallic) lattice structure at 68°C, accompanied by changes in both physical and optical properties, presents a wealth of opportunities for dynamic applications. Additionally, the tensile strain introduced by W doping within the lattice structure aids in stabilizing the metallic phase over the semiconducting phase.
Our experimental investigation of film reflectivity in the 4-14 μm range revealed remarkable perfect absorption characteristics. We observed a strong modulation of the VO_2 film's infrared reflectivity with temperature. Specifically, we demonstrated that the infrared optical response of the tunable film can be adjusted from complete to partial absorption by altering the applied temperature. Undoped VO_2 exhibits a reflectivity minimum at λ=11.8 μm at its conventional transition temperature of approximately 68°C, with a dynamic range as high as ΔR=85%. Interestingly, when W doping is introduced into the VO_2 lattice, both the phase transition temperature and the reflectivity minimum shift down to room temperature, making perfect absorber behavior achievable even at room temperature.

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