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Membrane-type polarization-controlled color filters on silicon substrate

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ABSTRACT

Two polarization-controlled color filters (CF), named CF-I and CF-II, are designed and implemented on an HfO_2-on-silicon platform. The devices are with a 200-nm-thick membrane structure realized by etching the silicon substrate beneath the grating patterns away. The spectral responses are characterized by a micro-reflection measurement system. CF-I outputs blue and green colors and CF-II generates yellow and red colors, for normal incident TM- and TE-polarized waves, respectively. Detailed results and analyses on them are also provided both theoretically and experimentally. Particularly, the achieved membrane-type color filters have the potential of being transferred from the silicon substrate to other foreign platforms by breaking off the support beams mechanically, and thus may be applied in several fields such as image sensors, display elements, and even wearable devices.

1. Introduction

Guided-mode resonance (GMR) occurs as a resonance anomaly effect when the incident wave is phase-matched with a leaky waveguide mode supported by the periodic waveguide grating structure. Since 1990s, it has attracted more and more attention due to its physical nature and broad applications. GMR grating filters with narrow linewidth, high resonant efficiency, and low sideband are a fundamental application of this effect [1–4].

As we know, GMR grating filters can be used to select a specific color from a beam of incident white light; under this circumstance, they are generally called color filters (CFs), which are key elements in various applications such as display devices, colorful decoration, image sensors [5,6]. A series of publications have reported their efforts to achieve CFs based on GMR gratings. Yoon et al. realized a blue CF using a subwavelength patterned grating in poly silicon on a quartz substrate [7]. Wang et al. exhibited their works on reproducing a color image based on GMR filter array with period variety to display three primary colors (blue, green, and red) [8]. Yu et al. gave a theoretical research on mechanisms and performances of transmissive/reflective CFs, together with their integration applications [9]. Kanamori et al. showed polymer-based GMR CFs with grating periods to be 600 nm, 350 nm, and 300 nm corresponding to the red, green, and blue colors, respectively [10]. Uddin et al. reported an angle-tuned highly efficient CF for projection display applications [11].

Particularly, the output color of a CF can be tuned or changed when the polarization of the incident wave varies resulting from the polarization-sensitivity. Based on this concept, Uddin et al. designed and demonstrated one-dimensional (1D) polarization-controlled CFs on a Si_3N_4-on-glass platform [12]. The output colors of their CFs could be changed just by transforming the polarizations of the incident waves.

In this paper, we investigate two novel membrane-type polarization-controlled CFs, named CF-I and CF-II. Being different from the counterparts shown in [12], both CF-I and CF-II here are implemented on an HfO_2-on-silicon platform and with a suspended membrane structure. The spectral characterizations show that CF-I outputs blue and green colors and CF-II generates yellow and red colors, for normal incident TM- and TE-polarized waves, respectively. Therefore, CF-I is a polarization-controlled blue-green CF, and CF-II is a polarization-controlled yellow-red CF. The silicon-based membrane-type devices here are ultra-compact and can be integrated with other silicon photonic devices. Particularly, they have the potential of being transferred from the silicon substrate to other foreign platforms by mechanically releasing the support beams. Transferrable optoelectronics is a new emerging area for meeting the comprehensive requirements of flexible wearable devices [13]. Transferred color filters can be easily incorporated into multicomponent systems for versatile applications such as image sensors, display elements, and even wearable devices.

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2. Design and simulations

HfO_2 is an excellent optical material due to its outstanding properties including high laser damage threshold, good thermal/-chemical stability and high transparency in the whole visible wavelength band [14–16]; on the other hand, compared with sapphire or silicon carbide substrate, silicon substrate has advantages of low cost, large size, good electrical/thermal conductivity, and is particularly easy to integration [17,18]. Therefore, the 1D polarization-controlled CF here, as shown in Fig. 1, is constructed on an HfO_2-on-silicon platform, which can be prepared via the evaporation of HfO_2 material on silicon substrate. The HfO_2-on-silicon platform we employ is made up of a ~200-nm-thick HfO_2 device layer and a ~200-µm-thick silicon substrate. Adopting a double-side process technique [14–16], the silicon substrate beneath the HfO_2 grating region can be removed completely. Thus, the device is with a freestanding membrane structure, and can operate across the whole visible band. We set n_{HfO2} (the refractive index of the HfO_2 material) to be ~1.97. Other parameters mainly refer to the grating period Λ, the grating ridge width W, the filling factor F, the grating layer thickness d_g, and the homogeneous waveguide layer thickness d_w. F is the ratio of W to Λ, i.e., F = W/Λ. TE-polarization is defined as the electric field (E-field) of the incident wave is parallel to the linear grating bars, while TM-polarization is defined as the E-field is perpendicular to the linear bars.

As we know, 1D grating filter is highly polarization-sensitive [6,11,12]; in other words, its resonant peaks for TE- and TM-polarized waves generally occur at different wavelengths. By taking advantage of this spectral feature, 1D polarization-controlled CFs can be achieved [12]. Our CF in Fig. 1 is designed and optimized by using RCWA, which is an accurate solution of Maxwell's equations for the electro-magnetic diffraction induced by grating structures [19,20]. Eventually, two sets of grating parameters are determined, corresponding to two CFs named as CF-I and CF-II, respectively. The parameters of CF-I are Λ = 320 nm, d_g = 70 nm, F = 0.5, while those of CF-II are Λ = 400 nm, d_g = 70 nm, F = 0.5. To facilitate fabrication, the parameters of CF-I keep consistent with those of CF-II except for grating period Λ.

The simulated reflectance curves of CF-I are shown in Fig. 2(a). For normal incident TM-polarization, the reflection peak is located at 484 nm, and the output color will be blue; for normal incident TE-polarization, the peak moves to 535 nm, and a green color will be observed. Therefore, CF-I is a polarization-controlled blue-green CF. Fig. 2(b) gives the simulated reflectance curves of CF-II. For normal incident TM- and TE-polarizations, two reflection peaks centered at 578 nm and 645 nm can be achieved, and the corresponding output colors will be yellow and red, respectively. Thus, CF-II is a yellow-red CF controlled by the polarization. The maximum resonance efficiencies of the four reflection peaks in Fig. 2 are all nearly 100%, and their full-width at half-maximums (FWHMs) distribute between 10 nm and 16 nm, which will yield very pure output colors.

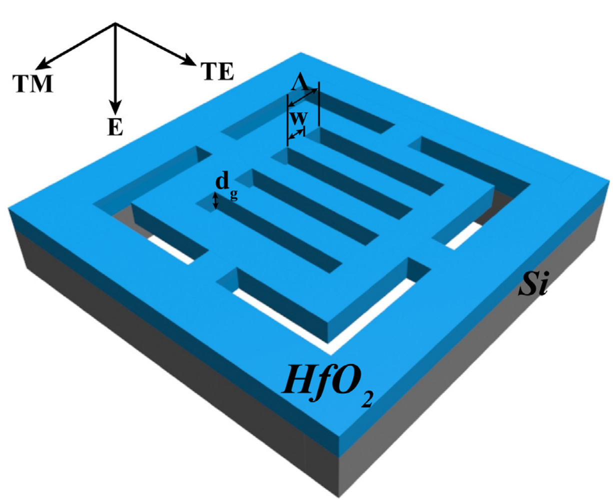

Fig. 1. A Schematic diagram of the polarization-controlled CF on an HfO_2-on-silicon platform.

Typically, each resonance peak in Fig. 2 corresponds to a GMR. To better understand this optical effect, we visualize it in Fig. 3, which illustrates the E-field distribution of CF-I at 535 nm wavelength for TE-polarized wave. Dark blue indicates areas with low field intensity, while dark red denotes regions with high field intensity. The HfO_2 grating layer as well as the HfO_2 homogeneous waveguide layer is outlined by the white solid lines. Both the +1st and −1st evanescent orders diffracted from the normal incident TE-polarized wave will be coupled to the fundamental TE waveguide mode, because phase-matching condition is satisfied at 535 nm wavelength. It can be clearly observed that standing wave patterns distribute regularly in the HfO_2 homogeneous waveguide layer, which is caused by the interference between the counter-propagating +1st and −1st evanescent orders. However, the waveguide mode related to the grating structure is leaky, and thus the ±1st evanescent orders coupled to the TE mode cannot travel very far. Instead, they will be scattered reciprocally to the zeroth diffraction order and interferes with the incident wave to generate obvious interference patterns, which can be observed evidently beneath the grating region in Fig. 3. Eventually, a high reflection peak nearly 100% reflectivity appears at 535 nm. Similar E-field distribution can be obtained for the TM-polarized wave at the corresponding resonance wavelength.

3. Fabrication and characterization

The fabrication process of the device is schematically shown in Fig. 4. We start by spin-coating a positive resist layer on the top surface of the platform, followed by the definition of grating patterns in this layer employing electron-beam lithography (EBL) (step a); then, the grating patterns is transferred to the HfO_2 layer using ion beam etching (IBE) technique, which adopts an energetic and highly directional Ar ion source to dig the HfO_2 material anisotropically (step b). Following the same process, four support beams of the membrane structure are generated (step c and d). Thereafter, both the top and bottom surfaces are spin-coated by thick photoresist layers, which can be used to remove the silicon substrate while protecting the topside grating patterns (step e). After standard photolithography from backside, the silicon substrate beneath the HfO_2 grating region is removed away completely by silicon deep reactive ion etching (DRIE) technique, which uses SF_6 and C_4F_8 mixture as etching gas (step f). After removing the residual photoresist, the target device with a suspended membrane structure on silicon substrate is finally achieved.

By removing the nether silicon away, the grating region is with a suspended membrane structure, and both top and bottom surfaces are surrounded with low index air, endowing the device with the ability to support waveguide modes; moreover, removing the substrate can eliminate additional optical loss caused by the silicon absorption.

Note that the grating region suffers from a stress relaxation process, which may probably lead to a crack or distortion of the ultra-thin HfO_2 membrane. Four support beams are designed in Fig. 1, which is an efficient scheme to solve this problem from the view of plate mechanics. In addition, the support beams can be broken