Spectral response modification of TiO_2 MSM photodetector with an LSPR filter

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Abstract: We fabricated UVB filtered TiO_2 MSM photodetectors by the localized surface plasmon resonance effect. A plasmonic filter structure was designed using FDTD simulations. Final filter structure was fabricated with Al nano-cylinders with a 70 nm radius 180 nm period on 360 nm SiO_2 film. The spectral response of the TiO_2 MSM photodetector was modified and the UVB response was reduced by approx. 60% with an LSPR structure, resulting in a peak responsivity shift of more than 40 nm. To our knowledge, this is the first published result for the spectral response modification of TiO_2 photodetectors with LSPR technique.

OCIS codes: (040.5160) Photodetectors; (040.7190) Ultraviolet; (250.5403) Plasmonics; (050.6624) Subwavelength structures.

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1. Introduction

In recent years, studies about the spectral response modification of photodetectors with plasmonic structures are rapidly increasing due to the needs for applications and the development of material quality and processing techniques. Some of the studies use plasmonic structures for enhancing the responsivity of photodetectors in some portions of the applicable wavelength range. There has already been some theoretical research showing that adding some designed nanostructures will enhance the responsivity [1,2]. Recently, an

#209543 - $15.00 USD Received 3 Apr 2014; revised 15 May 2014; accepted 26 May 2014; published 2 Jun 2014

experimental work about the enhancement of the ZnO photodetector response in visible spectrum with the plasmonic effect from self-assembled Ag nanoparticles was published [3]. Enhancement of 8 in the responsivity of an AlGaN photodetector with a grating structure was demonstrated [4] and 1.5 times enhancement was obtained by localized surface plasmon resonance (LSPR) structures [5] on GaN material. These works represent the enhancement of the photodetector response with plasmonic structures in various wavelengths.

In addition to field localization and enhanced transmission through subwavelength holes, plasmonic structures are used for color filtering purposes as well [6]. Especially in recent years, researchers have conducted experimental studies on plasmonic filters for CMOS image sensor applications in order to replace the organic material based color filters used in CMOS sensor arrays. Small area plasmonic filters for CMOS image sensors are demonstrated in visible wavelengths [7]. In another work, a plasmonic structure is designed that is separated from the active device with a relatively thick dielectric layer, where one can tune the filter response with device geometry tuned by process parameters [8]. In this work it is stated that this type of filters bring advantages of filter response tuning and ease of integration of different types of filters on the same chip. Those and similar studies showed that plasmonic filtering is feasible in visible and NIR range of the optical spectrum where most of the telecommunication and imaging efforts take place. UVC detection has wide range of applications such as solar blind detection for military and civil applications and UV dosimetry for medical and biological applications.

In this work, we present an LSPR filter to modify the peak spectral response of the TiO_2 metal semiconductor metal (MSM) photodetector from the UVB (280-315 nm) region to the UVC (190 – 280 nm) region [9]. The LSPR filter structure consists of a thick SiO_2 layer on top of the thin TiO_2 active layer and Al nano-cylinders are placed on top of the SiO_2 layer, as shown in Fig. 1(a). SiO_2 thickness, Al nano-cylinder diameter and period is optimized using finite-difference time-domain (FDTD) simulations, and designed structures were fabricated, as shown in Fig. 1(b), and characterized.

2. Design and fabrication

Designed filter structure was simulated using the FDTD method using the commercial software by Lumerical Solutions Inc. Simulated structure consists of the sapphire substrate, 25 nm TiO_2 absorbing layer, 360 nm thick SiO_2 separator layer, and 50 nm thick Al nano-cylinders in square lattice, as shown in Fig. 1(c)

To determine the optimum period and cylinder diameter values for the filter structure, parametric simulations were performed. Figure 2(a) shows the effect of the period and Fig. 2(b) shows the effect of the diameter of the cylinders on resonance behavior. As can be seen in the figures, the plasmonic resonance shifts to shorter wavelengths as the diameter and period of the cylinders decrease. With a 150 nm period, as the radius of the cylinders increase the resonance broadens due to the increased coupling between the cylinders. By using these simulation results, 180 nm period was chosen to suppress the UVB response of the photodetector while keeping the stopband edge in UVC and 70 nm diameter was chosen to obtain a wide resonance. Wider diameters and shorter periods were not chosen due to proximity effect issues in e-beam lithography process.

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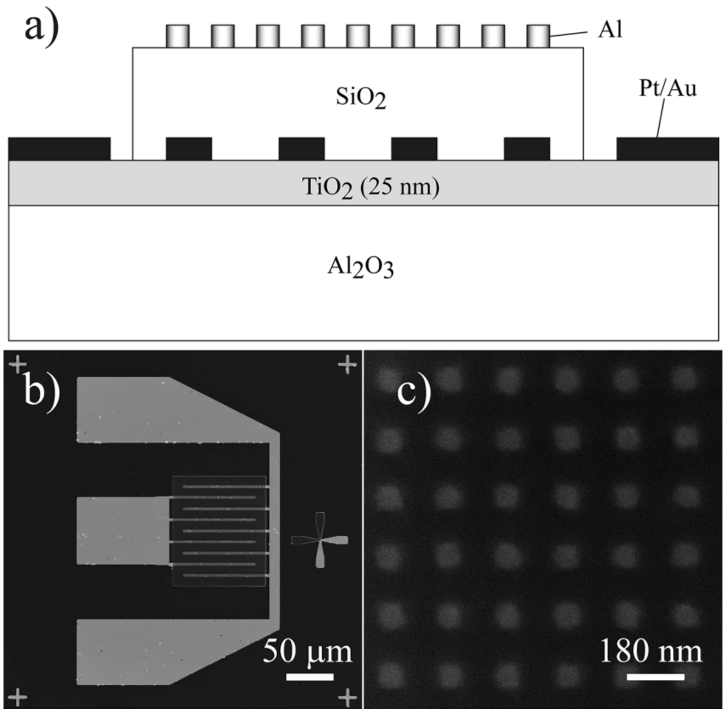

Fig. 1. Device structure. (a) Cross sectional view of device with the LSPR structure and SiO_2 spacer. (b) SEM image of the fabricated device. (c) SEM close-up image of the Al nano-cylinders with 180 nm period, 70 nm diameter.

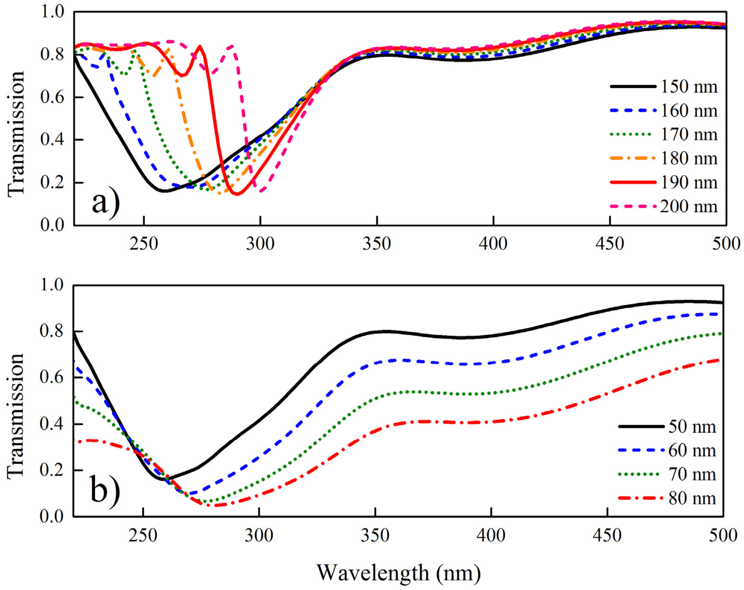

Fig. 2. Simulation of an LSPR filter transmission resonance for (a) different periods when the diameter is 50 nm and for (b) different particle diameters when the period is 150 nm.

Figure 3 illustrates the calculated responsivities of the photodetectors with no LSPR filter, with a 360 nm SiO_2 separator on top of 25 nm TiO_2 thin film and the complete structure including the plasmonic nano-cylinder array with diameter of 70 nm and period of 180 nm.

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Responsivity curves are calculated assuming that there is no photoconductive gain in the detector and the carrier collection efficiency is 1. Without the plasmonic structure and the spacer layer, the obtained result is the typical responsivity curve for a TiO_2 MSM photodetector. The addition of a SiO_2 spacer on top of the TiO_2 thin film changes the responsivity of the TiO_2 photodetector due to the interference effect. In case of adding an LSPR structure to the photodetector it can be clearly seen that the responsivity is significantly reduced around the resonance wavelength of the plasmonic cylinders. The inset in Fig. 3 shows the intensity distribution throughout the structure for different excitation wavelengths. At around resonance of 300 nm, the intensity is strongly localized around nano-cylinders and a very weak field reaches the active region. Inter-particle coupling between nano-cylinders can be seen as well at resonance, leaving almost no field passing through the SiO_2 spacer. At off-resonance wavelengths, field localization is weak around cylinders, and the interference effect is also visible.

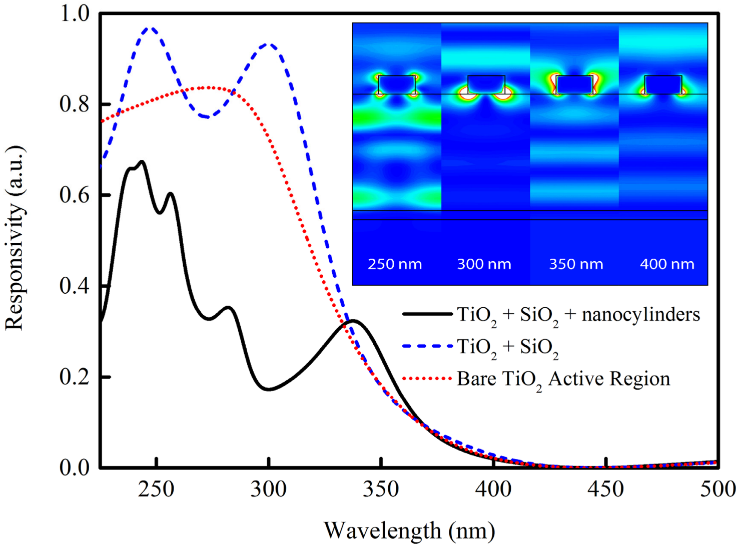

Fig. 3. Effect of SiO_2 spacer and LSPR structure on device responsivity. Inset: Intensity distribution for 250, 300, 350 and 400 nm wavelengths.

TiO_2 active layer deposition is performed with RF-magnetron sputtering and Pt contacts were deposited by e-beam evaporation. The details for these processes were explained elsewhere [10]. After Schottky contact deposition, 360 nm of SiO_2 was deposited using RF-magnetron sputtering. E-beam lithography was performed on 150 nm thick PMMA950K resist at 10 kV with a Raith E-Line Plus system, developed in 1:3 MIBK:IPA for 45 s and 50 nm Al was e-beam evaporated. Following the lift off, SEM inspection of the samples was carried out and 70 nm diameter and 180 nm period for the plasmonic nano-cylinder array was confirmed. IV measurements were performed with the Keithley 6430. A fiber probe, coupled to a monochromator with a Xe light source, was used for illuminating the device. The optical power was measured with an optical power meter with a UV enhanced Si photodetector at the fiber probe tip and used for responsivity calculations.

3. Results and discussion

Figure 4 shows the experimental and simulated responsivity results of fabricated photodetectors. Responsivities are measured at a 10 V bias for both devices. Simulation

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curves are normalized to the respective experiment maximums in order to include the gain effects. The simulated responsivity peak observed at 340 nm is thought to be due to the differences between the model of the material used in the simulation and deposited thin film material. It can be seen that the experimental results are in good agreement with the simulation results. Adding the LSPR filter to the photodetector reduced the responsivity to around 60% in the UVB band resulting in a more than 40 nm shift of the peak responsivity to the UVC band.

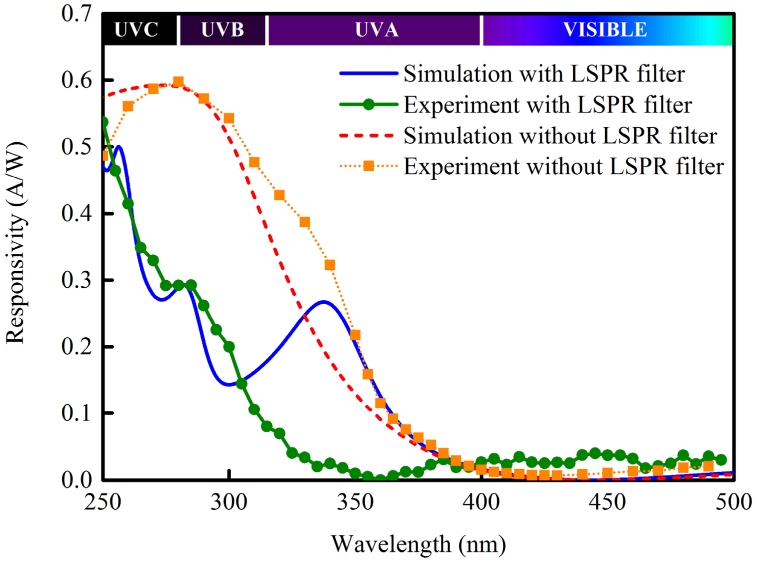

Fig. 4. Comparison of the simulation and experiment with and without LSPR filter.

4. Conclusion

In conclusion, we designed, fabricated, and characterized thin film TiO_2 photodetectors integrated with LSPR filters that suppressed responsivity in the UVB region which resulted in a responsivity peak shift to the UVC band. We showed that, in order to suppress or shift the absorption spectrum in UV bands, Al plasmonic particles can be used as LSPR filters above the active regions. Similar plasmonic structures could be designed to further increase the contrast between UVC and UVB bands.

Acknowledgments

This work is supported by the projects DPT-HAMIT, DPT-FOTON, NATO-SET-193 and TUBITAK under Project Nos., 113E331, 109A015, 109E301. One of the authors (E.O.) also acknowledges partial support from the Turkish Academy of Sciences.

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