Selective and efficient infrared detection by plasmonically heated vanadium-dioxide nanowire

Khan, Mohammad Wahiduzzaman, Sadri-Moshkenani, Parinaz, Islam, Md Shafiqul, Boyraz, Ozdal, Sullivan, Jonathan, et al.

Mohammad Wahiduzzaman Khan, Parinaz Sadri-Moshkenani, Md Shafiqul Islam, Ozdal Boyraz, Jonathan Sullivan, Ziqi Yu, Jaeho Lee, "Selective and efficient infrared detection by plasmonically heated vanadium-dioxide nanowire," Proc. SPIE 11462, Plasmonics: Design, Materials, Fabrication, Characterization, and Applications XVIII, 114622S (8 September 2020); doi: 10.1117/12.2568971

Event: SPIE Nanoscience + Engineering, 2020, Online Only

Selective and Efficient Infrared Detection by Plasmonically Heated Vanadium-dioxide Nanowire

Mohammad Wahiduzzaman Khan, Parinaz Sadri-Moshkenani, Md Shafiqul Islam, and Ozdal Boyraz[a] and Jonathan Sullivan, Ziqi Yu, Jaeho Lee[b]

[a]Department of Electrical Engineering and Computer Science, University of California - Irvine, CA 92697, USA

[b]Department of Mechanical and Aerospace Engineering, University of California - Irvine, CA 92697, USA

ABSTRACT

Phase-changing materials are promising due to their sharp temperature dependent characteristics and have high potential of being integrated in optical switching and sensing techniques. Among such materials, vanadium dioxide (VO_2) is the most utilitarian because of its transition temperature being close to the room-temperature. VO_2-based bolometers utilize the material's large temperature coefficient of resistivity to detect infrared radiation. However, to achieve large sensitivity, the active radiation absorption area needs to be large enough that allows sufficient temperature buildup from incident radiation absorbed by VO_2, thus requiring large pixel dimension and degrading the spatial resolution of bolometric sensing. Moreover, the absorption by the VO_2 material is not optimized for a specific frequency band in most of the applications. On the other hand, plasmonic nanostructures can be tuned and designed to selectively and efficiently absorb a specific band of the incident radiation for local heating and thermal imaging. In this work, we propose to incorporate plasmonic nanostructures with VO_2 nanowires that amplifies the slope of impedance change due to the thermal variations to achieve a higher sensitivity. We present the numerical analysis of the mid-infrared electromagnetic radiation absorption by the proposed detector showing near-perfect absorption by the plasmonic absorbers. Besides, the thermal buildup and the nanowire resistance change is predicted for different substrate, as the substrate plays a big role in heat distribution. We show high sensitivity and ultra-low noise equivalent temperature difference (NEDT) by our novel bolometric detector. We also discuss the fabrication of the VO_2 nanowires on the proposed devices.

Keywords: infrared detector, thermal camera, plasmonics, absorber, vanadium dioxide, VO_2, phase-changing material

1. INTRODUCTION

The two main types of infrared (IR) detectors are thermal detector and photon detector. The thermal detectors function based on the principles of temperature dependent phenomena - change in resistance, voltage generation in junction, change in polarization, thermal expansion of gas, etc. On the other hand, photon detectors functions by converting IR radiation to carrier generation - interband, intraband, impurity to band or between quantized levels. At present, high-performance infrared imaging technology is mainly based on epitaxially grown structures of the small-bandgap bulk alloy mercury-cadmium-telluride (MCT). Quantum-well infrared photodetectors based on InSb, GaAs, and others are also available. However, these technologies require very low operating temperature (50-100K) thus a bulky and costly cryogenic system. The need for increased performance of the infrared detectors has driven extensive research towards the improvement of current IR detection technology as well as spurred novel techniques and sensors.[1,2] The advancement of integrated optics[3,4] and photonic integrated circuits has brought forward both IR detection and readout capability in the same chip.[5–7]

Further author information: (Send correspondence to Ozdal Boyraz)
Ozdal Boyraz: E-mail: oboyraz@uci.edu
Mohammad Wahiduzzaman Khan.: E-mail: mohammwk@uci.edu

Plasmonics: Design, Materials, Fabrication, Characterization, and Applications XVIII,
edited by Din Ping Tsai, Takuo Tanaka, Proc. of SPIE Vol. 11462, 114622S

· doi: 10.1117/12.2568971

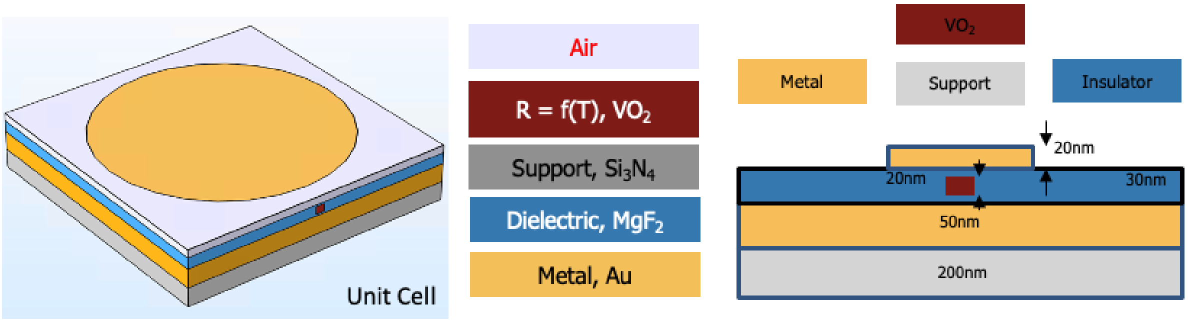


Figure 1. The unit cell of the infrared detector. The bottom layer is the silicon nitride support for the suspended bolometer pixel. On top of the support layer, there metal-insulator-metal plasmonic absorber to increase the absorbed radiation from a particular band of spectrum while keeping the size of the feature small. The VO_2 nanowire is buried in the insulator layer and is between the metal layers. This is to ensure that the local heating by plasmonic absorption effects the nanowire resistivity and thus the readout signals.

Phase changing materials (PCM) are the ones that changes their phase suddenly upon an external stimuli. A sharp change in material properties accompanies the phase transition. This makes the material interesting and highly promising in sensing applications. VO_2, V_2O_5, and GST are among the most common phase-changing materials. VO_2 is extensively investigated for bolometer[8,9] and modulator applications whereas, GST with its nonvolatile phase-change properties is investigated mostly for memory applications.[10] The instrinsic and engineered low transition temperature[11] of VO_2 makes it most suitable for radiation sensing applications.

The IR spectrum can be subdivided into - near IR (0.75-1 μm), short-wave IR (SWIR 1-3 μm), mid-wave IR (MWIR 3-5 μm), and long-wave IR (LWIR 8-14 μm). Major of the IR radiation of interest except 5.5-8 μm has high atmospheric transmittance. This is important for distant or remote thermal sensing of an object. For thermal imaging and night vision at or near room temperature, LWIR band is sensed. Human body is close to an ideal black-body radiator and the emission peak is around 9.6 μm. Therefore, thermal imaging devices for human subjects are most sensitive in the 8-12 μm band. Towards the larger wavelength, the IR detection becomes more and more challenging due to low emission power from object at lower temperature as well as low thermal contrast. A high thermal contrast allows to distinguish between object at slightly elevated temperature and surroundings at background temperature. Conventional approach to improve bolometer performance has been limiting the reduction of active detector area thus the spatial resolution. Unlike conventional bolometer and other novel approaches, in our current work, we propose to use VO_2 nanowires instead of VO_2 films to increase the radiation responsivity at the same time reducing pixel pitch. The absorption by the reduced active area of the detector is sustained by the incorporation of plasmonic elements. Plasmonic nanostructures increase the selectivity as well as amount of absorbed energy thus enhancing the performance of bolometric detection by the VO_2 nanowires at the same time having a much smaller footprint.

2. DETECTOR

The detector we propose has three key components - plasmonic absorber, VO_2 nanowire, and electronic readout. Plasmonic structure absorbs the radiation of a specific wavelength range emitted from the object. The absorbed energy contributes to the thermal buildup on the device. The VO_2 nanowire placed within the absorber element sees the temperature change. Since VO_2 resistivity is highly temperature dependent, particularly at the phase-transition, the device can be biased at an elevated temperature close to the VO_2 transition temperature[12,13] to get the highest sensitivity. The absorber with the transducing VO_2 nanowire needs to be thermally isolated as much as possible to enhance the temperature buildup and thus the responsivity. High thermal resolution and low noise-equivalent temperature difference can be achieved by suspending the active region and reducing the thermal escape mechanism. Suspending the layers is for low-power radiation detection as it decreases the heat escape through conduction. For high enough power, the suspended structure is not necessary. Silicon nitride is used as the support layer for holding the active detector components. The VO_2 nanowire is then connected to the electronic readout circuit for individual reads of detector pixels. The schematic of the detector pixel is shown in Fig.1.

2.1 ABSORBER DESIGN

Plasmonic nanostructures[14–16] have found its way into numerous novel applications such as active metasurfaces, tunable devices, efficient absorbers, localization of field and energy, etc. For sensing applications, plasmonics can allow enhanced cause-result interaction to significantly improve the sensitivity. In our design for bolometric sensor unit cell, we incorporate metal-insulator-metal type plasmonic absorber to enhance selective and efficient absorption of a particular band of IR radiation. The size and material of the plasmonic structures can be scaled for other wavelength range of interest. We focus to optimize the absorption at 10 um.

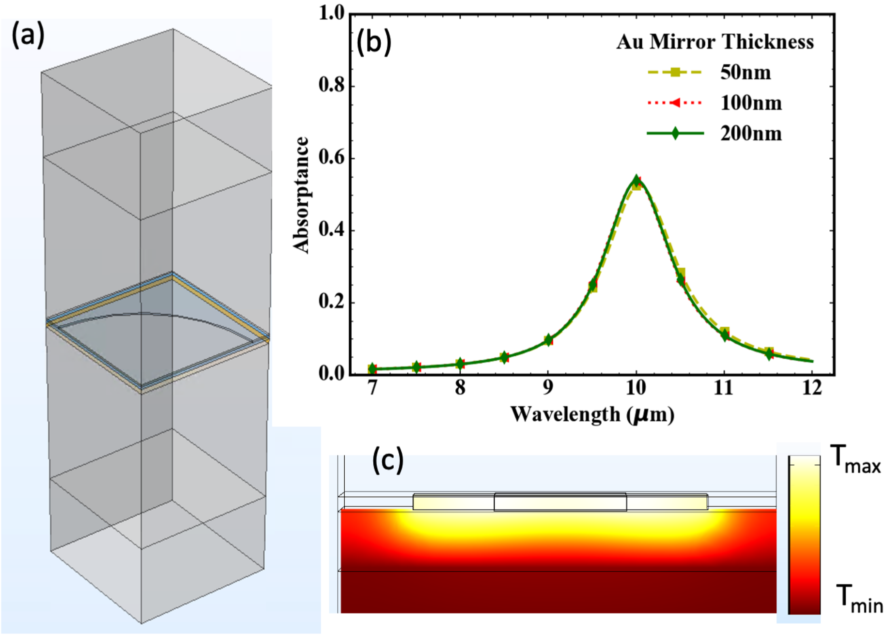


Figure 2. (a) The simulation model in COMSOL Multiphysics showing quarter of the unit cell. Symmetry boundary conditions are applied for calculation of the absorption profiel, (b) Absorption profile for different bottom gold layer thickness, and (c) Temperature profile within the insulator layer where the VO_2 nanowire is buried and the temperature variation is sensed.

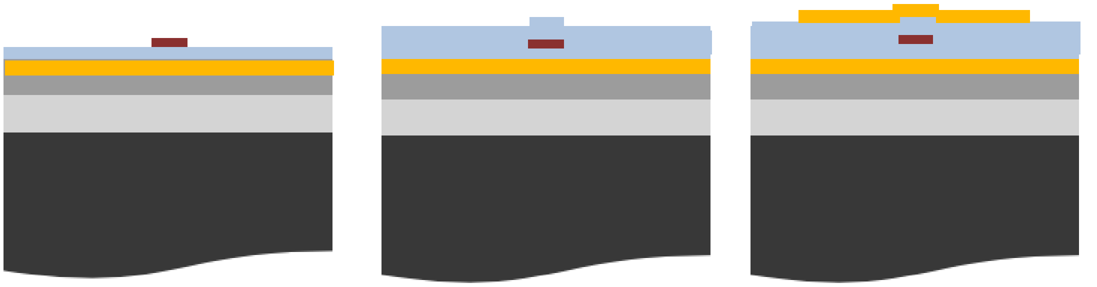
We carry out finite-element method (FEM) analysis on the absorber structure for different materials and sizes of features. The model in COMSOL Multiphysics is shown in Fig.2a. The absorptance by an array of pixels is calculated. We choose gold-MgF_2-gold plasmonic absorber with a pixel pitch of 3 um and top gold layer circular patch of 2.6 um diameter. For these parameters, we achieve an absorptance of over 55% at 10 um wavelength. The absorption profile is shown in Fig.2b. The peak absorbing wavelength can be tuned based on multiple design parameters - top patch metal diameter, insulator thickness, choice of materials, period and duty cycle. This makes the design scalable to other narrow bands of IR spectrum as well as multiband detection. The dielectric material is chosen to be MgF_2 for its wider transparency range in LWIR compared to commonly available SiO_2. For proper thermal trapping, the bottom metal needs to be thin so that localized heat does not spread to adjacent cells. From the absorption profile, we observe that the thickness of the bottom gold layer has little to no effect on the absorption profile. So, we chose 50 nm of thickness for the bottom metal layer.

2.2 NANOWIRE

In our proposed design of the detector pixel, VO_2 nanowire is the transducing element that converts the radiation induced thermal buildup to readable electronic signals. Due to its high temperature coefficient of resistance

(TCR), VO_2 is a material of choice for bolometer devices. However, due to close coexistence of different vanadium oxides like VO_3, V_2O_5, etc., deposited VO_2 films are not usually reported to be pure and as sensitive to radiation as one would expect. We optimize our VO_2 film deposition parameters to achieve highly dominant VO_2 film. In our design, we propose to use VO_2 nanowires instead of a film. The large length to cross-section ratio of the nanowire results in amplified resistance variation with respect to temperature change. The temperature profile in along the unit cell is shown in Fig.2c. We see the temperature distribution within the insulator layer where the nanowire is buried. The nanowire thus experiences the local thermal buildup and shows variation in resistance thus affecting the readout signal. The maximum temperature rise depends on the input radiation intensity as well as the heat escape mechanisms.

(a) LPCVD Nitride (b) Au Film Deposition (c) MgF_2 sputtering



(d) VO_2 Deposition and Etching (e) MgF2 Sputtering (f) Au Deposition and Lift-off

Figure 3. The fabrication steps for the infrared detector. The bump created by the nanowire does not significantly effect the absorption profile by the plasmonic abosorber.

3. FABRICATION STEPS

The infrared detector proof-of-concept fabrication steps are shown in Fig.3. The fabrication of the detector starts with the deposition of support layer of 200 nm silicon nitride. Then e-beam evaporation of adhesion layer (Ti/Cr) followed by gold of 30 nm. This metal layer will act like the ground plane. Then the dielectric layer will be deposited. The VO_2 film will be sputtered then patterend and structured to be a nanowire. Then again the dielectric layer will be deposited to bury the nanowire within. After that, adhesion layer and gold will be e-beam evaporated again and patterned based on the design using resist patterning and lift-off techniques. The subsequent depositions after the nanowire pattering will leave a tiny bump. However, this bump does not alter the absorption profile significantly. The deposited layers will be suspended by substrate etching and release process to create thermal isolation. The suspension is only necessary for very low power radiation detection. Metallic connectors and vias will be deposited and patterned and the detector will be finally suspended.

4. CONCLUSION

Vanadium-dioxide (VO_2) is a promising phase-changing material with a potential to be integrated in optical sensors. We study the integration of plasmonic absorbers and vanadium dioxide (VO_2) nanowire to selectively and efficiently detect incident mid-infrared radiation. We present the numerical analysis of the plasmonic absorber, calculate the radiation-induced local heating and the subsequent change of the nanowire resistance. The proposed device shows higher sensitivity due to the nanowire's enhanced dependence on temperature. In addition, we report higher resolution due to the reduction in the active absorption area. We also discuss the fabrication steps of the VO_2 nanowires for the proposed design.

REFERENCES

[1] Palaferri, D., Todorov, Y., Bigioli, A., Mottaghizadeh, A., Gacemi, D., Calabrese, A., Vasanelli, A., Li, L., Davies, A. G., Linfield, E. H., et al., "Room-temperature nine-μm-wavelength photodetectors and ghz-frequency heterodyne receivers," *Nature* **556**(7699), 85–88 (2018).

[2] Tan, C. L. and Mohseni, H., "Emerging technologies for high performance infrared detectors," *Nanophotonics* **7**(1), 169–197 (2018).

[3] Boyraz, O. and Jalali, B., "Demonstration of a silicon raman laser," *Optics express* **12**(21), 5269–5273 (2004).

[4] Donzella, V., Sherwali, A., Flueckiger, J., Fard, S. T., Grist, S. M., and Chrostowski, L., "Sub-wavelength grating components for integrated optics applications on soi chips," *Optics express* **22**(17), 21037–21050 (2014).

[5] Zhao, Q., Khan, M. W., Farzinazar, S., Lee, J., and Boyraz, O., "Plasmo-thermomechanical radiation detector with on-chip optical readout," *Optics Express* **26**(23), 29638–29650 (2018).

[6] Khan, M. W., Sadri-Moshkenani, P., Islam, M. S., and Boyraz, O., "Graphene-coated suspended metallic nanostructures for fast and sensitive optomechanical infrared detection," in [*CLEO: Science and Innovations*], JTu2A–51, Optical Society of America (2019).

[7] Khan, M. W., Zhao, Q., Sadri-Moshkenani, P., Islam, M. S., and Boyraz, O., "Graphene-incorporated plasmo-thermomechanical infrared radiation detection," *JOSA B* **37**(3), 774–783 (2020).

[8] Jerominek, H., Picard, F., Swart, N. R., Renaud, M., Levesque, M., Lehoux, M., Castonguay, J.-S., Pelletier, M., Bilodeau, G., Audet, D., et al., "Micromachined uncooled vo2-based ir bolometer arrays," in [*Infrared Detectors and Focal Plane Arrays IV*], **2746**, 60–71, International Society for Optics and Photonics (1996).

[9] Chen, C., Yi, X., Zhao, X., and Xiong, B., "Characterizations of vo2-based uncooled microbolometer linear array," *Sensors and Actuators A: Physical* **90**(3), 212–214 (2001).

[10] Lazarenko, P., Sherchenkov, A., Kozyukhin, S., Babich, A., Timoshenkov, S., Gromov, D., Shuliatyev, A., and Redichev, E., "Electrical properties of the ge2sb2te5 thin films for phase change memory application," in [*AIP Conference Proceedings*], **1727**, 020013, AIP Publishing LLC (2016).

[11] Golan, G., Axelevitch, A., Sigalov, B., and Gorenstein, B., "Metal–insulator phase transition in vanadium oxides films," *Microelectronics Journal* **34**(4), 255–258 (2003).

[12] Vikhnin, V., Lysenko, S., Rua, A., Fernandez, F., and Liu, H., "The model of metal–insulator phase transition in vanadium oxide," *Physics Letters A* **343**(6), 446–453 (2005).

[13] De Almeida, L., Deep, G., Lima, A., Khrebtov, I., Malyarov, V., and Neff, H., "Modeling and performance of vanadium–oxide transition edge microbolometers," *Applied Physics Letters* **85**(16), 3605–3607 (2004).

[14] Liu, N., Mesch, M., Weiss, T., Hentschel, M., and Giessen, H., "Infrared perfect absorber and its application as plasmonic sensor," *Nano letters* **10**(7), 2342–2348 (2010).

[15] Li, Z., Stan, L., Czaplewski, D. A., Yang, X., and Gao, J., "Wavelength-selective mid-infrared metamaterial absorbers with multiple tungsten cross resonators," *Optics express* **26**(5), 5616–5631 (2018).

[16] Tittl, A., Michel, A.-K. U., Schäferling, M., Yin, X., Gholipour, B., Cui, L., Wuttig, M., Taubner, T., Neubrech, F., and Giessen, H., "A switchable mid-infrared plasmonic perfect absorber with multispectral thermal imaging capability," *Advanced Materials* **27**(31), 4597–4603 (2015).