

Metal-insulator transition (MIT) materials for biomedical applications

Abstract

Transitional metal oxides get considerable interest in electronics and other engineering applications over few decades. These materials show several orders of magnitude metal-insulator transition (MIT) triggered by external stimuli. Bio-sensing using Vanadium dioxide (VO₂), a MIT material is largely unexplored. In this short article, we investigate the VO₂ based thermal sensor performance for measuring the biomolecule concentration. Active sensing layer is chromium and niobium co-doped VO₂ as it shows 11.9%/°C temperature coefficient of resistance (TCR) with practically no thermal hysteresis. Our study demonstrated that VO₂ based microsensors can be used to measure the biomolecule concentrations, which produce temperature changes in the mK range. For 1mK change in temperature, the maximum detection voltage is near 0.4V.

Keywords: vanadium dioxide, metal-insulator transition, temperature coefficient of resistance, biosensor

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Abbreviations: VO₂, Vanadium dioxide; TCR, temperature coefficient of resistance; VO_x, vanadium oxide mixture; MIT, metal-insulator transition; mK, milli-Kelvin

Introduction

Metal oxide semiconductor materials are widely used in sensing applications.^{1,2} Vanadium dioxide (VO₂) shows temperature induced metal insulator transition with several orders of magnitude change in resistivity above room temperature (transition temperature near 68°C).^{3,4} Among many other applications, it has been studied as uncooled bolometer for several decades, because of its large temperature coefficient of resistance (TCR).^{4,5} The temperature coefficient of resistance (TCR) reported for vanadium oxide mixture (VO_x) is more than 5% per °C⁶ and 25% per °C in a vanadium oxide diode.⁷ For pure vanadium dioxide (VO₂), TCR value can reach more than 70% near the transition temperature. But this material suffers from thermal hysteresis, which results in poor measurement reproducibility.

By chromium and niobium co-doping, TCR can be increased to 11.9%/°C with practically no thermal hysteresis.⁸ Strelcov et al.,⁹ proposed and tested a novel gas sensor using single crystal VO₂ nanowire.⁹ Single crystal VO₂ nanowire (VO₂) has sharp and superior transition properties.¹⁰ In addition, small size, low thermal capacitance, and high surface to bulk ratio of VO₂ nanostructure, make them potential candidate to be researched as a high sensitivity gas sensor. A shift in MIT transition voltage is used as the indicator for a change in environments (e.g., molecular composition, pressure, and temperatures etc.). Maximum sensitivity of VO₂ nanowire sensor is $\approx 10^{-3}$ V/Pa for light gases at low pressure range. Functionalizing the NW surface with catalysts, which promotes exothermic reactions, VO₂ based sensor can be used for various chemical and gas sensing with increase in sensitivity and selectivity. Byon et al.,¹¹ demonstrated a highly responsive and selective H₂ sensor, based on electro thermally induced MIT of Pd-nanoparticles decorated VO₂ nanowire.¹¹ Simo et al.,¹² reported a room temperature H₂ sensor using VO₂ (A phase) nanobelt pellet with concentration limit about 0.17ppm.¹² To the best of our knowledge, biosensing using VO₂ material is largely unexplored. Many biological process and biochemical reaction in living cell generates or absorbs heat.

These temperature changes are usually in milli-Kelvin (mK). Inomata et al.,¹³ demonstrated that a VO₂ thermal sensor can detect cholesterol and glucose with minimum 30 and 15µM detection limit respectively.¹³ However, poor thermal isolation associated with their diaphragm structure results in high power consumptions. A cantilever based suspended structure could give better thermal isolation and consequently high signal to noise ratio with low power consumptions. In this article we perform a simulative study on VO₂ cantilever based thermal sensor for biosensing applications.

Device description

In this article, we investigate the VO₂ based thermal sensor performance for measuring the biomolecule concentration. Cr and Nb co-doped VO₂ will be used for the active sensing material for its large TCR and no thermal hysteresis behavior as mentioned above. Our sensor's schematic is shown in Figure 1. There are two VO₂ layers, the first will act as the sensing layer and other will be the reference layer. The reference sensor is primarily used to cancel out the background and measurement noise. The sensing VO₂ layer is deposited on top of a silicon cantilever. This suspended structure will provide isolation to external signal and thermal noise. For more thermal isolation a Si₃N₄/TiO₂ layer can be used on top of the silicon cantilever before depositing the VO₂ layer.

The semiconducting material's resistance change with temperature is expressed using the following Arrhenius relationship¹⁴

$$R(T) = R_0 * e^{\frac{\Delta E}{k \cdot T}} \quad (1)$$

Where, k is Boltzmann's constant, R₀ is a constant, and ΔE is the activation energy. From this equation, we can solve for the TCR as

$$TCR = \frac{1}{R} \frac{dR}{dT} = - \frac{\Delta E}{k \cdot T^2} \quad (2)$$

Device temperature response can be expressed as¹³

$$V_{Det} = G * V_{Supply} * TCR * \Delta T \quad (3)$$

Where, V_{Det} is the detection voltage, G is the amplifier gain, TCR is the VO₂ temperature coefficient of resistance, and V_{Supply}. In our

study V_{Supply} is kept constant at 5V, ΔT is assumed in the range 1-10mK. The sensor sensitivity can be expressed as

$$S = \frac{V_{Det}}{\Delta T} = G * V_{Supply} * TCR \quad (4)$$

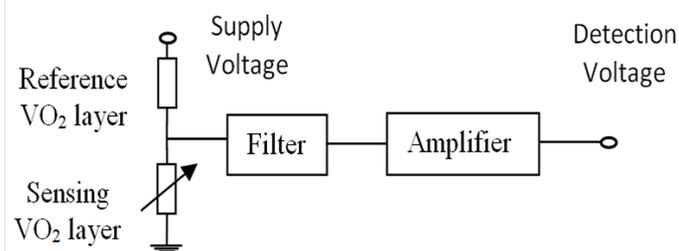


Figure 1 VO₂ sensor schematic for bio-molecule concentration detection.

Result and discussion

It is evident from Figure 2 that for 1mK change in temperature, the maximum detection voltage is near 0.4V, which is above the noise base. With Tungsten doping¹⁵ or interfacial strain engineering,¹⁶ the transition temperature can be tuned to the biological system's ambient temperature. At this temperature, TCR value is in the range of 10-70%.^{8,17} and the maximum detection voltage is about 3.73V for 1mK change in temperature. For a gain value of 1000 and TCR=5.0%, we can achieve 0.25V/mK sensitivity using our device. Still, an intensive investigation is required for design optimization to reduce the power consumption. High latent heat (over ~51kJ/kg) of MIT transition indicates that VO₂ sensor is power hungry¹⁸. Tuning the transition temperature^{15,16} close to the sensing environment will help to reduce power consumption and increase sensitivity with improved response time.

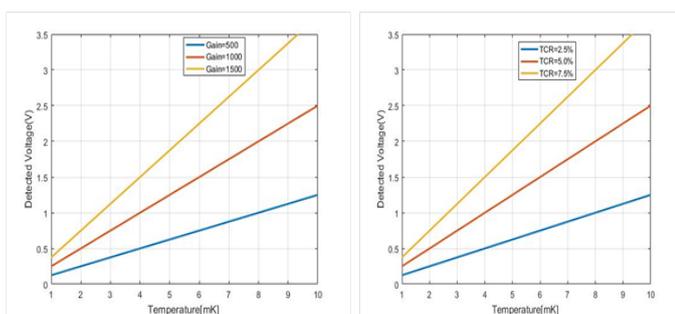


Figure 2 VO₂ sensor detection voltage as a function of temperature change in a biochemical process A) For different amplifier gain at TCR=5.0%. B) For different TCR values at gain=1000.

Conclusion

In this study, we demonstrate that VO₂ based microsensors can be used to measure the biomolecule concentrations based on their mK temperature sensitivity. In future work, we will address other technical issues, required when designing robust sensors, such as:

- I. Response time.
- II. Sensitivity.
- III. Reliability.

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Conflicts of interests

Authors declare that there is no conflict of interest.

References

1. Rahman MM, Ahammad AJ, Jin JH, et al. A comprehensive review of glucose biosensors based on nanostructured metal-oxides. *Sensors*. 2010;10(5):4855–4886.
2. Nandy T, Coutu RA Jr, Ababei C. Carbon Monoxide Sensing Technologies for Next-Generation Cyber-Physical Systems. *Sensors*. 2018;18(10):3443.
3. Morin FJ. Oxides which show a metal-to-insulator transition at the Neel temperature. *Physical review letters*. 1959;3(1):34.
4. Mahanta P, Munna M, Coutu R. Performance Comparison of Phase Change Materials and Metal-Insulator Transition Materials for Direct Current and Radio Frequency Switching Applications. *Technologies*. 2018;6(2):48.
5. Zerov VY, Kulikov YV, Leonov VN, et al. Features of the operation of a bolometer based on a vanadium dioxide film in a temperature interval that includes a phase transition. *Journal of Optical Technology*. 1999;66(5):387.
6. Jerominek H, Picard F, Vincent D. Vanadium oxide films for optical switching and detection. *Optical Engineering*. 1993;32(9):2092–2100.
7. Kuznetsov VA, Haneman D. High sensitivity to temperature and quantum effects in vanadium oxide diodes. *Journal of applied physics*. 1996;79(10):8109–8111.
8. Miyazaki K, Shibuya K, Suzuki M, et al. Chromium–niobium co-doped vanadium dioxide films: Large temperature coefficient of resistance and practically no thermal hysteresis of the metal–insulator transition. *AIP Advances*. 2016;6(5):055012.
9. Strelcov E, Lilach Y, Kolmakov A. Gas sensor based on metal–insulator transition in VO₂ nanowire thermistor. *Nano letters*. 2009;9(6):2322–2326.
10. Wu J, Gu Q, Guiton BS, et al. Strain-induced self-organization of metal–insulator domains in single-crystalline VO₂ nanobeams. *Nano letters*. 2006;6(10):2313–2317.
11. Byon JW, Kim MB, Kim MH, et al. Electrothermally induced highly responsive and highly selective vanadium oxide hydrogen sensor based on metal–insulator transition. *The Journal of Physical Chemistry C*. 2011;116(1):226–230.
12. Simo A, Mwakikunga B, Sone BT, et al. VO₂ nanostructures based chemiresistors for low power energy consumption hydrogen sensing. *International journal of hydrogen energy*. 2014;39(15):8147–8157.
13. Inomata N, Pan L, Wang Z, et al. Vanadium oxide thermal microsensor integrated in a microfluidic chip for detecting cholesterol and glucose concentrations. *Microsystem Technologies*. 2017;23(7):2873–2879.
14. Wood RA. Monolithic silicon microbolometer arrays. *Semiconductors and semimetals*. 1997;47:43–121.

15. Romanyuk A, Steiner R, Marot L, et al. Temperature-induced metal–semiconductor transition in W-doped VO₂ films studied by photoelectron spectroscopy. *Solar Energy Materials and Solar Cells*. 2007;91(19):1831–1835.
16. Muraoka Y, Hiroi Z. Metal–insulator transition of VO₂ thin films grown on TiO₂ (001) and (110) substrates. *Applied physics letters*. 2002;80(4):583–585.
17. Morin FJ. Oxides which show a metal-to-insulator transition at the Neel temperature. *Physical review letters*. 1959;3(1):34.
18. Berglund CN, Guggenheim HJ. Electronic Properties of VO₂ near the Semiconductor-Metal Transition. *Physical Review*. 1969;185(3):1022.