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Metal-insulator Transition (MIT) Materials for Biomedical Applications

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Research Article

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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 (VO_2), a MIT material is largely unexplored. In this short article, we investigate the VO_2 based thermal sensor performance for measuring the biomolecule concentration. Active sensing layer is chromium and niobium co-doped VO_2 as it shows 11.9%/°C temperature coefficient of resistance (TCR) with practically no thermal hysteresis Our study demonstrated that VO_2 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: VO_2, 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 (VO_2) 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°C [6] and 25% per °C in a vanadium oxide diode.[7] For pure vanadium dioxide (VO_2), 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 VO_2 nanowire.[9] Single crystal VO_2 nanowire (VO_2) has sharp and superior transition properties.[10] In addition, small size, low thermal capacitance, and high surface to bulk ratio of VO_2 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 VO_2 nanowire sensor is □10^{-3}V/Pa for light gases at low pressure range. Functionalizing the NW surface with catalysts, which promotes exothermic reactions, VO_2 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 H_2 sensor, based on electro thermally induced MIT of Pd-nanoparticles decorated VO_2 nanowire.[11] Simo et al.,[12] reported a room temperature H_2 sensor using VO_2(A phase) nanobelt pellet with concentration limit about 0.17ppm.[12] To the best of our knowledge, biosensing using VO_2 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 VO_2 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 VO_2 cantilever based thermal sensor for biosensing applications.

Device description

In this article, we investigate the VO_2 based thermal sensor performance for measuring the biomolecule concentration. Cr and Nb co-doped VO_2 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 VO_2 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 VO_2 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 Si_3N_4/TiO_2 layer can be used on top of the silicon cantilever before depositing the VO_2 layer.

The semiconducting material's resistance change with temperature is expressed using the following Arrhenius relationship[14]

$$R\left(\mathrm{T}\right) = R_o * e^{\frac{\Delta E}{k.T}} \qquad (1)$$

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

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

Device temperature response can be expressed as[13]

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

Where, V_{Det} is the detection voltage, G is the amplifier gain, TCR is the VO_2 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

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

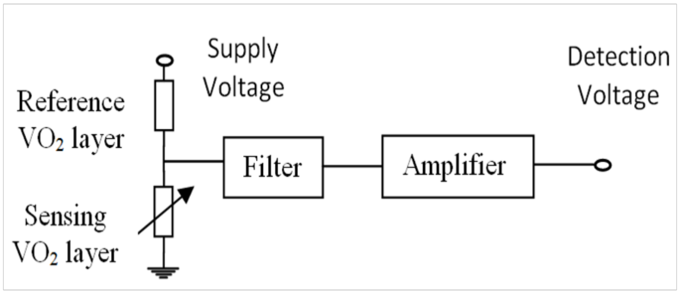

Figure 1 VO_2 sensor schematic for bio-molecule concentration detection.

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 doping[15] 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 VO_2 sensor is power hungry[18]. Tuning the transition temperature[15,16] close to the sensing environment will help to reduce power consumption and increase sensitivity with improved response time.

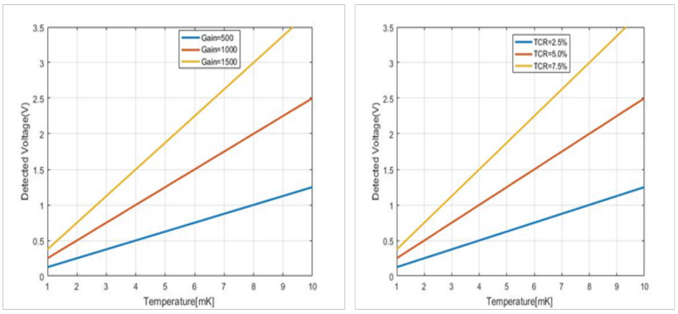

Figure 2 VO_2 sensor detection voltage as a function of temperature change in a biochemical process A) For different amplifier gain at TCR=5.0%. B) For different TCR values at gain=1000.

Conclusion

In this study, we demonstrate that VO_2 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.

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