# A NOVEL PIEZORESISTIVE PRESSURE SENSOR BASED ON CR-DOPED $V_2O_3$ THIN FILM

*Michiel Gidts, Wei-Fan Hsu, Maria Recaman Payo, Shashwat Kushwaha, Chen Wang, Frederik Ceyssens, Dominiek Reynaerts, Jean-Pierre Locquet and Michael Kraft*
KU Leuven, B-3000 Leuven, Belgium

2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS) | 978-1-6654-9308-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/MEMS49605.2023.10052552

## ABSTRACT

This paper reports the fabrication and characterization of a piezoresistive pressure sensor based on Cr-doped $V_2O_3$ thin film (Cr-$V_2O_3$TF). It is the first time that the piezoresistive effect of single crystalline Cr-$V_2O_3$TF is demonstrated experimentally and implemented as a pressure sensor. The Cr-$V_2O_3$TF piezoresistors on the membrane experience a stress change caused by a pressure input. This leads to a gradual phase transition of the material from an insulating phase to a metallic phase and results in a resistivity change. This new piezoresistive mechanism opens up the potential for developing highly sensitive piezoresistive sensors based on phase transition.

## KEYWORDS

Piezoresistive pressure sensor, transition metal oxides, thin film, phase transition, sapphire membrane

## INTRODUCTION

Piezoresistive MEMS sensors are among the earliest silicon micromachined devices. Successful integration of a piezoresistive material with micromachined flexure elements already enabled the implementation of the piezoresistive effect into various MEMS sensors and applications [1]. Though many materials like diamond [2], carbon nanotubes [3] and nanowires [4] show higher resistivity change with stress than silicon or germanium [1], they are harder to integrate in MEMS devices. However, thin film technology allows an easier integration of new piezoresistive materials in MEMS sensors [5,6]. Recently, vanadium oxide thin films have attracted much attention due to their high piezoresistive effect and integration feasibility to microfabrication [7,8]. Vanadium oxide materials are known for their interesting temperature-induced phase transition, termed as metal-insulator transition (MIT) [9,10]. This phase transition is associated with a three orders of magnitude resistivity change and has been successfully implemented in infrared microbolometer applications [11]. While most research about vanadium oxides focused on the resistivity change with temperature, vanadium oxide materials demonstrates great potential as piezoresistive material. The resistivity change with external stress has been previously investigated by Inomata et al. for sputtered $VO_x$ thin films (75% $V_2O_5$ and 25% Cr-$VO_2$) [7]. Though these $VO_x$ thin films demonstrated a high gauge factor, they did not show any obvious MIT property. Nevertheless, for single crystalline Cr-$V_2O_3$TF a gradual MIT transition at room temperature was observed when varying Cr doping level [12]. An in-plane lattice change caused by external stress was expected to cause a similar gradual MIT transition as a varying Cr doping level. Therefore, such a thin film material with a strain-caused phase transition could potentially allow the development of highly sensitive piezoresistive sensors. To demonstrate the piezoresistive effect and integration of single crystalline Cr-$V_2O_3$TF in MEMS devices, a pressure sensor based on this material was fabricated and measured.

## FABRICATION

### Material fabrication

The piezoresistive material was epitaxially grown on a (0001)-oriented $Al_2O_3$ (sapphire) substrate by molecular beam epitaxy (MBE) [12,13]. Other techniques such as magnetron sputtering [14], pulsed laser deposition [15] and chemical vapor deposition [16] epitaxial thin films have also been used to successfully fabricate $V_2O_3$ thin films. However, MBE offers several advantages. The deposition is done at low pressures (8.5 $10^{-6}$ Torr) reducing the number of impurities present in the thin film. The oxygen partial pressure in the MBE chamber and the substrate temperature can be precisely controlled allowing a good control of the stoichiometry and crystallinity of the growing layer. Finally, a low deposition rate by MBE allows a precise control of the thin film thickness.

### Sensor fabrication

Figure 1 shows the process flow for sensor fabrication. At first the membrane was micromachined on a sapphire substrate with a high-precision milling machine. The total membrane size is 2.5mm with a measured membrane thickness of 96 µm. Then the sapphire wafer was cleaned with a RCA cleaning prior to the epitaxial growth of Cr-$V_2O_3$TF with MBE. The material was subsequently patterned and etched with reactive ion etching (RIE). Au and Cr (adhesion layer) were sputtered as metal tracks for electrical connection.

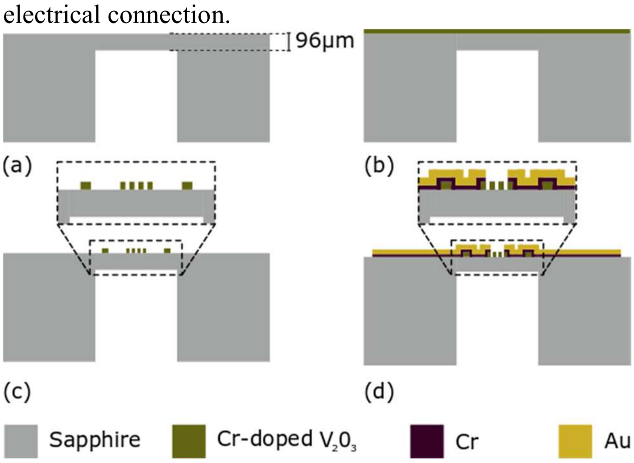


*Figure 1: Process flow for the fabrication of the Cr-doped V2O3TF pressure sensor. (a) Micromachining of the sapphire membrane (b) Deposition of the Cr-$V_2O_3$TF (c) Patterning of the Cr-$V_2O_3$TF (d) Deposition of Au and Cr.*

## DESIGN AND CHARACTERIZATION

### Sensor design

Figure 2 is a close-up top view of the sensor and sensor die bonded to a PCB. The total sensor die is 1x1 $cm^2$ with a frame thickness of 0.476 mm. The membrane is built on a sapphire substrate, which is a highly corrosion resistant material [17]. The elasticity modulus of sapphire is much bigger than silicon or stainless steel, resulting in a stiffer diaphragm with faster response time. Additionally, the piezoresistors are well isolated from the substrate, avoiding leakage currents that reduce the sensitivity of the pressure sensor. Four piezoresistors were fabricated on the membrane and connected in a Wheatstone bridge configuration through metal tracks and wire bonds. Two of the piezoresistors were placed at the center of the membrane where the stress change caused by a pressure input reaches to its maximum. The other two were placed more towards the edge of the membrane. The piezoresistors were designed with a meander shape to maximize the resistance in a limited membrane area. The piezoresistors at the center have a total length of 1.46 mm with a width of 20 µm. The piezoresistors on the outside have a length of 3.14 mm with a width of 43 µm. The bond pads are placed on the side of the sensor die Additional structures are placed on the die to characterize the material properties.

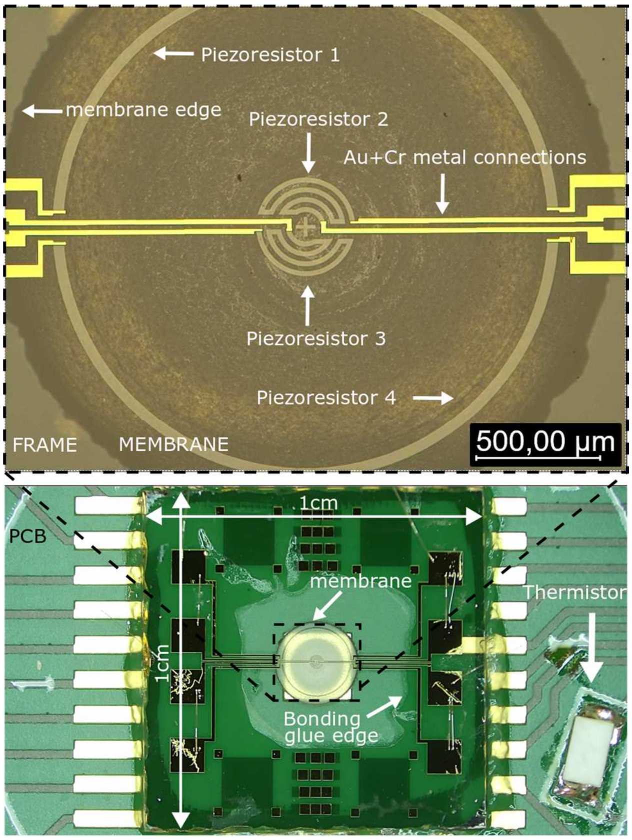


*Figure 2: Picture of the sensor and sensor die bonded on the PCB for testing.*

### Material characterization

After the patterning step, the Cr-$V_2O_3$TF thickness measured with stylus profiling was 30 nm. The resistivity of the thin film has been determined by placing additional structures on the sensor die and using the Van der Pauw (VDP) method [18] and Transfer Length Method (TLM) [19]. Both structures are shown in Figure 3. The VDP structure consists of a Cr-$V_2O_3$TF square (1.5x1.5 $mm^2$) with a Au contact pad at each corner. The contact pads and square overlap 30x30 $\mu m^2$. The TLM structure consists of Cr-$V_2O_3$TF rectangles (0.3x1.4 $mm^2$) with three Au contact pads on top. The distance between the contact pads was measured with an optical microscope. These structures were placed on the sensor die close to (see Figure 2). A resistivity of respectively 0.00188 Ω cm and 0.00151 Ω cm was measured at room temperature (20°C) by each method.

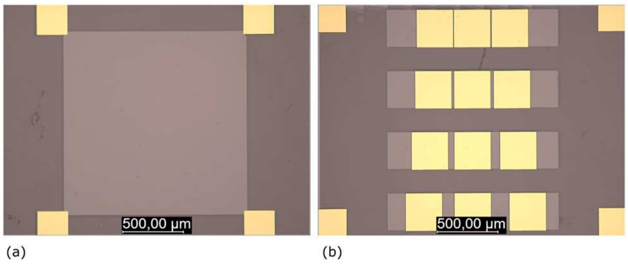


*Figure 3: (a) VDP structure (b) TLM structure*

### Sensor characterization

The pressure sensor was finally glued on a PCB and the electrical connections between the sensor and the PCB were made with wire bonds. The glue was applied extensively between the sensor die and the PCB to create a good hermetic seal. Any glue under the sensor membrane was avoided. The PCB had a hole just underneath the membrane to allow applying pressure to the membrane. A thermistor was placed close to the sensor to measure the temperature (see Figure 2). This pressure sensor was characterized under different pressures and temperatures with a measurement setup as shown in Figure 4. This measurement setup includes an accurate reference pressure sensor, a PC, a source meter, a NI data acquisition card, a temperature sensor and a pressure vessel.

The PCB was connected via HDMI cables to an external circuit. The pressure vessel was made of aluminium, it covered the entire sensor die and sealed the sensor hermetically from the outside. The temperature was controlled by placing the pressure vessel under a heat gun in a temperature chamber. For each temperature, the differential pressure was increased from 0 to 1.8 bar with steps of 0.1 bar.

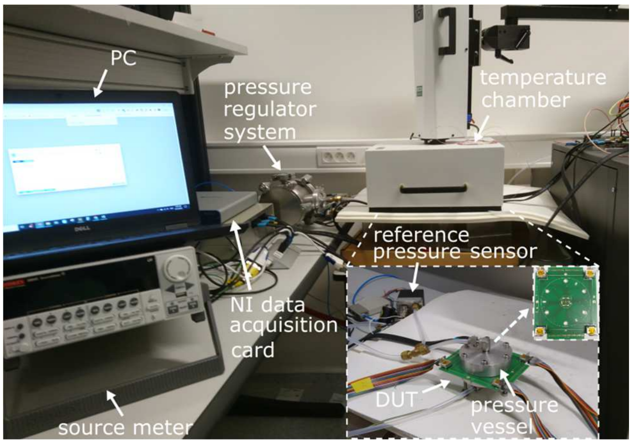


*Figure 4: Measurement setup for the characterization of the pressure sensor system.*

Figure 5 shows the output of the pressure sensor under differential pressures and temperature. At 20°C a sensitivity of 2.09 mV/V/bar was measured. The measured results showed that the pressure sensor demonstrated a linear response against pressure change. The larger the membrane size or smaller the membrane thickness are, the better the sensitivity of the pressure sensor is. The sensitivity and offset for different temperatures are listed in Table 1. With the increase of the temperature, the sensitivity was reduced while the offset was increased. The temperature coefficient of sensitivity (TCS) and offset (TCO) of the pressure sensor were -0.016 mV/V/bar/°C and 0.165 mV/V/°C respectively.

## CONCLUSION

This work reports a novel piezoresistive pressure sensor based on Cr-$V_2O_3$TF. This is the first time that the Cr-$V_2O_3$TF piezoresistivity is observed experimentally and implemented as a piezoresistive sensor. The Cr-$V_2O_3$TF piezoresistors were deposited on a micromachined sapphire membrane and characterized under different pressures and temperatures. The piezoresistivity is caused by external stress inducing a gradual MIT phase transition. This new piezoresistive mechanism opens up the potential of developing highly sensitive piezoresistive sensors based on this phase transition.

*Table 1: Measured sensitivity and offset of the pressure sensor.*

| Temperature | Sensitivity [mV/V/bar] | Offset [mV/V] |
|---|---|---|
| 20°C | 2.09 | -36.71 |
| 30°C | 1.77 | -34.28 |
| 40°C | 1.58 | -32.25 |
| 50°C | 1.53 | -30.76 |
| 60°C | 1.36 | -29.42 |
| 70°C | 1.29 | -28.48 |

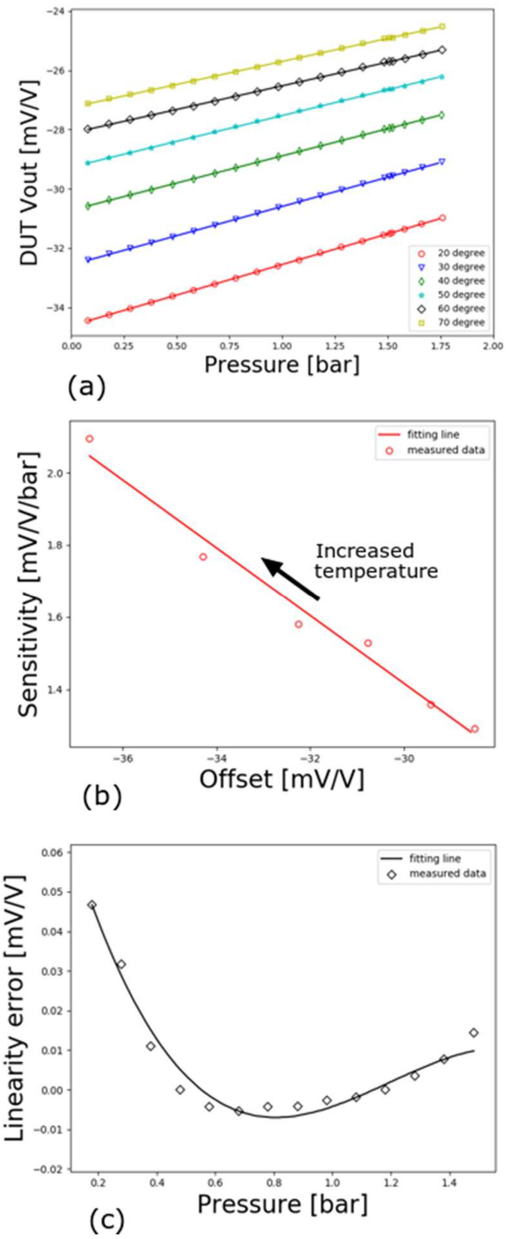


*Figure 5: Measured output of the pressure sensor. (a) Output voltage under differential pressures and temperature. (b) Sensitivity and offset. (c) Linearity error for 60 °C.*

## REFERENCES

[1] A. Barlian, W. Park, J. Mallon, ... and B. Pruitt, “Review Semiconductor Piezoresistance for Microsystems”, Proceedings of the IEEE, 97 (2009), pp. 513-552.

[2] S. Sahli, D.M. Aslam, “Ultra-high sensitivity intra-grain poly-diamond piezoresistors”, Sensors and actuators. A. Physical, 71 (1998), pp. 193-197.

[3] P. Regoliosi, A. Reale, A. Di Carlo, … and P. Lugli, “Piezoresistive behaviour of single wall carbon nanotubes”, IEEE Conference on Nanotechnology, 2004, pp. 149-151.

[4] K. Reck, J. Richter, O. Hansen and E.V. Thomsen, “Piezoresistive effect in top-down fabricated silicon

nanowires", IEEE MEMS conference, 2008, pp. 717-720.

[5] M. Mehregany, C. Zorman, N. Rajan and C.H. Wu, "Silicon carbide MEMS for harsh environments", Proceedings of the IEEE, 86 (1998), pp. 1594-1609.

[6] H. Phan, D.V. Dao, K. Nakamura, S. Dimitrijev and N.T. Nguyen, "The Piezoresistive Effect of SiC for MEMS Sensors at High Temperatures: A Review", Journal of microelectromechanical systems, 24 (2015), pp. 1663-1677.

[7] N. Inomata, N. Van Toan, M. Toda and T.Ono. "Evaluation of piezoresistivity property of vanadium oxide thin film", IEEE sensors letters, 2 (2018), pp.1-4.

[8] P. Homm, M. Menghini, J.W. Seo, S. Peters and J-P. Locquet, "Room temperature Mott metal–insulator transition in V2O3 compounds induced via strain-engineering", APL Mater. 9, 021116 (2021).

[9] M. Imada, A. Fujimori and Y. Tokura, "Metal-insulator transitions", Reviews of modern physics, 70 (1998), pp.1039-1263.

[10] L. Dillemans, T. Smets, R.R. Lieten, .... and J-P Locquet, "Evidence of the metal-insulator transition in ultrathin unstrained V2O3 thin films", Applied physics letters, 104, 071902 (2014).

[11] R. Darling and S. Iwanaga, "Structure, properties, and MEMS and microelectronic applications of vanadium oxides", Sadhana, 34 (2009), pp. 531-542.

[12] P. Homm, L. Dillemans, M. Menghini. ... and J-P. Locquet, "Collapse of the low temperature insulating state in Cr-doped V2O3 thin films", Applied physics letters, 107 (2015).

[13] L. Dillemans, R.R. Lieten, M. Menghini, ... and J-P. Locquet, "Correlation between strain and the metal–insulator transition in epitaxial V2O3 thin films grown by Molecular Beam Epitaxy", Thin solid films, 520 (2012), pp. 4730-4733.

[14] G. Sun, X. Cao, S. Long, R. Li and P. Jin, "Optical and electrical performance of thermochromic V2O3 thin film fabricated by magnetron sputtering", Applied physics letters, 111 (2017).

[15] S. Majid, D Shukla, F. Rahman, … and D. Phase, "Characterization of pulsed laser deposition grown V2O3 converted VO2", Journal of Physics: Conference Series, 755 (2016)

[16] C. Piccirillo, R. Binions, I. Parkin, "Synthesis and Functional Properties of Vanadium Oxides: V2O3, VO2, and V2O5 Deposited on Glass by Aerosol-Assisted CVD", Chemical vapor deposition, 13 (2007), pp. 145-151.

[17] S. Fricke, A. Friedberger, H. Seidel and U. Schmid, "A robust pressure sensor for harsh environmental applications", Sensors and actuators. A. Physical, 184 (2012), pp. 16-21.

[18] L L. J. Van der Pauw, "A method of measuring specific resistivity and hall effect of discs of arbitrary shape". Philips Res. Rep, 13 (1958), pp. 1-9.

[19] D. Schroder, "Semiconductor material and device characterization", 2006

## CONTACT

*Chen Wang: chen.wang@esat.kuleuven.be