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Effects of gamma irradiations on reactive pulsed laser deposited vanadium dioxide thin films

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Highlights

- Synthesis of VO₂ thin films by Reactive pulsed laser deposition has been achieved.
- VO₂ films shows the potential to be advantageously used for thermal shielding of small spacecrafts as their properties remain mainly unaffected when subjected to gamma ray doses similar to those encountered during space missions.
- The long range crystal structure of VO₂ remains intact upon irradiation on different doses up to 100 kGy
- XPS reveals a shift from V⁴⁺ to V⁵⁺ oxidation state upon irradiation, which is a consequence of frenkel pair formation on the surface rather than crystal structure modification.
- Irradiated films show the characteristic SMT of VO₂, although the electrical and optical properties are slightly affected.

Abstract

Vanadium oxide films are considered suitable coatings for various applications such as thermal protective coating of small spacecrafts because of their thermochromic properties. While in outer space, such coating will be exposed to cosmic radiations which include γ -rays. To study the effect of these γ -rays on the coating properties, we have deposited vanadium dioxide (VO₂) films on silicon substrates and subjected them to extensive γ -irradiations with typical doses encountered in space missions. The prevalent crystallographic phase after irradiation remains the monoclinic VO₂ phase but the films preferential orientation shifts to lower angles due to the presence of disordered regions caused by radiations. Raman spectroscopy measurements also evidences that the VO₂ structure is slightly affected by gamma irradiation. Indeed, increasing the gamma rays dose locally alters the crystalline and electronic structures of the films by modifying the V-V inter-dimer distance, which in turns favours the presence of the VO₂ metallic phase. From the XPS measurements of V2p and O1s core level spectra, an oxidation of vanadium from V⁴⁺ towards V⁵⁺ is revealed. The data also reveal a hydroxylation upon irradiation which is corroborated by the vanishing of a low oxidation state peak near the Fermi energy in the valence band. Our observations suggest that gamma radiations induce the formation of Frenkel pairs. Moreover, THz transmission measurements show that the long range structure of VO₂ remains intact after irradiation whilst the electrical measurements evidence that the coating resistivity decreases with gamma irradiation and that their transition temperature is slightly reduced for high gamma ray doses. Even though gamma rays are only one of the sources of radiations that are encountered in space environment, these results are very promising with regards to the potential of integration of such VO₂ films as a protective coating for spacecrafts.

Keywords: Vanadium dioxide; Thermochromic; Irradiation; Gamma rays; Thermal shielding.

1. Introduction

Thermal shielding protective coatings in spacecrafts will be increasingly important with the trend towards the reduction of the spacecraft size. Such low thermal mass spacecrafts, like Cubesats, will thus have to be designed to

retain or reject heat more efficiently [1]. The protective coating radiation device (PCR) is a new type of thermal control material for spacecraft that displays high potential to efficiently replace the current space thermal control systems, which rely on heaters with an additional power penalty to maintain spacecraft temperature close to room temperature during cold swings. As its emissivity changes without requiring any electrical instruments or mechanical parts, the PCR allows decreasing the requested power budget [2]. The VO₂-based PCR is one of the most promising parts of this functional thermal control surface and has the advantage of being lighter and free of moving devices. Indeed, VO₂ undergoes a reversible first order semiconductor-to-metal phase transition (SMT) at a critical temperature $T_c \approx 68^\circ\text{C}$. Above T_c , VO₂ has a rutile structure with the $P4_2/mmm$ (136) space group, corresponding lattice parameters $a_R = b_R = 4.55 \text{ \AA}$ and $c_R = 2.85 \text{ \AA}$ and all the V-V bonds are equidistant ($\sim 2.87 \text{ \AA}$), so the d orbital electrons are shared by all the vanadium ions along the V-V chain. At temperatures below T_c , VO₂ has a monoclinic structure with the $P2_1/c$ space group and lattice parameters $a_M = 5.75 \text{ \AA}$, $b_M = 4.54 \text{ \AA}$, $c_M = 5.38 \text{ \AA}$ and $\beta = 122.6^\circ$ [3]. This structure is characterized by a V-V dimerization and alternatively short ($\sim 2.65 \text{ \AA}$) and long ($\sim 3.12 \text{ \AA}$) V-V bonds that results in localization of d orbital electrons to individual ions. Both the rutile and monoclinic structures of VO₂ are based on a given oxygen bcc lattice for which the position of the vanadium ions (V⁴⁺) determine the different crystal phase kind. For the rutile structure, the vanadium atoms are located in the center of the oxygen octahedra while in the monoclinic structure, they are slightly shifted from the center. The zigzag-like distortion of the V-V chains leads to two different apical V-O bond distances of 1.77 and 2.01 $\text{\AA}$ and the metal atom pairing results in two long and two short equatorial V-O distances of 1.86, 1.89, 2.03 and 2.06 $\text{\AA}$. The unit cell of the rutile structure contains two formula units while the monoclinic structure contains four formula units due to the Peierls-like pairing of the vanadium atoms. The unit cell is thus doubled as the structure changes from rutile to monoclinic. This transition is accompanied by significant changes in the material electrical resistivity and optical transmission [4-8], which magnitude depends upon the microstructure and electronic properties of the material [9,10]. Because of its switching characteristics, VO₂ can thus be used as a thermal shielding coating to limit radiation on sensitive opto-electrical devices [11, 12, 13]. VO₂ thin films could eventually be integrated to PCR devices for the design of ZA Cube 2 [14], a nanosatellite conceived for space weather research missions that is currently in development, demonstrating their potential for space applications.

A large portion of the heat exchange between an object in space and the environment is performed throughout radiation, which is in turn determined by the object's surface properties. It is therefore crucial to ensure that the object's surface coating is not modified by the possible irradiations it might encounter in space environment. When solids are bombarded with radiation, electrons may be removed from their orbits and atoms may be knocked out of their sites. Furthermore, impurities may be introduced, either by nuclear transmutation, bombarding ions implanted in the material or by a strong coulomb field that creates charged particles which result in single and multiple point defects. As a result, irradiation of materials can modify their properties, either slightly or drastically [15-20]. Studies on the irradiation of VO₂ thin films with heavy ions [21-25] showed that displacement cascades occur, which is the driving mechanism through which disordered regions and defects are inhomogeneously generated in the thin films [26]. These studies also reported that the irradiation-induced defects alter the SMT of VO₂ by lowering both the phase transition temperature and the semiconductor phase resistivity. While studies on the displacement of atoms by gamma rays irradiation remains scarce, previous reports have shown that measurable defects can be produced [27]. At high energy

(± 1.5 MeV), Compton scattering and pair production are likely to be the interaction processes driving the atomic displacement. In this paper, we thus investigated the effects of the interaction of γ -rays on the displacement of atoms, the electronic structure, the crystal microstructure, the lattice vibrations and phonon modes as well as on the optical transmission and electrical properties of vanadium dioxide thin films irradiated with doses typical to those encountered in space missions.

2. Experimental details

2.1 Deposition of VO₂ thin film

A VO₂ thin film was deposited on a 3'' diameter Si (100) substrate by means of reactive pulsed-laser deposition (RPLD) from a vanadium target (99.95% purity, KJ Lesker) using a KrF excimer laser ($\lambda = 248$ nm, fluence ≈ 2 J/cm², repetition rate of 10 Hz). Prior to the deposition, the chamber was pumped down to a base pressure of $\sim 10^{-6}$ Torr while during deposition; the oxygen pressure was kept at 10 mTorr with a constant oxygen flow of 5 sccm. The target-to-substrate distance was set at 6.5 cm and the substrate temperature was kept at 500°C. The laser beam was moved over the target by means of a focusing lens that continuously translated and the substrate was rotated in order to get good film homogeneity. The deposition time to achieve the desired VO₂ film thickness of 200 nm was adjusted from the deposition rate (0.03 nm/s), which was determined from cross-sectional scanning electron microscopy (SEM) observations of a VO₂ test sample. Fig. 1(a) shows the cross-section SEM image of the 185 nm thick VO₂ test sample obtained for a deposition time of 6300 seconds, from which the deposition rate was determined.

2.2 γ -irradiations of VO₂ thin films

The 200 nm-thick VO₂ thin film was cut into smaller size samples (1 cm X 1cm) and irradiated at 3, 9, 60, 80 and 100 kGy gamma ray doses respectively. A Cobalt-60 point source panoramic irradiator (ARC Infruitec Stellenbosch, Western Cape, South Africa) was used to irradiate the samples. For irradiation experiments, the samples were mounted on a turntable at a distance of 250 mm from the source. The turntable, which is perpendicular to the source, rotates around the Z-axis at 2 rpm for the duration of the irradiation. Dose rate measurements were performed using Fricke Dosimeters with standard G-value for Fe³⁺ = 15.5/100 eV radiation energy absorbed. The dosimeter's response was checked with a Cobalt-60 radiation field setup (6 mm build-up and 50 mm backscatter in a 300 mm x 300 mm collimated field). The output factor was determined using a Farmer tissue equivalent ionization chamber calibrated in a standard field of National Metrology Laboratory (C.S.I.R.). The dose rate measured at the time of irradiation was 38.8 Gy/min, so the exposure times were calculated accordingly.

2.3 Characterization of VO₂ thin films

The microstructure of the VO₂ thin films was evaluated by grazing incidence X-ray diffraction (GIXRD, $\omega = 1.5^\circ$ and $\lambda (K_{\alpha 1}) = 1.5406$ Å) to overcome the intense Si substrate peaks present in the same region as the VO₂ peaks. Raman spectroscopy was performed at room temperature to get information on the vibrational modes of the as-deposited and irradiated thin films, with the Si mode from the substrate centered at 522 cm⁻¹ for calibration. The electronic structure

and the oxidation states of the as-deposited and irradiated VO₂ thin films were investigated by X-ray photoelectron spectroscopy (XPS) using the monochromatic Al K α radiation ($h\nu=1486.7$ eV). The electron take-off angle was 45° and the diameter of the measurement spot was $\sim 150\mu\text{m}$. The Au4f_{7/2} peak at 83.96 eV was used for the energy calibration of the instrument and no Ar-sputtering was performed prior to the measurements.

The optical properties of the VO₂ films were measured using a THz time-domain spectrometer (TeraFlash, Toptica) in the transmission configuration. The samples were mounted on a heating stage and measured in the range of temperature going from 40°C to 100°C for both heating and cooling segments. The electrical properties of the VO₂ thin films through the SMT were measured using a physical property measurement system (PPMS, (Quantum Design, model P600) using the four-probe geometry at temperature ranging from 27°C to 127°C for both heating and cooling segments.

3. Results and Discussion

Fig. 1(a) shows the GIXRD diffractograms of the as-deposited VO₂ film and the irradiated films at 3, 9, 60, 80 and 100 kGy doses respectively. The diffractogram of the as-deposited film closely matches that of the monoclinic phase of VO₂ (JCPDS No. 00-043-1051), which corresponds to the space group P21/c, with lattice parameters $a=5.75$ Å, $b=4.54$ Å, $c=5.38$ Å and $\beta=122.6^\circ$. No other phases were identified and the strong peak at $2\theta=28.03^\circ$ indicates the (011) preferred orientation of the film. Comparing the diffractograms of the as-deposited and irradiated VO₂ films, no significant structural modification with increasing the gamma ray dose is observed. Metal oxides subjected to irradiations have been reported to undergo complex structural modifications which depend on the nature of the material, the radiation energy and the dose [28]. Several studies already reported crucial information concerning the influence of defects on the growth and crystallization of Fe nanoclusters implanted in SiO₂ [29] as well as on ion-implanted TiO₂ crystals [30] and ZnO thin films [31,32] and crystals [33]. These effects on radiation-resistant materials usually consist of defects production, disordering and clustering, grain growth, fragmentation, swelling, and polygonization [34,35]. On the other hand, in materials with a higher susceptibility to damage accumulation, crystalline-to-crystalline phase transformations [36–39], amorphization [37,40] and chemical effects (cation reduction, anion loss) [41,42] are observed. As VO₂ is known to be thermodynamically stable and resistant to radiations, the irradiation doses reported above are likely to induce defects, clustering, disordering and atomic displacements whilst the long range structure of VO₂ is expected to remain unchanged. As observed in Fig. 1(b), while the peak position of the preferred (011) orientation remains very similar for the as-deposited and 3 kGy irradiated thin films, a shift to lower 2θ values is observed for the samples irradiated with doses from 9 kGy to 100 kGy. This reveals that the threshold gamma dose required for the radiation effects on the structure to become significant occurs between 3 kGy and 9 kGy. This shift is attributed to the atomic displacement in the lattice structure of VO₂ and to strain in the out-of-plane direction due to high energy irradiation that creates defects and disordered regions. Similar behavior was observed for VO₂ thin films irradiated by 200 MeV Au swift heavy ions, which indicates that irradiation results in a displacement cascade and a distortion of the structure of the VO₂ films, as also suggested by a shift of the (011) preferred orientation towards lower 2θ values with increasing fluence [43]. Fig. 2 shows the Raman spectra at room temperature of the as-deposited and the irradiated films. Intense peaks are present in the Raman spectra of the as-

deposited film at 195, 225 and 618 cm^{-1} while less intense peaks are present at 263, 309, 338, 391 and 497 cm^{-1} . All these peaks, which belong to the Ag and Bg symmetries, were reported to correspond to the signal of the structure of monoclinic VO_2 [44, 45]. The phonon modes at lower energies (~ 195 and 225 cm^{-1}) are assigned to the V—V vibrations [45], while the phonon modes in the intermediate and high-energy regions are assigned to V—O vibrations [45, 46]. Furthermore, the phonon mode at 618 cm^{-1} is assigned to the stretching mode of V—O vibration while the phonon modes in the intermediate energy range are associated with the different bending modes of V—O vibration. The presence of a Raman peak is also observed at $\sim 140 \text{ cm}^{-1}$ for all the studied samples. This low-frequency Raman peak is reported to have its origin from an external mode, which is determined by oscillating rigid O-V-O chains. While the intensity of the Raman peaks at 195 and 225 cm^{-1} slightly increases with gamma irradiation, the low, intermediate and high energy modes do not show any significant change with increasing dose, which indicates that the local VO_2 structure remains unaffected. The differences observed in the intensity of the Raman peaks for increasing gamma dose might be attributed to a difference in the degree of alteration induced by the irradiation, which modifies the electronic structure of the films. The induced crystalline defects, such as vanadium/oxygen displacements/vacancies, could disrupt the mode of the crystallographic transition or create mixed phases with altered switching behavior. [47] The higher intensity of the Raman peaks at 195 and 205 cm^{-1} could thus be attributed to stronger V-V interactions, which favors the presence of the VO_2 metallic phase by bringing the monoclinic short ($\sim 2.65 \text{ \AA}$) and long ($\sim 3.12 \text{ \AA}$) V-V dimers distances closer to the rutile uniform ($\sim 2.87 \text{ \AA}$) V-V distance. The observed behavior under gamma irradiations contrasts with that resulting from He-irradiation, which indicates a rearrangement of the phonon modes of VO_2 with increasing fluence [25]. Fig. 3 shows the XPS survey scan of the as-deposited VO_2 film measured in the energy range 0-700 eV with a step size of 0.5 eV, at a pass energy of 117.4 eV and both neutralizers on. Besides the expected presence of peaks from V and O contribution, Si is also observed for all samples, which can be attributed to a misalignment of the x-ray beam that would hit the cross-section of the sample. The traces of C, Na, Ca and N are due to surface contamination.

All detailed spectra that were recorded for determining the sample's vanadium oxidation states (V2p, O1s and the valence band) were measured at a pass energy of 58.70 eV with a step size 0.25 eV. The detailed spectra of the V2p core level of the as-deposited and irradiated films are shown in Fig. 4(a). The V2p_{3/2} peak, which is commonly used in core level XPS studies to account for the stoichiometry and oxidation state of vanadium oxide thin films [48-53], is observed at 516.03 eV for the as-deposited film, suggesting a V^{4+} oxidation state on the surface and confirming the stoichiometry of the VO_2 film. Because the samples were measured without being previously etched with argon to remove the surface contaminants, the top layer of the VO_2 films is likely to be over-oxidized. As a consequence, there might be a higher V^{5+} valence state content at the air/ VO_2 film interface than in the bulk of the film. The O1s spectra in Fig. 4(b) shows a peak at 529.6 eV, which is attributed to the presence of V^{4+} on the surface, and a peak at ~ 532 eV, which is related to the carbon contamination on the surface. The V2p_{3/2} peak shifts towards higher binding energies with increasing γ -dose, the largest shift being observed for the sample irradiated at 80 kGy dose. This is further corroborated by a shift of the V2p_{1/2} and O1s peaks towards higher binding energies, revealing the effects of gamma rays on the electronic structure of VO_2 films. The creation of defects and disordered regions in VO_2 thin films was observed for Au irradiation at high fluence [43] and it was accompanied by a shift of the V2p_{3/2} peak towards lower

binding energy values as the ion fluence increases, which is in close agreement with the V^{3+} valence state. This behavior was attributed to localized heating around VO_2 domains by the 200 MeV Au ions, which leads to oxygen deficiencies and increasing concentration of V^{3+} with fluence. In contrast with this study, we observe a shift of the $V2p_{3/2}$ peak towards higher binding energy values while irradiating the VO_2 thin film with gamma rays. In this case, the defects caused by gamma irradiation occur in the disordered regions. The displaced atoms creating these disordered regions are either in or very close to a vacant lattice site of the wrong kind (V^{5+}) [18]. Theoretical and experimental reports show that γ -rays interactions with energy above 25 eV produce Frenkel defects, whereby the atomic displacement may leave lattice vacancies, lodge in interstitial locations or even cause interchange/rearrangement of dissimilar atoms in the lattice structure [15-18]. The observed peak shift is thus due to the formation of a Frenkel pair defects caused by a series of cascade displacement of atoms in the disordered regions, which results in vacancy and interstitial atoms.

The γ -rays in the ^{60}Co MeV energy range interact with VO_2 surface atoms through Compton scattering. These Compton electrons are the source of atomic displacements, which leads to the formation of cation vacancies and cation interstitials observed between V^{4+} and V^{5+} region. When an incident γ -ray ejects an atom from its normal lattice position, the ejected atom, known as a primary knock-on, may in turn cause a cascade of atomic displacements before eventually coming to rest. The cascades of displaced atoms then result in an interstitial while the position initially occupied by the atom becomes a vacancy. Together, the interstitial and vacancy are referred to as a Frenkel pair. The production of these Frenkel pairs defects by the γ -irradiation induced cascaded displacement is thus at the origin of the observed $V2p_{3/2}$ peak shift, which is also accompanied by a reduction of its intensity.

Fig. 5 shows the valence band of the as-deposited and irradiated films. The valence band of the as-deposited VO_2 film displays two distinctive peaks; a broad intense peak centered at 6 eV, attributed to the O2p region, and a narrow low intensity peak around 1.5 eV, attributed to the V3d region. The position of these valence band peaks are in agreement with previously reported values [54-55]. The comparison of the valence band of the as-deposited VO_2 film with that of the gamma irradiated films highlights a reduction in the intensity of the V3d band with increasing dose and an increase in the intensity of the O2p band. This is in agreement with the observed shift of the $V2p_{3/2}$ peak towards higher binding energies due to the displacement of atoms towards or very close to the $V3d^0$ occupation.

The transmission properties of the VO_2 thin films were measured by terahertz time-domain spectroscopy between 0.1 and 1.5 THz. Fig. 6(a) shows the THz signal transmitted through air without sample in the THz beam (reference) as well as through the as-deposited VO_2 film in the semiconducting and metallic state respectively. The amplitude of the transmitted THz signal decreases significantly between $T=40^\circ C$ and $T=96^\circ C$ as metallic domains are created and spread across the VO_2 film area with increasing temperature. The Fourier transform of such a pulse reveals spectral properties in the THz range. Fig. 6(b) shows the spectra of the three pulses in Fig. 6(a) in the range of 0.1-1.5 THz. The absorption lines present in all three spectra are due to water absorption in air. The periodic fringes in the VO_2 measurements are due the interference of internal reflections in Si with the direct transmitted beam. The π -phase shift observed between $T=40^\circ C$ to $T=96^\circ C$ is further distinctive signature of the thermally-induced phase transition of the VO_2 film as reflections on a metallic interfaces induce a π -phase shift compared to a reflection at an insulating interface. The hysteresis cycle of the THz transmission through the semiconductor-to-metal phase transition for the

as-deposited and gamma irradiated VO₂ samples are shown in Fig. 6(c), where the THz transmission of the samples was normalized to that of the reference. Here, the shape of the hysteresis curves is seen to be independent of the γ -irradiation, which agrees with the previous results that show that the bulk of the VO₂ films is mainly unaffected by the gamma ray irradiation. Moreover, the shift of the transition temperature among the different samples is within an error of 1°C. However, a closer focus on the hysteresis width of the VO₂ films reveals a small increase with gamma treatment, as shown in Fig. 7. Since the relative temperature error is estimated to 0.3°C, the gamma irradiation might induce small defects in the bulk structure of the VO₂ film, which in turns increases the hysteresis width [56].

The temperature dependence of the electrical resistivity for the as-deposited and gamma irradiated VO₂ thin films is shown in Fig. 8. The as-deposited film exhibits a characteristic first order SMT at T~68°C, with a resistivity change by ~ 3 orders of magnitude between semiconducting and metallic states. The irradiated films also exhibit the typical thermally-induced switching behavior of VO₂, but noticeable changes are observed with increasing dose. Indeed, the transition temperature slightly shifts to lower temperatures as the gamma dose increases from 9 kGy to 60 kGy, whilst the width of the hysteresis of the film at 80 kGy is much broader. Both the optical and electrical properties of gamma irradiated films do not present any major change and the small changes that are observed here are due to gamma irradiation that creates localized defect sites and certain imperfections on the bulk structure of VO₂, which thus causes the observed enlargement of the hysteresis width at higher dose. Moreover, in the electrical measurements, the resistivity of the films in the semiconducting and metallic states is reduced, which suggests, as indicated by the larger intensity of the peaks assigned to V-V vibrations in the Raman spectroscopy measurements, that the disordered trails induced by irradiation create metallic domains which contribute to the conductivity enhancement of the irradiated films.

Conclusions

In conclusion, we have shown that the long range crystal structure of VO₂ remains intact upon γ -irradiation up to 100 kGy doses, although some weakening of the crystal structure appears at doses above 80 kGy. This is supported by Raman spectroscopy, which reveals that the crystallographic structure and phonon modes of VO₂ remain the same after gamma irradiation. However, the radiation doses used in this study create defects, disordered regions and displacement of atoms as indicated by the shift of the preferred orientation of VO₂ monoclinic structure ((011) peak). Irradiation also affects the VO₂ electronic structure as the 3d band is reduced while the V2p band is shifted towards higher binding energy values (higher valence cation state). This is the consequence of atomic displacement cascades which create interstitials in the lattice site of V⁵⁺ ions. The fact that the stoichiometry of the VO₂ films is maintained indicates that the observed core level shift is not due to a chemical gradient or structural phase transformation from V⁴⁺ to V⁵⁺, but is rather a consequence of the creation of defects and disordered regions in or very close to the lattice site of the V⁵⁺ ions. This is well supported by the optical and electrical properties studies that show the THz transmission and the electrical resistivity across the SMT being almost unaffected by gamma irradiation. We thus expect that VO₂ films could be advantageously used for thermal shielding of small spacecrafts as their properties remain mainly unaffected when subjected to gamma ray doses similar to those encountered during space missions.

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Fig. 1(a) SEM cross-section image of the 185 nm thick VO₂ test sample from which the deposition rate was determined. (b) GIXRD diffractograms and (c) Position of the (011) peak for the as-deposited and gamma irradiated VO₂ films.

Fig. 2. Room temperature Raman spectra exhibiting the Ag (*) and Bg (◇) modes of the as-deposited and gamma irradiated VO₂ films. The red dotted line is used to indicate the position of the 140 cm⁻¹ Raman peak, which is independent of the gamma irradiation dose.

Fig. 3. XPS survey scan spectrum of the as-deposited VO₂ thin film.

Fig. 4. Detailed spectra of the (a) V2p core level and (b) O1s core level of the as-deposited and gamma irradiated VO₂ thin films. The black dashed lines in (a) are used to indicate the position of the V2p_{3/2} and V2p_{1/2} peaks for the as-deposited thin film.

Fig. 5. Valence band of the as-deposited and gamma irradiated films. The black dashed line is used to indicate the position of the V3d peak for the as-deposited thin film.

Fig. 6(a) THz waveforms and (b) spectra of the transmitted THz pulses for the reference as well as for the as-deposited VO₂ film in the semiconducting (40°C) and metallic state (96°C). (c) Heating and cooling segments of the normalized THz transmission showing the hysteresis of the as-deposited and gamma irradiated VO₂ thin films across the semiconductor-to-metal phase transition.

Fig.7. Hysteresis width between the heating and cooling segments from the normalized THz transmission of the as-deposited and gamma irradiated VO₂ films as a function of the gamma dose.

Fig. 8. Electrical resistivity as a function of temperature for both heating and cooling cycles of the as-deposited and gamma irradiated VO₂ films.