Oxide Electronics Utilizing Ultrafast Metal-Insulator Transitions

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Abstract
Although phase transitions have long been a centerpiece of condensed matter materials science studies, a number of recent efforts focus on potentially exploiting the resulting functional property changes in novel electronics and photonics as well as understanding emergent phenomena. This is quite timely, given a grand challenge in twenty-first-century physical sciences is related to enabling continued advances in information processing and storage beyond conventional CMOS scaling. In this brief review, we discuss synthesis of strongly correlated oxides, mechanisms of metal-insulator transitions, and exploratory electron devices that are being studied. Particular emphasis is placed on vanadium dioxide, which undergoes a sharp metal-insulator transition near room temperature at ultrafast timescales. The article begins with an introduction to metal-insulator transition in oxides, followed by a brief discussion on the mechanisms leading to the phase transition. The role of materials synthesis in influencing functional properties is discussed briefly. Recent efforts on realizing novel devices such as field effect switches, optical detectors, nonlinear circuit components, and solid-state sensors are reviewed. The article concludes with a brief discussion on future research directions that may be worth consideration.
1. INTRODUCTION

Metal-insulator transition (MIT) in oxides (1) is a topic of long-standing interest in condensed matter materials sciences. Experimental and theoretical studies to unravel the mechanism of MIT have been ongoing for nearly half a century. A number of reviews on MIT mechanisms and materials in the past 40 years indicate the consistent interest in this subject (1–10). Significant interest in MIT in oxide materials (11–19) initiated from Morin’s (11) seminal paper on phase transitions in binary transition-metal oxides in the 1950s and was further promoted by MIT-relevant discoveries in correlated oxides such as, but not limited to, high-temperature superconductivity in cuprates (20) and colossal magnetoresistance in manganites (21). As Morin noted, the resistance in some transition-metal oxides, such as vanadium oxides [dioxide (VO2), sesquioxide (V2O3), and monoxide (VO)] and titanium sesquioxide (Ti3O5), increases by several orders of magnitude when the temperature decreases from high to low across the transition temperature ($T_{MIT}$) (11). Recent years have seen major advances in growth of thin-film oxides by a variety of techniques such as molecular beam epitaxy, sputtering, chemical vapor deposition (CVD), and pulsed laser deposition (PLD), and resurgence in the oxides MIT field is taking place, with growing emphasis on exploring device applications of this spectacular phenomenon. A principal focus of this review is on oxide materials and devices utilizing MITs, along with a qualitative discussion on the mechanisms. Particular emphasis is placed on emerging research devices operable near room temperature wherein the phase transition can be triggered by small thermal, electrical, or optical perturbations. We point the reader to the article by Imada et al. (8) for a detailed account on the theory of MITs.

Figure 1a shows a number of correlated oxides with corresponding MIT temperatures (3, 6, 8, 12, 22). The elementary mechanism leading to the transition as well as the resistivity magnitude change are different among these materials and are considered in later sections. Figure 1a shows only the oxides with MIT triggered by temperature, and not other correlated oxides with non-temperature-driven mechanisms (such as band-filling control, displayed by some manganites and cuprates). Among these correlated oxides, the $T_{MIT}$ of VO2 is close to room temperature, which is $\sim 340$ K in bulk crystals. This unique property coupled with an impressive five-order-of-magnitude resistance change (in single crystals) across the transition make VO2 a compelling candidate for exploratory device research. This article uses VO2 as a representative example for discussing the phase transition and potential devices that could be realized.

As mentioned above, a frequently employed approach to induce MIT is thermal triggering, i.e., changing the temperature by heating or cooling. As shown in Figure 1b (part i), with a temperature increase from 341 to 344 K, the resistance of the VO2 thin film decreases by nearly four orders (23). Other approaches to trigger the phase transition include electrical (19, 24), optical (19, 25, 26), magnetic (19), and strain (27) excitations. An example of each of these approaches is shown in Figure 1b, parts ii–v, respectively. Figure 1c shows how one could utilize MIT as a switch. An external perturbation in the form of thermal, electrical, optical, or magnetic field can trigger the phase transition, leading from a high-resistance OFF state to a low-resistance ON state, i.e., inducing the switching behavior. In some cases, combination of two or more excitations can lead to the transition at different thresholds.

Figure 2a points out potential applications for MITs in oxides in materials physics and solid-state electronics, whereas Figure 2b shows representative device concepts utilizing MIT in correlated oxides, including two-terminal electronic switches (28), three-terminal (gated) electronic switch devices (29), optical devices (30), electronic oscillators (31), metamaterials (32), memristive devices (33), thermal sensors (34), and chemical sensors (35). The subsections in which each is discussed in the review are indicated in Figure 2b. If one considers the physical
Figure 1

The metal-insulator transition (MIT) switch. (a) MIT temperature ($T_{MIT}$) of some selected oxides (bulk crystals). External stress or substrate-driven constraints can significantly influence the transition temperature and the resistivity change. (b) MIT-triggering approaches in correlated oxides. (i) Temperature-triggered MIT in VO$_2$. (ii) Electrically triggered MIT in Pr$_{0.7}$Ca$_{0.3}$MnO$_3$. (iii) Optically triggered MIT in Pr$_{0.7}$Ca$_{0.3}$MnO$_3$. (iv) Magnetically triggered MIT in Pr$_{0.7}$Ca$_{0.3}$MnO$_3$. (v) Strain/stress effects on MIT in VO$_2$. Panel $c$ adapted with permission from Reference 23; panels ii–iv adapted with permission from Reference 19; panel v adapted with permission from Reference 27. (c) Basic concept of utilizing MIT in correlated oxides as a switch, with the high-resistance, insulating and low-resistance, metallic states on both sides of MIT, defined as OFF and ON states, respectively. The switching of the device can be triggered thermally, electrically, optically, magnetically, and by strain drive, corresponding to the MIT-triggering approaches shown in panel $b$. 
Figure 2
Devices utilizing MIT in correlated oxides. (a) MIT in oxides: a compelling case for materials physics and solid-state electronics research. (b) A selected collection of device applications that use MIT in correlated oxides and that are discussed in this review, including two-terminal electronic switch devices, three-terminal (gated) electronic switch devices, optical devices, electronic oscillators, metamaterial devices, memristive devices, thermal sensors, and chemical sensors. The subsection numbers of each device in the review are indicated in blue text. Panel b adapted with permission from References 28–35.
scaling limits that Si complementary metal-oxide semiconductor (CMOS) field effect transistor (FET) technology is facing (36–40), novel, correlated oxide-based devices are worth exploring as alternate candidates for information processing, and ultrafast phase transitions may be interesting computational vectors.

2. ELEMENTARY MECHANISMS OF THE METAL-INSULATOR TRANSITION

Mott (1, 3, 6, 41) forwarded a model for MIT considering electron-electron interactions. Per Mott’s theory, a critical carrier density \( n_c \) is proposed as \( n_0^{1/3} a_H \approx 0.2 \), where \( a_H \) is the Bohr radius of the material. Once the carrier density in the material is larger than \( n_c \), a phase transition occurs due to the electron-electron interaction effect, i.e., correlation. The MIT discussed above is named Mott MIT (or Mott-Hubbard MIT), and the insulator therein is accordingly referred to as the Mott-Hubbard insulator. However, MIT phenomena can also happen due to reasons other than an electron correlation effect. For example, MIT can also occur from an electron-phonon (electron-lattice) interaction, which is referred to as Peierls MIT (42, 43). Generally, the Peierls MIT arises from a lattice structural change in a material. The structure change induces a lattice deformation, which modifies the periodic ionic potential in the material and consequently results in a band structure change. The blue bronze \( K_0.3MoO_3 \) is a typical example of a Peierls insulator, which undergoes a Peierls MIT at 181 K, with an evident conductivity change accompanied by a structure change (43). The electron localization effect due to disorder (44–46) can also lead to Anderson MIT. In the 1950s, Anderson (44) observed that randomly distributed lattice defects could lead to an insulating state. The disorder-induced electron localizations result in the existence of a mobility edge, which separates the localized and delocalized states in the bands. Insulating states form once the Fermi level is between a band edge and its mobility edge. Anderson MIT commonly appears in strongly disordered materials and materials with strong impurity scattering, such as heavily doped semiconductors (e.g., Si:P). An insulator under the frame of conventional band theory (without consideration of the electron-electron interactions) is termed a band insulator (or Bloch-Wilson insulator). Diamond and common undoped semiconductors are examples of band insulators. Table 1 briefly summarizes the above four categories of insulators. Mott-Hubbard insulator and charge-transfer insulator are other proposed classifications. The difference between the two is due to the magnitudes of two parameters: Hubbard Coulomb repulsion energy \( U \) and charge-transfer energy \( \Delta \). The smaller of the two parameters determines the type of classification. For example, \( V_2O_3 \) is a typical Mott-Hubbard insulator, whereas \( NdNiO_3 \) is a charge-transfer insulator.

Generally, the control parameters for MIT can be classified into three categories: temperature control, bandwidth control, and band-filling control. Temperature control, the most straightforward case, simply involves changes in temperature by heating or cooling. The oxide systems shown in Figure 1a display temperature-controlled MIT with a \( T_{MIT} \) defined in the x axis. Bandwidth control can be induced by external or internal pressure. Internal pressure can be achieved with substitutional doping with atoms of different sizes. A typical example is \( RNiO_3 \)-type (\( R = Pr, Nd \), and \( Sm \)) material. Band-filling control is related to tuning the doping level with donors or acceptors. MIT in most cuprates and manganites is the band-filling-control type; in these materials, high-temperature superconductivity and colossal magnetoresistance, respectively, are observed. Some materials can show more than one control parameter; for example, \( RNiO_3 \) can be either temperature or bandwidth controlled. Table 1 summarizes the three control types. In addition to the above three control parameters, dimensionality can also be a control parameter inducing
Table 1  Classification of insulators and control mechanisms of metal-insulator transition (MIT)

<table>
<thead>
<tr>
<th>Classifications of insulators</th>
<th>Type</th>
<th>Origin</th>
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<tbody>
<tr>
<td></td>
<td>Bloch-Wilson insulator (also known as band insulator)</td>
<td>Under the framework of conventional band theory</td>
</tr>
<tr>
<td></td>
<td>Mott-Hubbard insulator</td>
<td>MIT occurs due to electron-electron interactions (correlations)</td>
</tr>
<tr>
<td></td>
<td>Peierls insulator</td>
<td>MIT occurs due to electron-phonon (lattice) interactions</td>
</tr>
<tr>
<td></td>
<td>Anderson insulator</td>
<td>MIT occurs due to disorder-induced localization</td>
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<tr>
<th>Control mechanisms of MIT</th>
<th>Control type</th>
<th>Representative approach</th>
<th>Example materials</th>
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<tr>
<td></td>
<td>Temperature control</td>
<td>Heating/cooling</td>
<td>Materials in Figure 1a</td>
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<tr>
<td></td>
<td>Bandwidth control</td>
<td>Pressure tuning</td>
<td>R(\text{NiO}_3) (R = \text{Pr}, \text{Nd}, and \text{Sm})</td>
</tr>
<tr>
<td></td>
<td>Band-filling control</td>
<td>Doping with acceptors/donors</td>
<td>Y\text{Ba}_2\text{Cu}_3\text{O}_7−_ and \text{La}_1−_\text{Sr}_x\text{MnO}_3</td>
</tr>
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</table>

MIT. A typical example is stoichiometry change in layered perovskites that can induce changes between two and three dimensions (8), consequently altering the material’s electronic properties.

However, in some materials, the primary mechanism of MIT is still under debate. As shown in Figure 1b, the resistance of the VO\(_2\) thin film changes by approximately four orders of magnitude near 341–344 K, simultaneously accompanied with a structure change from a monoclinic (MoO\(_2\) structure) insulating phase (\(M_1\)) to a tetragonal (rutile structure) metallic phase (\(R\)), as shown in Figure 3a,b (47–51). The symmetry of the monoclinic MoO\(_2\) structure belongs to the \(P2_1/c\) space group, whereas that of the tetragonal rutile structure belongs to the \(P4_2/mnm\) space group. During the structure change from tetragonal to monoclinic, the vanadium atoms are displaced out of the octahedral planes and paired with each other, and the formed V-V bond is tilted with respect to the octahedral planes in the tetragonal structure. In the structure change, the following unit vector relations exist: \(a_{\text{mono}} = 2c_{\text{tetra}}\), \(b_{\text{mono}} = a_{\text{tetra}}\), and \(c_{\text{mono}} = a_{\text{tetra}} - c_{\text{tetra}}\). During MIT in VO\(_2\), the band structure also changes, as shown in Figure 3c. From the metallic phase to the insulating phase across the MIT, the 3\(d\)\(\parallel\) band is split into two bands—a lower-energy, filled bonding 3\(d\)\(\parallel\) band and a higher-energy, empty antibonding 3\(d\)\(\parallel\)∗ band—and the antibonding 3\(d\)\(\pi\)∗ band is pushed to a higher energy. As a result, a bandgap \(E_g \sim 0.6–0.7\) eV exists in the insulating phase.

Whether the above-mentioned structure change induces MIT in VO\(_2\) or the structure change is an accompanying phenomenon of the carrier-induced MIT determines whether VO\(_2\) is the Peierls type or the Mott-Hubbard type. Zylbersztejn & Mott (52) initially pointed out in the 1970s that MIT in VO\(_2\) may not be the simple Mott-Hubbard type on the basis of band-splitting alignment analyses. In the 1990s, Wentzcovitch et al. (53, 54) reopened the discussion on the nature of MIT in VO\(_2\). They claimed that VO\(_2\) may be more likely to be a band insulator than a Mott-Hubbard insulator on the basis of local density approximation calculations on the monoclinic \(M_1\) structure, which results in a semimetal with a very small number of carriers (53, 54). Rice et al. (55) commented that Wentzcovitch et al. did not consider the other insulating phase (\(M_2\)) of VO\(_2\), that the \(M_2\) phase is the Mott-Hubbard type, and that the \(M_1\) phase is a superposition of two lattice distortions of the \(M_1\) type. Recently, Cavalleri et al. (56) used ultrafast spectroscopy to investigate the structural and electronic effects in VO\(_2\) in the time domain and observed that MIT is delayed with respect to hole injection (which was used to initiate the formation of the metallic phase). Cavalleri et al. suggest that MIT in VO\(_2\) is not the Mott-Hubbard type. Kim et al. (57) used femtosecond pump-probe measurements and observed that the rutile metal phase of VO\(_2\) does not form simultaneously with MIT in VO\(_2\); instead, a monoclinic and correlated metal
Figure 3
Structure and band diagram of VO₂. (a,b) Structure change of VO₂ from the monoclinic insulating phase (M₁) to the tetragonal rutile metallic phase (R) during MIT in (a) a three-dimensional view and (b) a cross-sectional view. (c) Band structure change of VO₂ across the MIT. The left and right panels show the band structures for the insulating and metallic phases, respectively. Panel a adapted with permission from Reference 51; panels b and c adapted with permission from Reference 50.

phase exists between MIT and the structural phase transition. Kim et al. interpreted this finding as possible evidence for a Mott-Hubbard transition.

The phase transition in VO₂ happens at ultrafast timescales. Table 2 summarizes experimentally measured phase transition time constants in VO₂ using optical pump-probe, terahertz spectroscopy, time-resolved X-ray diffraction, four-dimensional ultrafast electron microscopy, and pulsed voltage measurements. The timescale of the phase transition is typically picosecond or faster, with the exception of pulsed voltage measurements that may well be limited by the resolution of the instrumentation. That the phase transition can be triggered at subpicosecond timescales naturally opens up the intriguing possibility of creating an ultrafast switch! If one can trigger the transition electrically, then there is indeed a compelling case to consider for high-performance logic. The hysteresis usually accompanying the structural transition qualitatively leads to interesting memory device candidates. Looking deeper, one could exploit the dynamics of the transition to create artificial structured materials with nanoscale metallic and dielectric states.
### Table 2  Experimentally measured switching time for the ultrafast metal-insulator transition in VO₂

<table>
<thead>
<tr>
<th>Method</th>
<th>Reference</th>
<th>VO₂ form</th>
<th>Phase transition triggering (pump source)</th>
<th>Phase transition time</th>
<th>Criteria for determining phase transition</th>
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<tbody>
<tr>
<td>Optical pump-probe methods</td>
<td>127</td>
<td>Polycrystalline thin films grown by sputtering</td>
<td>780-nm Ti:sapphire laser</td>
<td>~5 ps</td>
<td>Refractive index changes to a steady state derived from reflection/transmission spectra</td>
</tr>
<tr>
<td></td>
<td>151</td>
<td>Crystalline thin films on glass substrate</td>
<td>800-nm 50-fs optical pulse</td>
<td>100 fs to 50 ps</td>
<td>Reflectivity of the probe change (phase transition time is dependent on probe excitation power)</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>Thin films on Si with Si₃N₄ buffer layer</td>
<td>15-fs optical pulse</td>
<td>75 to 454 fs</td>
<td>Reflectivity of the probe change (phase transition time is dependent on probe pulse duration)</td>
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<td></td>
<td>133</td>
<td>Thin films grown on sapphire, MgO, and glass substrates by PLD</td>
<td>400-nm 130-fs 50-Hz Ti:sapphire laser pulse</td>
<td>10 ps to 1 ns</td>
<td>Reflectivity of the probe changes (phase transition time is dependent on VO₂ thin film thickness and probe excitation power)</td>
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<tr>
<td>Terahertz pump-probe methods</td>
<td>152</td>
<td>Polycrystalline thin films on diamond window</td>
<td>1.55-eV 12-fs 800-kHz Ti:sapphire laser pulse</td>
<td>130 fs</td>
<td>Temporal delay time for the first cycle of electronic conductivity changes</td>
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<td></td>
<td>128</td>
<td>Single crystals and thin films grown on sapphire by PLD</td>
<td>800-nm 50-fs/150-fs 5-kHz/1-kHz Ti:sapphire laser pulse</td>
<td>~10 ps</td>
<td>Saturation of conductivity changes</td>
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<tr>
<td>Time-resolved X-ray diffraction (laser pump + X-ray probe)</td>
<td>151</td>
<td>Crystalline thin films on glass substrate</td>
<td>800-nm 50-fs optical pulse</td>
<td>~1 ps</td>
<td>Rutile-phase (110) peak at 13.78° changes to monoclinic-phase (011) peak at 13.9° in X-ray diffraction</td>
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<td></td>
<td>57</td>
<td>Thin films grown on sapphire by sol-gel method</td>
<td>780-nm 20-fs 92-MHz Ti:sapphire laser pulse</td>
<td>~300 fs</td>
<td>Metal-phase X-ray diffraction (110) peak at 13.8° appears after X-ray irradiation</td>
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<td>153</td>
<td>Highly oriented thin films grown on sapphire by PLD</td>
<td>800-nm femtosecond optical pulse</td>
<td>25 ps</td>
<td>Monoclinic-phase (020) peak at 39.86° changes to rutile-phase (020) peak at 39.77° in the X-ray diffraction pattern</td>
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<td>~100 ps</td>
<td>Structural change–induced atom vibrations abate</td>
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<td>Method</td>
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<td>Four-dimensional ultrafast electron microscopy (laser pump + electron probe)</td>
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<td>Polycrystalline thin films prepared on mica substrate by sol-gel method</td>
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<td>776-nm femtosecond laser pulse</td>
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<td>Amplitude of (301)(-M) electron diffraction peak changes</td>
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<td>Polycrystalline thin films prepared on mica substrate by sol-gel method</td>
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<td>Integrated intensity of (302)(-M) electron diffraction peak changes</td>
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<td>51</td>
<td>Single crystals</td>
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<td>800-nm femtosecond laser pulse</td>
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<td>Vanadium-vanadium bond dilation is indicated by electron diffraction</td>
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<td>On order of ps</td>
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<td>Displacement of vanadium atoms is indicated by electron diffraction</td>
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<td>On order of 100 ps</td>
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<td>Sound wave shear motion is indicated by electron diffraction</td>
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<td>108</td>
<td>Oriented thin films grown on sapphire by PLD</td>
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<td>Voltage pulse</td>
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<td>Abrupt voltage change across VO(_2) is indicated by digital oscilloscope</td>
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*PLD denotes pulsed laser deposition.*
that could be electrically tuned. The rest of this review discusses these possibilities and snapshots of representative research being carried out regarding this exciting opportunity. High-quality films with reproducible transition characteristics for probing the fundamental physics as well as exploratory devices are among what are needed to experimentally investigate these ideas. This challenge is discussed next.

3. CORRELATED OXIDE THIN-FILM SYNTHESIS: THE CATION VALENCE STATE PROBLEM AND OXYGEN VACANCIES

The general problems concerning oxide syntheses in thin-film form center around epitaxial or highly crystalline stoichiometric films on suitable substrates with controlled defect concentrations. The structure is optimized by choice of lattice-matched substrates, deposition temperature, and deposition method, whereas stoichiometry is often adjusted through precursor deposition rates, background pressure, and postdeposition anneals. Given that oxides form in ionic lattices and defects are often charged, nonstoichiometry can have severe consequences for functional properties and, in some cases, leakage currents that significantly degrade the device performance or complicate interpretation of electrical measurements. The transition-metal cations can take on multiple-valence states in such oxides and lead to challenging synthesis problems. For example, the multiple-valence states of vanadium ions lead to several vanadium oxide phases with diverse V/O ratios (58–60), such as Magneli phases ($V_nO_{2n-1}$) (58–60) and Wadsley phases ($V_{2n}O_{5n-2}$) (59, 61). Figure 4a shows the phase diagram of the vanadium oxide system (60). VO$_2$ has been synthesized in various forms as bulk single crystal (62); thin films in both epitaxial (63–65) and polycrystalline (66–73) forms; and nanostructures, such as nanoparticles (74–76), nanobeams (27, 31, 77–79), nanowires (35, 80–84), and nanobelts (85). Different synthesis methods have been employed for thin-film VO$_2$ growth, including PLD (65, 86, 87), CVD (88, 89), sputtering (66–73), sol-gel coating (90, 91), electron beam (e-beam) evaporation (92, 93), and ion beam deposition (94, 95). Panels b (69) and c (66) of Figure 4 show how sensitive VO$_2$ thin-film growth is to oxygen flow rates and growth temperatures, respectively, through use of the dc-magnetron sputtering technique. The growth windows for VO$_2$ films in terms of oxygen flow rate and growth temperature are approximately 7.8–8.8% and ~550°C. Only the VO$_2$ films grown within the optimized growth window show a more-than-three-order-of-magnitude resistance change across the MIT, indicating good stoichiometry of the film because studies of polycrystalline VO$_2$ thin films show that the resistance change across MIT and MIT temperature are sensitive to the degree of nonstoichiometry (96–98). Hence, growing high-quality homogeneous VO$_2$ films without formation of nonstoichiometric phases is a challenge (96). Different substrates have been employed for thin-film VO$_2$ growth; such substrates include glass (88), Si (28, 73), Ge (99), Al$_2$O$_3$ (66, 68, 70–72), TiO$_2$ (63, 64, 87), amorphous SiO$_2$-coated Si (29, 66, 67, 69), HfO$_2$-coated Si (100), and yttria-stabilized zirconia (YSZ) buffer layers on Si (65). The choice of substrate can significantly influence MIT characteristics, including the $T_{MIT}$, in part by affecting the strain state.

4. SOLID-STATE-DEVICE CONCEPTS

4.1. The Ultrafast Oxide Metal-Insulator Transition Switch

As discussed in the introduction, a central theme in devices exploring MIT is an ultrafast switch. The high-resistance, insulating state and the low-resistance, conducting state on both sides of MIT define the OFF and ON states of the switch, as shown in Figure 1c. The switching behavior, i.e., changes between the OFF and ON states due to the phase transition, can be triggered by an external
perturbation (that is thermal, electrical, optical, or magnetic) or by removal of the excitation. In some cases, combination of two or more excitations can also efficiently lead to the transition. Depending on the mechanism leading to the transition, the OFF and ON transitions can have different time constants. Hence, in a device, the slower time constant will dominate the speed of the switch. The energy needed for transition onset corresponds to the switching energy. Additionally, latent heat changes may need to be accounted for in thermodynamic analyses, depending on the

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**Figure 4**

Growth optimization of VO$_2$. (a) Phase diagram of the VO$_x$ system. (b) Oxygen flow effect on VO$_2$ growth. (c) Growth temperature effect on VO$_2$ growth. Panel a adapted with permission from Reference 60; panel b adapted with permission from Reference 69; panel c adapted with permission from Reference 66.
material system and transition mechanism. The hysteresis during the transition is yet another variable that could be exploited for devices such as memory. In some cases, multiple steps during the transition (such as in domain switching) lead to additional possibilities such as the creation of nonlinear resistor circuits. The following subsections discuss emerging phase transition–based electronic devices, optical devices, and thermal/chemical sensors.

4.2. Phase Transition Electronic Devices

The ability to trigger the phase transition electrically at or near room temperature in two- or three-terminal device configurations creates the potential for novel, low-power oxide electronics. The phenomena of resistive switching behavior in VO$_2$ can be traced back to the early 1970s, with nonlinear I-V characteristics, discontinuity of resistance change with applied voltage, and electric oscillations reported (101–103). Furthermore, several elementary switch devices were demonstrated on the basis of nonlinear I-V characteristics in VO$_2$. However, this nonlinear resistive switching behavior in VO$_2$ was perhaps not associated with electrically triggered MIT (E-MIT) until more recently. In 2000, Stefanovich et al. (104) reported that electric field or electron injection into VO$_2$ can trigger MIT. Although investigators have argued that the current-induced heating effect may also induce MIT, theoretical simulations indicate that the Joule heating effect from leakage current is likely insufficient to trigger MIT in the case of homogeneous current flow (105). Recently, a variety of groups have studied E-MIT (28, 104, 106–111). A field-driven phase transition may lead to a Mott field effect transistor (MottFET) (29, 110) and further provide valuable insights into the physics of the transition. In a MottFET, a Mott insulator is employed as the channel, and the external gate voltage switches the channel between the insulating OFF state and the metallic ON state (112–115). Qualitatively, this approach offers an alternate three-terminal switch concept to a conventional semiconductor FET. Due to the much higher electron carrier concentration possible in a metallic channel, this approach may have additional advantages.

4.2.1. Two-terminal switches utilizing electrically triggered metal-insulator transition.

Figure 5a shows the structure of a planar VO$_2$ electronic switch device employed by Stefanovich et al. (104) for E-MIT studies. The VO$_2$ channel length, width, and thickness are 0.2 mm, $\sim 10$ $\mu$m, and 0.1 $\sim 1$ $\mu$m, respectively. The thickness of the SiO$_2$ layer is $\sim 70$ nm on the p-Si substrate (0.1 $\Omega$ cm). Al contacts were deposited via thermal evaporation. The I-V characteristics of the VO$_2$ channel are S shaped, as shown in Figure 5b, indicating that MIT occurred at a certain threshold voltage $V_{\text{th}} \sim 2$ V at room temperature. Experiments showed that $V_{\text{th}}$ decreases as temperature increases. When the temperature is above $T_{\text{MIT}}$, the E-MIT effect no longer occurs. Figure 5c shows the I-V characteristics of a planar VO$_2$ switch device at various temperatures: (1) 293 K, (2) 241 K, (3) 211 K, (4) 144 K, (5) 91 K, and (6) 15 K (109). $V_{\text{th}}$ increases as temperature decreases. The increased $V_{\text{th}}$ was attributed to the increased VO$_2$ channel conductivity at lower temperatures. Figure 5d shows the cross-sectional schematic of a two-terminal VO$_2$ switch device reported recently with improved quality of the VO$_2$ thin films (108). VO$_2$ thin films were deposited on $r$-plane sapphire substrates using PLD, and Au/Cr electrodes were deposited and patterned using a lift-off process. Figure 5e shows the I-V characteristics of the VO$_2$ switch device shown in Figure 5d with a load resistance at room temperature (108). An evident MIT behavior in VO$_2$ thin films was triggered by a dc voltage, with a critical voltage $V_{\text{MIT}} \sim 7$ V. The current jump at $V_{\text{MIT}} \sim 7$ V indicates MIT from the insulator state and metal in the VO$_2$ thin film. The same research group also proposed that this device is a varistor (variable resistor) toward electrostatic discharge protection (111).
Figure 5

Two-terminal electronic switch devices utilizing MIT in VO$_2$. (a) Schematics of the planar structure of VO$_2$ switch devices. (b) $I$-$V$ characteristics of a VO$_2$ switch device at room temperature, showing an S shape with a threshold voltage $V_{th}$ of $\sim$2 V for electrically triggered MIT (E-MIT). (c) $I$-$V$ characteristics of a planar VO$_2$ switch device at various temperatures. $V_{th}$ decreases with temperature. The dashed lines indicate unstable (transient) regions of the $I$-$V$ curves. The right-hand axis shows the low-conductivity regions of curves 5 and 6 in an extended scale denoted as 5' and 6'. (d) A cross-sectional view of a two-terminal planar VO$_2$ switch. (e) $I$-$V$ characteristics of the VO$_2$ switch device shown in panel d with a load resistance at room temperature, showing that a dc voltage (with a critical MIT voltage of $\sim$7 V) triggers MIT in VO$_2$ thin films. The inset shows the circuit diagram. The left-hand and right-hand y axes show current and current density, respectively. (f) $I$-$V$ characteristics of a vertical VO$_2$ switch device at different temperatures. E-MIT is observed at $1.5 \sim 2$ V at temperatures below the thermally triggered MIT (T-MIT). Panels a and b adapted with permission from Reference 104; panel c adapted with permission from Reference 109; panels d and e adapted with permission from Reference 108; panel f adapted with permission from Reference 107.

The two-terminal VO$_2$ devices discussed in Figure 5a–e are planar junctions. E-MIT was also recently observed in out-of-plane VO$_2$ devices. Figure 5f shows $I$-$V$ characteristics of a VO$_2$ capacitor at different temperatures (107). The VO$_2$ thin films were grown on $n^+$-Si substrates by rf-magnetron sputtering, and Pd metal was deposited as the top contacts using e-beam evaporation with a shadow mask (107). The electrical measurements were carried out using top Pd and bottom $n^+$-Si contacts. An abrupt change in leakage current is seen with both increasing $T$ and $E$. E-MIT can be seen up to 55°C. $V_{MIT}$ for E-MIT is slightly lower than 2 V at 25°C, corresponding to
an electric field of \( \sim 10^7 \text{ V m}^{-1} \) (consistent with the typical fields observed in planar devices).

The \( I-V \) curves present an ohmic relationship in the insulating phase. At larger voltages, both low-temperature and high-temperature states show nearly identical resistance, further suggesting the validity of E-MIT.

Whether E-MIT persists when VO\(_2\) reaches the nanoscale is a key issue for scaled devices. Ruzmetov et al. (28) performed experiments in similar VO\(_2\) capacitor devices, but with much smaller top contacts. In these devices, the top contacts were \( \sim 200\)-nm Au dots fabricated by \( e \)-beam lithography. The electron transport measurements were performed with a conducting atomic force microscopy (AFM) tip. E-MIT phenomena were observed in these nanoscale VO\(_2\) capacitor devices in similar voltage ranges. Sakai & Kurisu (116) studied the effect of hydrostatic pressure on E-MIT in a two-terminal planar VO\(_2\) device. These investigators observed that the critical current to trigger MIT increases with pressure, whereas voltage at the transition is independent of pressure, which further suggests that MIT is triggered electrically, i.e., not by Joule heating alone.

Figure 6 demonstrates controlled local phase switching in VO\(_2\) thin films through use of a biased conducting AFM tip (106). Figure 6a shows the geometry and Figure 6b shows the height profile in an AFM line scan. Figure 6c shows several consecutive \( I-V \) sweeps at 107 K. Panels d and e of Figure 6 show 200 consecutive \( I-V \) sweeps at two different representative locations at 293 K. Figure 6f shows an AFM image depicting the surface morphology of the VO\(_2\) thin film. Panels g–k of Figure 6 show current mapping at different bias voltages. The metallic puddle is initially seeded at two grains (Figure 6f–h) at small bias. The number of grains grows with increasing bias voltage. Single-grain switching with reproducible hysteresis demonstrates the existence of E-MIT in VO\(_2\) down to the few-nanometer range. These preliminary results on voltage triggering of MIT down to the nanoscale are encouraging for further explorations of integrated devices and circuit components.

4.2.2. Three-terminal gated field effect switches. In a three-terminal VO\(_2\) FET-like device, an electric field introduced by applied external gate voltage (separated from the channel by an insulator) can modulate the resistance of a VO\(_2\) channel. The conductivity of the VO\(_2\) channel may be switched between the high-resistivity insulating state and the low-resistivity metal state. The device behaves as a MottFET (112–115) with a VO\(_2\) channel. In other words, three-terminal electronic switches utilizing E-MIT may potentially demonstrate functional MottFET for logic operations in a CMOS-like architecture. Additionally, a three-terminal VO\(_2\) FET device structure facilitates fundamental studies to clarify E-MIT or Joule heating–induced MIT in VO\(_2\) because the possibility of a current-induced heating effect can be further minimized in a three-terminal VO\(_2\) device compared with a two-terminal VO\(_2\) device. This subsection discusses results on three-terminal FET-like VO\(_2\) devices, although systematic studies on this important problem are still in the early stages.

Figure 7a shows an early proposed three-terminal VO\(_2\) switch device by Chudnovskiy et al. (117). The device is composed of a VO\(_2\) channel, a gate dielectric layer on top of the VO\(_2\) channel, a gate electrode on top of the gate dielectric layer, and source and drain electrodes at both ends of the channel. The device operating temperature is set above \( T_{\text{MIT}} \), and the channel is in the metallic phase in the absence of a gate voltage, although the channel goes to the dielectric state once a gate voltage is applied. This is similar to a MOSFET working in the depletion mode instead of the enhancement mode, which is generally employed. Panels b and c of Figure 7 show an experimental example of a three-terminal VO\(_2\) device by Kim et al. (110). The inset in Figure 7b shows the device’s structure. The VO\(_2\) thin films were deposited on SiO\(_2\)/Si (and sapphire) substrates using
AFM studies of electrically triggered MIT in VO₂.

(a) Schematic of the AFM tip and the sample geometry.

(b) AFM line scan.

(c) Fourteen consecutive I-V sweeps at $T = 106.75$ K.

(d,e) Two hundred consecutive I-V sweeps at two different representative locations at $T = 293$ K. The color scale bar shows the times of sweep.

(f) AFM image showing the surface morphology of the VO₂ thin film.

(g–k) Current mapping at different bias voltages. Grain boundaries are drawn in white. Adapted with permission from Reference 106.
Figure 7
Three-terminal gated electronic switch devices utilizing MIT in VO₂. (a) An early proposed three-terminal gated VO₂ switch device. (b) Current density versus electric field applied on the VO₂ channel with the gate open at room temperature. The inset shows the three-terminal VO₂ device structure. (c) Current density versus electric field applied on the VO₂ channel with applied negative gate voltages at room temperature. (d) Optical microscopy image of the top view of a three-terminal VO₂ device. (e) The effect of the back-gate (gate 2) voltage on the source-drain resistance of the VO₂ channel of a three-terminal VO₂ device with double-gate structure from the top view as shown in panel d. The inset shows a cross-sectional schematic of the device. Panels b and c adapted with permission from Reference 110; panels d and e adapted with permission from Reference 29.

PLD at 400°C with gas flows of Ar + 10% O₂ under 55 ~ 60-mTorr growth pressure. The VO₂ thin films are ~90 nm thick. The VO₂ thin film (on sapphire) shows an MIT transition at ~340 K with a change in resistance of approximately four orders across the MIT. The SiO₂ underneath the VO₂ thin film was used for the gate oxide, and Au/Cr and WSi were used for the source-drain and gate contacts of the three-terminal device. The VO₂ channel length and width are 5 and 25 μm, respectively. Figure 7b shows the source-drain current density versus electric field applied on the VO₂ channel with the gate open at room temperature. The device is turned on and off at effective electric fields of ~4.8 and ~2.8 MV m⁻¹, respectively. Figure 7c shows the source-drain current density as a function of electric field under different applied negative gate voltages. When the magnitude of the negative gate biases increases, the turn-on voltage (for
triggering MIT) increases, which Kim et al. (110) attributed to the decrease in conductivity due to increased hole carrier density.

Panels $d$ and $e$ of Figure 7 present a recent study on three-terminal VO$_2$ devices (29). The inset in Figure 7e shows the cross-sectional schematic of the device. A uniform Al$_2$O$_3$ dielectric layer was grown on a high -n$^+$- Si substrate using atomic layer deposition. The n$^+$-Si substrate was used as the back gate of the device (shown as gate 2 in Figure 7e). A VO$_2$ thin film was grown on top of the Al$_2$O$_3$ dielectric layer using magnetron sputtering. The device channel was patterned using photolithography. The top gate (shown in Figure 7e), source, and drain electrodes were deposited using e-beam evaporation and the lift-off process. A SiO$_2$ layer was used as the top-gate dielectric layer. Figure 7d shows a planar view optical microscopy image of the three-terminal VO$_2$ device. Figure 7e shows how the back-gate (gate 2) voltage affects the source-drain resistance of the VO$_2$ channel. A systematic resistance decrease occurs when a negative gate voltage of $-0.5$ V is applied, whereas no evident resistance change is observed when a positive gate voltage up to 0.5 V is applied. The authors (29) noted that the magnitude of the applied voltages was restricted to 0.5 V due to the gate oxide leakage issue. At $-0.5$ V gate voltage, the decrease in VO$_2$ channel resistance is $\sim 120$ $\Omega$. The results discussed in Figure 7e are significant in that the reversible modulation of the VO$_2$ channel resistance by an external gate voltage was demonstrated in an all-electrical three-terminal VO$_2$ device configuration. Future research directions in this topic include low-leakage gate dielectric fabrication to increase the gate voltage that could be applied to induce a larger field in the channel or ionic electrolyte gating (118) to achieve larger critical carrier densities in the channel as well as thinner conformal VO$_2$ layers to increase the field penetration into most of the channel region.

### 4.2.3. Metal-insulator transition oscillators

Oscillators are used in electronic circuits in which a periodic repetitive signal is needed, such as signal-broadcasting transmitters and clocks. Oscillators can be made of different components, such as piezoelectric materials (e.g., quartz), resistor-capacitor/inductor (RC/RL) circuits, transistor circuits, and Gunn diodes. In this subsection, we discuss oscillators utilizing E-MIT in VO$_2$ materials. Oscillation phenomena in VO$_2$ have been explored since three decades ago (102, 103). Figure 8 shows an example of an oscillator device utilizing E-MIT in VO$_2$ at room temperature (119). A VO$_2$ thin film of $\sim 100$ nm was grown on a sapphire substrate using the sol-gel technique (90). Ni and Au were deposited on the lithographically patterned VO$_2$ film as contact electrodes using sputtering. The cross-sectional view and planar view of the device structure are shown in the insets of Figure 8a. The surface morphology of the VO$_2$ film is shown in the right inset of Figure 8a, with a root-mean-square roughness of $\sim 5$ nm using atomic force microscopy. Figure 8a shows the $I$-$V$ characteristics of a VO$_2$ device with both a voltage sweeping mode ($V$ mode) and a current sweeping mode ($I$ mode). In $V$ mode, the $I$-$V$ curves show two threshold voltages of $V_{t1} \sim 9.7$ V and $V_{t2} \sim 4$ V, at which the current increases and decreases abruptly. The current readings at $V_{t1}$ and $V_{t2}$ are $I_{t1} \sim 0.43$ mA and $I_{t2} \sim 1.34$ mA, respectively. In $I$ mode, as the current flowing through the device ($I_0$) increases, the voltage across the device ($V_M$) increases exponentially until it reaches $V_{t1}$. Once $V_M$ exceeds $V_{t1}$, however, it starts to decrease until it reaches $V_{t2}$ (as shown with a negative differential resistance). Then $V_M$ stays at $V_{t2}$ regardless of the current increase. Figure 8b shows the oscillator circuit, which is a single-loop circuit composed of a two-terminal VO$_2$ device (as shown in Figure 8a), a standard resistor $R_{EXT} = 7$ k$\Omega$, and a voltage source $V_S$. When a rectangular voltage pulse (with a dc offset of 10 V) was supplied from the voltage source, as shown in Figure 8d, the $I_0$ and $V_M$ were recorded with an oscilloscope (Figure 8d). Periodic oscillations are clearly observed. The amplitudes of $I_0$ and $V_M$ and oscillation frequency $f_0$ are $\sim 0.8$ mA, $\sim 5.7$ V, and $\sim 0.317$ MHz, respectively.
We next briefly discuss the mechanism of oscillations utilizing E-MIT of VO₂ in the circuit of Figure 8b. Initially, with insufficient external voltage, \( V_M \) \( (V_M = V_S - R_{EXT}I_0) \) is smaller than \( V_{t1} \), and the VO₂ film is in an insulating state with a high resistance. Once \( V_M \) reaches \( V_{t1} \), induced by a sufficient external voltage supply \( V_S \), the VO₂ film enters the low-resistance metallic state due to E-MIT, accompanied with an abrupt \( I_0 \) jump. Simultaneously, \( V_M \) decreases while \( V_R \) \( (V_R = V_S - V_M) \) increases abruptly because \( R_M \) becomes orders of magnitude smaller due to MIT. Once \( I_0 \) approaches \( (V_S/R_{EXT}) \), \( V_M \) becomes small enough such that the VO₂ film changes from the metallic state to the insulating state. Hence, \( V_M \) increases whereas \( V_R \) decreases accordingly due to the increased \( R_M \). When \( V_M \) increases to \( V_{t1} \), the circuit enters the starting point of the next oscillation. This is a complete period of oscillation, which is comparable in analog to a simple series RC circuit. Figure 8 shows a single oscillation period of the circuit. With appropriate tuning of \( R_{EXT} \), different oscillation frequencies can be designed (119, 120). Furthermore, MIT-induced oscillations have also been demonstrated in nanoscale VO₂-based materials, such as W-doped VO₂ nanobeams (31). These results pave the way to explore an oscillator circuit utilizing E-MIT.

4.2.4. Memristive devices utilizing metal-insulator transition. The idea of fabricating logic or memory devices from two-terminal device configurations has seen a renaissance with memristors (121, 122) and in a broader context may enable neuromorphic circuits (123). Correlated oxide crossbar arrays may be interesting candidates for circuit elements, and the ability of these devices to trigger phase transition at room temperature by a voltage makes such technology particularly attractive. This subsection discusses an example of a VO₂ device for memristors and memory capacitors. A memristor is a two-terminal device whose resistance is not determined by the instantaneous applied voltage (current) but rather is reliant on the dynamic history of the system’s charge flow. Figure 9a shows a schematic of a VO₂ memristor device (33). The VO₂ material, grown on a sapphire substrate using the sol-gel technique (91), shows an up-to-four-order-of-magnitude resistivity change across MIT. The measurement temperature is set at 340 K, close to the onset of MIT in VO₂. At this temperature, the resistance of the VO₂ film is a sensitive and highly hysteretic function of temperature. The \( I-V \) characteristics of the device were investigated during a ramped voltage pulse (50 V in 5 s). Figure 9b shows three measured \( I-V \) curves (33). Two typical memristive characteristics are evident in the \( I-V \) curves. First, the \( I-V \) curves are nonlinear,
Figure 9
A memristive device utilizing MIT in VO₂. (a) Schematic of a VO₂ memristor device. (b) Three I-V curves showing the hysteretic nonlinear memristive behavior of the VO₂ memristor device. The arrows pointing up indicate increasing voltage, and the arrows pointing down indicate decreasing voltage. (c) Memory capacitance of a hybrid VO₂ device during heating and cooling. Panels a and b adapted with permission from Reference 33; panel c adapted with permission from Reference 124.

and second, the I-V curves are hysteretic, which is associated with MIT in VO₂. The hysteresis contains the memory aspect of the memristor. Figure 9c demonstrates a memory capacitance system utilizing MIT in VO₂ (124). The temperature perturbation–induced capacitance changes demonstrate memory behavior (as shown in Figure 9c), which is associated with hysteretic MIT behavior of VO₂.

4.3. Phase Transition Optical Devices, Thermal Sensors, and Chemical Sensors
This section briefly discusses optical devices, thermal sensors, and chemical sensors utilizing phase transitions. The sharp change in carrier concentration in the proximity of a phase transition creates unique opportunities for novel electronics that can be monolithically integrated.

4.3.1. Optical devices utilizing metal-insulator transition. In the early 1970s, VO₂ was proposed for optical storage due to its first-order MIT transition (125, 126). From that point, optically triggered MIT in VO₂ (56, 127–130) has been studied periodically, and models (131) have been proposed to explain the light-induced MIT phenomena. On the basis of these studies, optical detector/sensor/switch devices (132–136), microwave switch devices (137, 138), and modulator devices (30) based on VO₂ material have been proposed and demonstrated. Figure 10a shows a schematic of the experimental setup of a light pulse detector (135) with a 20-nm-thick VO₂ thin film and 330-nm-thick Si₃N₄ on Si. When excited with a near-infrared laser pulse, the VO₂ thin film undergoes photo-induced MIT. Owing to this behavior, this device works as a detector for light pulses. The optical pump-probe setup is based on a cavity-dumped Ti:sapphire oscillator. Figure 10a shows the frequency-resolved VO₂ reflectivity variation, measured as a function of the delay between the probe pulse and the VO₂ switching triggered by the pump pulse. Figure 10b shows the time traces at different wavelengths. Figure 10c shows the frequency-resolved reflectivity variation. The significant changes in absorption VO₂ across MIT, combined with ultrafast
Figure 10
Optical and metamaterial devices utilizing MIT in VO₂. (a) The time- and frequency-resolved reflectivity variation measured on a VO₂ film. (b) Time traces at different wavelengths. (c) The frequency-resolved reflectivity variation. (d) Schematic of time- and frequency-resolved setup. Abbreviations: SC, supercontinuum; PDA, photodiode array. (e–g) Schematics of a VO₂ split-ring resonator (SRR) hybrid metamaterial. In panel e, green and blue represent the metallic phase and the insulating phase, respectively. (h,i) Experimentally retrieved permittivity and permeability bandwidths for the hybrid metamaterials. The shaded areas show the range of values accessible with the hybrid SRR-VO₂ device. Panels a–d adapted with permission from Reference 135; panels e–i adapted with permission from Reference 140.
switching, make VO₂ an attractive candidate for the next generation of active integrated optical components suitable for broadband applications. Briggs et al. (30) fabricated a compact Si photonic waveguide modulator utilizing MIT of VO₂ thin films. The VO₂ thin films were grown using PLD, were patterned by lithography, and were integrated with Si-on-insulator photonic waveguides to demonstrate a compact absorption modulator toward photonic circuit applications. Through use of single-mode waveguides at \( \lambda = 1.55 \) μm, optical modulation of the guided transverse-electric mode of more than 6.5 dB with a 2-dB insertion loss over a 2-μm active device length was demonstrated. A sharp decrease in resonator quality factor is observed above 70°C, corresponding to VO₂ entering the metallic phase across MIT with an ~78% decrease in transmission.

4.3.2. Metal-insulator transition metamaterials. Metamaterials are artificial materials composed of designed inclusions, which show properties that are not readily available in nature, such as negative refractive index (139). Researchers have recently proposed several intriguing applications of metamaterials, such as cloaking, ultrafast optoelectronic switching, and imaging. The optical properties of VO₂ can be strongly and quickly tuned via external stimuli due to its MIT. Utilizing MIT in VO₂ toward metamaterial applications (32, 124, 140–142) opens a new research direction. In this subsection, we use a simple example to discuss VO₂ metamaterial applications for dynamic tuning of an infrared resonance (140). Panels e–g of Figure 10 show the schematics of a VO₂ split-ring resonator (SRR) hybrid metamaterial. Figure 10e shows a close-up view of the SRR on top of a near-field image of a VO₂ thin film during MIT. Figure 10f shows the device layout and experimental setup. Gold SRRs (100 nm thick) of a 20-μm period were fabricated using lithography on top of a 90-nm-thick VO₂ thin film on a sapphire substrate. Figure 10g shows a single SRR pattern and illustration of the overlap of the SRR fields with the VO₂ thin film. The resonance frequency of the SRR metamaterial is highly sensitive to the dielectric property of the material placed nearby, especially in the vicinity of the SRR gaps. Panels h and i of Figure 10 show experimentally retrieved permittivity and permeability bandwidths for the hybrid metamaterials, demonstrating the controllability of resonance in VO₂-based hybrid metamaterials.

4.3.3. Thermal sensors utilizing metal-insulator transition. Because the resistivity of VO₂ changes sharply with temperature, VO₂ can be used for thermal switches and thermal detectors (this application is being explored in night vision systems). Here, we use a programmable critical temperature sensor (34) as an example. Figure 11a shows the temperature dependency of the conductivity of a VO₂ thermal sensor device (34). The ~100-nm VO₂ thin films were grown on m-plane sapphire substrates using the sol-gel method. The two-terminal device dimensions are shown in the inset of Figure 11a. The critical voltage for E-MIT is ~21 V. As applied voltage increases from 1 to 22 V, an abrupt conductivity jump occurs above 5 V. \( T_{\text{MIT}} \) gradually shifts from 68°C at a 1-V bias to room temperature at a 21-V bias. Through use of this property (different MIT temperatures at different voltages), a prototype thermal sensor based on VO₂ was demonstrated. Recently, Yang et al. (100) demonstrated a solid-state thermal capacitor device with a VO₂ thin film as an active layer, which shows a more-than-one-order-of-magnitude capacitance change from room temperature to 100°C due to the dielectric constant change of VO₂ across the phase transition. This could possibly be explored further as thermal sensors in solid-state circuits.

4.3.4. Chemical sensors utilizing metal-insulator transition. The carrier concentration changes dramatically in the vicinity of \( T_{\text{MIT}} \). VO₂ nanowire gas sensors (35, 84) have been demonstrated accordingly. Figure 11b shows a schematic of a VO₂ nanowire gas sensor thermistor device (35). VO₂ nanowires were grown on a SiO₂/Si substrate using the vapor solid method. Droplets of liquid metal alloys (Ga-In-Sn) were used for soft contacts on both ends of the VO₂ nanowire. The
Figure 11

Thermal sensor and gas sensor devices utilizing MIT in VO2. (a) A VO2 thermal sensor device. Shown are the temperature and voltage dependency of the conductivity and the coplanar VO2 device. The inset shows the device structure. SPT denotes structural phase transition. (b) Schematic of a VO2 nanowire gas sensor device. P_G and P_L indicate heat flux dissipating into the gas environment and metal contacts, respectively. (c–e) Microscopic images of a VO2 nanowire with increased self-Joule heating induced by the flowing current. (f) I-V characteristics of the VO2 nanowire gas sensor device at different Ar pressures. Panel a adapted with permission from Reference 34; panels b–f adapted with permission from Reference 35.

soft contacts were used to prevent any strain-induced \( T_{\text{MIT}} \) shift. A resistor of 11 k\( \Omega \) was connected in series with the VO2 nanowire device to limit current. Joule heating is sustained by an externally applied periodic voltage bias on the device. Panels c–e of Figure 11 show microscopic images of the VO2 nanowire under different voltage biases (different heating) (35). During the heating process, the metallic domain and insulating domain were observed. Figure 11f shows the I-V characteristics of the VO2 nanowire gas sensor device under different Ar gas pressures (35). Thermal loss of the gas sensor to the environment increases with Ar pressure, which results in forward shifts of the transition voltage to larger values. Hence, significantly different I-V loops are observed for different gas pressures, as shown in Figure 11f. This is a simple demonstration of a chemical sensor.

4.4. Devices Utilizing Metal-Insulator Transition in Correlated Oxides Other than VO2

Although this article focuses on VO2, a plethora of transition-metal–oxide systems show correlated phenomena that could be interesting for novel solid-state devices. High-temperature superconductors, such as in the Y-Ba-Cu-O system, have been consistently studied for superconducting quantum interference devices, Josephson junctions, and related low-temperature electronics (143). Colossal magnetoresistance in manganites (144), such as in the La-Ca-Mn-O family, is
interesting for magnetic tunnel junctions and magnetic field sensors. The recent observation of a high-mobility electron gas at the interfaces between LaAlO$_3$ and SrTiO$_3$ (145) has naturally led to speculation as to novel devices that could exploit this exotic phenomena (146, 147). Coupling effects from layered oxide heterostructures also lead to novel phenomena involving multiferroic properties. Strain is yet another parameter that can magnify the response to external stimuli or in some cases lower the energy barrier for switching. The field of quantum materials in general is seeing explosive growth. Correlated oxides are at the forefront of this revolution, and research in this area has benefited from advances in thin-film growth techniques, lithography, and spatially resolved characterization over the past few decades. The topic is interdisciplinary and offers significant intellectual challenges for condensed matter physicists, materials scientists, and device physicists alike.

5. CONCLUDING REMARKS

In this brief review, we discuss the exploration of correlated oxide phase transitions in novel electronics, photonics, and related devices. Although this area has intrigued researchers for several decades ever since the original observation of MIT in oxides, the twenty-first-century grand challenge of continued innovation in information processing sciences beyond CMOS scaling creates an opportunity to seriously consider alternate computing vectors that may offer unique advantages. Lithographic scaling is essentially close to its limits, and alternate state variables are important to address in a timely manner (39). Strongly correlated oxides could well serve that role due to strong electron-electron and electron-lattice interaction effects and the ability to manipulate such effects through synthesis and compositional control. The ultrafast nature of the phase transition along with spectacular changes in the electrical/dielectric properties create several possibilities for logic and memory devices, some of which could potentially be transformative. A practical advantage could be ease of integration onto Si platforms given that the thin-film technology is compatible with traditional semiconductor processing and near–room temperature operation.

Once the governing physics is better understood, a critical study would then be needed to benchmark elementary devices and the projected limits of the technology, followed by reliability analyses. For example, can structural distortions during a MIT be tolerated in practical devices that may require millions of switching operations? In terms of correlated electron physics, Mott insulators and their interfaces present model systems for fundamental research. In addition, phase transitions create unique and enabling opportunities for defense electronics, such as in addressing directed energy, protection, and sensing. Finally, given the quasi-two-dimensional nature of MIT (the high carrier concentration even in the insulating state leads to a small field penetration depth), one can explore interface-driven phenomena as well with thin-film model systems. For example, a recent theoretical study predicts semi–Dirac point behavior at VO$_2$-TiO$_2$ interfaces (148, 149), which could be very interesting to experimentally investigate. Furthermore, this prediction may be generalized to interfaces between a Mott insulator and a band insulator. This leads to a fascinating question: Can one realize graphene-like electron transport phenomena in oxides displaying phase transitions?

SUMMARY POINTS

1. An ultrafast switch can be demonstrated utilizing metal-insulator transition in correlated oxides, with the ON and OFF states defined as a low-resistance, metallic phase and a high-resistance, insulating phase of the material, respectively. Switching may be triggered with electronic, optical, thermal, or magnetic perturbations or a combination thereof.
2. Room temperature MottFETs with correlated oxides may be potential candidates for future computing elements. Utilizing a functional correlated oxide for information processing may lead to three-dimensional circuits and integration on polycrystalline or arbitrary substrates.

3. The highly nonlinear current-voltage characteristics of two-terminal devices with phase transition elements coupled with hysteresis lead to intriguing possibilities in varistors, memristive devices, neuromorphic circuits, and a variety of solid-state circuit architectures.

4. High-quality quantum materials are central to experimentally realizing these devices. Rigorous materials science studies would advance synthesis of correlated oxides with superior functionality along with a fundamental understanding of the role of microstructure and defects.

FUTURE ISSUES

Above we review published literature on phase transitions and ongoing efforts to realize novel electron devices utilizing sharp transitions. Here, we briefly explore what else could be possible. Indeed, some of these ideas rely simply on the phase transition phenomena driven by thermal excitations or in some cases by a current and hence may be possible with existing materials.

1. Thermal switch for directing heat flow: Phase transition leads to a conductance change that is accompanied by a large change in mobile carrier concentration. There may quite possibly be a thermal conductivity change during this transition (150). Hence, exploring oxide systems wherein one can design solid-state thermal switches by exploiting phase transitions may be an interesting avenue of research. Such research may lead to self-regulating thermal barriers whose thermal conductivity dynamically adjusts to the surrounding temperature.

2. Information processing in a thermal gradient: If an array of phase transition elements is placed in a thermal gradient in the temperature range in which phase transition can spontaneously happen, then one may be able to design a circuit that can naturally switch and perform computation using thermal waves. The heat flow across the gradient (such as in a solid-state device that dissipates heat) may hence be exploited for useful computational work. This could be a novel approach to utilize part of the dissipated heat, which is often a challenge to manage effectively in high-performance devices.

3. Spin-dependent metal-insulator transition: By fabricating a phase transition electrode onto a spin tunnel junction, one may be able to realize a spin-polarized current driving a phase transition. Hence, creating a spintronic device that incorporates ultrafast phase transitions may be possible.

4. Materials discovery: Oxide materials that possess low dielectric loss and can be reversibly switched to a conducting state would be particularly interesting to realize low-standby-power electronics.
DISCLOSURE STATEMENT

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