SEMICONDUCTOR DEVICES II: Metal Insulator Transition Switches

Lecture #6

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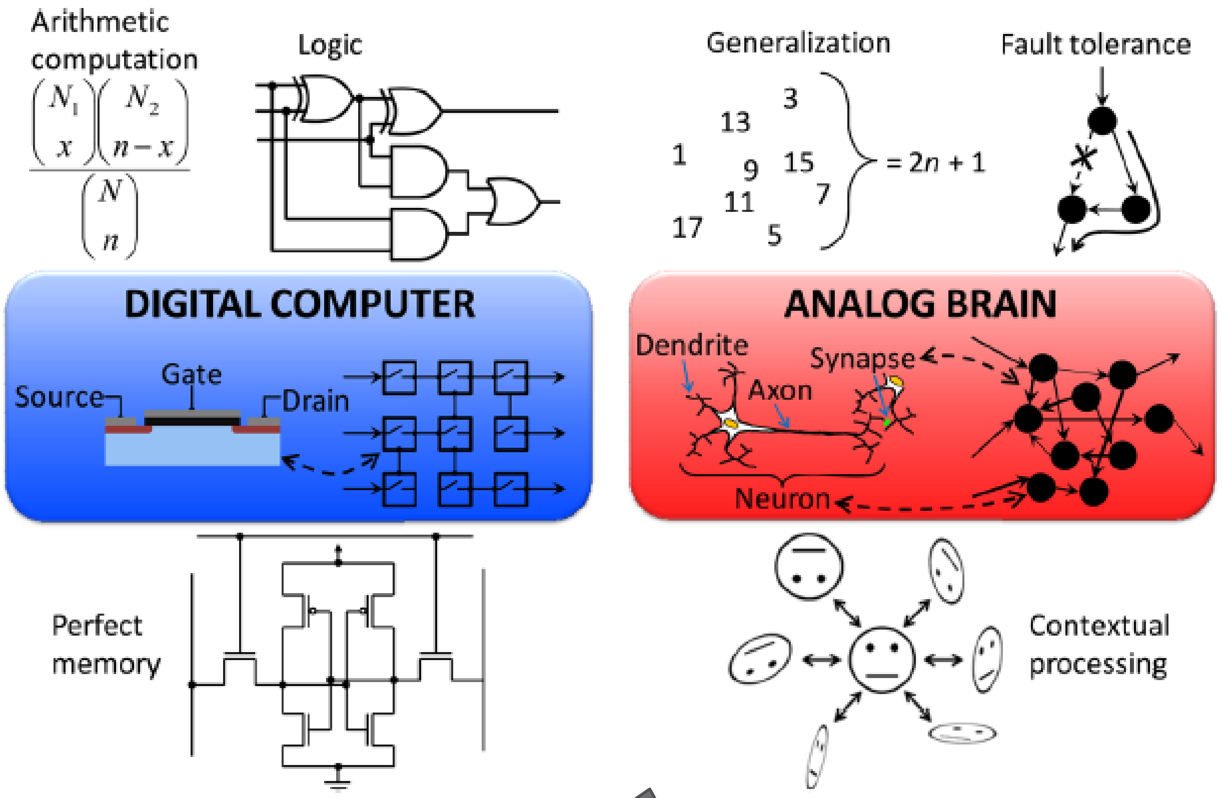
Outline

- **Functional/adaptive oxide electronics: introduction**
- **Metal-Insulator-Transition in Vanadium dioxide (VO_2) material**
- **Technology**
- **Electronics applications:**
  - **Steep slope switches**
  - **Spiking neurons for neuromorphic stochastic machines**
  - **Radio-Frequency devices**
  - **Sensors**
- **Conclusions**

Functional/adaptive oxide electronics

In general terms, adaptive information processing refers to systems in which there is dynamic self-adjustment of system parameters during operation rather than fixed output-to-input relationship. Efficiency increases as the system evolves through self-adjustment. As a basic example, a standard signal filter has a fixed frequency response, but an adaptive filter may sharpen its output function over time across certain frequency ranges in response to input patterns. A common implementation of adaptive computation is in artificial neural networks, which are biologically inspired systems wherein nodes (~neurons) send signals between each other through weighted edges (~synapses). This is illustrated in the center-right panel of Fig. 2, where nodes are black circles and edges are arrows. The edge weights are independently adjustable and determine the effect of one node on the next. This is in contrast to digital computers, in which binary field-effect transistor (FET) switches are interconnected with fixed weight.



Sieu D. Ha and Shriram Ramanathan, , “Adaptive Oxide Electronics: a Review”, J. Appl. Phys, 2011.

Examples of adaptive/functional oxides

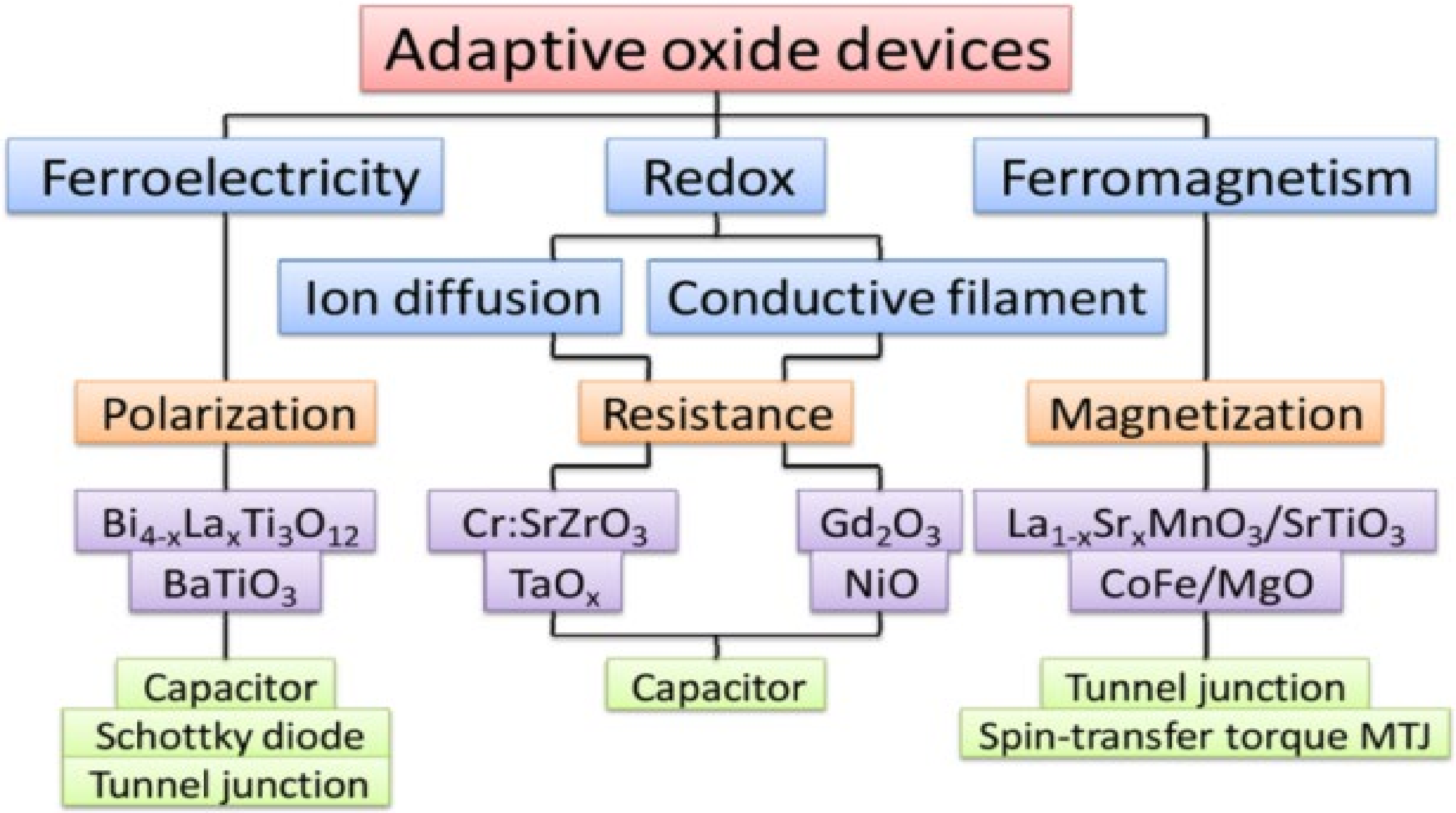


FIG. 5. (Color online) Diagram of adaptive oxide devices surveyed in this review. The levels of the diagram are switching mechanism (2nd), internal state (3rd), representative oxides (4th), and device structures (5th). We discuss devices that have internal state modified by ferroelectricity, ion diffusion, conductive filament formation, and ferromagnetism.

Functional oxides: resistive switching

TABLE I. List of functional oxides used in redox resistive switching devices that may be suitable for adaptive electronics applications. Relevant device properties are specified in the header. Dashes denote that data was not specified in publication. Endurance and retention values do not necessarily reflect device failure limit, only the extent to which respective devices were tested. TE = top electrode and BE = bottom electrode.

Oxide	TE-BE	Multilevel	$\Delta R = R_{Hi}/R_{Lo}$	Switching speed	Retention time(s)	Endurance
Redox resistive						
Binary, bipolar						
CoO	Ta-Pt	-	10^3	20 ns	-	100
Cu_xO	Ti/TiN-Cu	-	10^2	50 ns	10^5 @ 90 °C	600
$HfLaO_x$	TaN-Pt	-	10^6	10 ns	10^4 @ 27 °C	10^4
HfO_x/TiO_x	TiN-TiN	Y	10^3	5 ns	10^4 @ 200 °C	10^5
TaO_x	Pt-Pt	Y	10^1	10 ns	10^7 @ 150 °C	10^9
TiO_2	Pt-TiN	Y	10^3	5 ns	10^6 @ 85 °C	10^6
ZrO_2	TiN-Pt	-	10^1	1 μs	10^4 @ 27 °C	10^3
Binary, unipolar						
Gd_2O_3	Pt-Pt	-	10^6	-	10^5 @ 85 °C	60
HfO_2	Pt-Pt	-	10^2	-	10^6 @ 27 °C	140
Lu_2O_3	Pt-Pt	-	10^3	30 ns	10^6 @ 27 °C	300
NiO	Pt-Pt	-	10^2	5 μs	10^7 @ 27 °C	10^6
TaO_x	Cu-Pt	-	10^2	80 ns	10^6 @ 27 °C	100
TiO_x	Pt-Pt	-	10^4	-	-	25
WO_x	TiN-W	Y	4	300 ns	10^4 @ 100 °C	10^7
ZnO	Pt-Pt		10^4	-	-	100
Perovskite, bipolar						
$Cr{:}Ba_{0.7}Sr_{0.3}TiO_3$	$Pt\text{-}SrRuO_3$	Y	4	0.2 s	10^4 @ 27 °C	10^4
$Pr_{0.7}Ca_{0.3}MnO_3$	$Ag\text{-}YBa_2Cu_3O_{7-x}$	Y	10^2	8 ns	-	10^5
$Pr_{0.7}Ca_{0.3}MnO_3$	Al-Pt	-	10^2	20 μs	10^4 @ 125 °C	10^3
$Cr{:}SrTiO_3$	Au-Au	Y	10	1 ms	8×10^4 @ 27 °C	10^3
$Nb{:}SrTiO_3$	Pt	Y	10^2	50 μs	10^8 @ 125 °C	10^7
$Cr{:}SrZrO_3$	$Au\text{-}SrRuO_3$	Y	20	100 ns	10^7 @ 27 °C	-
$Cr{:}SrZrO_3$	$Al\text{-}LaNiO_3$	-	10^2	500 μs	10^3 @ 85 °C	-

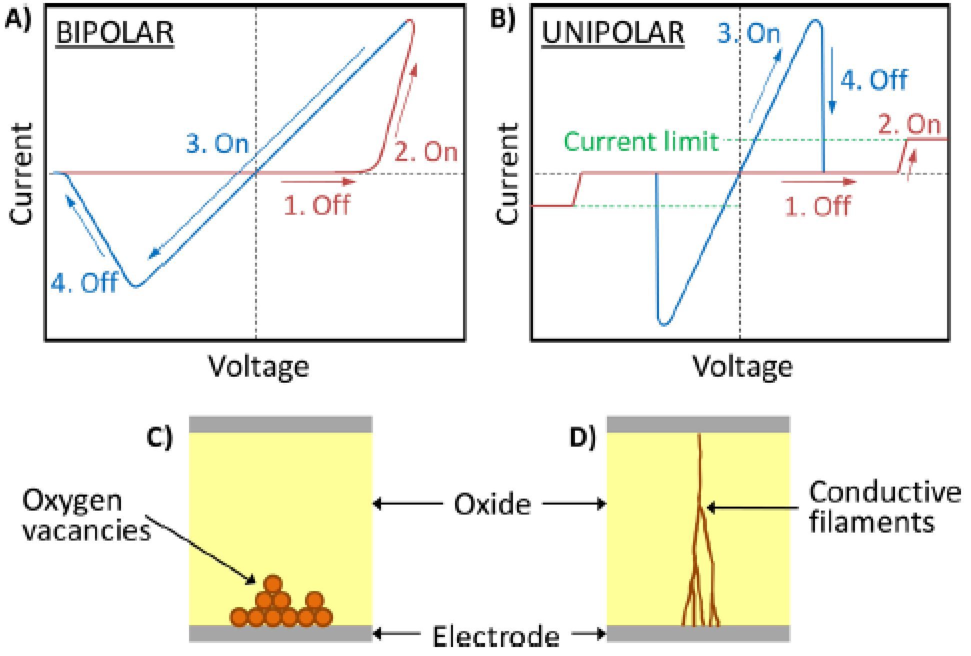


FIG. 6. (Color online) Typical *I-V* characteristics of (A) bipolar and (B) unipolar resistance switching. In bipolar switching, a device in a high resistance state switches to a low resistance state at high positive voltage and remains in that state until a large negative voltage is applied. In unipolar switching, a device in a high resistance state switches to a low resistance state at high voltage of either polarity and switches back to a high resistance state at lower voltage, again at either polarity. Prospective models of the respective low resistance states are given in (C) and (D). In (C), oxygen vacancy accumulation lowers the Schottky barrier at one electrode. In (D), conductive filaments that span from one electrode to the other effectively shunt the oxide. (Adapted from *Materials Today*, A. Sawa, Resistive switching in transition metal oxides, **11**, 28, © 2008, with permission from Elsevier.)

Basics: Mott insulators

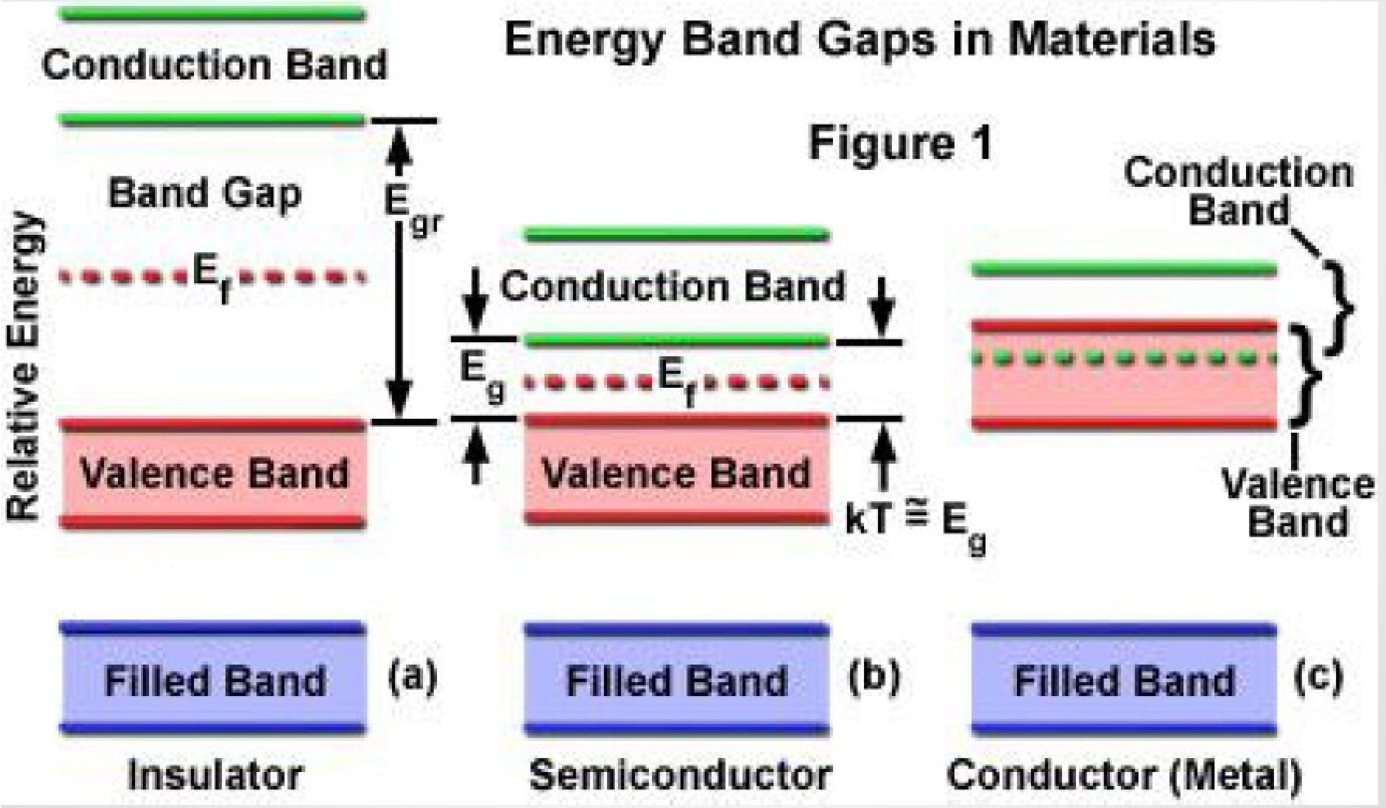
- **Definition: What is a Mott Insulator?**
- **Metal that stops conducting under certain conditions (low temperature or high pressure), despite classical theory predicting conduction.**

- **Band Gap Theory**
  - ➢ Conduction and valence bands
  - ➢ Tuning the bandgap
- **Mott Insulators**
  - ➢ Origins
  - ➢ Theory

● Sir Nevill Francis Mott
(30 September 1905 – 8 August 1996) was a British physicist who won the Nobel Prize for Physics in 1977 for his work on the electronic structure of magnetic and disordered systems (amorphous semiconductors).
● Pointed out flaw in central approximation in band theory: *inter-electron forces are not negligible*

Band gap and type of materials

- Band Gap (or lack thereof) responsible for conductors, semiconductors, and insulators.
- Fermi Level: naturally half-way between conduction and valence bands



Oxide Electronics Utilizing Ultrafast Metal-Insulator Transitions

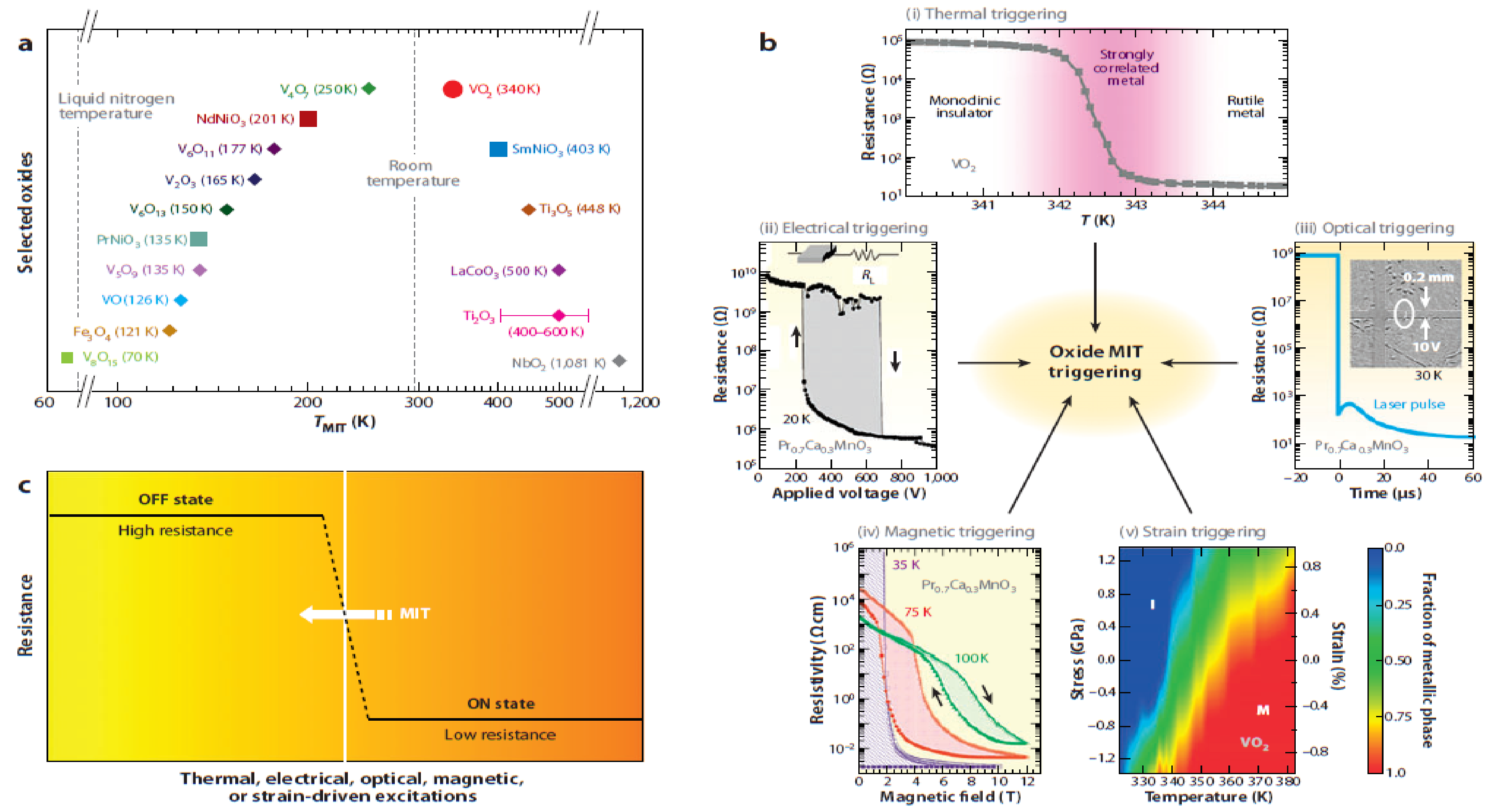


Figure 1

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 *i* 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*.

Z. Yang, C. Ko and S. Ramanathan
Annu. Rev. Mater. Res. 2011. 41:337–67

Mott insulators: theory

When is a metal not a metal? Steven C. Erwin (Nature, Vol. 441, 2006).

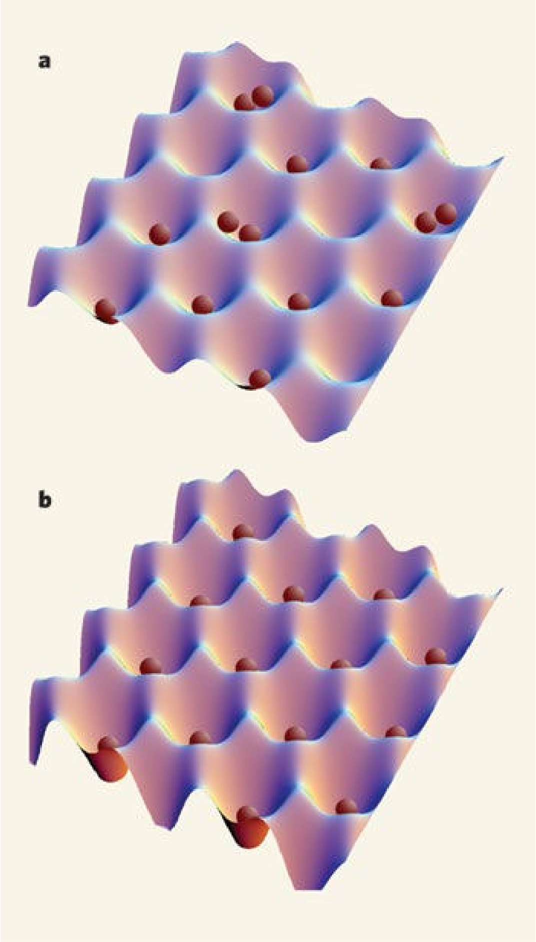
Exception to band theory.

- Materials that **owe their insulating nature to correlations in the motions of different electrons**. These correlations arise from the classical Coulomb repulsion between charge particles. They can be decisive in materials in which the *two competing tendencies of electrons* exist in balance:

(1) the desire to be spatially localized to minimize Coulomb repulsion

(2) the need to be delocalized to minimize the cost in kinetic energy from spatial confinement.

- Surfaces of semiconductors: electrons are effectively confined to two dimensions. Mott insulators have been created over the past decade on the surfaces of many common semiconductors.



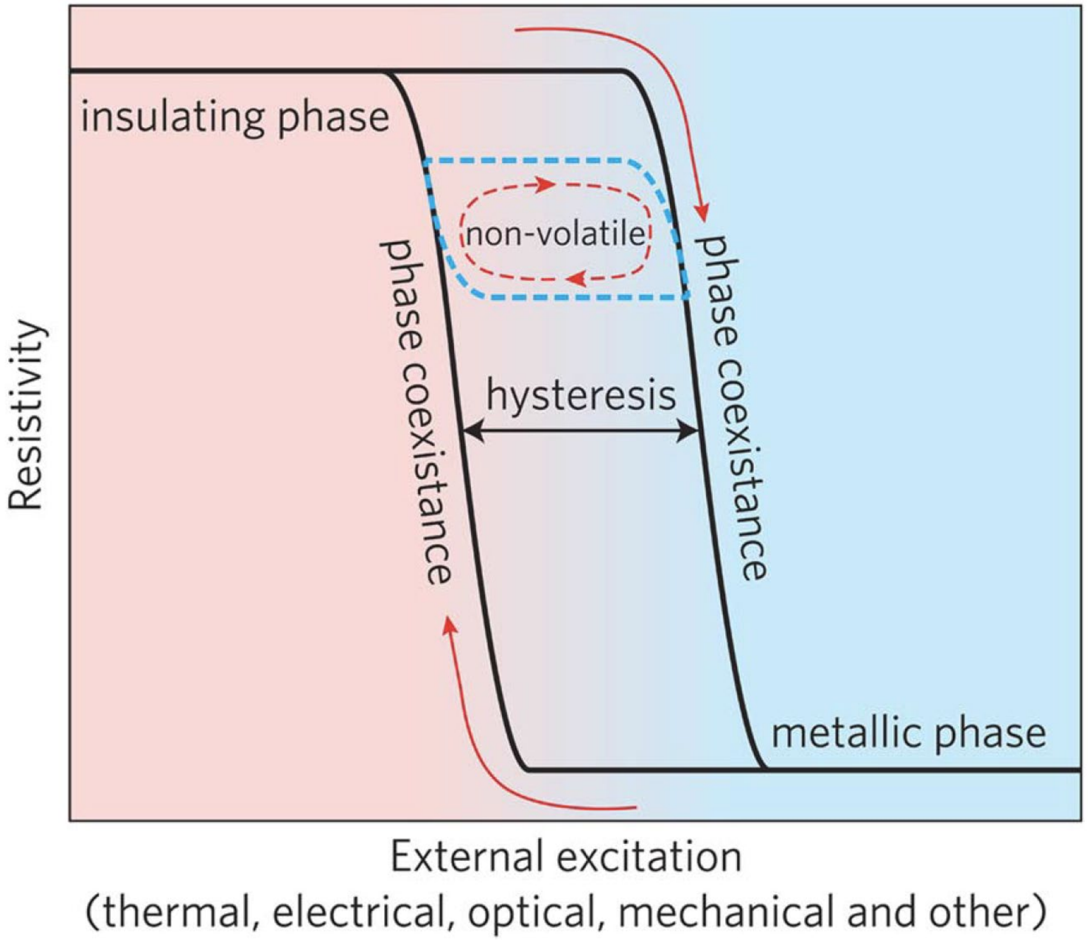
a) The regular potential wells of a normal metallic state of a material with, on average, one electron per atom.

b) If the confining potential is a little stronger (deeper wells), electrons find it harder to delocalize and so do not conduct — despite what the band theory of solids predicts.

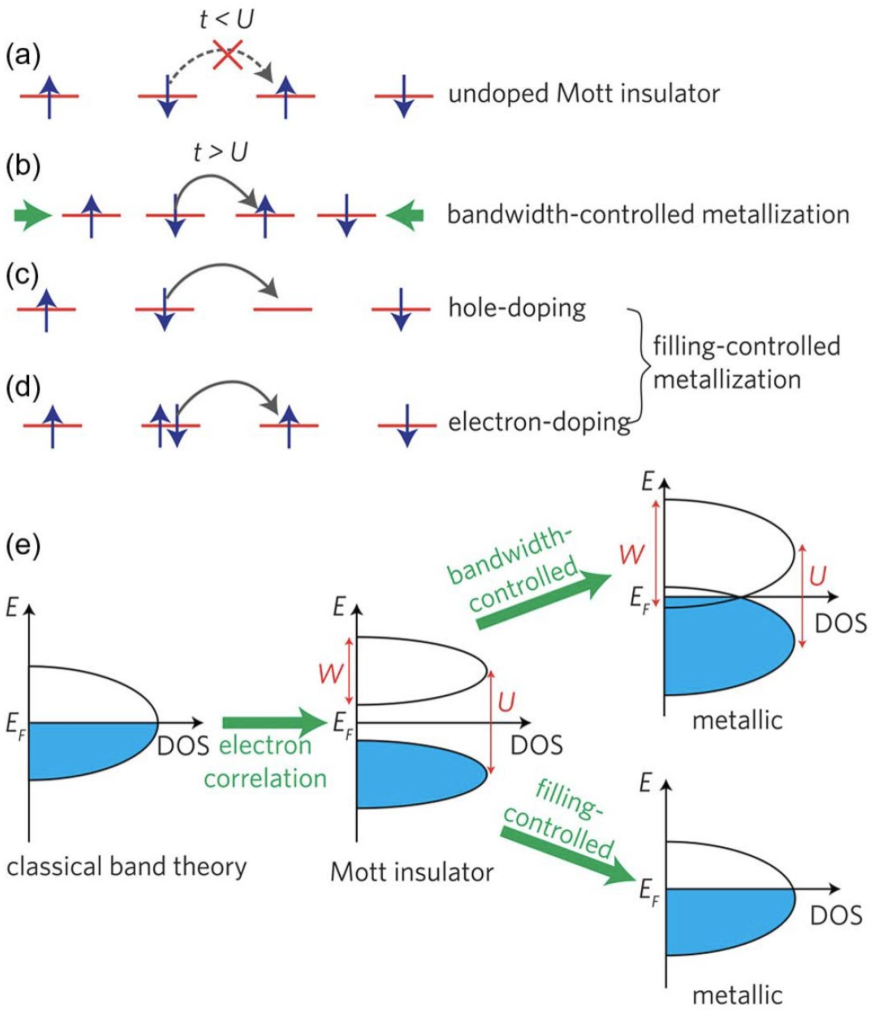
The material is a Mott insulator.

Generic features of metal-to-insulator (MIT) transitions

- The **metal-to-insulator transition in Mott insulators can be driven by various kinds of external perturbations**.
- Above a threshold perturbation, the material **resistivity changes drastically by several orders of magnitude**.
- Near the threshold, phase coexistence of both insulating and metallic phase can occur.
- Many of the transitions also exhibit hysteresis. Within the hysteresis window, the system's resistance could be nonvolatile.



Mechanisms of phase change in Metal-Insulator-Transition materials



(a) In the **insulating phase, electron transport/hopping is forbidden because Coulomb repulsion** between electrons, U, is much larger than electron's kinetic energy, t.

(b) Bandwidth-controlled metal-to-insulator transition: decreasing the interatomic distance increases the electronic bandwidth and delocalization energy t and drives an insulator-to-metal transition when t becomes larger than U.

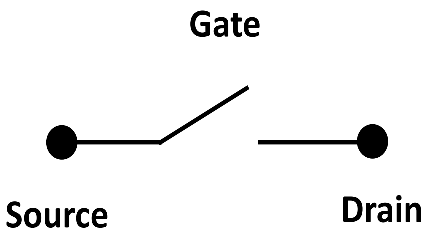
(c), (d) Filling controlled metal-to-insulator transition: hole- and electron-doping create empty or doubly occupied atomic sites, respectively. Since there is **no more energy penalty for electron hopping to occur, the insulator becomes a metal**.

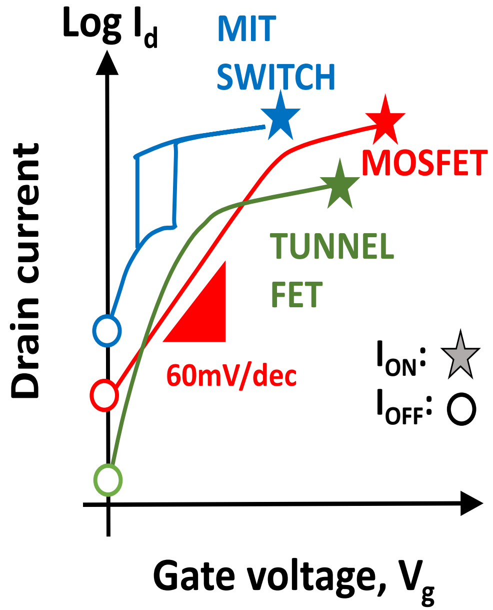
(e) The electronic band diagram evolution during metal-to-insulator transitions: classical band theory predicts that a Mott insulator has nonzero density of states at the Fermi level and is metallic. In reality, **the band splits into two as a result of electron correlation** and Fermi energy lies in the gap.

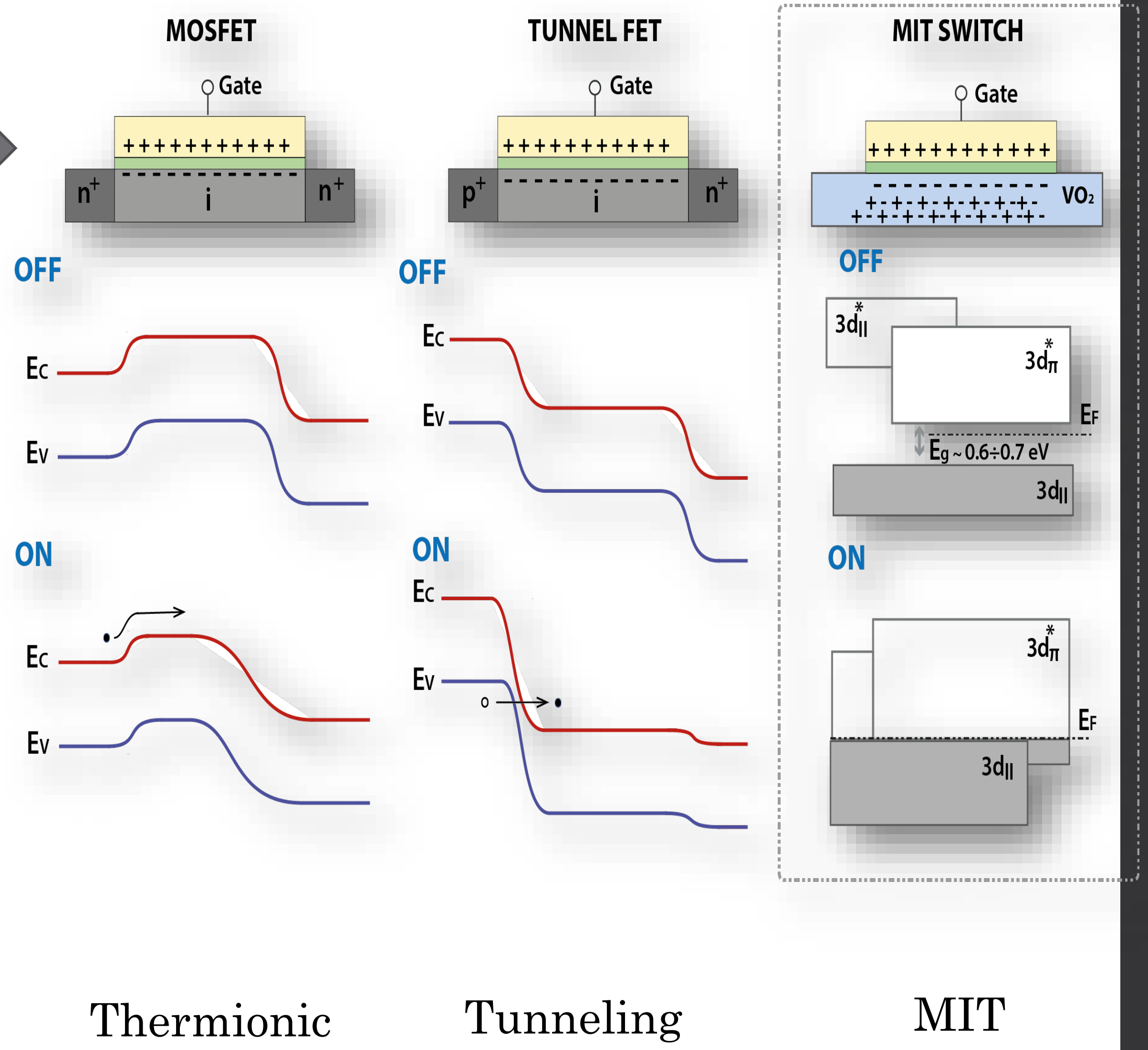
MIT steep slope switch

- Three solid-state devices qualitatively compared.
- **Metal-Insulator-Transition involves a completely different principle:**

In the so-called <u>MIT-FET or Mott-FET</u>, the gate charge then induces a charge in the channel, which then converts the whole channel type from insulator into a metallic phase.







Metal-to-Insulator Transition Speed in Various Mott Insulators

Material	Driving method	Probe	Speed
$Pr_{0.7}Ca_{0.3}MnO_3$	Mid-IR vibrational excitation	Reflectivity	1ps
$Pr_{0.7}Ca_{0.3}MnO_3$	Mid-IR vibrational excitation	Electrical conductivity	4 ns
V_2O_3	Voltage pulse	Electrical conductivity	390 ps
V_2O_3	Near-IR excitation	Far-IR conductivity	20 ps
VO_2	Voltage pulse	Electric conductivity	2 ns
VO_2	Near-IR excitation	Reflectivity	75 fs
VO_2	Near-IR excitation	Electron diffraction	300 fs
NbO_2	Voltage pulse	Electric conductivity	700 ps
$1T$-TaS_2	Near-IR excitation	Time-resolved ARPES	100 fs

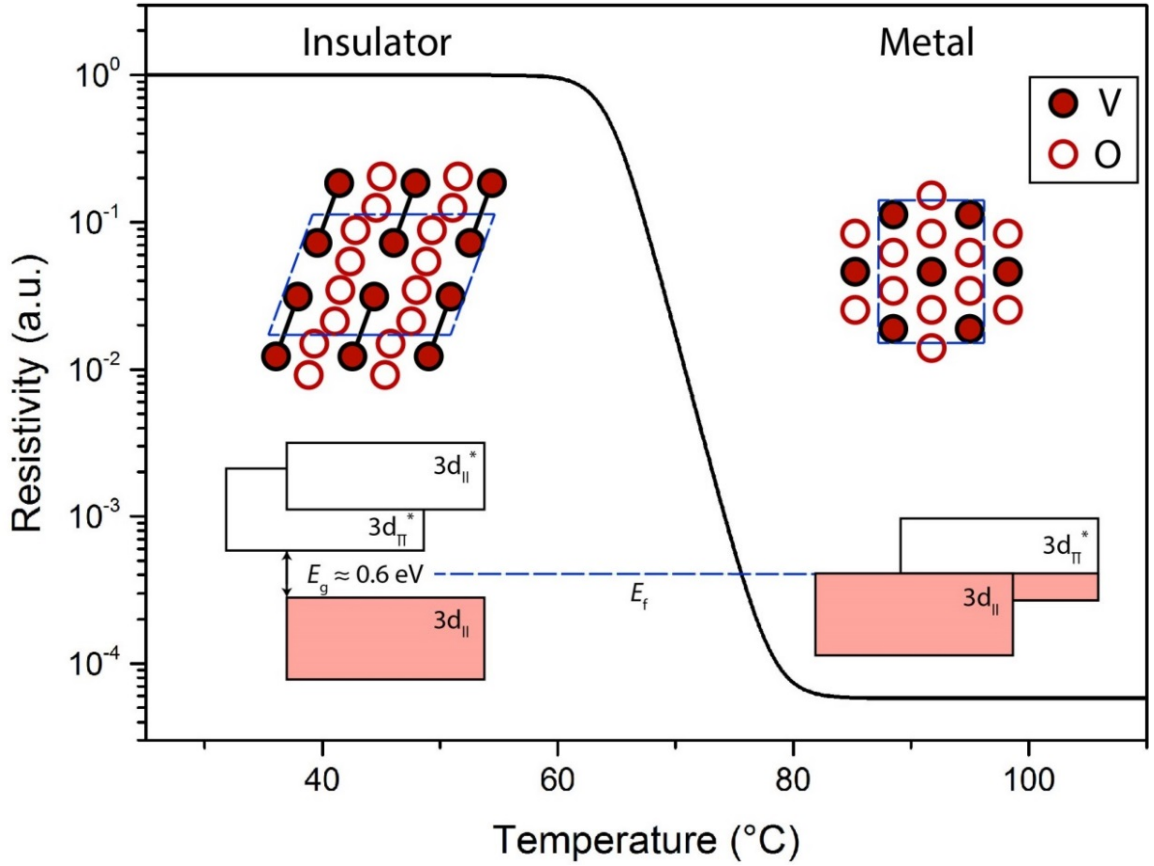
Reported values of switching on time in VO2, NbO2, and other oxides range from **10^{-1} to 10 ns.**

Such speed is fast enough for many memory applications.

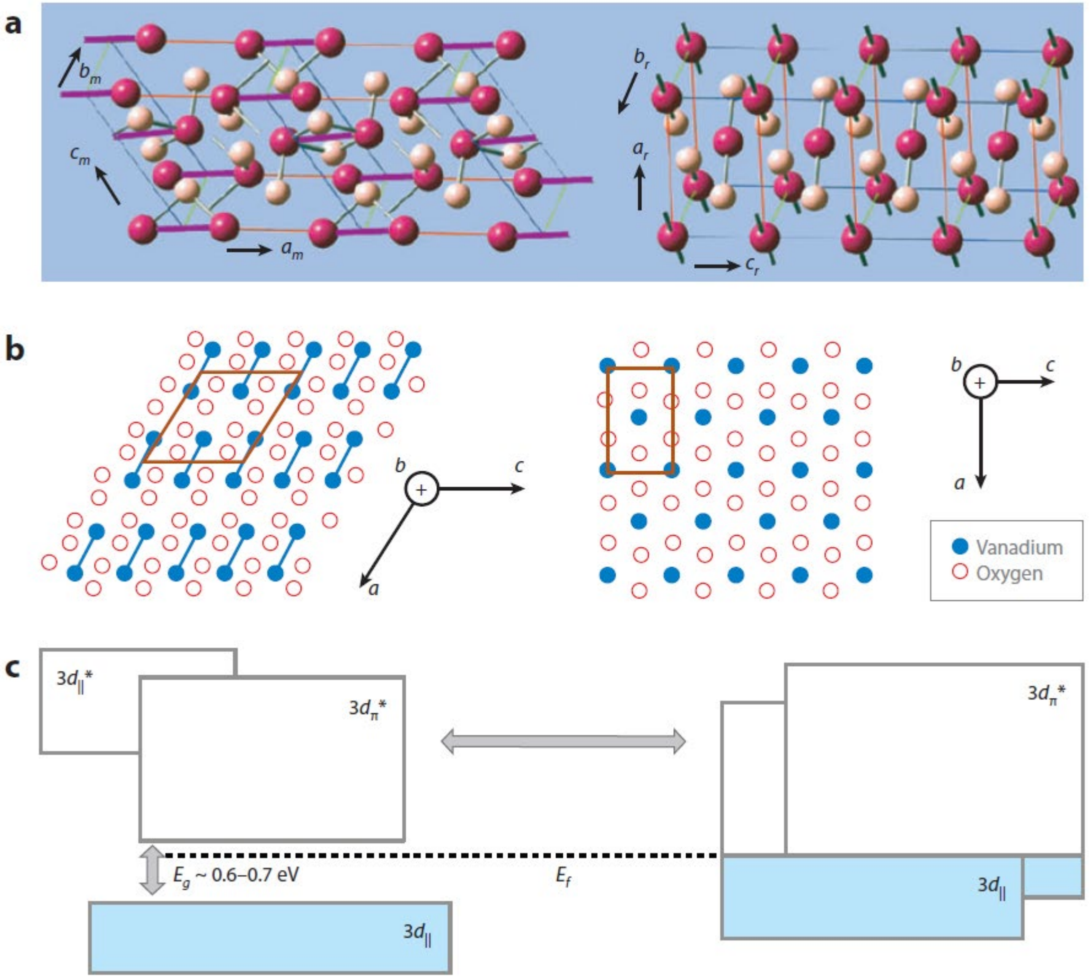
Metal-Insulator Transition (MIT) in Vanadium Dioxide

- Vanadium dioxide (VO_2) undergoes a structural phase transition at ~68 °C accompanied by a steep decrease in resistivity.
- The monoclicic phase presents a **bandgap ~0.6 eV.**
- The tetragonal phase presents **metallic behavior.**

How to exploit this behavior for integrated electronic (switching) functions?



Bandgap modulation in VO_2

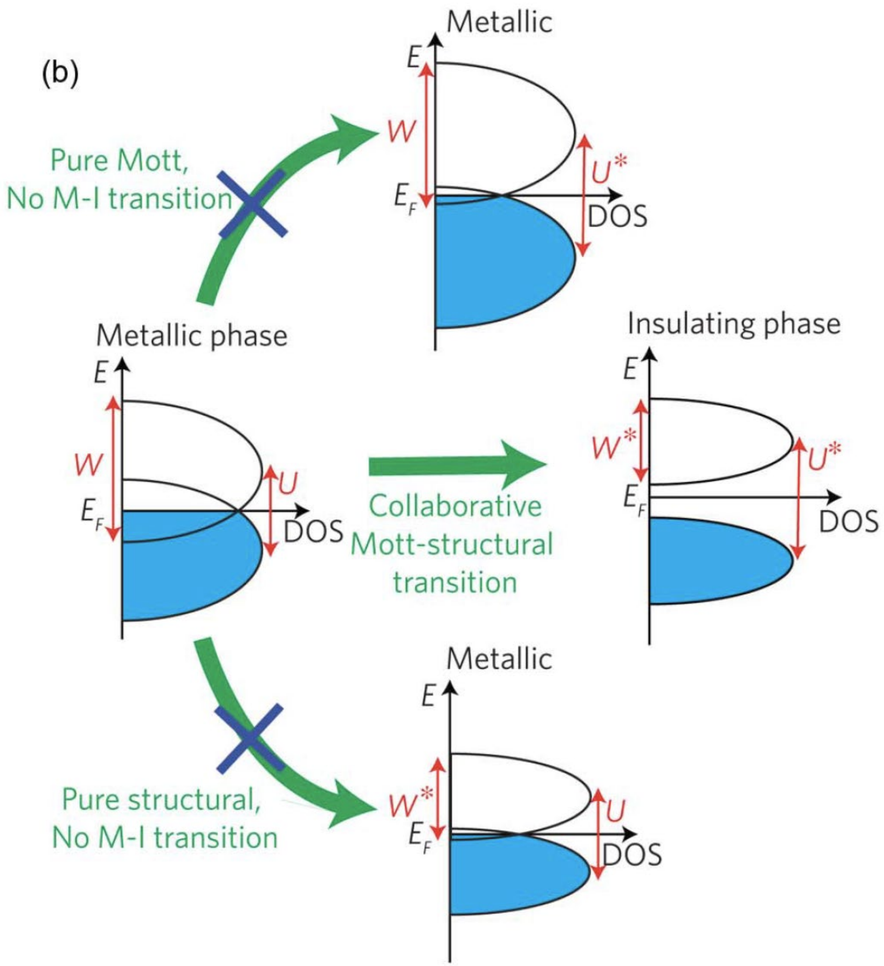


Structure and band diagram of VO_2:

(*a*, *b*) Structure change of VO_2 from the monoclinic insulating phase (M_1) 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 VO_2 across the MIT. The left and right panels show the band structures for the insulating and metallic phases, respectively.

The VO2 MIT-IMT mechanisms



Cooperative lattice and electronic phase change in correlated insulators.

Illustration of collaborative Mott structural Transition:

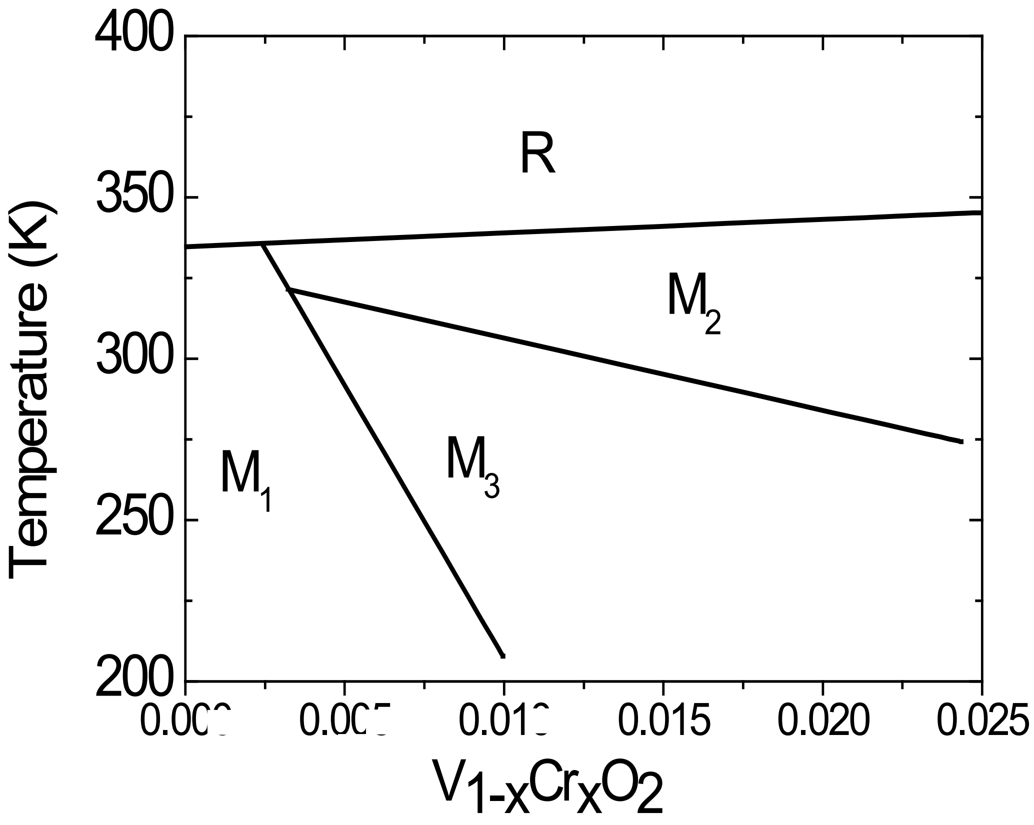
- A Mott transition reduces effective electron correlation U, but may not be enough to induce a metal-to-insulator transition.
- The decrease of band width W from structural change alone may also be insufficient to trigger the transition.
- A simultaneous increase in U and a decrease in W can drive the transition in a collaborative fashion.

Doped VO_2 for bandgap engineering

- The MIT for VO_2 occurs at 340K between the conducting rutile phase and the monoclinic M1-M3 phases .

- VO_2 is of broad interest because its MIT occurs **just above room temperature**. However, the band gap of the insulating phase of VO_2 is only 0.6 eV which, with band edge tailing, means that the on-off resistance range is only about 10^4 which is insufficient for a FET.

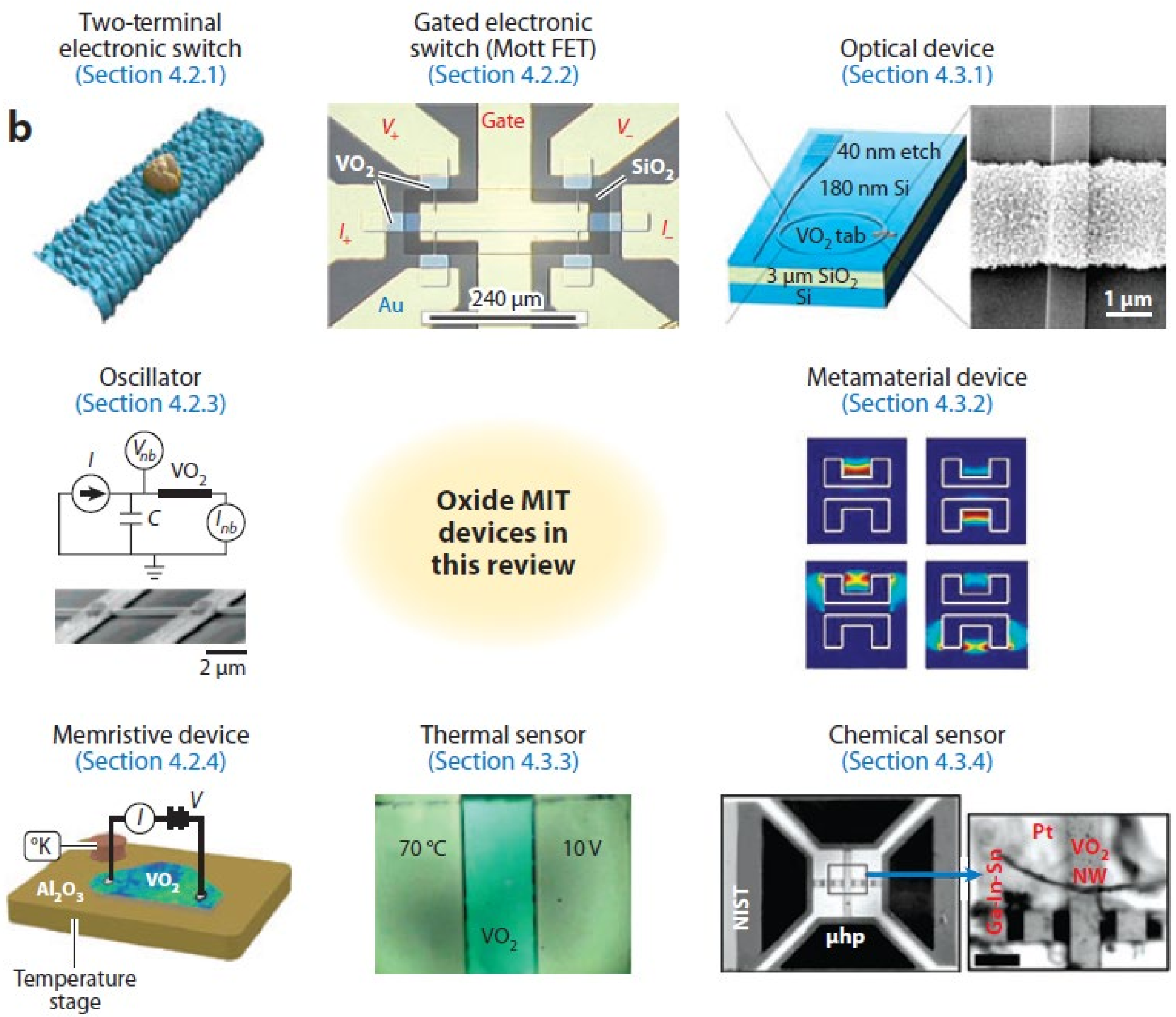
- **Challenge: Doping techniques to increase the band gap in the off state is needed: Mg? Cr? Ge?**



Ultrafast electronic devices and applications with VO_2

- Recent interest in VO_2 triggered by demonstration of more ‘actuation’ mechanisms.
- Ultrafast switching (~10 ns) by electronic excitation.
- Interest in explaining the physics of the MIT.
- Novel device structures and functionalities introduced in multiple fields.

What electronic functions are possible with VO_2?

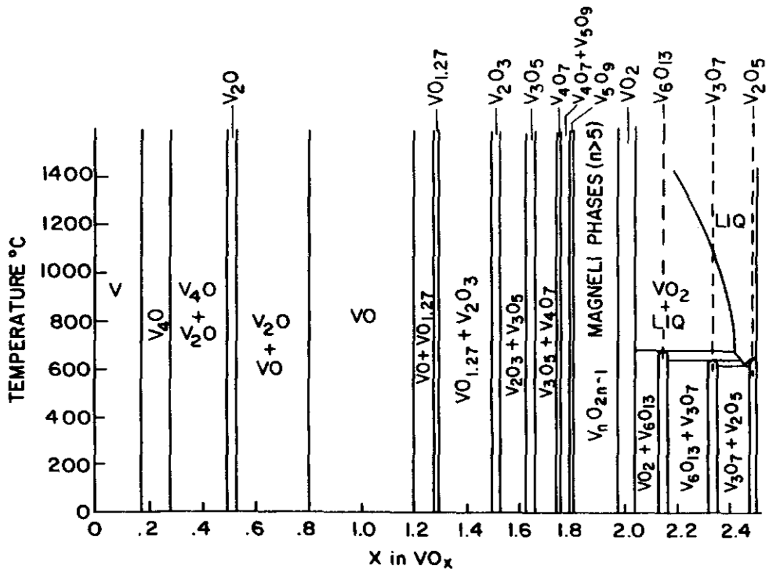


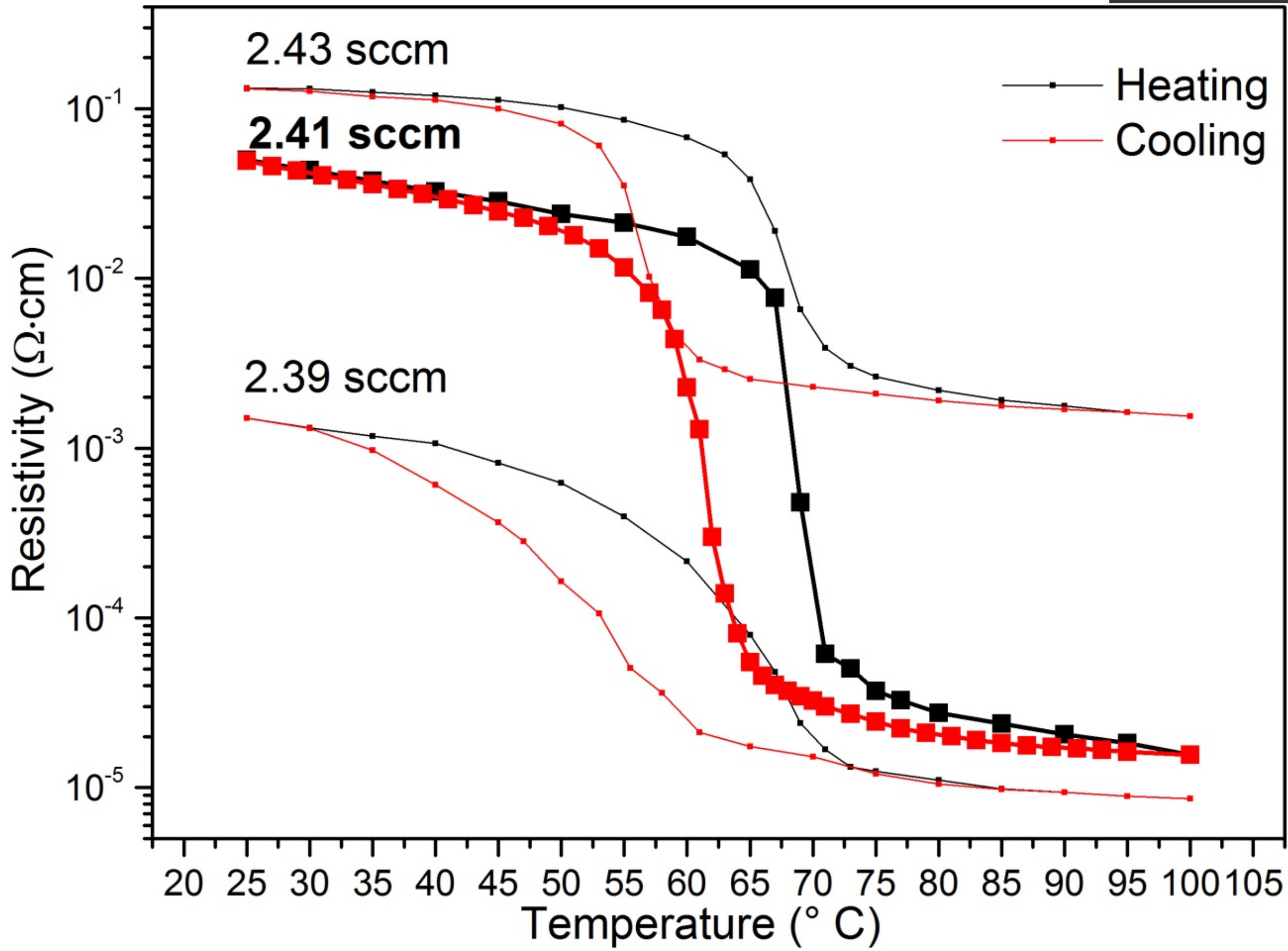
O_2 Growth Optimization Window in VO_2 reactive magnetron sputtering

Sputtering conditions

- Pure V target.
- High T for film crystallinity.
- High-vacuum conditions.
- Deposition rate ~ 3 nm/min
- *O_2 flow critical parameter for the VO_x phase.*

Phase diagram of vanadium oxides



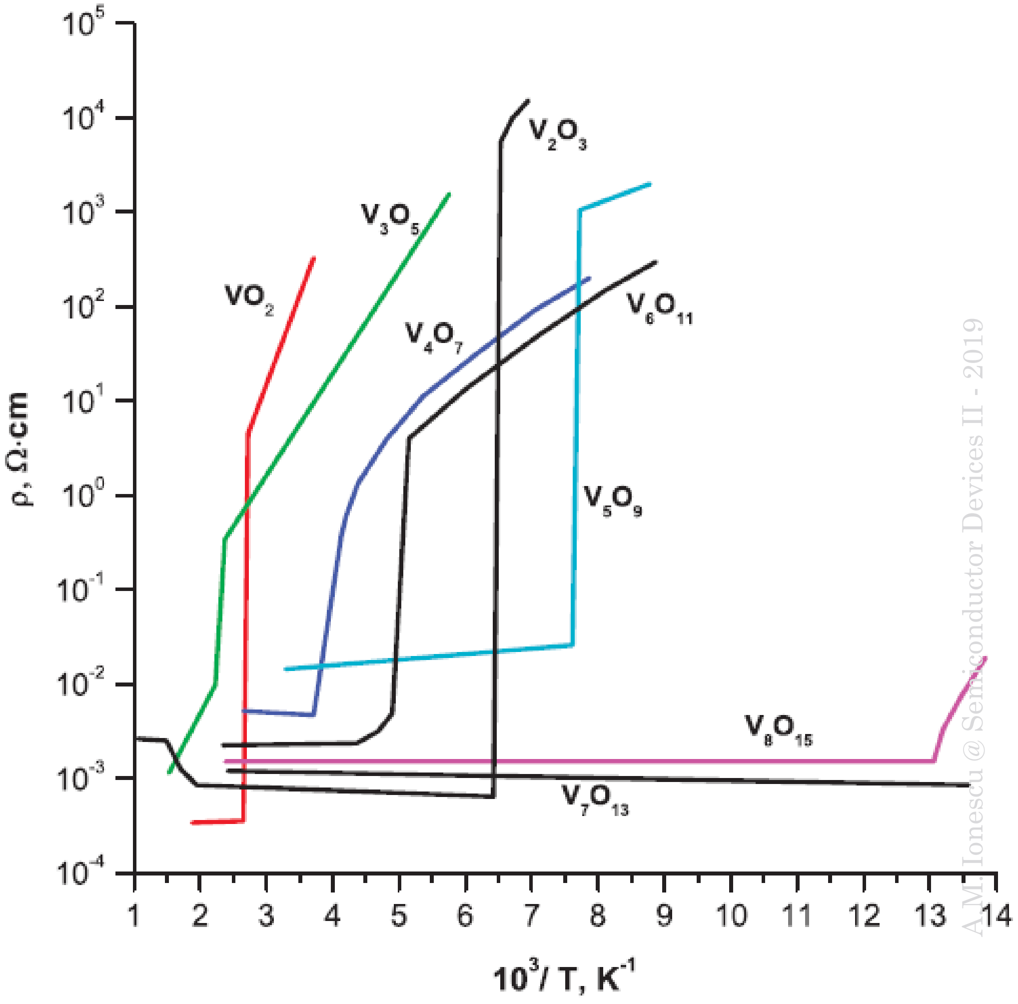


Influence of stoechiometry on transition temperature

TABLE I
VANADIUM OXIDES [47], [48], [54]

n in formula V_nO_{2n-1}	Oxide	T_t, K
(1)	VO	–
(2)	V_2O_3	150
3	V_3O_5	450
4	V_4O_7	240
5	V_5O_9	130
6	V_6O_{11}	170
7	V_7O_{13}	–
8	V_8O_{15}	70
(∞)	VO_2	340
(-6)*)	V_6O_{13}	150
(-2)	V_2O_5	–

*) V_6O_{13} and V_2O_5 formally correspond to the series V_nO_{2n-1} with negative *n*, though actually they belong to the Wadsley phases $V_{2n}O_{5n-2}$ [56].



VO_2 2-terminal diode-like switch

Harvard

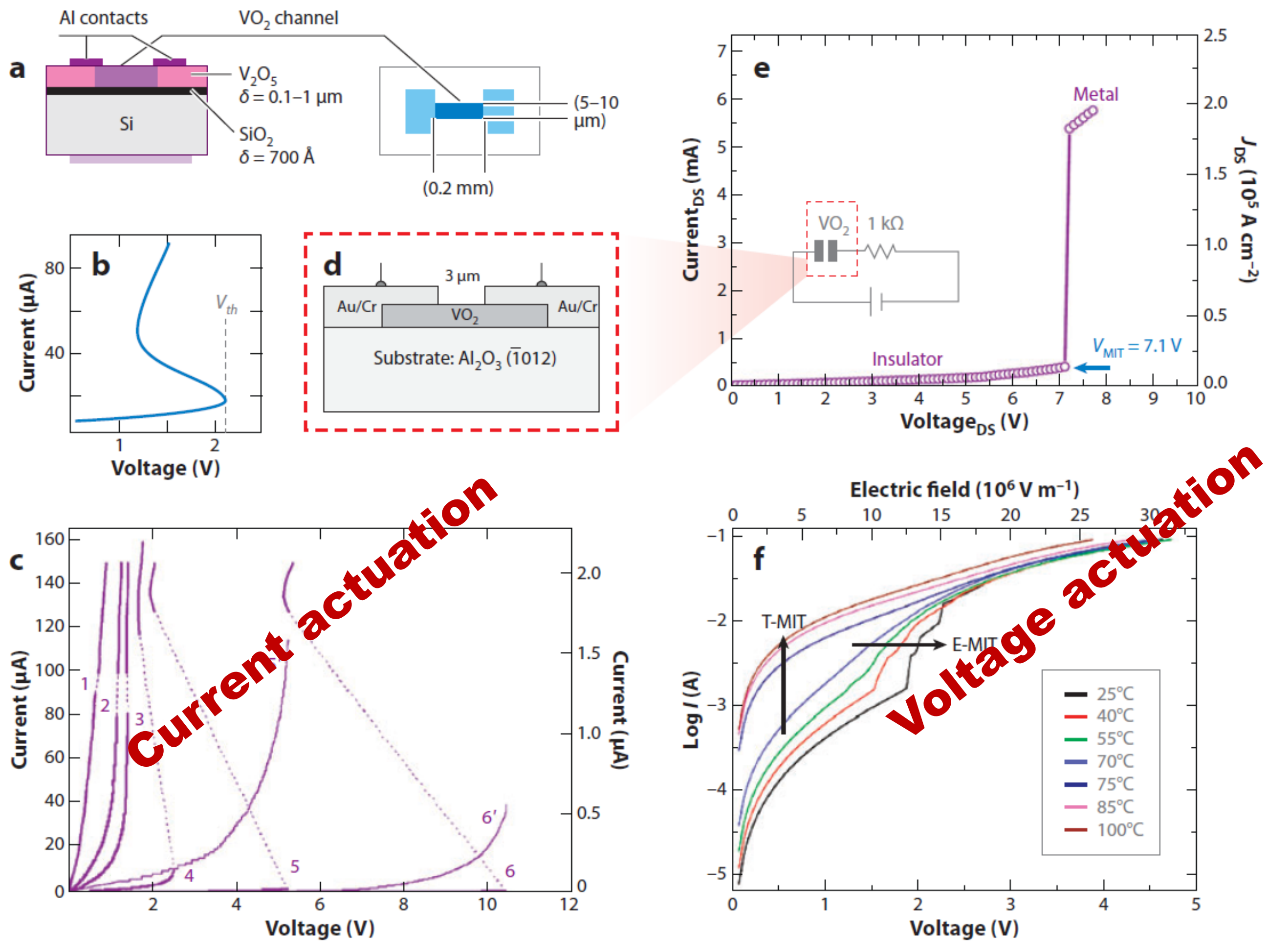
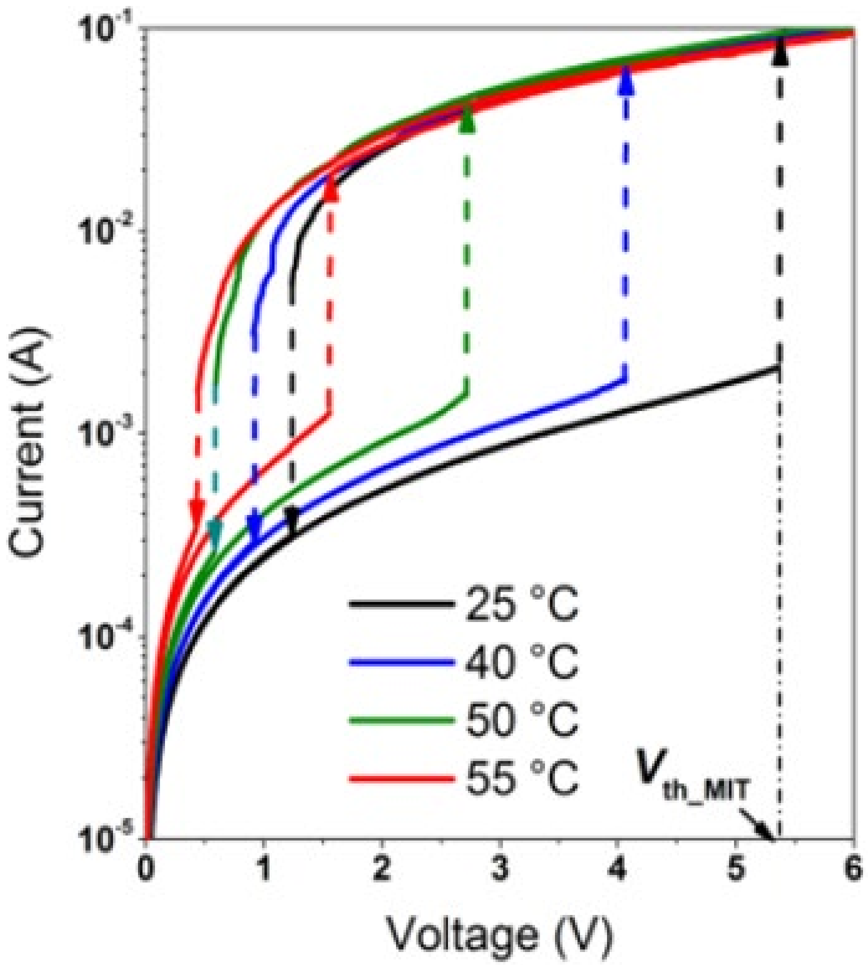
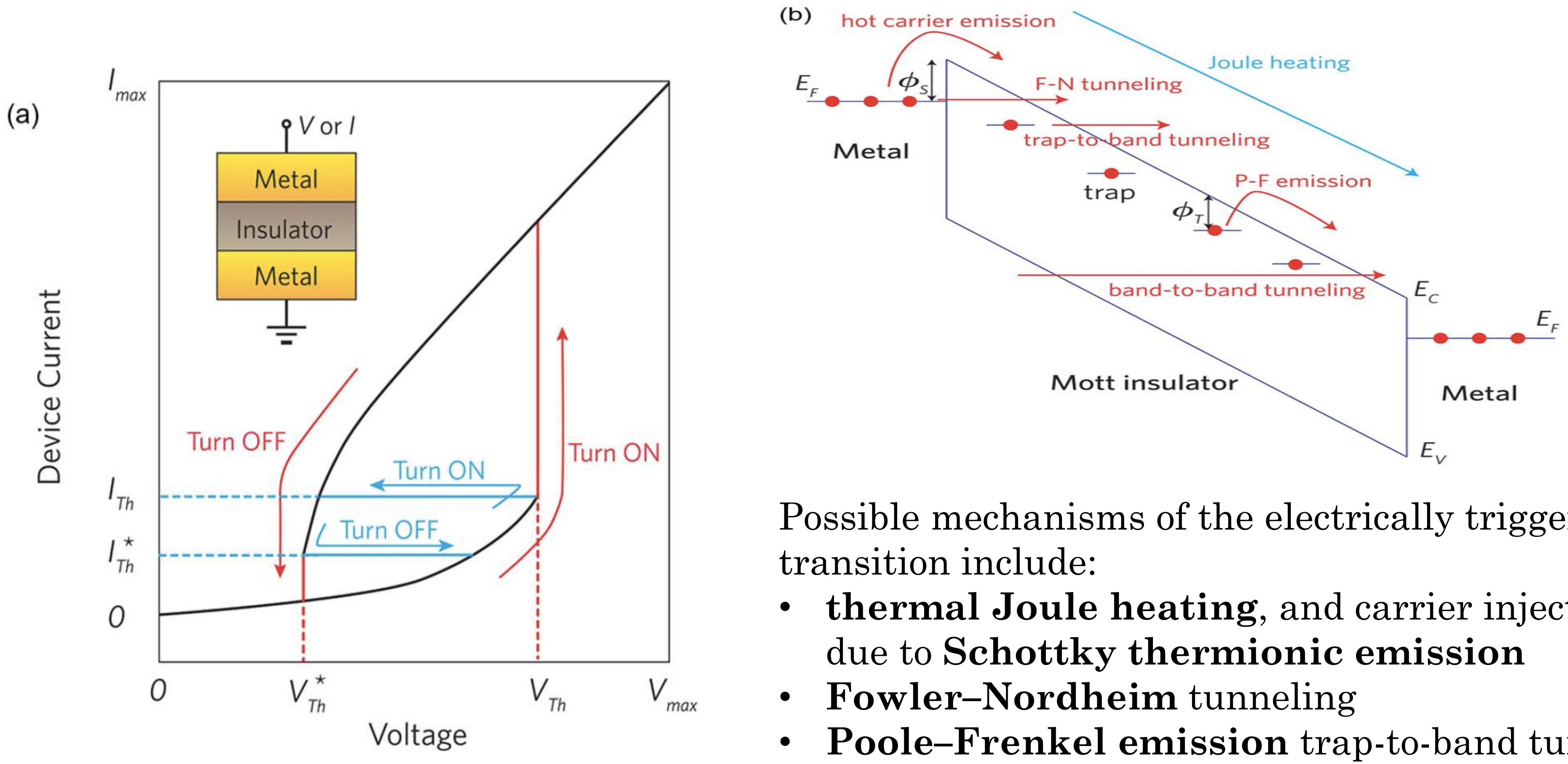


Figure 5

EPFL



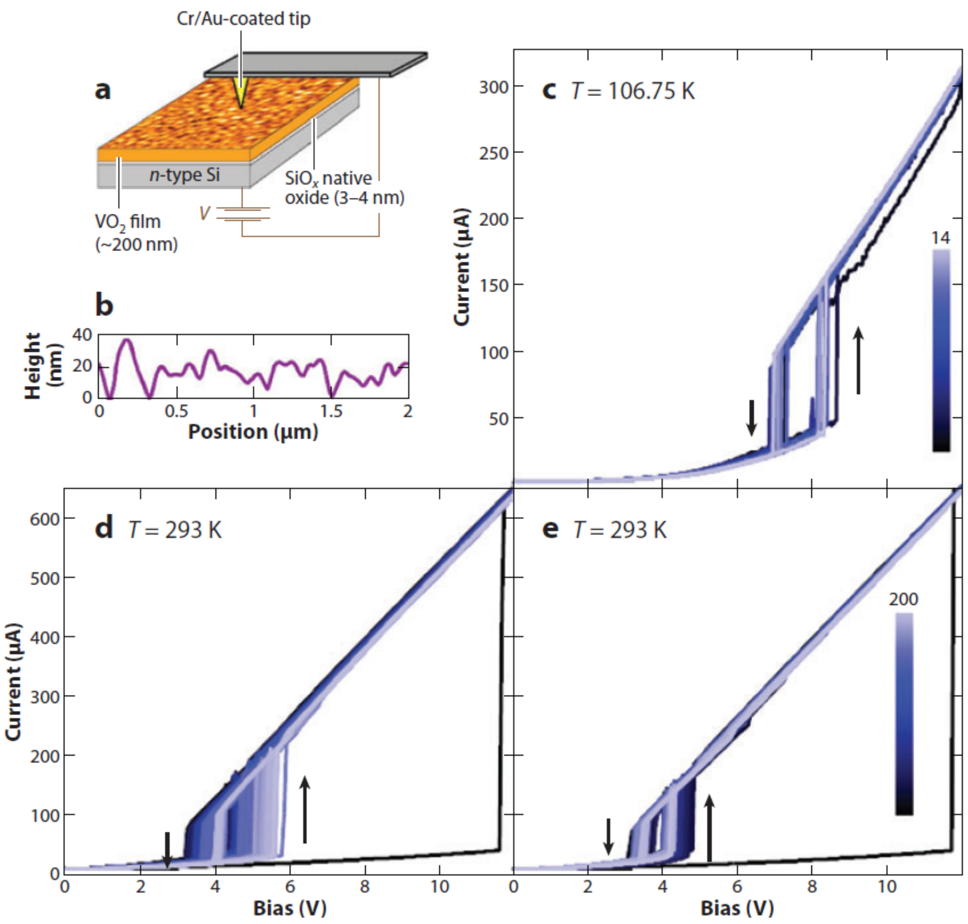
Physical mechanisms of the phase transition in VO2 switches



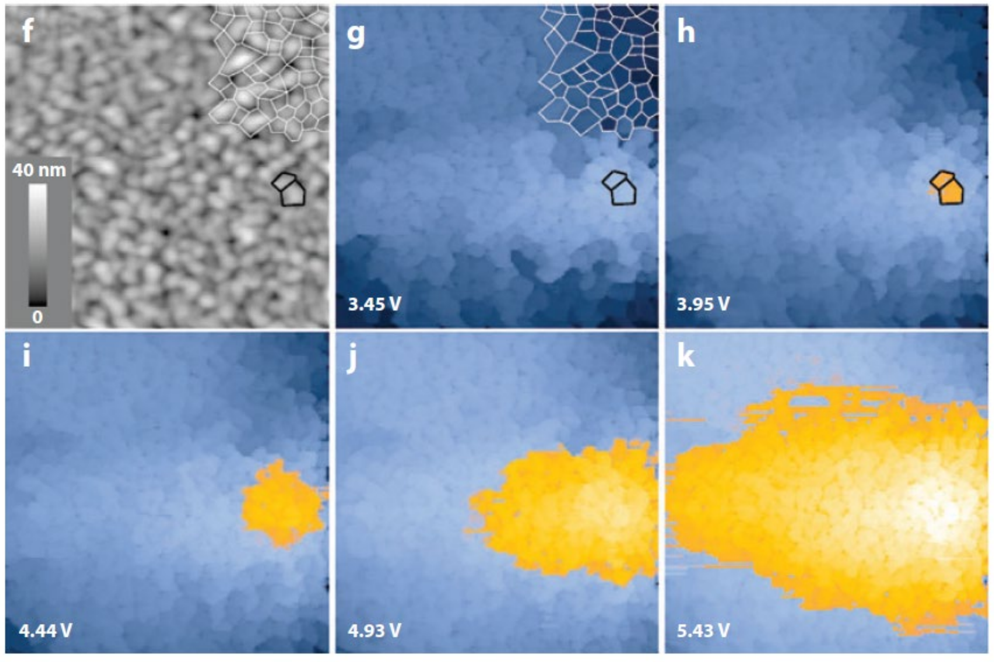
Possible mechanisms of the electrically triggered transition include:

- **thermal Joule heating**, and carrier injection due to **Schottky thermionic emission**
- **Fowler–Nordheim** tunneling
- **Poole–Frenkel emission** trap-to-band tunneling
- **band-to-band tunneling**.

Electrically triggered MIT transition



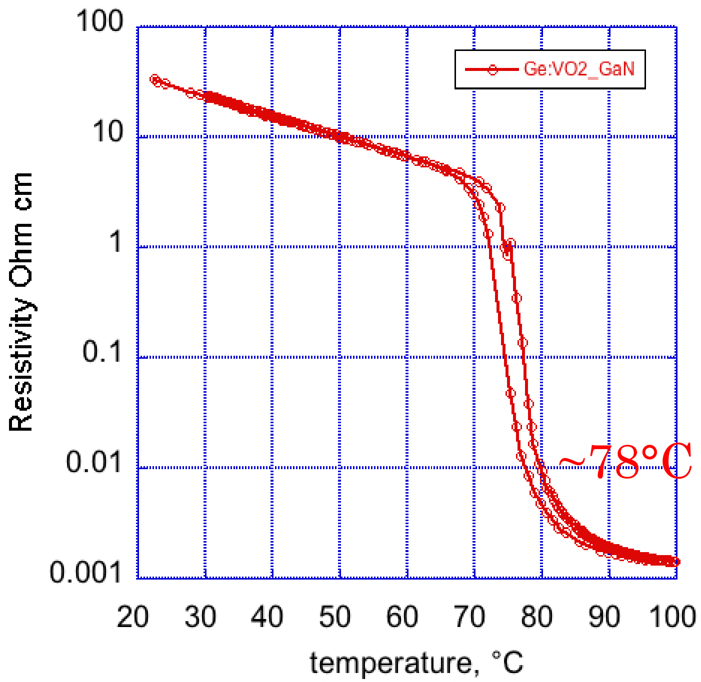
AFM studies of electrically triggered MIT in VO_2. (*a*) Schematic of the AFM tip and the sample geometry. (*b*) AFM line scan. (*c*) Fourteen consecutive *I-V* sweeps at $T = 106.75$ K. (*d,e*) Two hundred consecutive *I-V* sweeps at two different representative locations at $T = 293$ K. The color scale bar shows the times of sweep. (*f*) AFM image showing the surface morphology of the VO_2 thin film. (*g–k*) Current mapping at different bias voltages. Grain

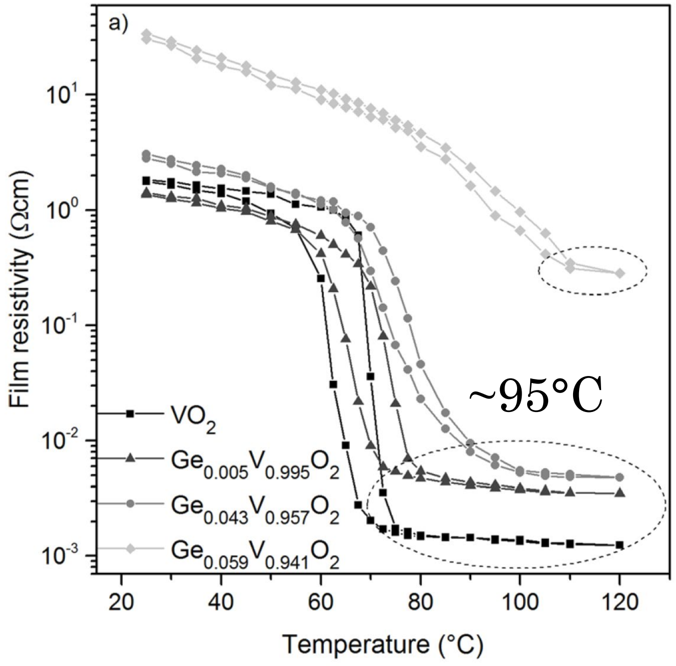


A.M. I

Ge-doped high temperature transition MIT switch

- donor-like dopants with large ionic radii (W, Mo, and Nb) decrease the transition temperature, while acceptor-like elements of low oxidation state and smaller ionic radii (Al, Cr, Fe) increase the transition temperature
- effect of Ge-doping on the insulator-to-metal phase transition in vanadium oxide and found that the transition temperature can be controlled and be significantly increased upon Ge doping, slighty over 90°C





MIT-based memory devices

Mott memory selectors

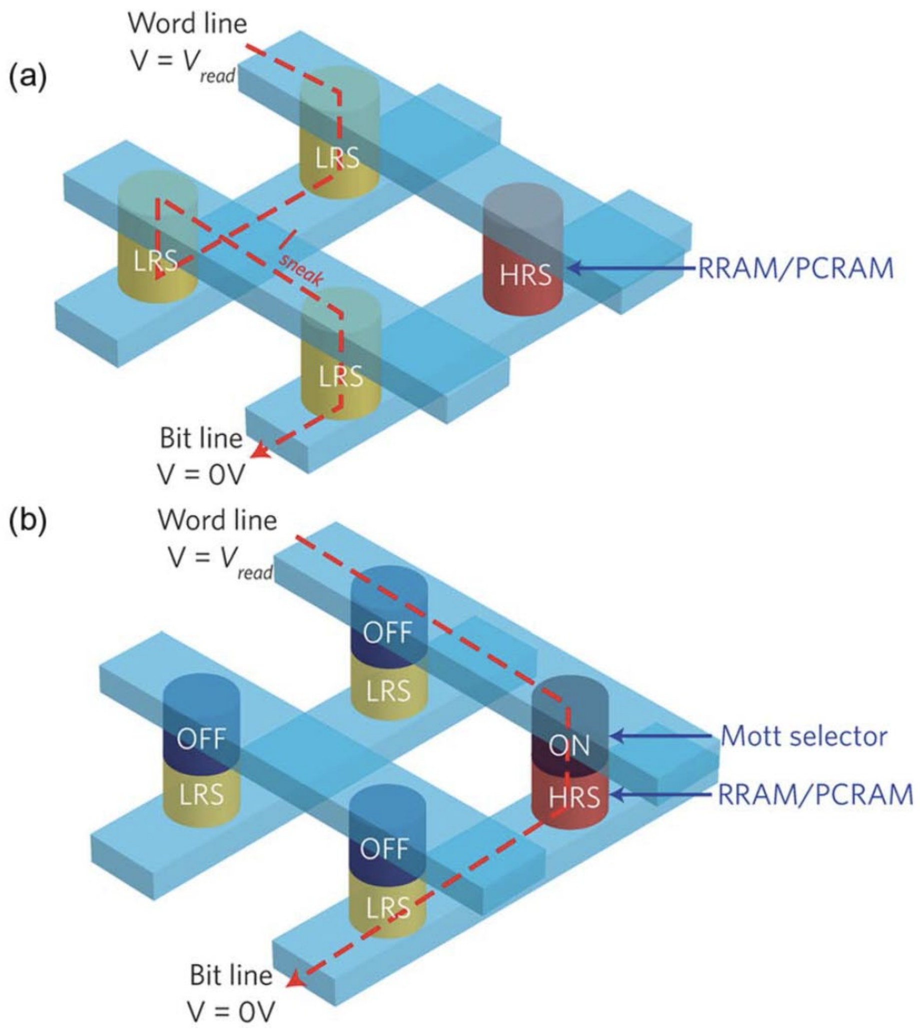
Mott insulators may be utilized as selector devices in the cross-point nonvolatile memory arrays such as for RRAM or PCRAM.

Cross-point arrays offer one of the densest packing for nonvolatile RRAM andPCRAM with a cell size as small as 4F2.

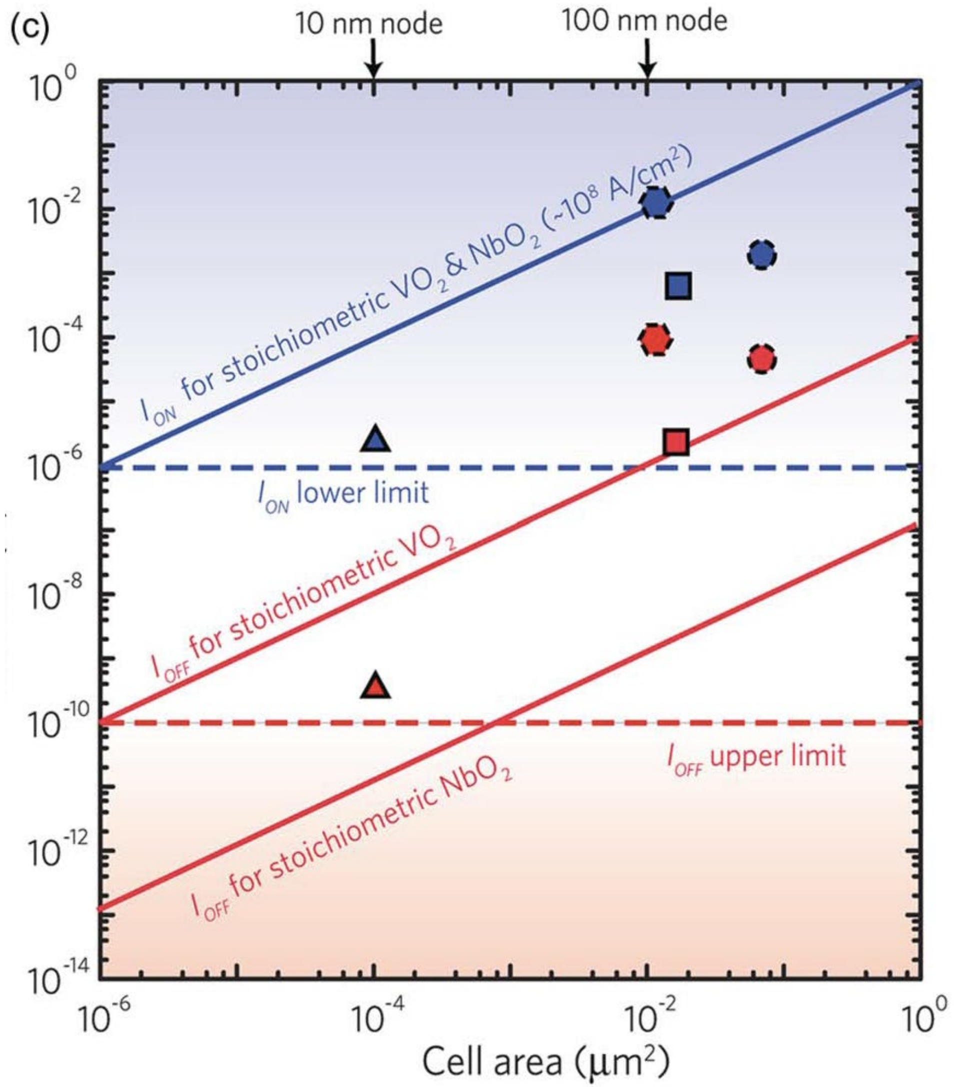
(a) Without Mott selector: sneaking effect!

(b) With Mott selector: sneaking currents are prevented.

Zhou and Ramanathan: Mott Memory and Neuromorphic Devices, Proceedings IEEE, 2015.



Design space of Mott selector devices



- Considering the criterion for the ON/OFF current, VO2 is the most appropriate.
- A selector cell must have an on current over the horizontal dashed blue line and an off current below the dashed red line.
- The on/off ratio of the selector must be at least four orders of magnitude (ROFF > $10^4 R_{LRS}$ ~$10^4 R_{ON}$). In practice, it is challenging to fabricate VO2 devices with on/off ratio approaching the ideal case in cross-points, as the grown VO2 films are typically nonstoichiometric on elemental metal electrodes.

The spiking biological neuron

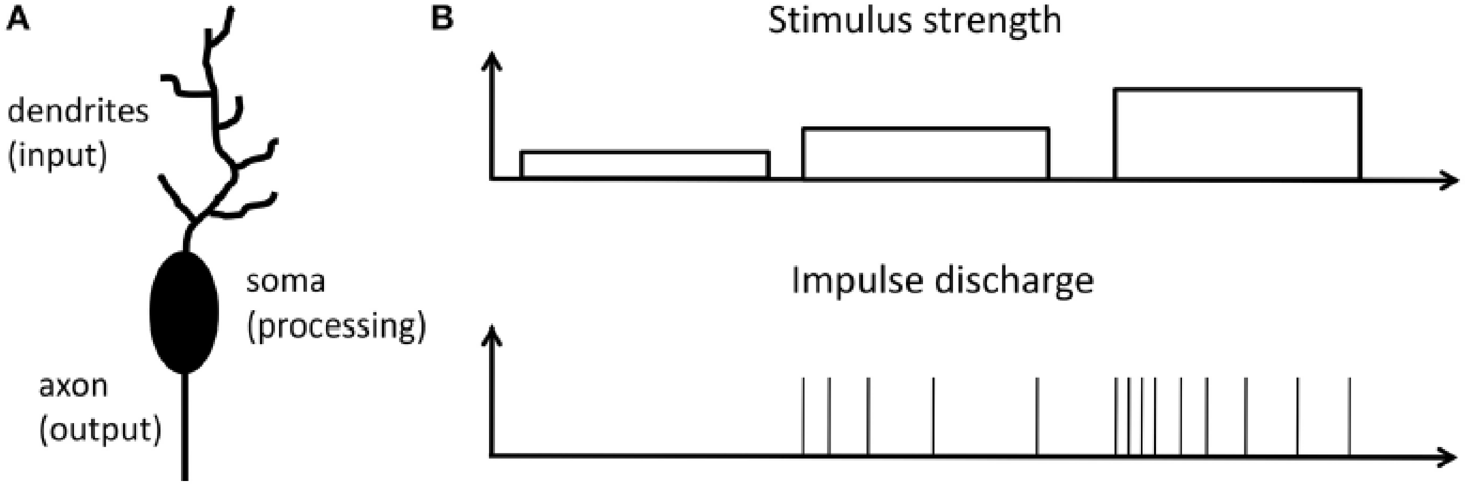
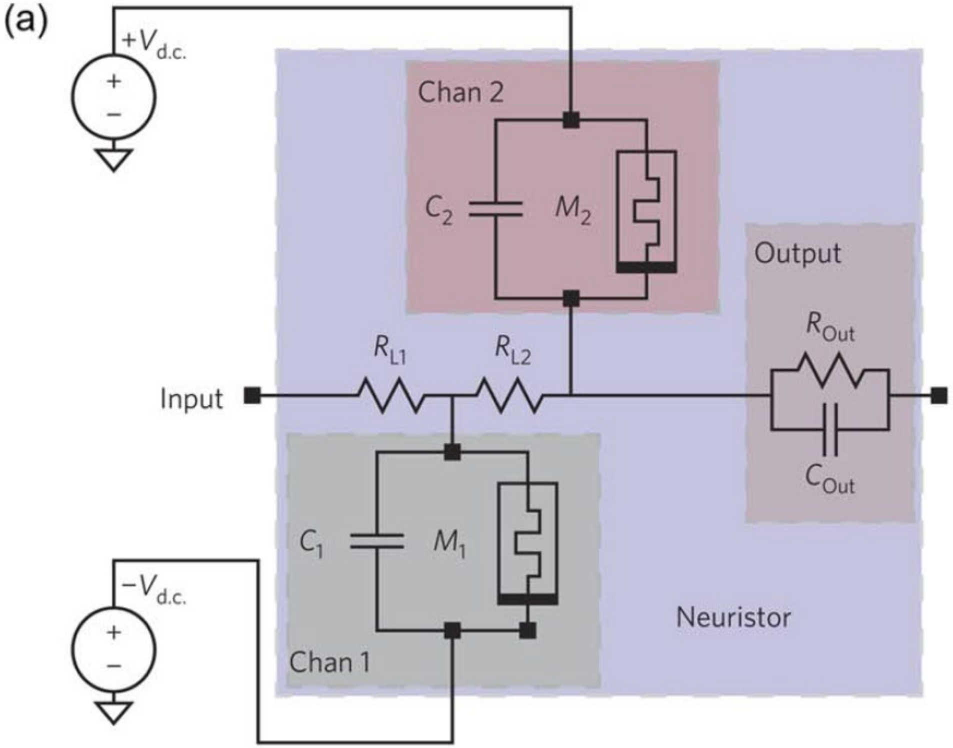
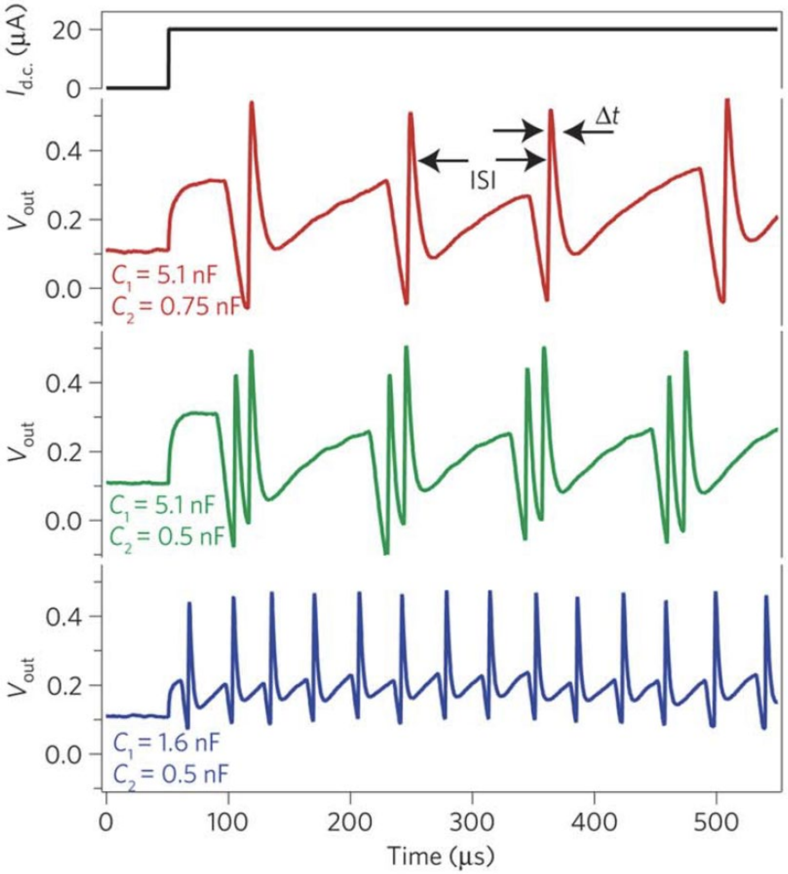


FIGURE 1 | Response to a stimulation principle: (A) Schematic of a single neuron, which can be divided into three functional parts: Dendrites, collect signals from other neurons; cell body (soma), the central processing unit of a neuron; axon, neuronal output stage. (B) Relationship between firing rate of a neuron and the strength of input stimulation reflecting the response to a stimulation principle as proposed by E. D. Adrian in 1926 (Adrian, 1926, 1928; Maass and Bishop, 2001).

VO2-based neuristor



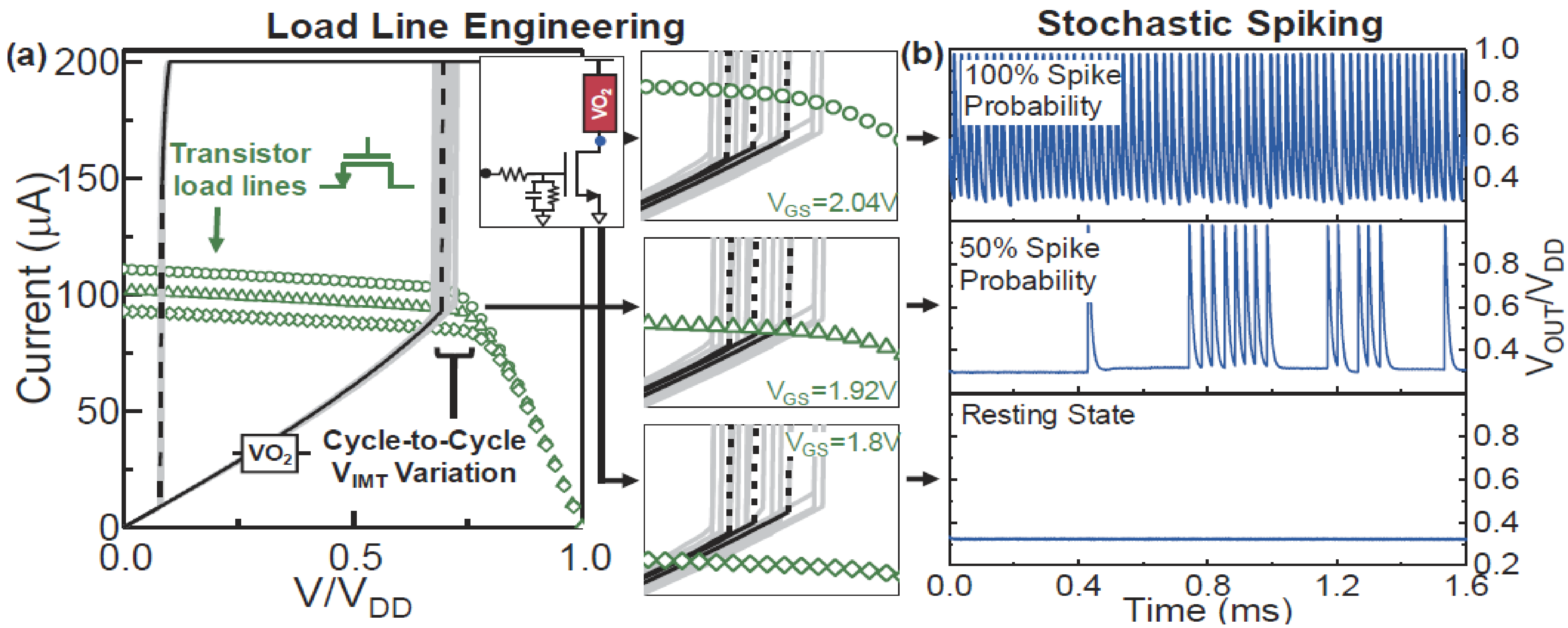


Three types of spiking patterns: regular spiking, chattering, and fast spiking could be achieved in single circuit by adjusting the values of capacitors.

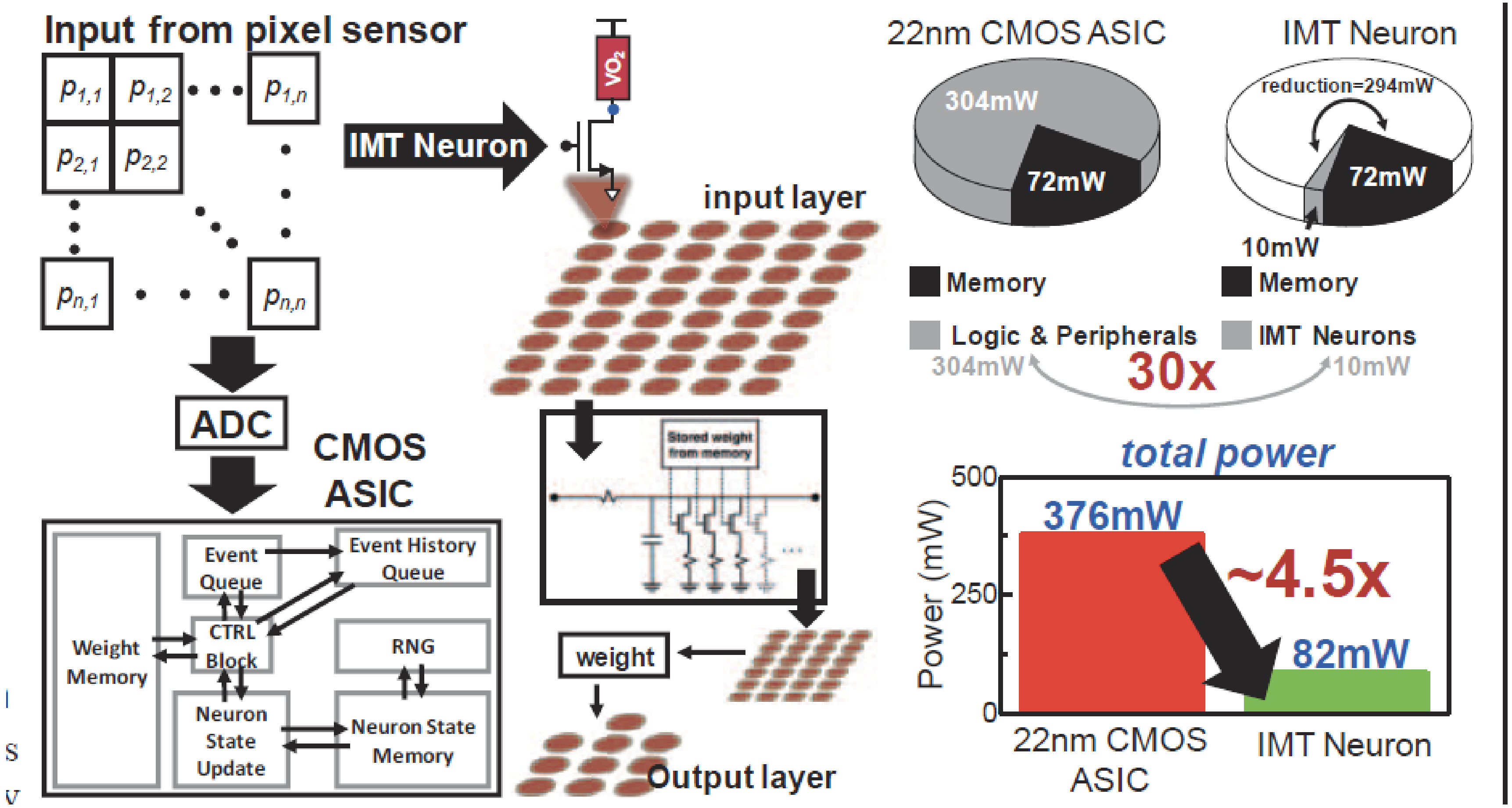
M. D. Pickett, G. Medeiros-Ribeiro, and R. S. Williams, "A scalable neuristor built with Mott memristors," Nature Mater., 2013.

MIT neuron

Tuning the probability of spiking in a loaded VO2-Transistor!

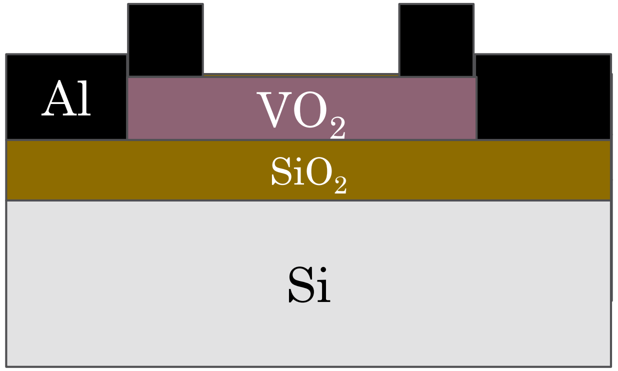


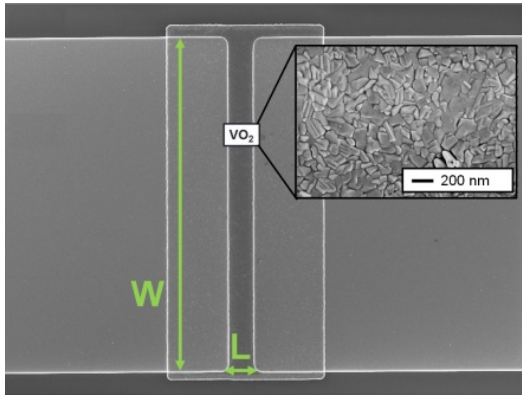
Application to Stochstic Samplig Machines



Fabrication of VO_2 Radio Frequency switch (EPFL)

1. LPCVD of 500 nm SiO_2 on silicon substrate.
2. Reactive magnetron sputtering of 360 nm VO_2 thin film at 490 °C using a V target.
3. Patterning of VO_2 with standard optical lithography and ion beam etching.
4. Lift-off of a 400 nm Al layer to define the contacts to induce E-MIT in VO_2.

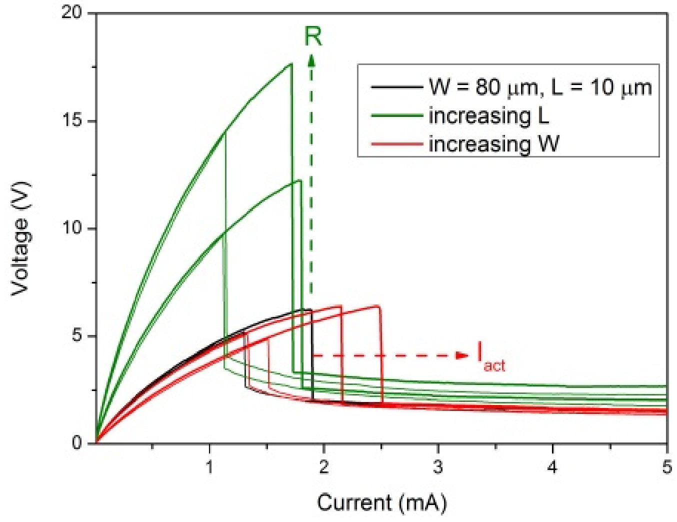




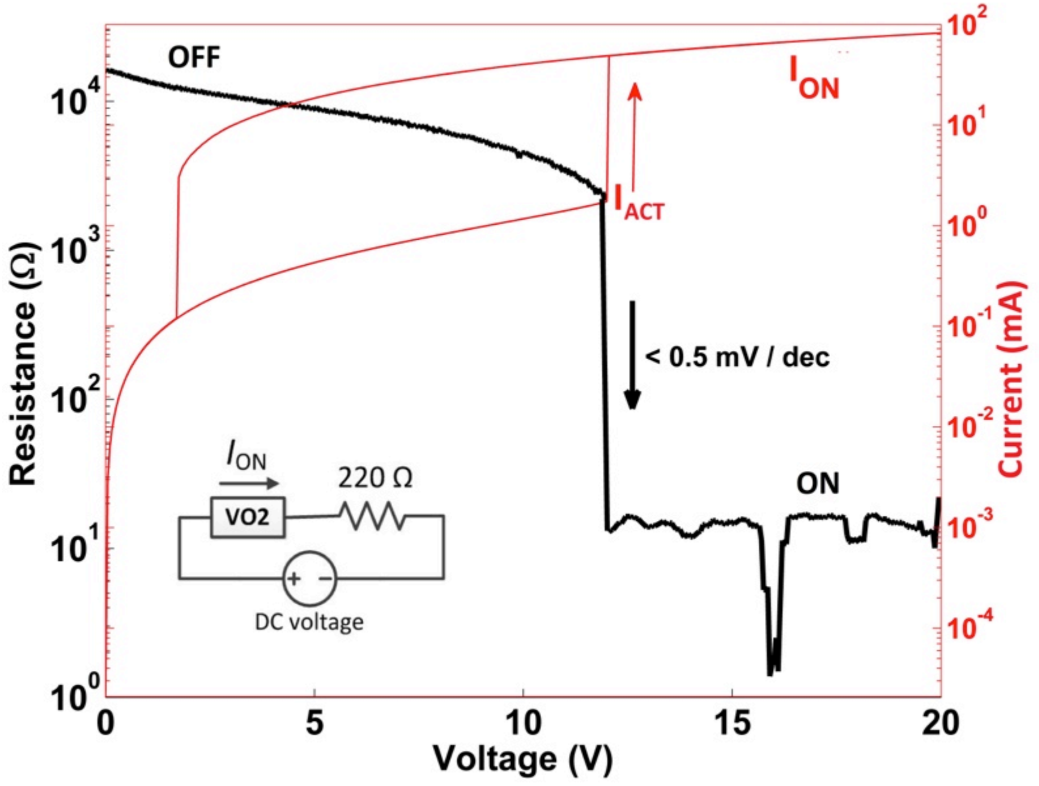
W. A. Vitale et al., "Growth optimization of vanadium dioxide films on SiO2/Si substrates", *40th Micro and Nano Engineering Conference*, Lausanne, Switzerland, September 22-26, 2014
W. A. Vitale et al., "Growth optimization of vanadium dioxide films on SiO2/Si substrates for abrupt electronic switches", *Microelectronic Engineering Journal, 2015.*

Abrupt switching with steep slope

- Reconfiguration of three decades in resistance (10^4 Ω to 10 Ω) achieved by E-MIT.
- Steep transition observed with a slope lower than 0.5 mV / dec.



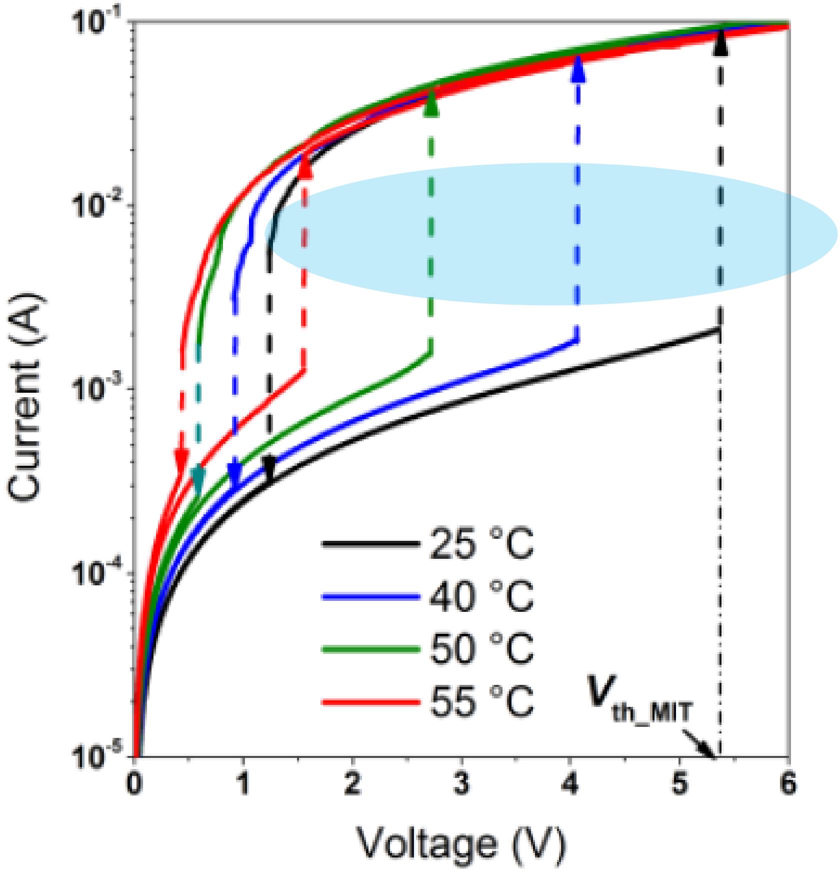
- Current actuation in VO_2-based abrupt electronic switches

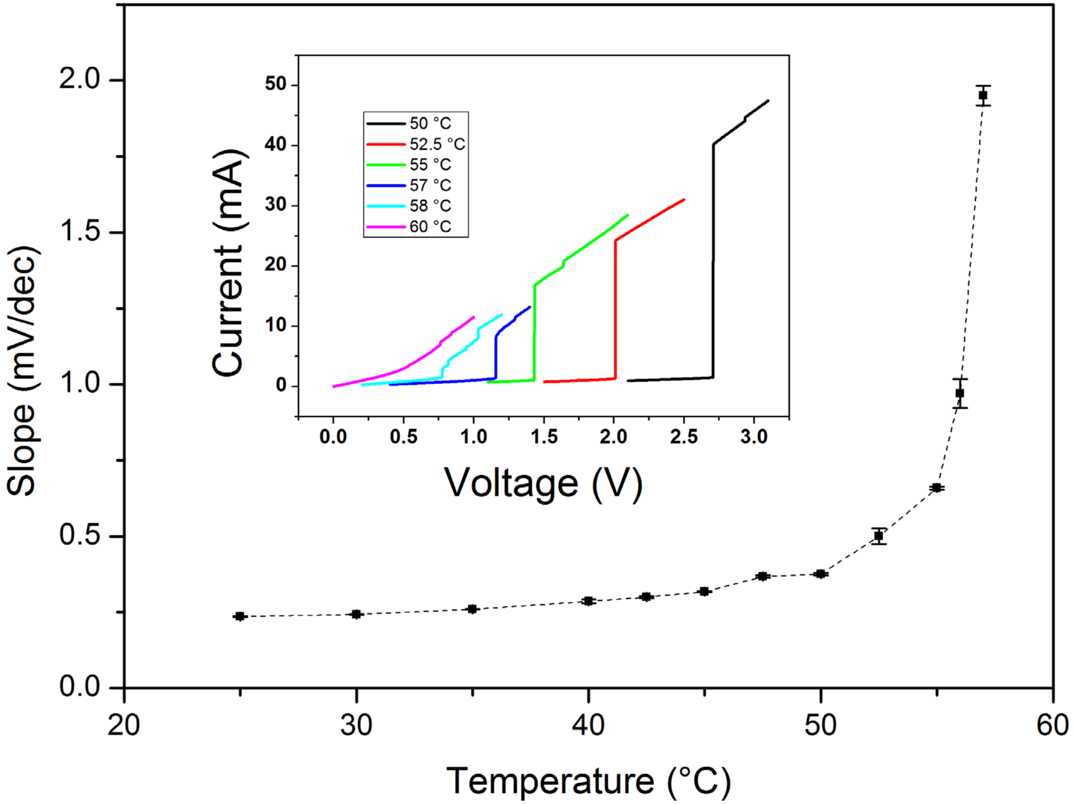


- Voltage actuation in VO_2-based abrupt electronic switches

W. A. Vitale et al., "CMOS-compatible abrupt switches based on VO2 metal-insulator transition", *Ultimate Integration on Silicon Conference*, 2015.

Steep slope, S < 10mV/dec, characterization

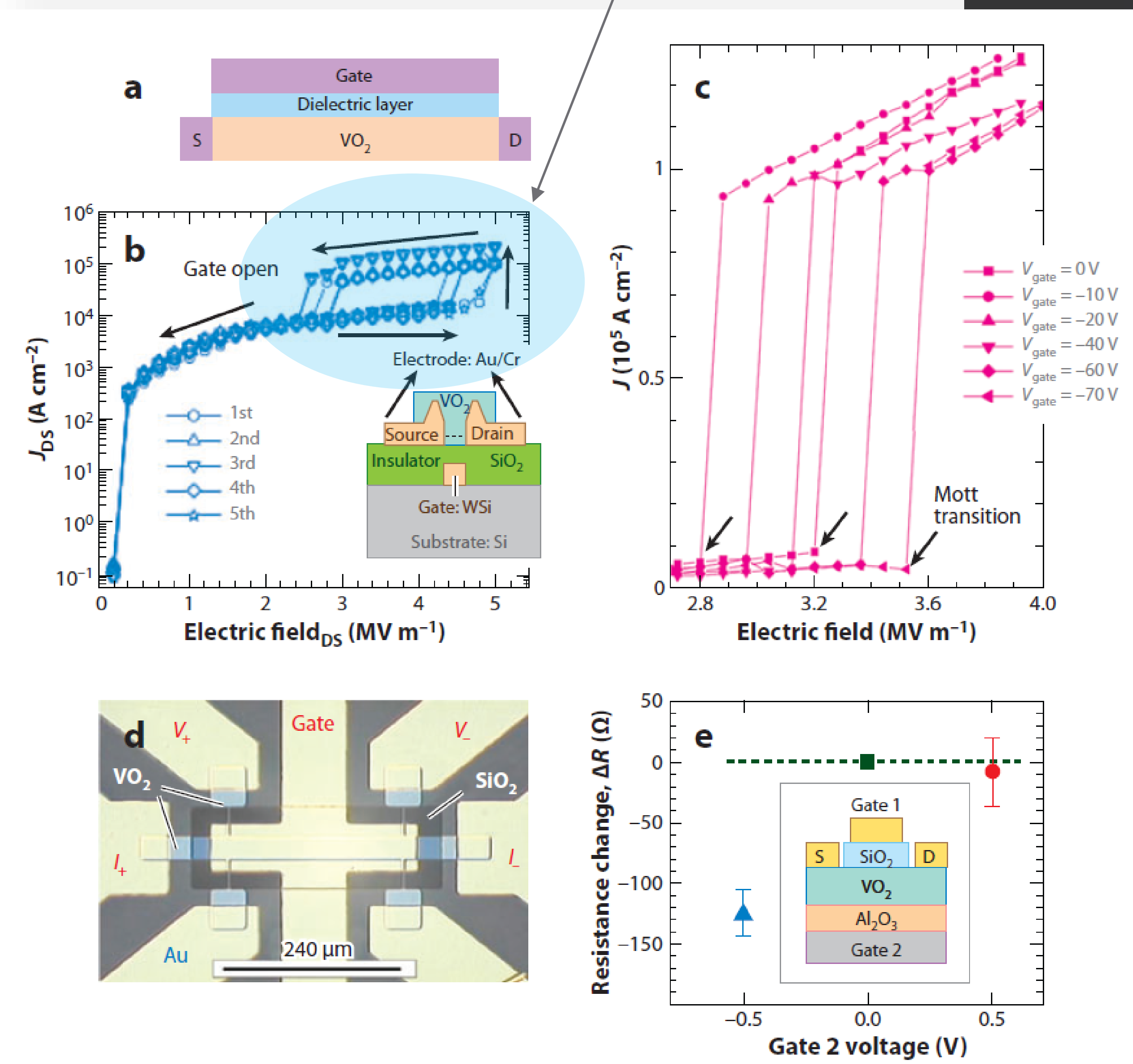




- Steep slope < 1 mV/dec up to 57 °C
- Issue #1: hysteresis control.
- Issue #2: is just a diode, not a transistor.
- Issue #3: upper temperature < 60°C

Three-terminal VO_2 electronic switch

Not in the desired region



Three-terminal gated electronic switch devices utilizing MIT in VO_2.

(a) An early proposed three-terminal gated VO_2 switch device.

(b) Current density versus electric field applied on the VO_2 channel with the gate open at room temperature. The inset shows the three-terminal VO_2 device structure.

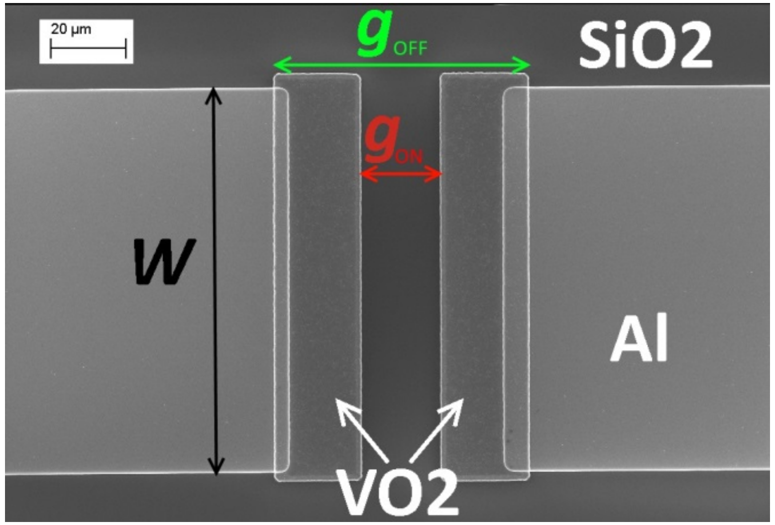
(*c*) Current density versus electric field at room temp.

(*d*) Optical microscopy image of the top view of a three-terminal VO_2 device

(*e*) The effect of the back-gate (gate 2) voltage on the source-drain resistance of the VO_2 channel of a three-terminal VO_2 device with double-gate structure from the top view as shown in panel *d*.

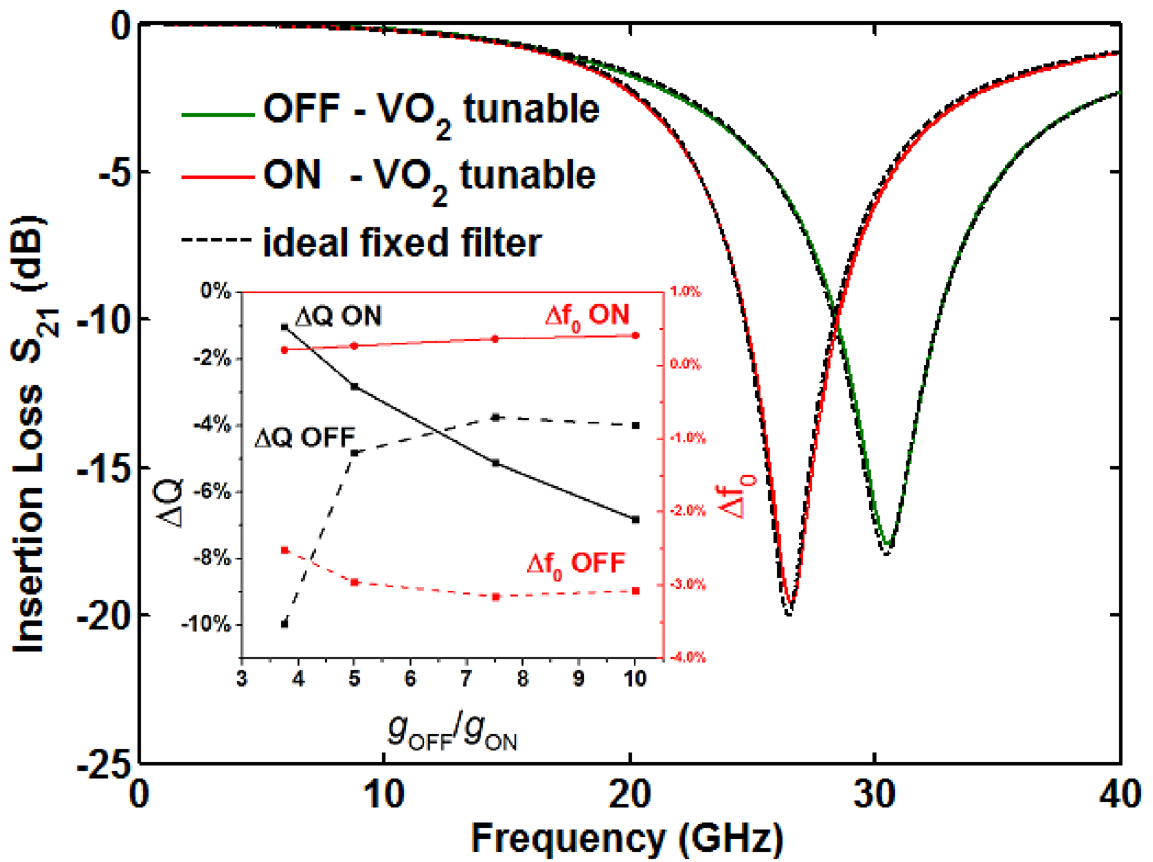
VO_2-based tunable RF filters with programmable insulating gaps

- VO_2-based RF devices for microwave tunable filters with low insertion loss.
- Design method adaptable to any planar coupled-resonator microwave filter.



- Idea VO_2-based tunable capacitive gap:

The equivalent insulating gap thickness and capacitance change when reversibleMIT takes place.



- Comparison between VO_2 tunable filters and corresponding “ideal” fixed filters.

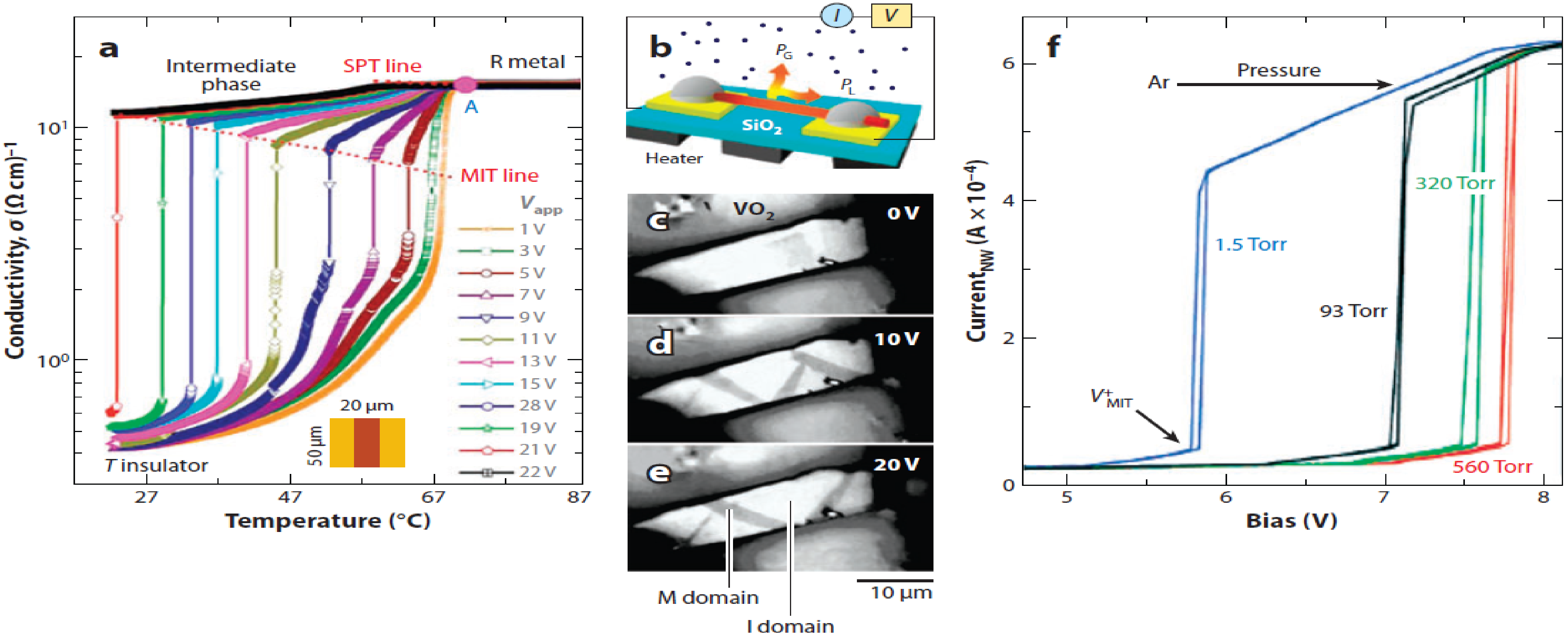
Low power VO_2 gas sensors (1)

Thermal sensor and gas sensor devices utilizing MIT in VO2.

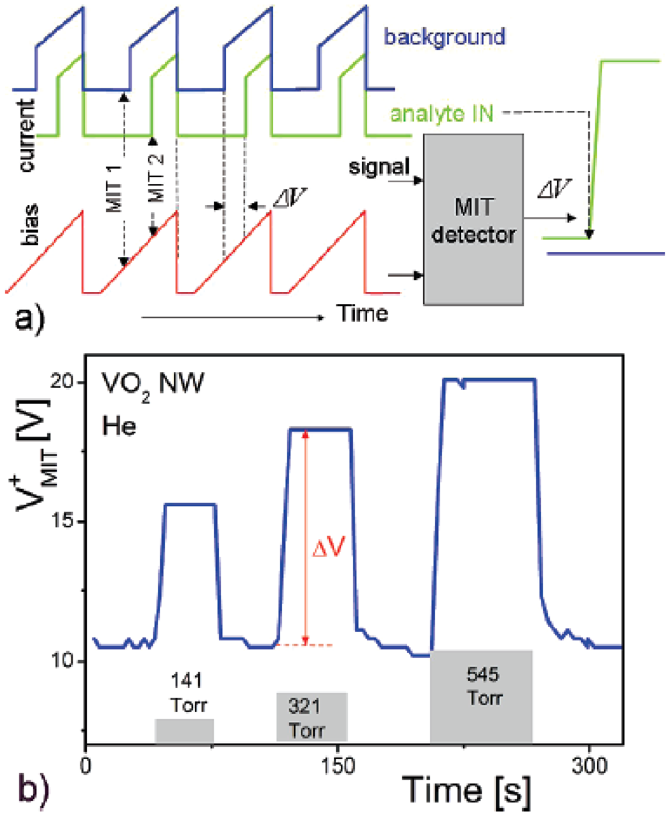
(a) A VO2 thermal sensor device. Shown are the temperature and voltage dependency of the conductivity and the coplanar VO2 device. The inset shows the device structure. SPT denotes structural phase transition.

(b) Schematic of a VO2 nanowire gas sensor. *P*G and *P*L indicate heat flux dissipating into gas environment and metal contacts.

(*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.



Low power VO_2 gas sensors (2)

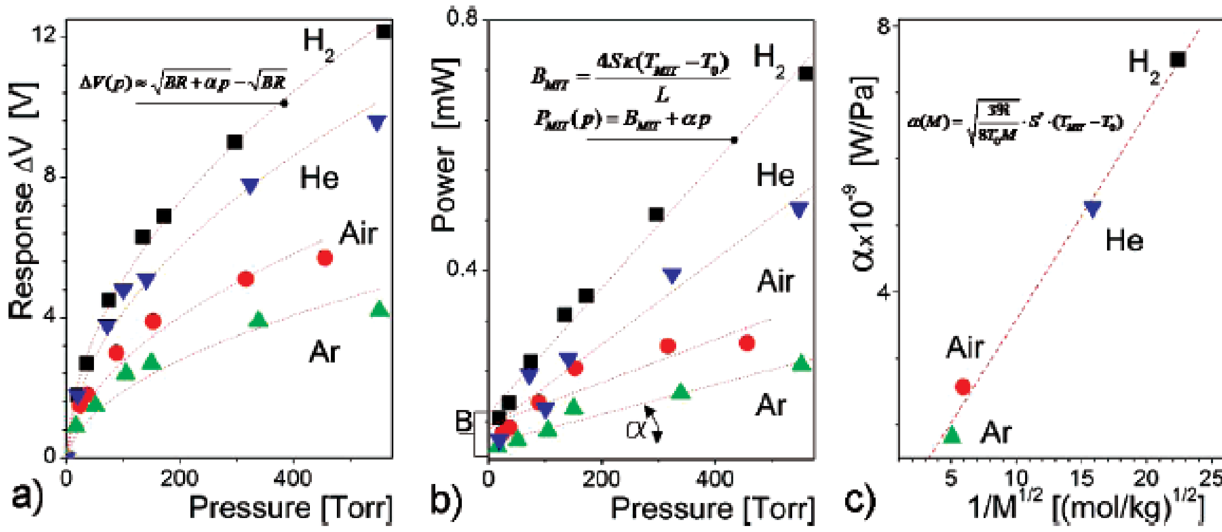


Principle:

- VO_2 NW acts as a preheated thermistor whose temperature (and thus resistance) depends on the delicate balance between the incoming Joule heat and outgoing heat fluxes.
- Any variations in the **thermal conductivity of the ambient gas** will be recorded as shifts in the transition voltage for MIT.
- **Significant advantage of this transduction principle: inherent independence on the chemical reactivity of a gas, what allows detection of chemically inert gases!**

$$S \equiv \frac{dV}{dp} = \left(\frac{\alpha R}{B/\alpha + p}\right)^{1/2}$$

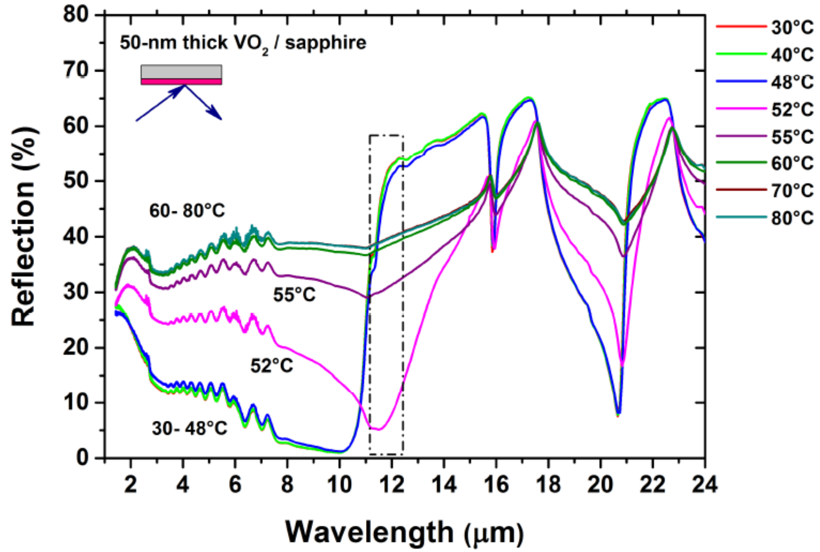
Better sensitivity at low pressure and for lighter molecules (10^{-2}Pa pressure change).



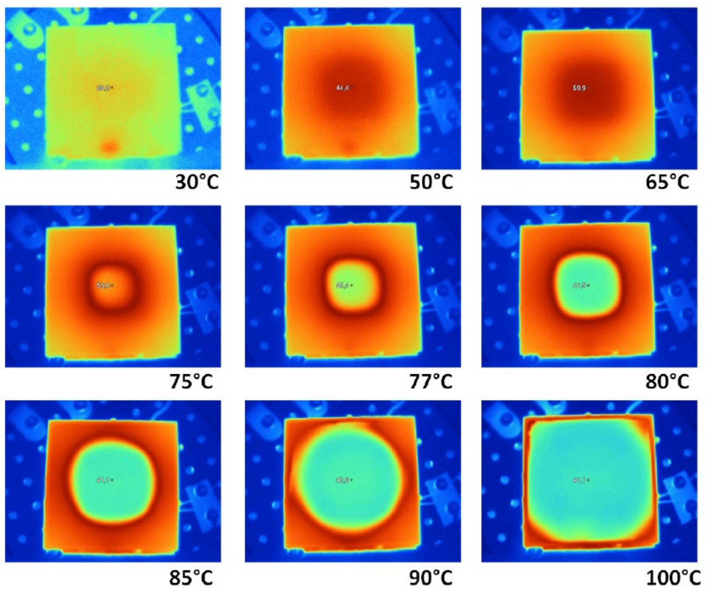
VO_2 unique optical switching behavior

Electric field-assisted metal insulator transition in vanadium dioxide (VO2) thin films: optical switching behavior for various applications:

- planar optical devices and electrical-activated optical modulators for visible-infrared signals with high discrimination between the two state
- anomalous emissivity change under thermal- end electrical activation **(negative differential emittance phenomenon)** with potential applications in active coatings for thermal regulation, optical limiting or camouflage coatings, optical tunable metamaterials (in infrared and far-infrared).



Crunteanu et al. Proc. SPIE 9364, Oxide-based Materials and Devices VI, 93640J (March 13, 2015)



The VO2 displays negative differential thermal emittance above the MIT transition temperature (around 70°C): **the sample appears cooler even if the applied temperature is > TMIT**.

Conclusions

- A fast 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 even with magnetic actuation.***

- VO_2 is one of the most promising researched MIT material because of its transition temperature near room temperature:
  - > 3-4 orders of magnitude with few volts actuation, sharp transition in resistivity has been reproduced with electrical actuation, enablingnovel device structures for reconfigurable electronics.

- Room temperature Mott FETs with correlated oxides may be potential candidates for future computing elements: ***steep switches and cross-point memories*****.**

- Applications ***@ short term: reconfigurable RF functions in GHz to THz range.***

- Applications ***@ long term: steep slope electronic switches (with hysteresis: can serve neuromorphic computing.***