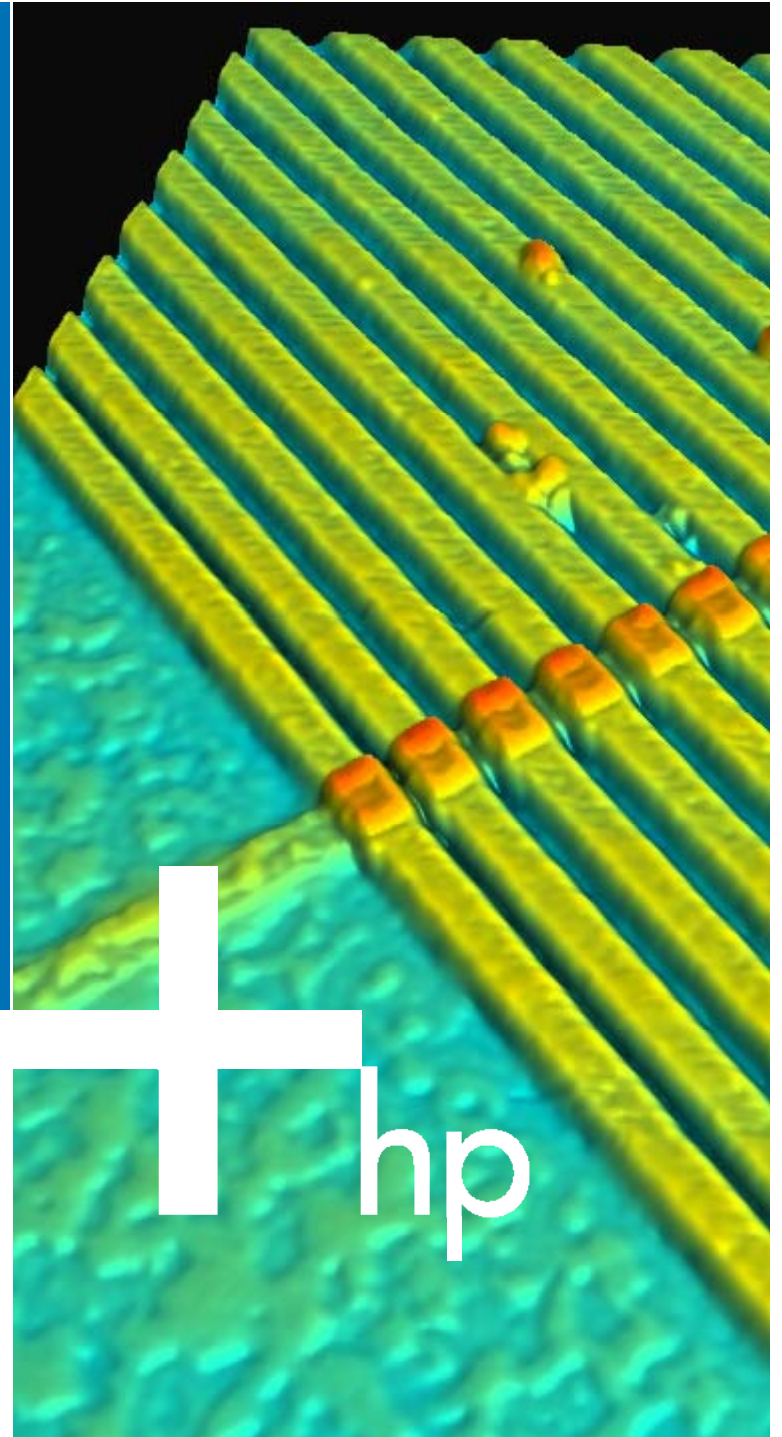




Physics and Materials Science of Memristive devices

Hewlett-Packard Laboratories, Palo Alto
CA

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The information contained herein is subject to change without notice



People



- Jianhua Yang;
- Dmitry Strukov;
- Julien Borghetti;
- Matthew Picket;
- John Paul Stracham;
- Doug Ohlberg;
- Duncan Stewart;
- Phil Kuekes;
- Stan Williams;

Outline



- Memristor definition;
- Mixed conduction and memristive effect;
- Implementation;

- Memory effect in early MIM junctions (Au:SiO):

6. MEMORY CHARACTERISTICS

(a) Method of obtaining memory

If a voltage corresponding to the lowest point of the negative resistance region ($\approx 8\text{ V}$) is applied to the sample and then reduced to zero in about 0.1 ms , i.e. an 8 V pulse with a trailing edge faster than 0.1 ms , and then the voltage reapplied but of magnitude less than V_T , it is found that the original low-impedance characteristic

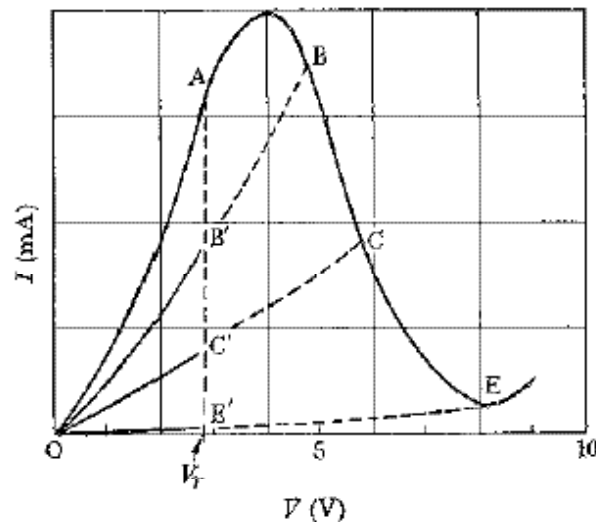


FIGURE 6. Schematic diagram of dynamic characteristics, illustrating several impedance states and the threshold voltage.

by Simmons and Verderber, Proc. Royal Society of London A, 301 (1967) 77

Currently....

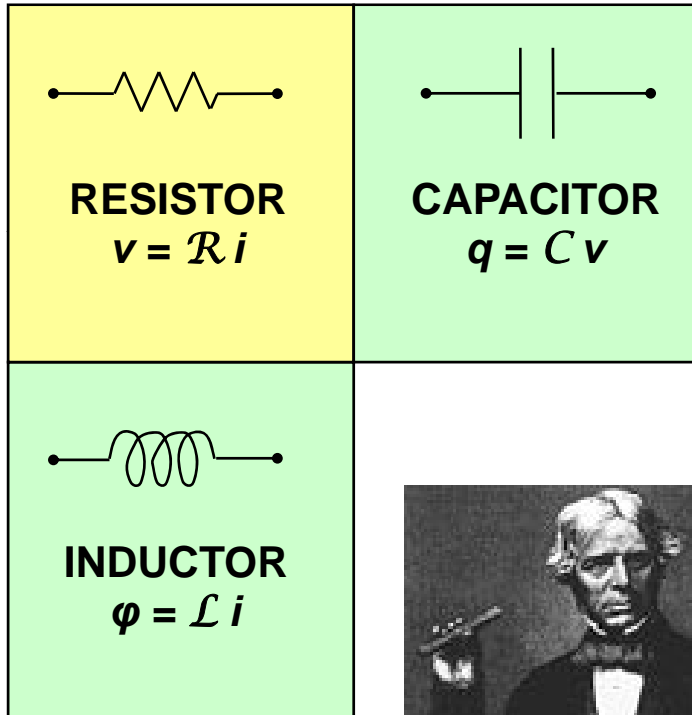


- Stanford, U. Houston, Aachen, Julich, Université Paris-Sud, Orsay,...
- AMD, HP, IBM, Motorola, Samsung, Sharp...

3 fundamental circuit elements

Resistor – 1827

Georg Ohm



Inductor – 1831

Faraday

Joseph Henry



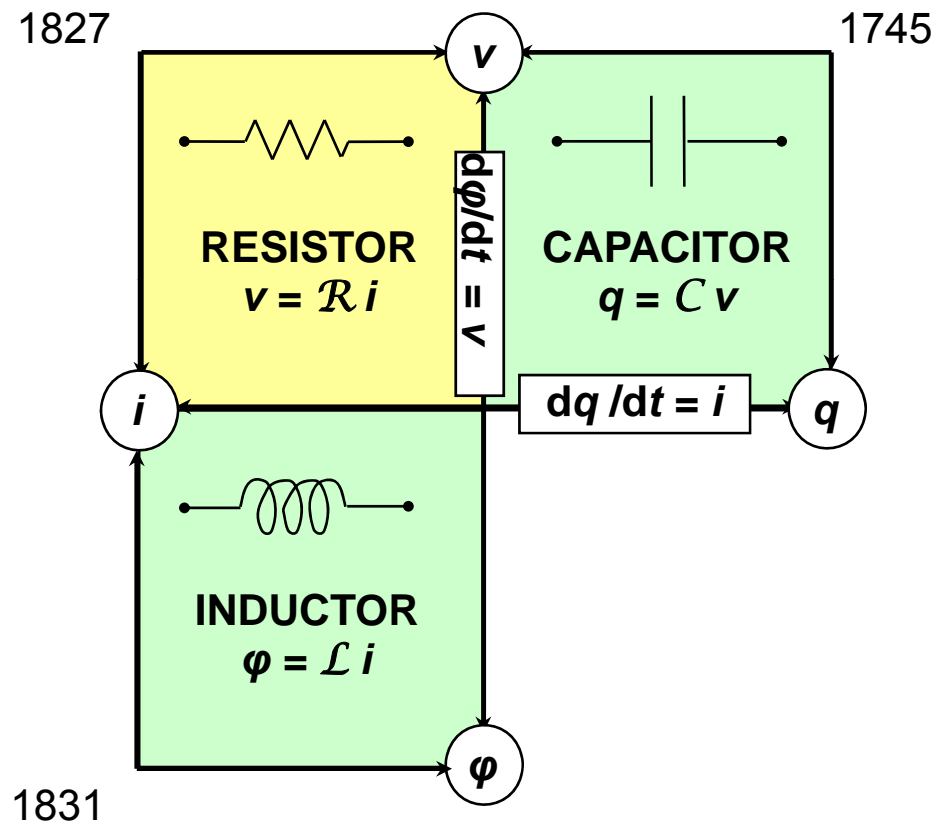
Capacitor - 1745

Volta / von Kleist & van Musschenbroek

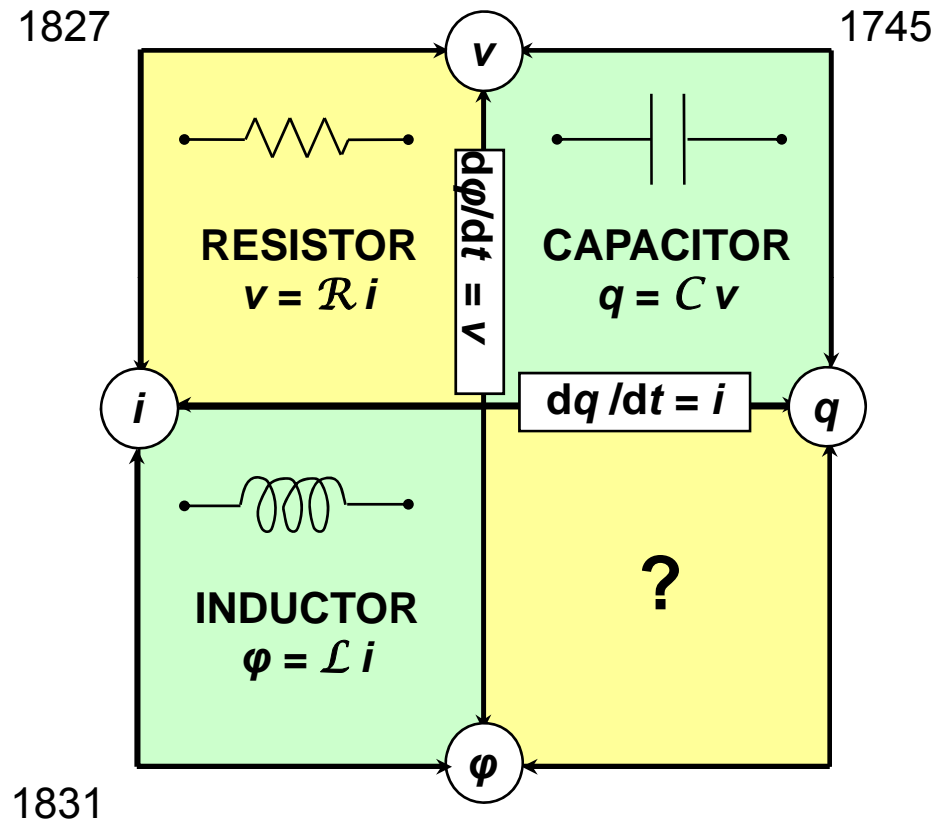
Benjamin Franklin



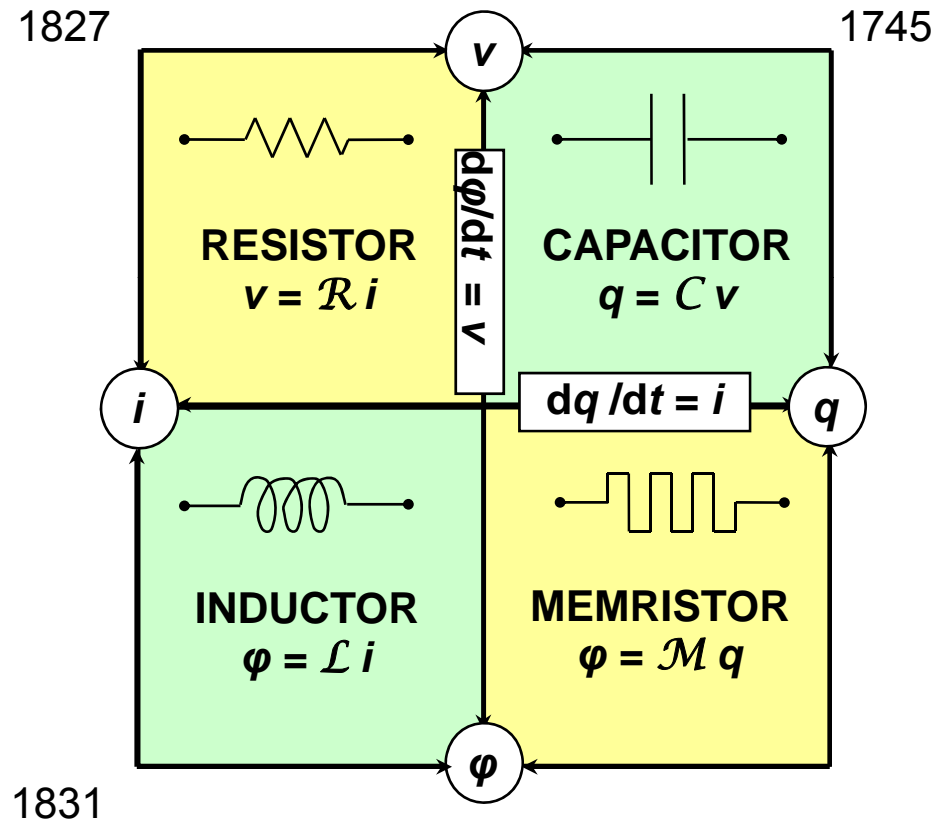
3 fundamental circuit elements



Leon Chua 1971

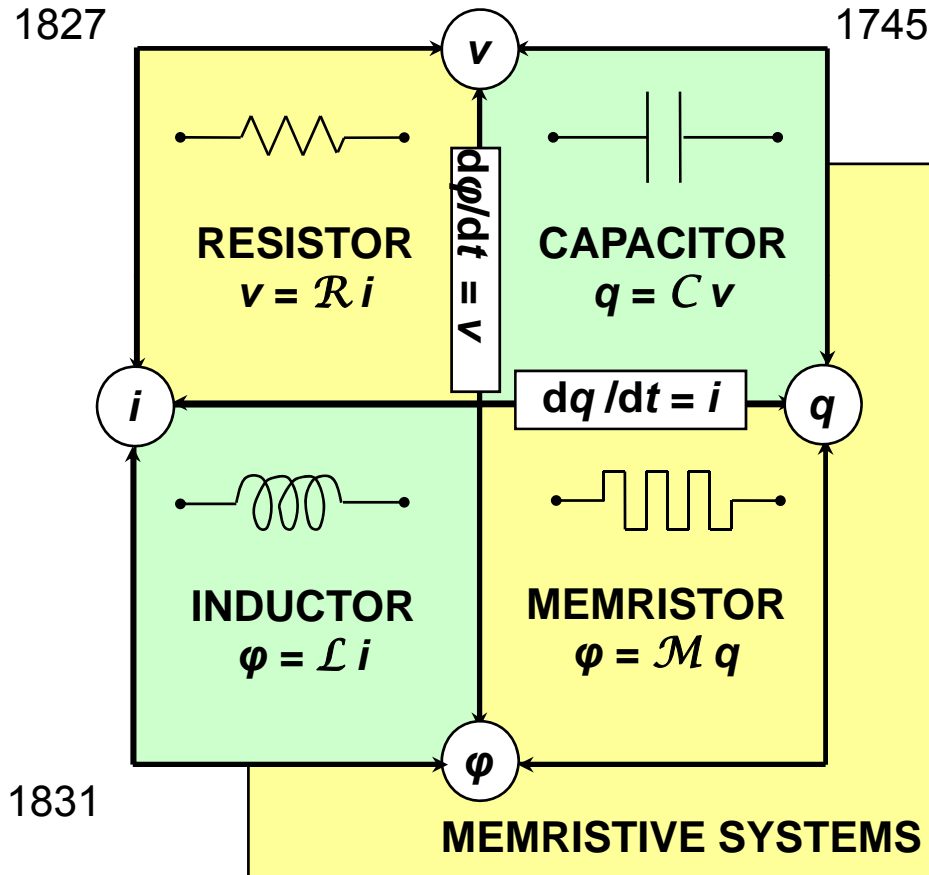


Leon Chua 1971 – the memristor



L. O. Chua, "Memristor - the missing circuit element," *IEEE Trans. Circuit Theory* 18, 507-519 (1971).
L. O. Chua and S. M. Kang, "Memristive devices and systems," *Proc. IEEE*, 64 (2), 209-23 (1976).

Leon Chua 1971 – the memristor



Simple Memristor:

$$v = M(w)i$$

$$\frac{dw}{dt} = i$$

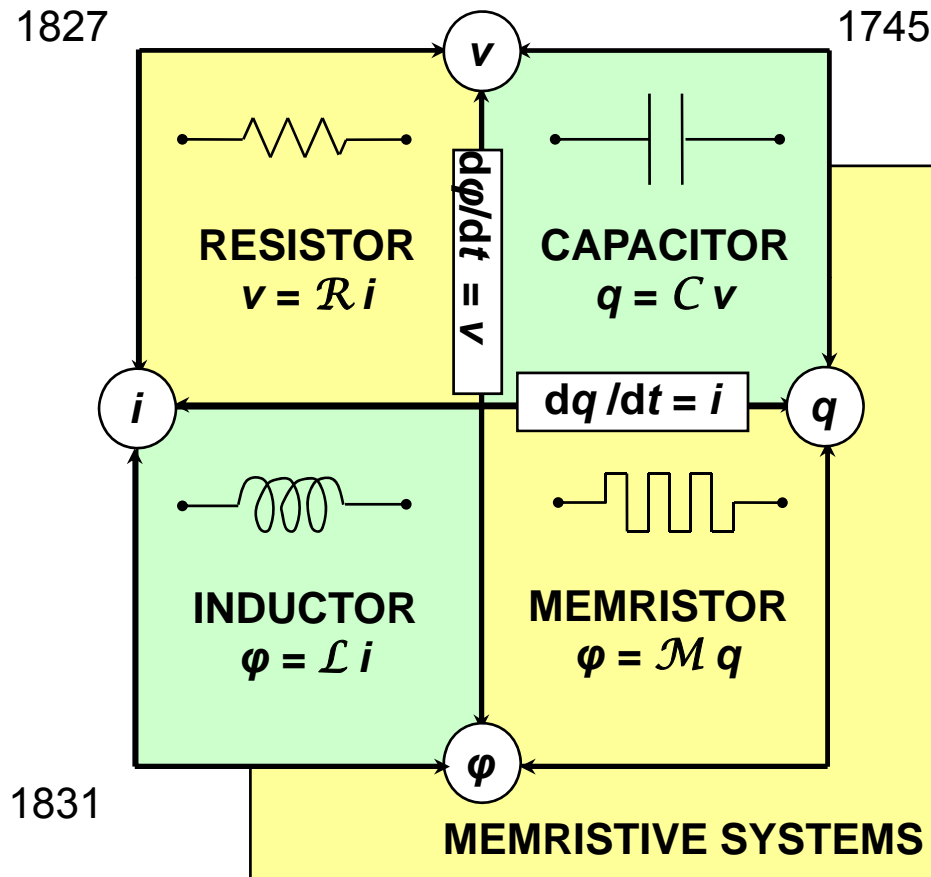
Generalized Memristor
(*Memristive system*):

$$v = M(w, v)i$$

$$\frac{dw}{dt} = f(w, i)$$

L. O. Chua, "Memristor - the missing circuit element," *IEEE Trans. Circuit Theory* 18, 507-519 (1971).
L. O. Chua and S. M. Kang, "Memristive devices and systems," *Proc. IEEE*, 64 (2), 209-23 (1976).

Leon Chua 1971 – the memristor



Simple Memristor:

$$v = M(\omega) i$$

$$\frac{d\omega}{dt} = i$$

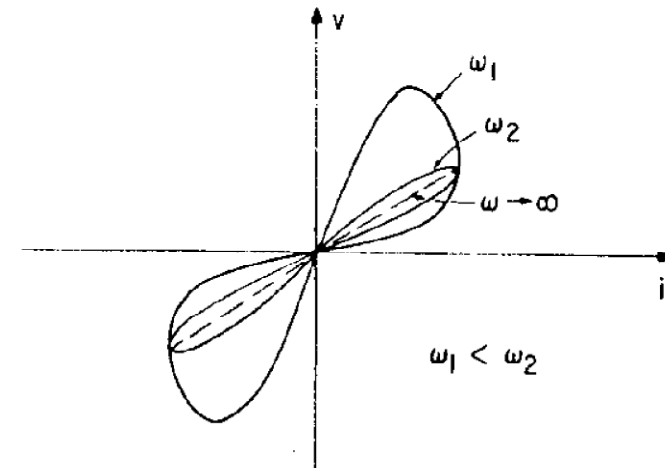


Fig. 6. Frequency response of Lissajous figures.

L. O. Chua, "Memristor - the missing circuit element," *IEEE Trans. Circuit Theory* 18, 507–519 (1971).
 L. O. Chua and S. M. Kang, "Memristive devices and systems," *Proc. IEEE*, 64 (2), 209-23 (1976).

Implementation



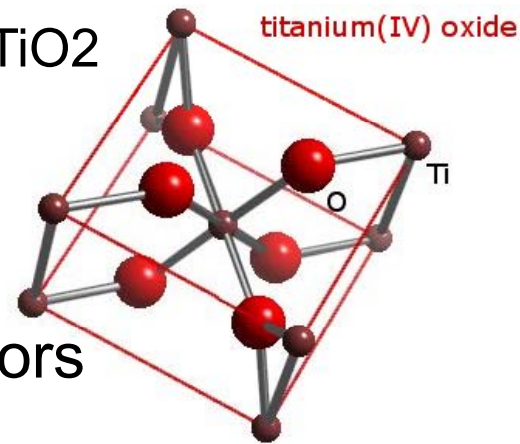
- Solid state ionic transport;
- Modulation of electronic transport;
- Dynamic electronics;

TiO₂

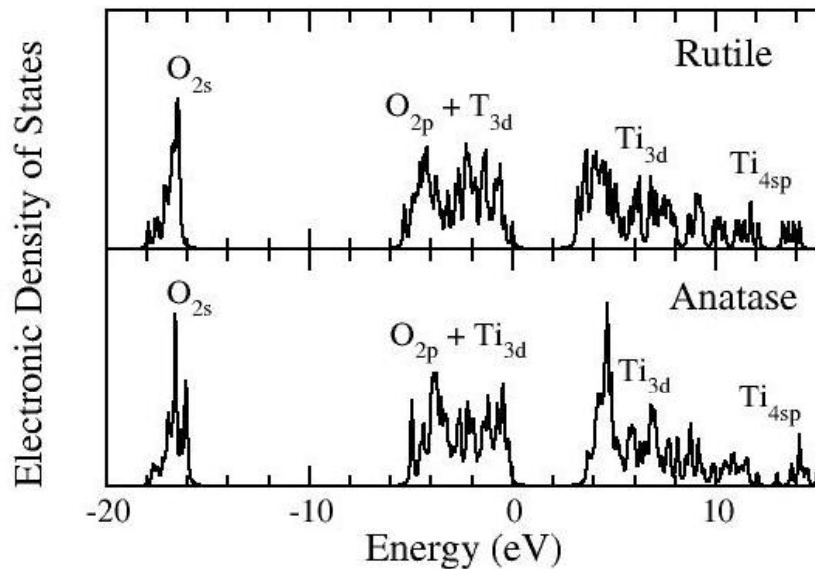
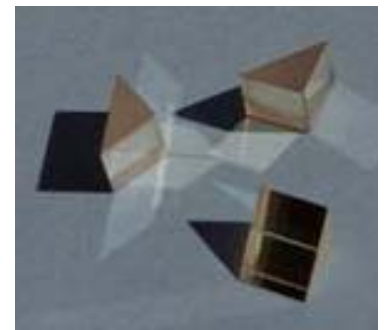
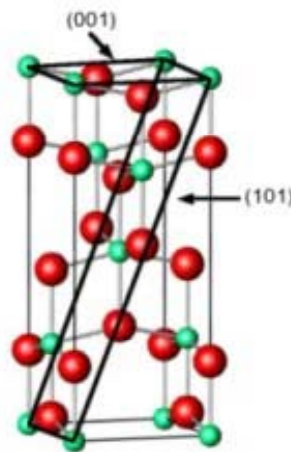


3.0/3.2 eV semiconductor
dielectric $\epsilon \sim 80$, bi-refringent
pigment, photocatalyst, O₂ sensors
TiO₂ : 1x Ti⁴⁺ + 2x O²⁻

rutile TiO₂

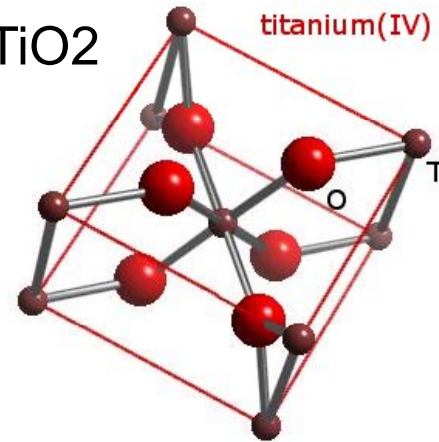


anatase TiO₂



rutile TiO₂

titanium(IV) oxide



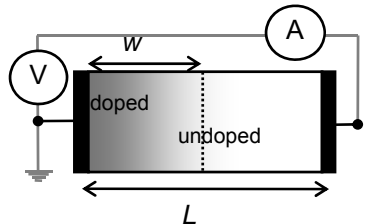
3.0/3.2 eV semiconductor

TiO_{2-x} : $x \sim 10^{-3} - 10^{-2}$ dopants all ionized $E_i < 0.1$ eV

oxygen vacancies V_O^{2+} @ low $T < 800$ C & high $P(O_2)$ and
Ti interstitials Ti_i^{4+} @ high $T > 1000$ C & low $P(O_2)$:

creation $\sim 3-5$ eVdiffusion $\sim 0.7 - 1.1$ eVmobility $\sim 10^{-10} - 10^{-14}$ cm²/Vs

O vacancy drift model for TiOx switch



$$\frac{dw(t)}{dt} = \mu_V \frac{R_{ON}}{L} i(t) \quad w(t) = \mu_V \frac{R_{ON}}{L} q(t) \quad v(t) = \left[R_{ON} \frac{w(t)}{L} + R_{OFF} \left(1 - \frac{w(t)}{L} \right) \right] i(t)$$

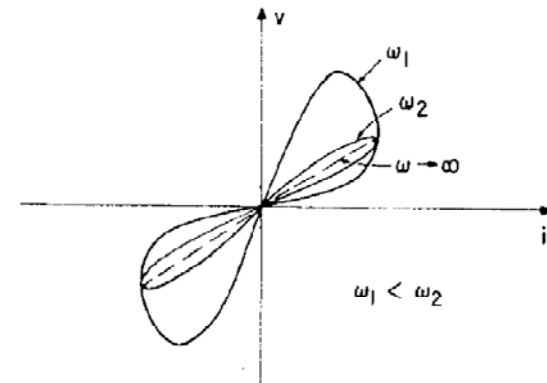
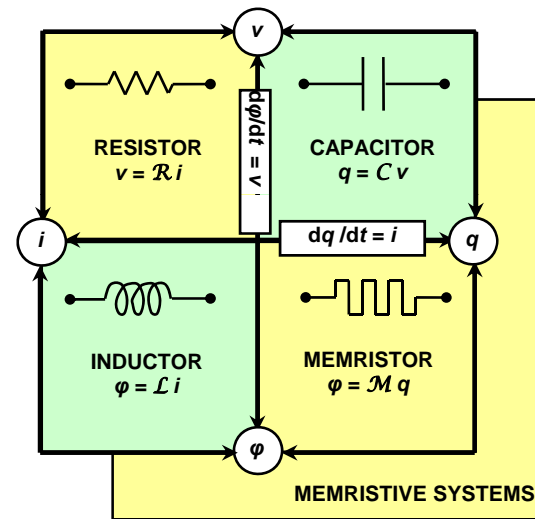
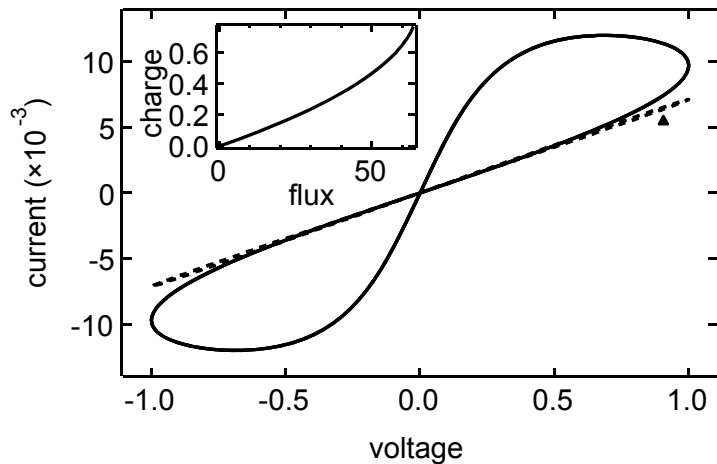
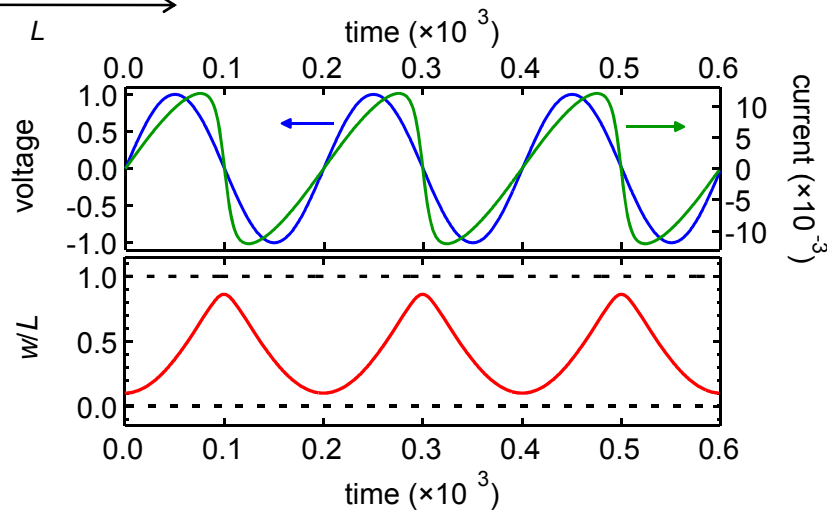
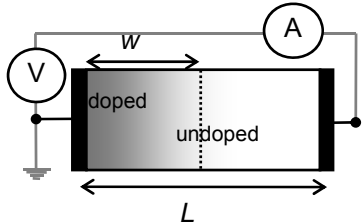
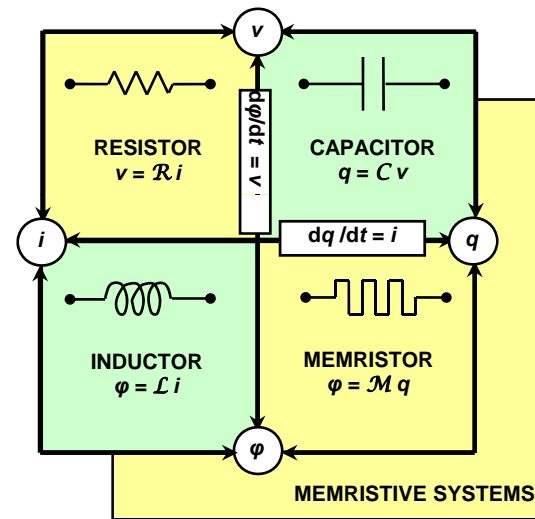
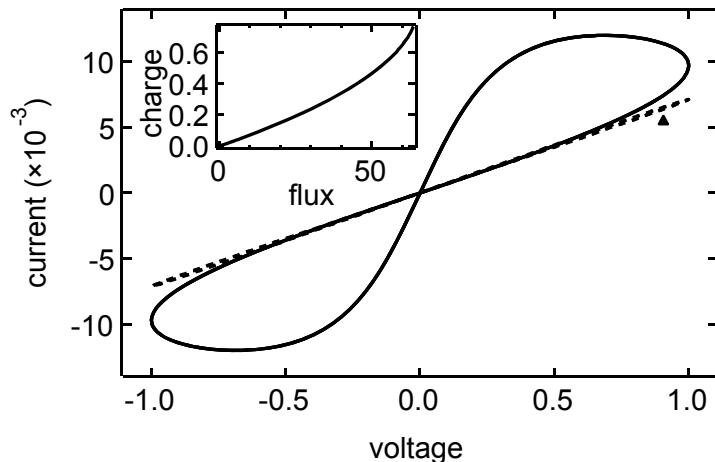
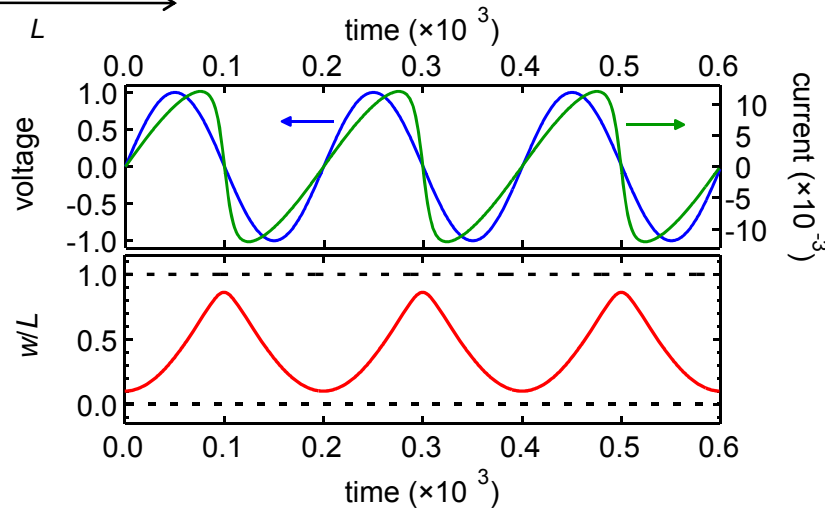


Fig. 6. Frequency response of Lissajous figures.

O vacancy drift model for TiOx switch



$$\frac{dw(t)}{dt} = \mu_V \frac{R_{ON}}{L} i(t) \quad w(t) = \mu_V \frac{R_{ON}}{L} q(t) \quad v(t) = \left[R_{ON} \frac{w(t)}{L} + R_{OFF} \left(1 - \frac{w(t)}{L} \right) \right] i(t)$$

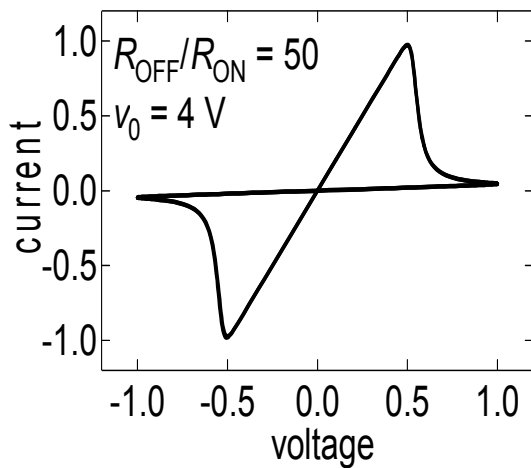
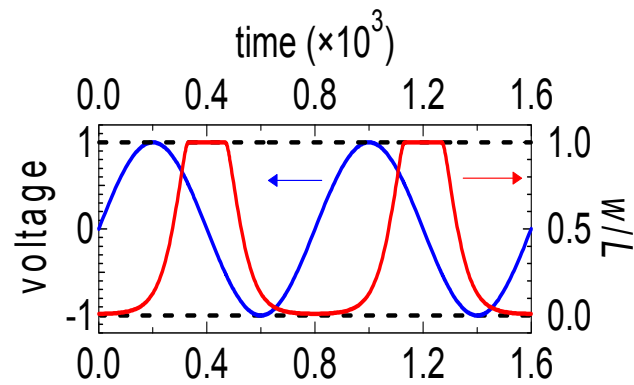
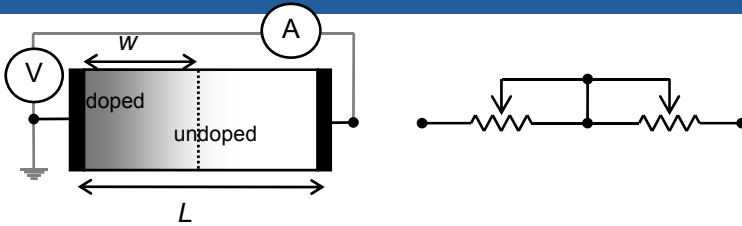


Generalized Memristor
(Memristive system):

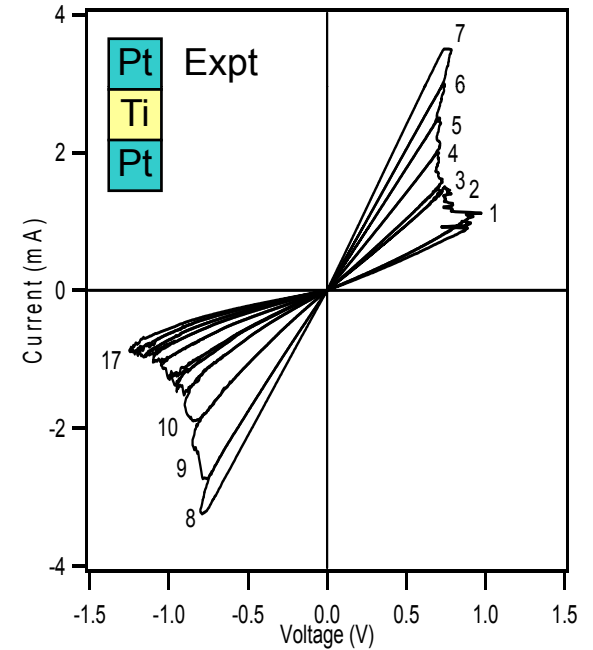
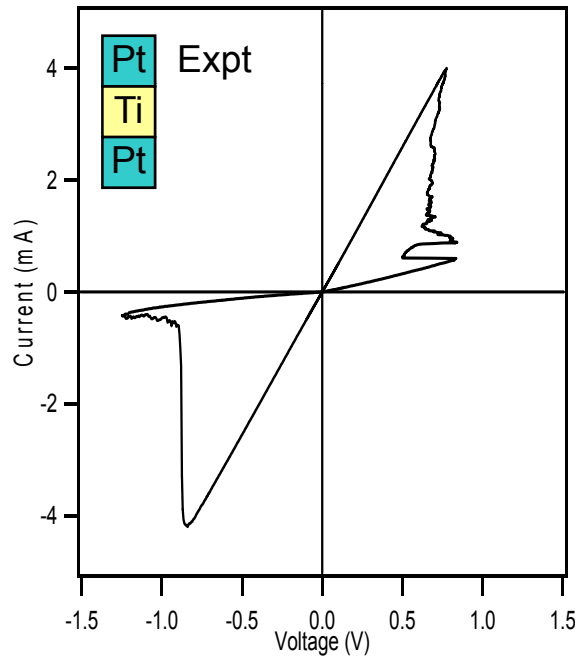
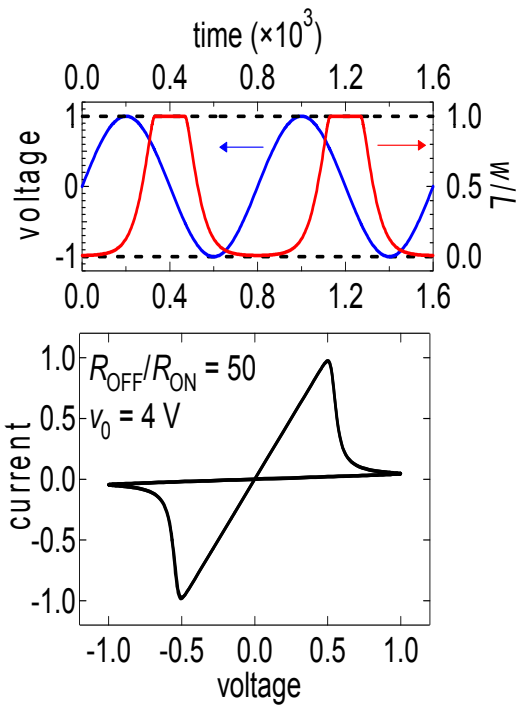
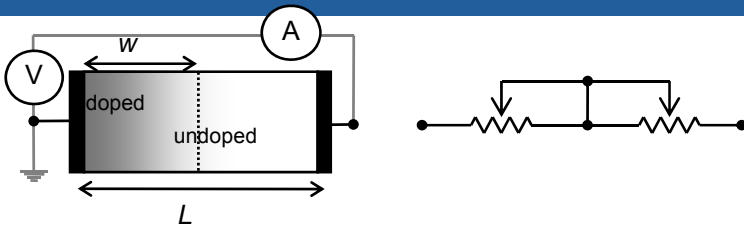
$$v = M(w, v) i$$

$$\frac{dw}{dt} = f(w, i)$$

O vacancy drift model for TiOx switch



O vacancy drift model for TiOx switch



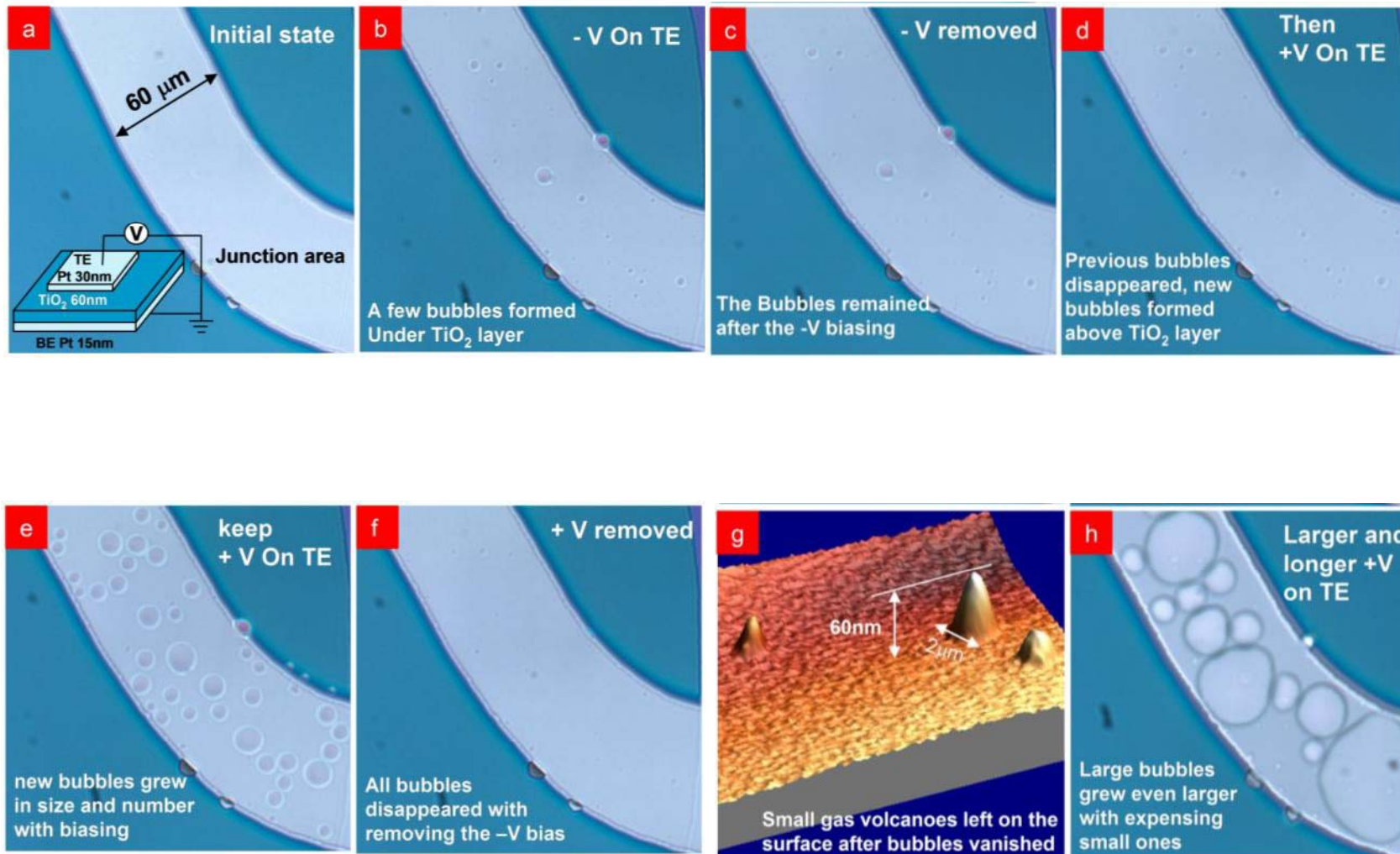
Dmitri Strukov, Greg Snider,
 Duncan Stewart, R. Stanley Williams,
Nature **453**, 80 - 83 (01 May 2008)

Device operation

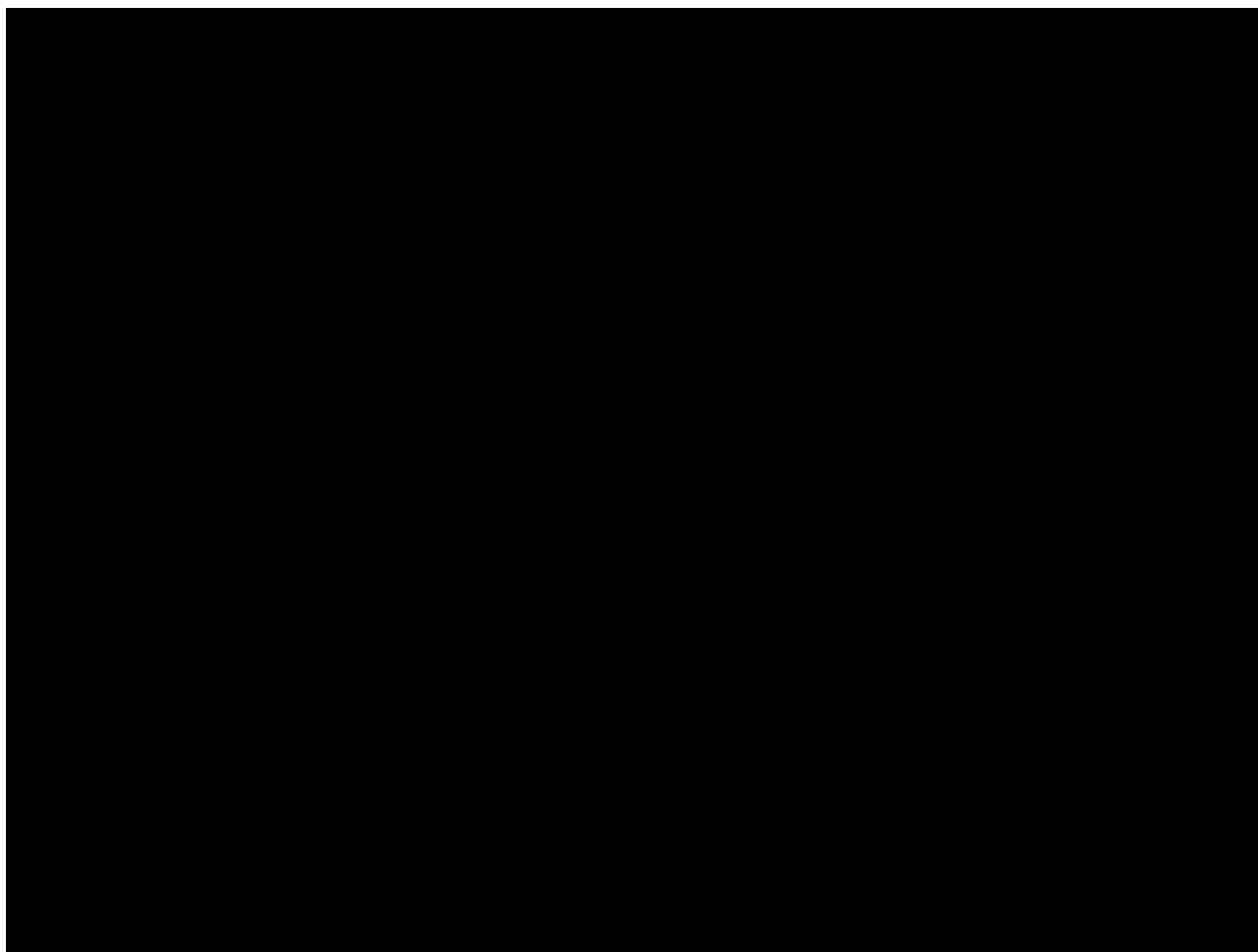


- Electroforming and bubbling
- Endurance;
- Interface effects;
- Scalability;

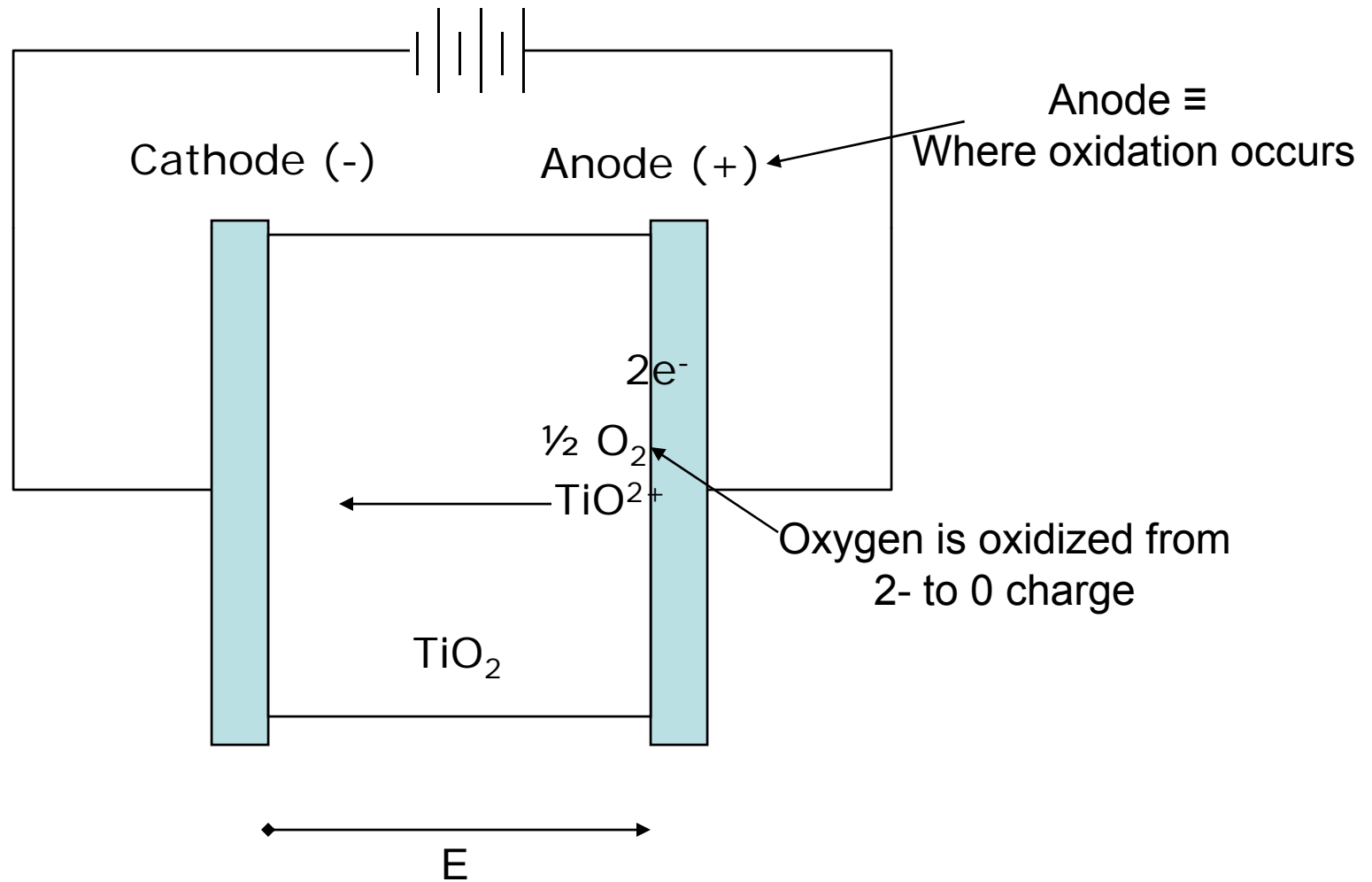
O₂ reduction at anode creates bubbles in micron-sized devices



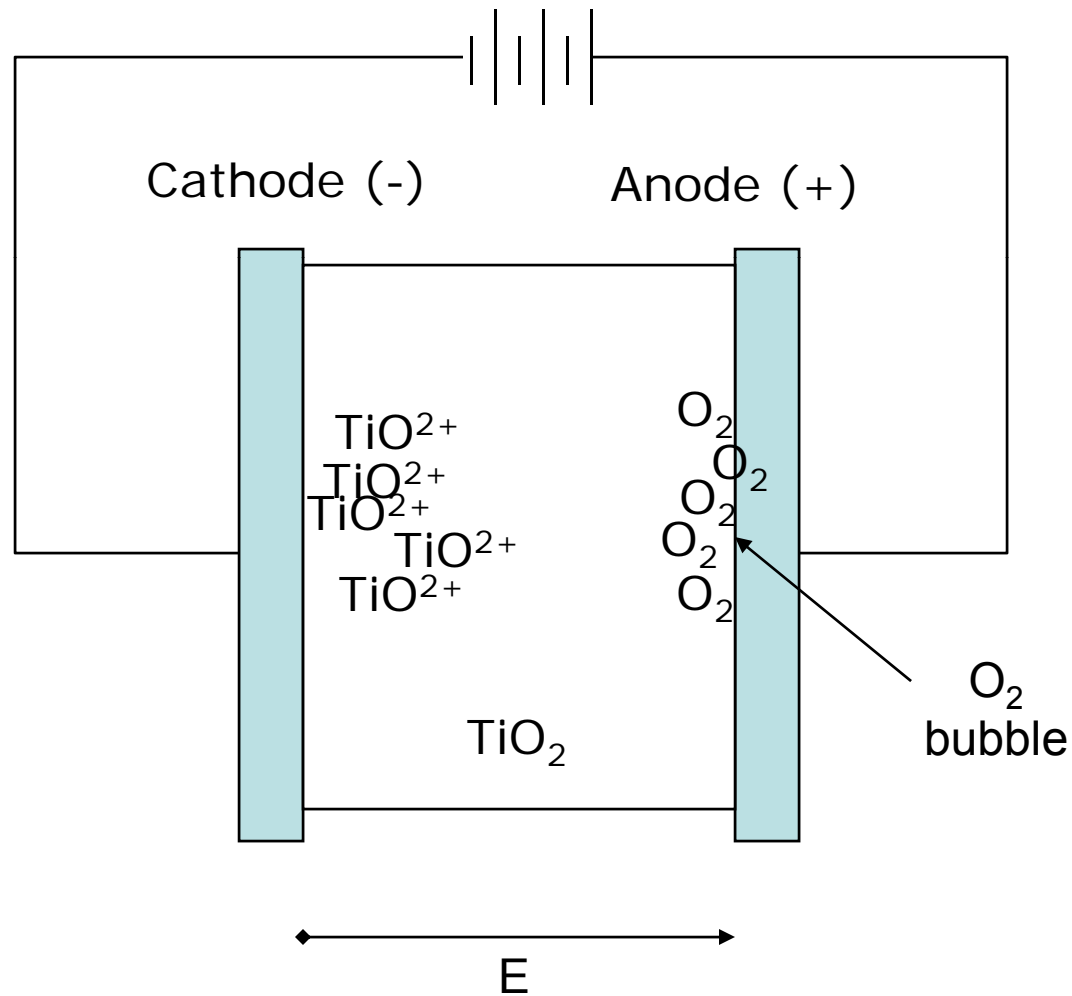
O2 bubble movie



Electroforming can induce O₂ reduction at anode



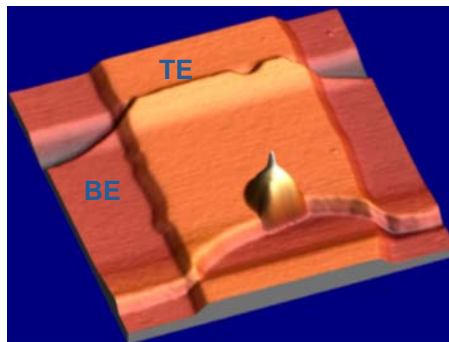
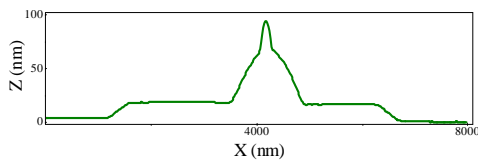
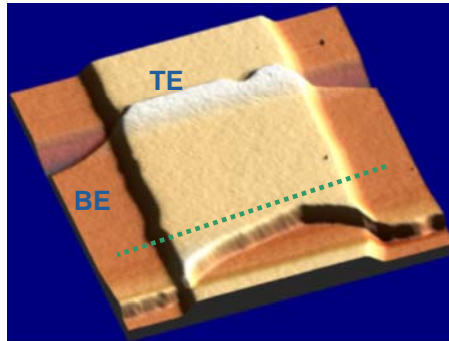
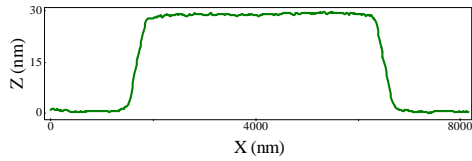
Electroforming can induce O₂ reduction at anode



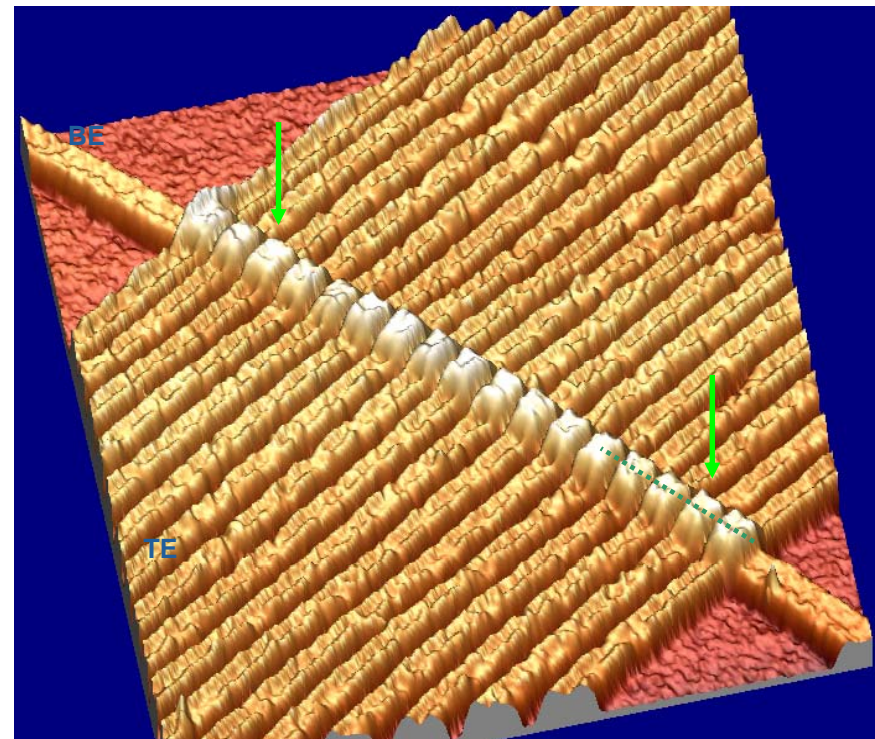
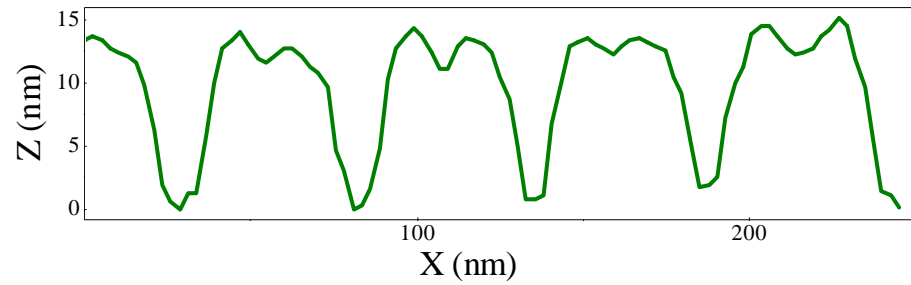
Nano-devices do NOT show bubbles



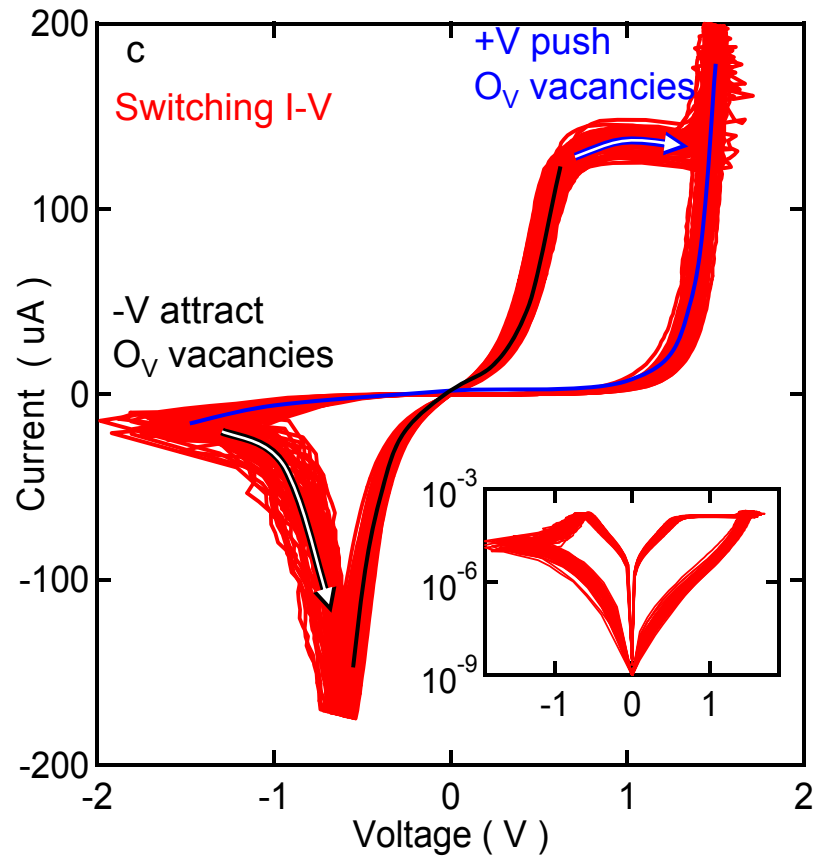
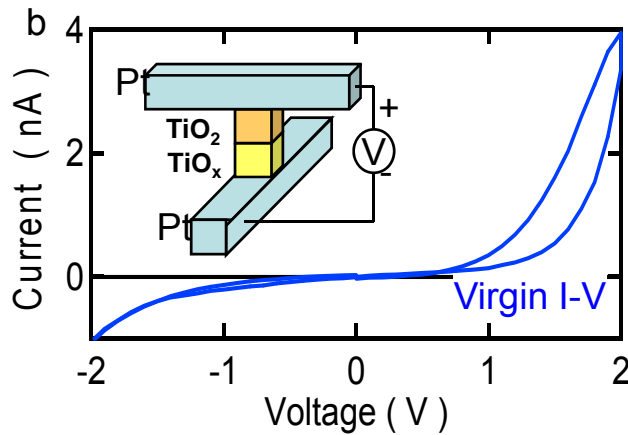
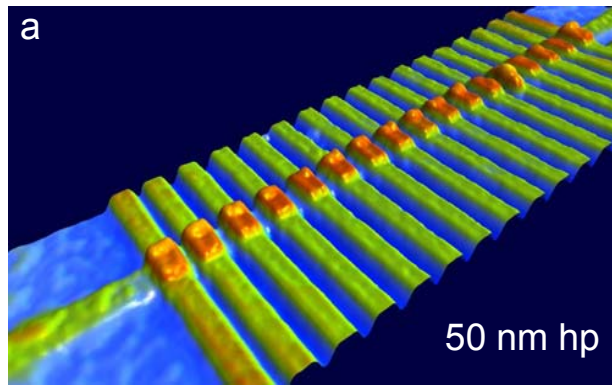
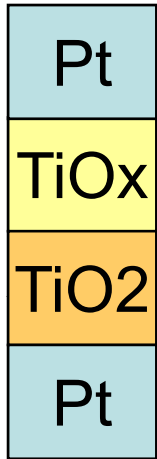
Micron-sized



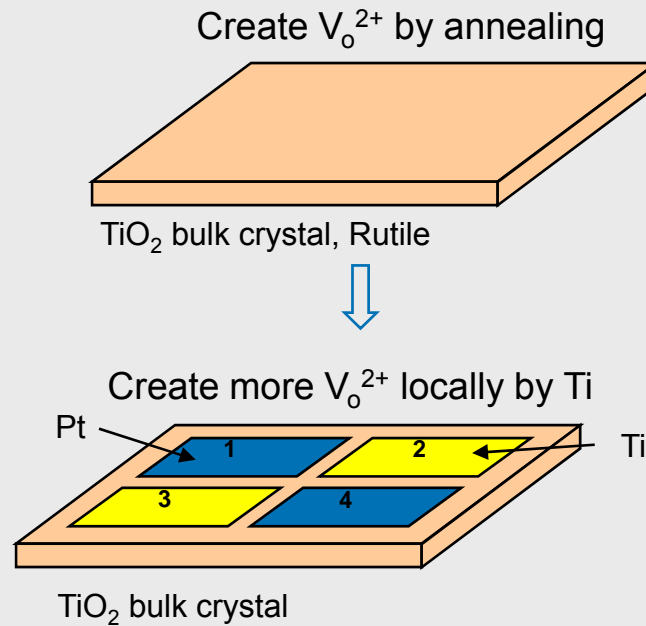
Nano-sized



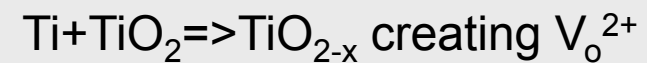
Endurance: 200-400 traces on 50 nanometer Pt/TiOx/Pt devices



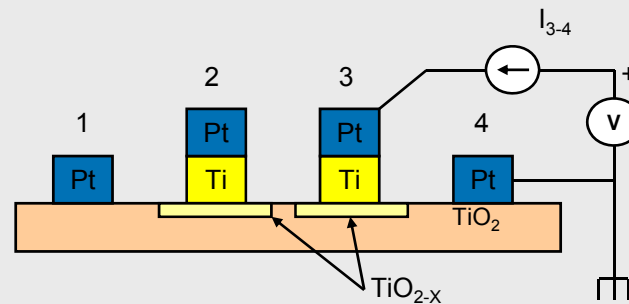
Role of interface: Devices on Single crystal TiO₂ Preparation



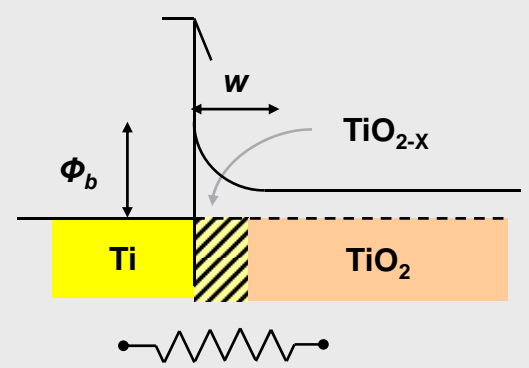
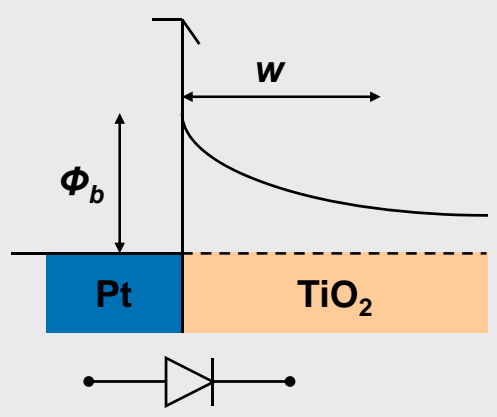
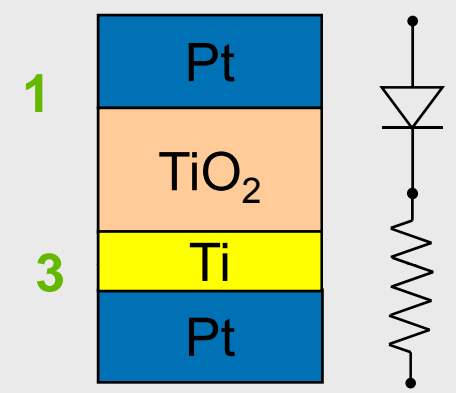
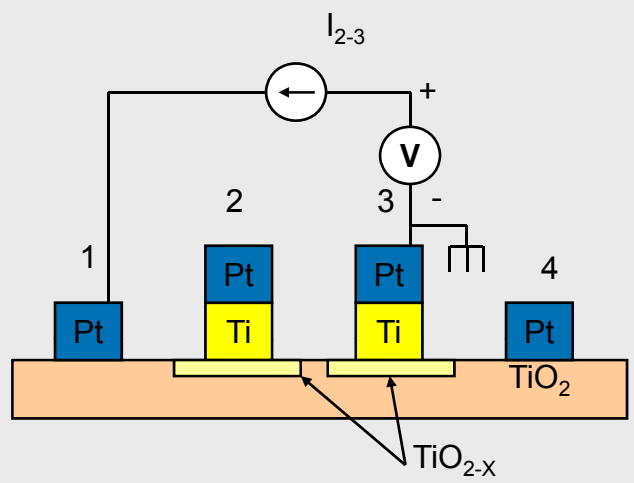
Single crystal TiO₂ rutile was annealed at 700 °C in N₂/H₂ for 2hrs;



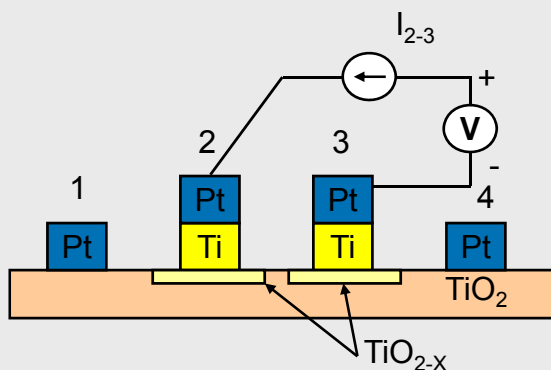
Many two-terminal permutations (devices)



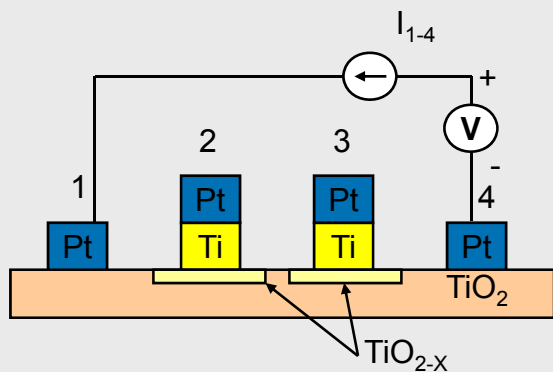
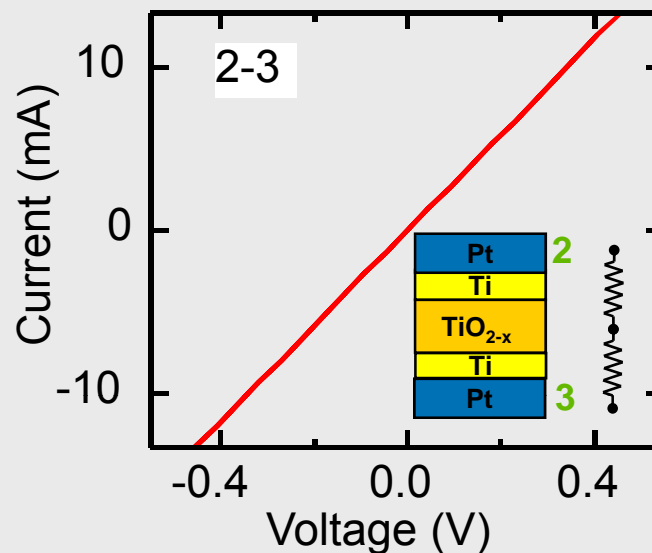
Role of interface



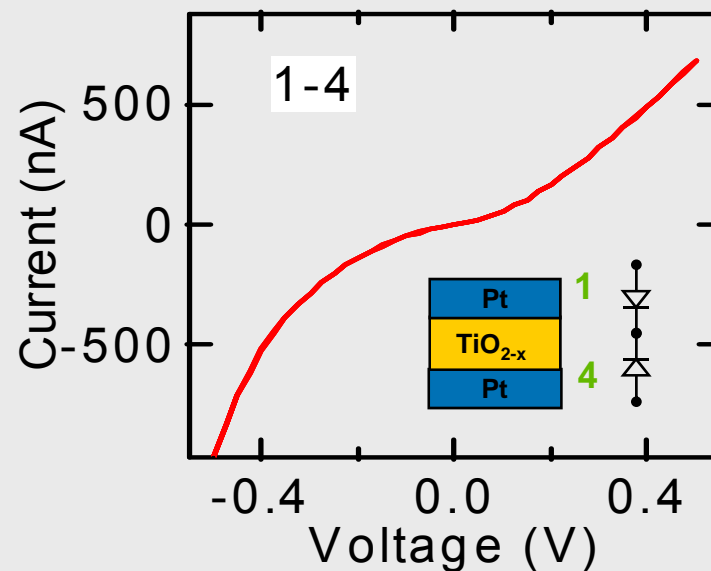
Role of interface: I-V curves



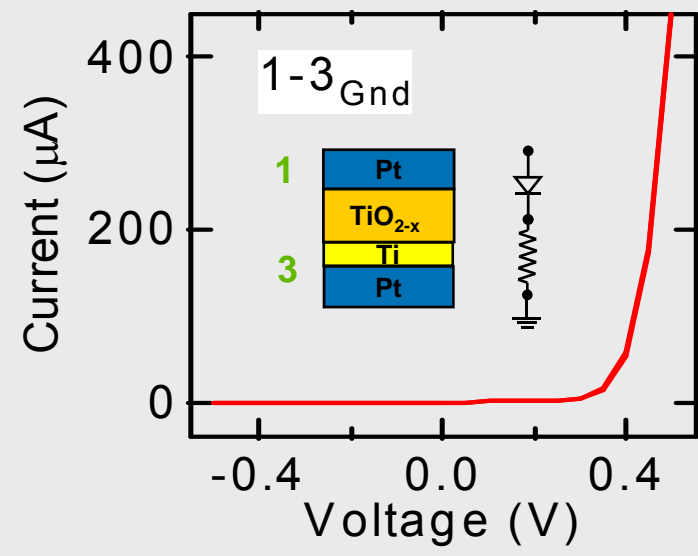
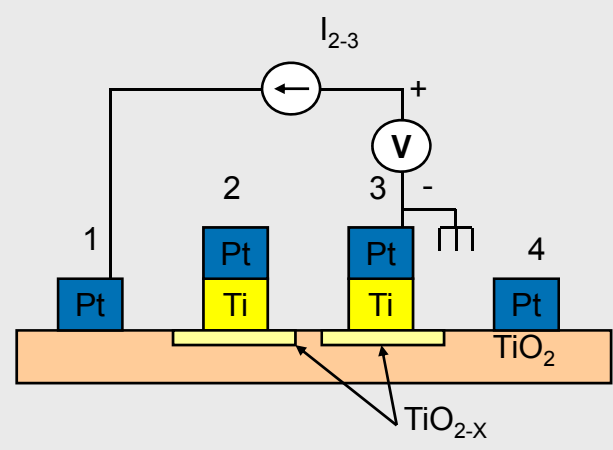
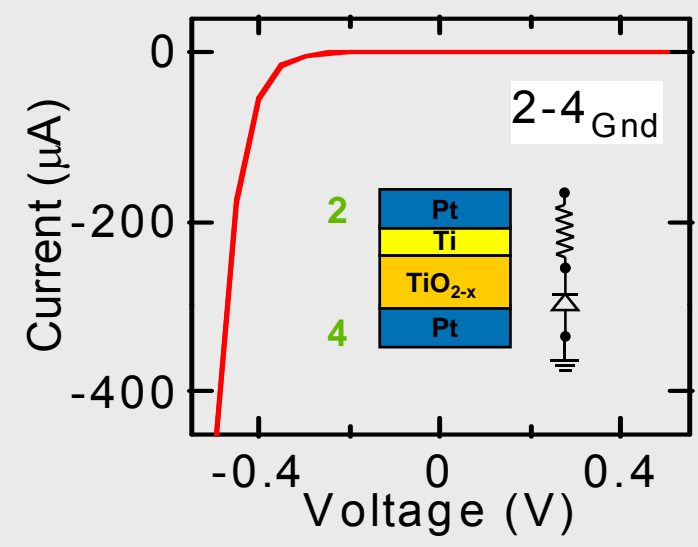
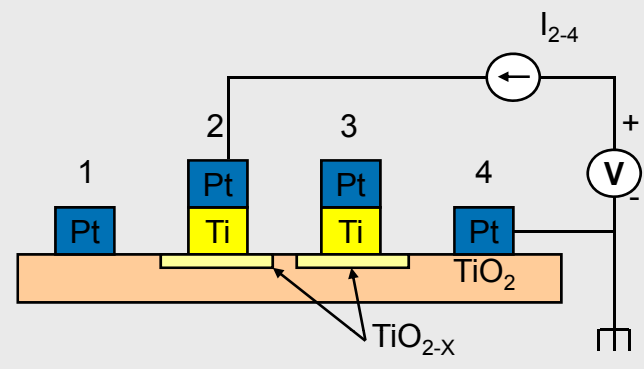
- identical contacts \rightarrow Symmetric I-V;
- 5nmTi/TiO₂ \rightarrow Ohmic contacts (Pads 2,3);
- The single crystal TiO₂ is very conductive;



- identical contacts \rightarrow Symmetric I-V;
- Pt/TiO₂ \rightarrow Schottky contact (pads 1,4);
- Interfaces dominates the I-V (bulk TiO₂ contact).



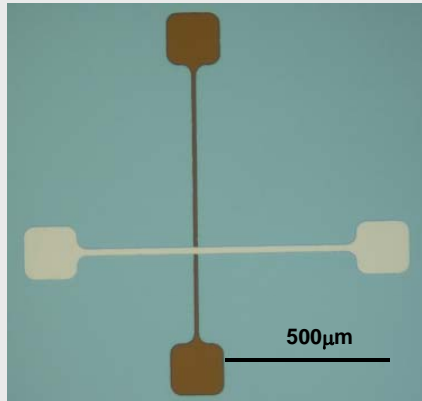
Role of interface: I-V curves



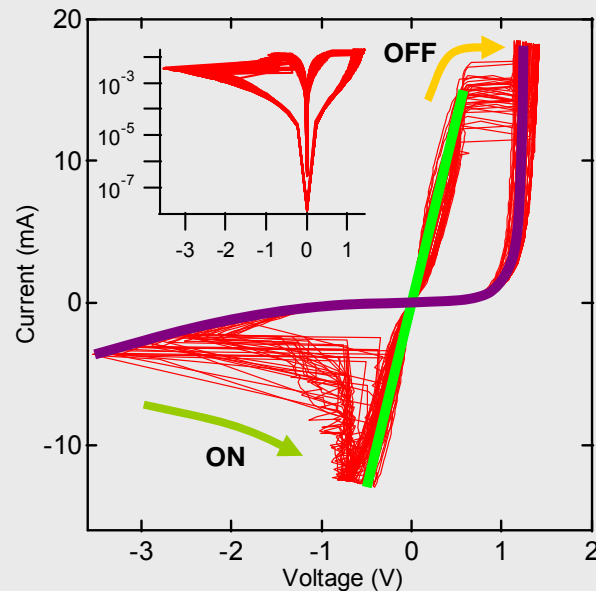
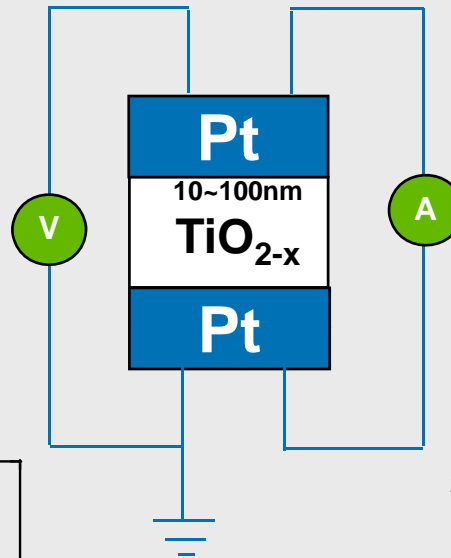
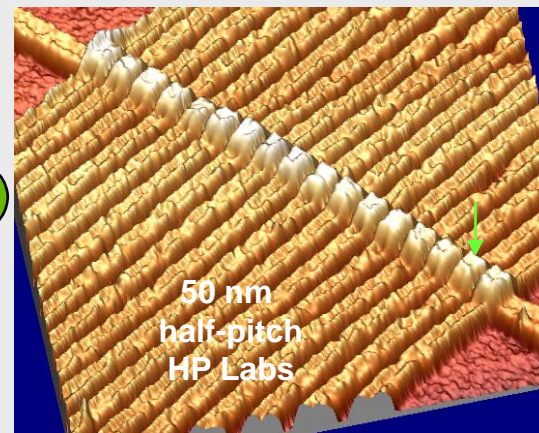
Scalability: from micron- to nano-crosspoint junctions



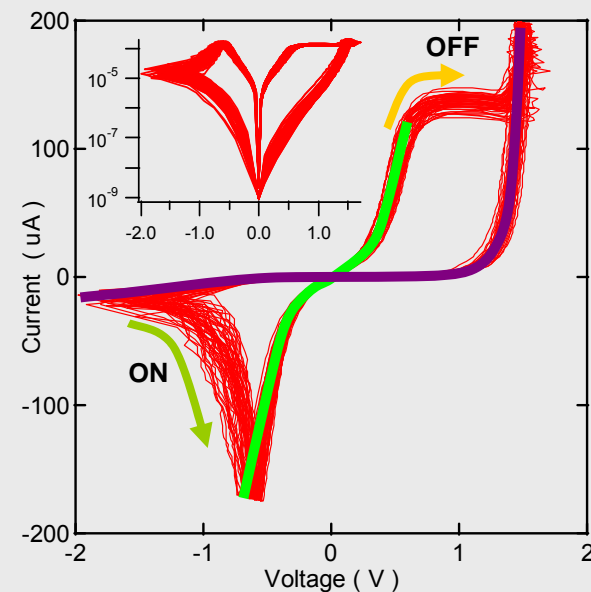
5x5 micronmeter²



50x50 nanometer²



- Large on/off ratio ($\sim 10^3$)
- Low power, (~ 10 pJ/b)
- Fast (< 50 ns)
- Bi-polar
- Non-volatile



J. Joshua Yang

Conclusions



- Dynamic electronics opens up a new class of devices, that can be configured in real time;
- New applications can be found in memory, signal conditioning, etc.

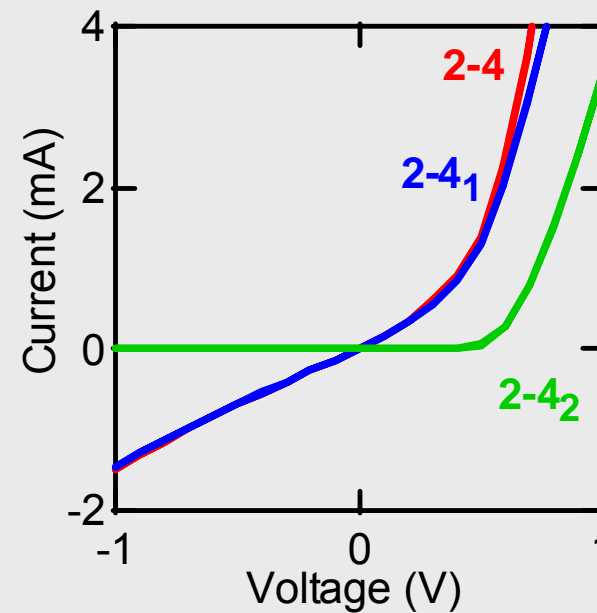
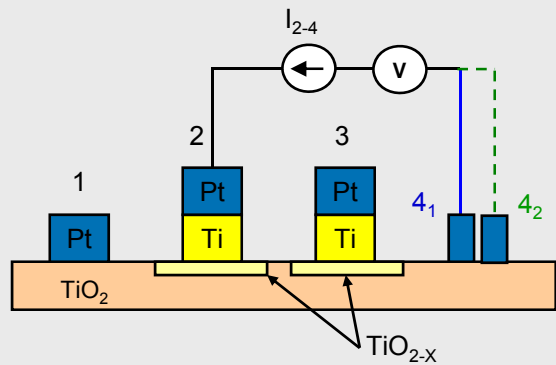


- The end

Switching features: localized or uniform



Question: Is pad 4 uniformly or locally changed?!



3. Localized channels