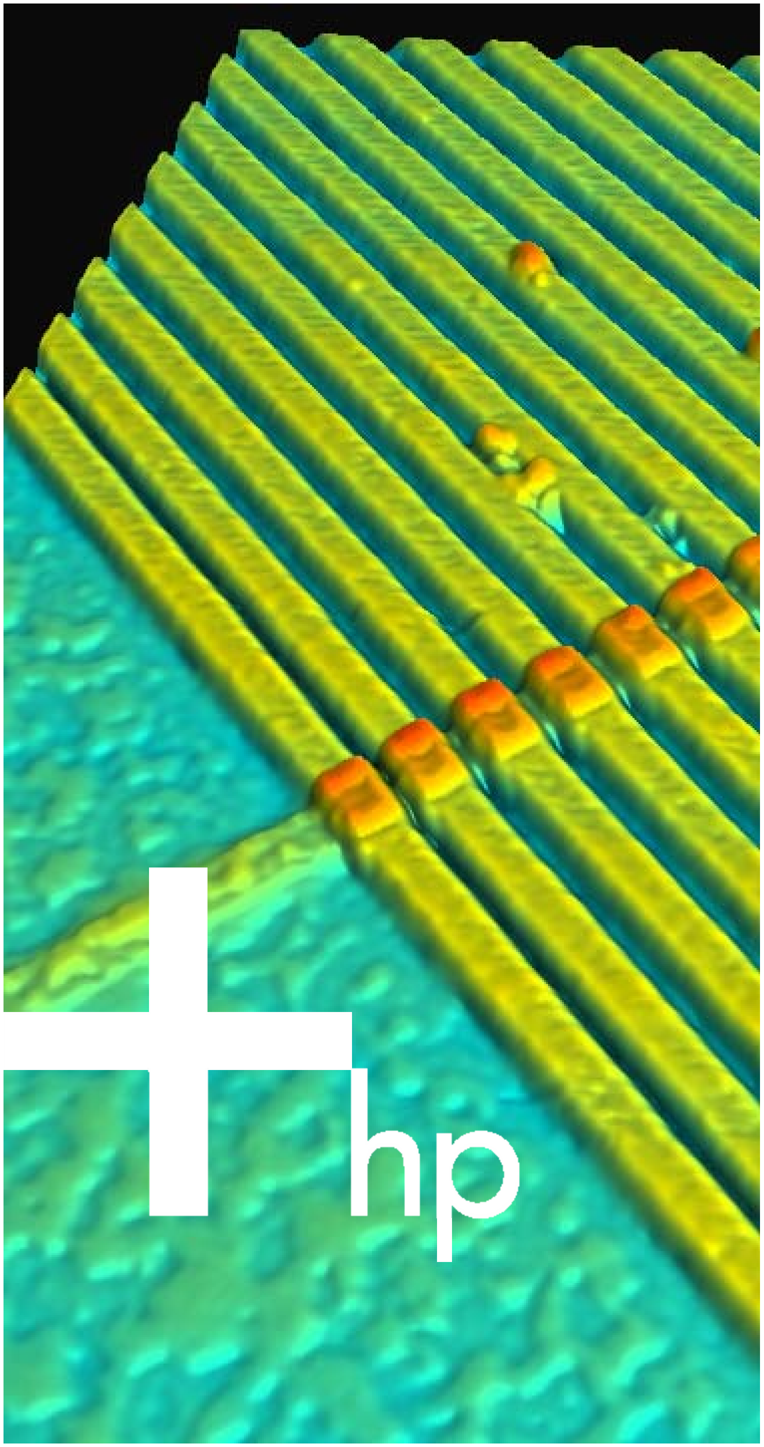
Physics and Materials Science of Memristive devices



Hewlett-Packard Laboratories, Palo Alto CA

People

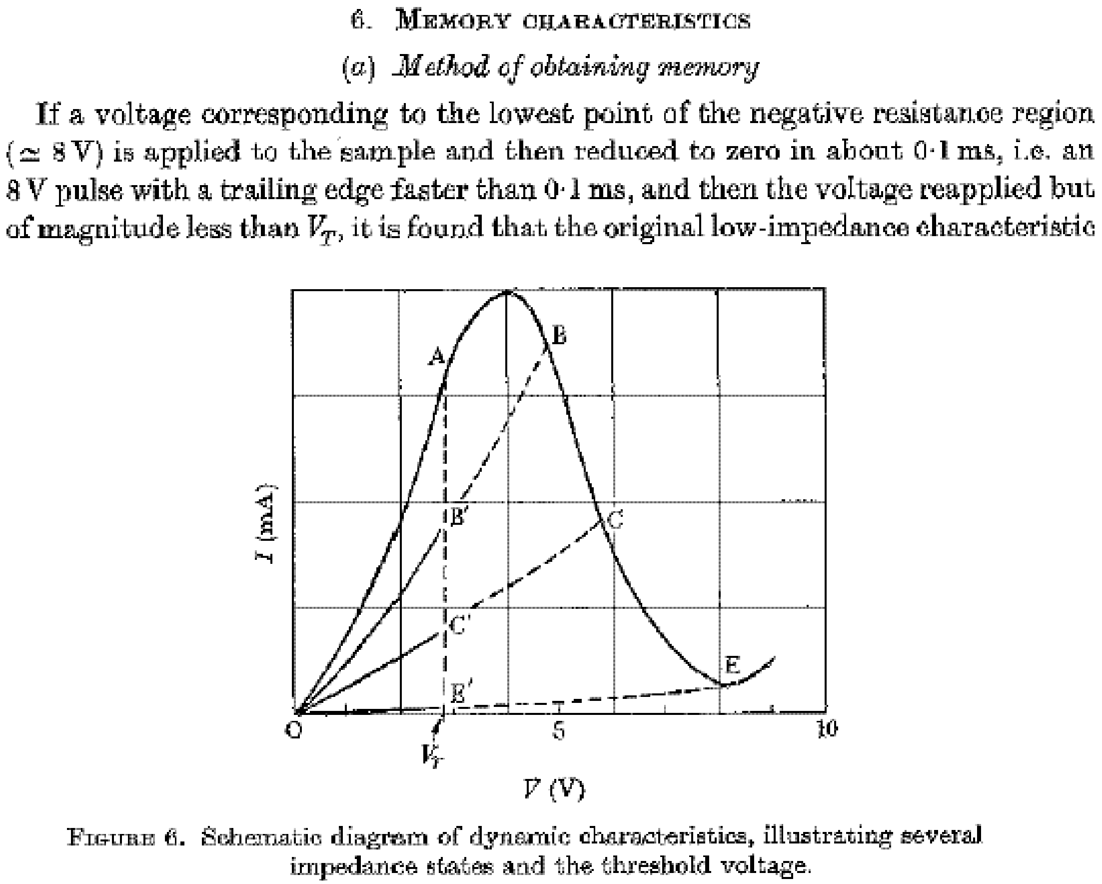
- Jianhua Yang;
- Dmitry Strukov;
- Julien Borghetti;
- Matthew Picket;
- John Paul Stracham;
- Doug Ohlberg;
- Duncan Stewart;
- Phil Kuekes;
- Stan Williams;

Outline

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

History

- 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 ($\simeq 8$ 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.

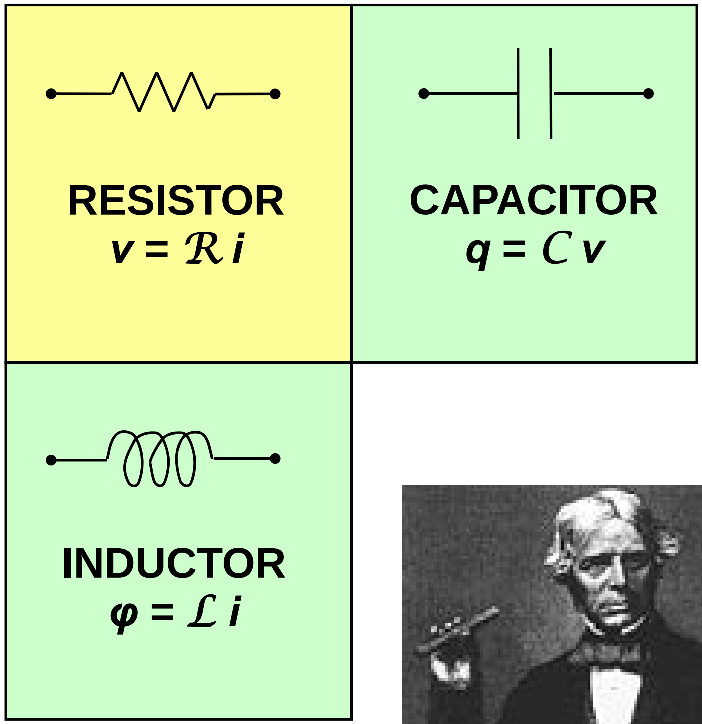
by Simmons and Verderber, Proc. Royal Society of London A, 301 (**1967**) 77

Currently….

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

3 fundamental circuit elements

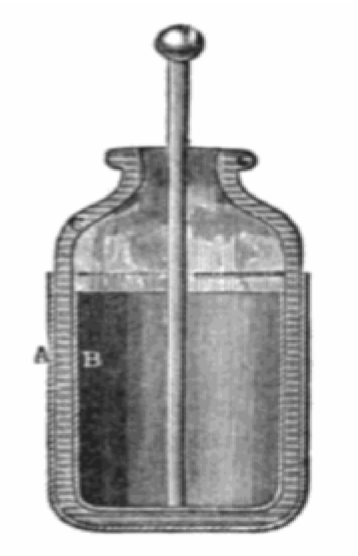
Resistor – 1827
Georg Ohm



RESISTOR
$v = \mathcal{R}\, i$

CAPACITOR
$q = \mathcal{C}\, v$

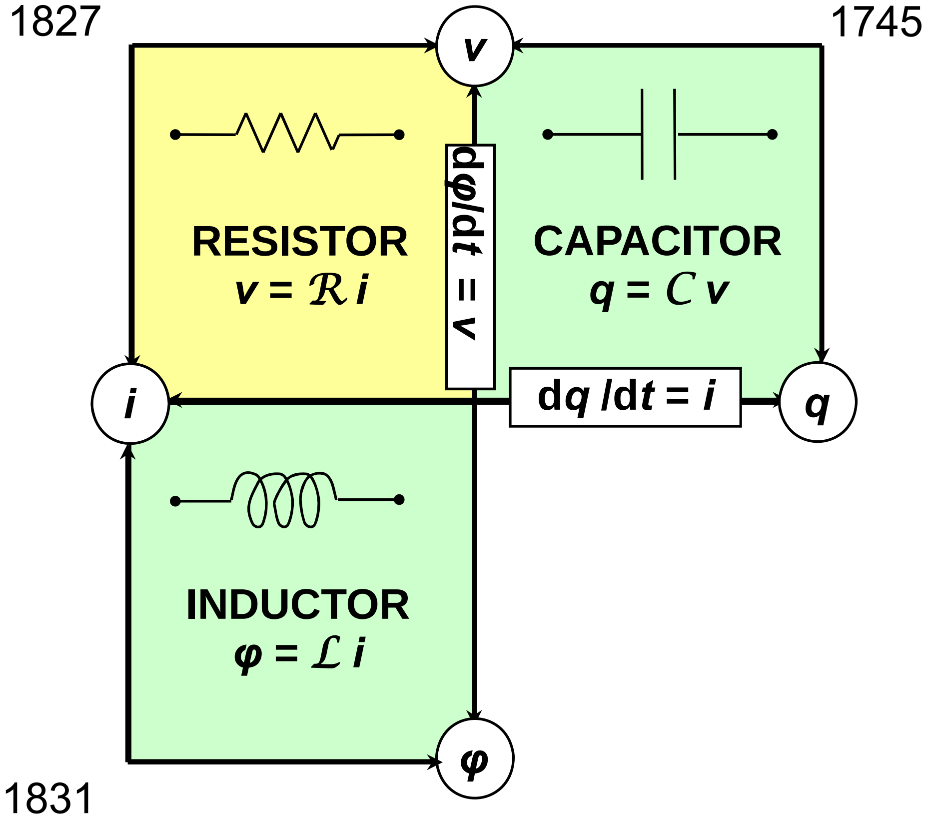
INDUCTOR
$\varphi = \mathcal{L}\, i$



Capacitor - 1745
Volta / von Kleist & van Musschenbroek
Benjamin Franklin

Inductor – 1831
Faraday
Joseph Henry

3 fundamental circuit elements



1827

1745

1831

RESISTOR
$v = \mathcal{R}\, i$

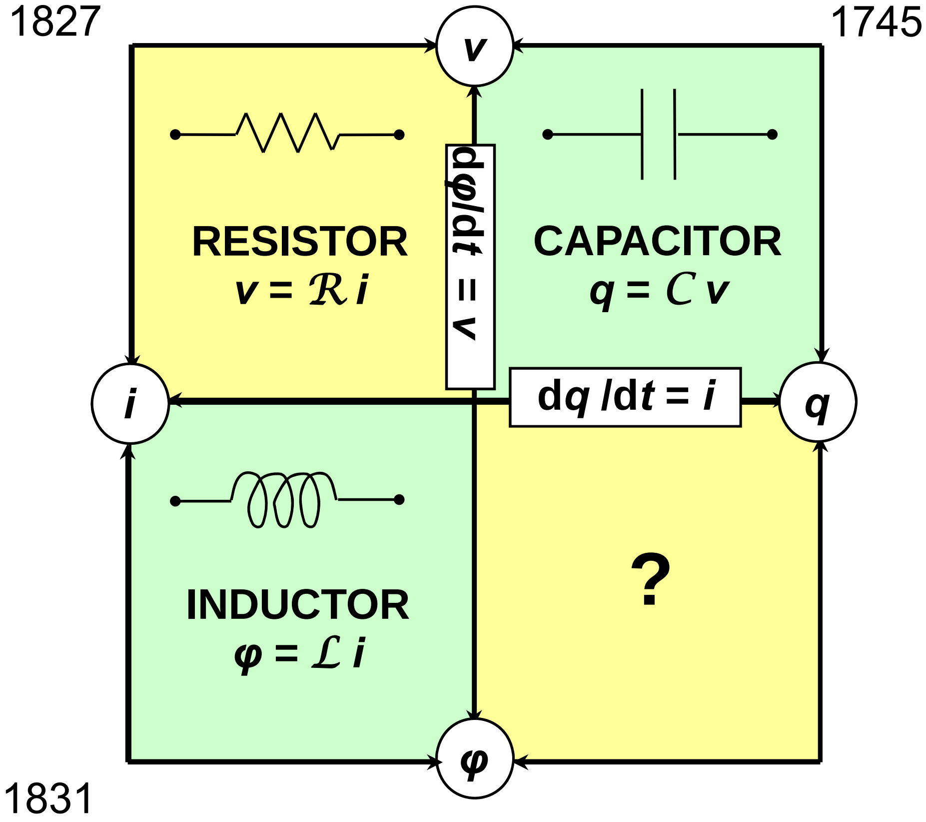
CAPACITOR
$q = \mathcal{C}\, v$

INDUCTOR
$\varphi = \mathcal{L}\, i$

$d\varphi/dt = v$

$dq/dt = i$

Leon Chua 1971



1827

v

1745

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i

$dq/dt = i$

q

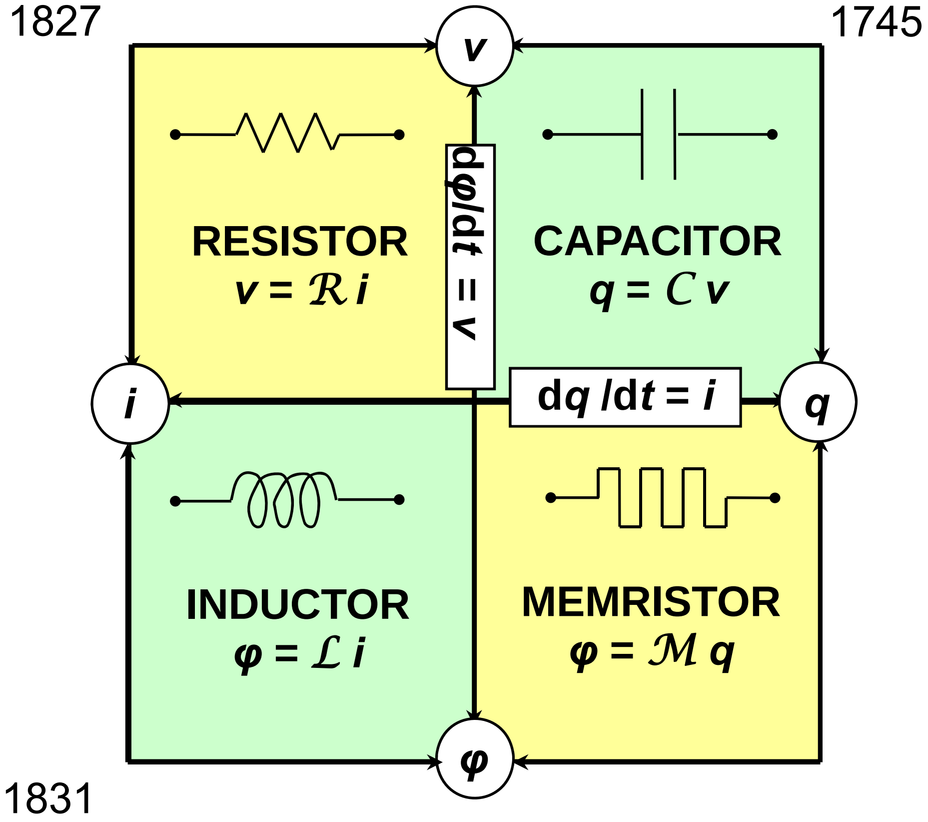
INDUCTOR
$\varphi = \mathcal{L}\, i$

?

φ

1831

Leon Chua 1971 – the memristor



1827

1745

1831

v

i

q

φ

RESISTOR
$v = \mathcal{R}\, i$

CAPACITOR
$q = \mathcal{C}\, v$

INDUCTOR
$\varphi = \mathcal{L}\, i$

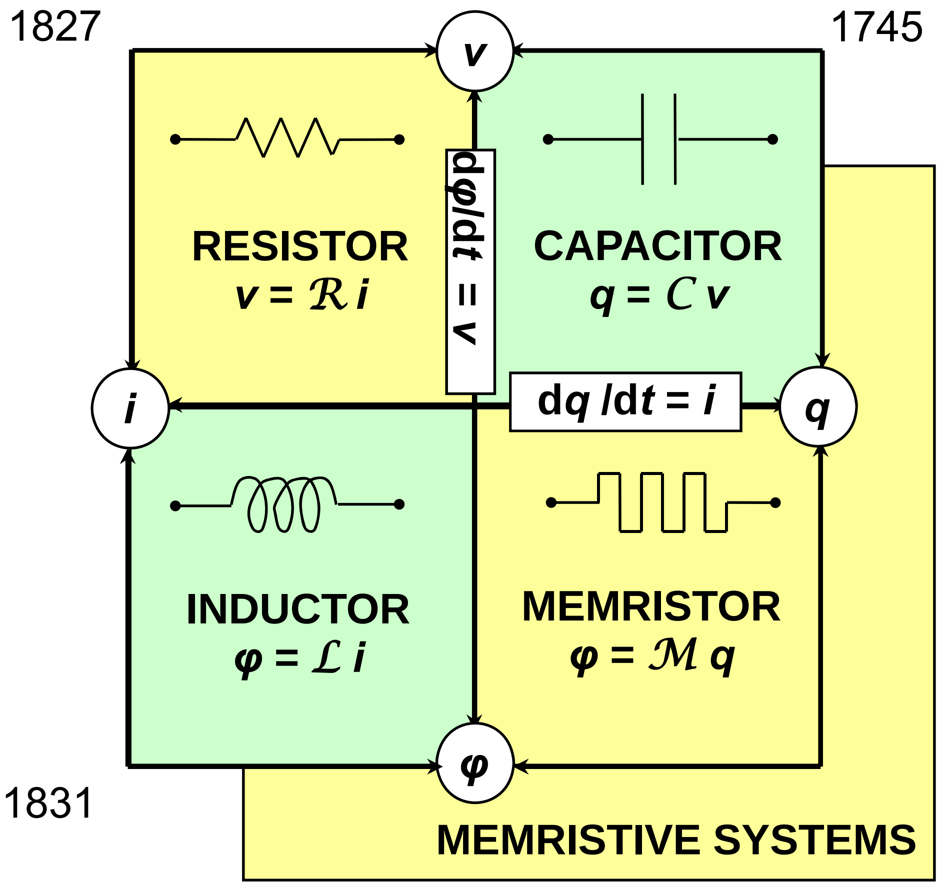
MEMRISTOR
$\varphi = \mathcal{M}\, q$

$d\varphi/dt = v$

$dq/dt = i$

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



1827

1745

v

RESISTOR
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$d\varphi/dt = v$

CAPACITOR
$q = \mathcal{C}\, v$

i

$dq/dt = i$

q

INDUCTOR
$\varphi = \mathcal{L}\, i$

MEMRISTOR
$\varphi = \mathcal{M}\, q$

φ

1831

MEMRISTIVE SYSTEMS

Simple Memristor:

$$v = M(w)i$$

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

Generalized Memristor
(Memristive system):

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

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

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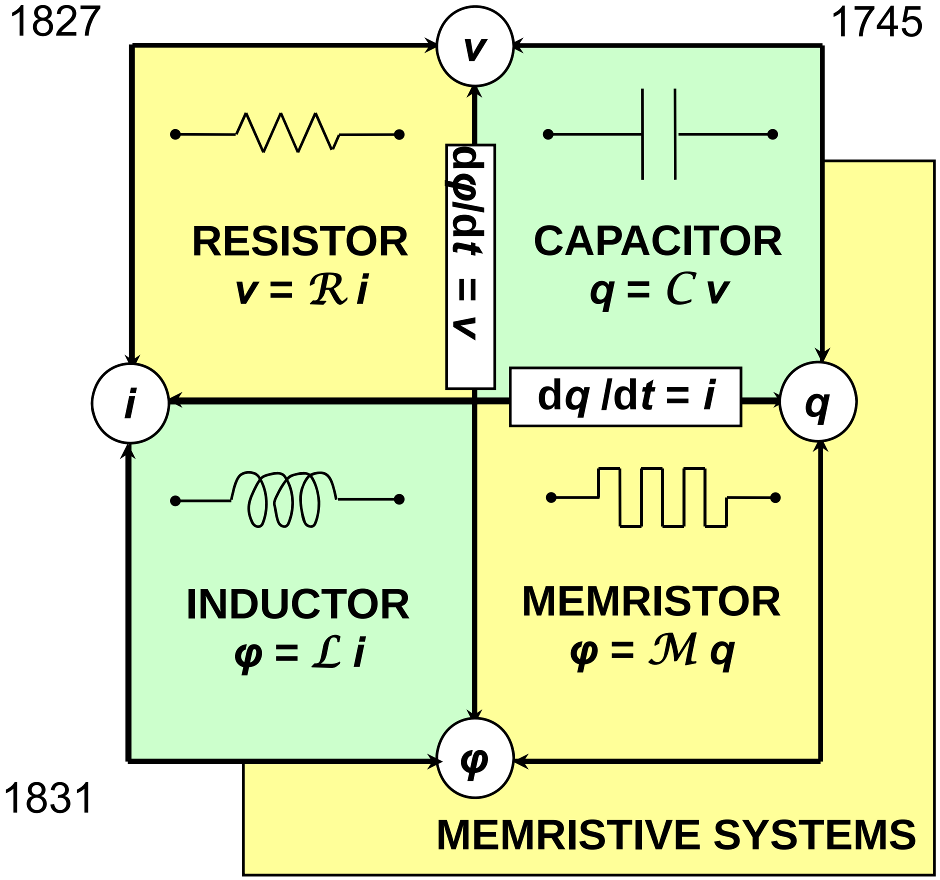

1827

1745

1831

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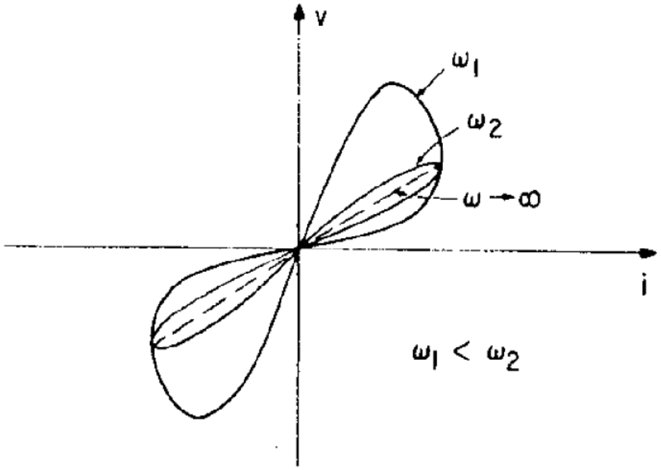

Fig. 6. Frequency response of Lissajous figures.

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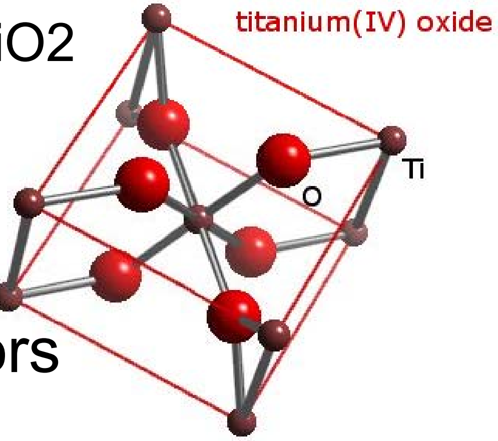
L. O. Chua and S. M. Kang, "Memristive devices and systems," ***Proc. IEEE,*** **64 (2), 209-23 (1976).**

Implementation

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

TiO_2

rutile TiO2

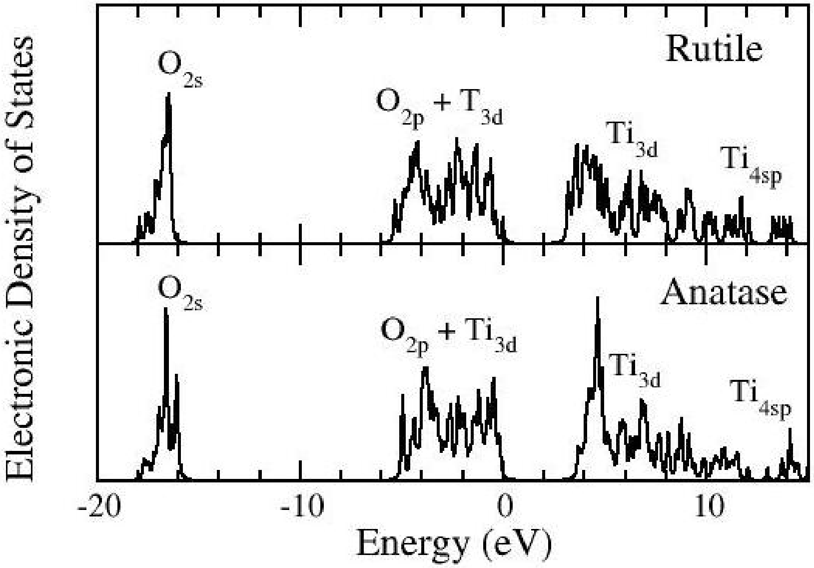


3.0/3.2 eV semiconductor

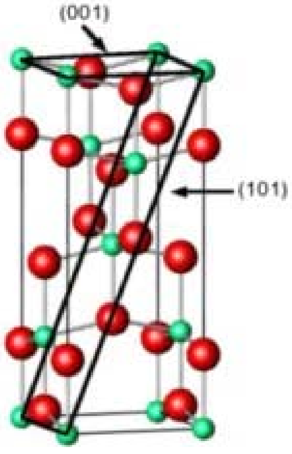
dielectric ε ~ 80, bi-refringent

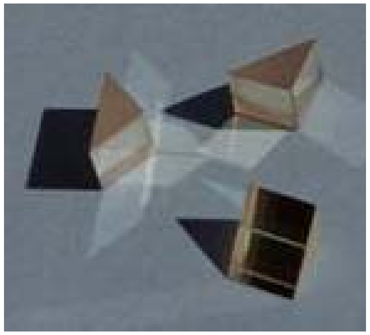
pigment, photocatalyst, O_2 sensors

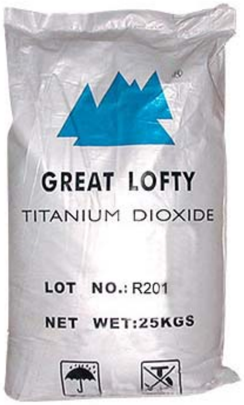
TiO_2 : 1x Ti^{4+} + 2x O^{2-}



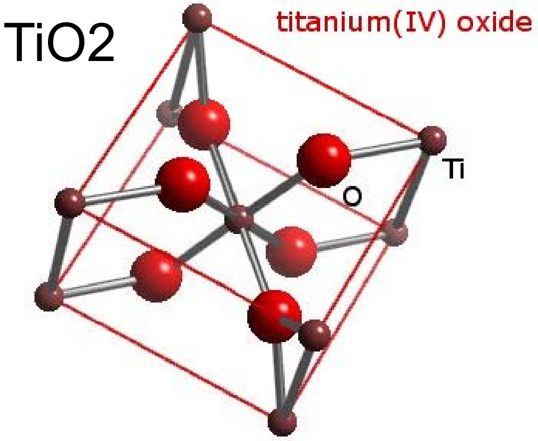
anatase TiO2







TiO_{2-x}



3.0/3.2 eV semiconductor

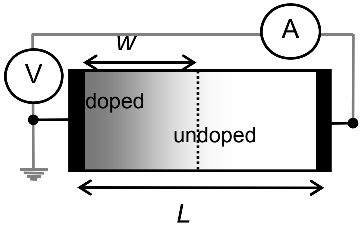
TiO_{2-x} : $x \sim 10^{-3} - 10^{-2}$
dopants all ionized $E_i < 0.1$ eV

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

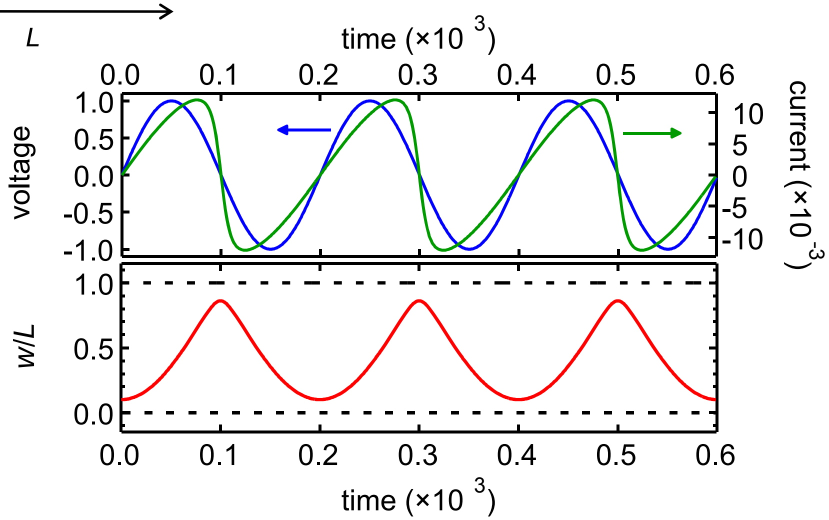
creation ~ 3-5 eV
diffusion ~ 0.7 - 1.1 eV
mobility ~ $10^{-10} - 10^{-14}$ cm^2/Vs

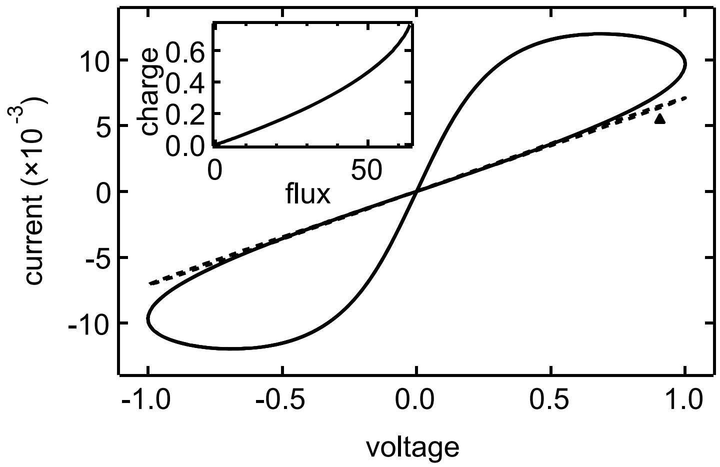
Solid State Ionics 177 (2006) 229 – 236

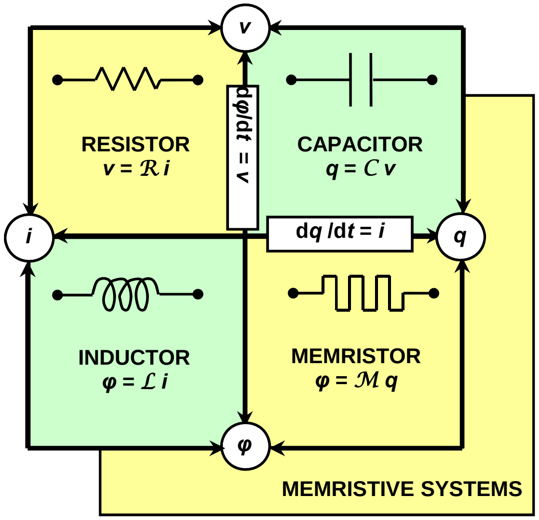
O vacancy drift model for TiOx switch



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







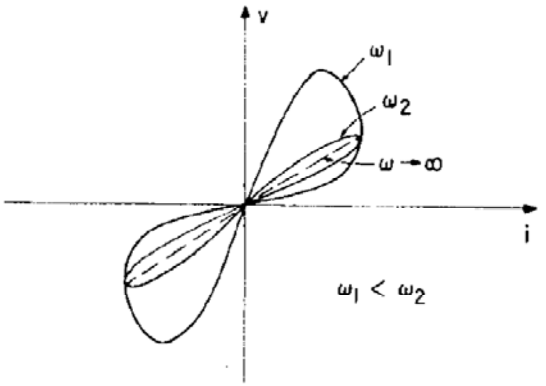
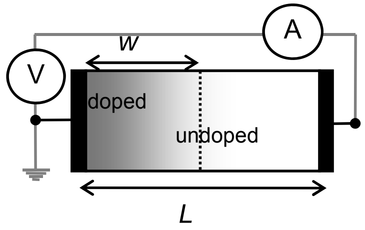


Fig. 6. Frequency response of Lissajous figures.

O vacancy drift model for TiOx switch



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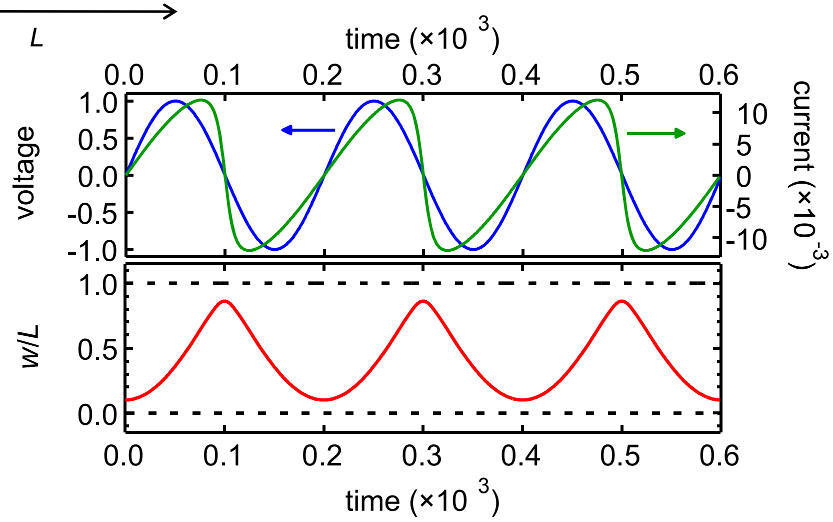

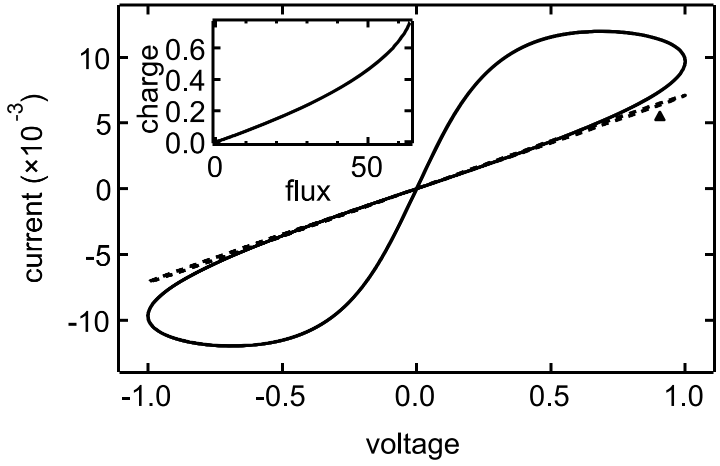

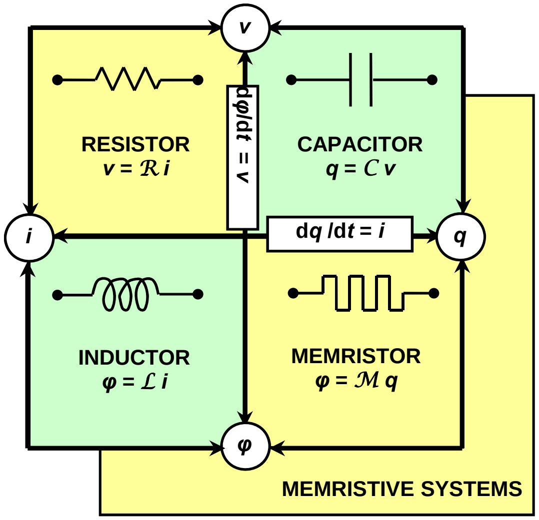

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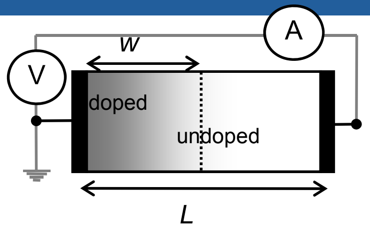

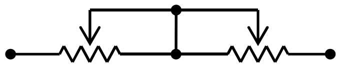

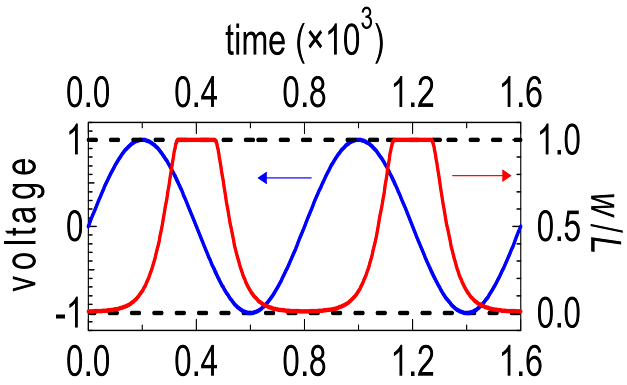

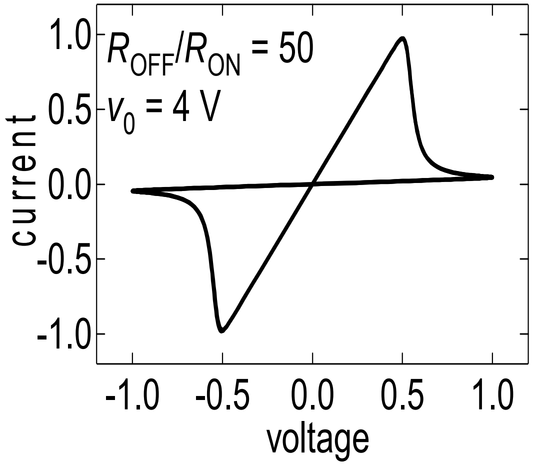

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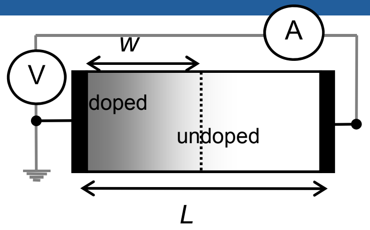
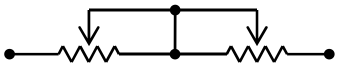
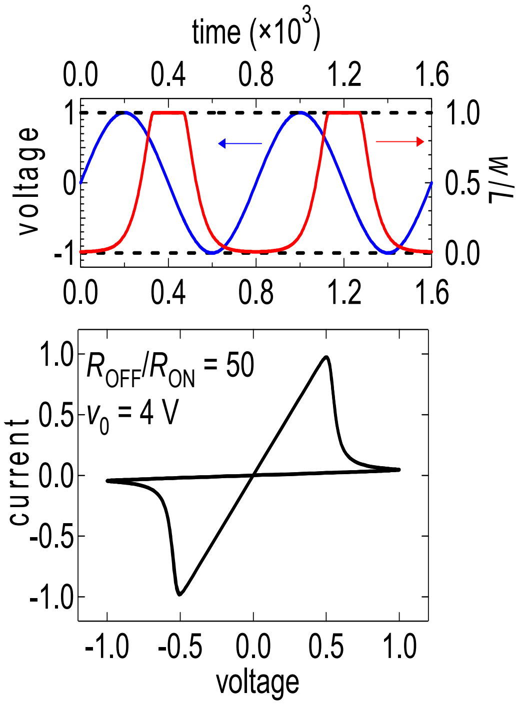
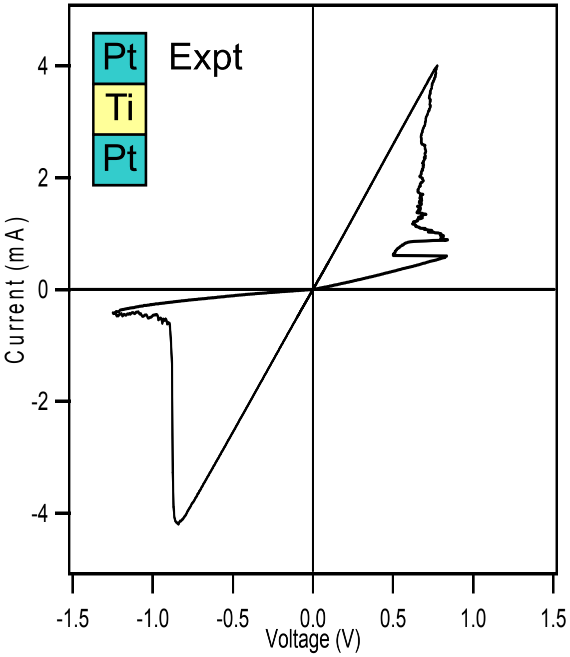
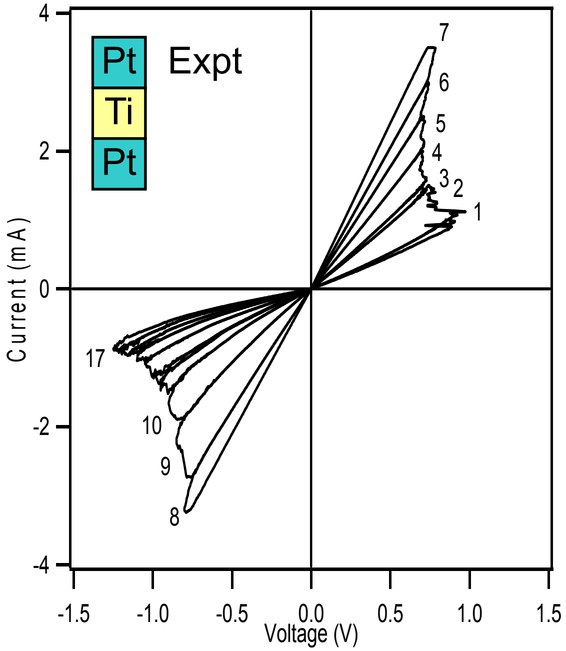








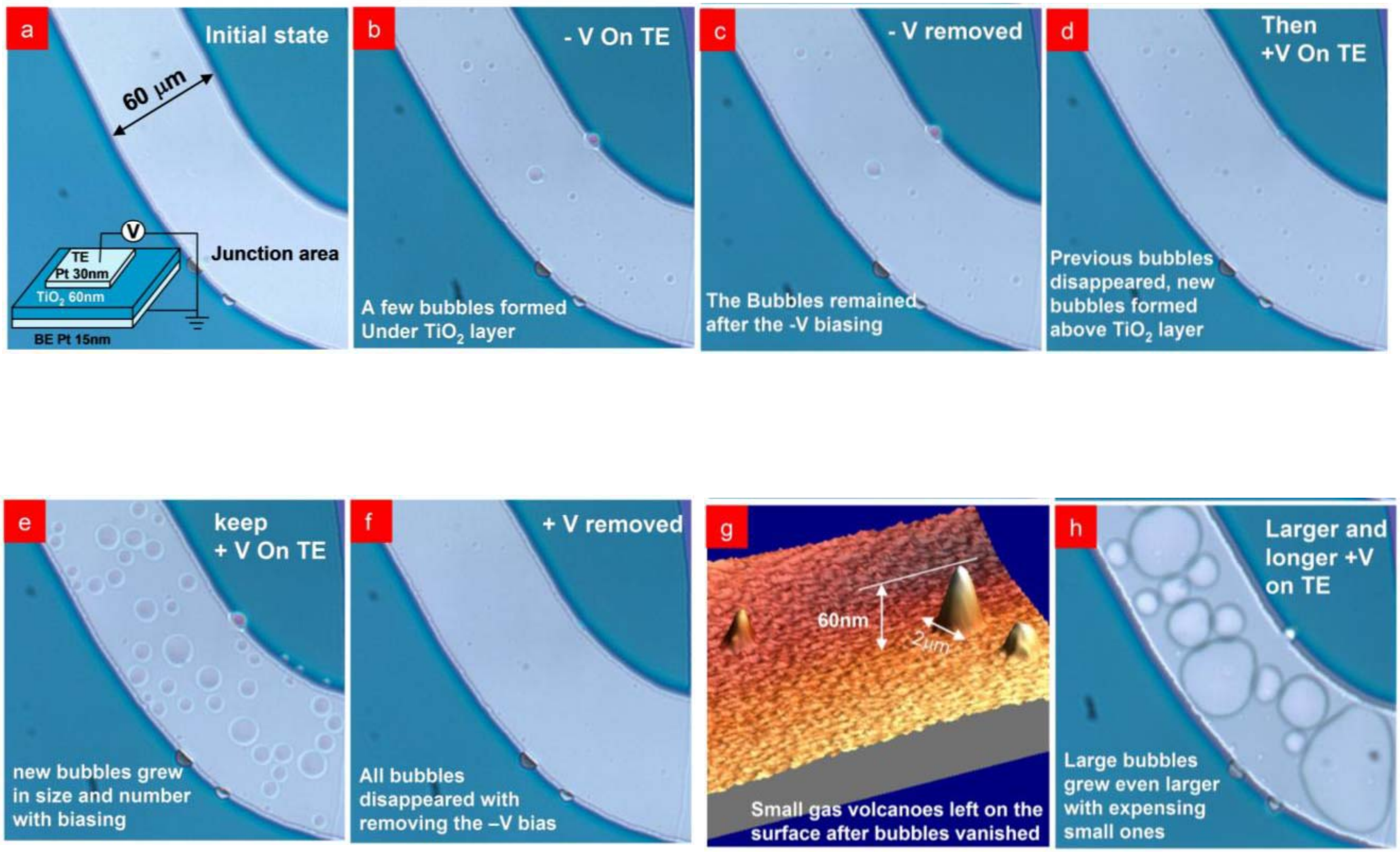


Dmitri Strukov, Greg Snider,
Duncan Stewart, R. Stanley Williams,
Nature **453**, 80 - 83 (01 May 2008)

Device operation

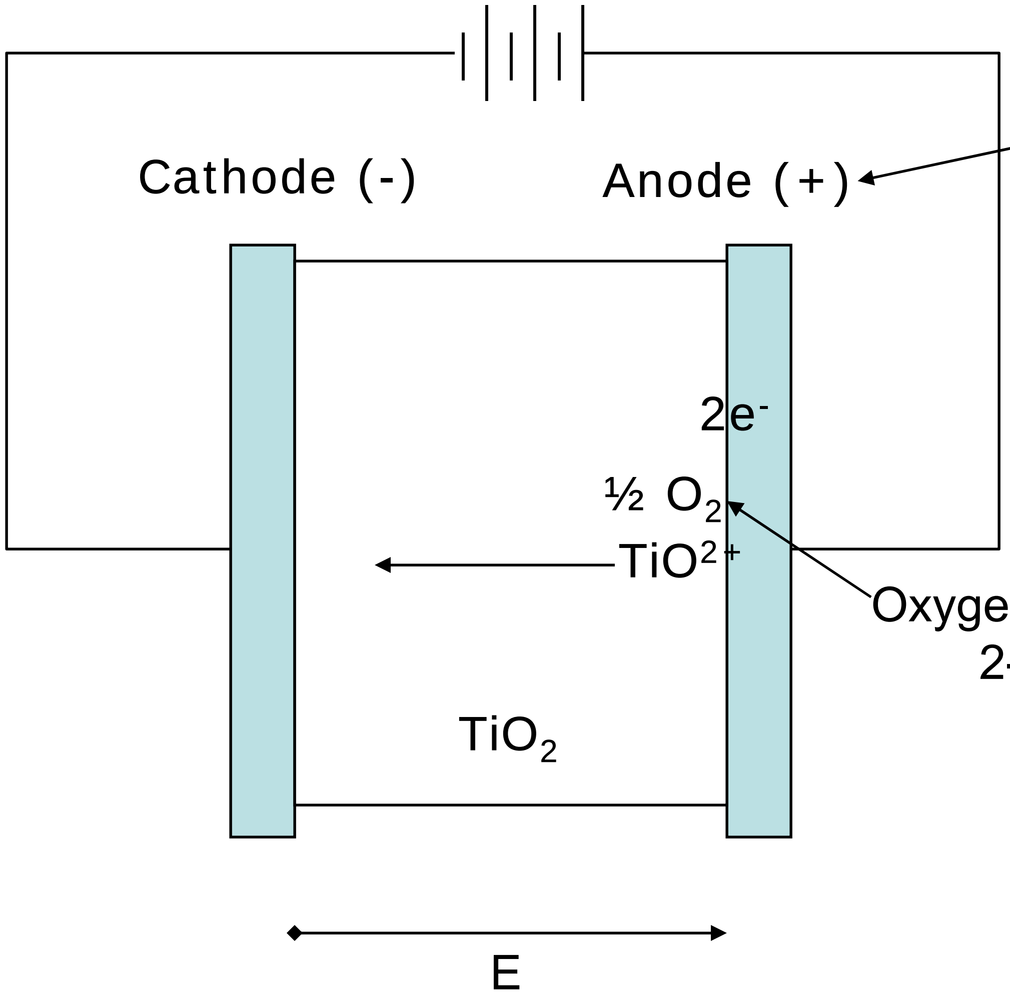
- Electroforming and bubbling
- Endurance;
- Interface effects;
- Scalability;

O2 reduction at anode creates bubbles in micron-sized devices



O2 bubble movie

Electroforming can induce O2 reduction at anode



Cathode (-)

Anode (+)

Anode ≡
Where oxidation occurs

$2e^-$

½ O_2

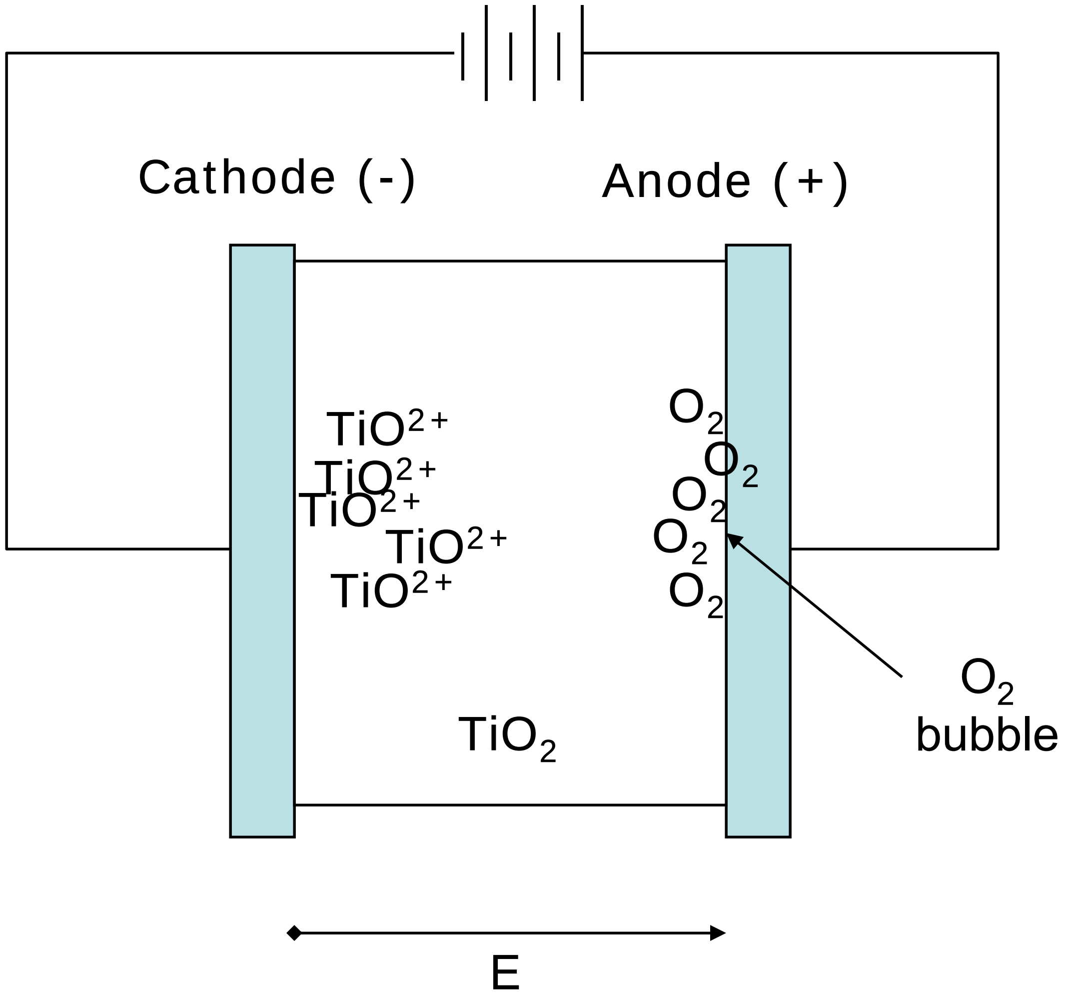
TiO^{2+}

Oxygen is oxidized from
2- to 0 charge

TiO_2

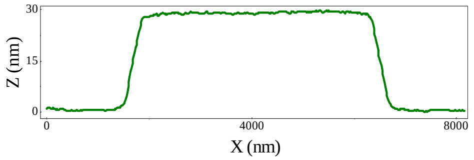
E

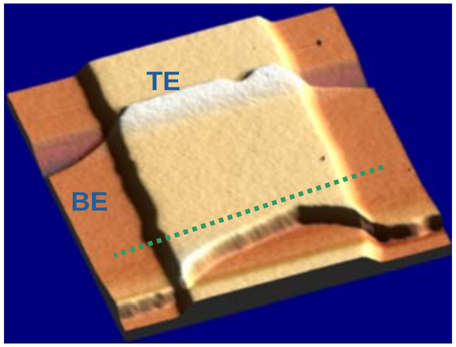
Electroforming can induce O2 reduction at anode

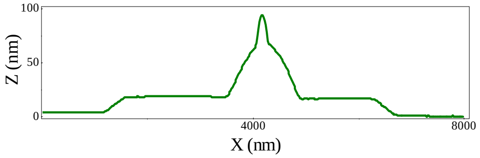


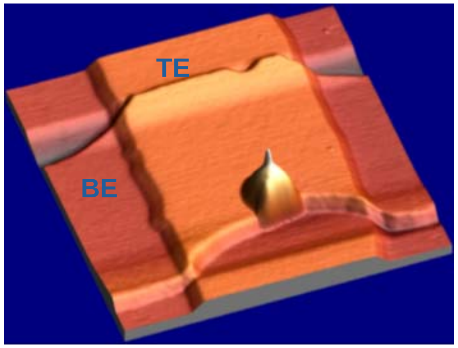
Nano-devices do NOT show bubbles

Micron-sized

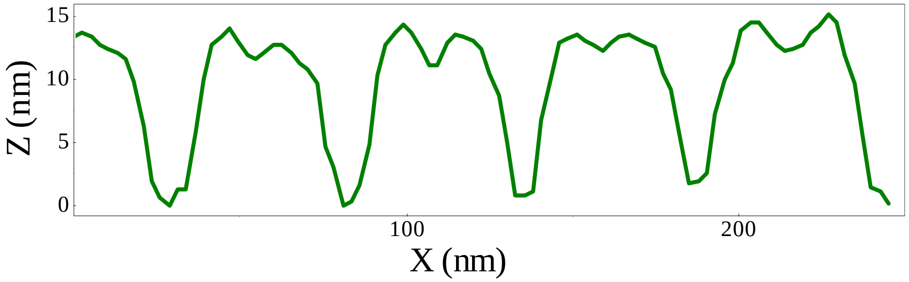


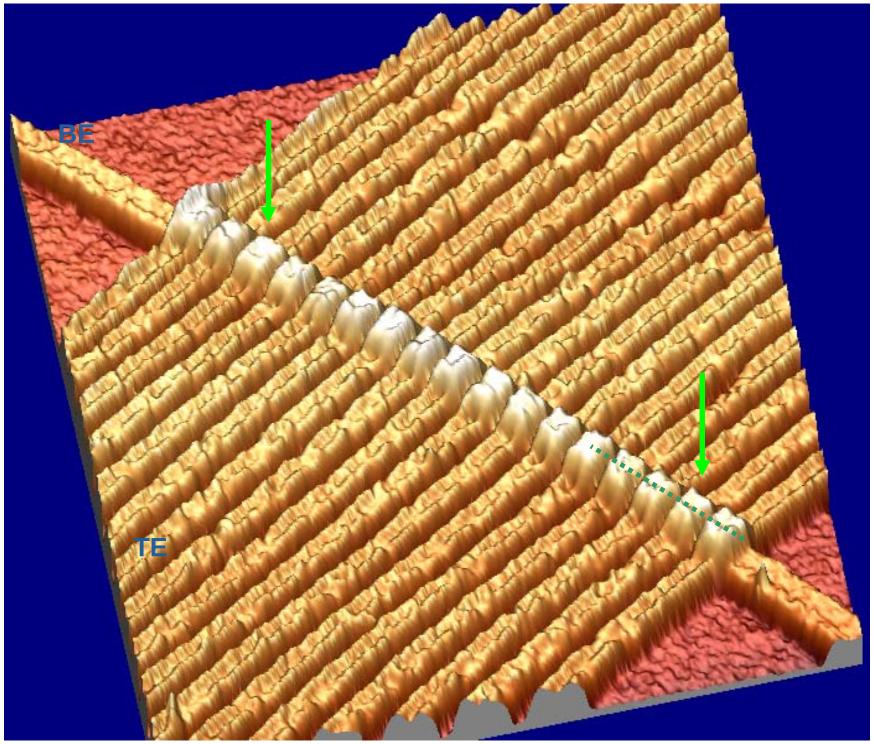






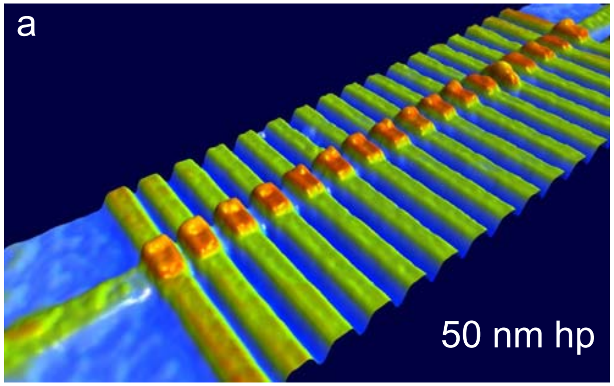
Nano-sized

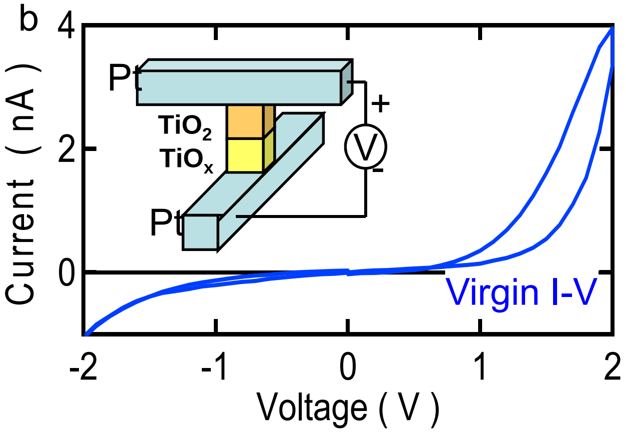


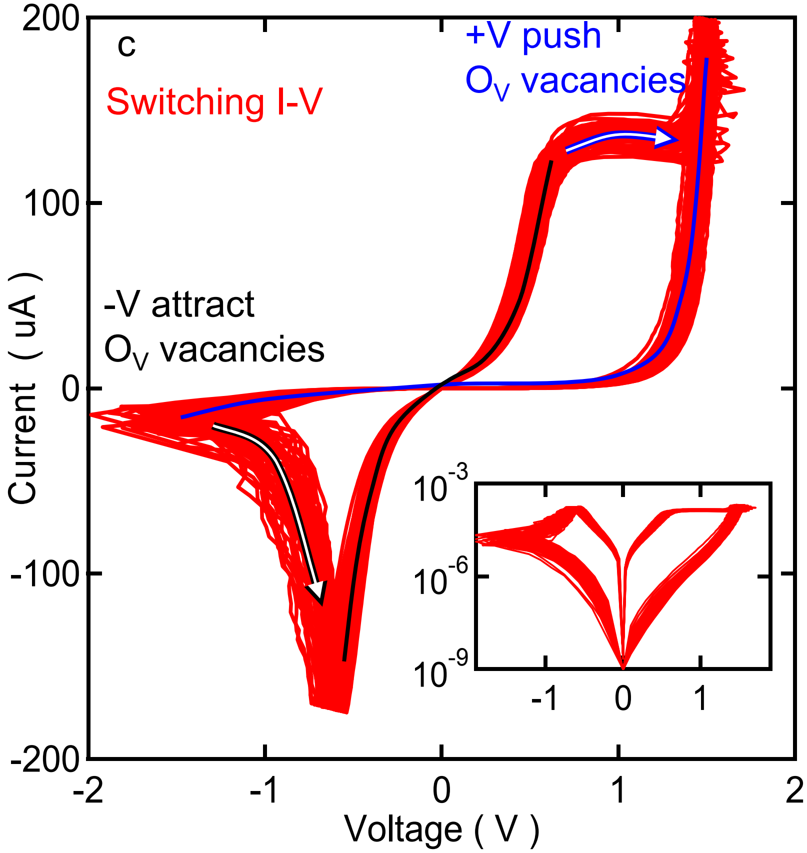


Endurance: 200-400 traces on 50 nanometer Pt/TiOx/Pt devices

Pt
TiOx
TiO2
Pt







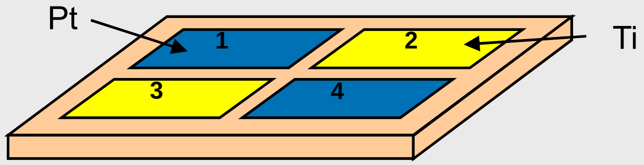
Role of interface: Devices on Single crystal TiO_2 Preparation

Create V_o^{2+} by annealing

Single crystal TiO_2 rutile was annealed at 700 °C in N_2/H_2 for 2hrs;

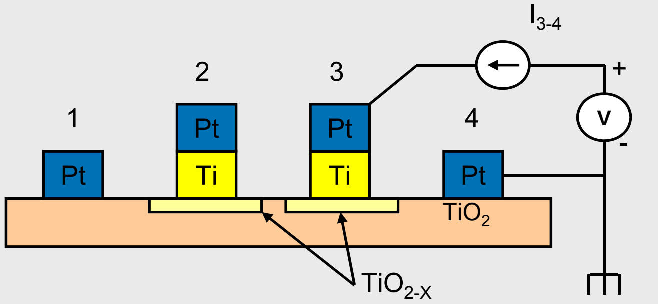
⇩

Create more V_o^{2+} locally by Ti

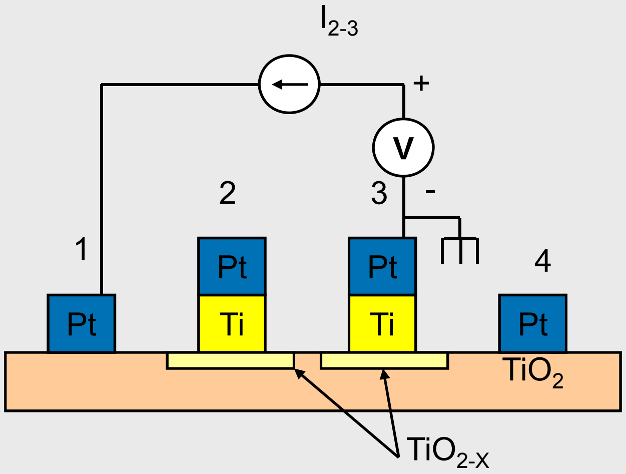


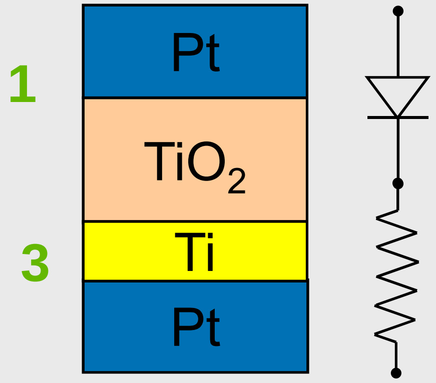
$Ti+TiO_2 \Rightarrow TiO_{2-x}$ creating V_o^{2+}

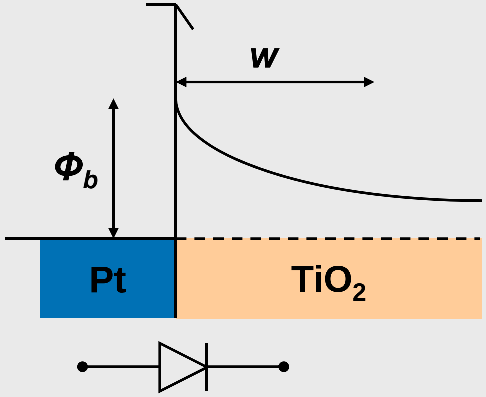
Many two-terminal permutations (devices)

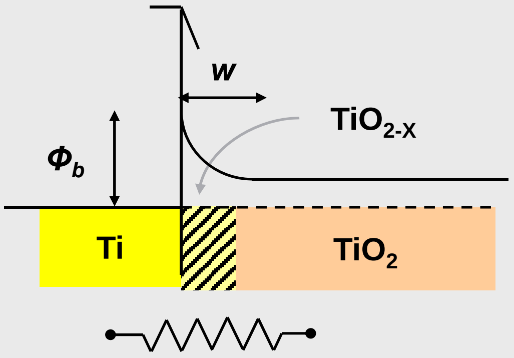


Role of interface

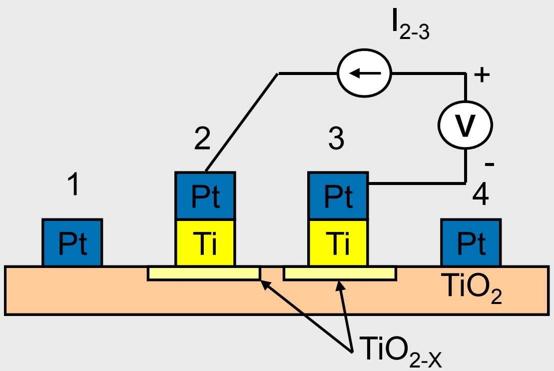




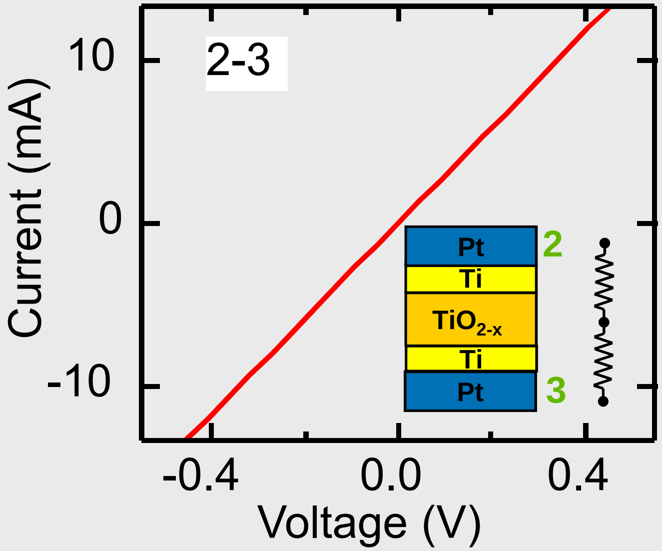


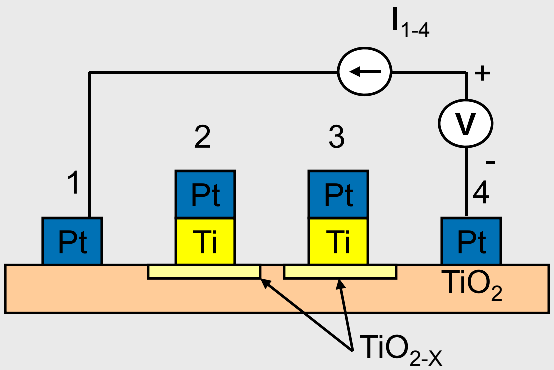


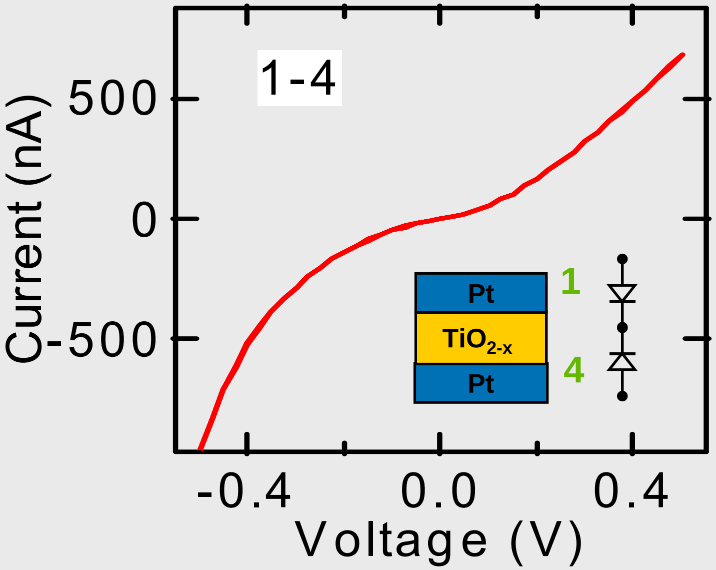
Role of interface: I-V curves



- identical contacts → Symmetric I-V;
- 5nmTi/TiO2→Ohmic contacts (Pads 2,3);
- The single crystal TiO_2 is very conductive;



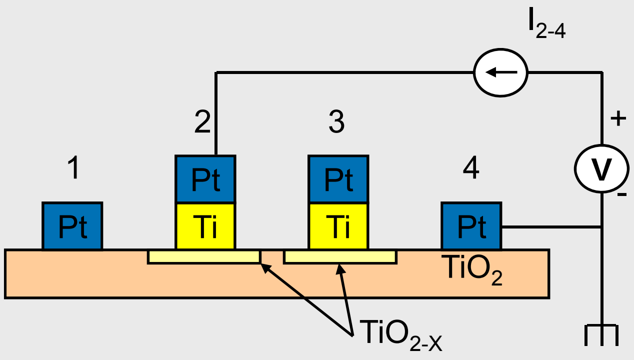


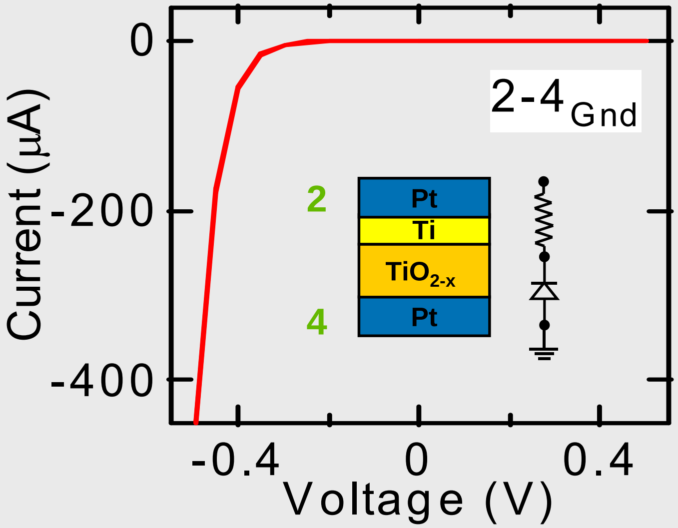


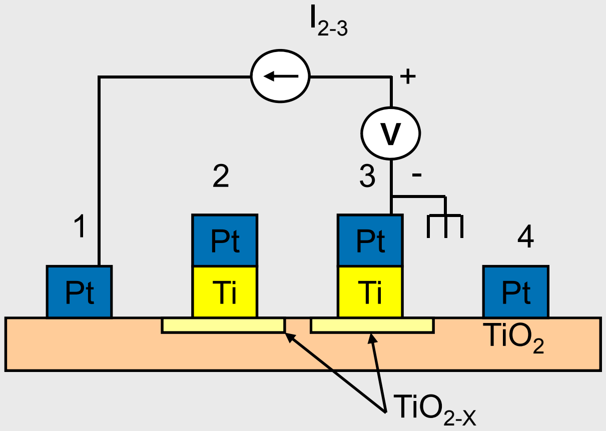
- identical contacts → Symmetric I-V;
- Pt/TiO2→Schottky contact (pads 1,4);
- Interfaces dominates the I-V (bulk TiO_2 contact).

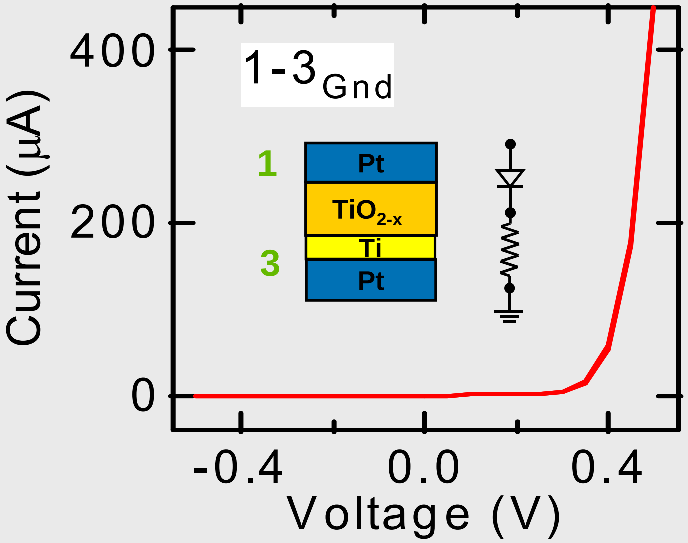
J. Joshua Yang

Role of interface: I-V curves



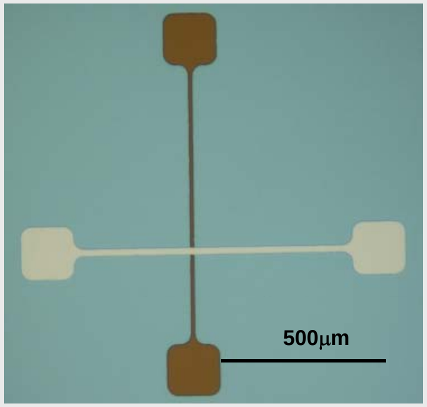


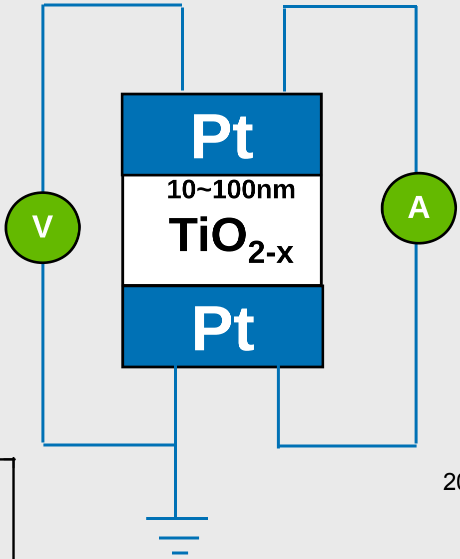




Scalability: from micron- to nano-crosspoint junctions

5x5 micronmeter^2



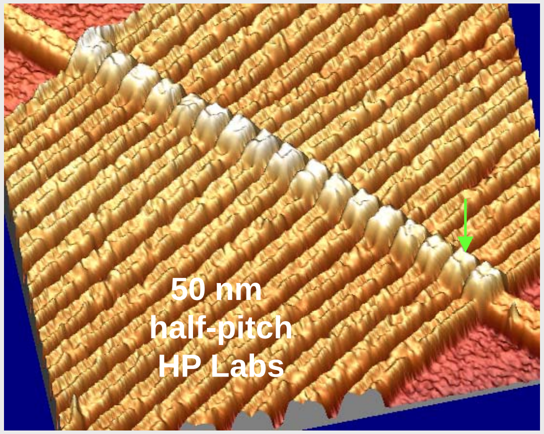

Pt

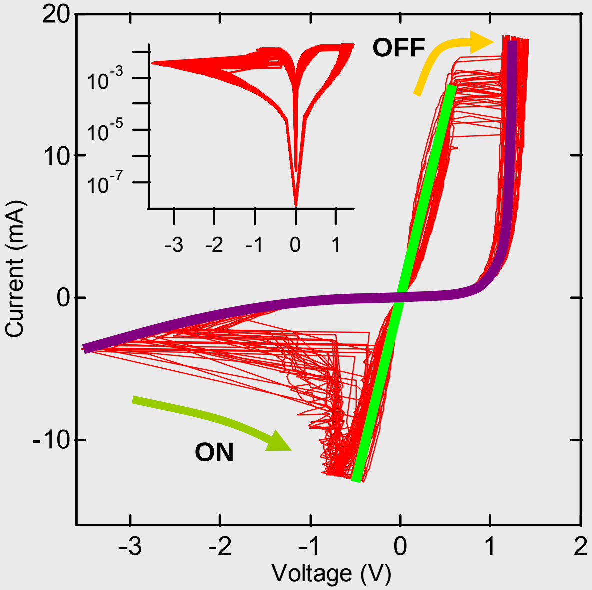
10~100nm

TiO_{2-x}

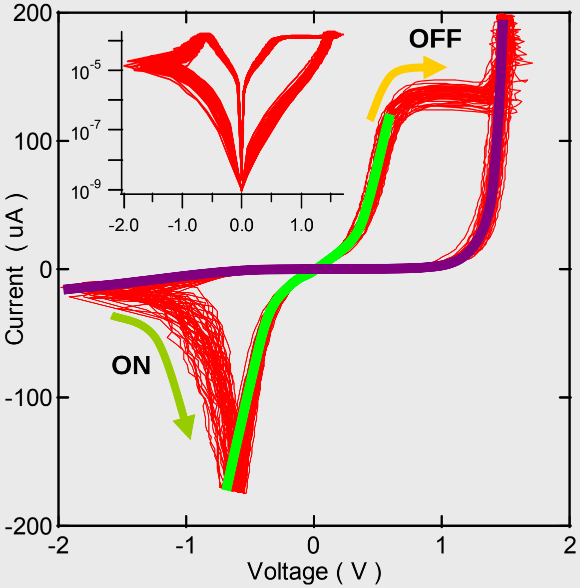
Pt

50x50 nanometer^2





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



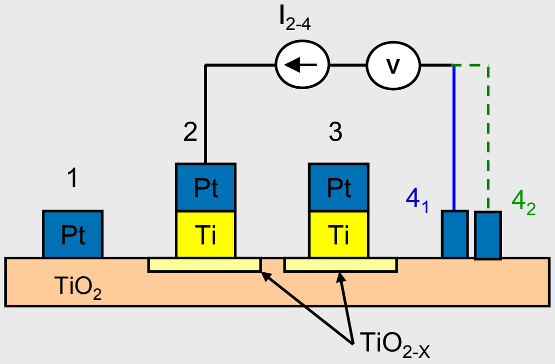
Conclusions

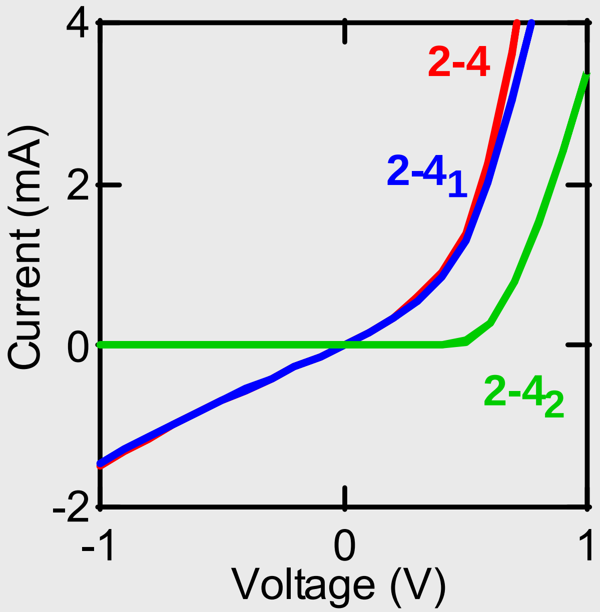
- Dynamic electronics opens up a new class of devices, that can be configured in real time;
- New applications can be found in memory, signal conditioning, etc.

- The end

Switching features: localized or uniform

Question: Is pad 4 uniformly or locally changed?!





3. Localized channels