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Educational, Scientific
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"Workshop on Ion Beam Studies of Nanomaterials:
Synthesis, Modification and Characterization"

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Nanoclusters and -tubes for Swift Heavy Ion Track Electronics (SITE)

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Nanoclusters and -tubes for Swift-Heavy Ion Track Electronics (SITE)

D.Fink, HMI Berlin

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  Latent and etched tracks / etched track filling /applications

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  - TEAMS & TEMPOS

    Cuurent-Voltage characteristics / theory / sensors

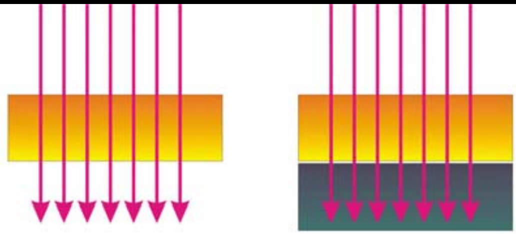
    - Negative differential resistances

      electronic devices / Sterilizing foils / NCs for tailored conductivity / NC architecture

- Nanotubes

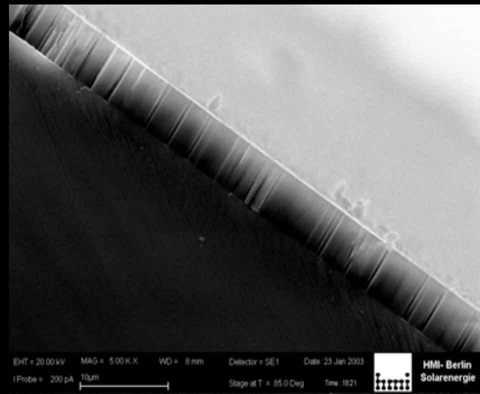
  CNTs in TEMPOS structures / PCVD and thermal CVD / field emission / 3D nanoelectronics

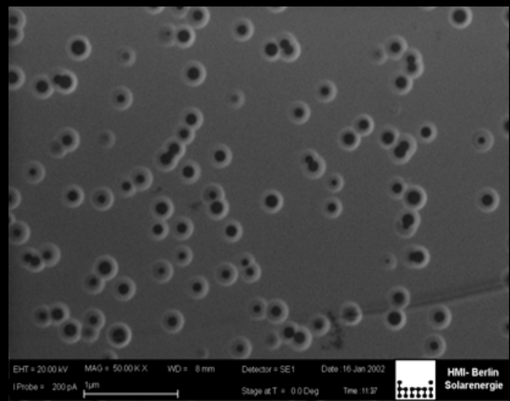
The basic concept of SITE:

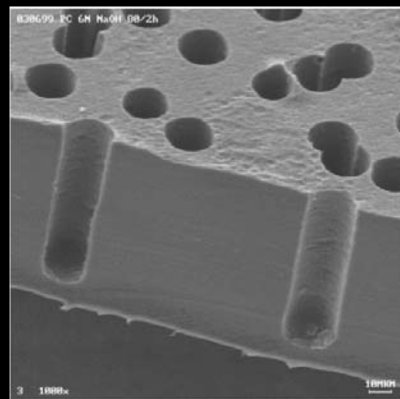


irradiate insulator with swift heavy ions
(carrier-free or on semiconductor substrate)

Etch the latent tracks, fill them with
(semi)conductors, contact both sides







Why Swift Ion Track Electronics (SITE) ?

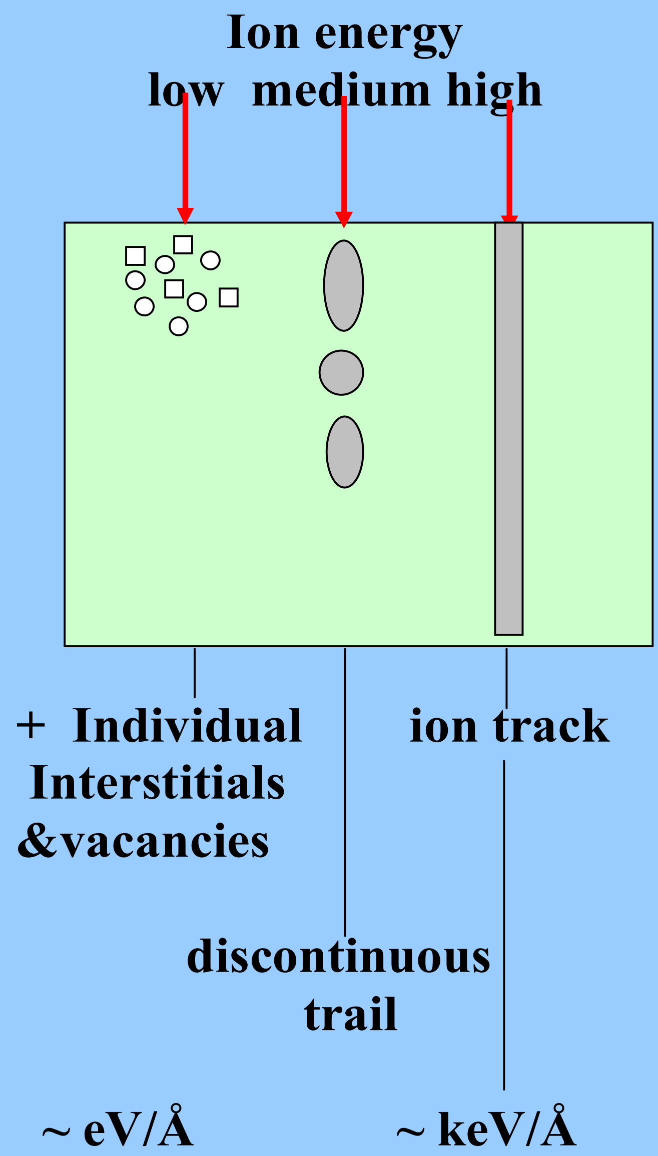
There are at least 4 competing techniques in nanoelectronics:

- **a) self organizing nanostructures**
- **b) nanomanipulations**
- **c) nanolithography**
- **d) molecular electronics**

all these 4 techniques are excellent, but –
a,d) restricted to relatively few systems
b.c,d) very difficult, time consuming and expensive

For contrast, SITE has a number of advantages which make this technique interesting:

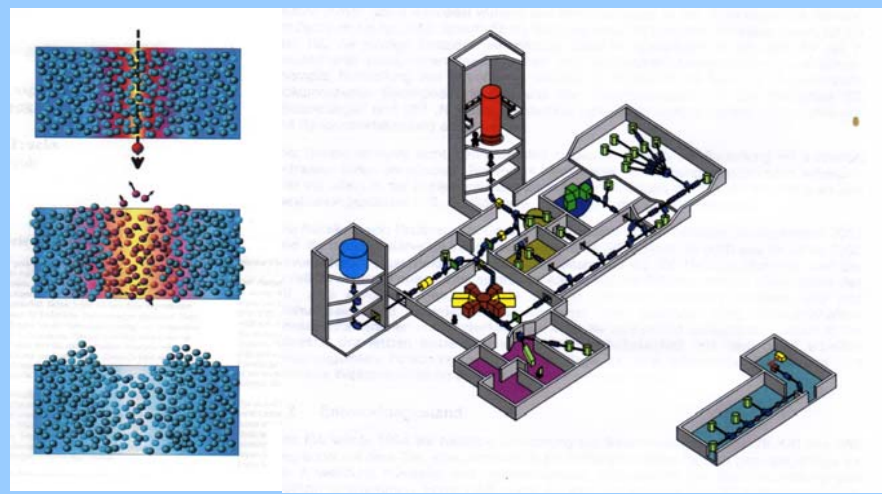
- ***Simple*** ***fast*** ***cheap ($10^{-9...10}$ €/track (for $10^{6...7}$ cm^{-2}))***
- ***precise*** ***light-weight*** ***large area devices (> 1 m x 100 m)***
- ***mechanically flexibile*** ***environmentally friendly***
- ***… and has an extremely high variability in its parameters***



<u>Swift Heavy Ions:</u>

continuous damage
high energy transfer
high aspect ratio
r ≈ nm l ≈ 100 µm
permanent damage
(also recombination)

"latent tracks"



SITE: Great variability in material´s properties

- **Host material for tracks..**insulators, semiconductors
- polym., SiO_2, SiON, organomet., C_{60}, SnO_2,..
- **Substrate…………………...** Self-supporting, Si, glass, metal
- **Track type…………………**latent ←→ etched tracks
- **Track shape………………**conical, cylindrical, funnel-like,..
- **Inner track material……..**metals, semicond., electrolytes
- **Ag, Au, Pd, Ni, C_{60}, CNTs, Phthcy, SnO_2, TiO_2, CdS, organometals, cond. Polymers, nanocomposites,……**
- **Inner track structure…….**wires, fibrilles, nanotubules, nanoclusters, gel, liquid; axially or radially structured
- **Track density……………..**individual or overlapping tracks
- **Applications………………**Passive, active electronic elements
- **resistors, capacitors, inductors, sensors, transformers, diodes, transistors**
- **Peculiarity:………………..**hybrides with Si electronics possible
- **Novel track-specific applications:** TEAMS & TEMPOS

Latent Tracks

Radiochemical changes

Structural changes

Phase Transitions

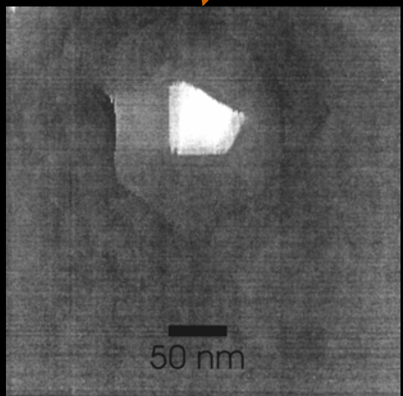
Dangling bonds → sensors

Chem. React. Polysil. → SiC

Rad.induced free volume → incorporate matter

Defects → trap matter

Diam., C_{60} → conducting phases



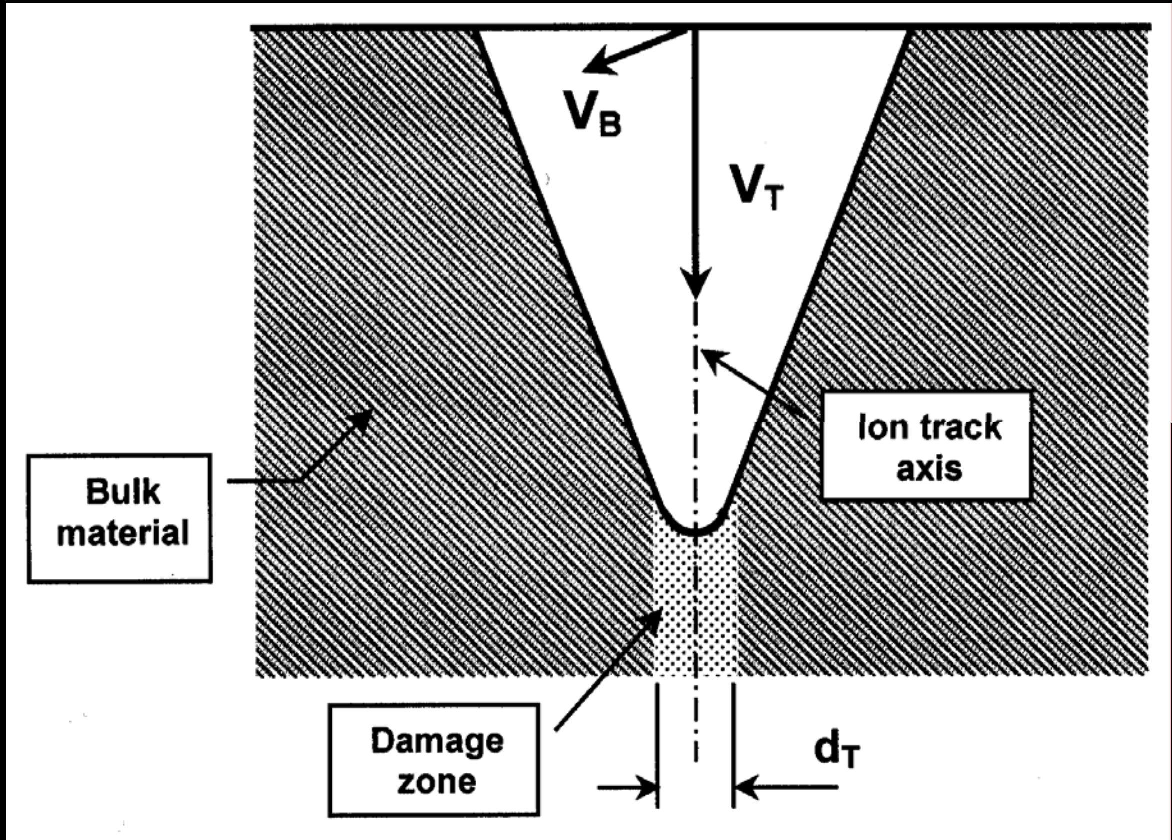
If matter is (semi)conducting → (semi)conducting nanowires

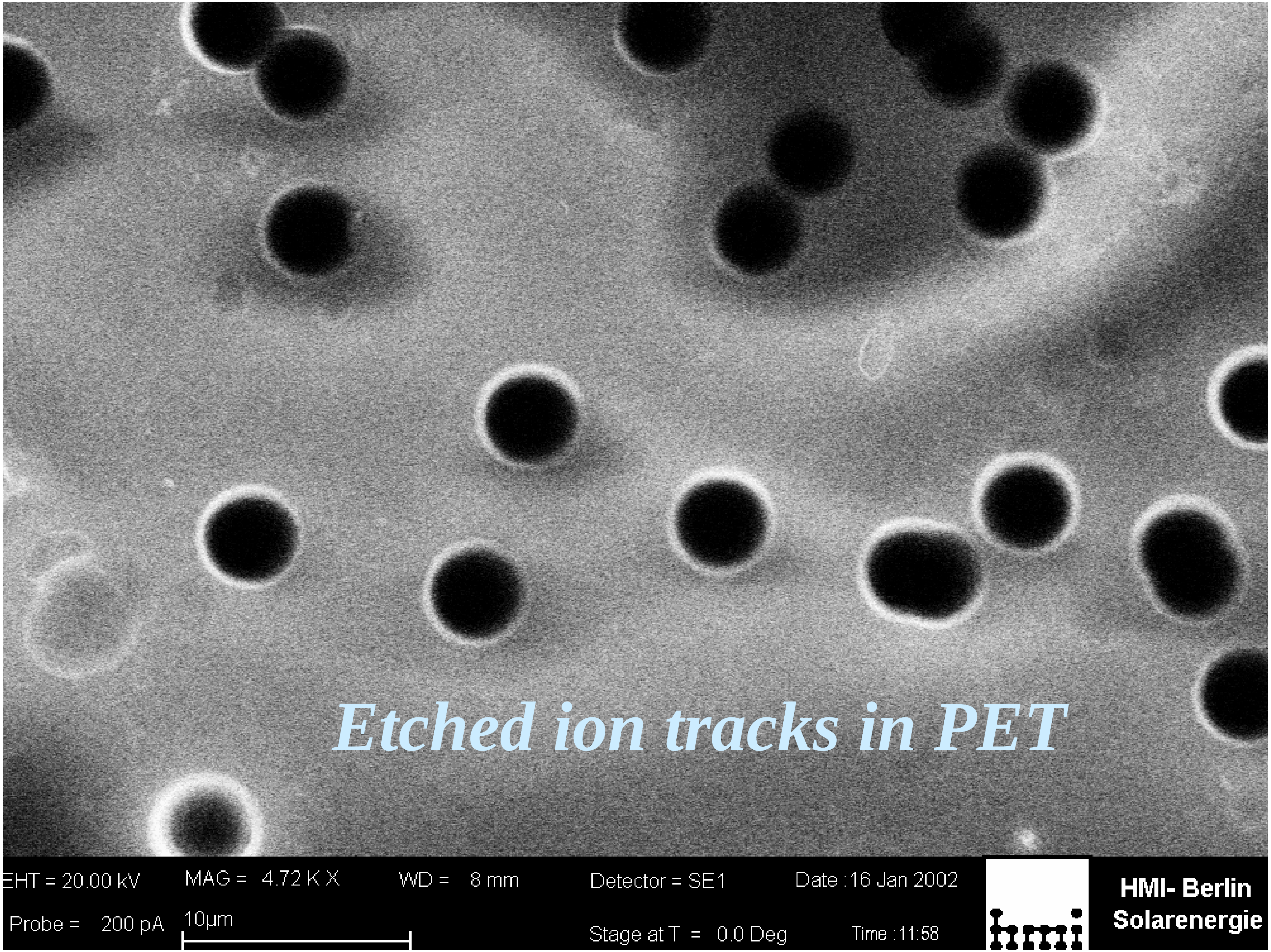
Medium becomes electronically anisotrop

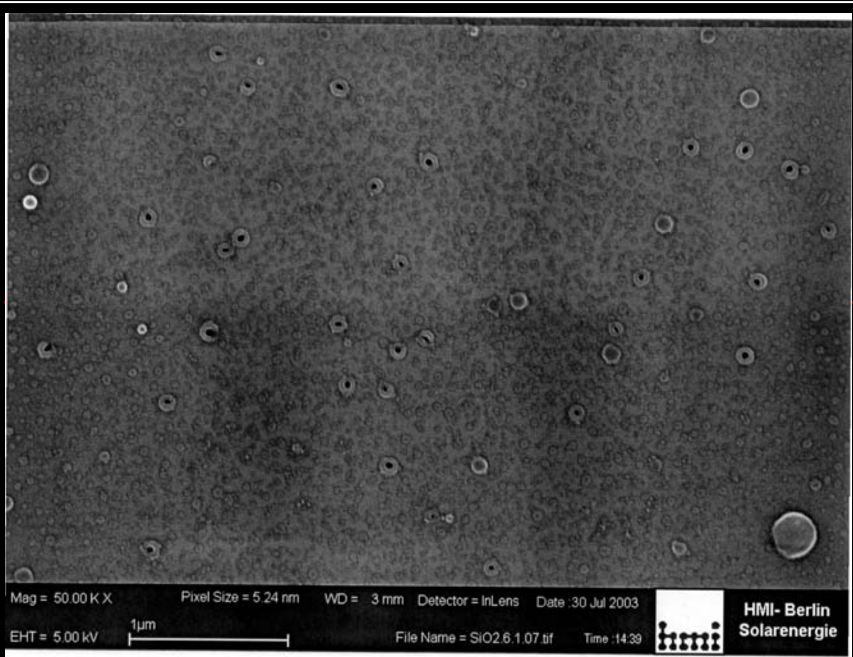
Production of etched tracks

Strong etching enhancement around track

→pore formation

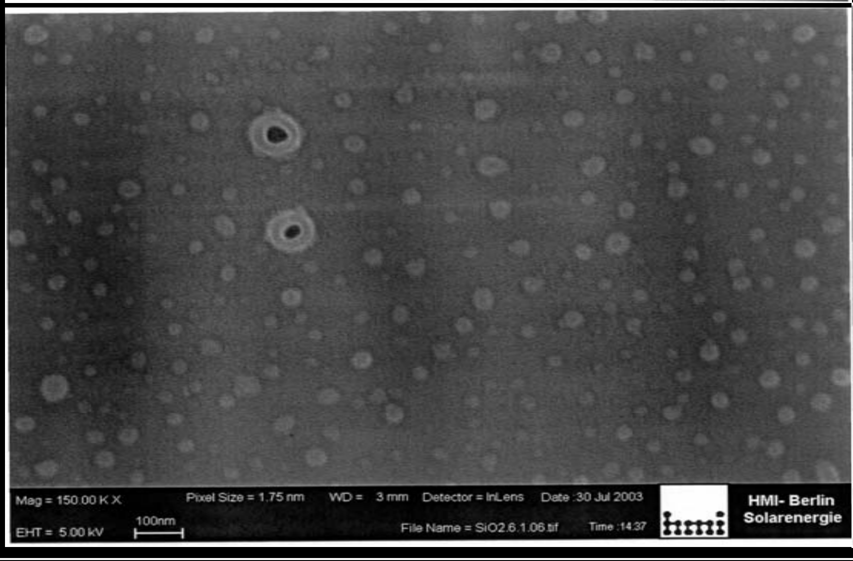


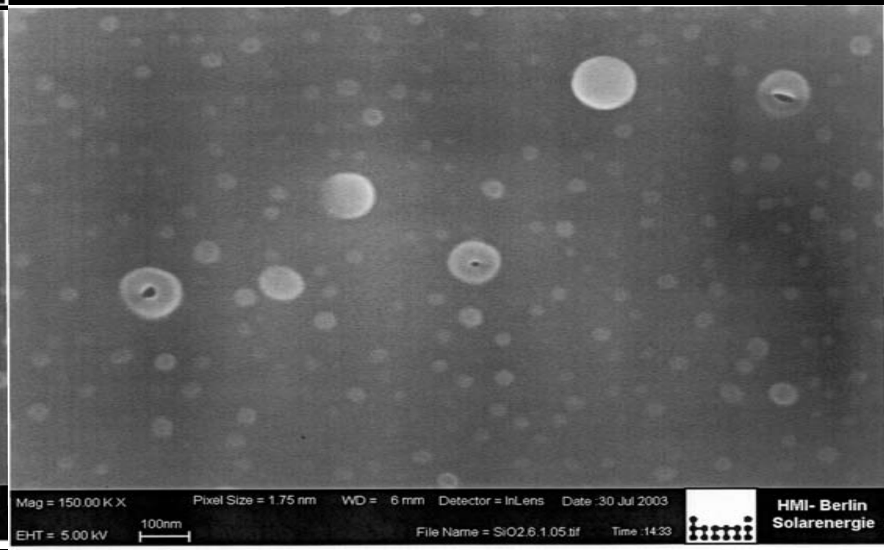

Etched ion tracks in PET
EHT = 20.00 kV
MAG = 4.72 K X
WD = 8 mm
Detector = SE1
Date :16 Jan 2002
Probe = 200 pA
10µm
Stage at T = 0.0 Deg
Time :11:58
HMI- Berlin
Solarenergie

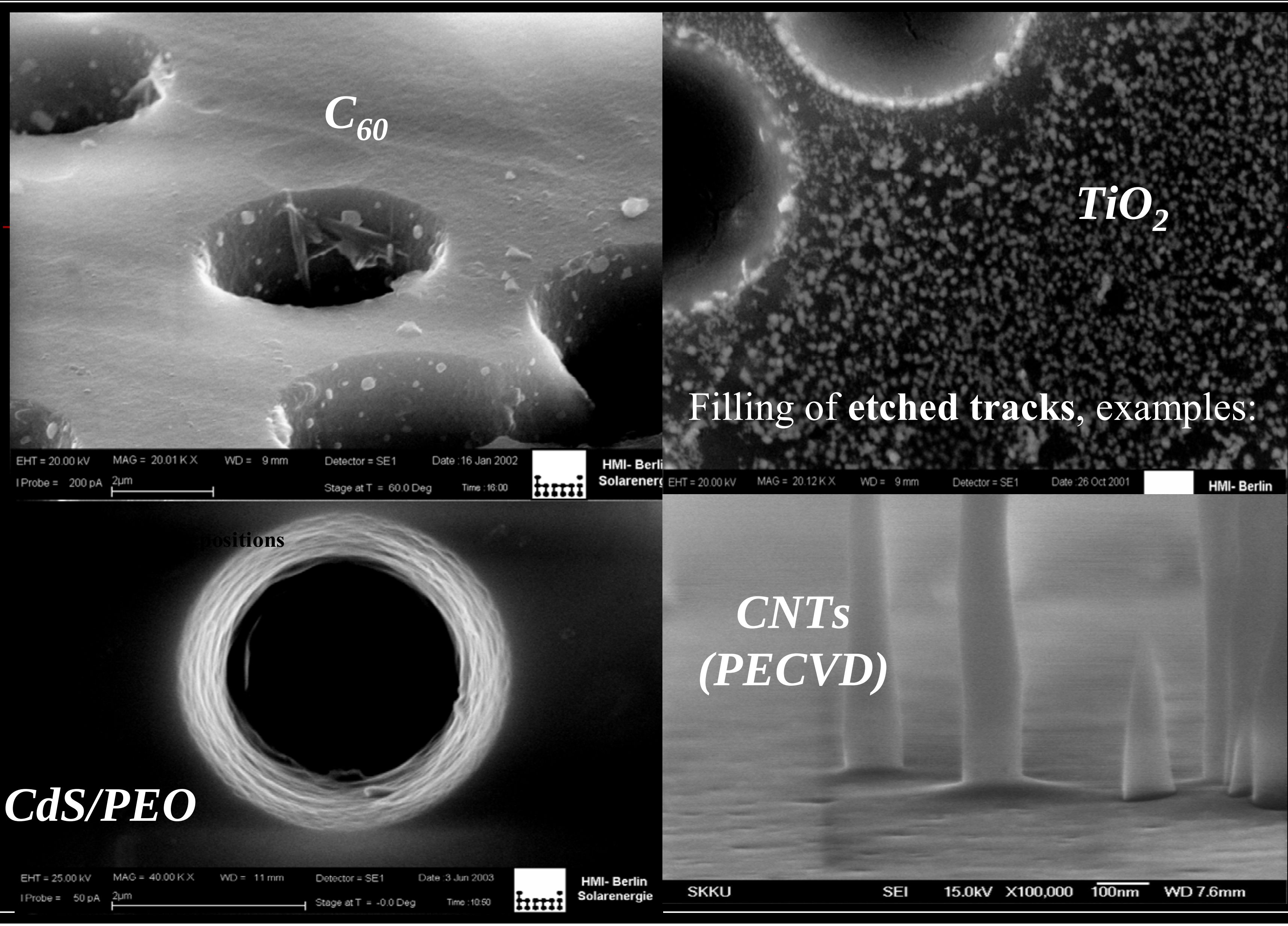


Etching of ion-irradiated SiO_2 surface.

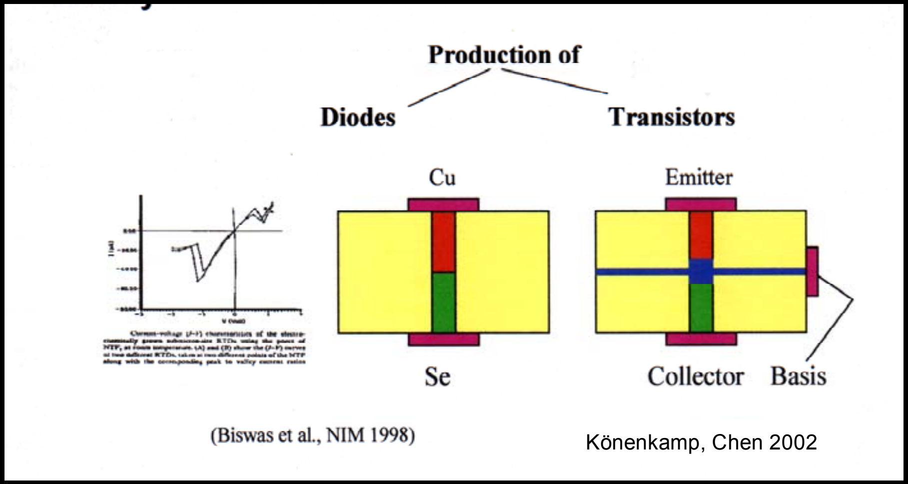
Intrinsic defects yield etch pits, ion tracks yield conical pores.

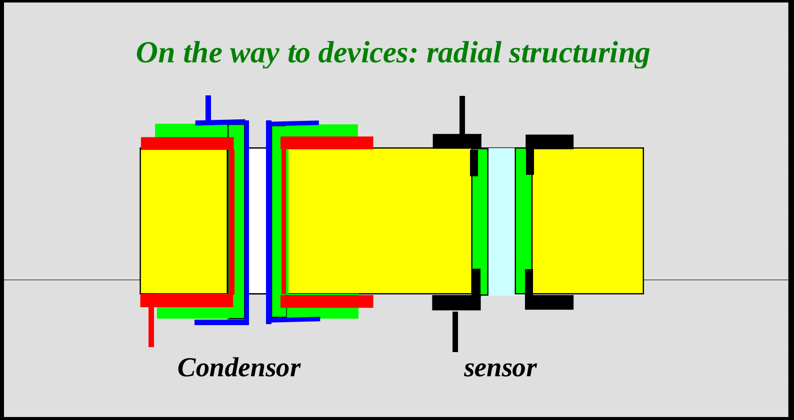


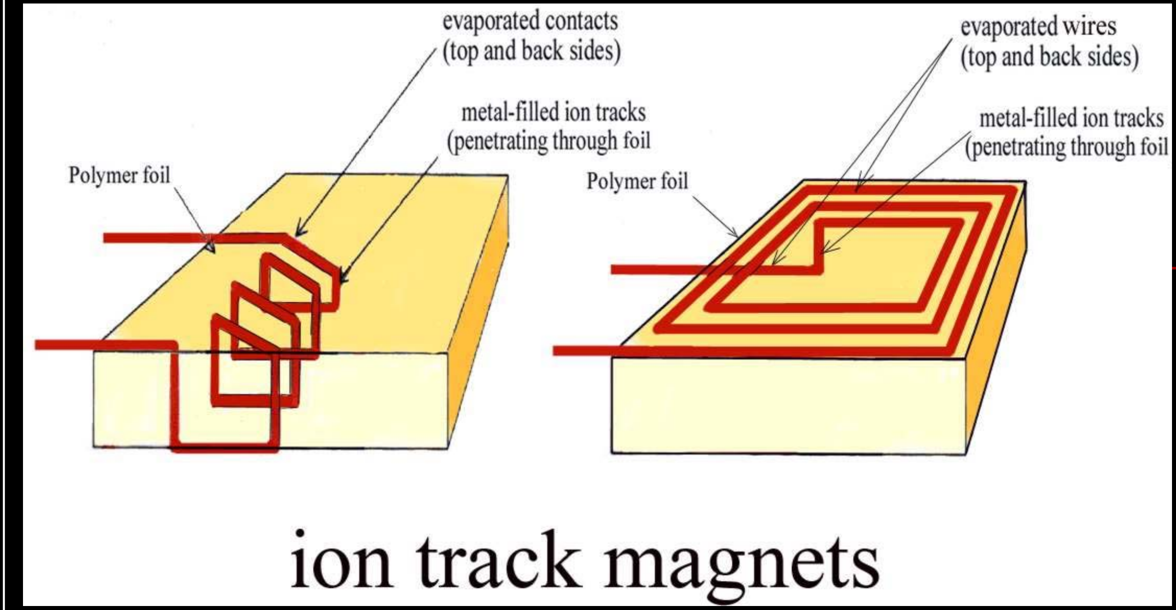


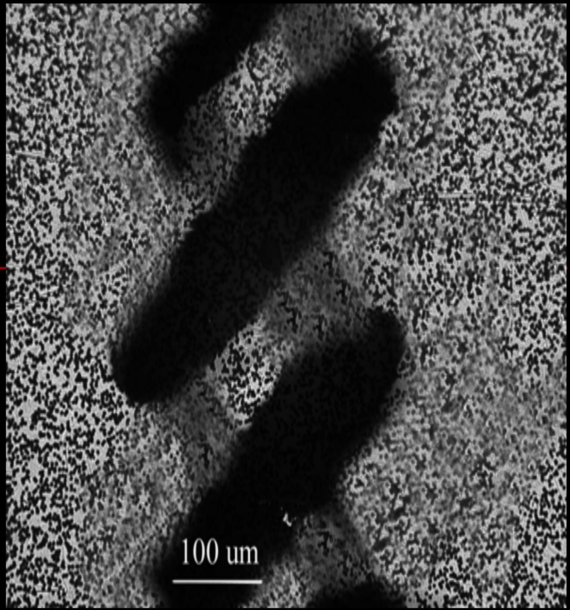

Filling of **etched tracks**, examples:
C60
TiO2
CdS/PEO
CNTs
(PECVD)
EHT = 20.00 kV MAG = 20.01 K X WD = 9 mm Detector = SE1 Date :16 Jan 2002
I Probe = 200 pA 2µm Stage at T = 60.0 Deg Time :16:00
HMI- Berlin
EHT = 20.00 kV MAG = 20.12 K X WD = 9 mm Detector = SE1 Date :26 Oct 2001
HMI- Berlin
EHT = 25.00 kV MAG = 40.00 K X WD = 11 mm Detector = SE1 Date :3 Jun 2003
I Probe = 50 pA 2µm Stage at T = -0.0 Deg Time :10:50
HMI- Berlin
Solarenergie
SKKU SEI 15.0kV X100,000 100nm WD 7.6mm

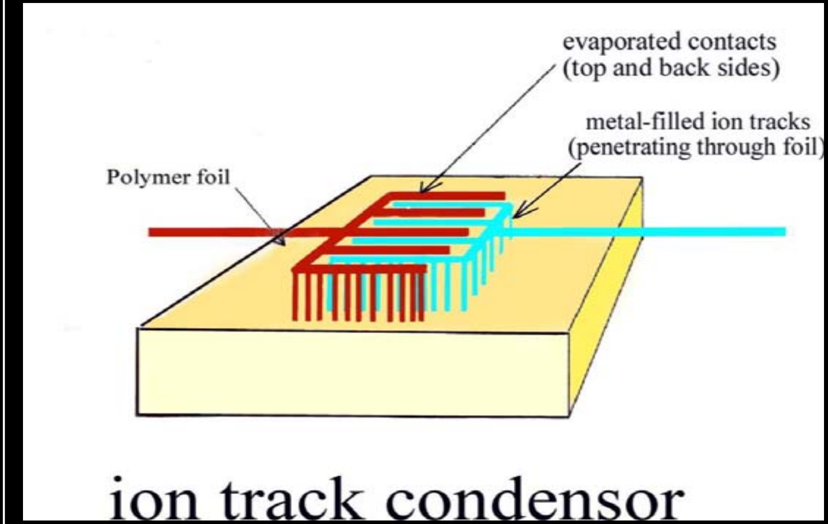
On the way to devices: axially and radially modified structures

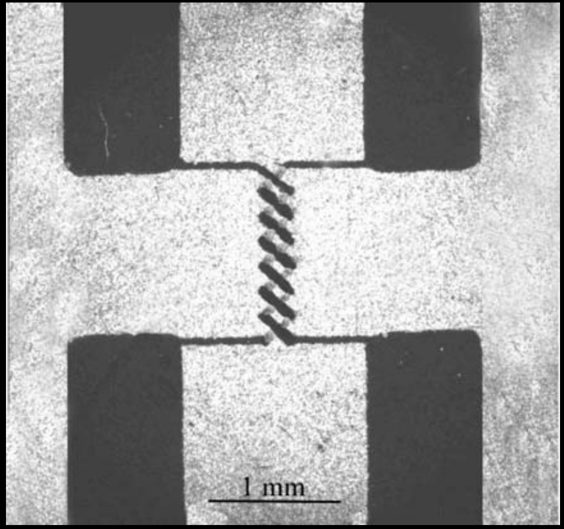


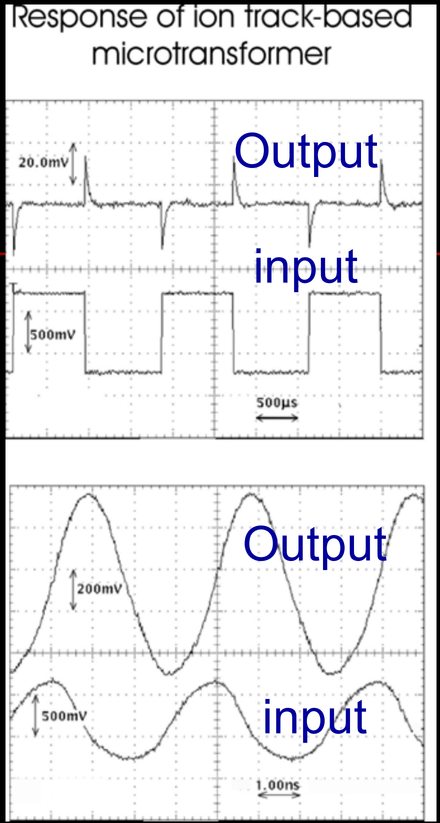



evaporated contacts
(top and back sides)
metal-filled ion tracks
(penetrating through foil
Polymer foil
evaporated wires
(top and back sides)
metal-filled ion tracks
(penetrating through foil
Polymer foil
ion track magnets


100 um

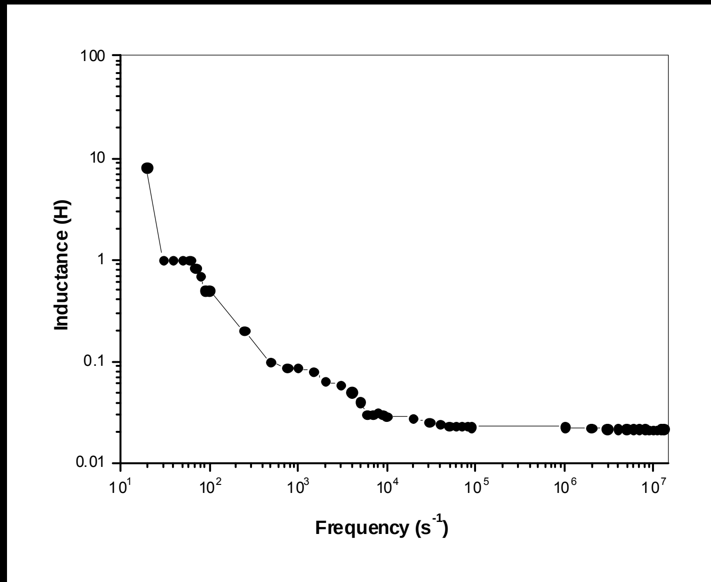

evaporated contacts
(top and back sides)
metal-filled ion tracks
(penetrating through foil)
Polymer foil
ion track condensor


1 mm



Comparison of input and output signals
for rectangular
and sinusoidal iput at various frequencies

Frequency dependence
of the coil
inductivity



Why nanoclusters for SITE?

Microscopic:

- Quantum effects can be exploited

Macroscopic:

- Higher overall surface of NCs
- Conductivity can be tailored:
  well-defined order of magnitude, voltage and temperature dependence
- NCs store a considerable amount of charge
- NCs can be used as „building bricks“ for construction of refined structures t
  conducting nanowires,…

Quantum confinement: single electron transistor

From:
D.K.Ferry, ,M,Goodnick,
Transport in nanostructures, 1977

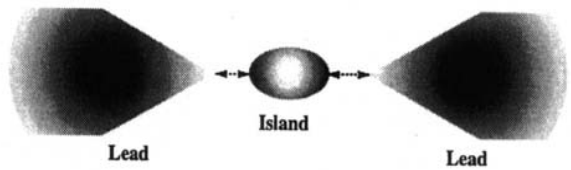
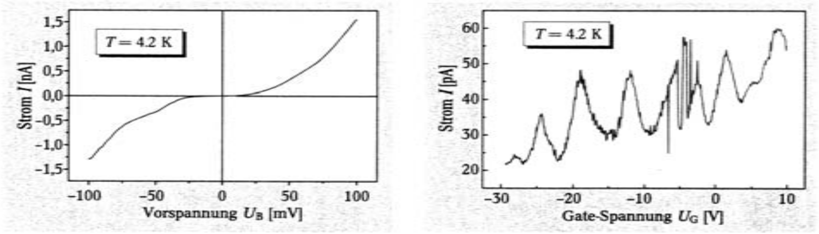
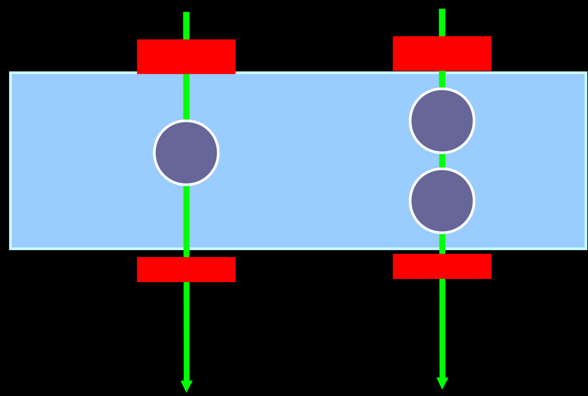
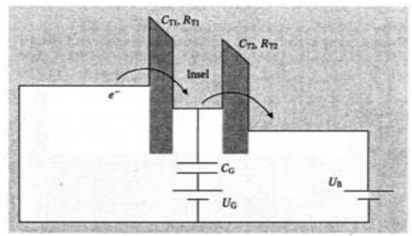


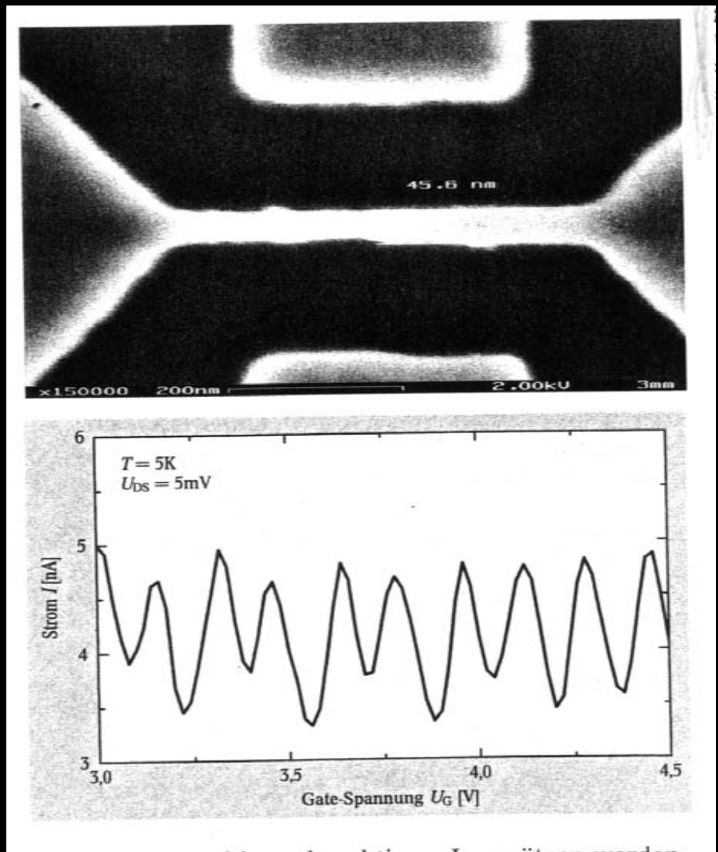
Fig. 4.10. A quantum dot coupled to two leads connected to an external circuit.



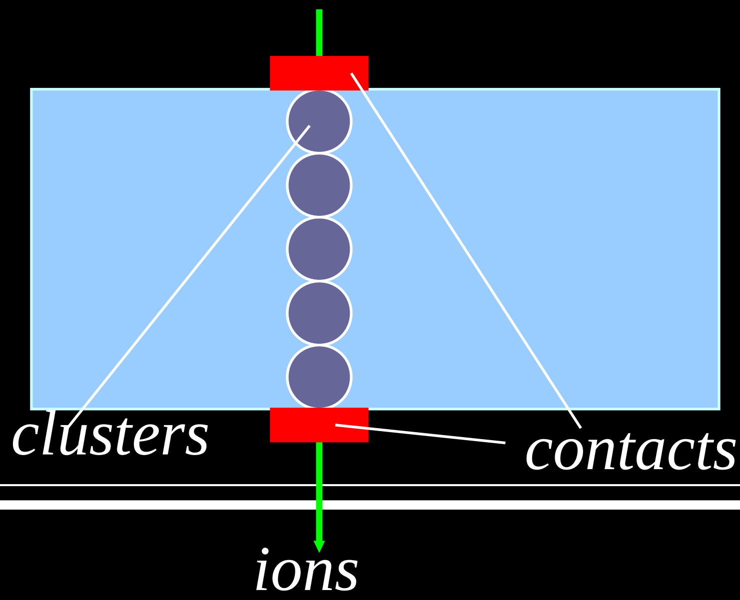




Quantum confinement of narrow wires



Formation of quantum wires by string of closely touching nanoclusters ?



possible realization with ion irradiation:

FET or SET formation by combined –

•High energy irradiation

•Etching

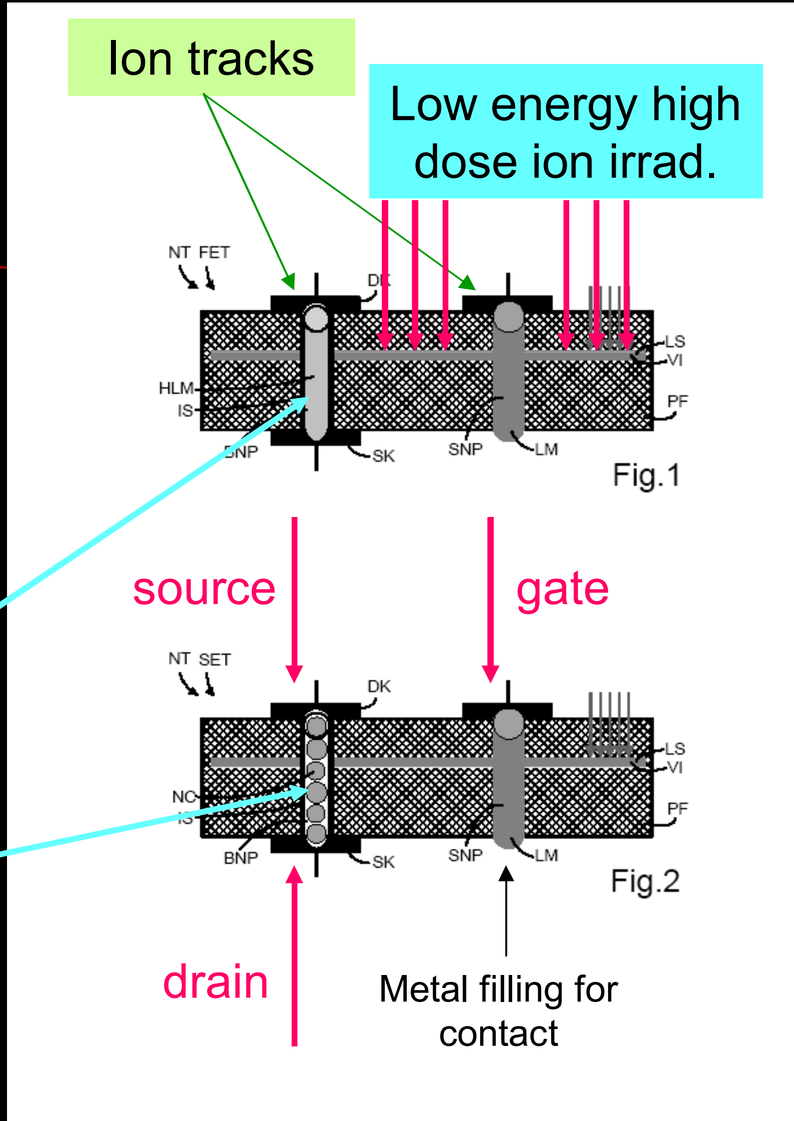
•Deposition

•Low energy irradiation

•contacting

•FETs: homogeneous filling

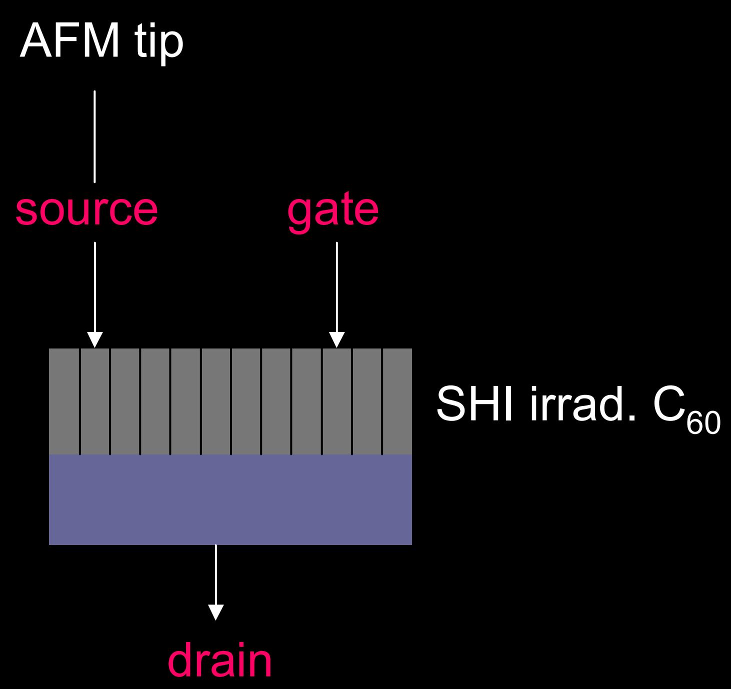
•SETs: nanocluster filling

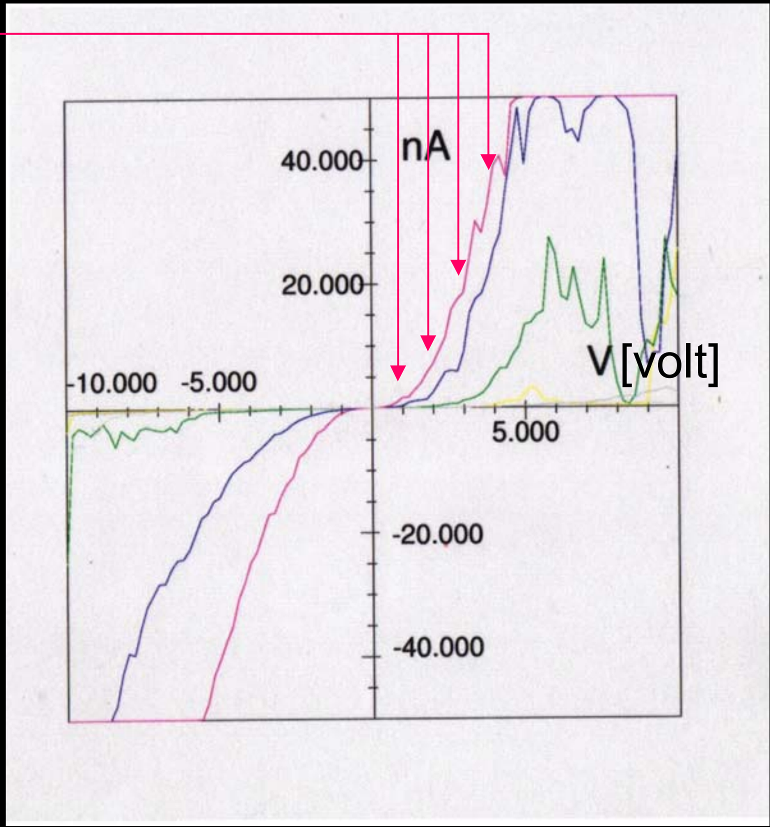


Patent DE10361934.8-33 (2002)

Quantum electronic ion track device, first result:

Small periodic stairs

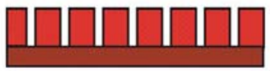




Higher overall surface of NCs:

Active areas of different pore/NC designs

estimations are based on the assumptions of 1 cm^2 large and 10 μm thick foils each, with 5×10^7 pores/cm^2 of cylindrical shape with 1 μm diameter, and with a close packing of TiO_2 nanoparticles with 50 nm diameter on the whole foil surface.

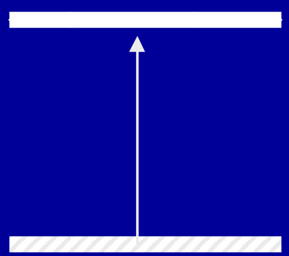
Membrane Arrangement	Massive TiO_2 membrane	TiO_2 fibrilles on a supporting foil	TiO_2 nanoparticles adsorbed to sufaces of microporous foil
Overall photoactive TiO_2 area [cm^2]	2 	15.4 	40.6 

Gas & Water purification by photocatalysis

Destruction of - virusses, bacteriae, fungi, algae
- ethylene gas (= aging hormone)

$$C_2H_4 + 3\,O_2 \xrightarrow[\text{cat.}]{TiO_2} 2\,CO_2 + 2\,H_2O$$

Preferential
Phase: Anatase



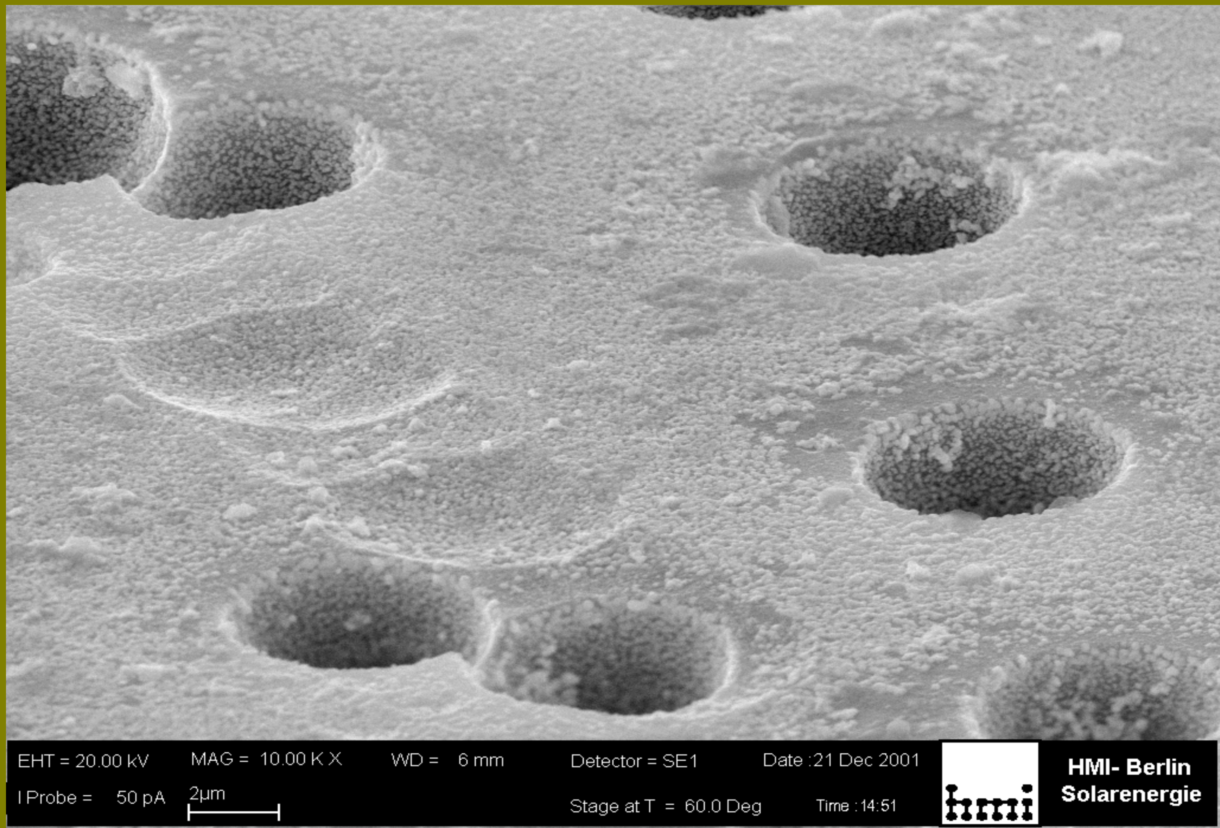
Band gap 3.2 eV

--> λ< 390 nm

Holes diffuse to surface, react with adsorbed H_2O, form there OH^- and H_2O_2 radicals --> atomic O
As E_{pot}(radicals) > E_{bond}(organics)--> destruction

candidates

TiO_2 ,
ZnO,
SnO_2,
$CaTiO_3$,
Fe_2O_3,
MoO_2,
MoS_2,
NbO_5,
CdS,
$KNbO_3$,
$SrTiO_3$,
CdSe,
CdS,
WO_3,
$Ti_xZr_{1-x}O_2$,
SiC



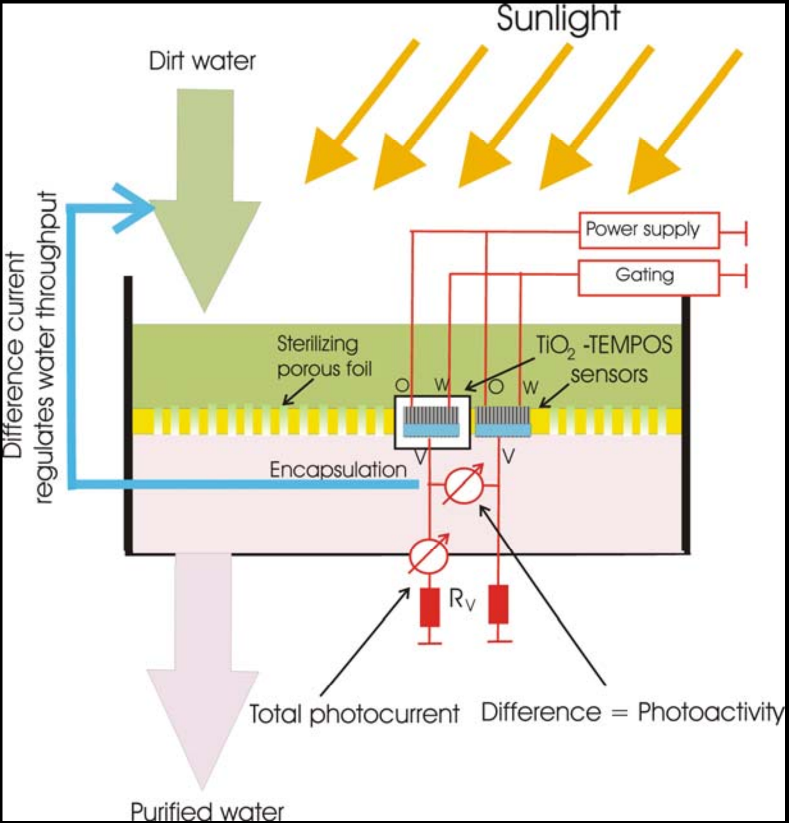
TiO_2 nanoparticles on Ag tubules in track; PI matrix

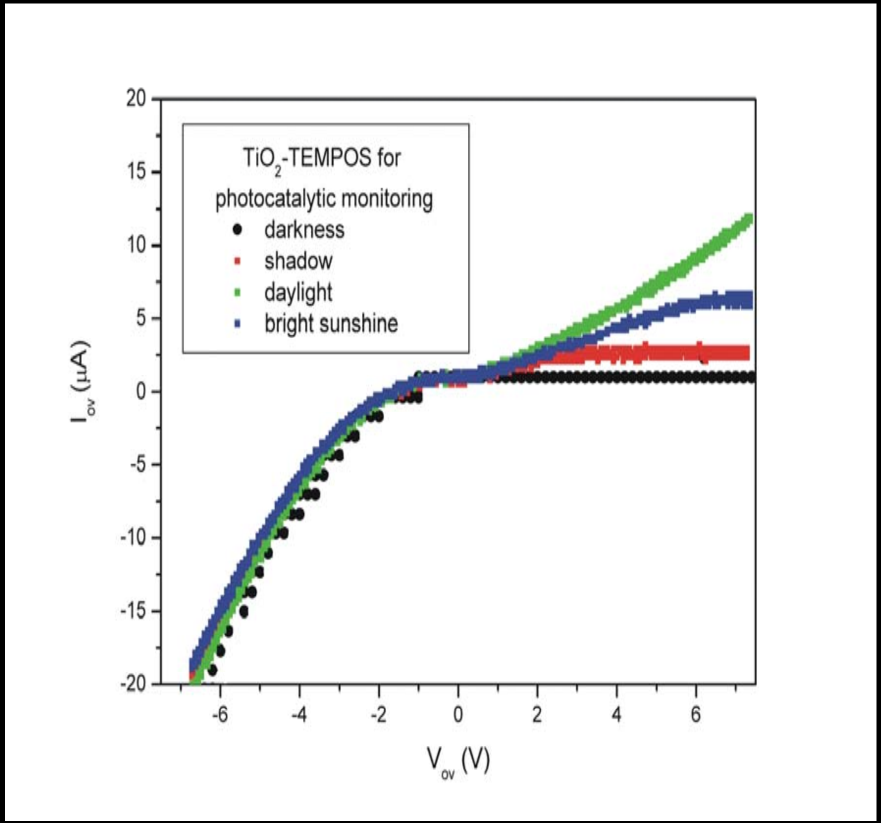
What can be seen are not the nanoparticles, but clusters of them (nanoparticle diameter: 20 nm)

Food sterilization with TiO_2-track-foil

Intelligent solar water purification system

Anatase sensor records the photocatalytical activity of anatase

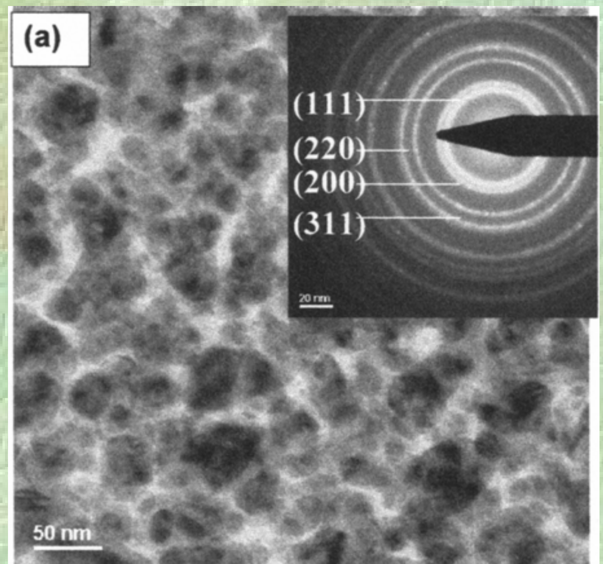


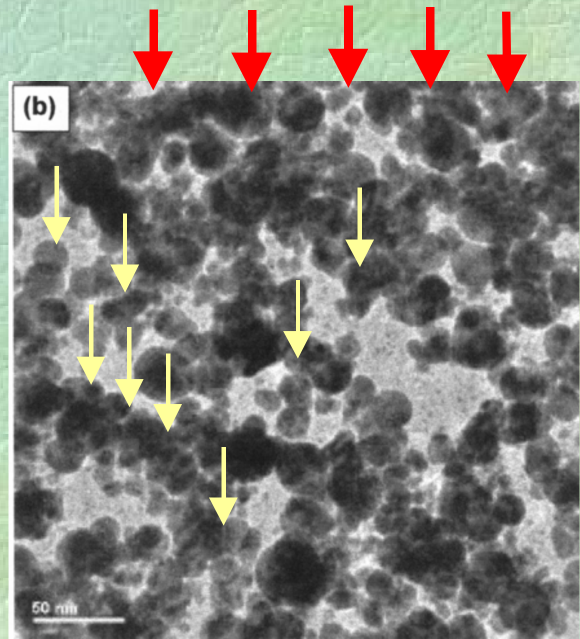


Nanocluster architecture:

nanowire formation by SHI irradiation

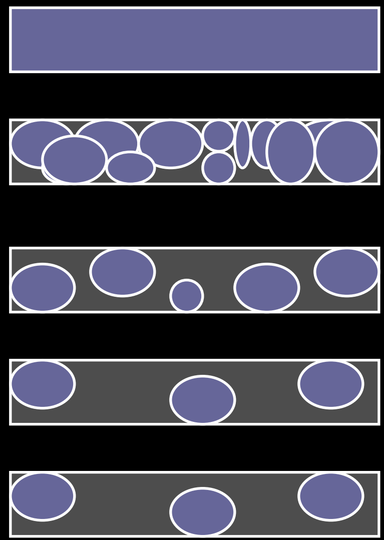
Biswas et al. 2002/2003:
120 MeV Au → Au/Teflon AF





alignment of Au clusters along the ion tracks

Macroscopic properties of dispersed conducting nanoclusters: tailoring of conductivity



Bulk metal		metallic conductivity (Ohmic)
touching clusters		percolation (*grain boundaries)*
small distance		tunneling (*quantum physics)*
larger distances		Schottky emission (*thermal)*
larger distances		field emission *(high fields)*
contaminants, moisture	→	*ionic conductivity*

From: S.M.Sze, Physics of semiconductor devices. John Wiley & Sons, 1981

Basic conduction mechanism in insulators

for a supposed MIS (metal-insulator-semiconductor) arrangement.

Process Name	Description
Schottky emission	Thermionic emission
Frenkel-Poole emission	Field-enhanced thermal excitation of trapped electrons into the conduction band
Tunnel or field emission	Field ionization of trapped electrons into the conduction band, or by electron tunneling from the metal Fermi energy into the insulator conduction band
Space-charge limited current	carrier injection into the insulator, where no compensating charge is present
Poole-Frenkel, Gill	Current is carried by thermally excited electrons hopping from one isolated state to the next
Ohmic conduction	Migration of electrons
Ionic conduction	Diffusion of ionic charge carriers

From: S.M.Sze, Physics of semiconductor devices. John Wiley & Sons, 1981

Quantitative relations for various conduction mechanisms

Process	Voltage and temperature dependence
Schottky emission	$\sim T^2 \exp(c_1\sqrt{V}/T - c_2/T)$
Frenkel-Poole emission	$\sim V \exp(2c_1\sqrt{V}/T - c_2/T)$
Tunnel or field emission	$\sim V^2 \exp(-c_3/V)$; temperature indep.
Space-charge limited current	$\sim V^2$; temperature indep.
Poole-Frenkel, Gill	$\sim \exp(V^{1/2} / T)$
Ohmic conduction	$\sim V \exp(c_4/T)$
Ionic conduction	$\sim V \exp(c_4/T)$

The c_i are coefficients containing information about the barrier height, insulator dynamic permittivity, effective charge carrier mass, insulator thickness, and/or the activation energy of the charge carriers, respectively.

From: S.M.Sze, Physics of semiconductor devices. John Wiley & Sons, 1981

Tailoring of nanowire properties by aligning (semi)conducting nanoclusters along latent or etched tracks

A possible recipe:

Bring nanoparticles into solution as colloides by attaching to them hydrophile ligands, let the solution dry within the tracks

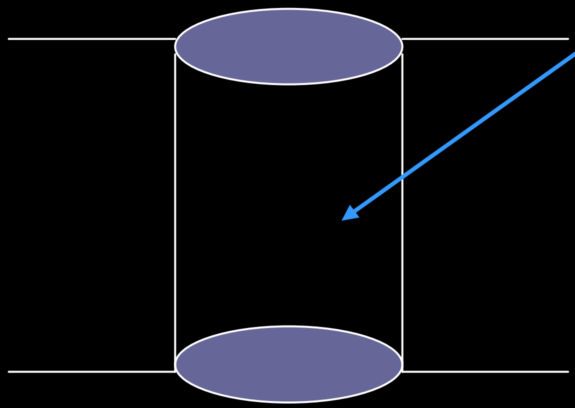
Other recipe:

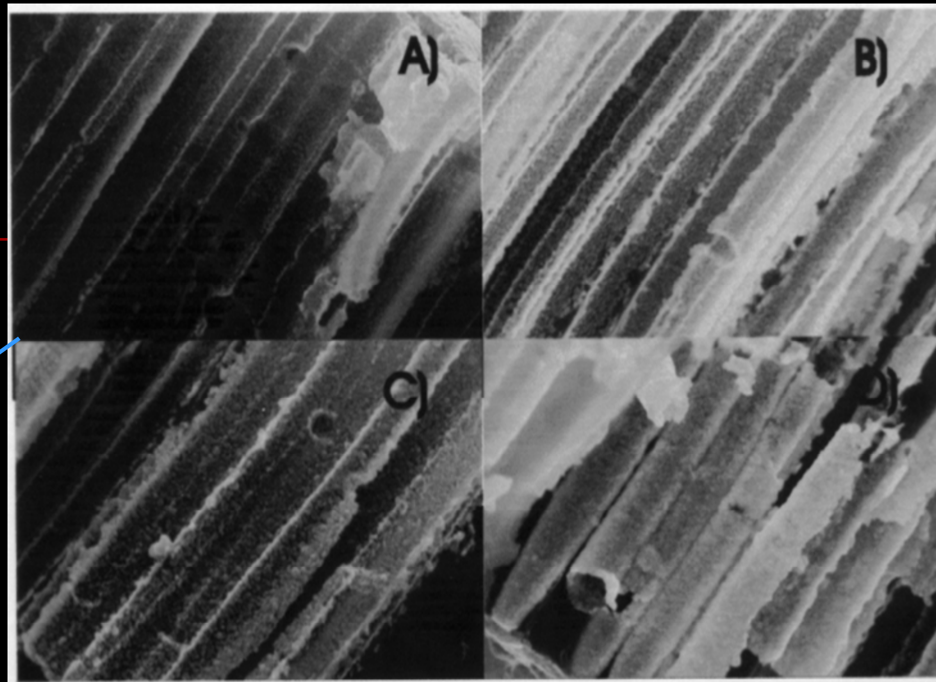
let a solid precipitate from solution at preferred nucleation centers; interrupt the precipitation process in a very early stage

Examples verified by us:

$LiNbO_3$, SiO_2, TiO_2, Cu, Ag, Au, Ni, Pd, CdS, PbS, …

Time dependence of chemical deposition of Ag

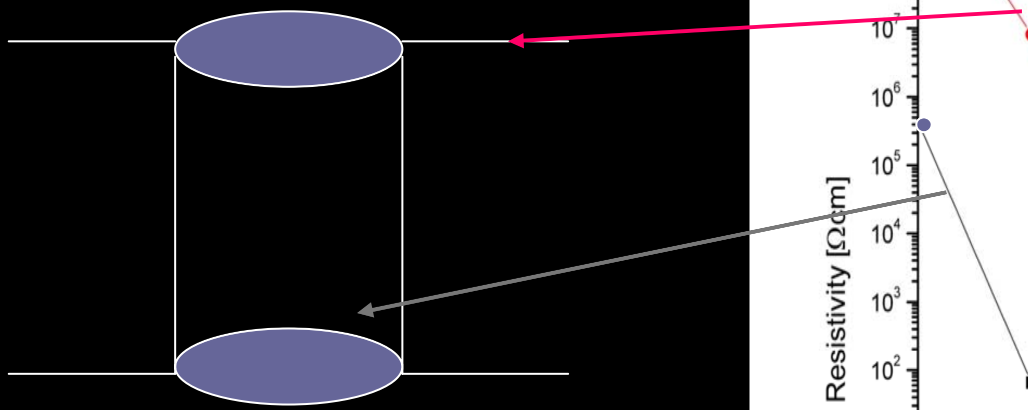


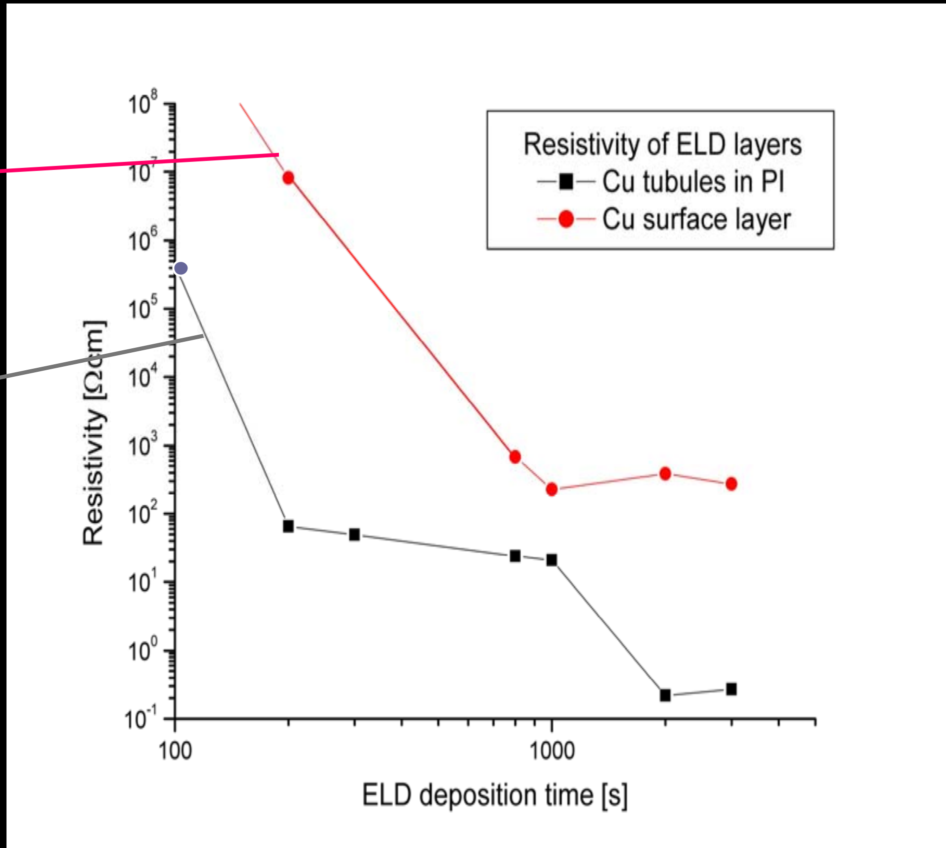


Ag nucleation on $SnCl_2$ pretreated etched tracks
a) 1 min, b) 2 min, c) 5 min, d) 10 min exposure
1 µm

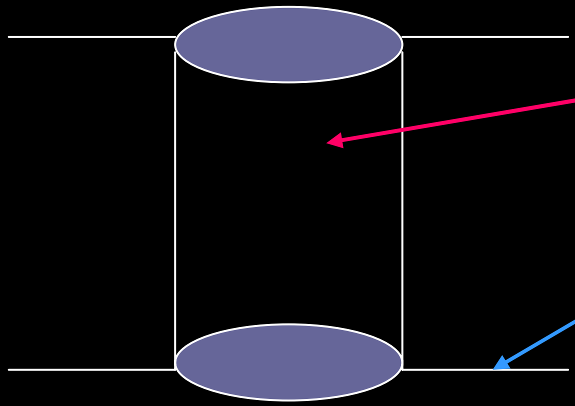
A	**first deposition on nucleation centers**	**< 10 nm**
B	**monolayer of metallic clusters**	**~ 20 nm**
C	**clusters touch each other**	**~ 50 nm**
D	**mechanically stable tubule**	**> 50 nm**

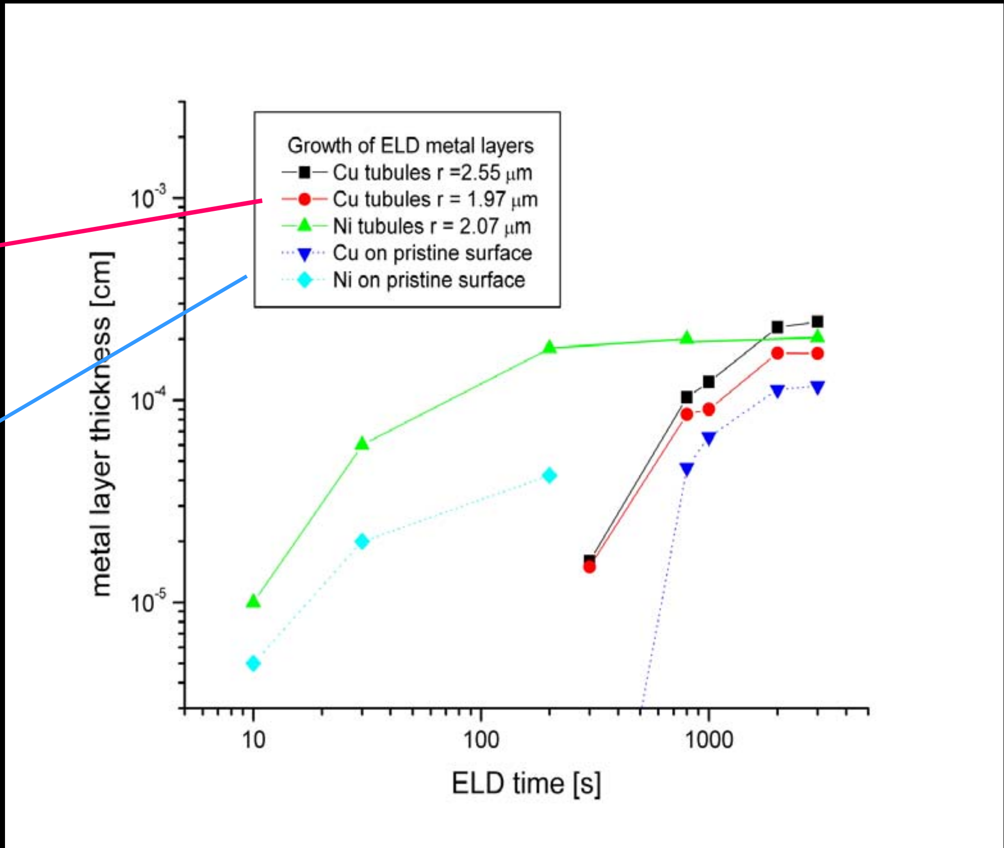
Time dependence of chemical deposition of Cu nanoclusters



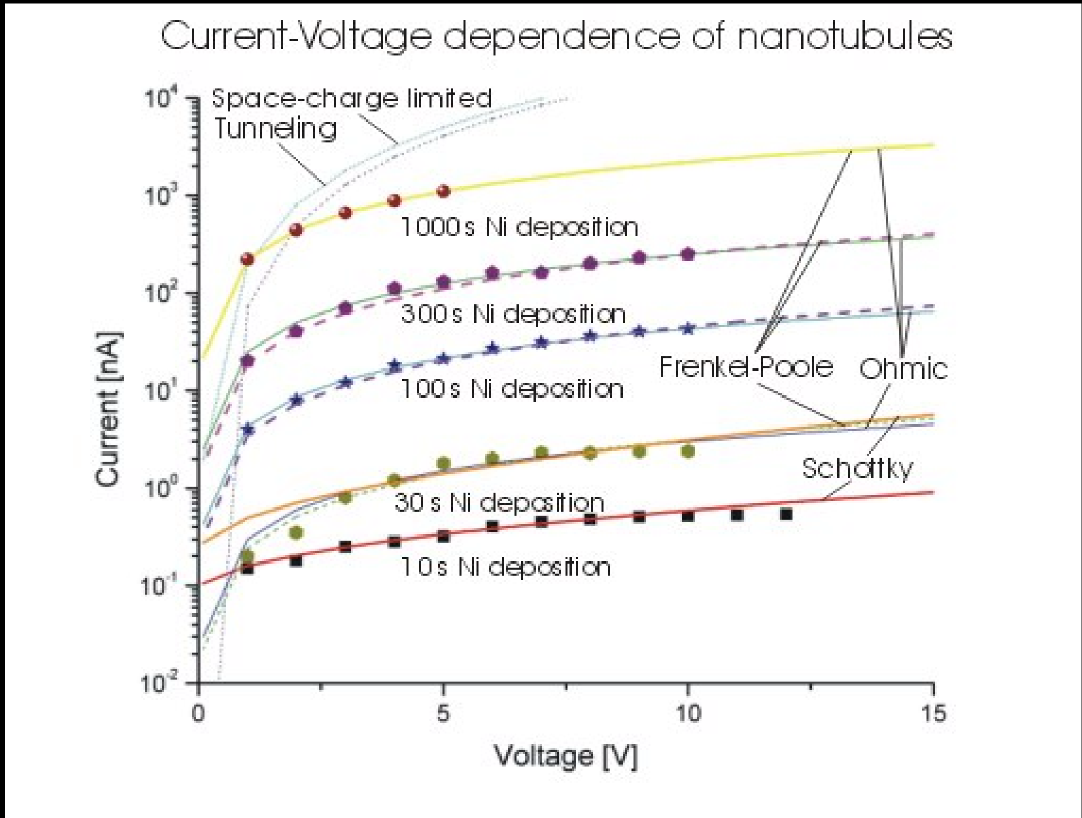


Time dependence of chemical deposition of Cu and Ni nanoclusters





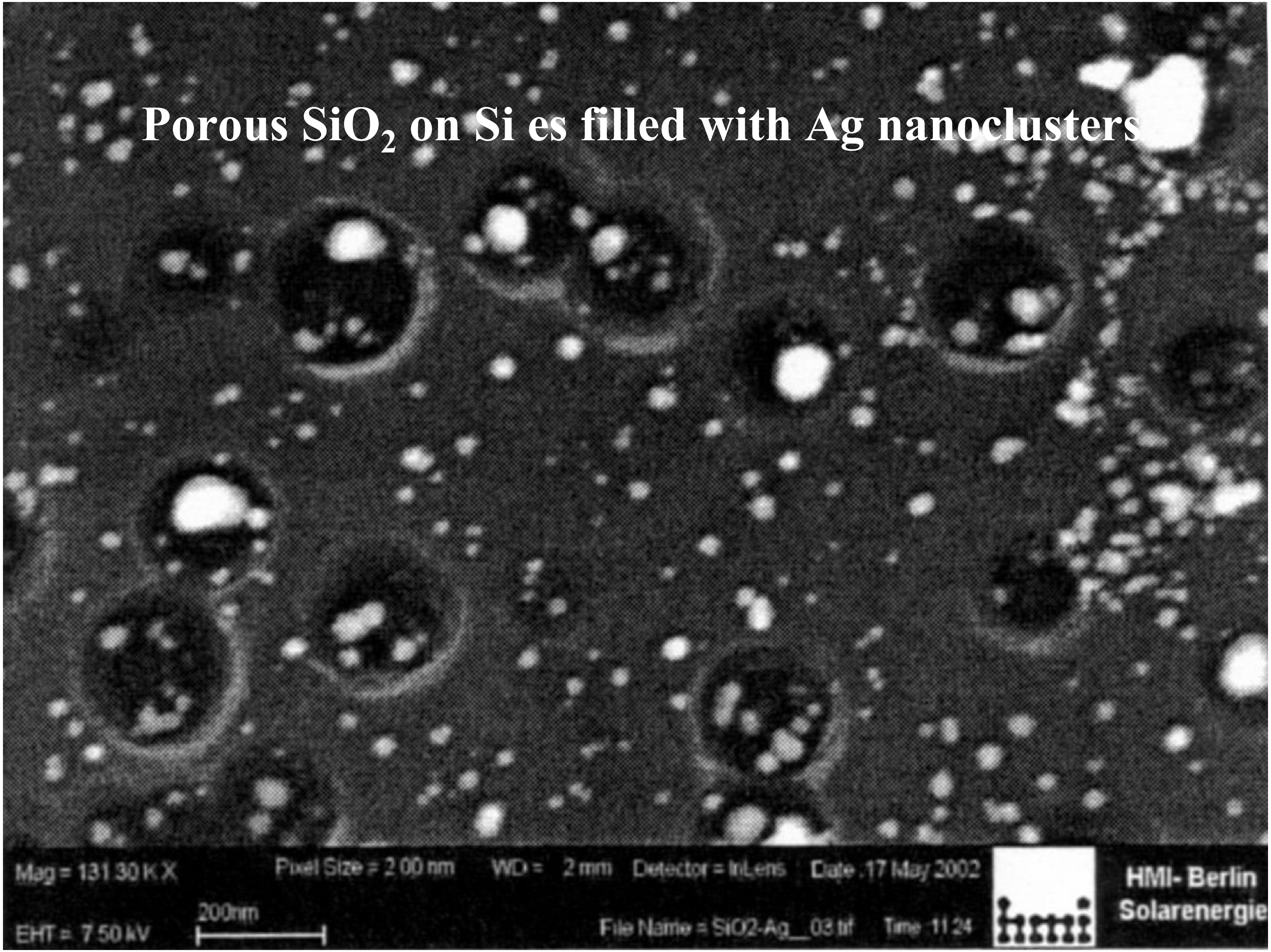
Current/voltage relations

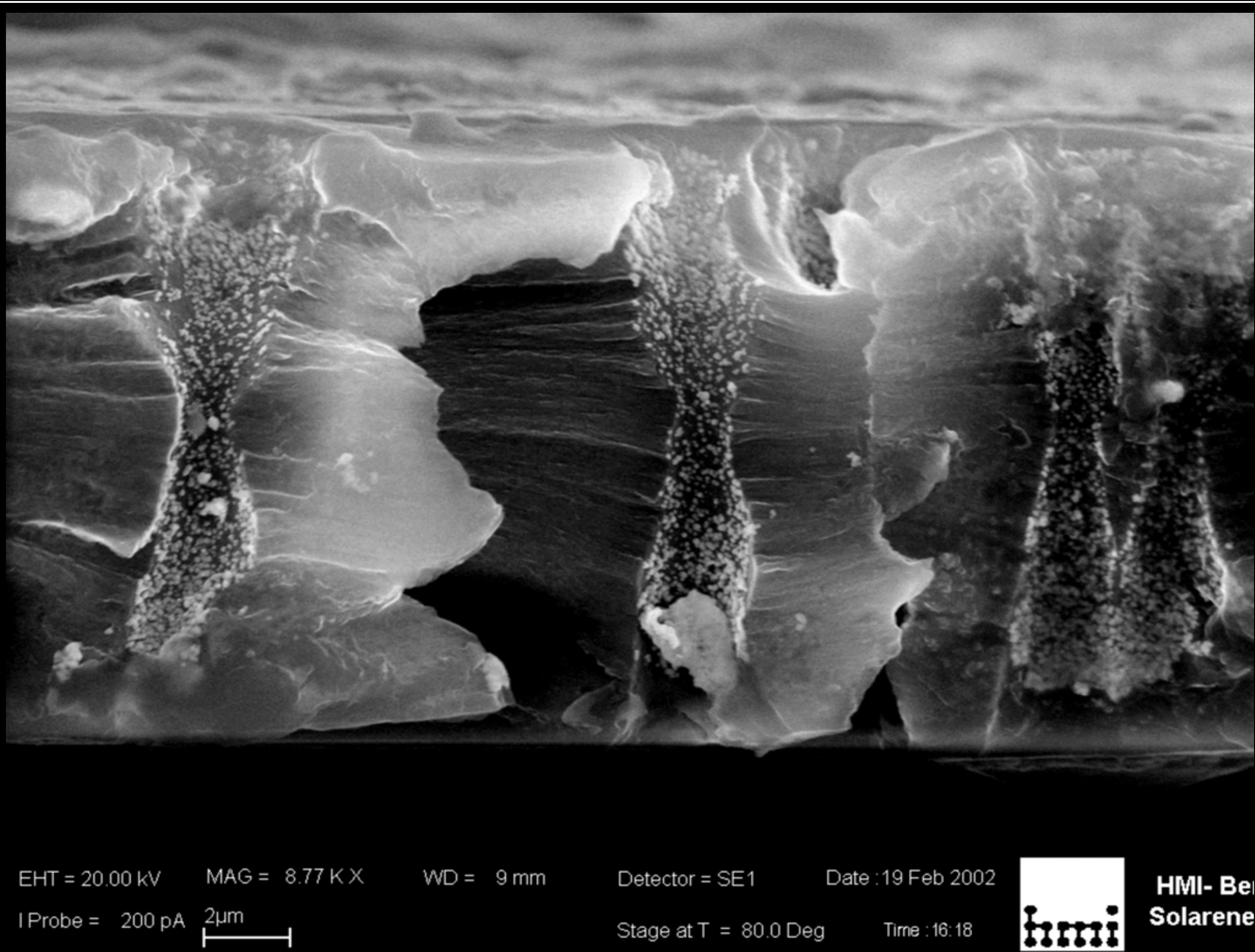


The current/voltage characteristics of Ni-filled micropo- rous PET foils, as compared with se-veral conduction theories. Conduc-tivity values mea-sured along the ion track directions (i.e. through the foils).

10 s: Schottky emission
≥ 30 s: Ohmic conduction

Porous SiO_2 on Si es filled with Ag nanoclusters





Ag nanoclusters in etched tracks in polyimide

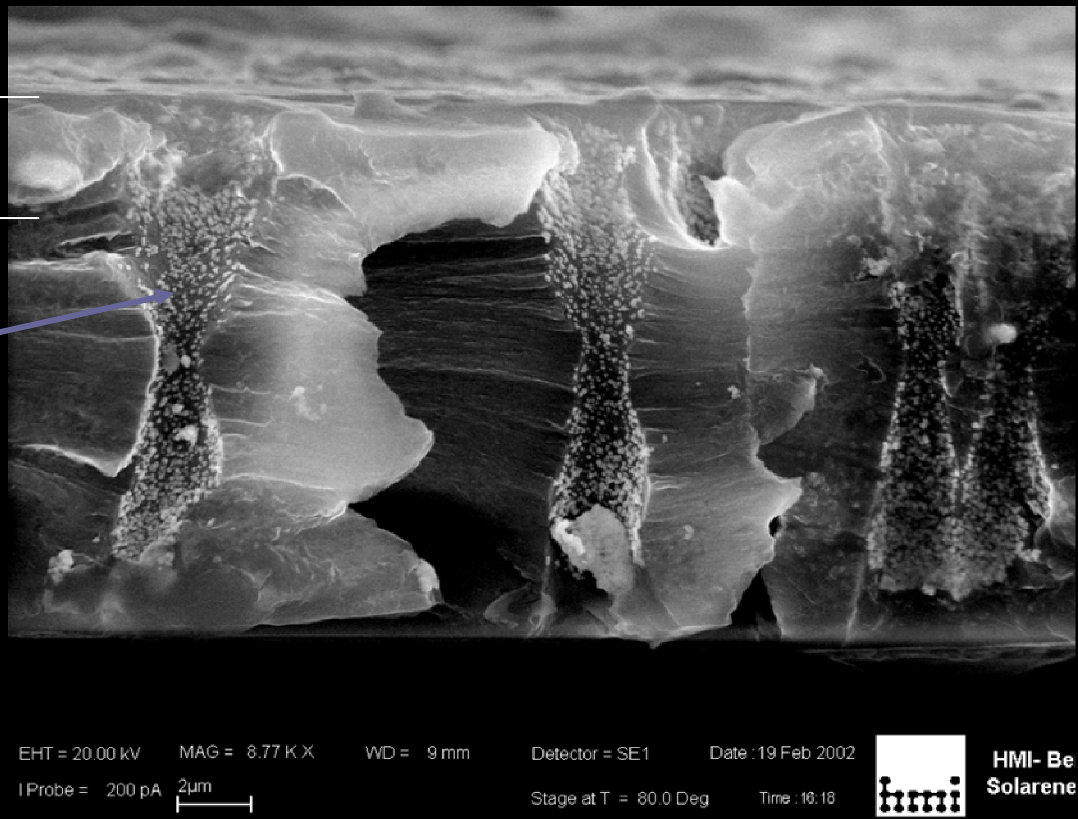
Important: the role of nucleation centers

Nucleation center formation by physics or chemistry

mechanical, Laser, energetic ion irradiation   *metal atoms bond to substrate*

Ion range

Intrinsic defects act as nucleation centers



Nanoparticle architecture: tailoring of nanocluster parameters

Distribution

density

size

in case of nucleation center formation by ion irradiation:

Ion beam position

deposited energy density

deposition time

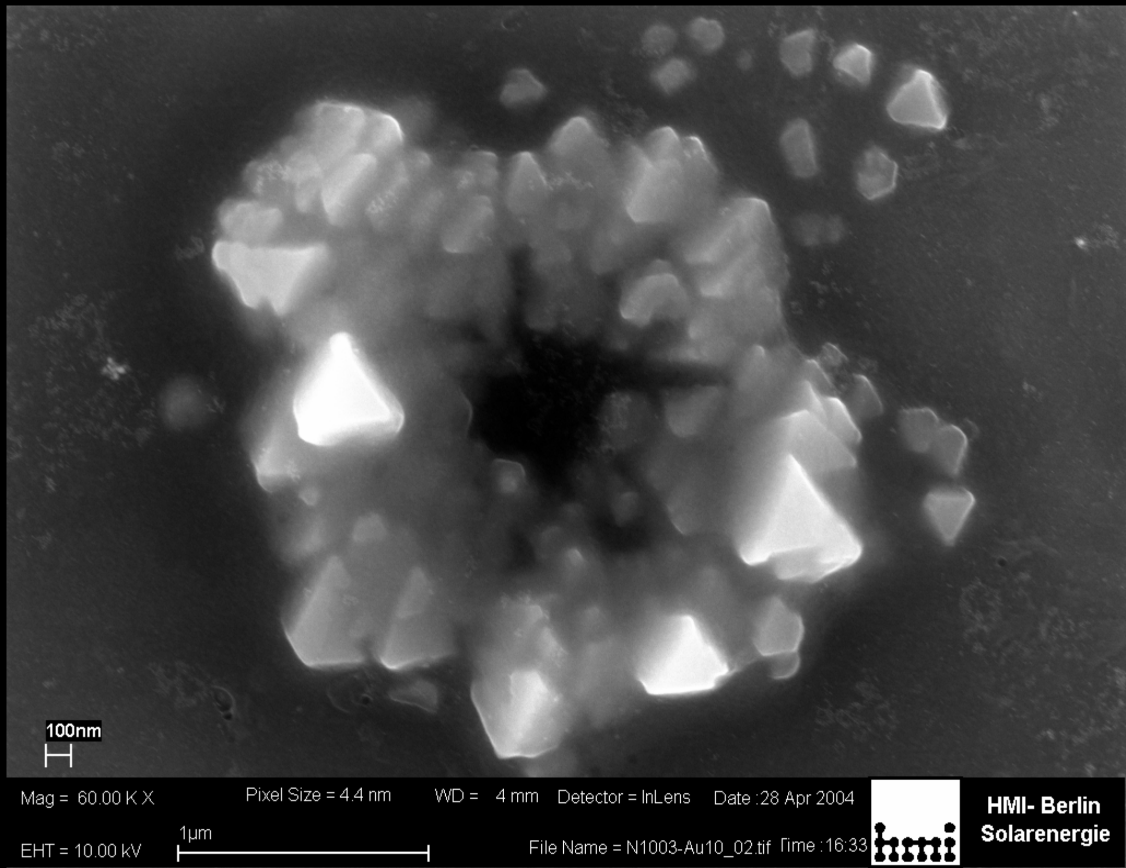
ion specie

energy

fluence

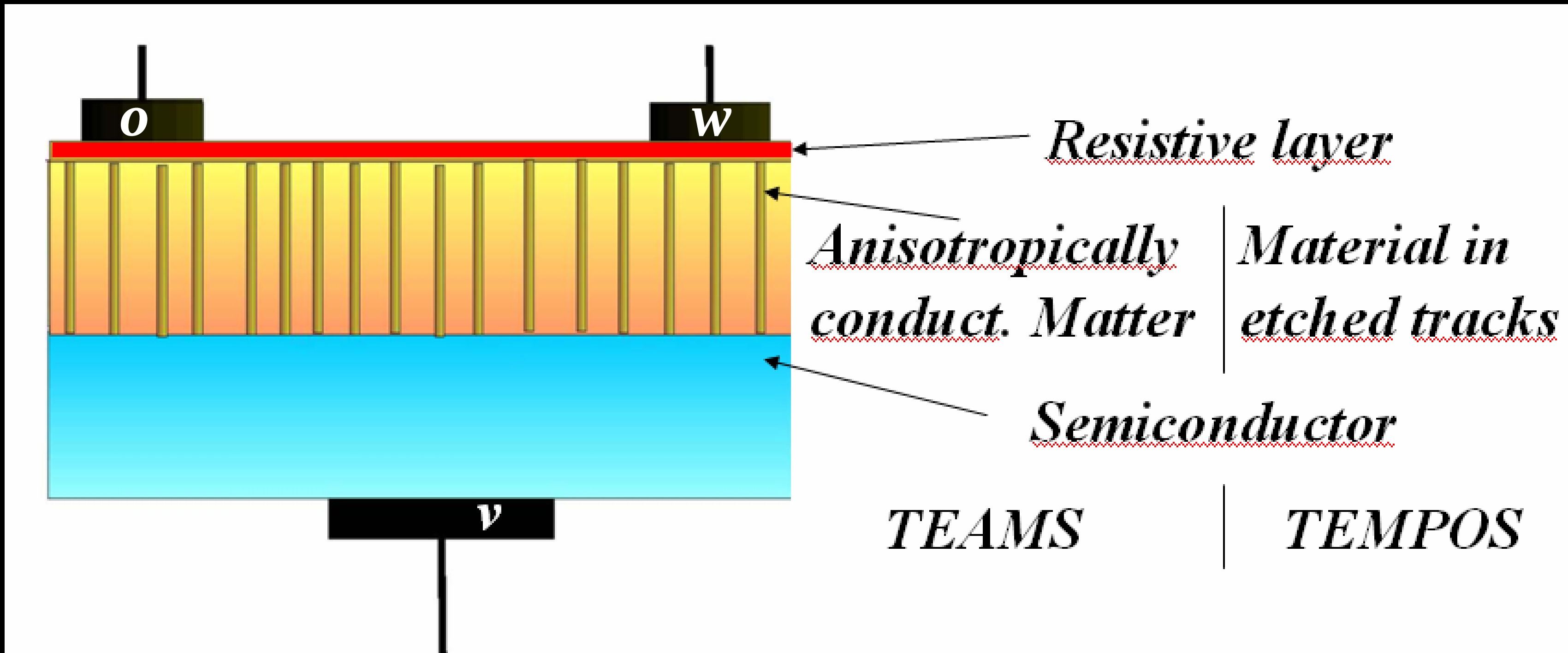
Au nanoparticles in etched tracks:

Formation of tetrahedral superstructures

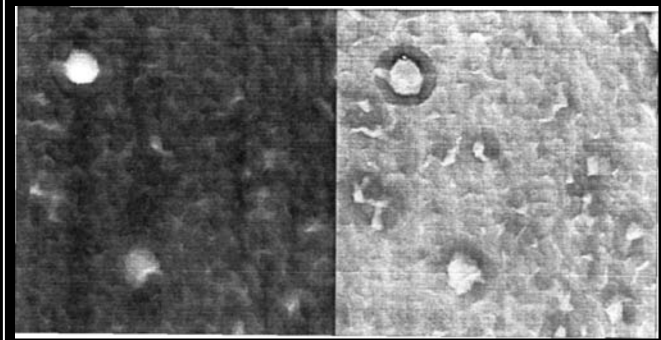


Tuneable Electronically Anisotropical Material on Silicon (TEAMS)

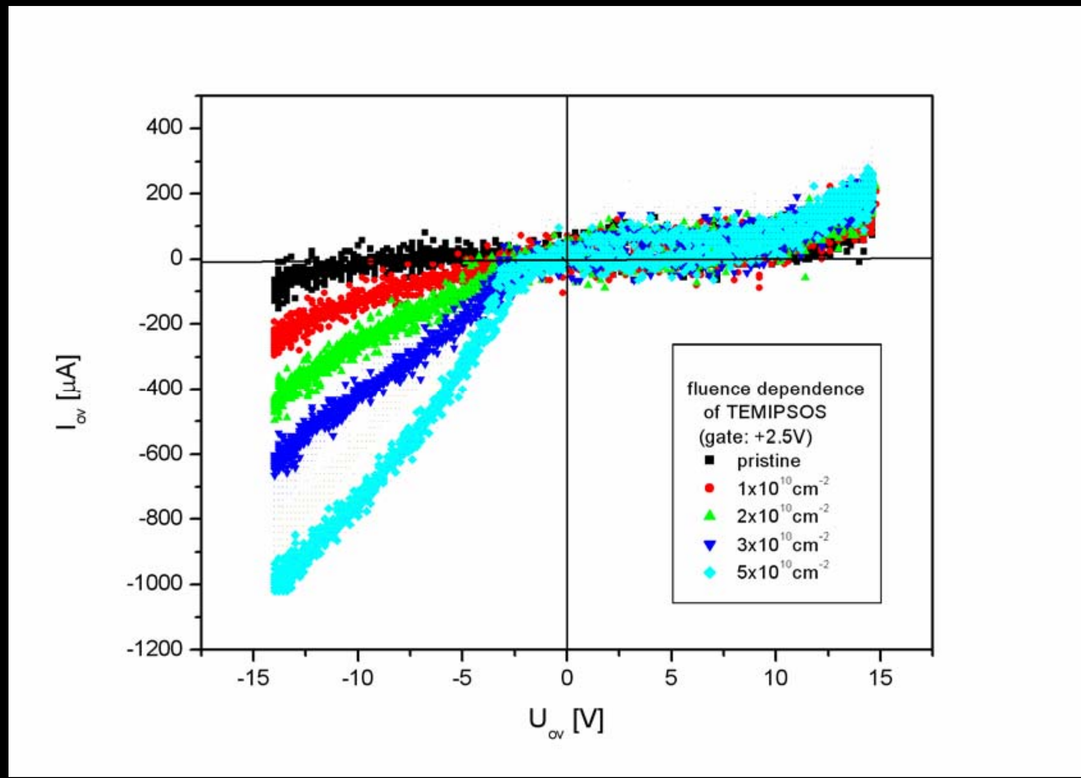
Tunable Electronic Material with Pores in Oxide on Silicon (TEMPOS)



Example of an in-situ measurement: Polysilane-TEAMS (350 MeV $^{197}Au^{26+}$ at ISL,HMI Berlin)



The creation of SiC nanorods along the ion tracks changes the I/V characteristics



Result:

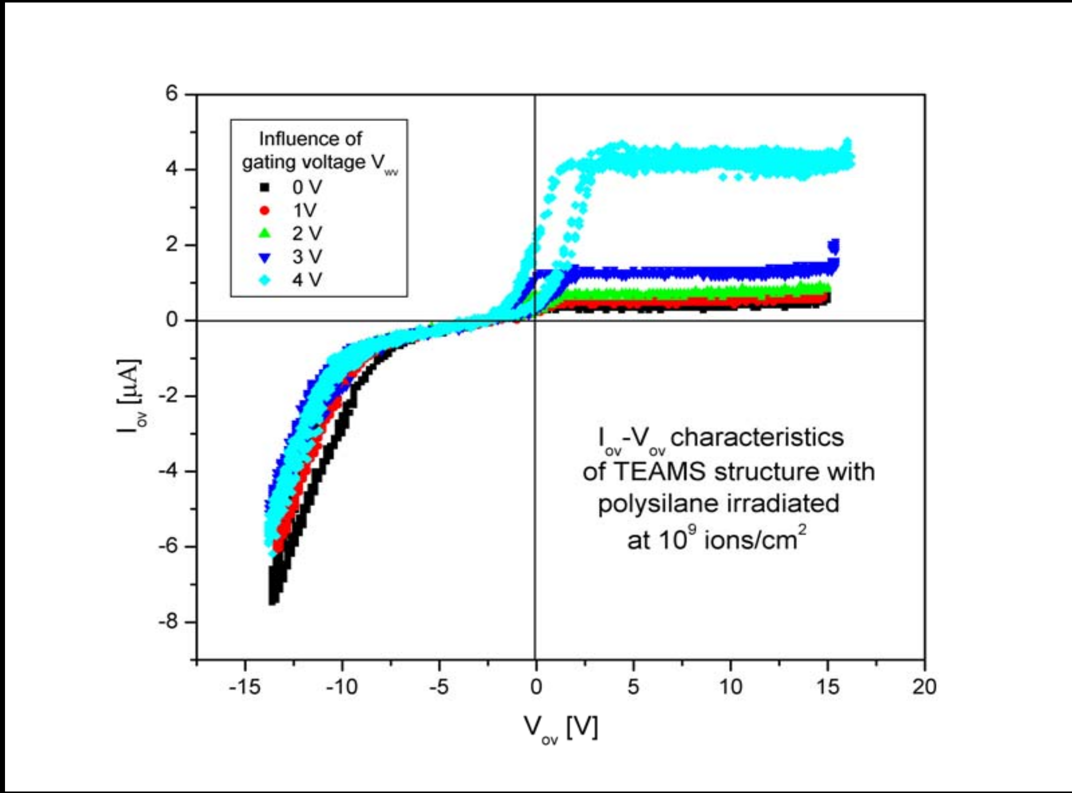
GATING VOLTAGE DEPENDENCE OF POYLSILANE-TEAMS

PECULIARITIES:

Transistor-like gating in 1st quadrant,

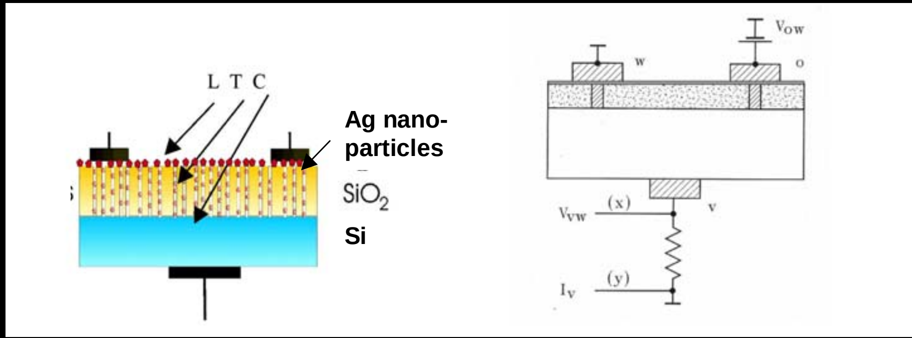
diode dependence in 3rd quadrant,

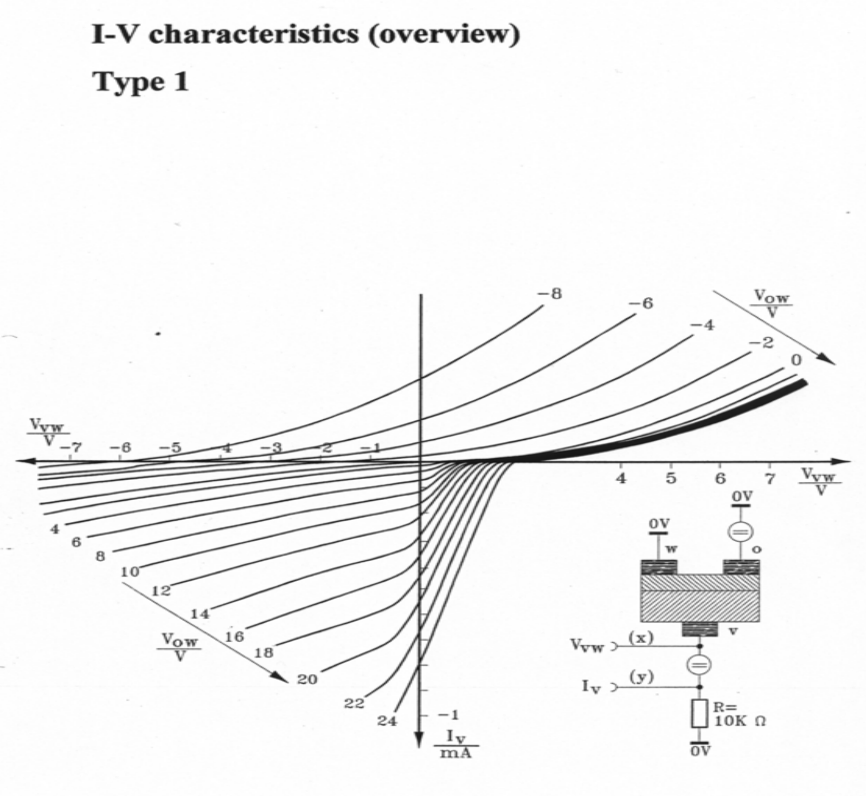
hysteresis near the origin

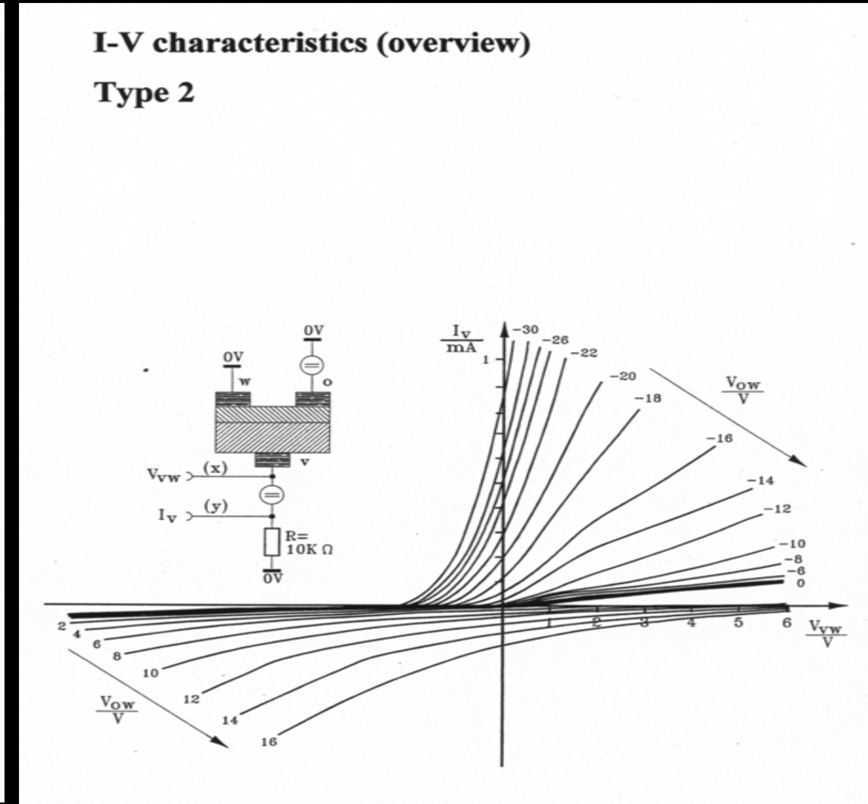


Example:

TEMPOS structures



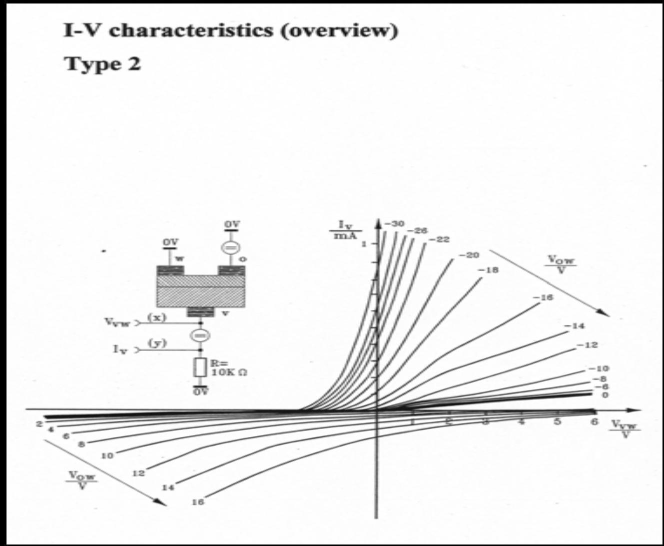


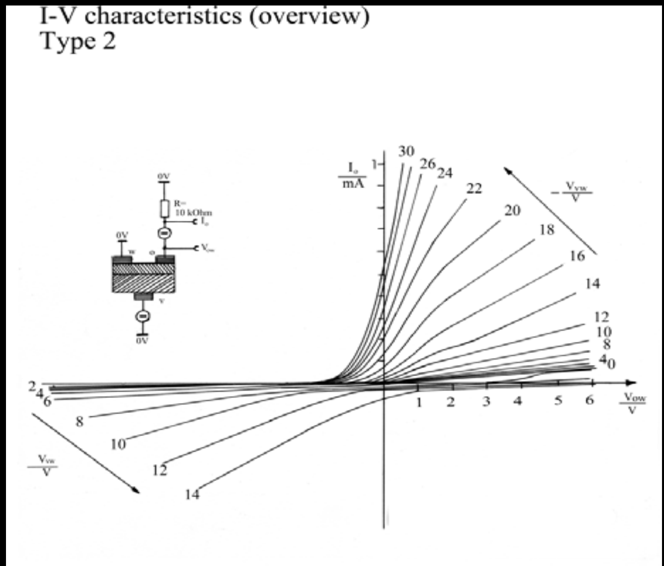


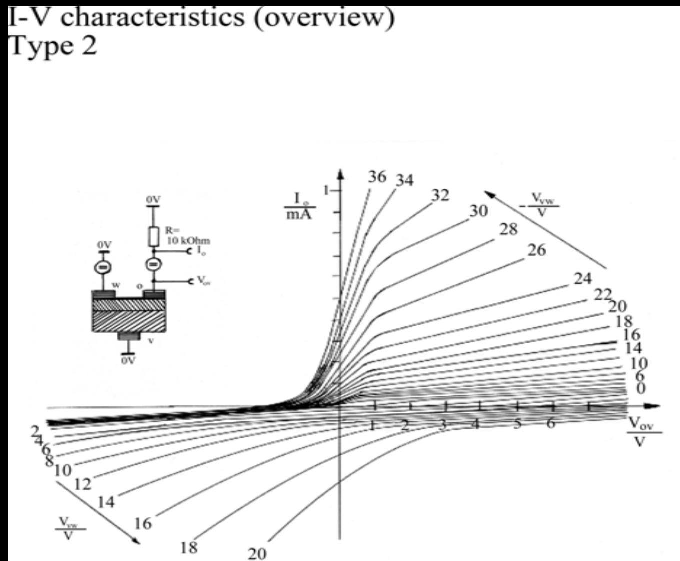
$I_v(V_{vw})$

$I_o(V_{ow})$

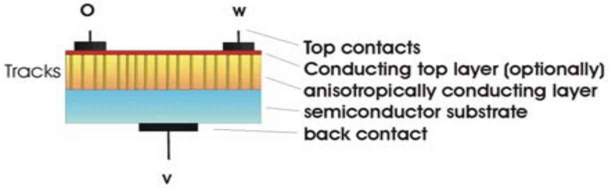
$I_o(V_{ov})$



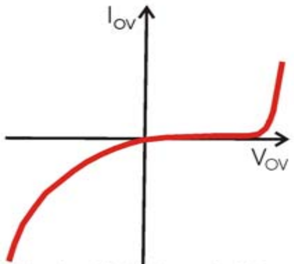




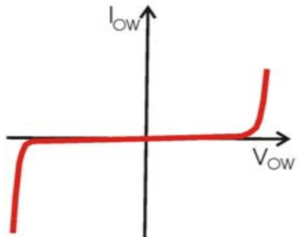
Schematic current/voltage characteristics of TEAMS and TEMPOS structures



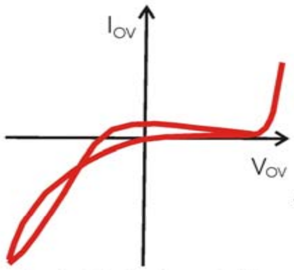
2 contacts active, 3rd contact dangling



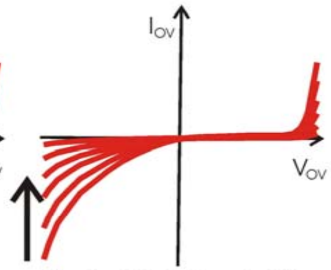
Standard diode characteristics; breakthrough at excessive voltage



Double diode characteristics; breakthrough at excessive voltage

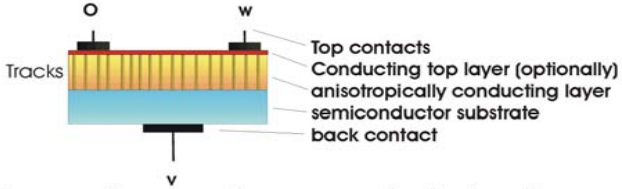


Standard diode characteristics; breakthrough at excessive voltage; hysteresis due to capacitive effects

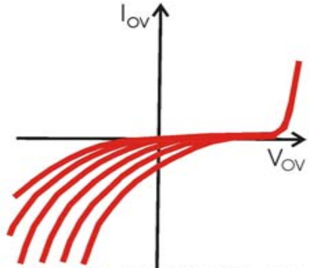


Standard diode characteristics; breakthrough at excessive voltage; decreasing current with time due to charge carrier depletion

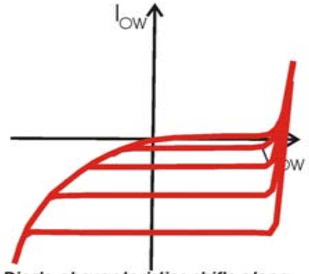
Schematic current/voltage characteristics of TEAMS and TEMPOS structures



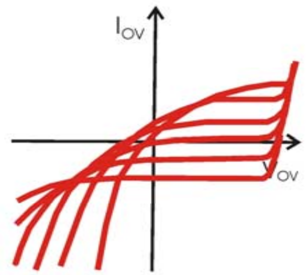
Dependence of source-drain (o-v) current on gate (w) voltage



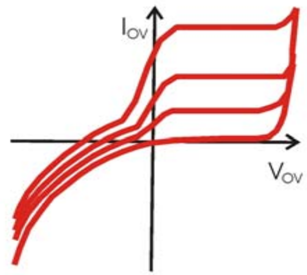
Diode characteristics shifts along abcissa if surface layer resistance < track resistance



Diode characteristics shifts along ordinate if surface layer resistance > track resistance

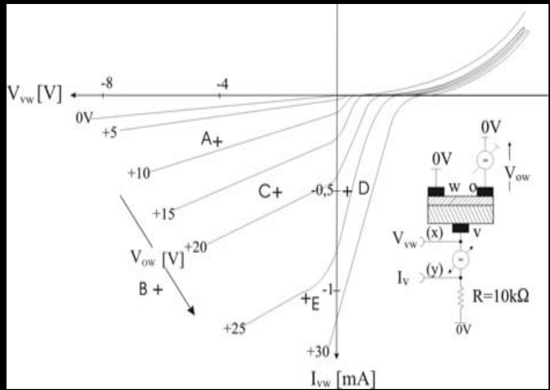


Diode characteristics shifts along both axes if surface layer resistance is comparable with track resistance



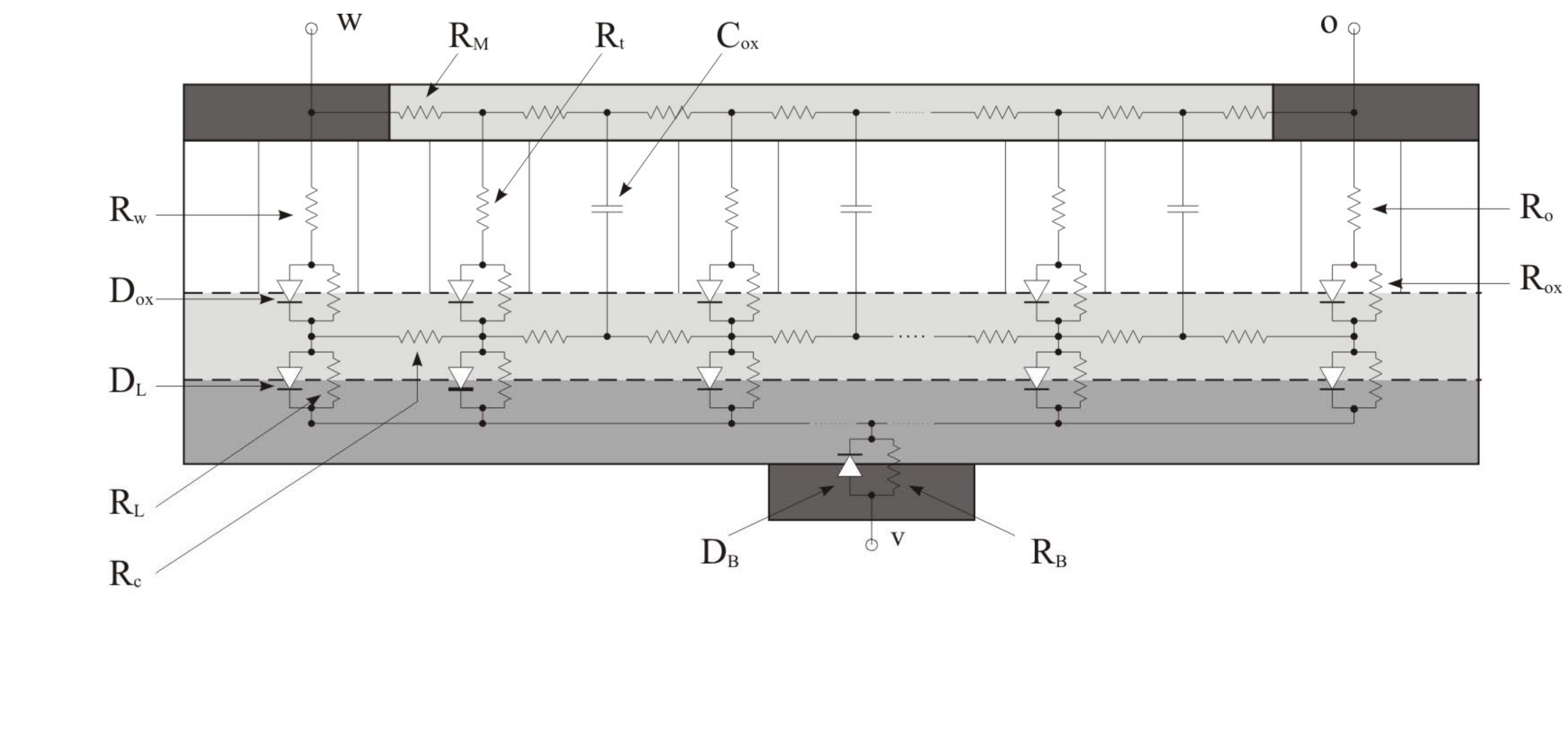
Charge injection into reverse-biased track nanodiodes

Transistor properties at some operating points



Measurement point	A V_{vw} = -4 V I_v = -0.2 mA	B V_{vw} = -6 V I_v = -1.0 mA	C V_{vw} = -2 V I_v = -0.6 mA	D V_{vw} = 0.5 V I_v = -0.5 mA	E V_{vw} = -1 V I_v = -1.1 mA
M_P Common emitter	0.18	1.17	0.64	0.054	0.053
common base	0.4	0.12	0.04	0.64	**1.12**
common collector	0.05	**24**	0.034	0.017	0.074

Equivalent circuit for TEMPOS



Theoretical approach to TEMPOS

* Calculate voltages V along tracks, resistive surface coating, and channel

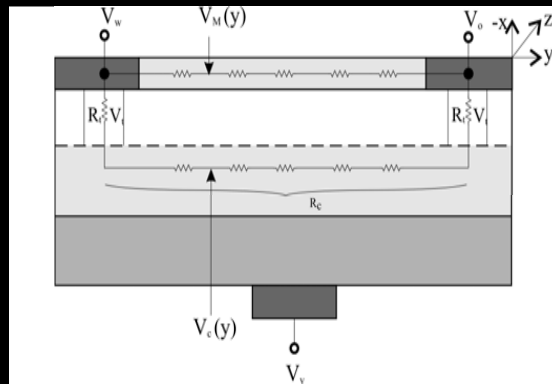
--> get drain current by differentiation:

$I_o = \int j(x,y)\, dx\, dz = W \mu (-dV_c/dy) \int n(x,y)\, dx$

(integral is surface charge density σ(y) related to oxide field by: $\sigma(y) = \varepsilon_{ox} E_{ox}$

* with $E_{ox} = \Delta V/d_{ox}$ --> *calculate* ΔV

* insertion, integration -->



$$I_o = \beta\, (R/(R+2))\, (V_v + V_w)\, (V_o - V_w)$$

$$\text{with: } \beta = C_{ox}\, \mu\, W/L$$

valid for small V_{ow}, else prevailing field effect

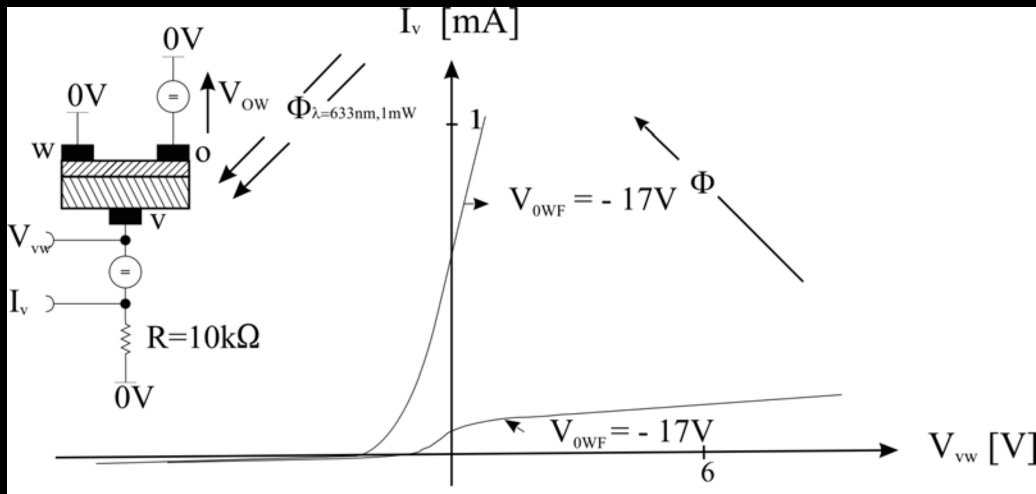
--> approaches to classical MOS transistor

TEAMS & TEMPOS sensors

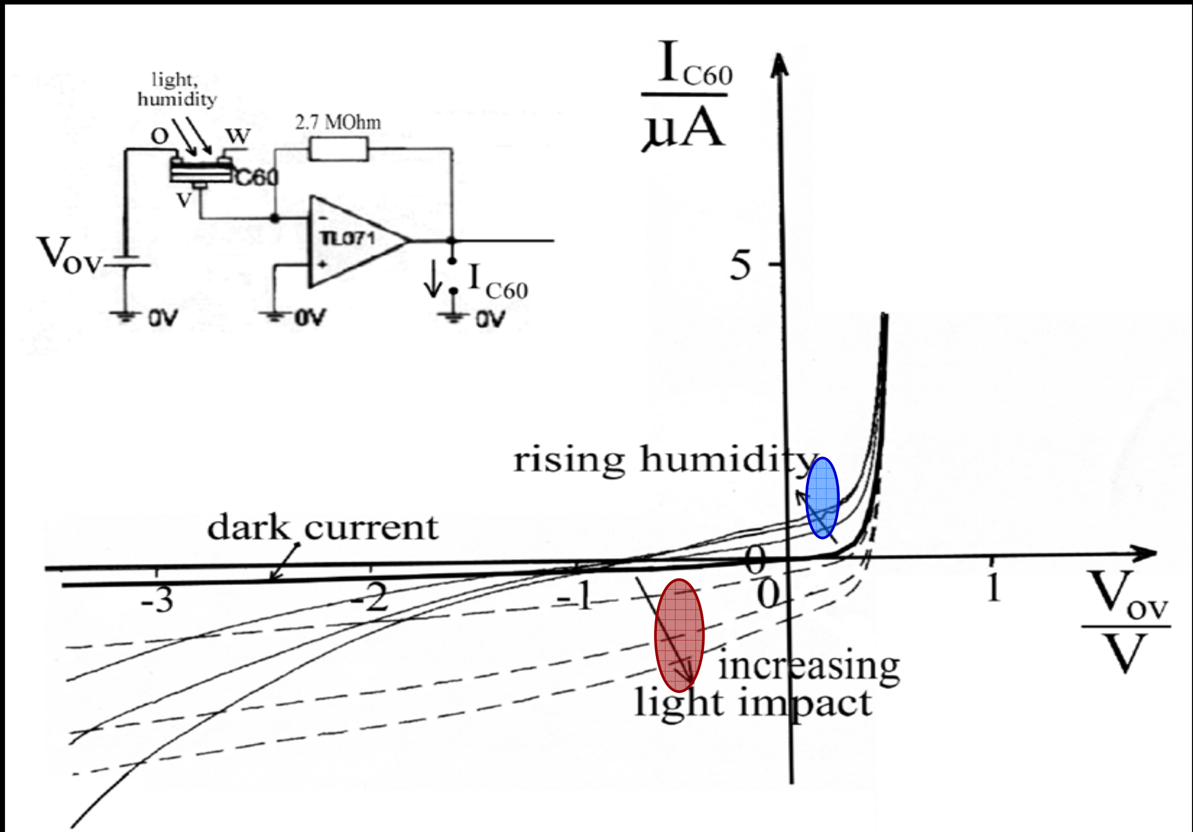
There are some intrinsic physical properties which enable the TEAMS & TEMPOS structures to act as a sensor.

Example: light sensitivity.

Application of a light source shifts the characteristic from a low conductive state to a high conductive one
due to increase in carrier concentration in space charge region



Humidity sensing with TEMPOS



$Si/SiO_2(C_{60})$:

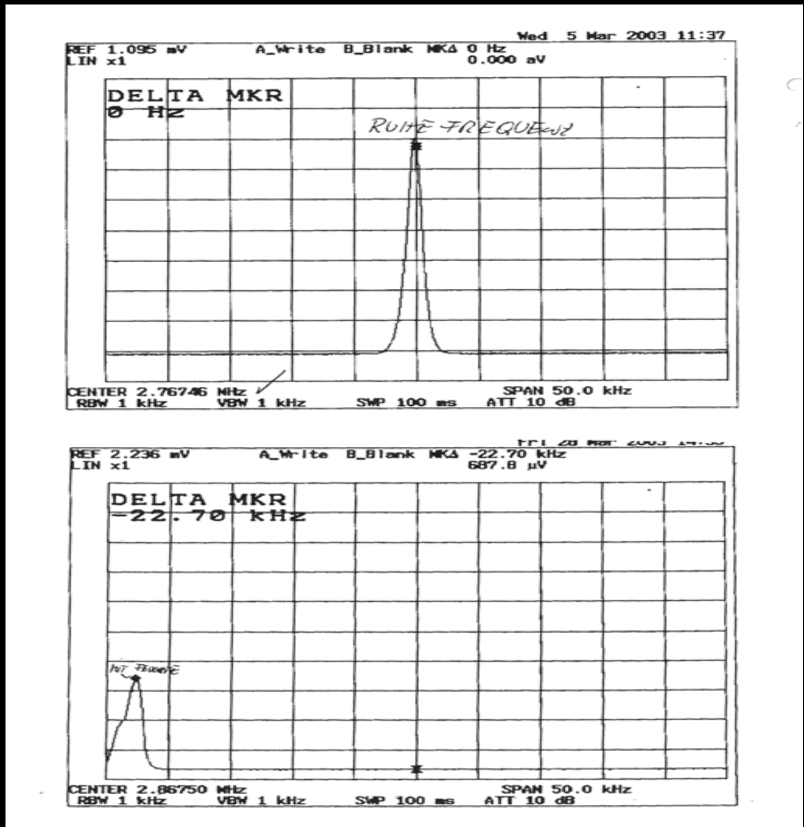
Humidity:

I_v increases

Light, alcohol:

I_v decreases

Humidity sensing with TEMPOS:



Sensitive humidity recording

by frequency measurement

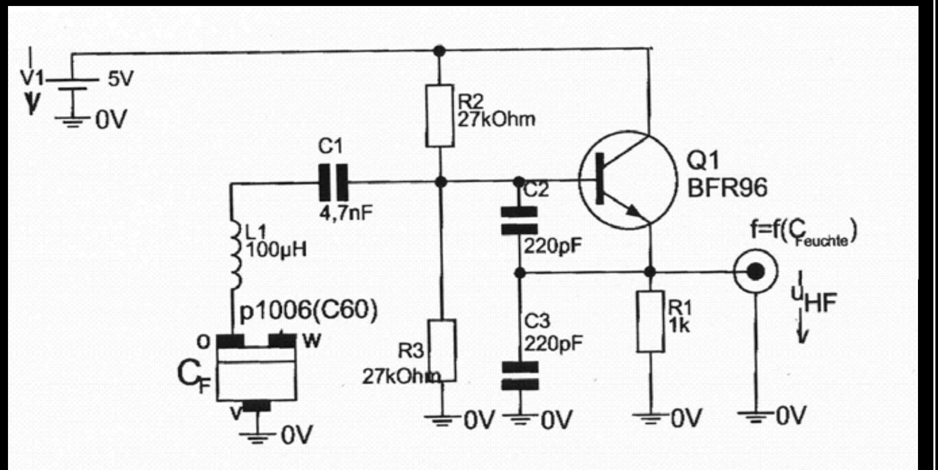
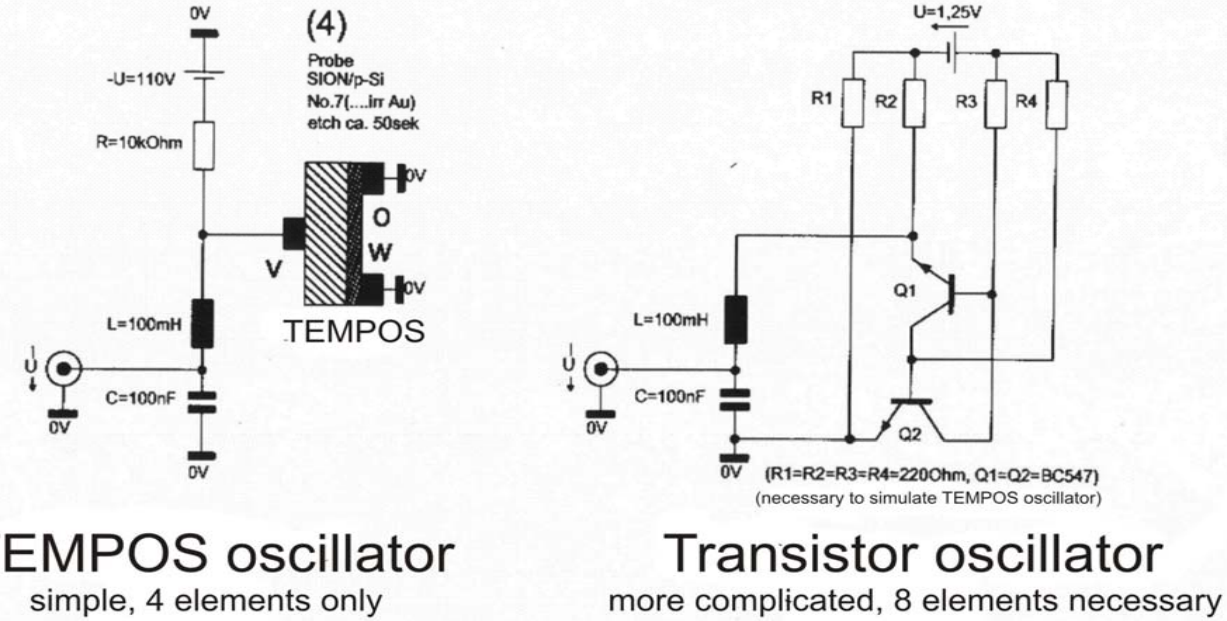


Abb. 52 Feuchtegesteuerter HF-Oszillator FCO

Comparison of transistor electronics and SITE



The internal complexity of TEMPOS leads to simplified circuits.

→ easier and cheaper circuits than with conventional transistor technology;faster electronics.

A common feature for SITE:
Negative differential resistances (NDR)

NDRs can have two origins:

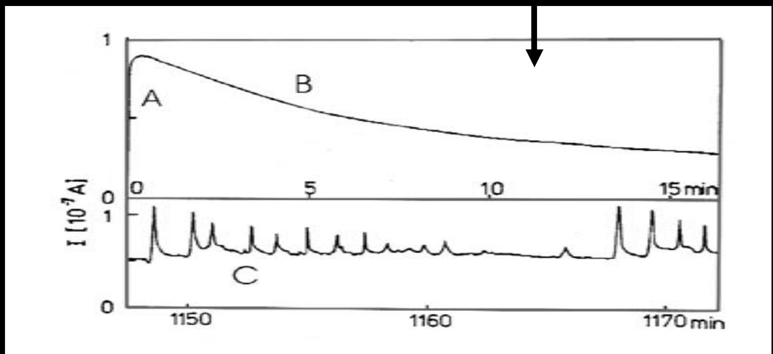
- Instabilities in individual entities (traps, tracks)
- Collective track-track interactions

In spite of different mechanisms, both effects lead to similar effects

First hints for NDRs in pores from biology ~ 1970

Current-Voltage relationship of the electrogenic pump in Acetabularia mediterranea. by: D.Gradmann, W.Klemke in: Membrane Transport in Plants, U.Zimmermann and J.Dainty eds., Springer 1974, p.131-138

Also frequent pore effects:
Pulsating current in latent tracks in PET
(Correlation with NDRs?)



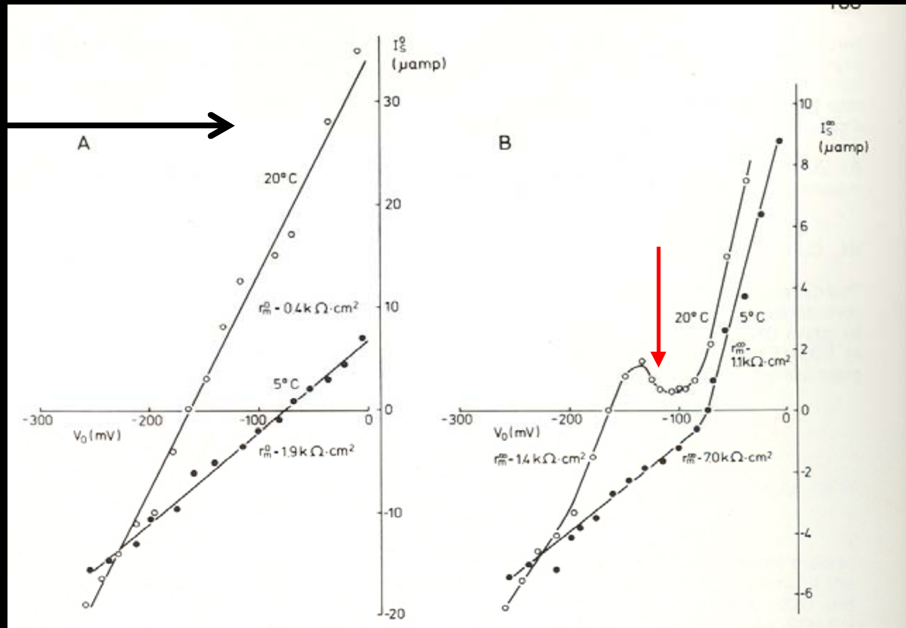


Fig. 2 A. early; B. steady state voltage clamp input I–V relationship. Recording from one cell in darkness at 20°C (○—○), and 5°C (●—●).

At 20°C, when the pump is operating, additional current passes through the pump channels. The most striking feature of the steady state I–V curve at 20°C is its N-shape under depolarisation; it finally merges with the high conductance potassium branch. This is certainly a rather complex phenomenon, since voltage- and space-dependent events in different pathways seem to be involved. At ~~the moment this question will not be pursued further.~~

NDR of individual entities

(shown here for the example of deep traps)

Suppose -

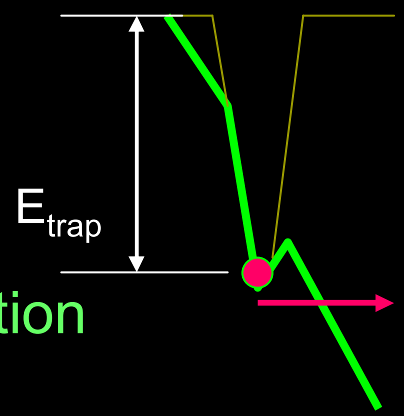
- deep traps are produced by irradiation of a material, e.g. SnO_2 in a TEAMS structure
- these traps are filled by charge carriers
- the sample is subject to a strong field gradient

→Then a slight trigger may release all charges simultaneously

→ Strong “stimulated emission“ current

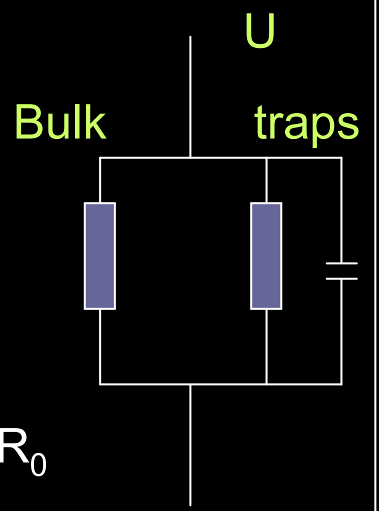
→ Breakdown of applied voltage

→ Negative differential resistance



Permanent repitition of this game → pulsation

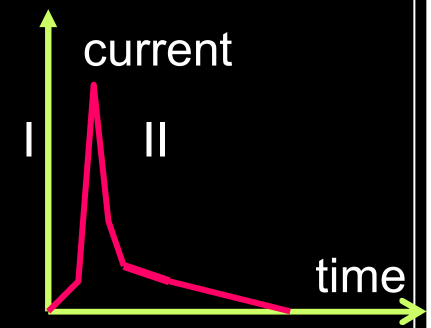
Theory of stimulated current emission from deep traps in tracks



- Total equivalent circuit = bulk branch + parallel trap branch
- Equivalent circuit for deep traps = parallel R_{trap} +C_{trap} described by a macroscopic trap resistance R_0
- For $U < E_{trap}$: $R_{trap} \rightarrow \infty$;   for $U > E_{trap}$: $R_{trap} \rightarrow R_0 \sim 0$

- In this case: discharge current $I_{disch} = -dQ/dt = -C_{trap}\, dU/dt = U/R_0$ (adds to I_{bulk})

→ $Q/C_{trap} = R_0\, dQ/dt$ → $Q = C_{trap} U_0 \exp(-t/(R_0 C_{trap}))$
→ $I_{disch} = dQ/dt = C_{trap} U_0/(R_0 C_{trap}) \exp(-t/(R_0 C_{trap}))$

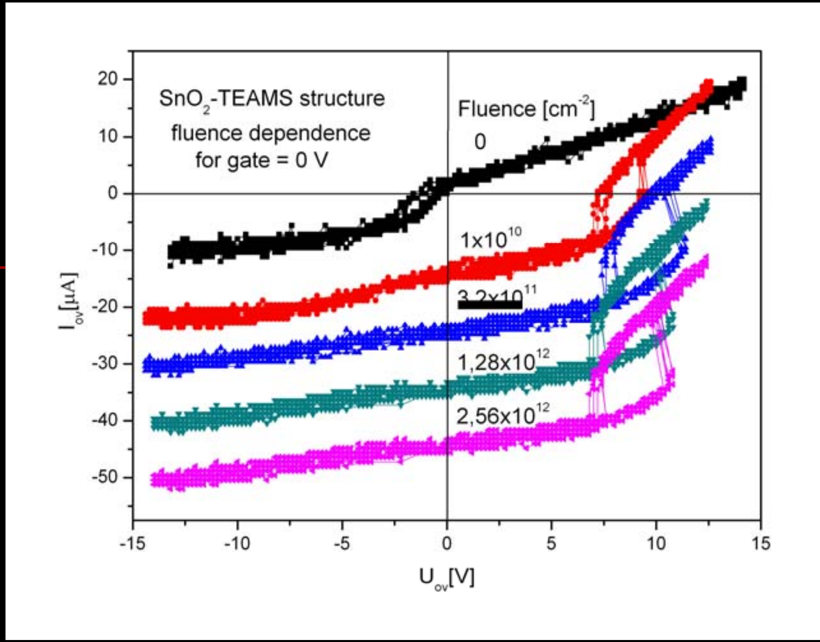


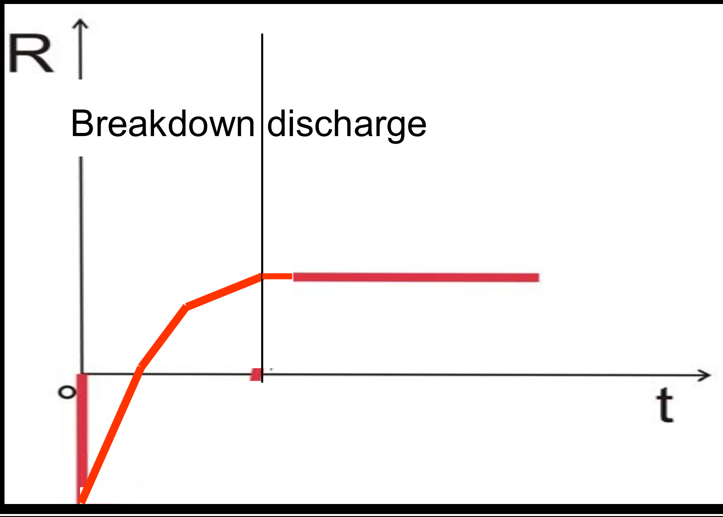
→ Voltage drop $\Delta U = \Delta Q/C_{trap} = Uo\,/(R_0 C_{trap})^2 \exp(-t/(R_0 C_{trap}))$
→ $R_{eff}\,(t) = (U_0 - \Delta U(t)\,)/I = R_0 - f \exp(-t/(R_0 C_{trap}))$

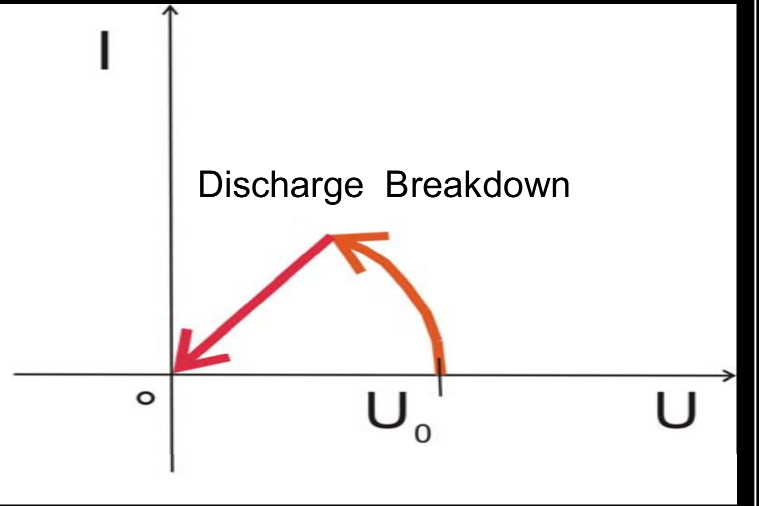
→ Phase I (pulse buildup): negative trap resistance
→ Phase II (pulse discharge): trap resistance becomes positive → saturation

NDR of SnO_2-TEAMS

evolution of the discharge pulse, schematic:



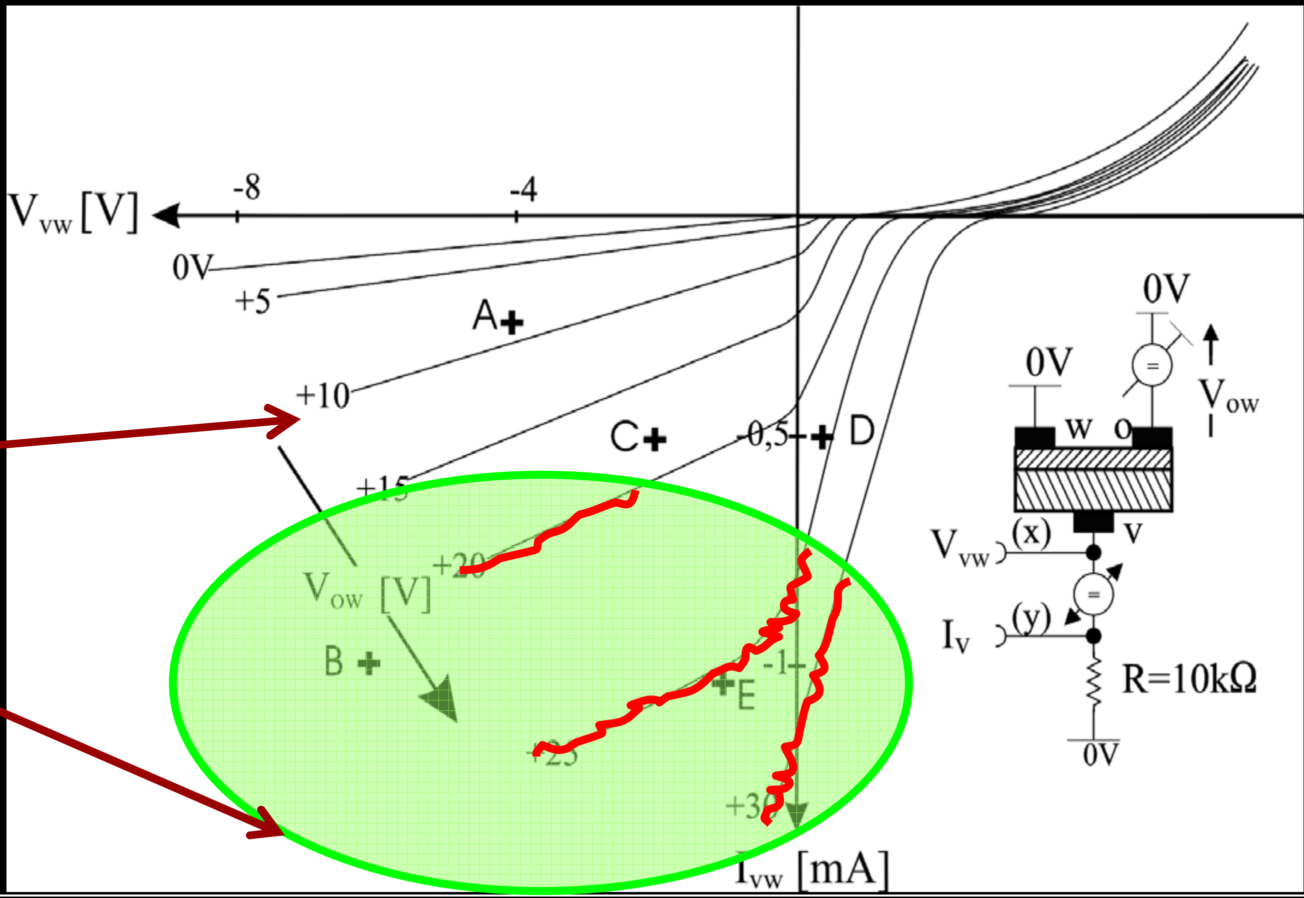




NDR of TEMPOS due to collective track interactions
example: electronic noise at high currents

no noise

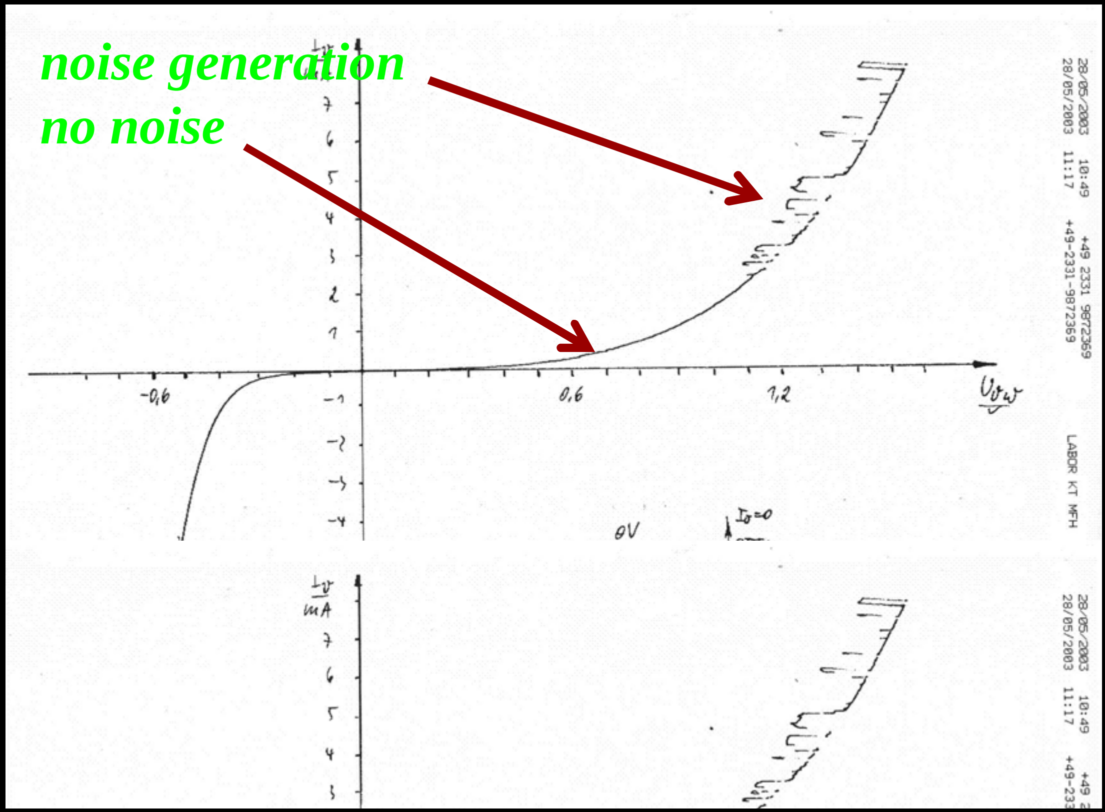
noise generation



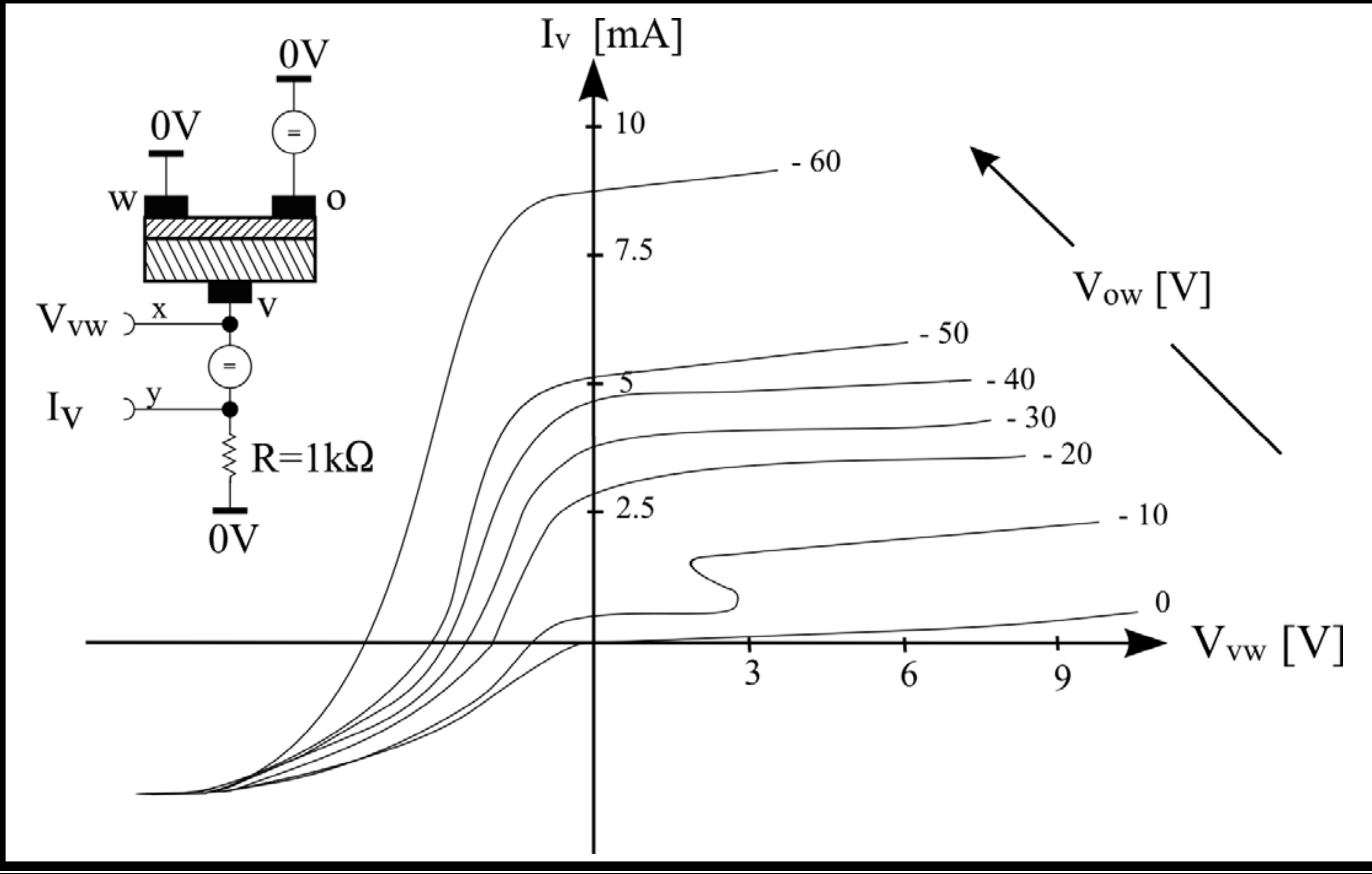
P-type Si/SiO_2

Negative resistance of TEMPOS
example: electronic noise at high currents

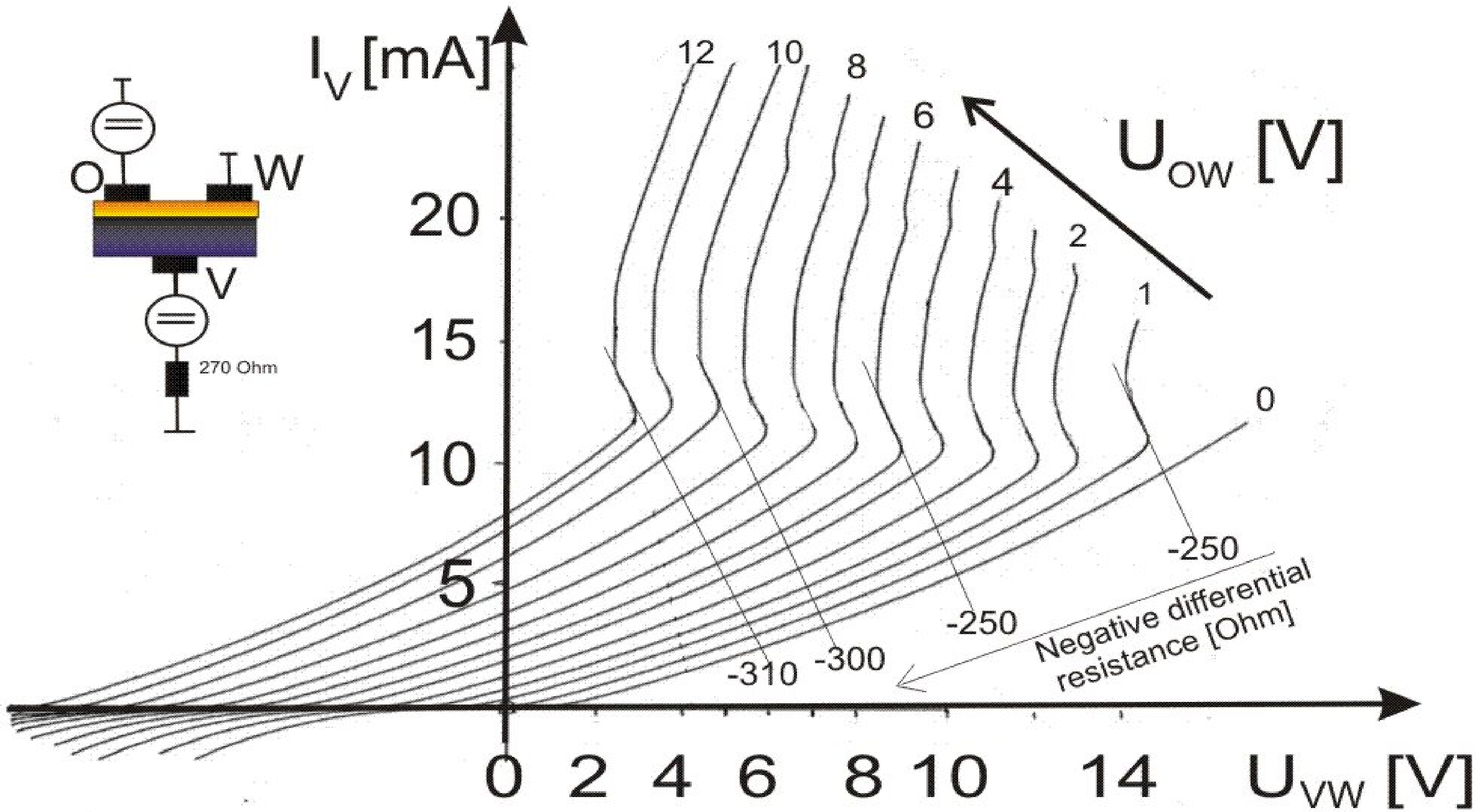
N-type Si/SiO_2



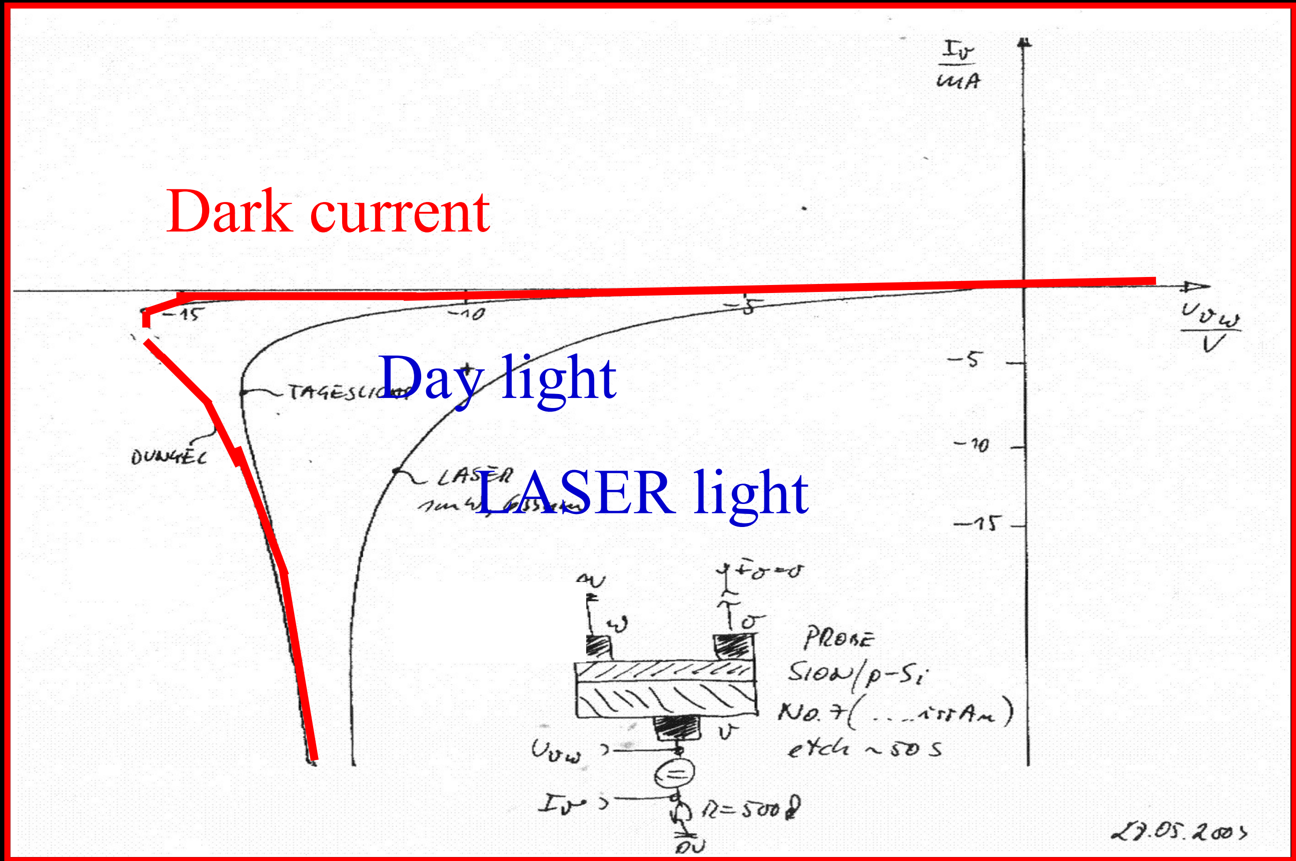
Negative resistance of TEMPOS
example: local differential negative resistance



Tunable Negative Differential Resistance of Ag-Nanocluster-TEMPOS



Negative resistance of TEMPOS
example: extended negative resistance



The amount of amplification can be controlled by the intensity of impinging light.

Above threshold light intensity: amplification breaks down.

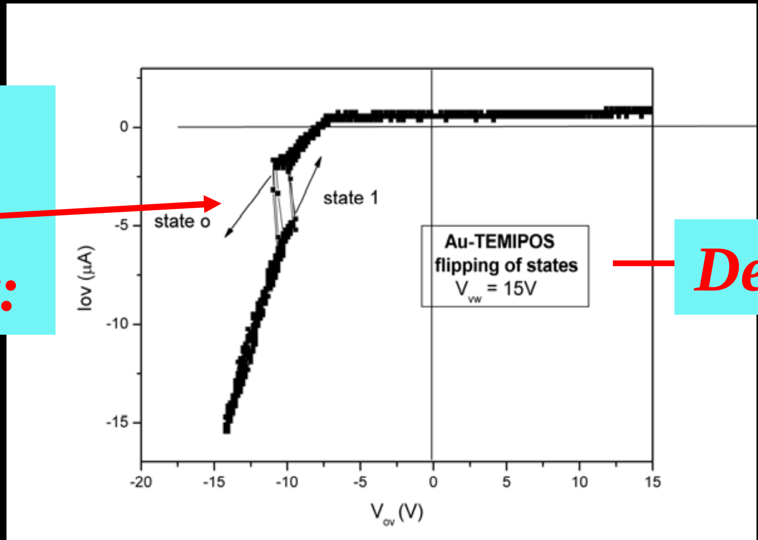
TEMPOS acts like Esaki or tunnel diode

Peculiarity of TEAMS structures:

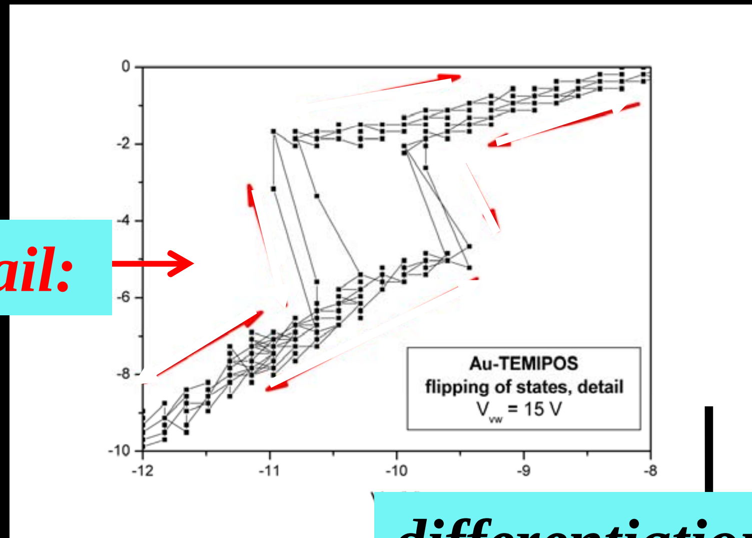
two working states + negative differential resistance

(due to track-track interaction)

Au NCs in pores in photoresist:

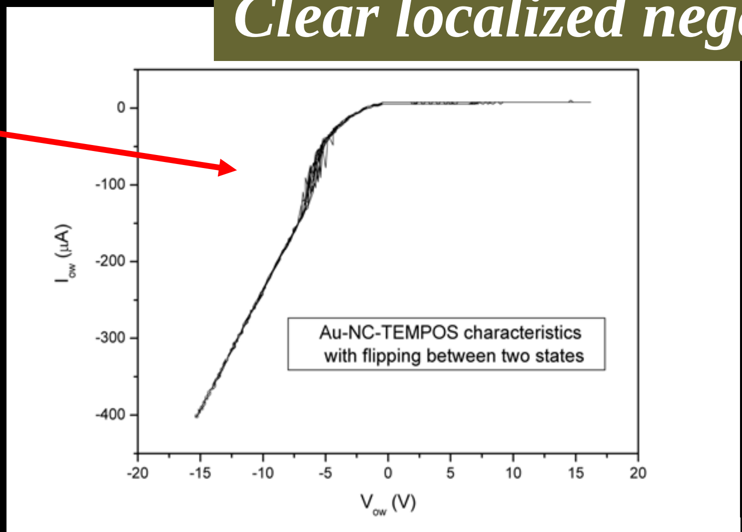


Detail:

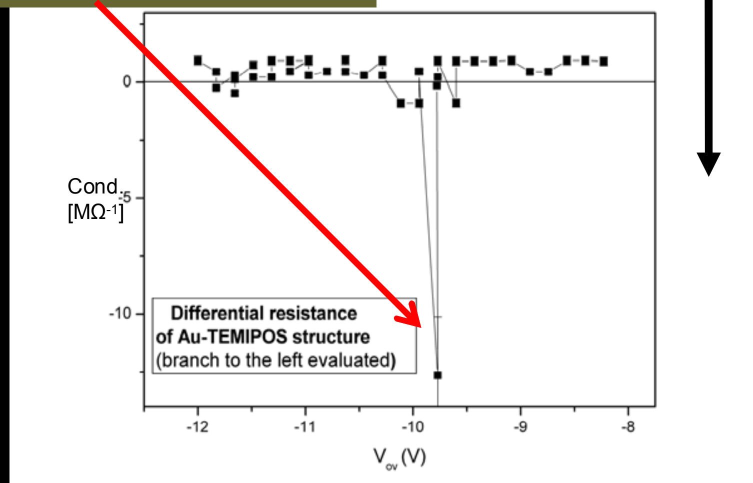


differentiation

Au NCs in pores in SiO_2:



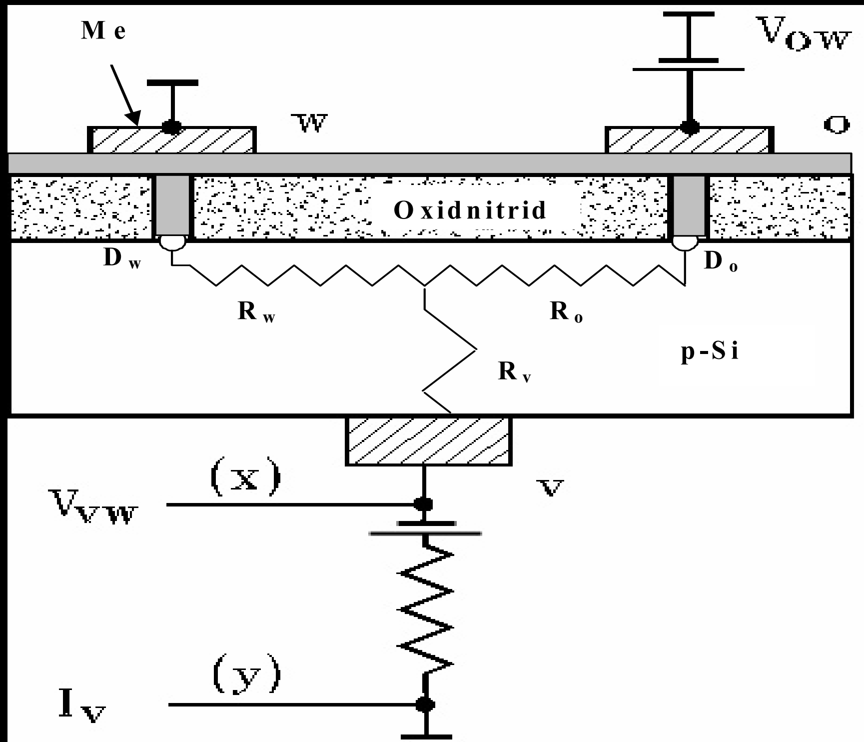
Clear localized negative resistance



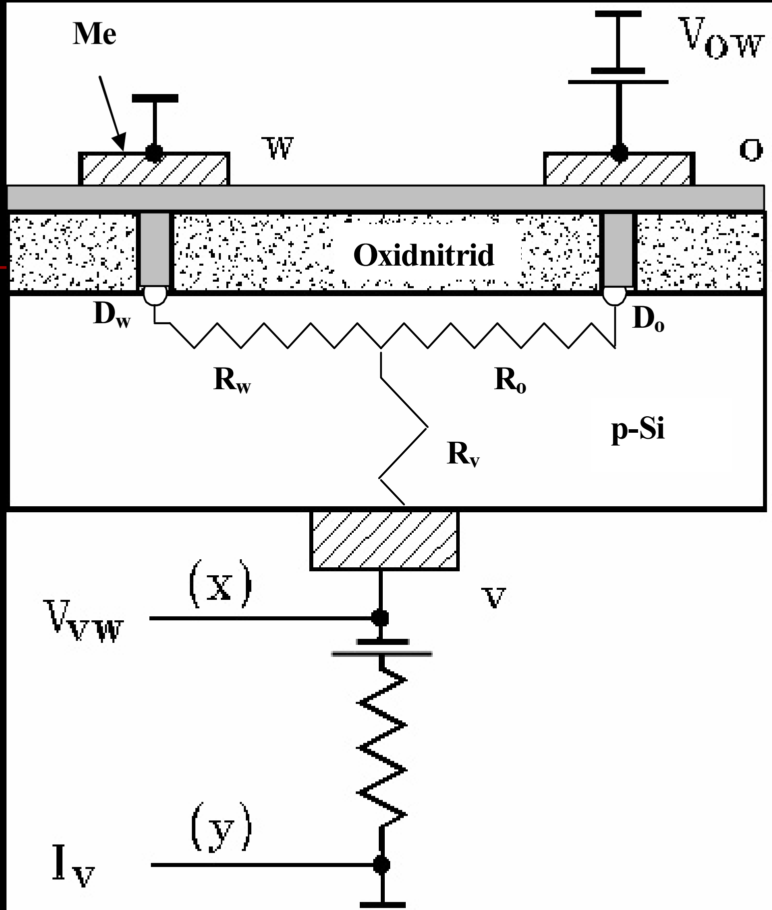
Switching behaviour of TEMPOS structures

simplifications:

1) take SiON as dielectric layer
→ cylindrical tracks
2) restriction to only one track each below the surface contacts.
3) restriction to p-Si only (simplest case: no inversion layers)
--> equivalent circuit



- negative voltage at o + positive voltage at v
  - diode Do open
  - Ohmic current from v-o.
- low positive voltages at v --> negative voltage below track w
  - diode Dw backwards polarized.
- with voltage at v increasing
- voltage drop below w becomes positive
  - diode Dw becomes conducting
  - hole injection into the neighbored p-region.
  - Reduction of resistance Rw
  - Positive voltage above w increases
  - More holes injected via the diode Dw, etc.
  - Resistances Rw, Ro vanish; current limitation only by diode
  - i.e. switching from high Ohmic state to low Ohmic state.
  - Backward current/voltage characteristic;
  - negative differential resistance



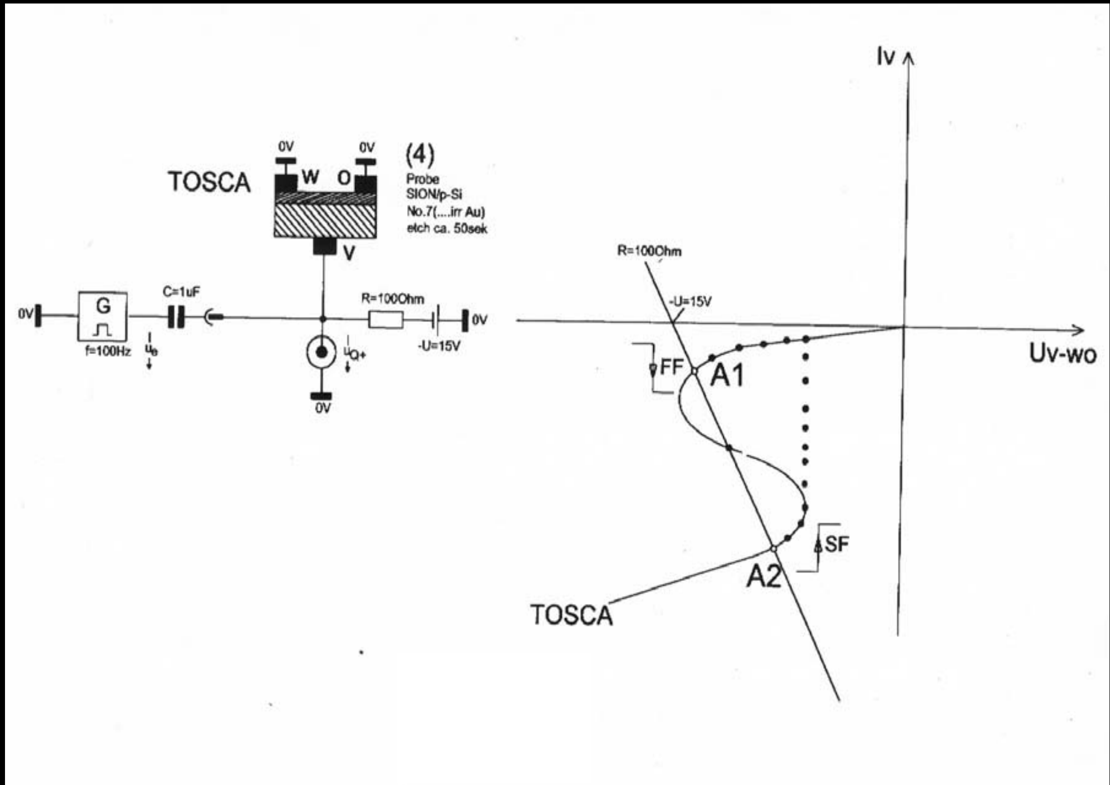
…in other words, TEMPOS structures behave similarly as Esaki diodes or double-base diodes = unijunction transistors = filamentary transistors

NDRs, Conclusions → Applications:

- Many SITE structures (e.g. TEAMS + TEMPOS) show instabilites (due to individual or collective jumps between two working states)
  → flip-flop construction → digital electronics…

- Instabilities have often negative differential resistances
- Can be explained by collective interaction of neighboring diodes
  → application for amplifiers, oscillators

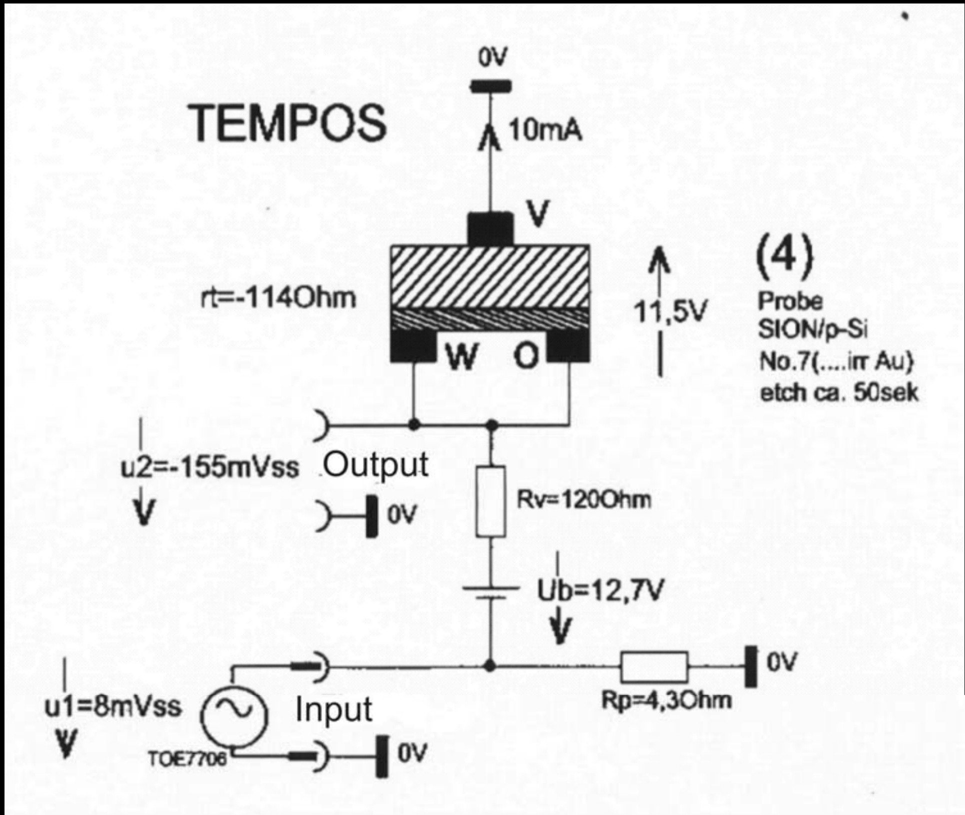
Flip-Flops with TEMPOS



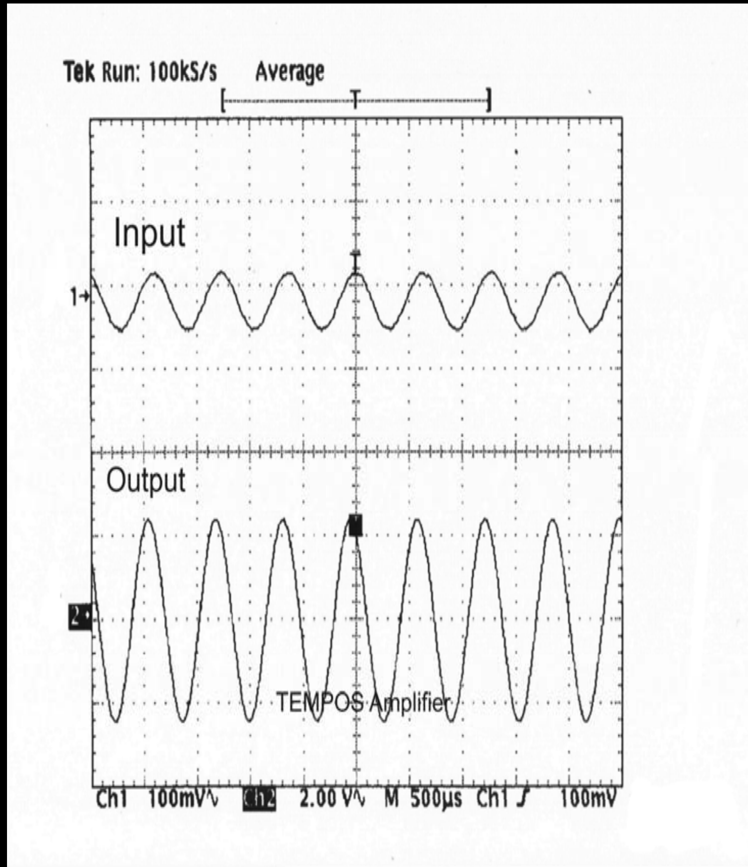
One can exploit the Esaki diode-like negative characteristics to produce flip-flops, with A_1 and A_2 being the working points.

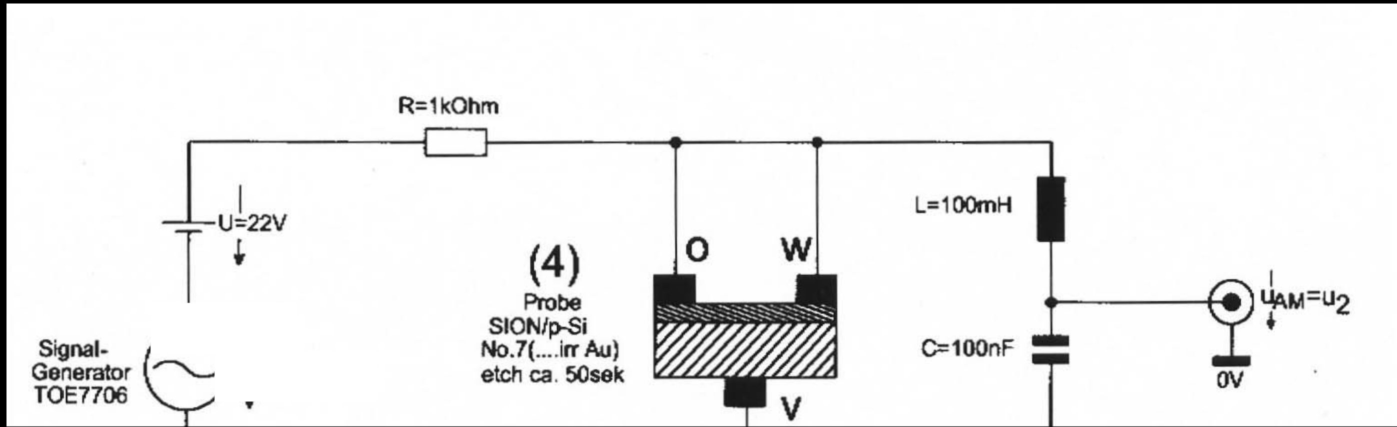
This means, one can produce transistor-less computers!

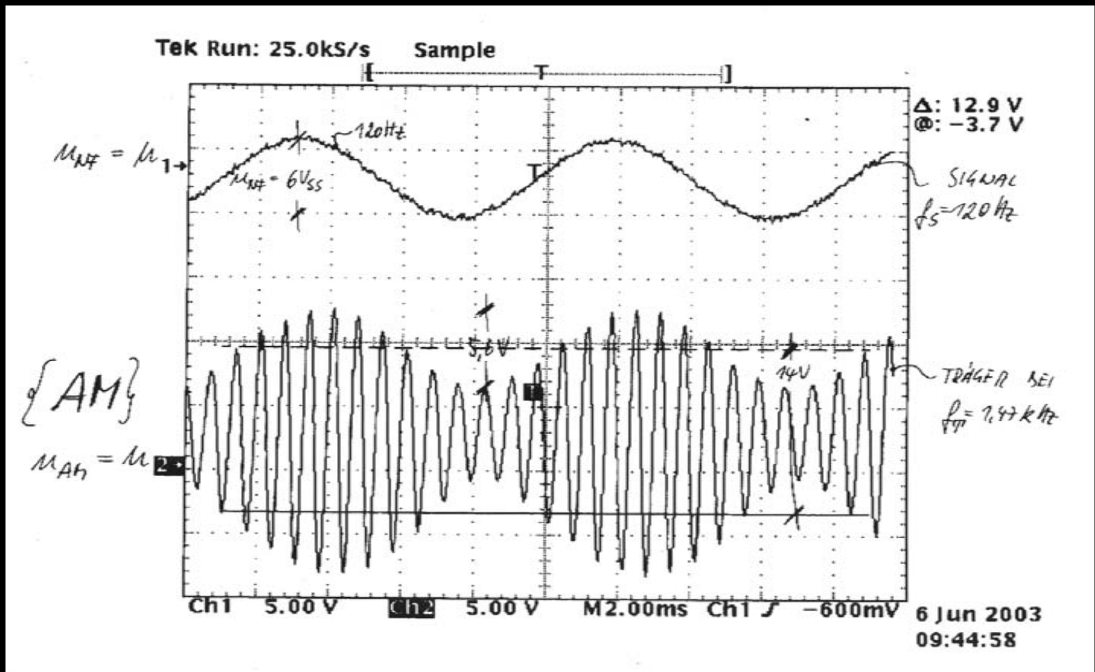
TEMPOS Amplifier



TEMPOS Amplifier







Oscillator and AM mixer

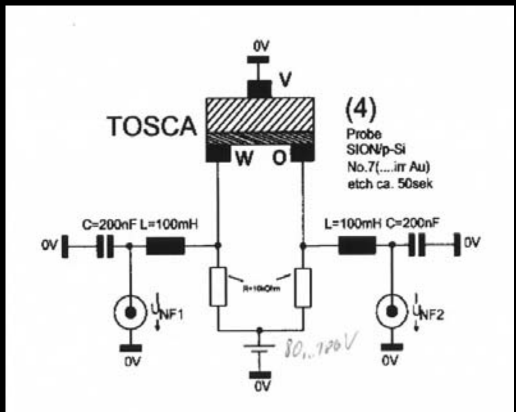
(self oscillating AM modulator)

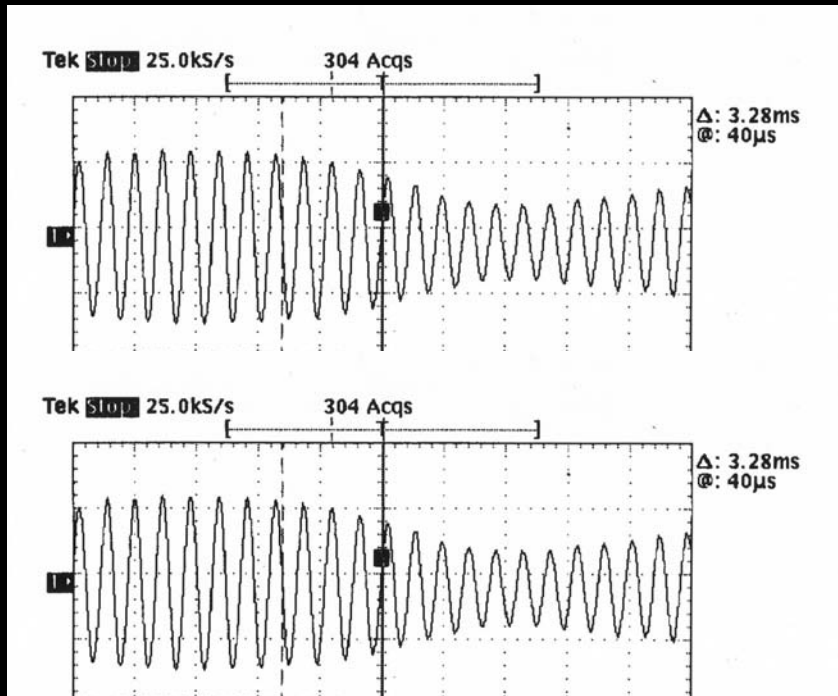
based on TEMPOS

Tandem Oscillators with TEMPOS

As only one surface contact is used for amplification or oscillation, one can build tandem devices.

Attention: capacitative coupling might influence the circuits.



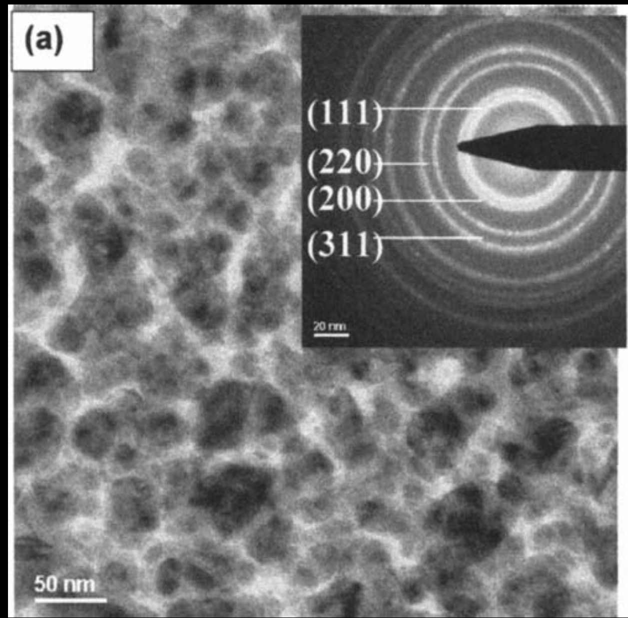


Conclusions and Outlook for TEAMS&TEMPOS:

- TEAMS/TEMPOS: in principle now well-established and understood

Future:

- Study TEAMS/TEMPOS with –
  - \+ metal-polymer nanocomposites
  - \+ biological systems
  - \+ diamond / EG /CNTs
- CNT-TEMPOS for 3D structuring
- direction-dependent TEMPOS sensors
- 2D position sensitive TEMPOS sensors
- intelligent TEAMS/TEMPOS systems
- GHz TEMPOS modulators & transducers



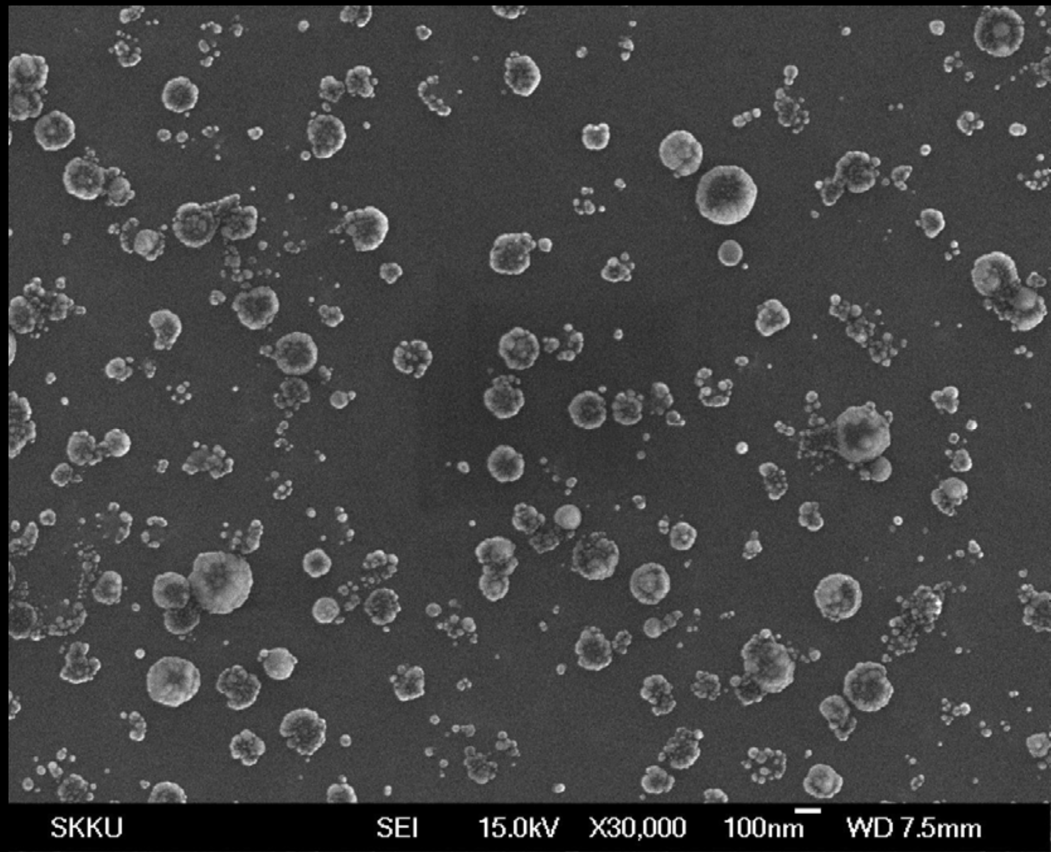
Growth of carbon nanotubes in etched tracks.

1st step:

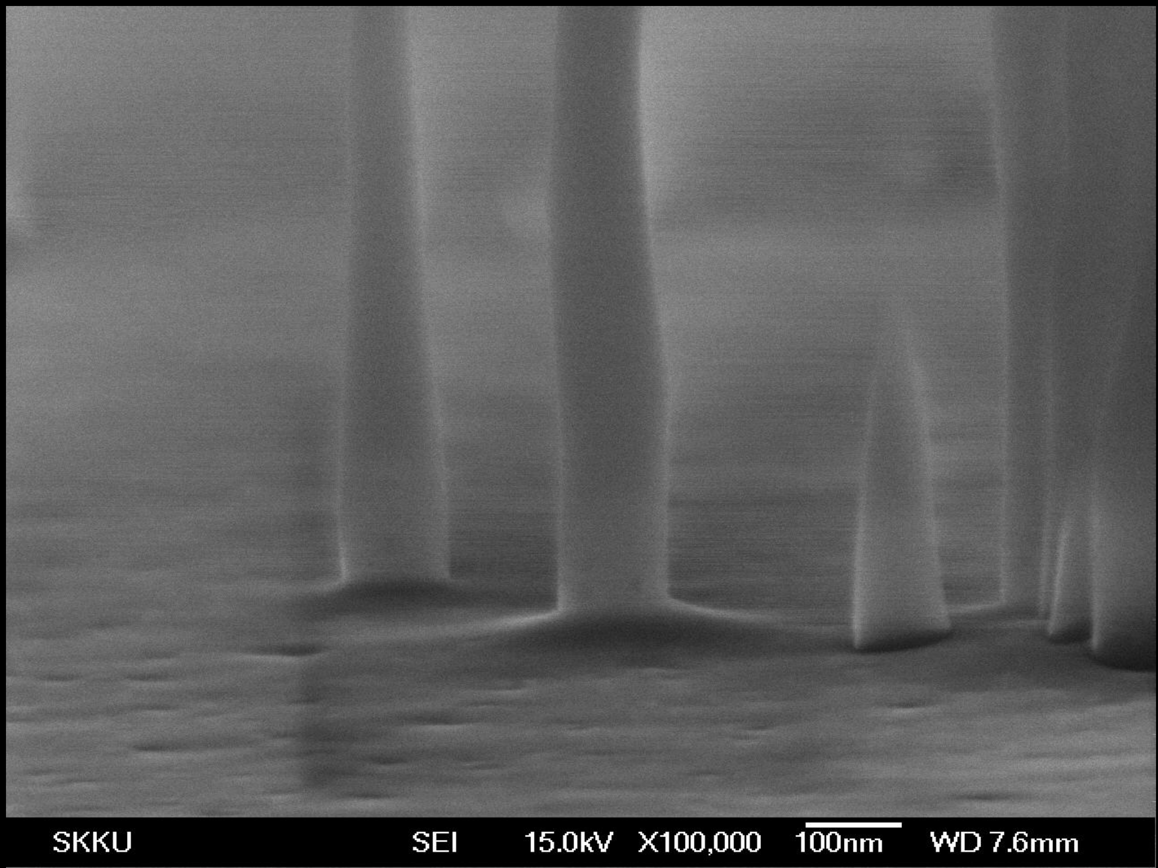
deposit Ni or Fe nanocluster catalysts in tracks by electrochemical routes

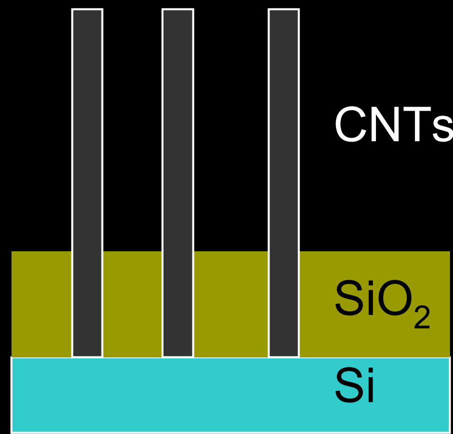
(~ 4 sec, 4V)

→ Growth of carbon nanotubes with base diameter equal to the inner diameter of the etched tracks

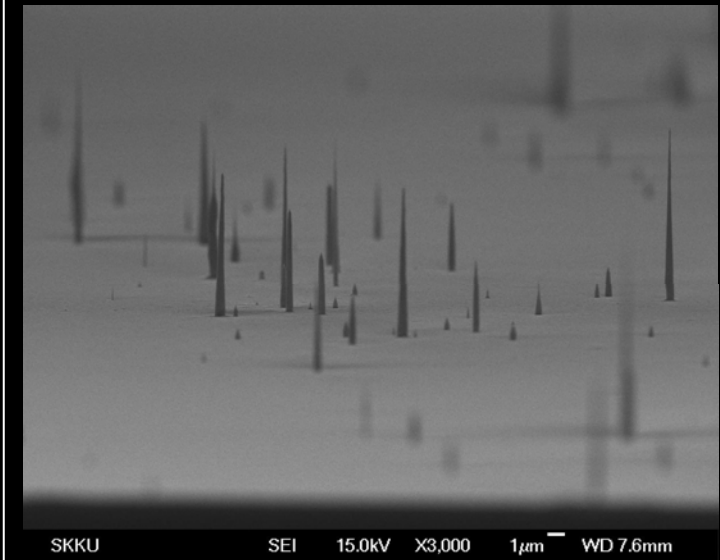


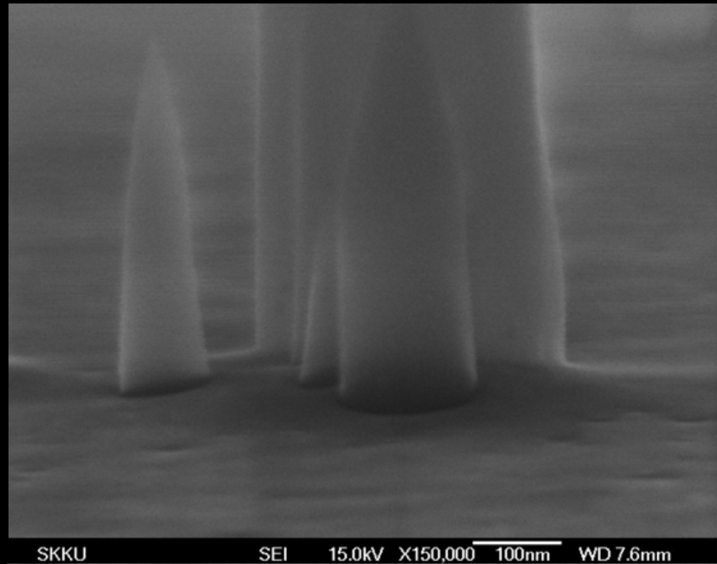
PCVD Growth of CNTs in etched tracks

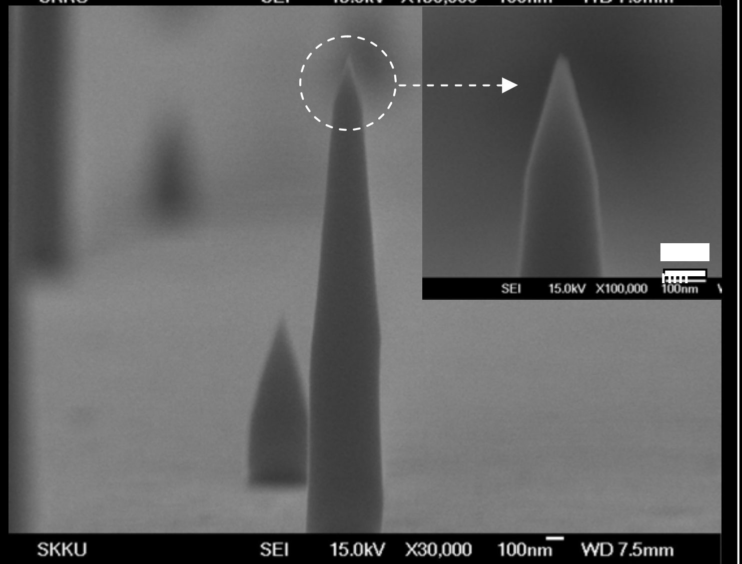


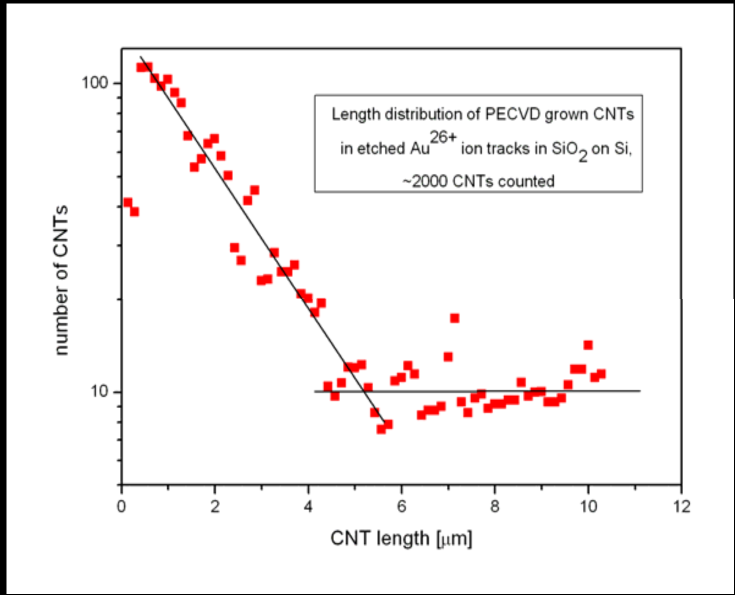


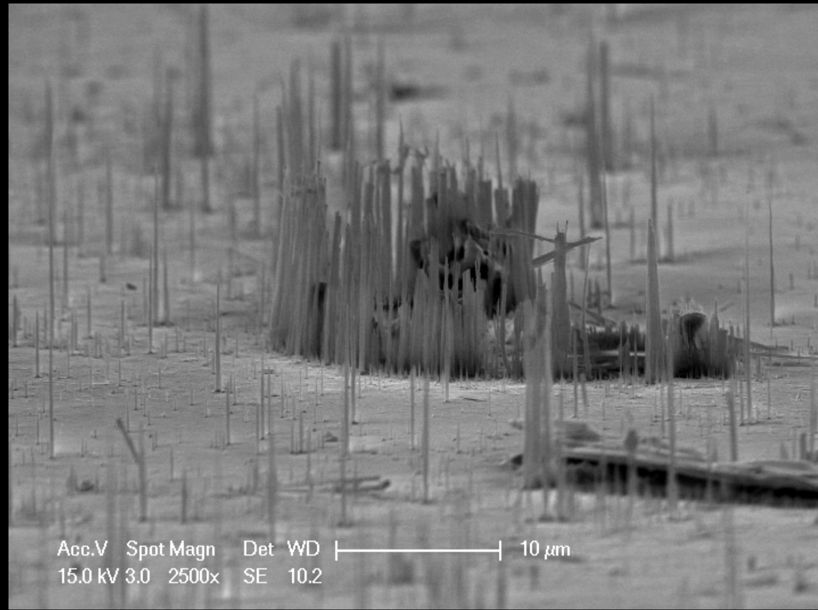
More images of PCVD grown CNTs in etched tracks

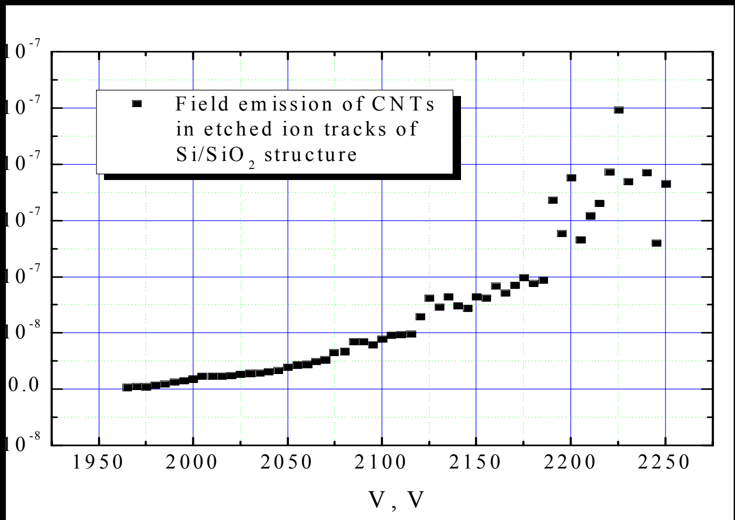


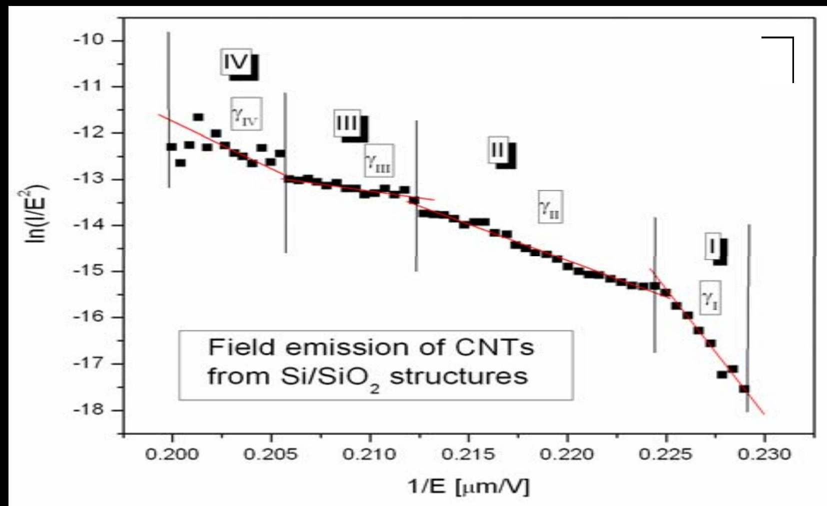




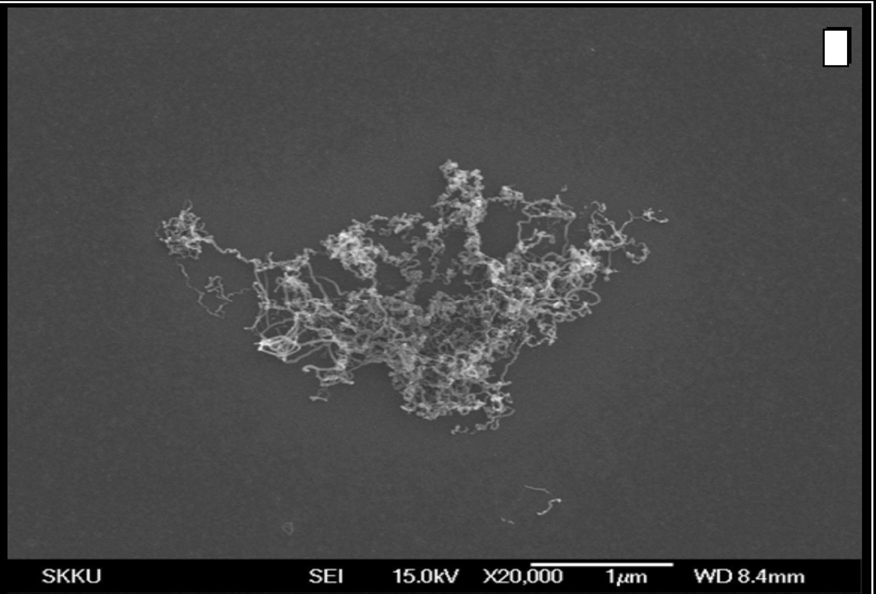

Length distribution of PECVD grown CNTs
in etched Au26+ ion tracks in SiO2 on Si,
~2000 CNTs counted
number of CNTs
CNT length [µm]
100
10
0
2
4
6
8
10
12

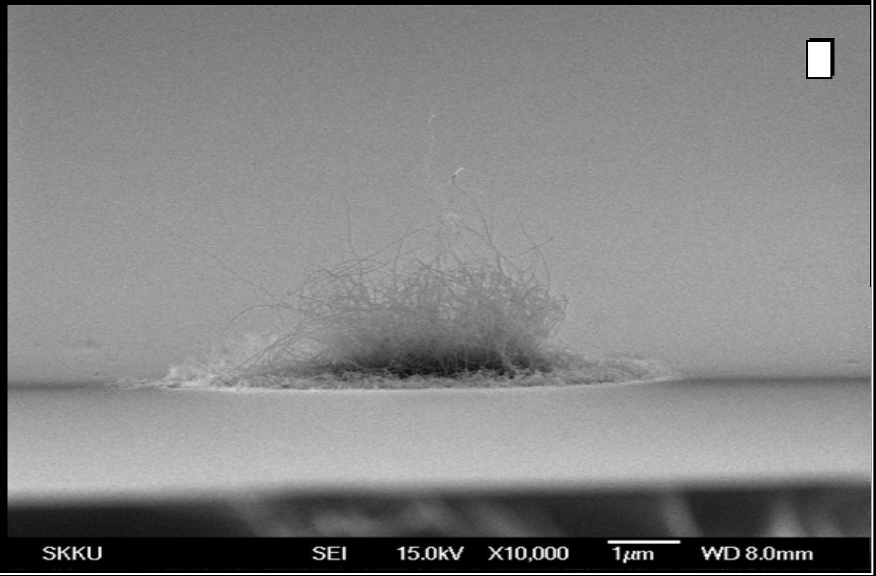

Acc.V Spot Magn Det WD 10 µm
15.0 kV 3.0 2500x SE 10.2


Field emission of CNTs
in etched ion tracks of
Si/SiO2 structure
V, V
1950
2000
2050
2100
2150
2200
2250


IV
III
II
I
Field emission of CNTs
from Si/SiO2 structures
ln(I/E2)
1/E [µm/V]
-10
-11
-12
-13
-14
-15
-16
-17
-18
0.200
0.205
0.210
0.215
0.220
0.225
0.230

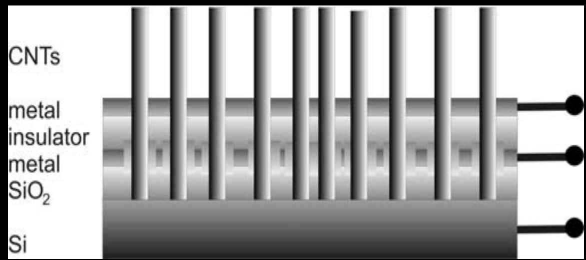
For comparison:
Thermal CVD grown
CNTs in tracks

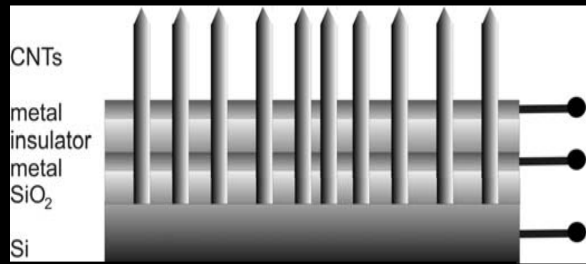


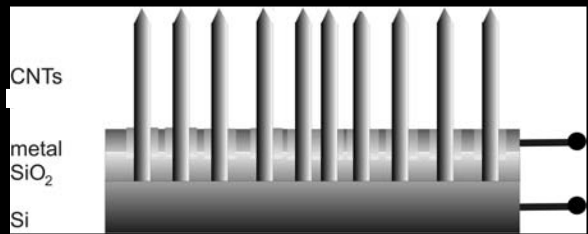


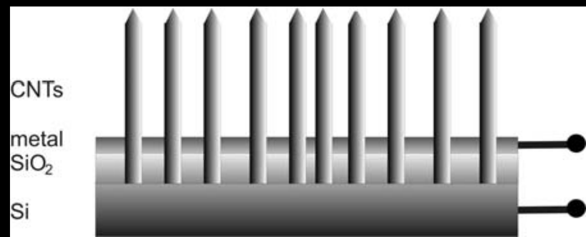
The aim: 3D nanoelectronics with PCVD-grown CNTs

examples:









Conclusion and Outlook:

- Nanoclusters and nanotubes are valuable building blocks for nanoelectronics, specifically to SITE
- As well „classical“ as novel electronic devices can be constructed with the help of NCs and NTs
- Especially promising are –

  * NCs for sensors

  * NCs for TEMPOS structures

  * CNTs for 3D nanoelectronics

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