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NanoSciences Innovation Centre

David T Britton

Nanoscience, Nanotechnology, and Nanovation

NANOSCIENCE
Basic and Applied Research into nanostructured materials and nanoscale processes.

NANOTECHNOLOGY
Applied Research and Development using nanoscale materials and nanoscale processes

NANOVATION
Social and Commercial Innovation enabled by Nanotechnology and founded on Nanoscience

But, what is Nano?

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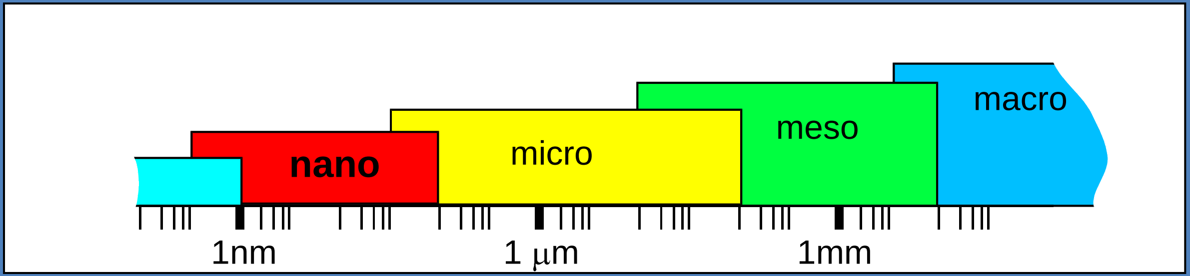
What is nano?

Attic Greek for “dwarf”

Nano- is the SI prefix for 10^{-9}
Nano- usually refers to sizes 1 to several hundred nm
(no fixed limits)



Nanomaterials: pieces of material with at least two external dimensions in the nanoscale. The remaining dimensions are usually microscopic or mesoscopic.

nanoparticles, nanorods, nanotubes and nanofibres

Nanostructures: objects which have been fabricated with nanoscale feature sizes.

transistors in a silicon chip, X-ray mirrors

Nanostructured materials: mesoscopic or microscopic pieces of material with an internal structure with at least one dimension in the nanoscale.

nanocomposites and nanocrystalline materials

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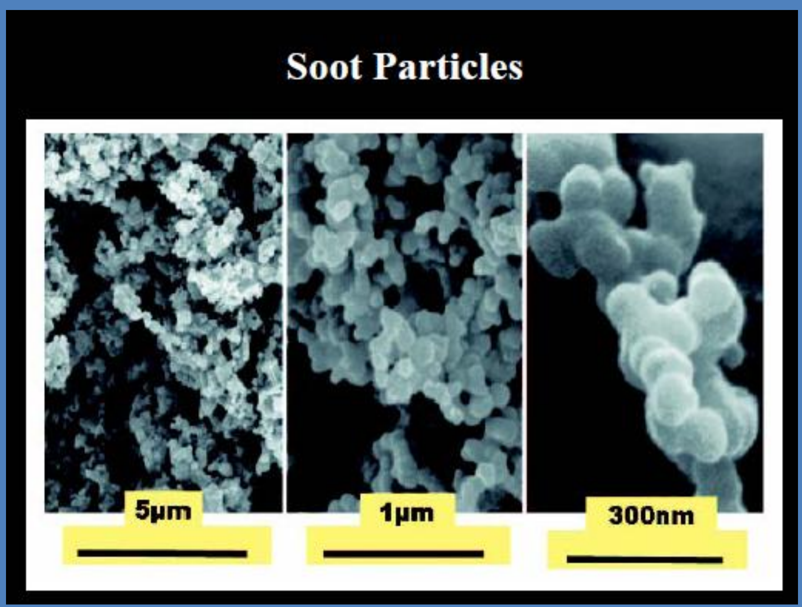
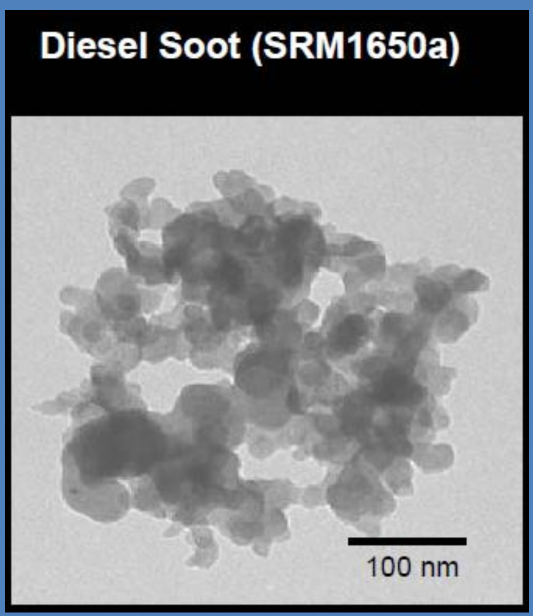
Is Nano Safe?

Most concerns are around nanomaterials
So far there is no legal definition of different nanomaterials or nanotechnologies
ISO Technical Standard 80004 (2010) & SA technical Standard 8004 (2011) for vocabulary in draft.
SA Legislation only in Hazardous Substances Act 15 of 1973 (as amended)
Draft Risk assessment ISO Technical report 13121





Nanomaterials are already here, and have been for a long time

NanoSciences

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Nanoscience is the study of materials, properties and phenomena on the nanoscale
The NanoSciences are physics, chemistry and biology

Size Effects
Metals become insulators
Metals and semiconductors become transparent

Structure Changes
Gases become solid


British Museum

Lycurgus Cup (c. 400 ad)
Gold nanoparticles in glass
are yellow in reflection,
red in transmission

Surface properties dominate
- Gold melts at room temperature
- Insulators become conductors
- Colours change
- Chemical reactivity changes
- Different forces become important


University of Akron

So why is Nano so important, now?

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NanoTechnology

Nanotechnology is the use of nanoscale materials and processes to do something useful

Generations of Nanotechnology

Generation 1 established Nanotechnology
Pigments
Catalysis
Colloids
Composites

Generation 2 new developments
Nanoporous membranes,
sensors,
printed electronics
solar cells
Nanocomposite materials
Ultra Large Scale Integation Chips
Synthetic antibodies

Generation 3 distant future
Molecular machines
Single molecule transistors
Synthetic virus
Self replicating structures

Generation 4 science fiction?
Nanobots
Grey goo
Nanosurgery
(all exist in nature)

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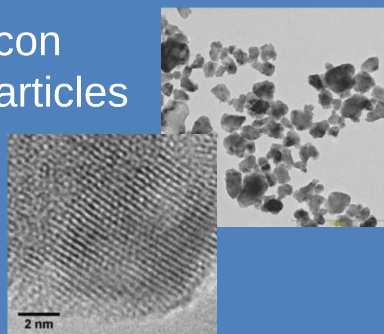
NanoTechnology: Printed Silicon

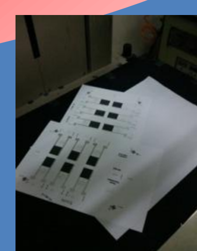
silicon nanoparticles



ink formulation

device design

printing on any substrate



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Nanotechnology: Why Silicon?

convenient band gap ~ 1.1 eV
energy where “nature also works”

~ atomic energy level spacing
↓
good coupling to metals for contacts

~ energy of visible light
↓
light sensitivity

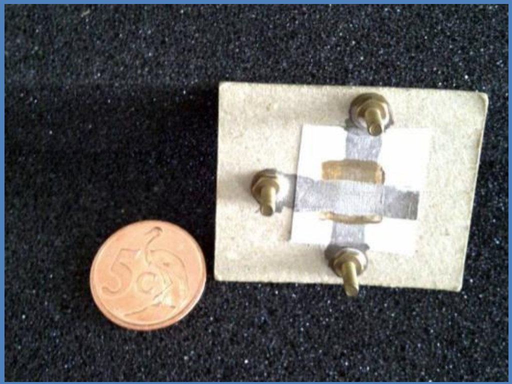
thermal excitation without saturation
↓
temperature sensitivity

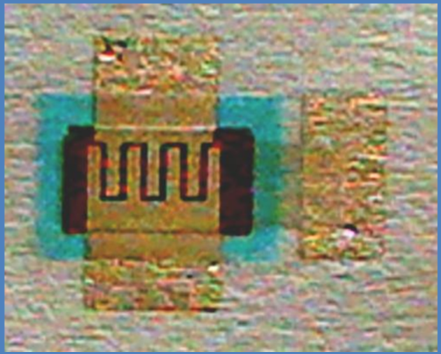
Silicon does not need band gap engineering

Silicon is the most widely studied and most widely used semiconductor
Silicon is safe and non-toxic

In 2001 everybody knew : Printed Electrons = Plastic Electronics

First Transistor printed in 2002

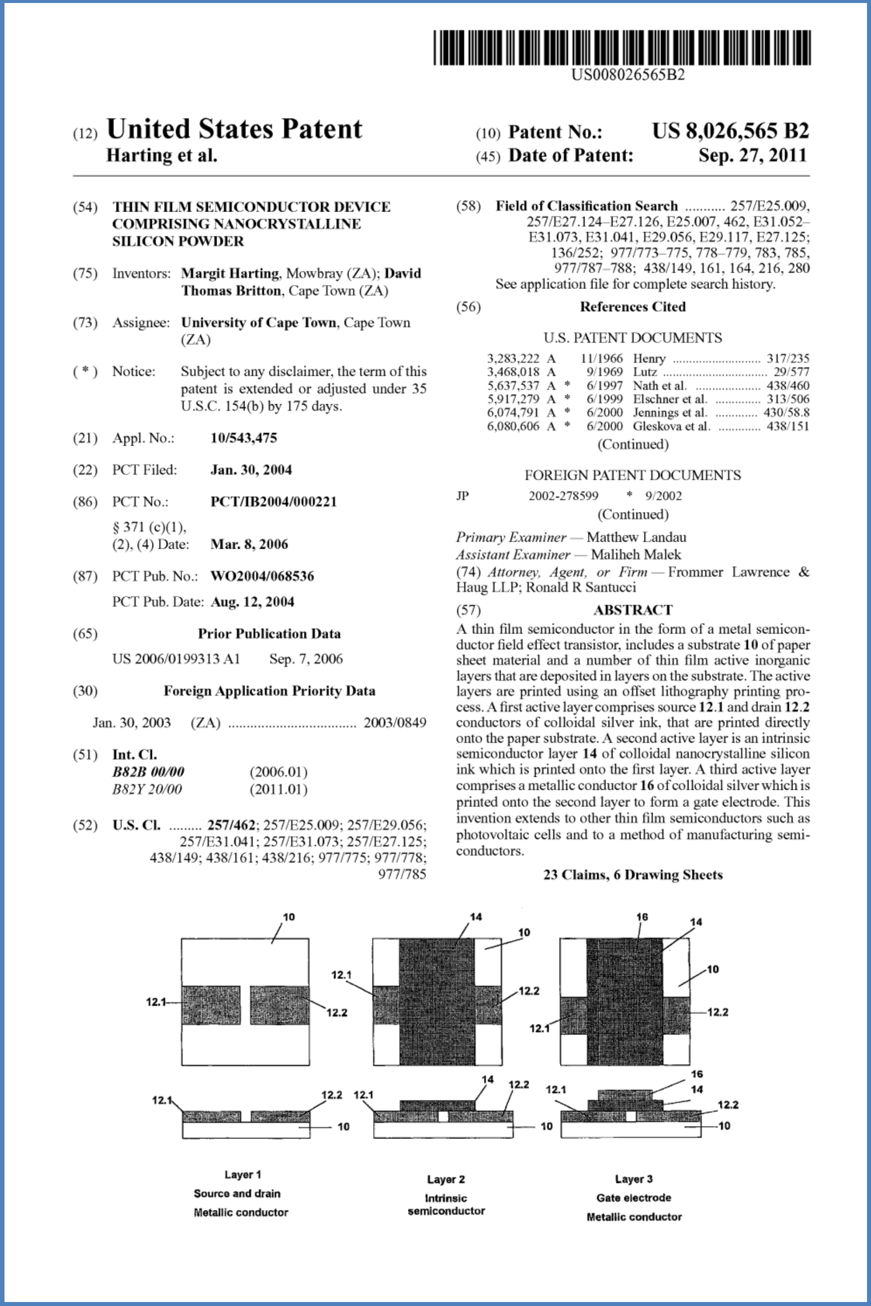




Härting, Gamota, Zhang & Britton, Appl Phys Lett 2009

It works…

…HOW?



US008026565B2

(12) **United States Patent**
Harting et al.

(10) **Patent No.: US 8,026,565 B2**
(45) **Date of Patent: Sep. 27, 2011**

(54) **THIN FILM SEMICONDUCTOR DEVICE COMPRISING NANOCRYSTALLINE SILICON POWDER**

(75) Inventors: **Margit Harting**, Mowbray (ZA); **David Thomas Britton**, Cape Town (ZA)

(73) Assignee: **University of Cape Town**, Cape Town (ZA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 175 days.

(21) Appl. No.: **10/543,475**

(22) PCT Filed: **Jan. 30, 2004**

(86) PCT No.: **PCT/IB2004/000221**

§ 371 (c)(1), (2), (4) Date: **Mar. 8, 2006**

(87) PCT Pub. No.: **WO2004/068536**

PCT Pub. Date: **Aug. 12, 2004**

(65) **Prior Publication Data**

US 2006/0199313 A1 Sep. 7, 2006

(30) **Foreign Application Priority Data**

Jan. 30, 2003 (ZA) 2003/0849

(51) **Int. Cl.**
B82B 00/00 (2006.01)
B82Y 20/00 (2011.01)

(52) **U.S. Cl.** **257/462**; 257/E25.009; 257/E29.056; 257/E31.041; 257/E31.073; 257/E27.125; 438/149; 438/161; 438/216; 977/775; 977/778; 977/785

(58) **Field of Classification Search** 257/E25.009, 257/E27.124–E27.126, E25.007, 462, E31.052–E31.073, E31.041, E29.056, E29.117, E27.125; 136/252; 977/773–775, 778–779, 783, 785, 977/787–788; 438/149, 161, 164, 216, 280
See application file for complete search history.

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(Continued)

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(Continued)

Primary Examiner — Matthew Landau
Assistant Examiner — Maliheh Malek
(74) *Attorney, Agent, or Firm* — Frommer Lawrence & Haug LLP; Ronald R Santucci

(57) **ABSTRACT**

A thin film semiconductor in the form of a metal semiconductor field effect transistor, includes a substrate **10** of paper sheet material and a number of thin film active inorganic layers that are deposited in layers on the substrate. The active layers are printed using an offset lithography printing process. A first active layer comprises source **12.1** and drain **12.2** conductors of colloidal silver ink, that are printed directly onto the paper substrate. A second active layer is an intrinsic semiconductor layer **14** of colloidal nanocrystalline silicon ink which is printed onto the first layer. A third active layer comprises a metallic conductor **16** of colloidal silver which is printed onto the second layer to form a gate electrode. This invention extends to other thin film semiconductors such as photovoltaic cells and to a method of manufacturing semiconductors.

23 Claims, 6 Drawing Sheets

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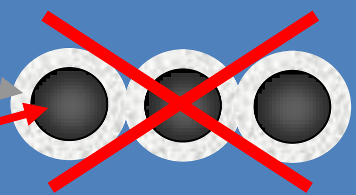
NanoScience: Silicon Nanoparticles

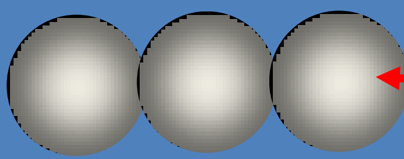
No capping layer

SiO_2 is highly insulating

SILICON



Electrical contact between particles



SILICON

Britton and Härting, Pure & Appl. Chem. 2006

No Confinement or only weak localization

Particle size > 10 nm

No Luminescence

e.g 1.6 eV luminescence band competes with electrical conductivity – either surface or size effect.

Control of the particle surface and interparticle interface is essential

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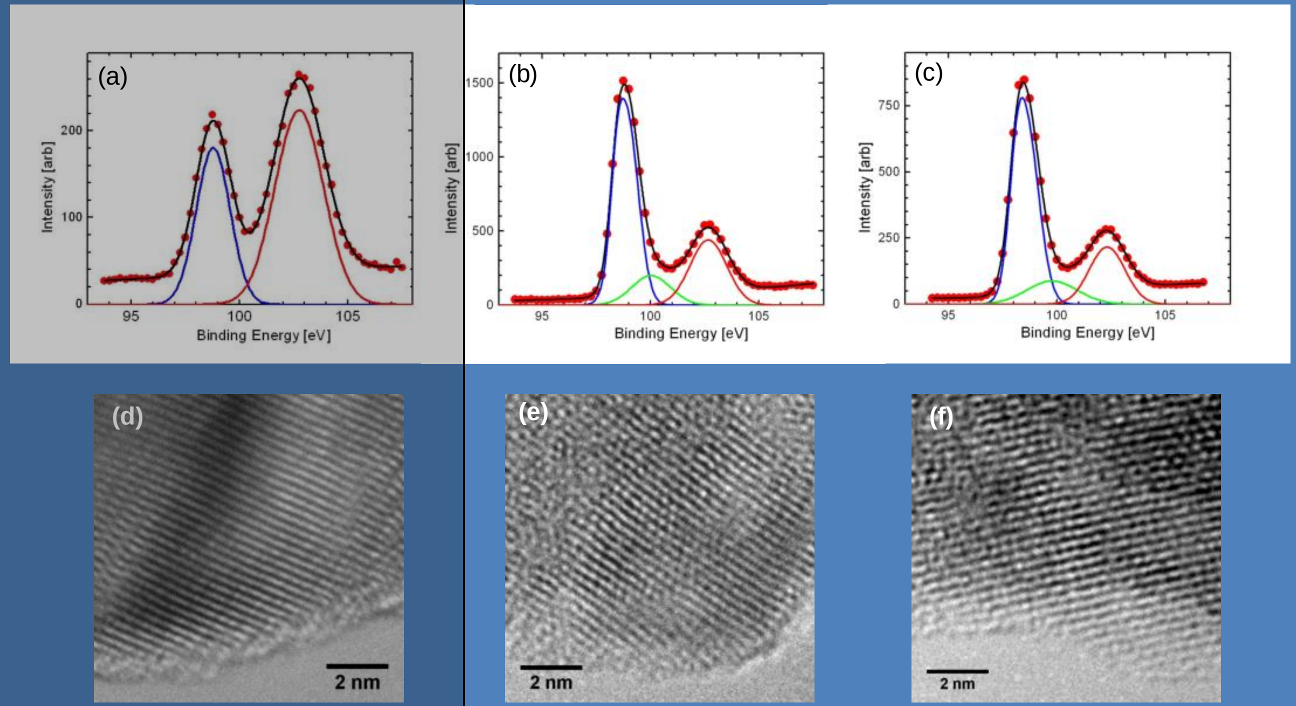
NanoScience: Silicon Nanoparticles

Si 2p XPS

HRTEM

Bad particle

Good Particles



Britton, Materials World 2010

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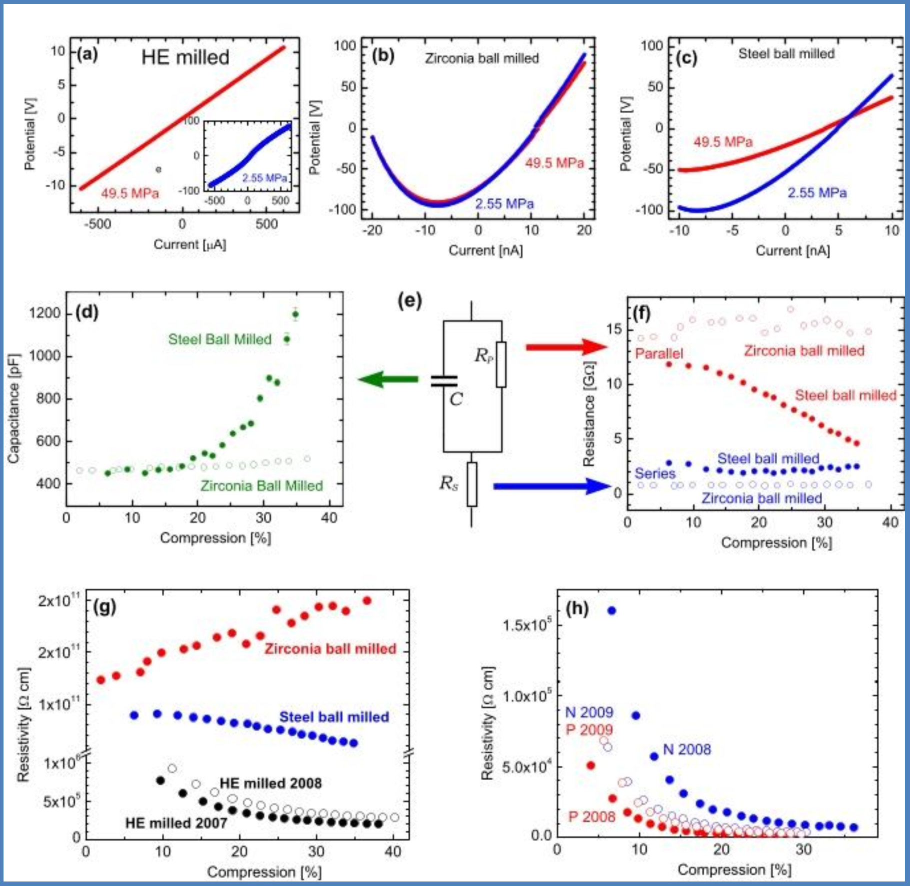
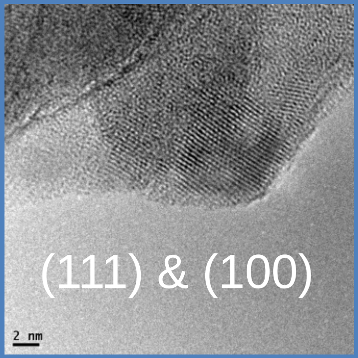
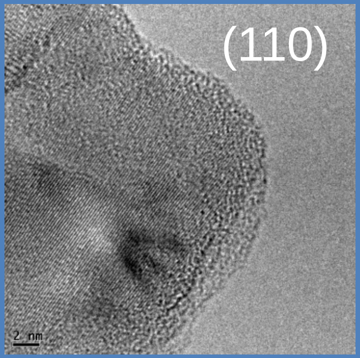
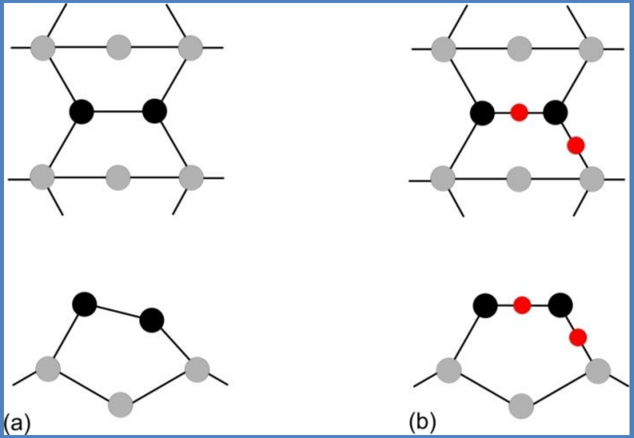
NanoScience: Silicon Nanoparticles









Härting et al, J. Phys Chem submitted

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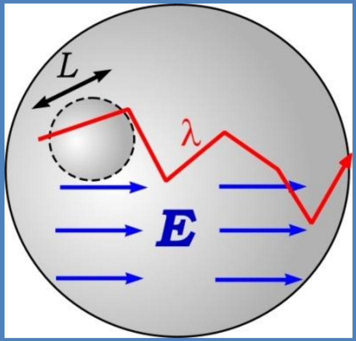
NanoScience: Nanoscale Charge Transport



Transport within a single particle or grain.

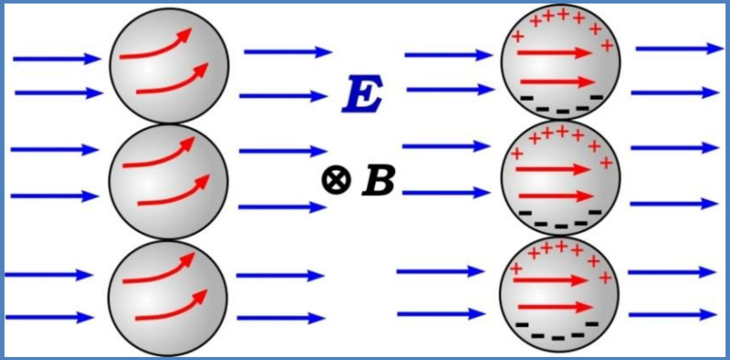
Ballistic for small particles at low temperature.

Limiting constant mobility

Drift in large particles at high temperature.

Mobility is dominated by scattering processes

$$\vec{J} = \left(n_h \mu_h - n_e \mu_e\right) \vec{E}$$



Hall Mobility is a local measurement.
Charge collection at boundary opposes magnetic force.
Hall mobility is independent of particle size.

But… particle size affects the carrier concentration.

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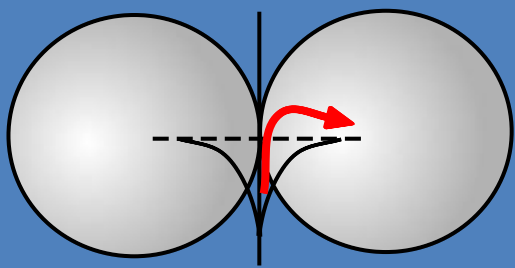
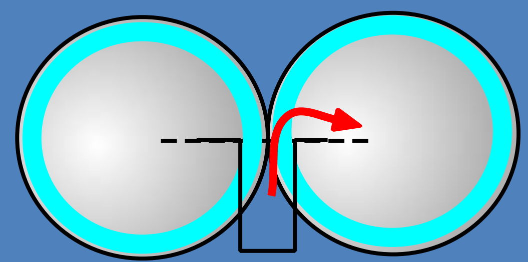
NanoScience: Microscale Charge Transport

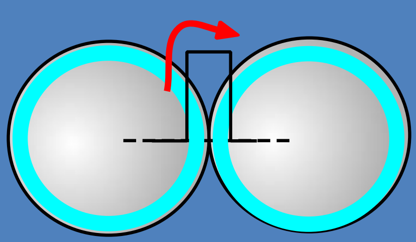
Charge collection at interface depletes carriers (depletion layer)
Could also be a real well.



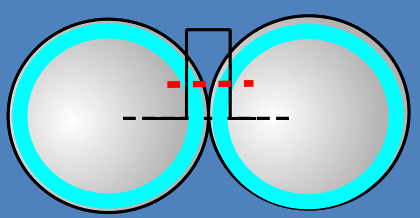


- Single range hopping between weakly localised states
- FE mobility low - similar to a-Si:H (except variable range)

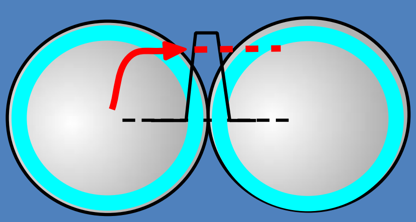
Also possible to have a barrier between particles



thermal activation



tunneling



thermally
activated tunneling

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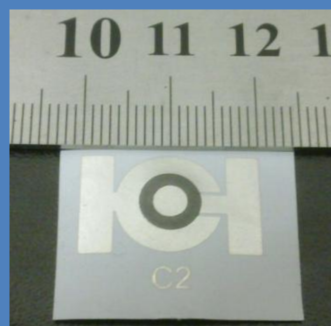
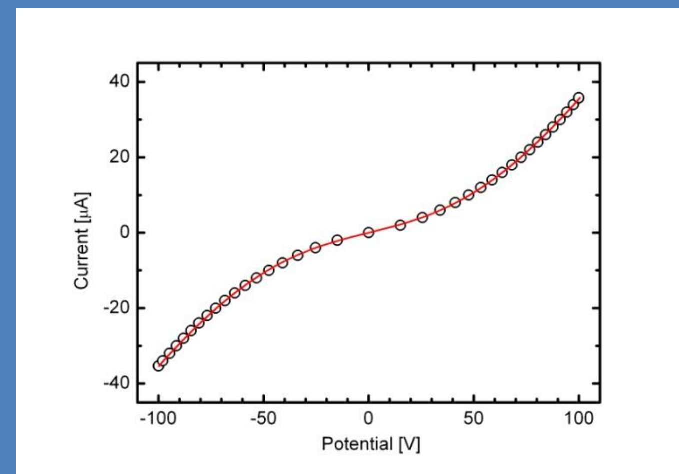
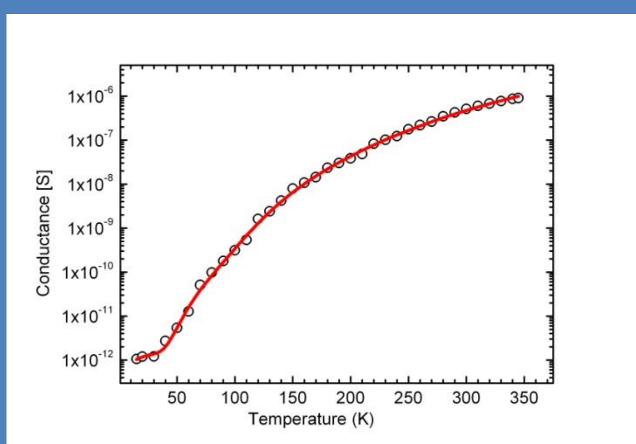
NanoScience: Microscale Charge Transport

Electrical properties of printed silicon



$$I = I_0 \left(\exp\left(e(V - IR_S)/nkT \right) - \exp\left(-e(V - IR_S)/nkT \right) \right)$$





4 Activation energies

0.7 ± 0.4 meV

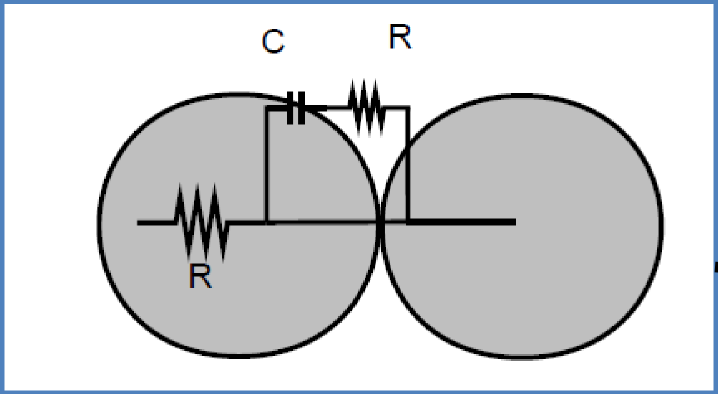
33 ± 3 meV

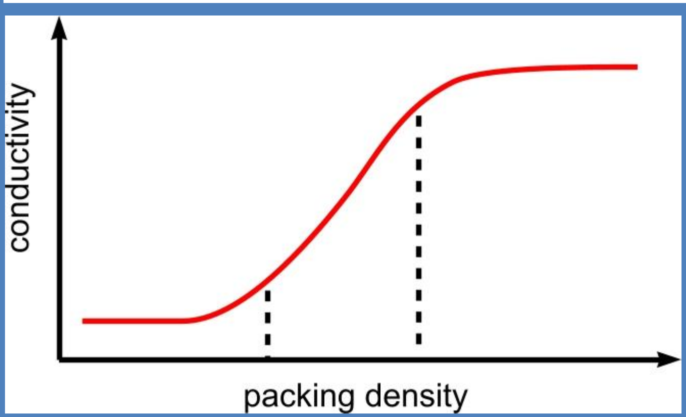
93 ± 9 meV

180 ± 35 meV

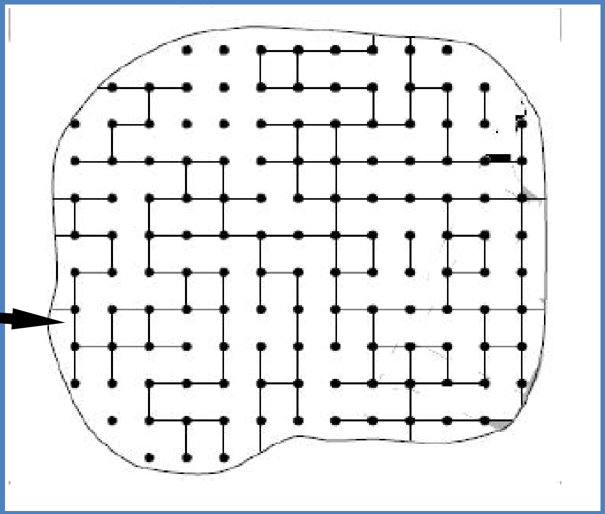
NanoScience: Mesoscale Charge Transport

Resistive and capacitive links between particles





Bond percolation model

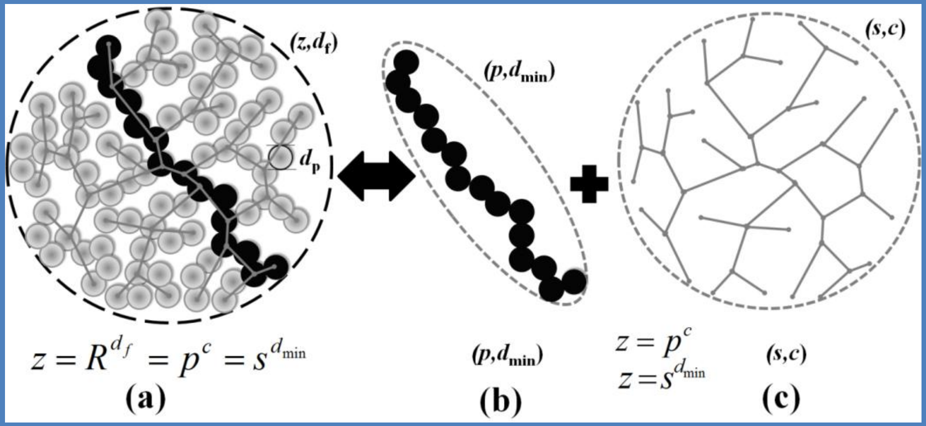


Two percolation thresholds

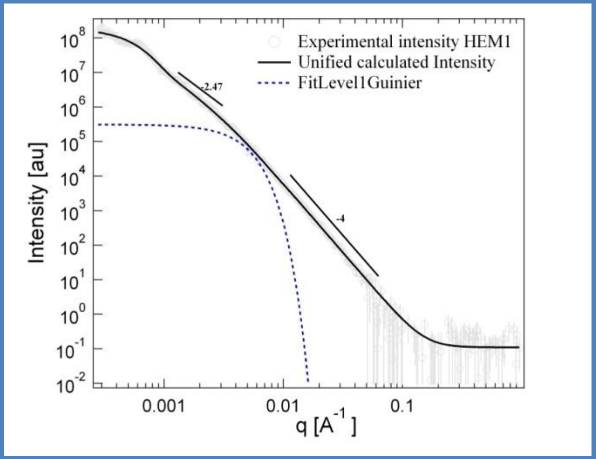
- Matrix (binder) dominates at low C
- Particle interconnections at high C

Interesting behavior in between

NanoScience: Mesoscale Structure



Rai et al, J. Chem. Phys 2012



Jonah et al, J. Nanopart. Res. 2012

Can use a “polymer chain” model to describe nanoparticle structures

Fluid flow determines large scale structure, but not local packing.

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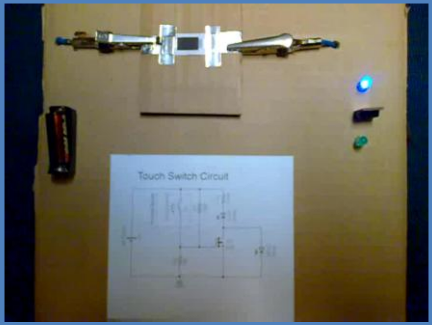
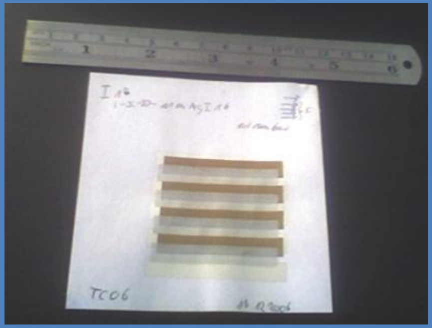
NanoTechnology: Printed Silicon Applications

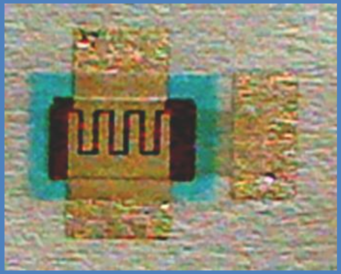
Electronic Devices using Silicon Nanoparticles



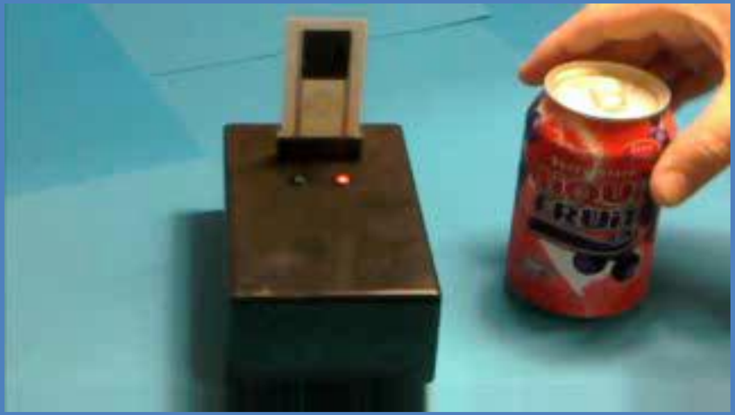
Touch switch



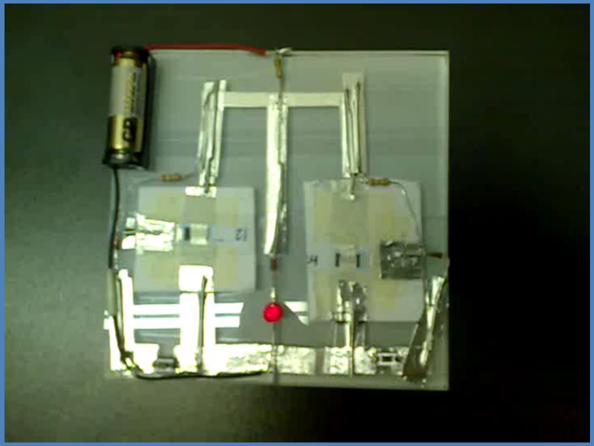
Solar cell



Printed silicon transistor



Temperature sensor



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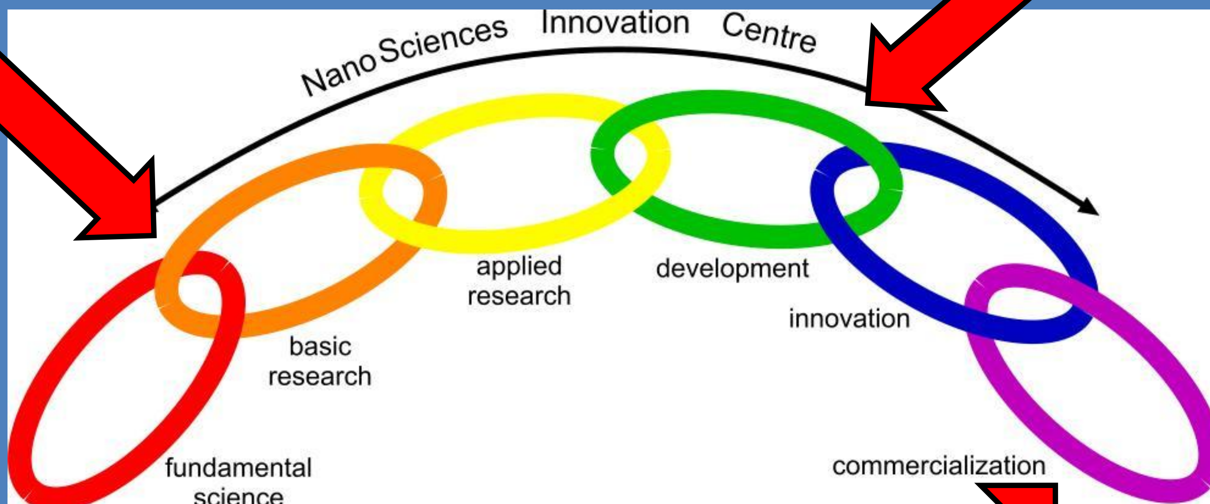
Innovation: 3 Golden Rules

Understand the basics

Don't copy - Innovate



Make something somebody wants

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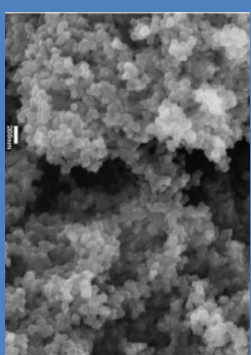
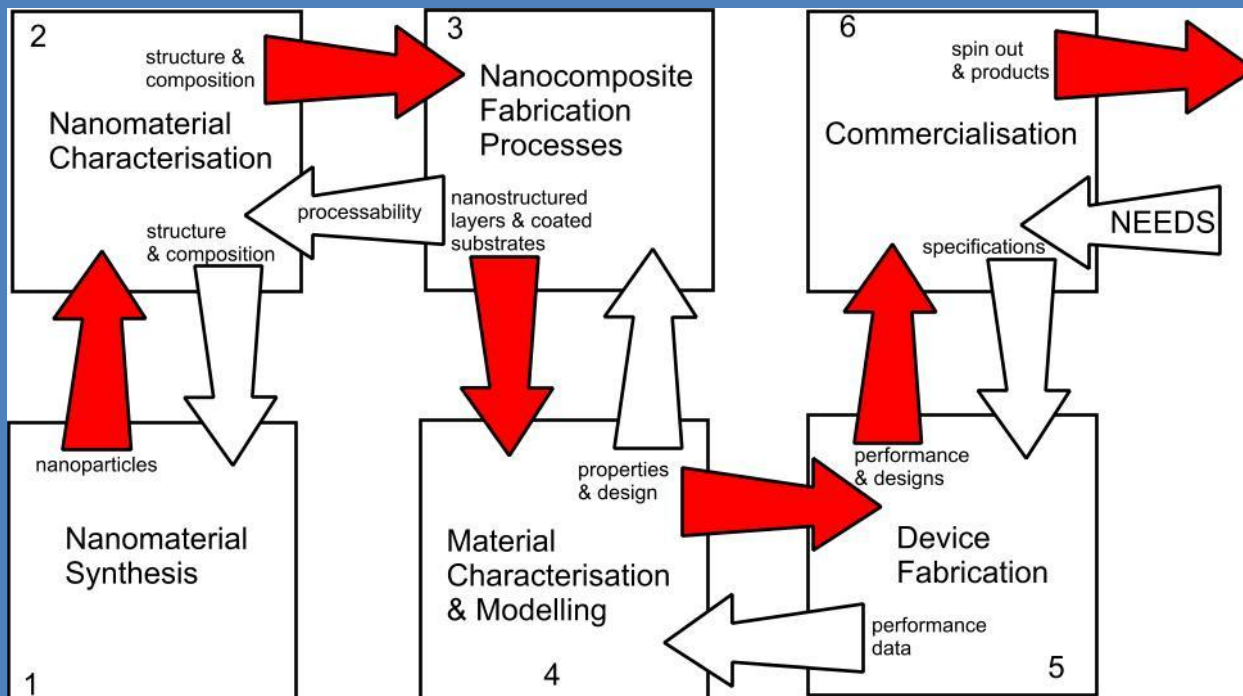
Innovation: Technology Road Map

To get from here…





… to here

needs a holistic view of the innovation chain and collaboration

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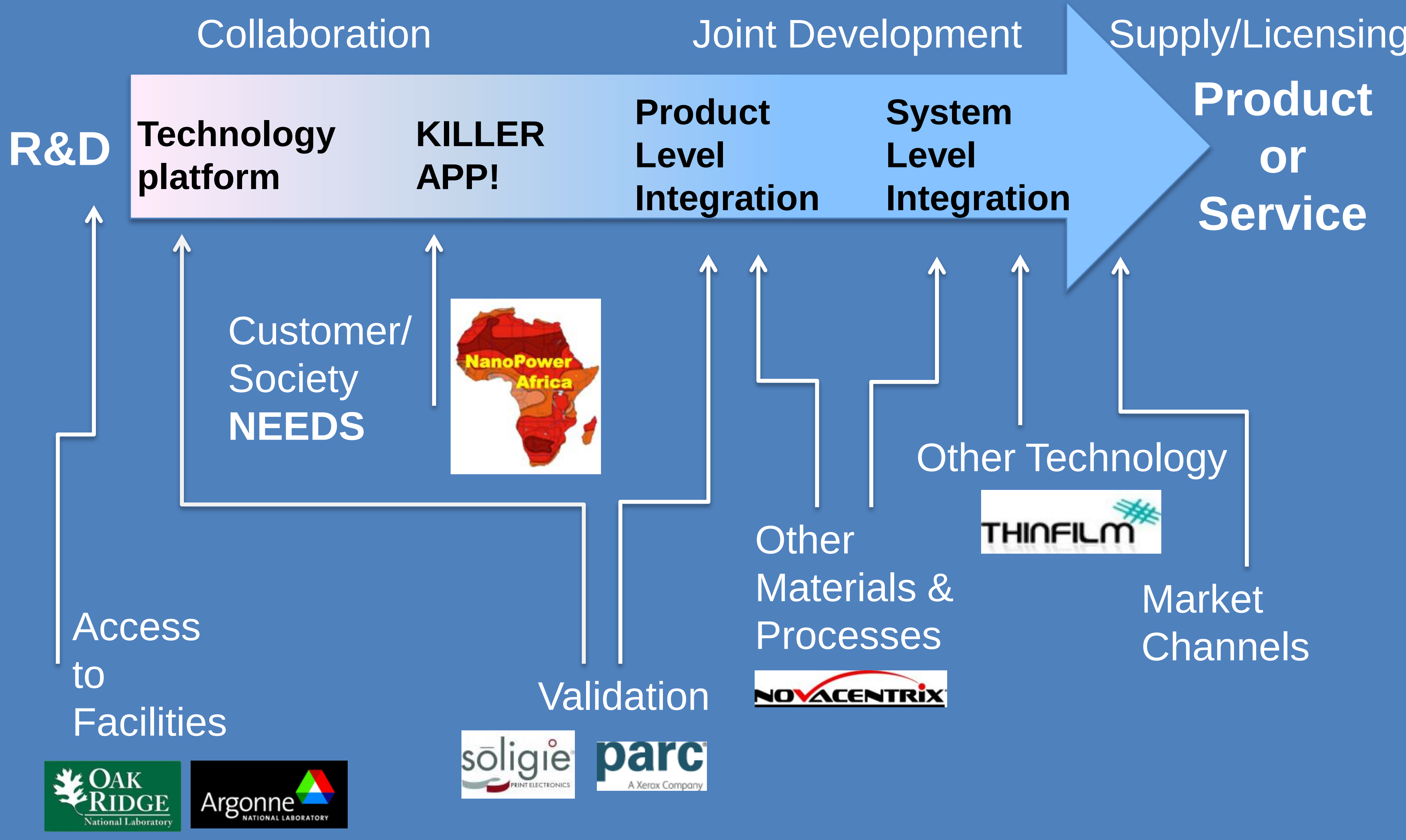
Innovation: Partnerships



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Structured Partnerships

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Materials research, device physics, IP generation

Technology Development

Product development, commercialisation

Capacity building, application development, social innovation

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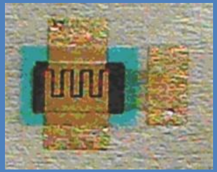
PST SENSORS

Nanovation: The Killer App!

The first product is not what you expect it to be

Work closely with marketing and business experts to identify the best opportunity
Collaborate with potential end-users
Market-Pull is better than Technology Push!

Prove it works



Collaborate with industrial and academic labs, including giving out samples
Dan Gamota & **Jie Zhang**, Motorola Central Research Labs/Printovate

Independent (industry) validation of prototype and production

sōligie PRINT ELECTRONICS

Find Customers & end-use applications

Beta test by sampling products
Work with market research companies

IDTechEx

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PST SENSORS

Nanovation: Temperature Sensors

NTC thermistor: electrical resistance decreases as temperature increases

Nominal resistance at 25 ^{0}C

current regulation (low end):
100 Ω< R_{25} < 1 MΩ

temperature sensors (high end):
R_{25} > 100 kΩ

conformable

printable on any substrate with suitable ink formulation

can be integrated in circuits

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PST SENSORS

Nanovation: Temperature Sensors

Sensors

Add Functionality

Enable Functionality

- Power
- Processing
- Memory
- Display
- Communication

Choice of partners and other technologies is important
Depends on the final application

Time –temperature tag for food and pharmaceutical products

IMPRINT energy · THINFILM · parc A Xerox Company · acreo

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NanoPower Africa

Social Innovation: Low Cost Solar

Solar power is already helping quality of life - largely through foreign NGO’s and government intervention.

Solar Light for Africa

Tanzania, Uganda, Rwanda, Liberia

1.6 billion people off-grid
1/2 vaccines lost
health & pollution problems

Low cost solar power has no commercial market pull

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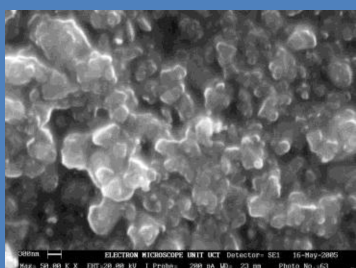
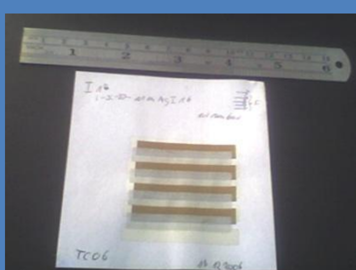
NanoPower Africa

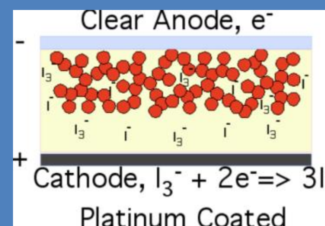
Social Innovation: Low Cost Solar

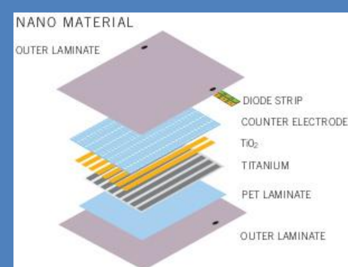
Printed silicon

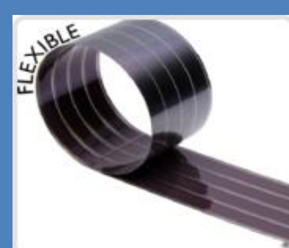




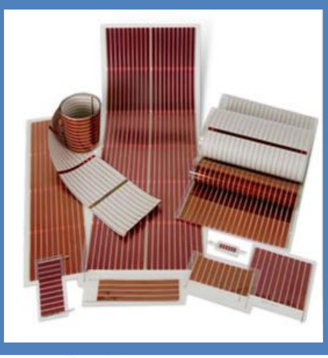
Photochemical

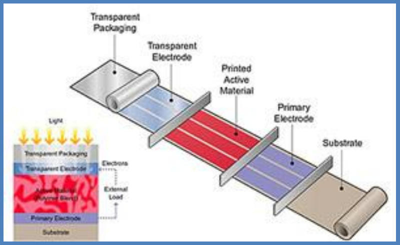






Nano + organic





More than just silicon
More than just science

UNIVERSITY OF CAPE TOWN
NanoSciences Innovation Centre

NanoPower Africa

Nano Power Africa Goals

develop and enhance teaching and research capacity in the academic disciplines supporting nanoscience and technology

develop the science and technology to commercialize an indigenous African solar cell technology.

develop a research network which will support entrepreneurial activities.

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NanoPower Africa

Nano Power Africa: Year 1

Successful implementation of video lecture course (UC, UCT, RU, HU, KIE & UB)

SAXS measurements at ANL led by UCT student
SANS measurements at ORNL led by HU staff member
Electrical and microscopy studies at UCT
First joint publication with Ethiopian address

1% efficiency from hybrid (non-printed) solar cell

Students install commercial solar modules in rural Ethiopia

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On behalf of myself, my colleague Margit Härting,
and the “Nanovators” of the NanoSciences Innovation Centre

Batsirai Magunje (ZW)
Emmanuel Jonah (NG)
Stephen Jones (ZA)
Stanley Walton (US)
Serges Zambou (CM)
Claire van den Berg (ZA)
Rhyme Setshedi (ZA)
Ulrich Männl (DE)
Rudolf Nüssl (DE)
David Unuigbe (NG)
Getinet Ashebir (ET)
Dereje Woldemariam (ET)
Tsige Atilaw (ET)

THANK YOU