Mechanics meets Electronics in nanoscale:

Fundamentals of nanoindentation and application for Electronic materials

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Aalto University, Finland

NORDIC HYSITRON LABORATORY

What is it about?

Towards plasticity of semiconductors equipped with nanoindentation and atomistic simulations

Nano-Stimulus => Atom-Simulus

To honor Prof. Aifantis, Antalya, *2015*

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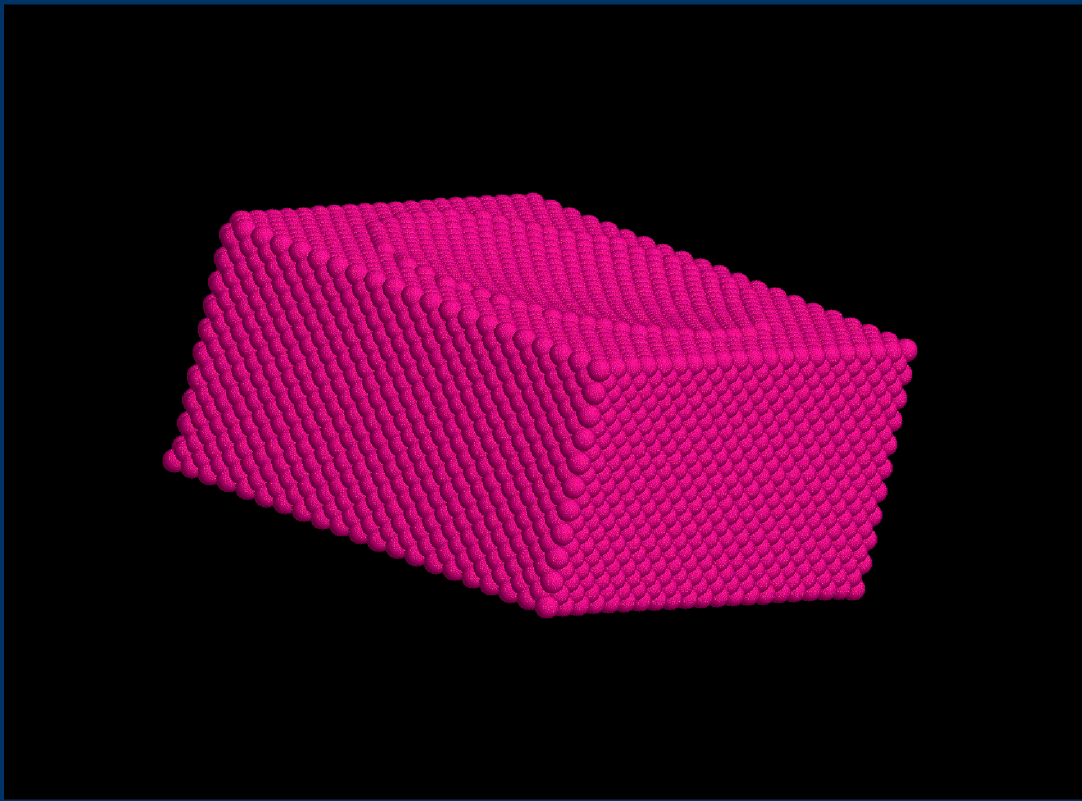
Nnanodeformed semiconductors



School of Chemical Technology 2012

NANOINDENTATION

THE TECHNIQUE CAPABLE TO DETERMINE **MECHANICAL PROPERTIES** OF MATERIALS AVAILABLE IN A **TINY** VOLUME !

What we face nowadays?

- The recent spectacular development of NEW MATERIALS
- The new questions and requirements brought by continued MINIATURIZATION in Electronics and development of NANOSTRUCTURED materials
- Necessity of concerted crystallographic, atomistic and quantum consideration in Materials Research

ALL THESE ALTER the expectations directed towards NANOINDENTATION

HARDNESS TEST → NANOINDENTATION PROCEDURE

→

FEM-aided SURFACE NANO-CONTACT PROBING

→

Atomistic calculations

Mechanical behavior - what is possibly in common with Electronics?

1) Mechanical properties frequently essential to design optoelectronic devices

2) Nanoscale contact deformation provides new means for nanopatterning substrates

3) "Phase-change materials" – future of optoelectronics. Localized high-pressure control.

4) Implementation of nanoindentation for internal stress measurements, interlayer film thickness (difussion/reaction barriers for electronics) …

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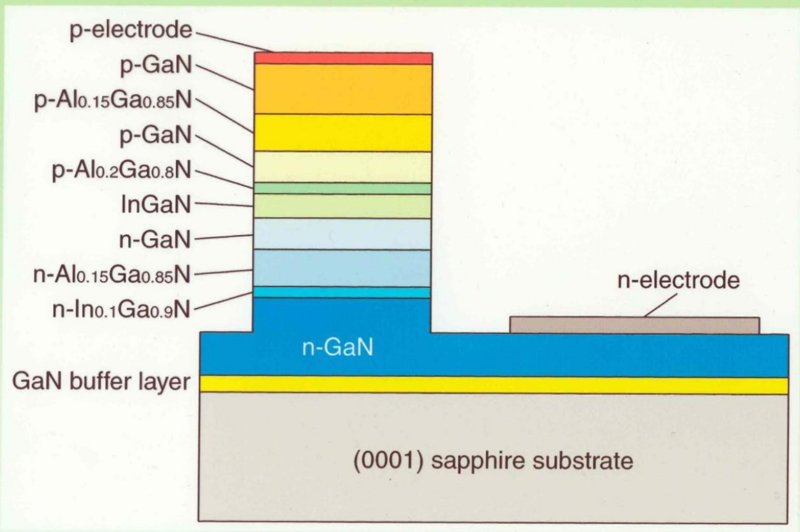
EXAMPLE 1



Nakamura at al.
Jpn. J. Appl. Phys. 35 (1996) L74

The difficulties with the production of a crack-free GaN layers were critical for Nakamura's construction of his first "blue laser"

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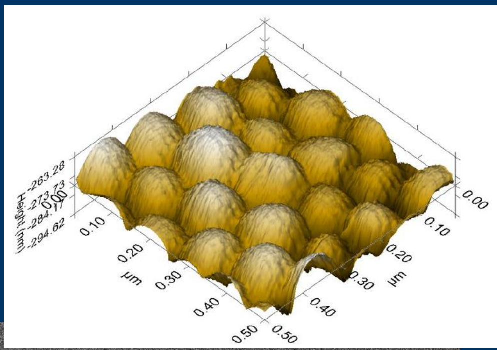
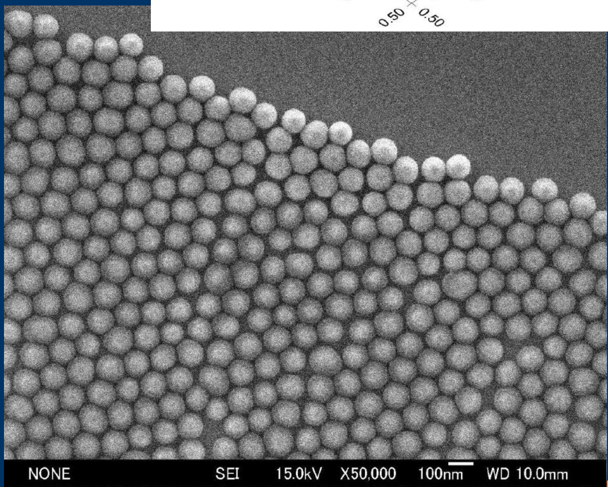
EXAMPLE 2

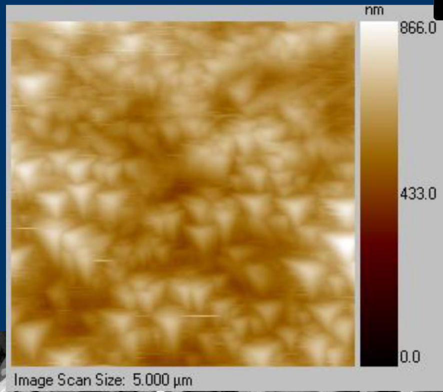
Nanomaterials

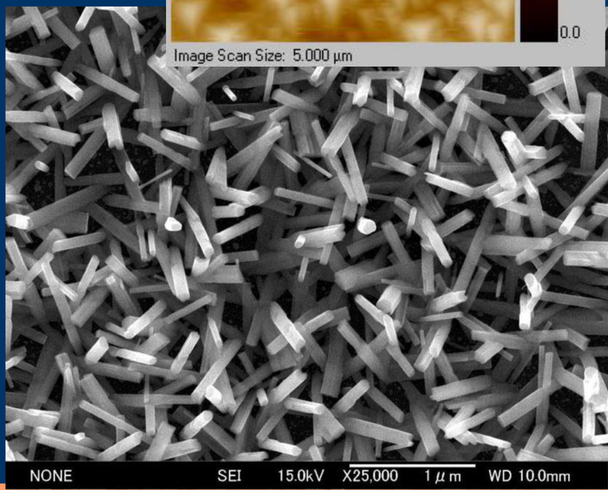
RAM
SiO_2 nanoballs (ϕ 100 nm)





COLOUR DISPLAYS
$W_{18}O_{49}$ nanowhiskers (ϕ 50 nm)





Manipulation of nanostructure – a great challange

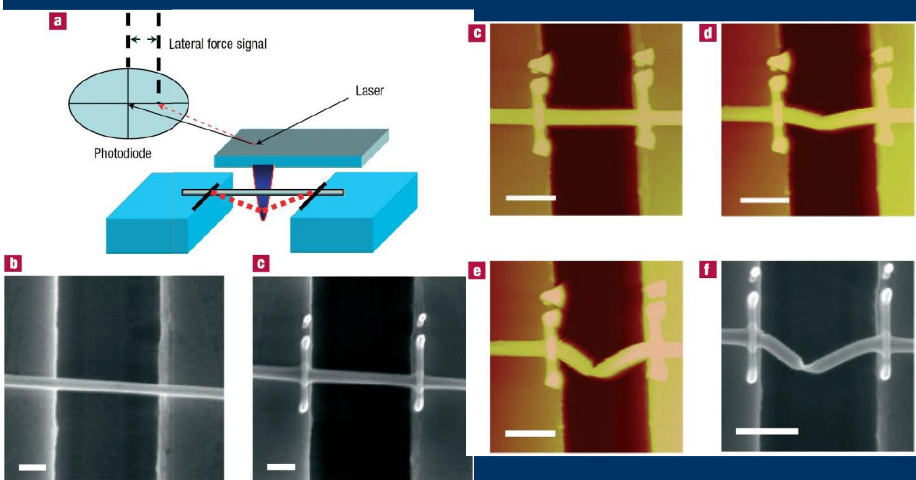
EXAMPLE 3

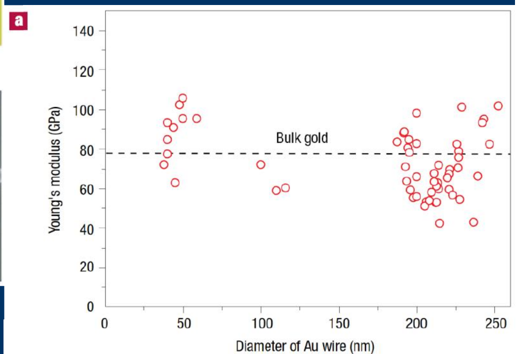
LETTERS

Mechanical properties of ultrahigh-strength gold nanowires

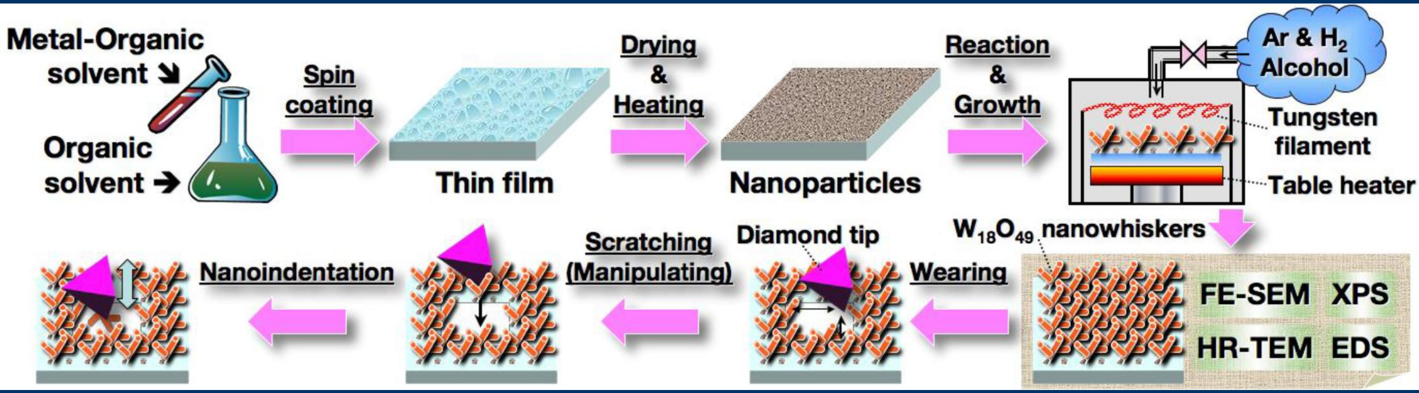
BIN WU[1]*, ANDREAS HEIDELBERG[1,2]* AND JOHN J. BOLAND[1†]
[1]Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) and the Department of Chemistry, Trinity College Dublin, Dublin 2, Ireland
[2]AGEF e.V.-Institut an der Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany
*These authors contributed equally to this work
†e-mail: jboland@tcd.ie

nature materials | VOL 4 | JULY 2005 | www.nature.com/naturematerials





EXAMPLE 3



All of this to improve colour displays

Hence, finally, what is the nanoindentation and how to use it?

Is nanoindentation extension of hardness testing? Why not?

Let's start from the basic equation that made career for decades:

$$H = \frac{P_{max}}{A_p} = \frac{4P_{max}}{\pi d^2}$$

$$H = p = 3\sigma_Y$$

Meyer's definition of hardness

H-s relationship found 1948 by Tabor, in 1989 proved theoretically by Hill

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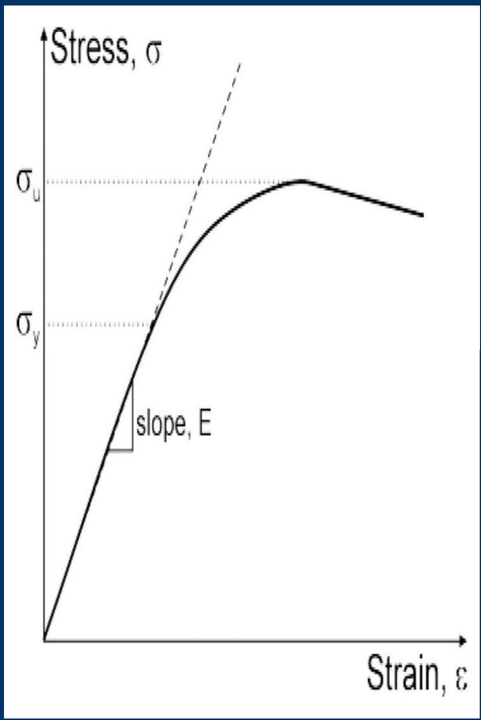
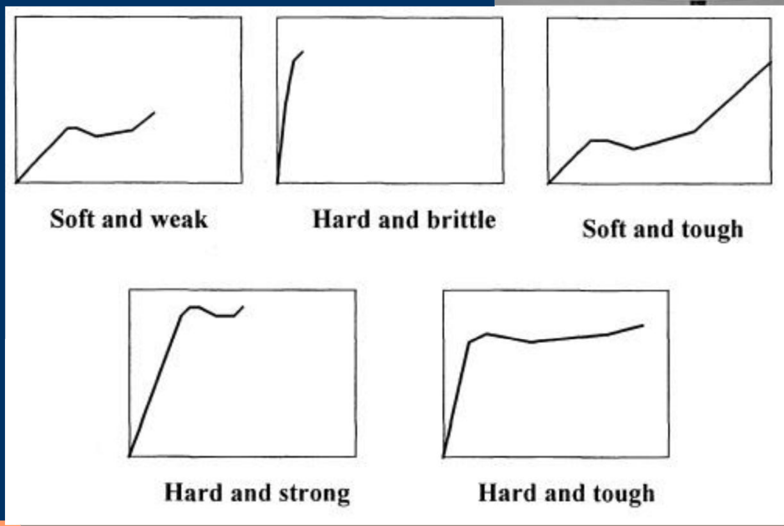
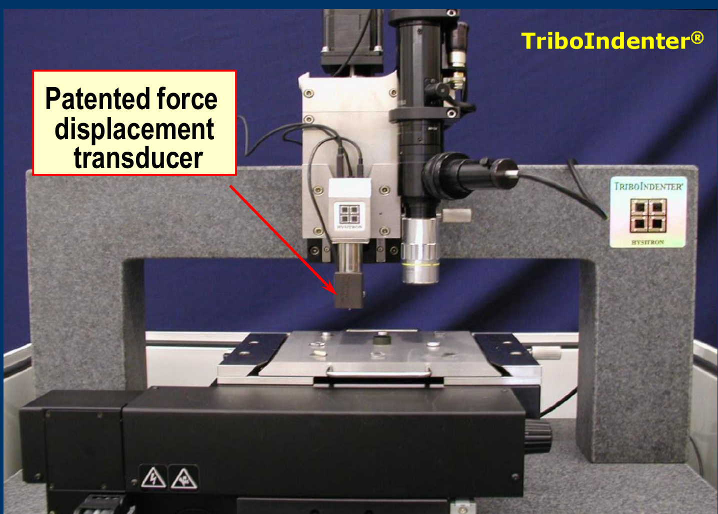
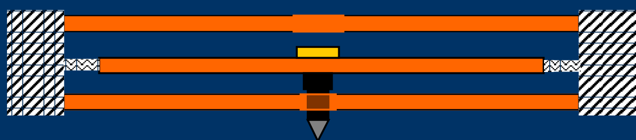


What is it all about?
Mechanical properties?



Nanoindentation– Unique method for near-surface-area characterization of advanced materials





- 3-Plate capacitive transducer
- Depth sensing
- Force generation
- Indentation & SPM *in-situ* imaging

Specifications

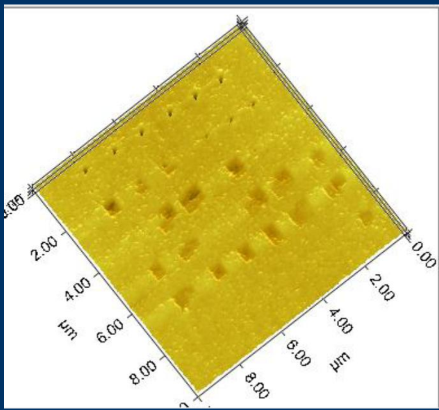
Maximum Force:	10,30mN
Load Resolution:	1nN
Load Noise Floor:	100nN
Maximum Depth:	20µm
Disp. Resolution:	0.04nm
Disp. Noise Floor:	0.2nm
Thermal Drift:	<0.05nm/sec

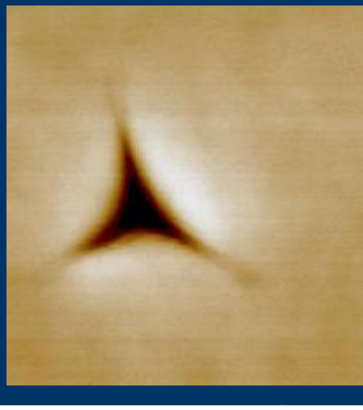
- **Nanoindentation**
  - -Hardness, Elastic Modulus, Stiffness
  - -Creep, Stress Relaxation
  - -Fracture Toughness

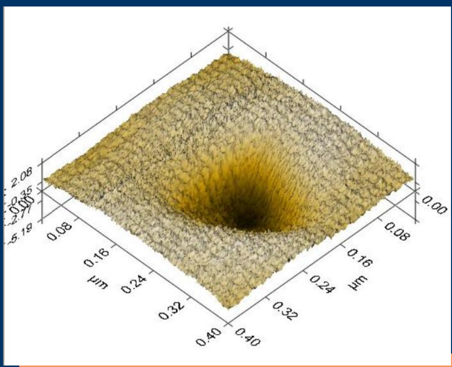
- **Nanoscratch**
  - -Coefficient of Friction
  - -Scratch Resistance, Critical Load
  - -Thin Film Adhesion, Delamination

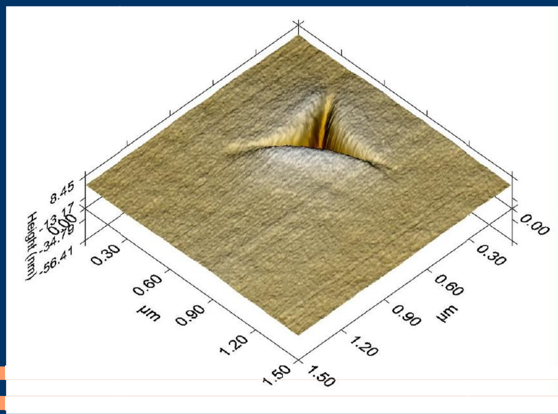
- **Nanowear**
  - -ScanningWear
  - -Wear Depth, Wear Resistance
  - -Nanomachining, Nanolithography

Nanoindentation with ***SPM imaging***



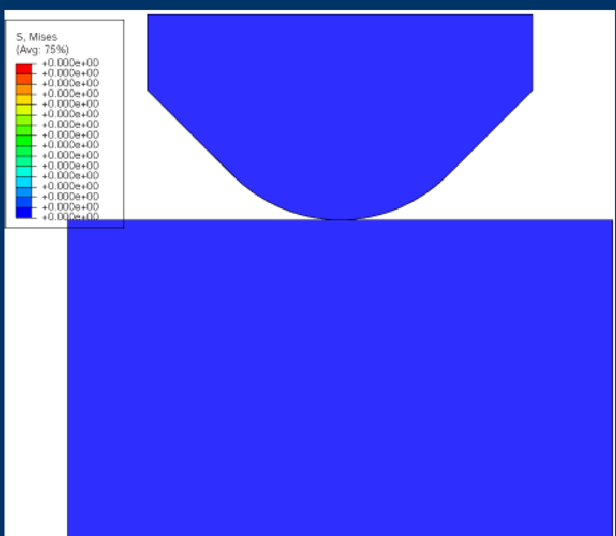


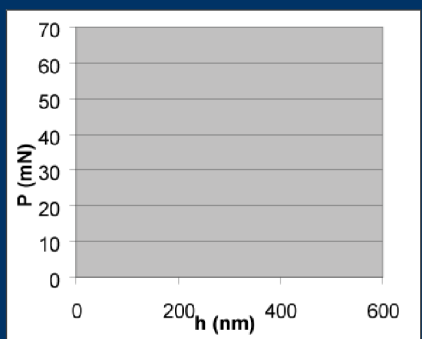


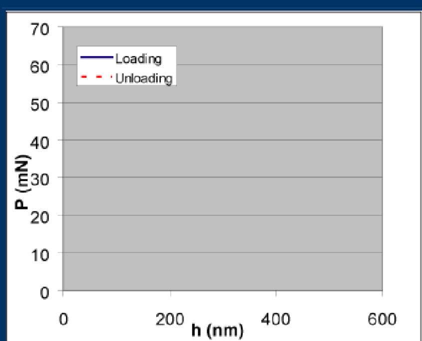


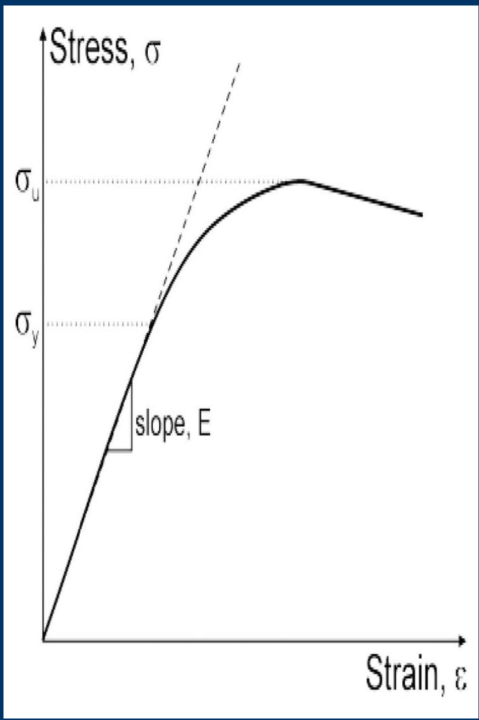
Contact probing of solid surfaces

MICRO-SCALE









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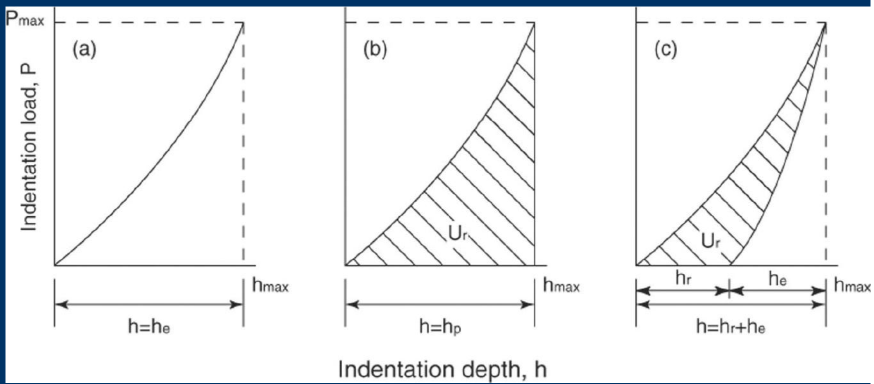
Mechanical properties?



WHERE IS PHYSICAL BACKGROUND HERE?

H. Hertz, J. reine und angewandte Mathematik **92**, 156-71 (1882)
H.R. Hertz, *Miscellaneous Papers*, Macmillan, London (1986), chaps. 5 and 6

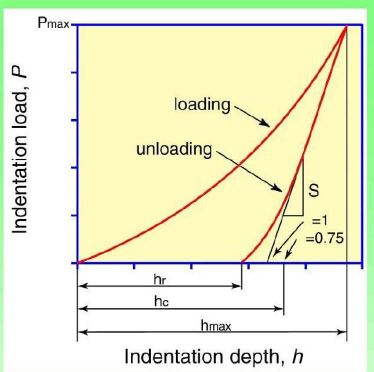
$$\frac{1}{E_{eff}} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

Bulychev, V.P. et al. Int. Lab. **41**, 1409-12 (1975)
R.B. King, Int. J. Solids Structures **23**, 1657-64 (1987)

$$S = \frac{dP}{dh} = \frac{2}{\sqrt{\pi}} E_{eff} \sqrt{A}$$

CONVENTIONAL ANALYSIS OF NOINDENTATION

Doerner – Nix / Pharr – Oliver approach



Schematic of the indentation load-displacement curve with the parameters used in the Oliver and Pharr analysis.

$$h_e = h_{max} - h_p = \frac{P_{max}}{S}$$

$$P = \alpha h^m$$

$$P = B(h - h_f)^m$$

$$h_c = h_{max} - \varepsilon \frac{P_{max}}{S}$$

$$S = \frac{dP}{dh}\Big|_{h=h_{max}} = B(h_{max} - h_f)^{m-1}$$

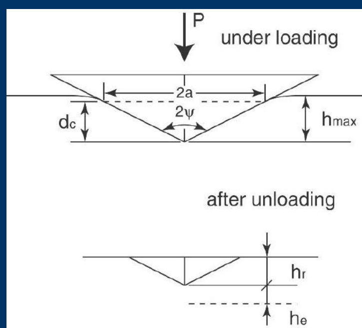
$$\frac{1-\nu_1^2}{E_1} = \frac{1}{E_{eff}} - \frac{1-\nu_2^2}{E_2} = \frac{2}{S\sqrt{\pi}}\sqrt{A} - \frac{1-\nu_2^2}{E_2}$$

$$E_{eff} = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A}}$$

INTERESTING PHYSICAL APPROACH
ENERGY PRINCIPLE OF INDENTATION

U_r* – energy *(Sakai & Nowak 1992)

Conical/Triangular indentation



$$h = \gamma a \cot\psi$$

$$p = \frac{P}{\alpha_o a^2}$$

For perfectly plastic contact *p=H*

$$P = A_p h_p^2$$ where $$A_p = H\frac{\alpha_o}{\gamma_p^2}\tan^2\psi$$

For perfectly elastic contact *(Sneddon)*

$$P = A_e h_e^2$$ where $$A_e = \frac{E}{2(1-\nu^2)}\frac{\alpha_o}{\gamma_e^2}\tan^2\psi$$

Constitutive equation

$$h = h_e + h_p$$

ENERGY PRINCIPLE OF INDENTATION

For elasto-plastic contact:

$$P = A_H h^2 \quad \text{where} \quad A_H = \hat{H}\frac{\alpha_o}{\gamma_H^2}\tan^2\psi \qquad \hat{H} = H_T\left(\gamma_H^{-1} + k\sqrt{\frac{H_T(1-\nu^2)}{E}}\right)^{-2}$$

$$k^2 = \frac{2\gamma_e^2}{\gamma_H^2}\tan^2\psi$$

Compatibility condition

$$A_H h^2 = A_e(h-h_p)^2 \Rightarrow P = A_e(h-h_r)^2$$

The shape of P(h) defined!

$$U_r = \int_0^{h_{max}=h_r} A_p h^2 dh = H_T V$$

$$U_r = \int_0^{h_{max}} A_H h^2 dh - \int_{h_r}^{h_{max}} A_e (h-h_r)^2 dh = \Gamma_I V$$

$$\Gamma_I = H_T\left(1 + k\sqrt{\frac{H_T(1-\nu^2)}{E}}\right)^{-3}$$

$$U_r = \left(3\sqrt{\alpha_0}\tan\psi\right)^{-1} H_T^{-\frac{1}{2}} P_{max}^{\frac{3}{2}} = C P_{max}^{\frac{3}{2}}$$

EPI confirmation

Giannakopoulos and P.L. Larsson, Mech. Mater. 25, 1-35 (1997)

$$P = 2.0746(1 - 0.1655\nu - 0.1737\nu^2 - 0.1862\nu^3)\frac{E}{1-\nu^2}h^2$$

$$P = -\int \sigma_{2j} N_j dA_c = Ch^2$$

$$U_r = \int_0^{h_{max}} P dh = \frac{P_{max}^{3/2}}{3C^{1/2}}$$

EPI-based previous research

M. Sakai and R. Nowak, Fracture toughness and brittleness of ceramic materials, ***Proc. Int. Ceram. Conf. AUSTCERAM 92****, ed. by M.J. Bannister, CSIRO Publications, 922-931(1992)*

R. Nowak and M. Sakai, Energy principle of indentation contact: The application to sapphire, ***J. Mater. Res. 8****, 1068-1078 (1993)*

W. Ensinger and R. Nowak, On the influence of the low energy Tantalum ion implantation on indentation fracture and hardness of α-alumina single crystals, ***Nucl. Instr. Meth, Phys. Res. B80****, 1085-1090 (1993)*

W. Ensinger, R. Nowak, Y. Horino and K. Baba, Modification of mechanical properties of single crystal aluminum oxide by ion beam induced structural changes, ***Ceram. Forum Int. 70****, 164-167 (1993)*

R. Nowak and M. Sakai, The anisotropy of surface deformation of sapphire: Continuous indentation of triangular indenter, ***Acta metall. et materialia 42****, 2879-2891 (1994)*

R. Nowak, C.L. Li and S. Maruno, Low-load indentation behaviour of HfN thin films deposited by reactive r.f. sputtering, ***J. Mater. Res. 12****, 64-69 (1997)*

We will return again to these theories later on. They are commented at this point merely to introduce the main ideas and to explain the scale of difficulty.

OUR MAIN GOAL REMAINS – MECHANICS MEETS ELECTRONICS IN NANOSCALE

Nordic Hysitron Laboratory

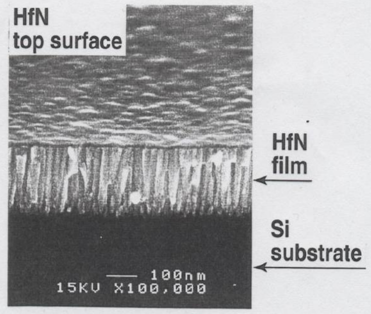
The Japanese Laboratory
inside
The European University

PRL May 2007

What are
Nano-structured Materials & Thin Films?

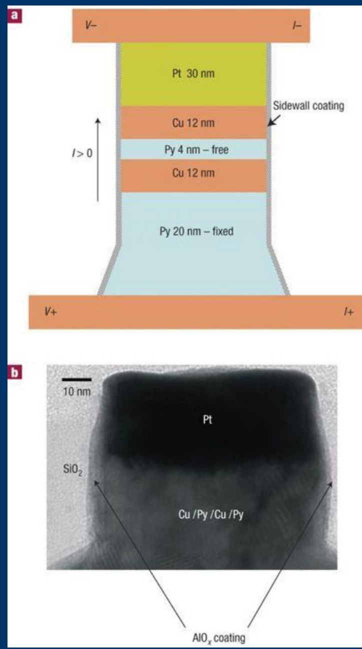
Evolution of definition? Evolution of our understanding?

1999



The columnar structure of HfN films, sputter-deposited on a silicon substrate. The FE-SEM micrograph illustrates the morphology typical for both virgin and ion-modified layers.

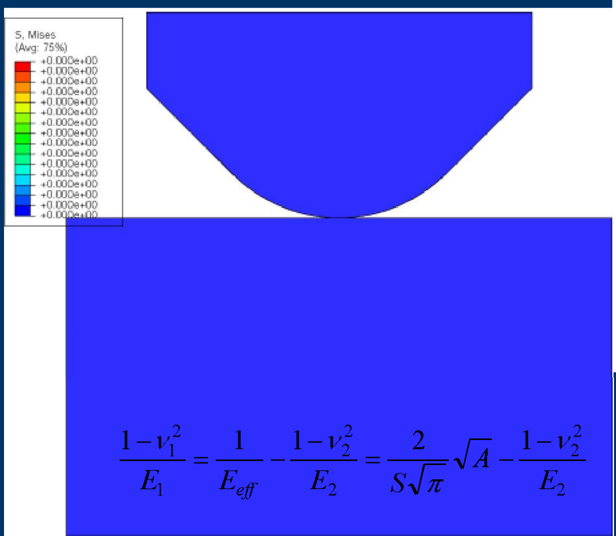
2008



Ozatay et al. Nature Materials 7, 567 (2008)

Contact probing of solid surfaces

NANO-SCALE



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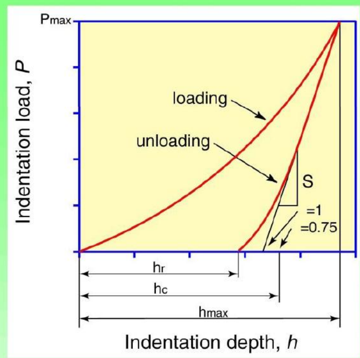
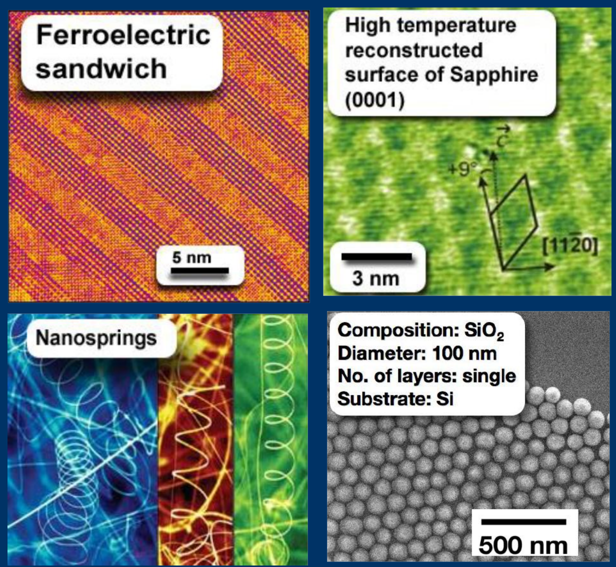


Schematic of the indentation load-displacement curve with the parameters used in the Oliver and Pharr analysis.

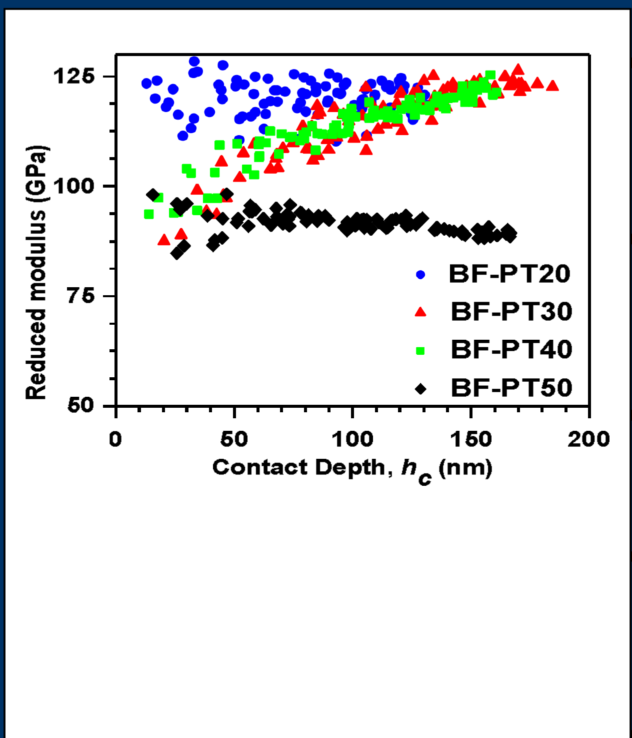
▲ Not in nano !!!

Targeted Advanced Materials and Structures



- New multiferroic thin films prepared in Japan by sol-gel **$BiFeO_3$-$PbTiO_3$**
- Crystalline substrates for electronics (Al_2O_3, Si, SiC)
- Outer layer of human bones
- Nano-balls (SiO_2) and Nano-whiskers ($W_{18}O_{49}$)
- Surface of semiconductors (GaAs, GaN)

Targeted Advanced Materials and Structures



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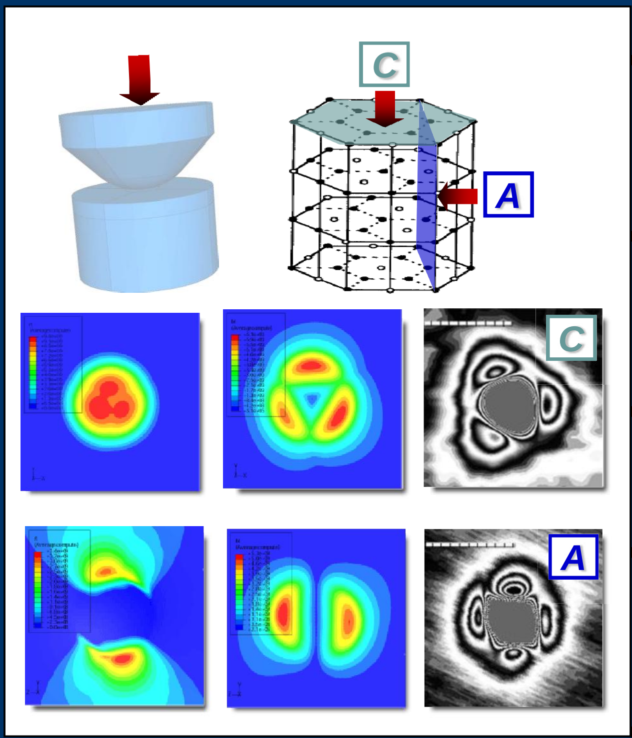
Advanced Materials and Structures Evaluated by our Group



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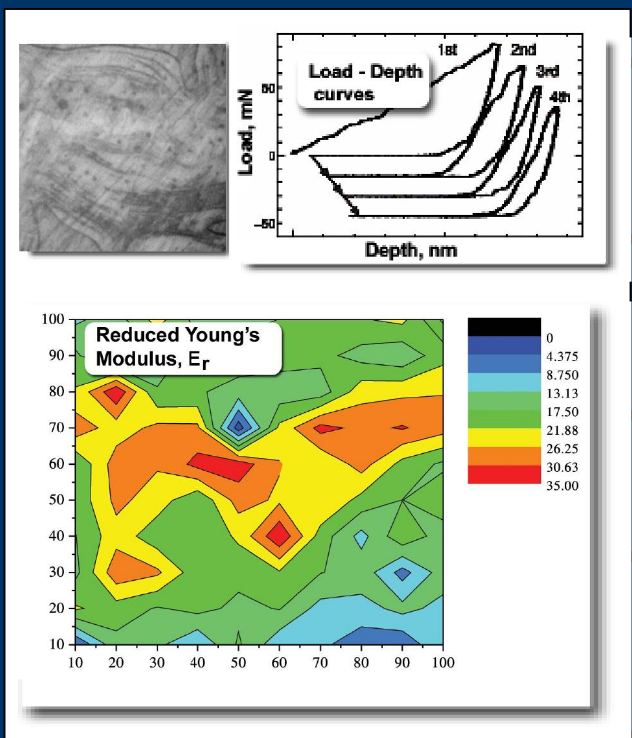

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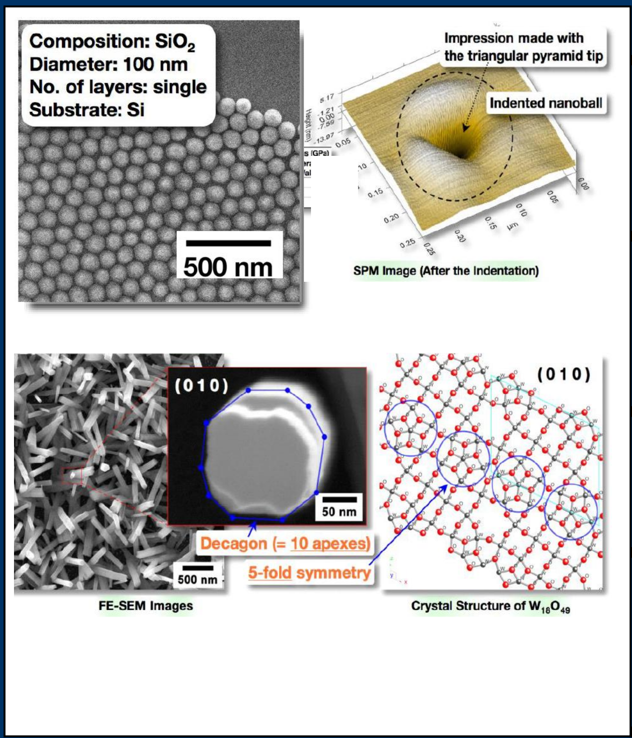
Advanced Materials and Structures Evaluated by our Group



- New multiferroic thin films prepared in Japan by sol-gel
- Crystalline substrates for electronics (Al_2O_3, Si, SiC)
- Outer layer of human bones
- **Nano-balls (SiO_2) and Nano-whiskers ($W_{18}O_{49}$)**
- Surface of semiconductors (GaAs, GaN)

2005 - founded

2006 - Physical Review B

(Nagao-JAPAN, Nordlund-FINLAND, Nowak-?)

2007 - Physical Review Letters

(Chrobak-POLAND, Nordlund-FINLAND, Nowak-?)

2009 - Nature Nanotechnology

(Nowak, Chrobak, Nagao-?/Poland/JAPAN
Vodnick, Berg - USA HYSITRON INC.
Tukiainen, Pessa - FINLAND)

2011 - Nature Nanotechnology

(Nowak, Chrobak-?/Poland/JAPAN
Tymiak, Bieber, Ugurlu, Gerberich USA)

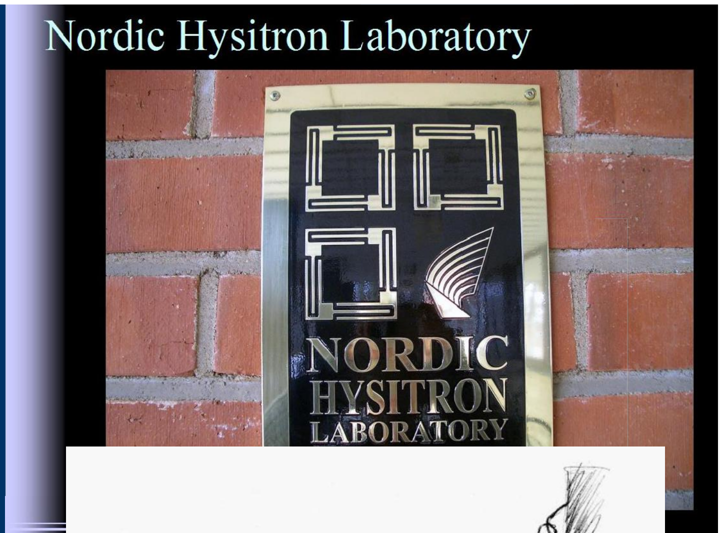
EVOLUTION

What makes NHL special?

- initial idea
- Japanese-style devotion
- lucky selection of individuals as members
- our stubborn non-orthodox approach close to Finnish SISU-style

Nordic Hysitron Laboratory = Hunters of Curiosities

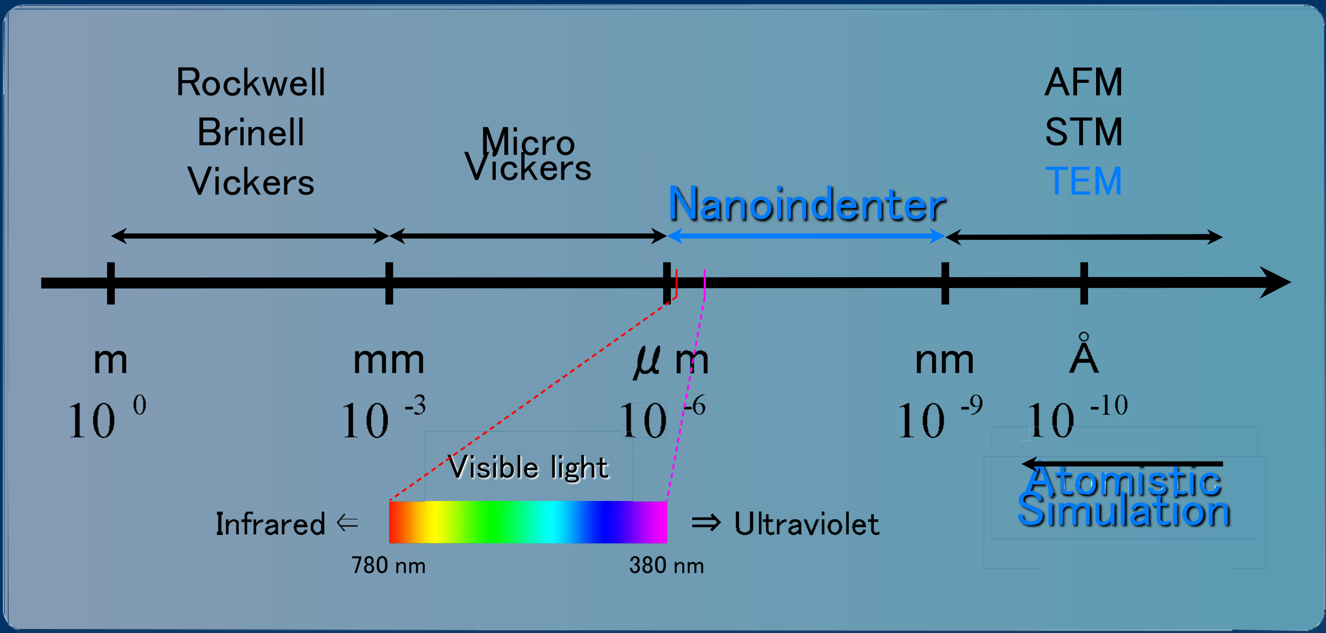
Dr. Masaki Fujikane



Dr. Fujikane
&
HYSITRON
TRIBOINDENTER

The fatal attraction to a new discovery!!!

1. 背景　～測定方法～



ナノインデンテーションの結果を視覚的にとらえるためには、
AFM, STM, TEMかシミュレーションが必要！！

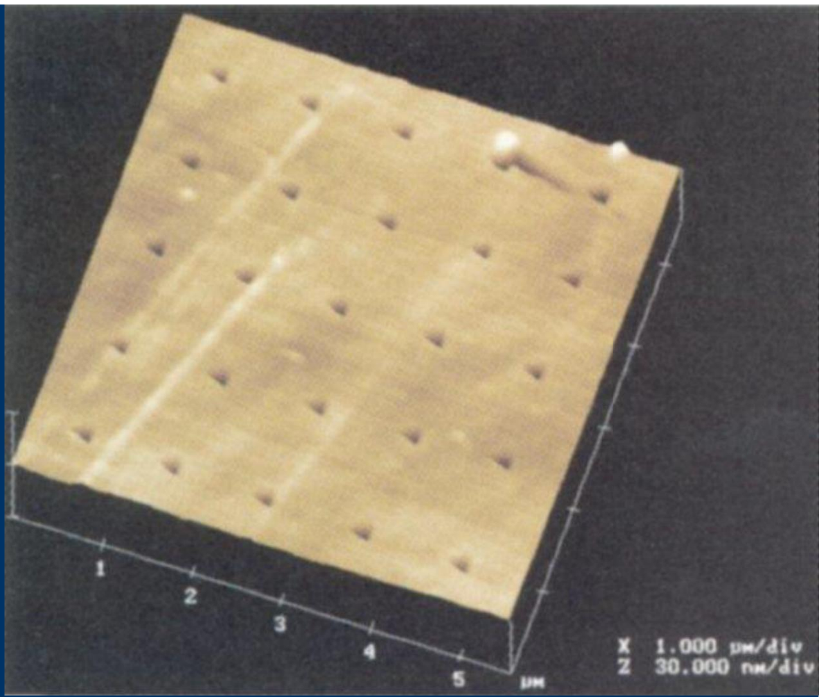
MECHANICS MEETS ELECTRONICS IN NANOSCALE

Per aspera ad astra

Hunting a curiosity

NORDIC HYSITRON LABORATORY

To come to laser via nanomechanical treatment?



The subject stems from experimental research

The goal was to introduce initial defects to GaAs surface in a regular, controlled way (NANOINDENTATION PATTERNING), and subsequently, to employ MBE to grow quantum dots in the defined location

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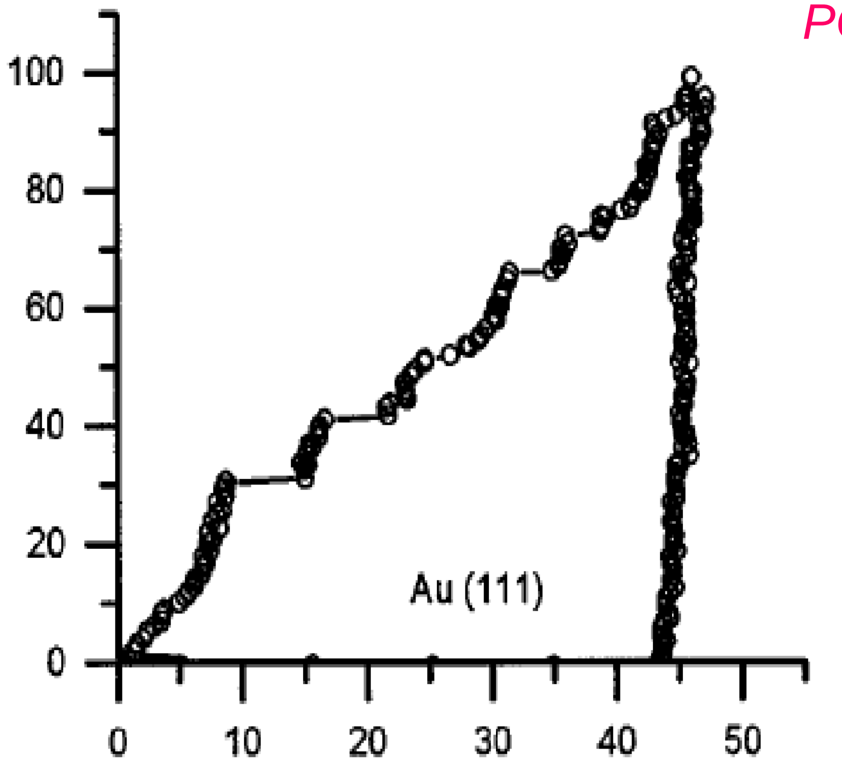
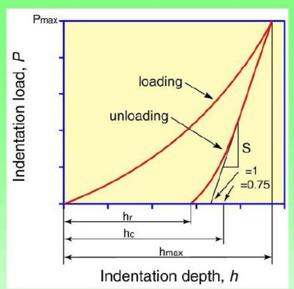
The widely accepted mechanism of pop-in in metals is related to the nucleation of the initial dislocations

POP-IN EFFECT





Schematic of the indentation load-displacement curve with the parameters used in the Oliver and Pharr analysis.

Corcoran *et al.*, Phys. Rev. B 55, R16057 (1997)

Is it hot-topic???

Shan et al., Mechanical annealing and source-limited deformation in submicrometre-diameter Ni crystals, **Nature Mater. 7**, 115 - 119 (2007)

Minor *et al.* A new view of the onset of plasticity during the nanoindentation of aluminum. ***Nature Mater.* 5**, 697-702 (2006).

P. Schall, I. Cohen, D.A. Weitz and F. Spaepen, Visualizing dislocation nucleation by indenting colloidal crystals, ***Nature* 440**, 319-323 (2006)

G.L.W. Cross, A. Schirmeisen, P. Grütter and U.T. Dürig, Plasticity, healing and shakedown in sharp-asperity nanoindentation, ***Nature Mater.*** **5**, 370-376 (2006)

S. Suresh, Crystal deformation: Colloid model for atoms, ***Nature Mater***. **5**, 253-254 (2006)

I. Szlufarska, A. Nakano and P. Vashista, A crossover in the mechanical response of nanocrystalline ceramics, ***Science* 309**, 911-914 (2005)

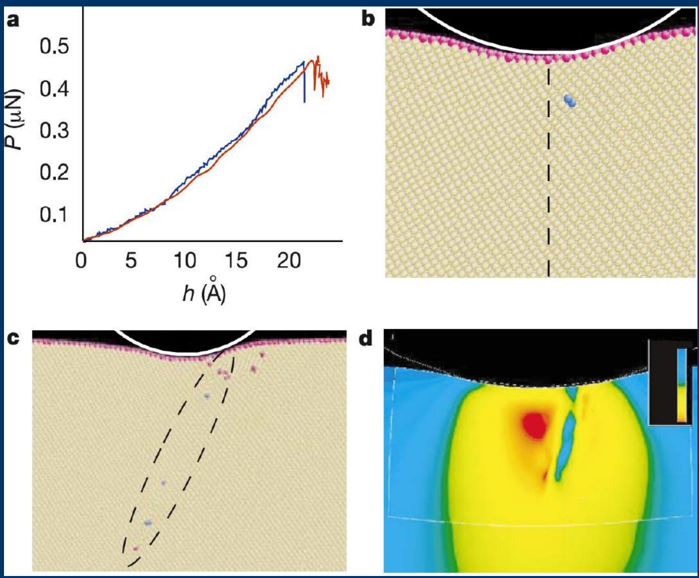
W. Gerberich and W. Mook, A new picture of plasticity, ***Nature Mater***. **4**, 577-578 (2005)

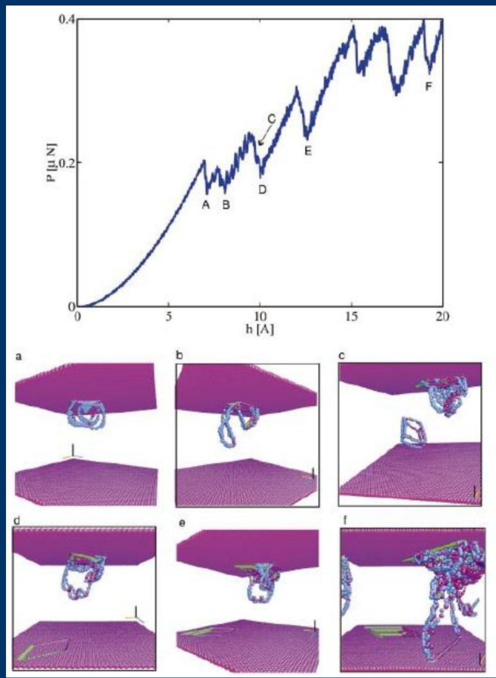
C.A. Schuh, J.K. Mason and A.C. Lund, Quantitative insight into dislocation nucleation from high-temperature nanoindentation experiments, ***Nature Mater*. 4**, 617-621 (2005)

J. Li, K.J. Van Vliet, T. Zhu, S. Yip and S. Suresh, Atomistic mechanisms governing elastic limit and incipient plasticity in crystals, ***Nature* 418**, 307-310 (2002)

A. Guldstone, K.J. Van Vliet and S. Suresh, Nanoindentation: Simulation of defect nucleation in a crystal, ***Nature* 411**, 656-657 (2001)

The widely accepted mechanism of pop-in in metals is related to the nucleation of the initial dislocations



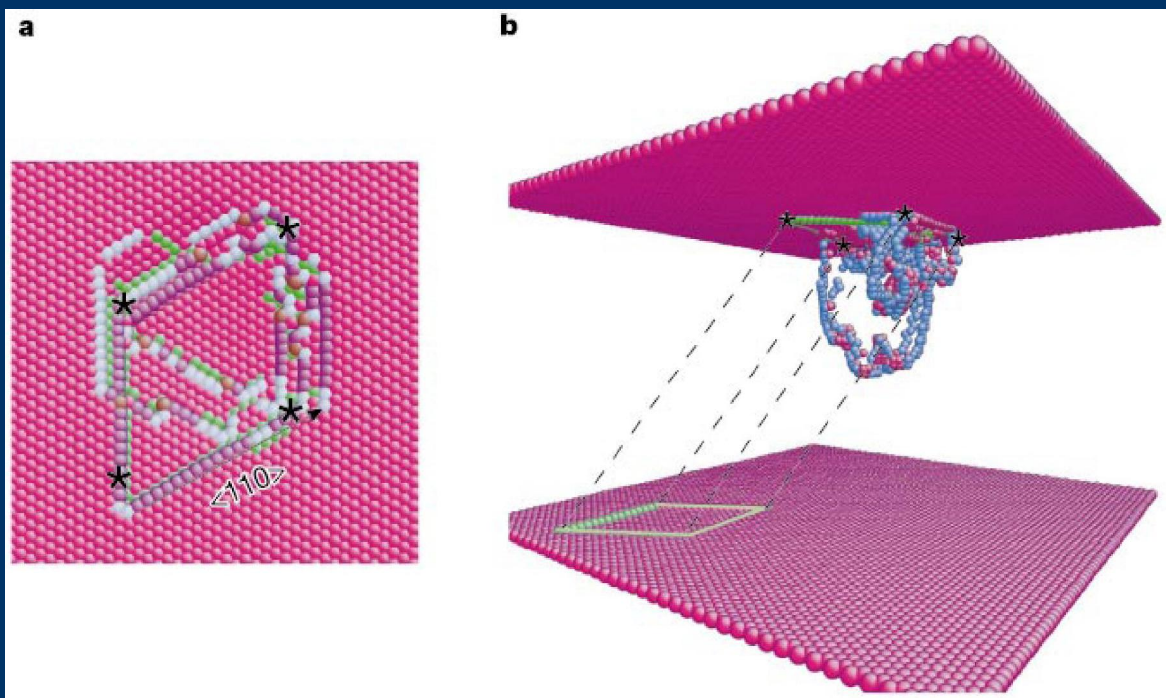


Theoretical confirmation for Al
by molecular dynamics (MD)

Van Vliet *et al.*, Nature 418, 307-310 (2002)

The widely accepted mechanism of pop-in in metals is related to the nucleation of the initial dislocations

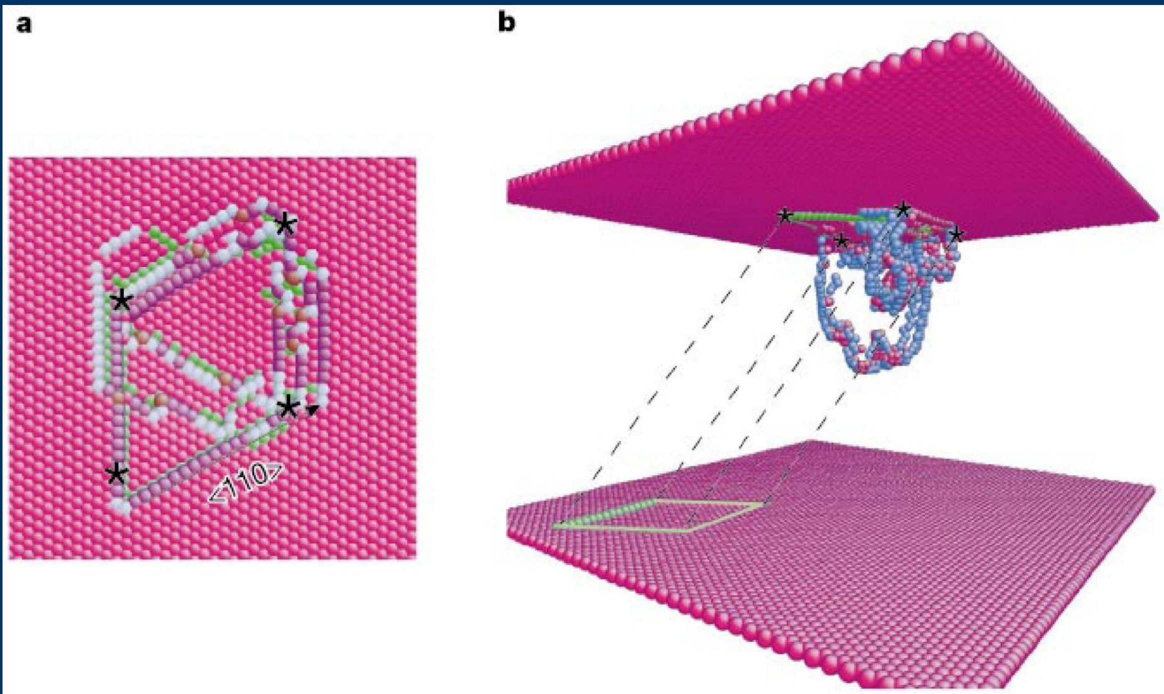
POP-IN EFFECT



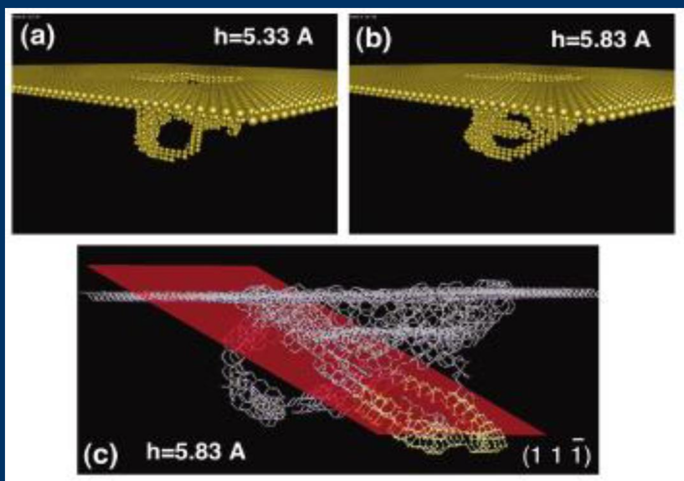
Nature 418, 307–310 (2002).

The widely accepted mechanism of pop-in in metals is related to the nucleation of the initial dislocations

POP-IN EFFECT



Nature 418, 307–310 (2002).



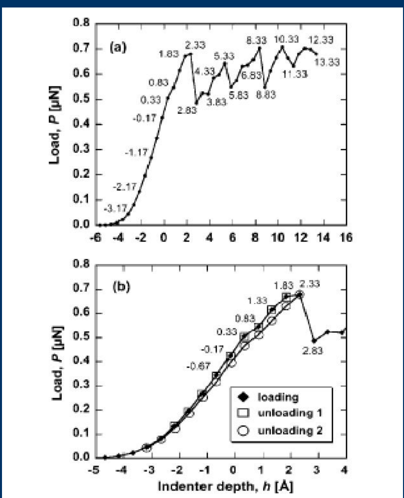


FIG. 2. Load-displacement (P-h) response: (a) Loading curve. (b) Unloading curves from h=1.83 Å (squares) and h=2.33 Å (circles) superimposed on the loading curve. Note different scales on the horizontal axes in (a) and (b).

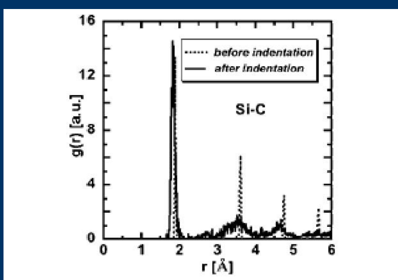
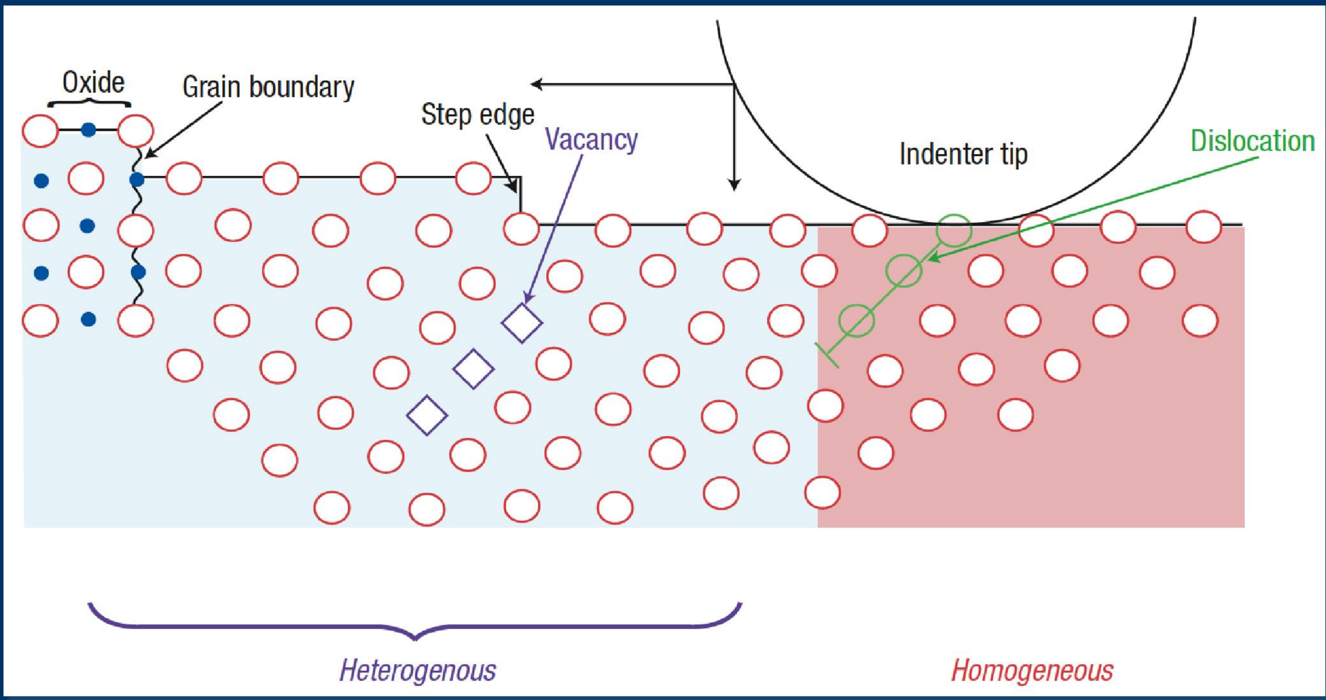


FIG. 10. Radial distribution function $g_{\alpha\beta}(r)$ before (dotted line) and after (solid line) indentation in the substrate 12–17 Å below the initial surface.

Solid sharped line reflects amorphous SiC.

I. Szlufarska *et al.*,, Phys. Rev. B 71, 174113 (2005); Science 309, 911-914 (2005)

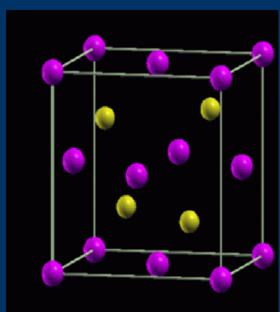
Non-homogeneous nucleation of dislocations



Schuh, Mason & Lund, Nature Mater. 4, 617 (2005)

Our QD-oriented nanoindentation project – entirely unsuccessful! Why? (!)

GaAs structure → zinc-blende of a=5.635Å



Ga – magenta
As – yellow

GaAs compound is an important semiconductor widely used to make devices such as:

- infrared light-emitting diodes
- laser diodes
- high efficiency solar cells → The combination of GaAs with germanium and indium gallium phosphide is the basis of a triple junction solar cell which holds the record efficiency of over 32% and can operate also with light as concentrated as 2.000 suns.

Mechanical properties of GaAS are important to make devices of high structural quality

Pop-in events in GaAs – unexplored mechanism of incipient plasticity

Nanoindentation → Young modulus, *E*=97GPa

Nanoindentation → Hardness, *H*=7.5GPa

Nanoindentation → Incipient plasticity (first dislocation nucleation)

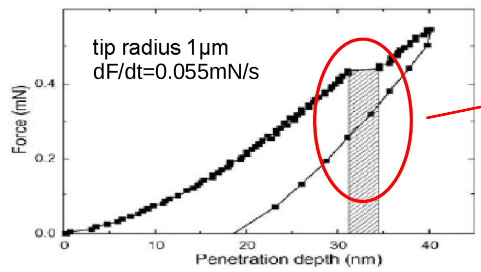


Fig. 1. Force versus penetration depth for a nanoindentation experiment on a polished (001)-oriented GaAs wafer. The discontinuity in the curve at the force of about 45 mN is referred to as the pop-in effect. The upper branch corresponds to the loading, the lower one to the unloading of the diamond tip. The lines are to guide the eye.

What is the origin of pop-in in GaAs?

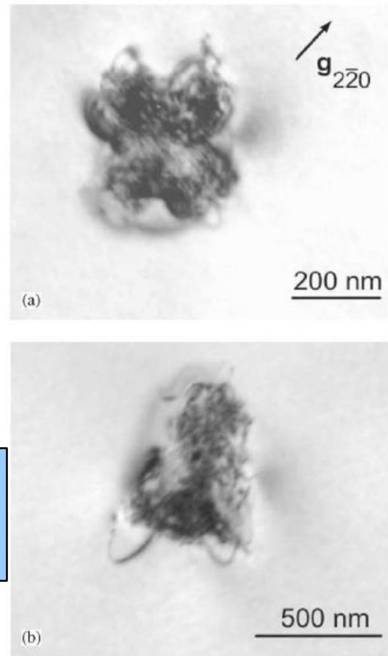
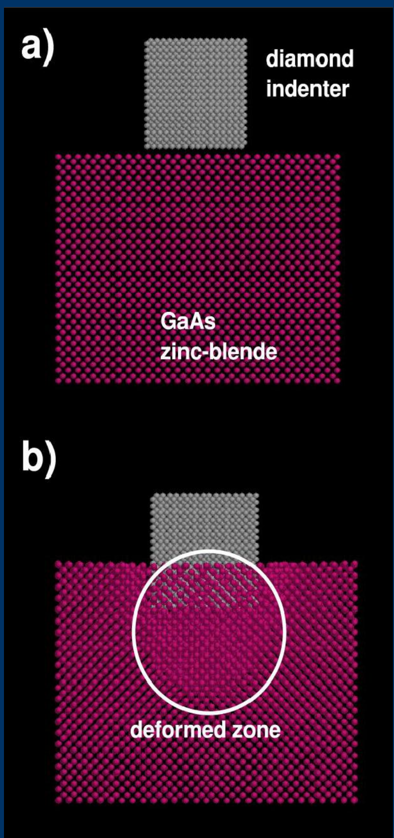


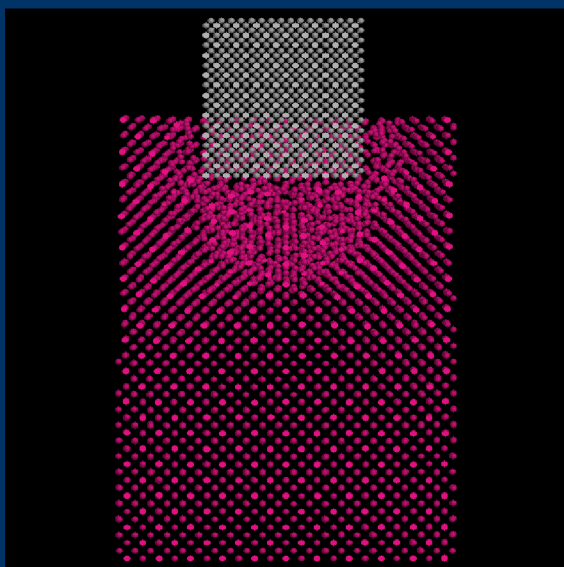
Fig. 2. Plan view TEM bright-field images of the dislocation rosettes at nanoindentations in (001) GaAs (a) and (111) GaAs (b). The diffraction vector **g** is $2\bar{2}0$.

H. Leipner *at al.*, Phys. Rev. B 172101 (2003)

Molocular Dynamics simulation of the tip - GaAs contact

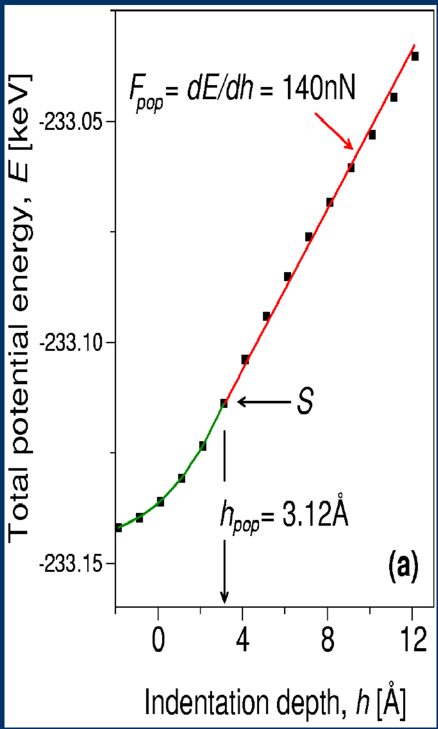


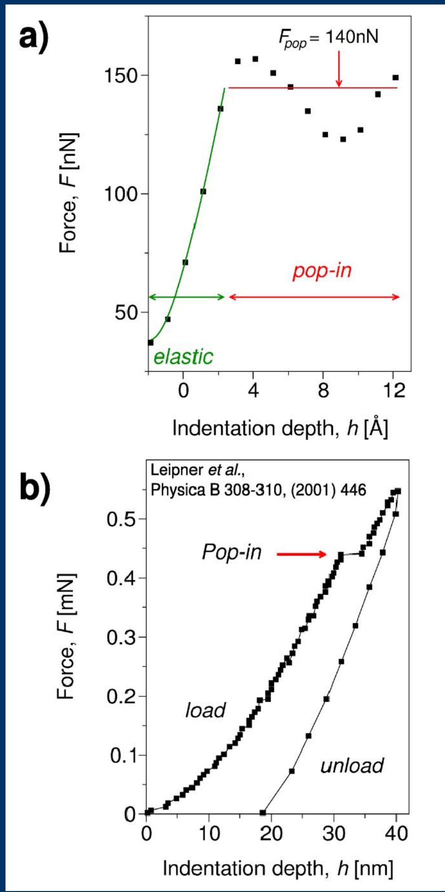
MD simulation of zinc-blende GaAs:
- indented surface: (001)
- bulk dimensions: 316x316x158 A
- total number of atoms: 700 425
- diamond cube indenter with edge length 28 A
- indenter was shifted by 1A in [001] direction
- and then structural relaxation within 20 000 time steps took place



Chrobak, Nordlund and Nowak Phys. Rev. Lett. (2007)

Molocular Dynamics simulation





Chrobak, Nordlund and Nowak Phys. Rev. Lett. (2007)

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Slip vector analysis

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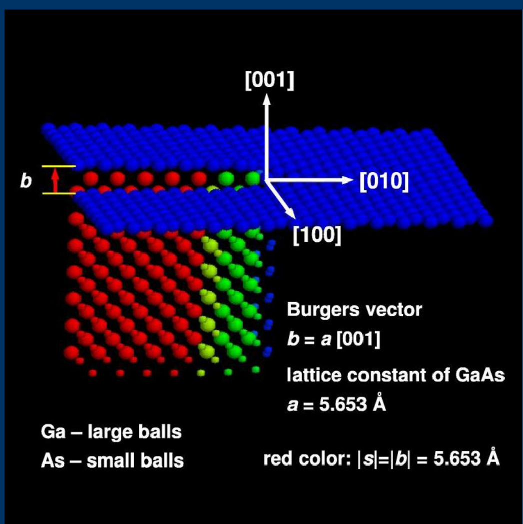
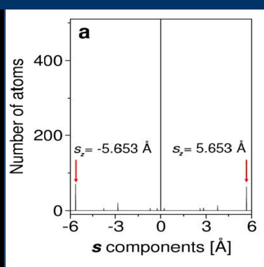
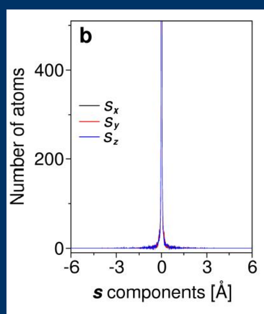
Slip vector gives information about Burgers vector of dislocations.

$$s(i) = \frac{1}{4}\sum_{j=1}^{4}\left[x(i,j) - x^0(i,j)\right]$$





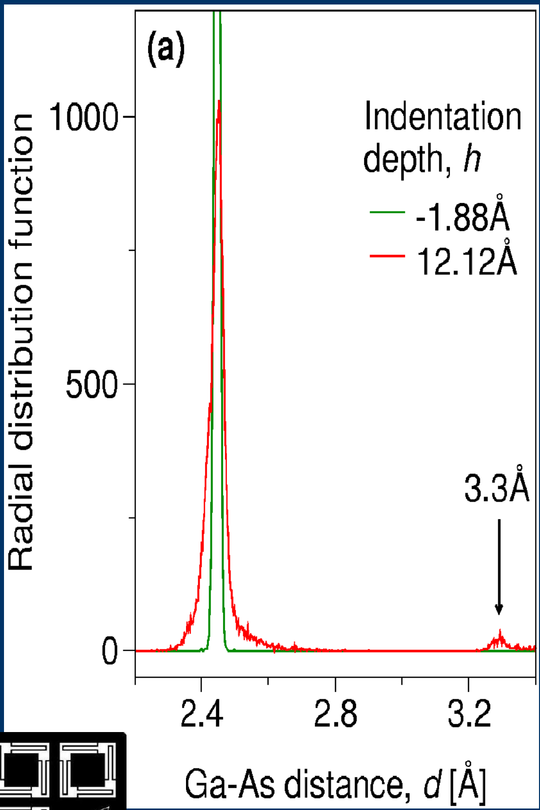


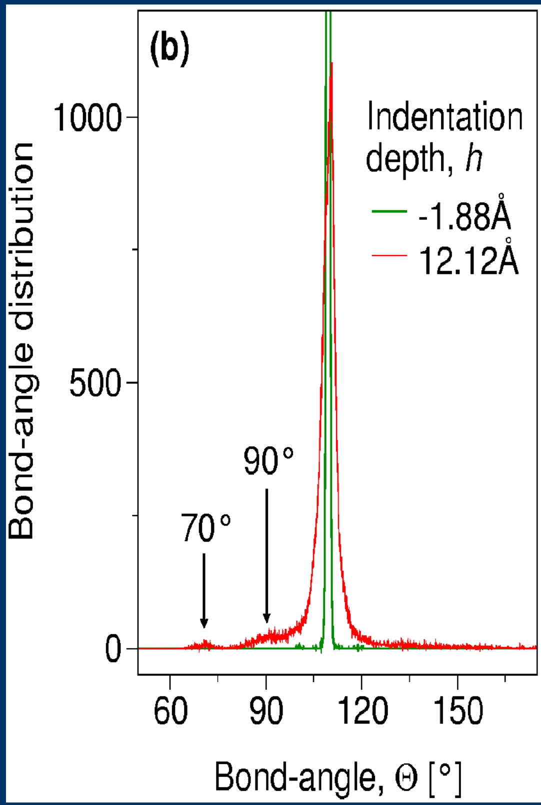
There is no slip planes in our system.

[1] J.A. Zimmerman *et al.*, Phys. Rev Lett, 87, 165507 (2001)

Pop-in events in GaAs –unexplored mechanism of incipient plasticity

there is no dislocation in affected volume

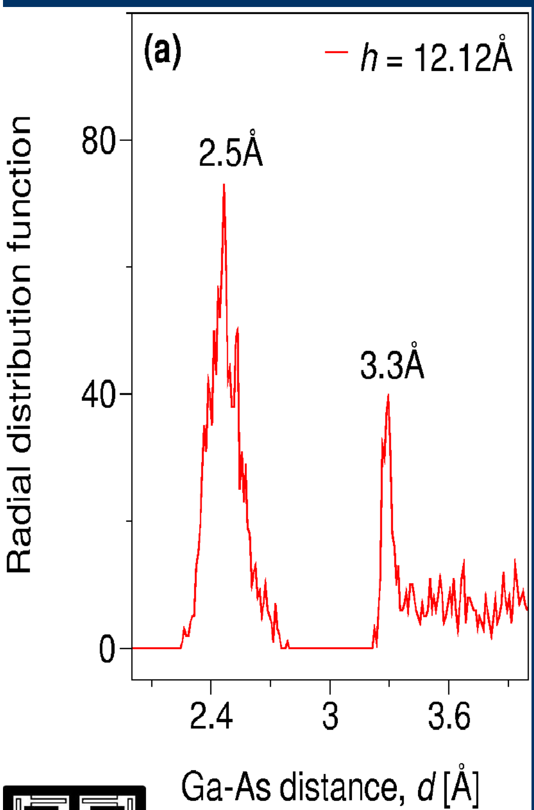


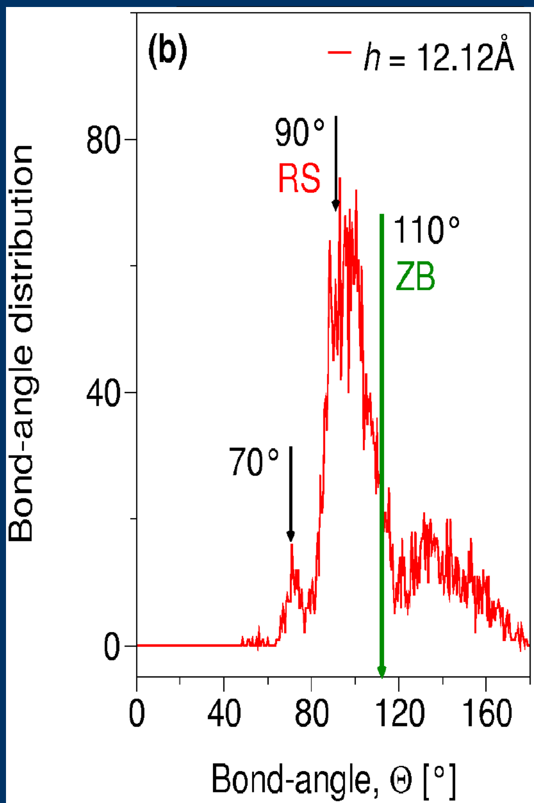


Bond-angle distribution is shifted to lower angles

Pop-in events in GaAs –unexplored mechanism of incipient plasticity

there is no dislocation in affected volume

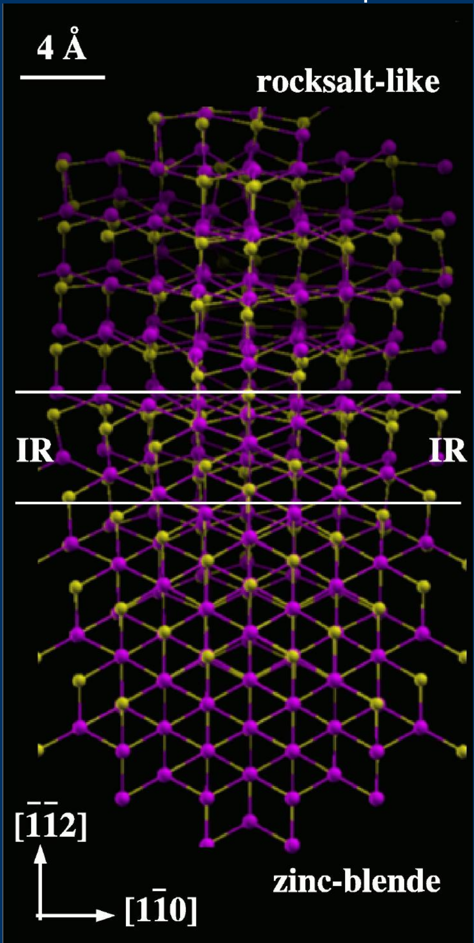




Bond-angle distribution is shifted to lower angles

Visualization of the *U* – domain along the [111] direction

Pop-in events in GaAs –unexplored mechanism of incipient plasticity



What is origin of the pop-in?

there is no dislocation in affected volume

Visualization of the *U* – domain along the [111] direction

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Pop-in events in GaAs – unexplored mechanism of incipient plasticity

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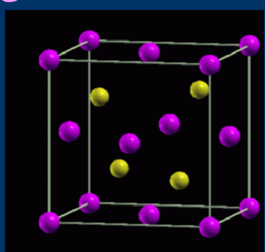
There is transformation from GaAs-I to GaAs-II phase [1-3]

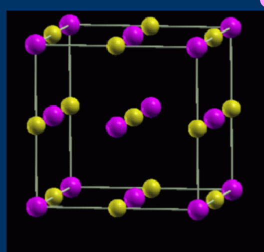
SEMICONDUCTING



zinc-blende structure
with bond angles of ~110 degrees

pressure range:
16 - 22 GPa

CONDUCTING



rocksalt structure
with bond angles of 90 degrees

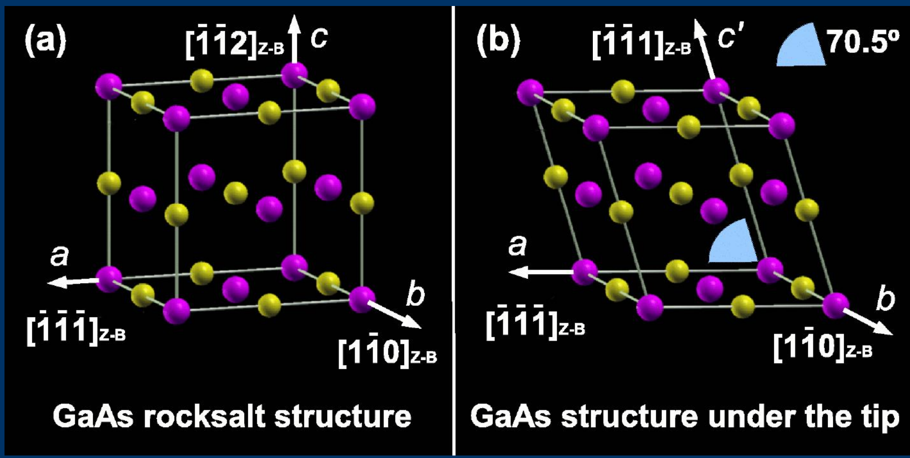
The average hydrostatic pressure in thin volume (28x28x17 A, *U* - domain) under indenter was equal to 18 GPa

[1] S.T. Weir *et al.*, Phys. Rev. B 39, 1280 (1989)
[2] J.M. Benson *et al.*, Phys. Rev. B 44, 4214 (1991)
[3] S.B. Zhang *et al.*, Phys. Rev. B 39, 1450 (1989)

Pop-in events in GaAs – unexplored mechanism of incipient plasticity

The undistorted rocksalt structures (a) with edges along certain zinc-blende direction and idealization of the structure recognized in *U* – domain (b)

CONDUCTING !!!

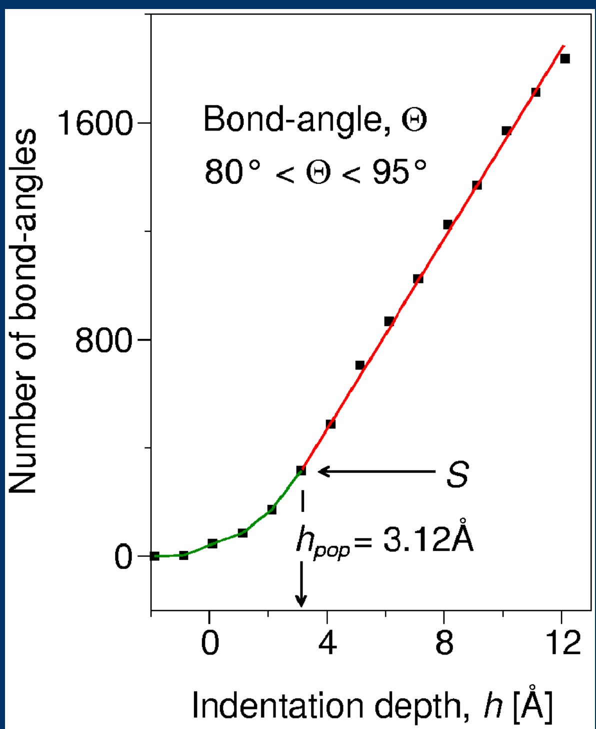


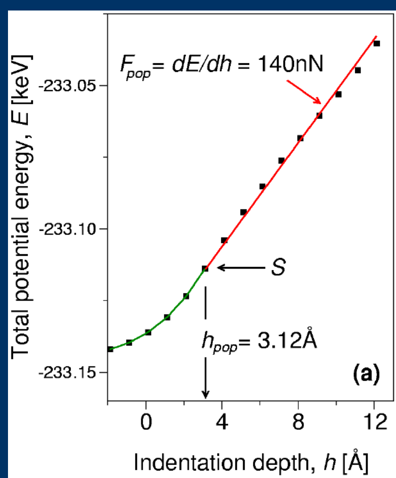
The existence of ~70 degrees bond angles was confirmed by BADF analysis for U - domain.

☆

Valentini, Gerberich & Dumitrica, Phase-transformation plasticity response in uniaxially compressed silicon nanospheres. Phys. Rev. Lett. 99, 175701 (2007).

Another confirmation of the thesis that points towards phase transition at the end of the elastic nanoscale deformation





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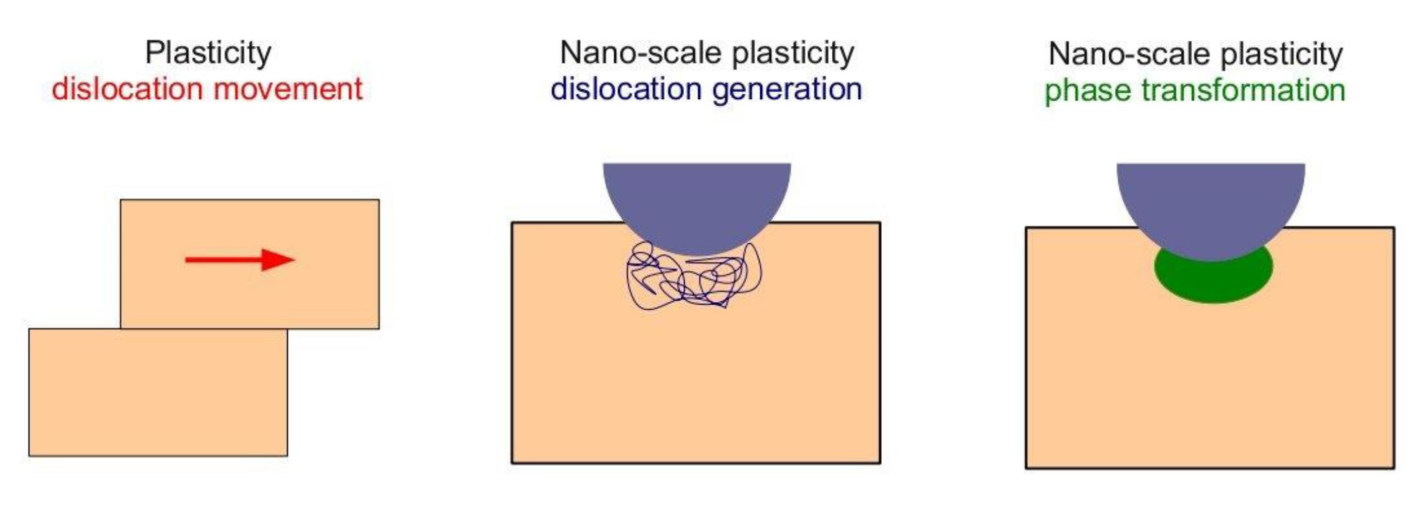
Important consequences



Nanoscale plasticity revised

Technological way-out

Fabrication of mesa-structured SiO2-on-GaAs templates for nano-indentation

This task concerns the fabrication of SiO2-on-GaAs templates with SiO2 mesa-structure. SiO2 is first grown on epi-ready n-GaAs(100) substrate by plasma-enhanced chemical vapour deposition (PECVD). Subsequently, the surface of GaAs wafer is patterned either by standard photolithographic methods and etching or by nanoimprint lithography (NIL) to form variable sized SiO2 mesa structure.

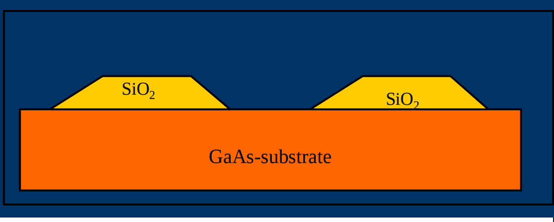


Fig. 1 SiO_2 mesa structures prepared by ORC on GaAs substrate

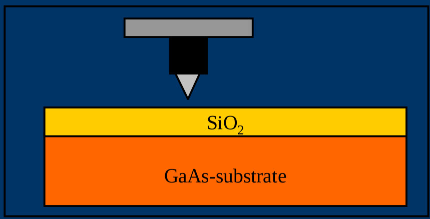


Fig. 2. The schematic set-up prior to the contact.

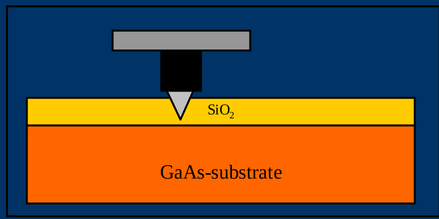


Fig. 3. Nanoindentation into the top-layer.

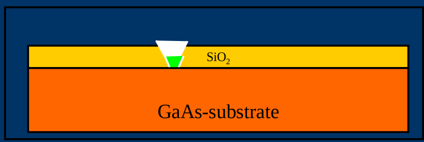


Fig. 6 The onset of QD growth inside the dimple

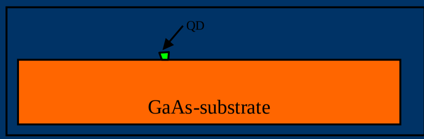


Fig. 7 The QD left on GaAs after SiO2 removal

The essence of the idea proposed in NAKAMA-EXT is to perform indentation in the deposited SiO_2 coating, instead in the GaAs wafer (see Figs. 2 and 3). Subsequently, the SiO_2 film would be selectively etched in order to expose the GaAs surface at the spot where indentation was performed, as schematically presented in Figs. 4 and 5. QDs are grown by MBE, and further the remaining SiO_2 part would be removed by etching (Figs. 6 and 7). The method offers possibility of control of the hole since it no longer sharply depends on tip shape and size and can be moderate by etching process (relatively large tip will act merely as a marker for etching process).

Technological way-out

Fabrication of mesa-structured SiO2-on-GaAs templates for nano-indentation

This task concerns the fabrication of SiO2-on-GaAs templates with SiO2 mesa-structure. SiO2 is first grown on epi-ready n-GaAs(100) substrate by plasma-enhanced chemical vapour deposition (PECVD). Subsequently, the surface of GaAs wafer is patterned either by standard photolithographic methods and etching or by nanoimprint lithography (NIL) to form variable sized SiO2 mesa structure.

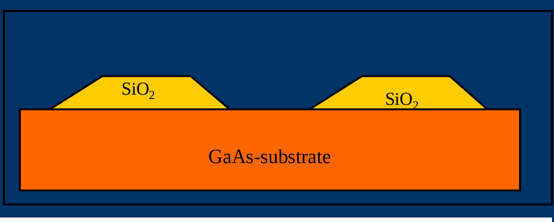


Fig. 1 SiO_2 mesa structures prepared by ORC on GaAs substrate

MECHANICS MEETS ELECTRONICS IN NANOSCALE

New discoveries and further developments

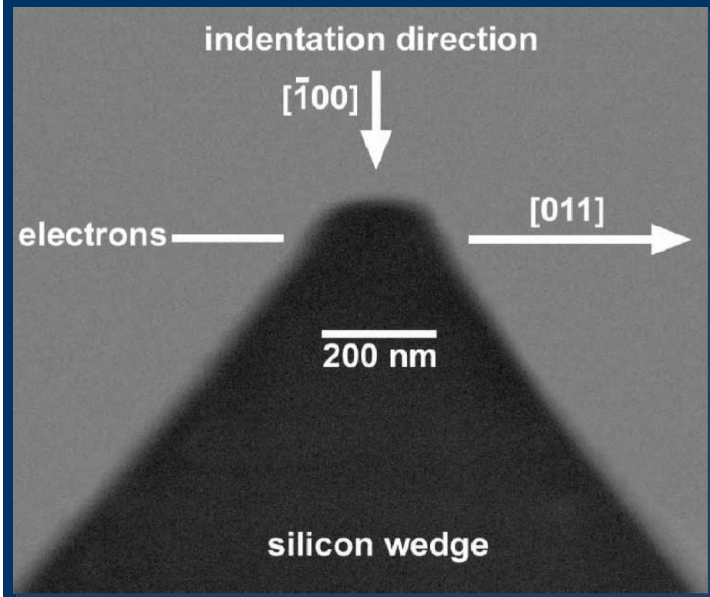
In situ electrical measurements

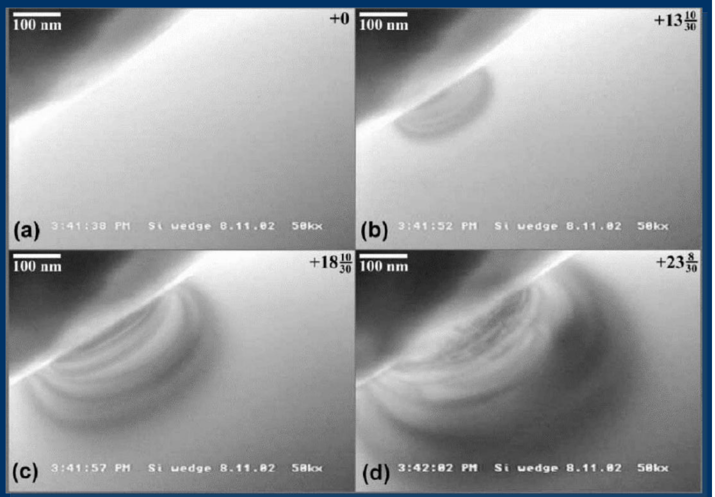
In search for a newly formed phase in nanoscale

Diffraction?

TEM?

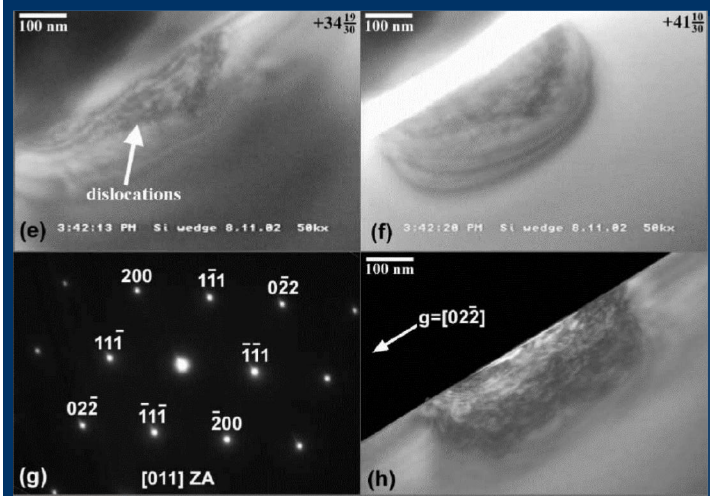
Inside TEM indentation

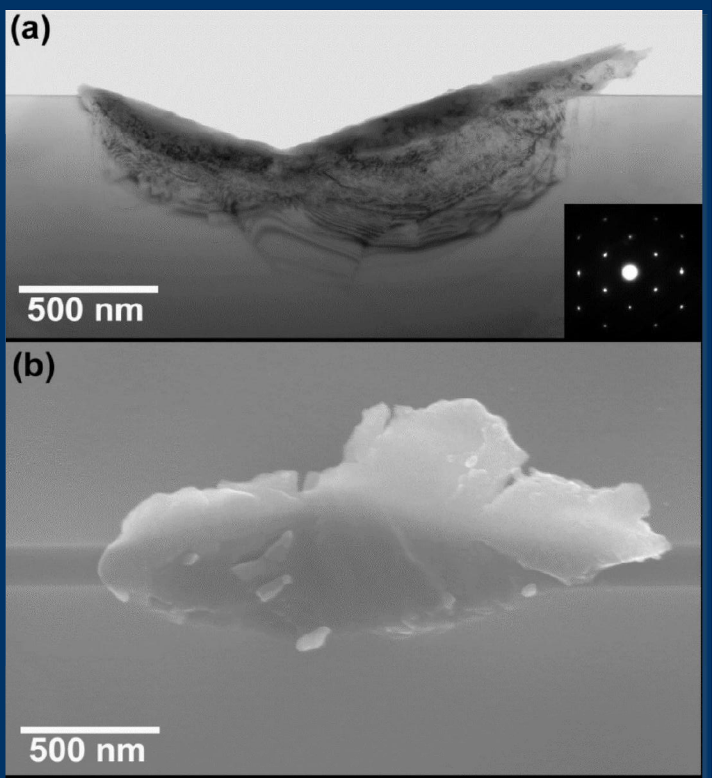




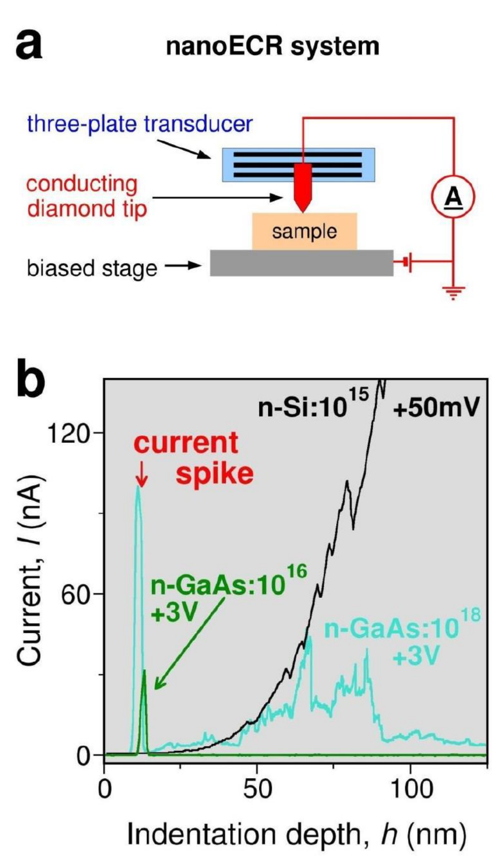
Nature Mater (2007).

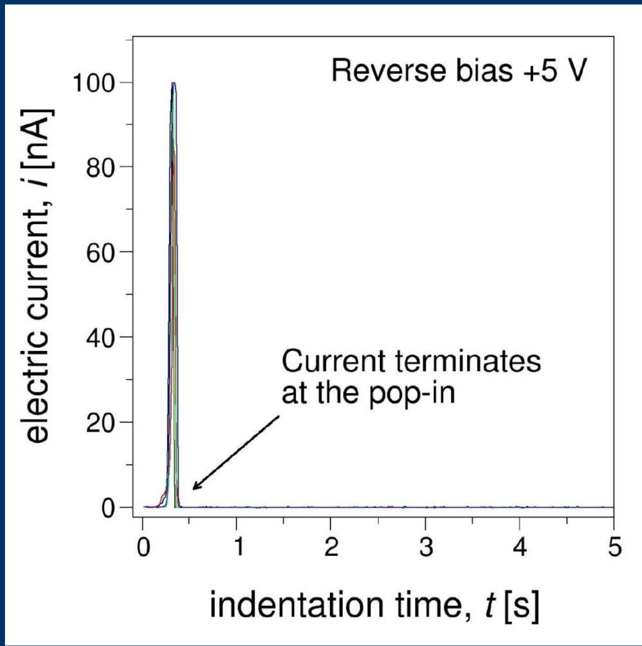
In TEM indentation ???



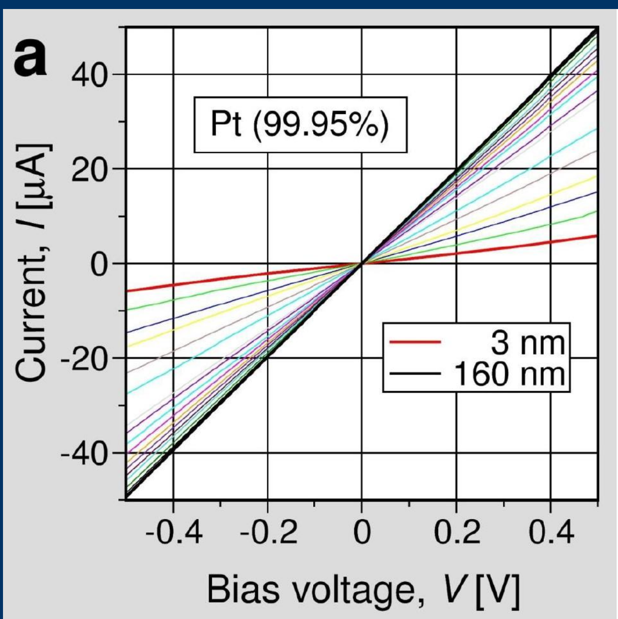


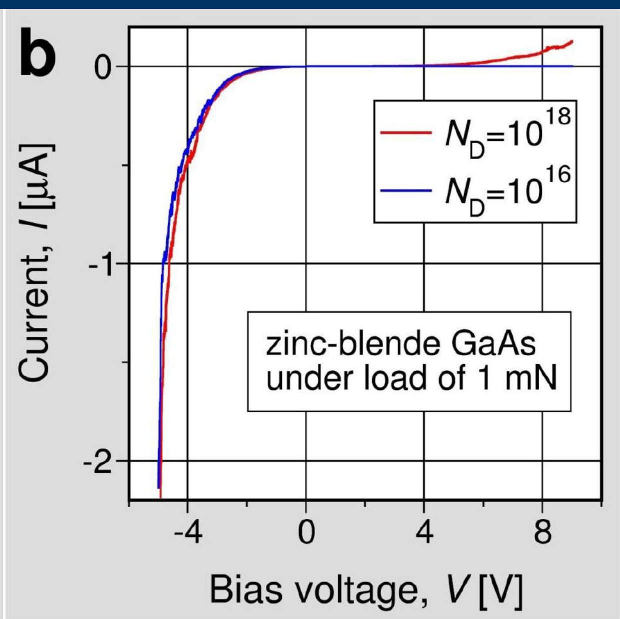
NanoECR measurements of GaAs



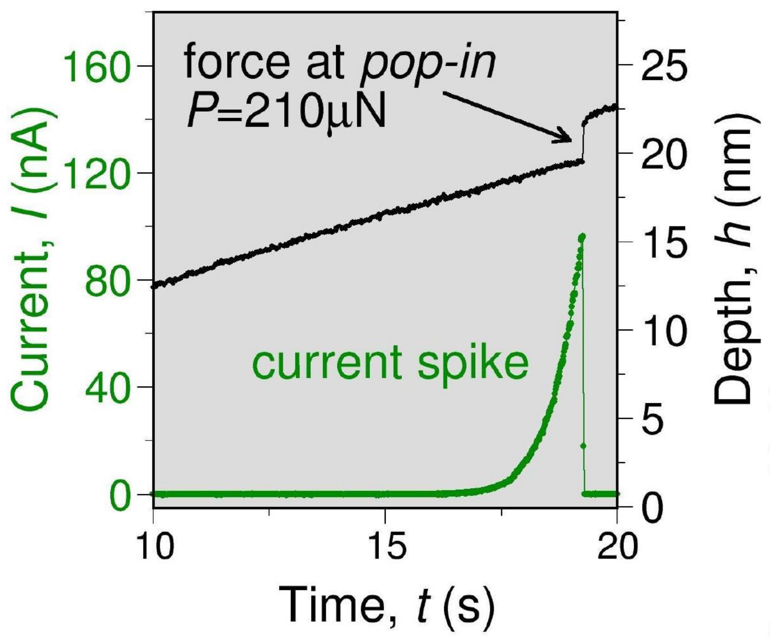


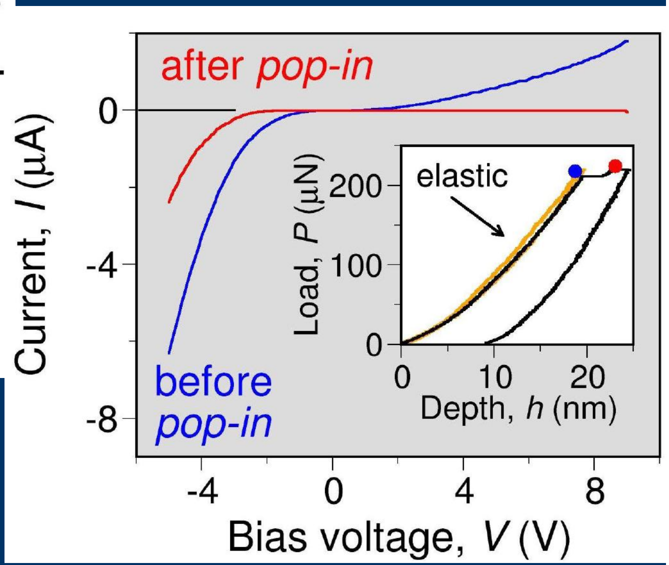
NanoECR measurements of GaAs





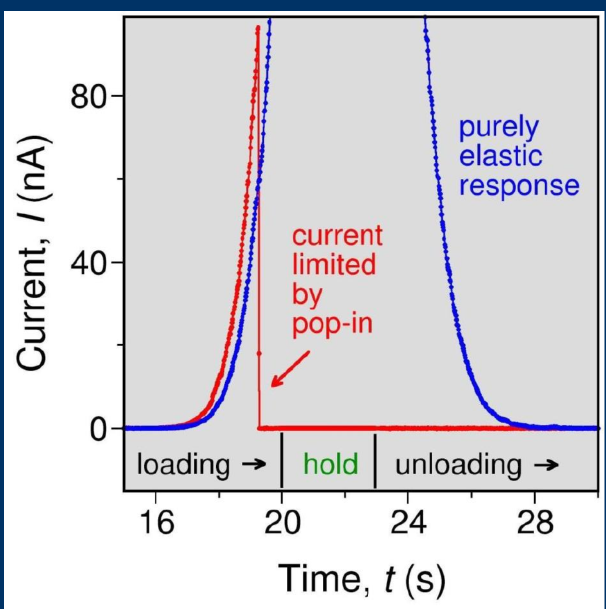
NanoECR measurements of GaAs

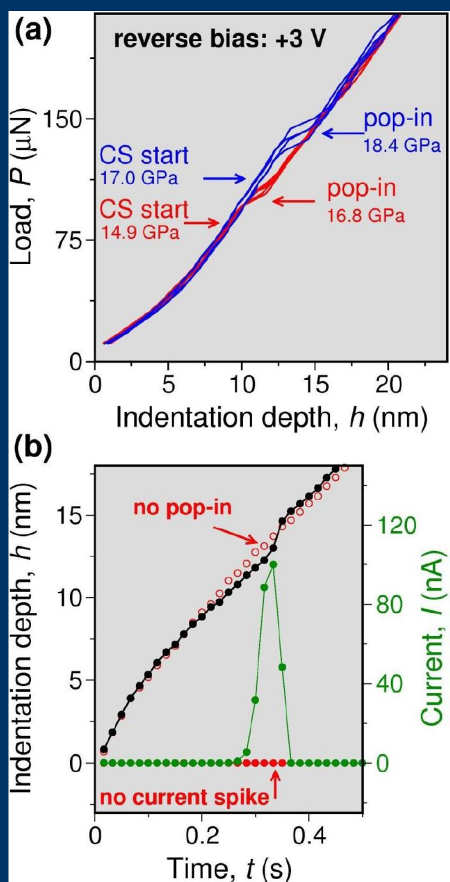




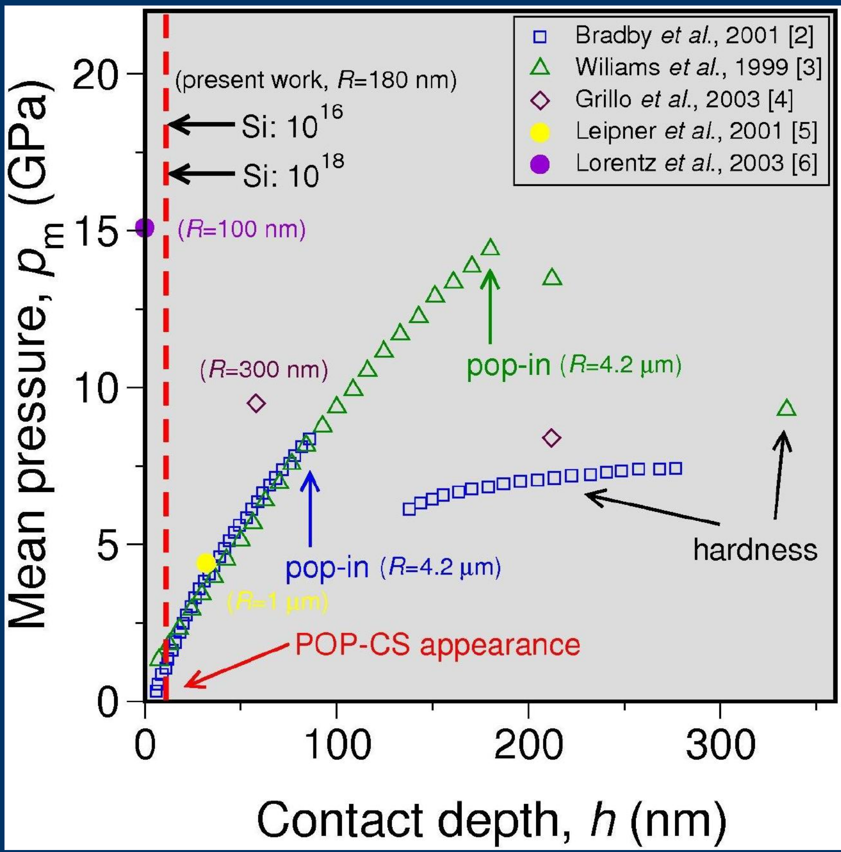
Nowak et al. Nature Nanotechnology ***4****, 287 (2009)*

NanoECR measurements of GaAs

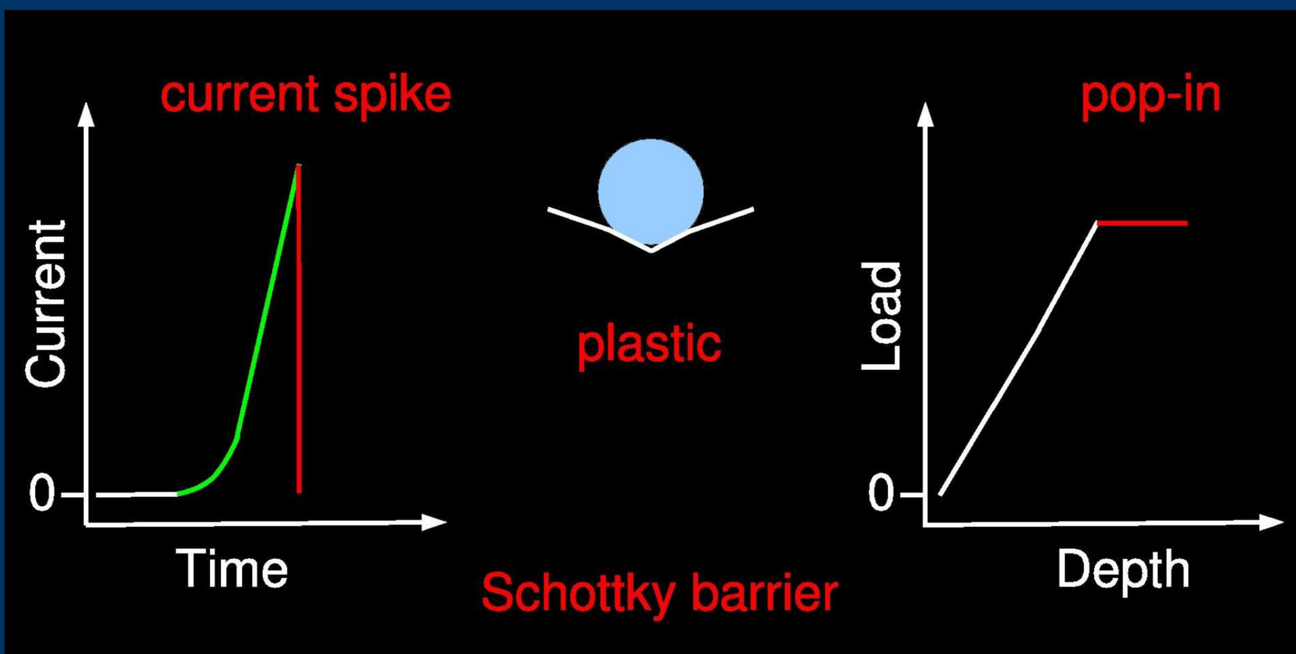




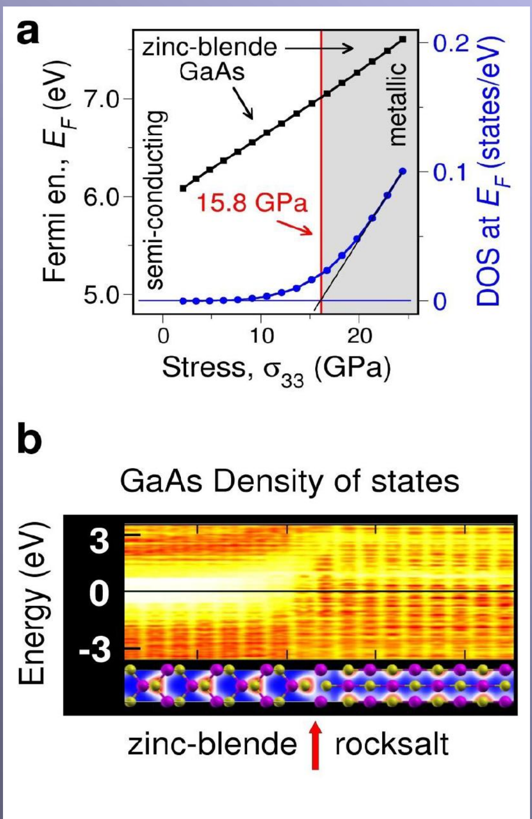
Pop-in events in GaAs - NANO or NON-NANO?

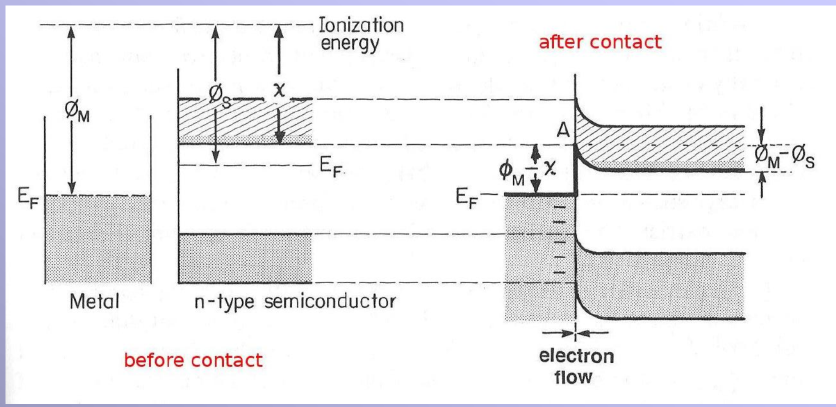


NanoECR measurements of GaAs



Ab initio calculations indicate how to clarify the NEW PHENOMENON

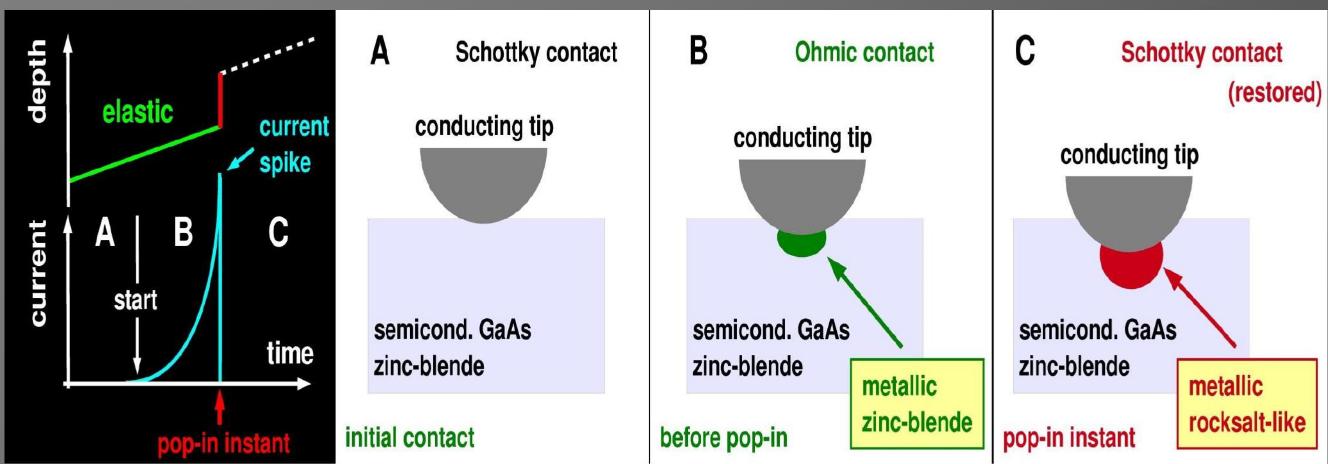




A) *Ab initio* calculation results revealing metallization of GaAs for pressures above 15.8 GPa and the Ohmic-type contact between semiconducting and metallic GaAs (note the increase of *EF* – Fermi level that reaches finally conduction band).

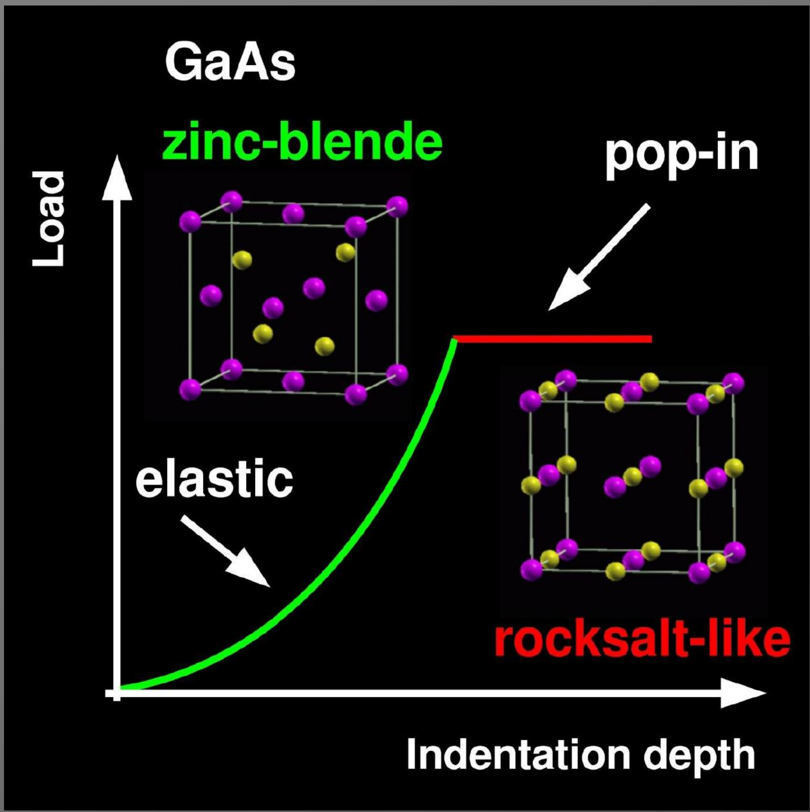
B) The same kind of theoretical considerations proved that the Schottky barrier prevails between GaAs zinc-blende and rocksalt structures (the details of calculated band-structure close to the junction are shown together with schematic unit cells to emphasize a difference between two phases of GaAs).

NanoECR measurements of GaAs



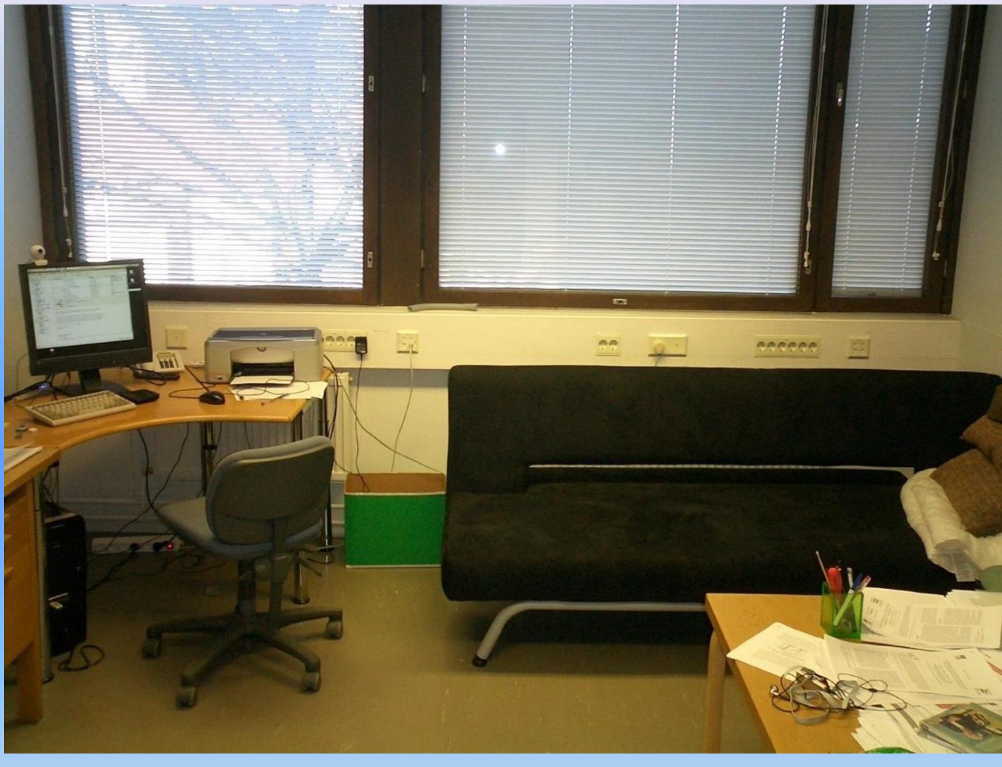
The schematic explanation of the phenomena responsible for a singularity in mechanical (pop-in) and electrical (current spike) response in nanoindented GaAs. The initial GaAs-conducting contact is of Schottky type (A). Under the imposed pressure the junction leaks in B-stage of the indentation due to introduced metallization of a certain part of zinc-blende structure, while the appearance of metallic rocksalt structure (C) halts the CS-spike current and restores the Schottky contact.

NanoECR measurements of GaAs



GaAs-120-0104.avi

HIMITSU



The secret of our success

The discovery of GaAs as **phase-switching material** when deformed in the nano-scale provides a way to new, hitherto unrecognized applications

R N

This has practical implications for the fabrication and ultimate strength of nanostructures formed in glassy polymers and other free volume materials by nanoimprint manufacturing

Graham L.W. Cross, Nature Nanotechn. 2011

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Future: GaAs regarded as a locally stress-controlled "phase-change material"?

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INSTEAD OF CONCLUSIONS

Thank you very much for your kind attention