Presented at the COMSOL Conference 2010 Boston

Modification of the Ion Angular Distribution in Plasma Sheath

Modeling Approach under COMSOL Multiphysic

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Outline:

- Technological opportunity – IADF control
- Finding the approach

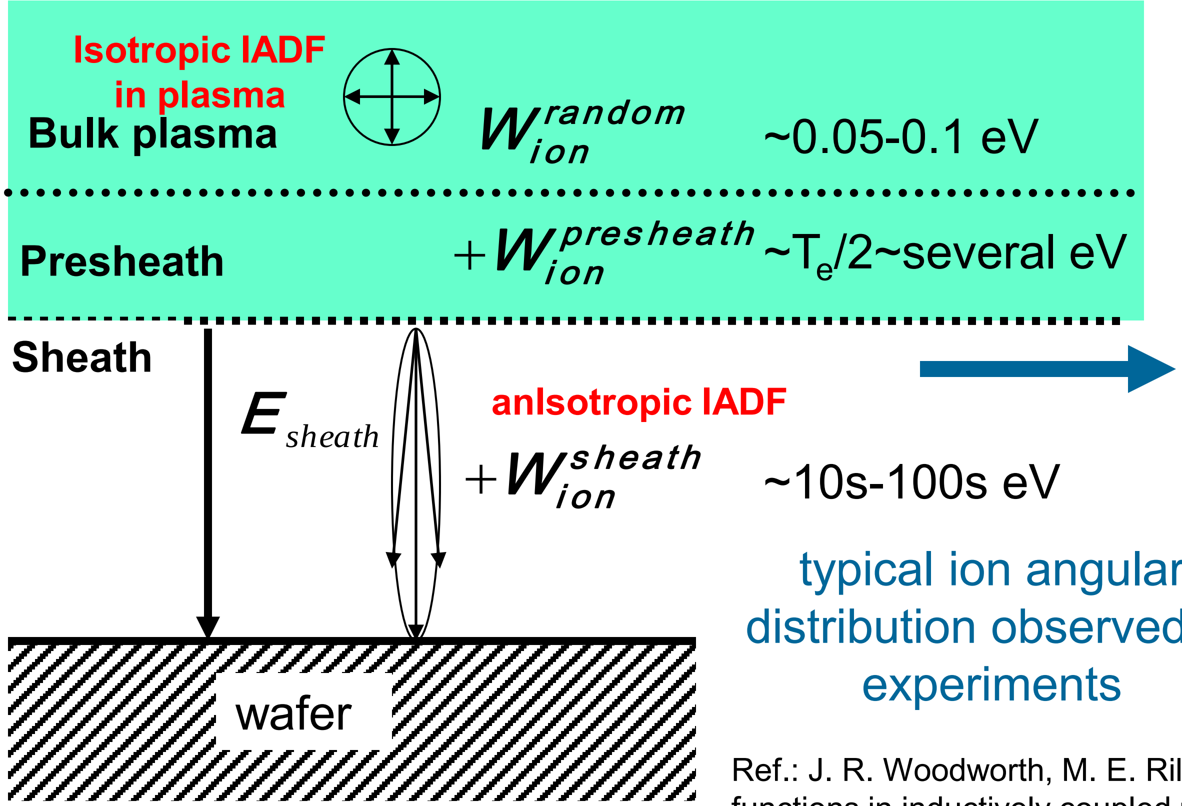
What we need for feasibility study

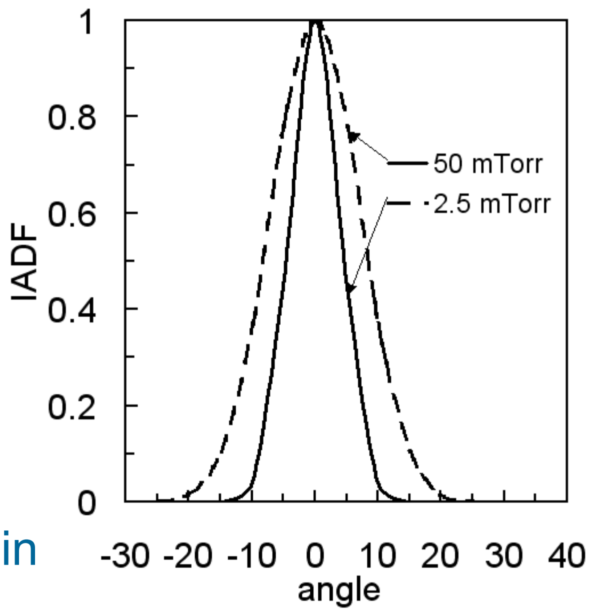
What we want to get from feasibility study

- Concept of prototype
- Model components
- Implementation within computational domain
- Results
- Next strategy

How is IADF generated?

- ❑ In existing technology the profile of the IADF is given by **pressure**, wafer **bias** and single or dual **frequency** choice





typical ion angular distribution observed in experiments

Ref.: J. R. Woodworth, M. E. Riley, and P.A Miller, Ion distribution functions in inductively coupled radio frequency discharges in argon-chlorine mixtures, J. Vac. Sci. Technol. A 15(6), 1997, 3015-3023.

Technological opportunity – IADF control

semiconductor technology

- ➔etch profile modification (in-situ)
- ➔CD control & variation
- ➔deposition conformality (sidewall coverage)
- ➔plasma immersion ion implantation

➔it is applicable for core plasma technology

Technological opportunity – IADF control

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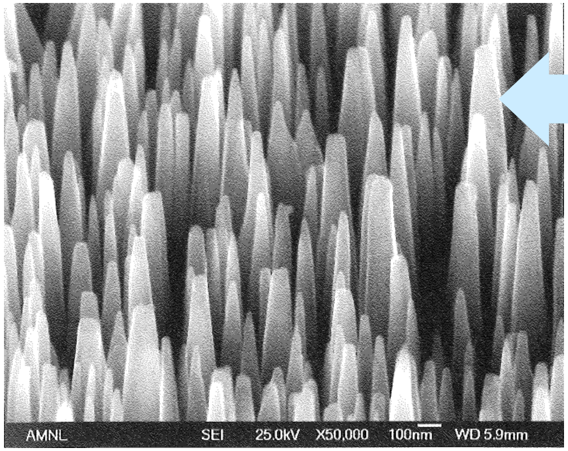
➔ **it is applicable for core plasma technology**

- ➔ Surface structuring w/o need of the pattern transfer (nanotechnology, …, self-assembling, …, MEMS, ….) – avoiding additional technological steps such as litho, resist, ….
- ➔ Creating conditions and impact on the film growth and its structure
- ➔ Surface roughness tailoring
- ➔ Tailoring film properties in PVD, …

➔ **it is applicable for new technology**

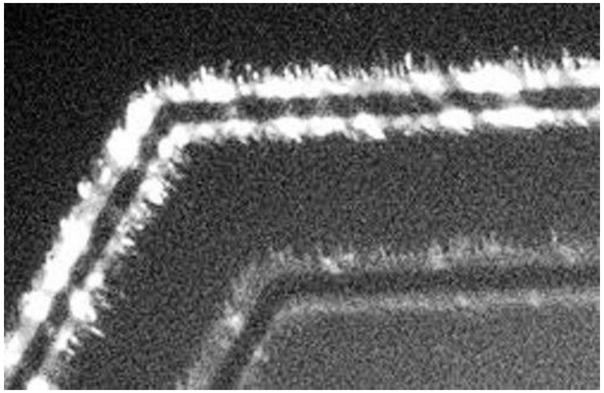
Technological opportunity – IADF control

- **Nanotubes (NT) growth in low temperature plasma**
- **NT alignement is perfectly the same as that of electric field in sheath[1]**



- **The ion fluxes that are most responsive to the E-fields. Applying an external DC electric field parallel to the substrate surface – carbon NT can be bent in sharp predetermined angles = L-shaped NTs[2]**

Growing nanowires horizontally yields nano-LEDs



Source: image by NIST, OptoIQ, Sep 29, 2010

[13] B. Nikkoobakht and A. Herzing, *ACS Nano*, published online Sept. 15, 2010

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[1] k. Ostrikov and S. Xu, Plasma-Aided Nanofabrication, Wiley-VCH Verlag GmbH & Co., KGaA, Weinheim (2007)

[2] J.F.AuBuchon, L-H. Chen, and S. Jin, Jour. Phys. Chem. B**109**, 6044 (2005)

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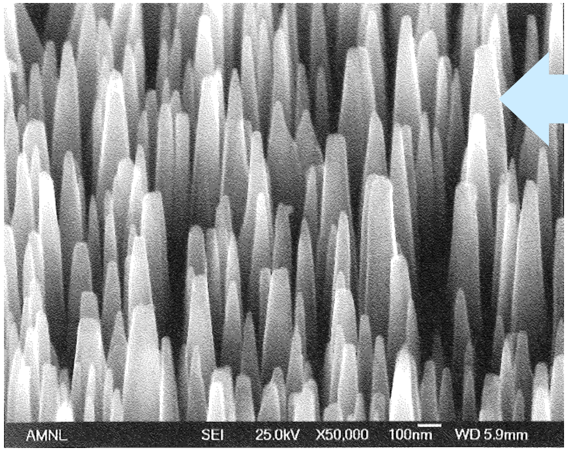

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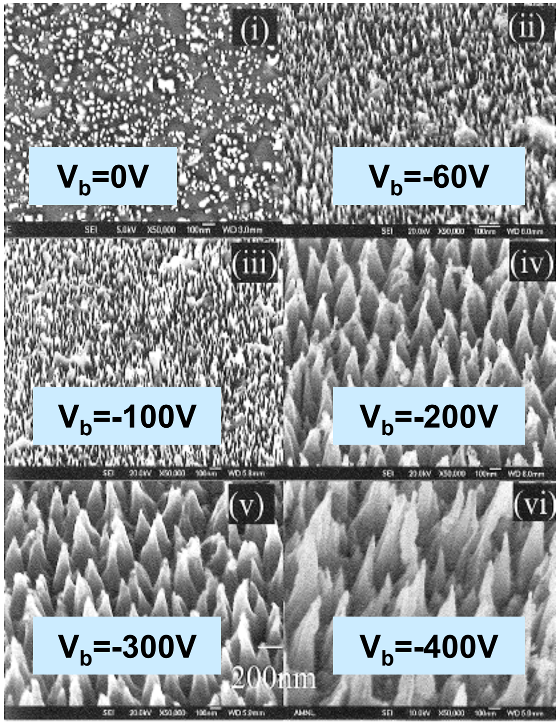
- **Surface bombardment – impact on fragmentation & nanostructurization of catalyst layers that are widely used to synthesize carbon NT**



Field emission scanning electron microscopy of carbon structures grown at different DC biases

DC variation has impact (A) on local T, and (B) even a modest change in the substrate bias (~50-100 V) results in in structural transformation (at unheated surfaces)[3]

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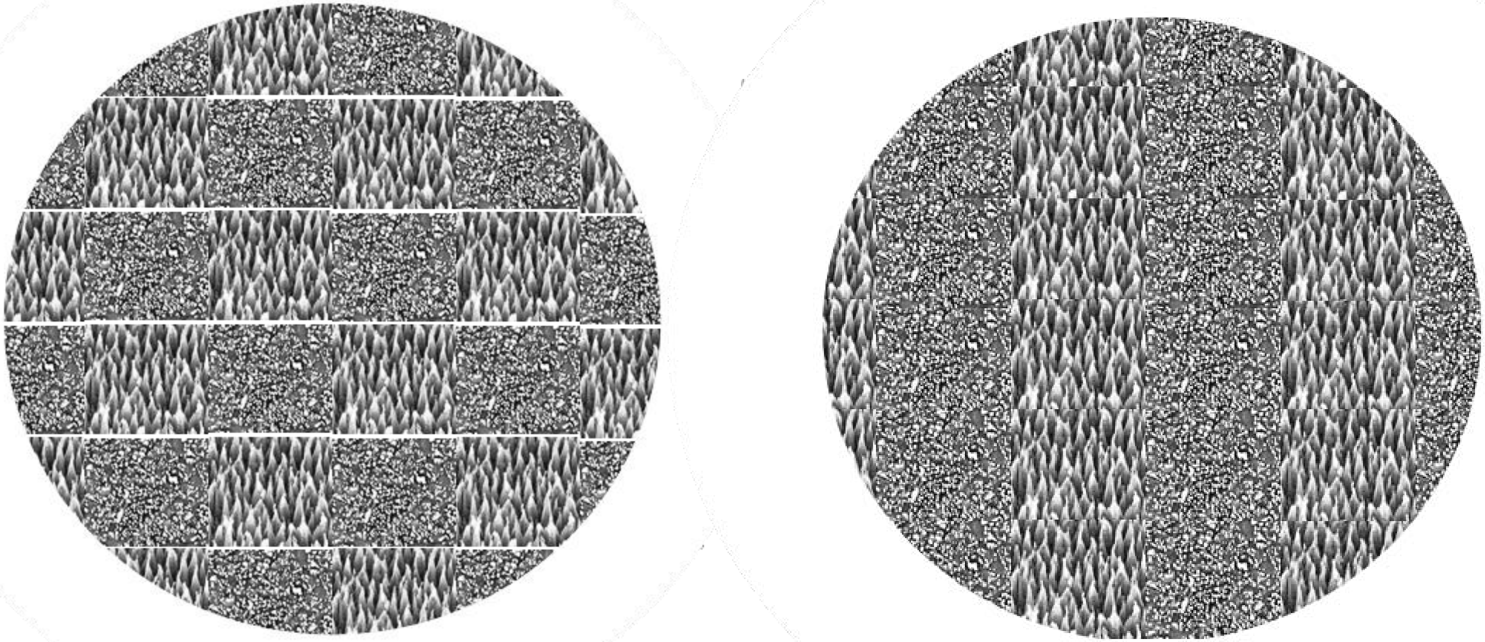
[3] Z. L. Tsakadze, K. Ostrikov and S. Xu, Surf. Coat. Technol. 191/1, 49 (2005)

Diversification of conditions on the single wafer and instant processing

- **DC variation visualization of the parametrized growth on the single wafer**



This is as an idea example only from previous slide…[4]

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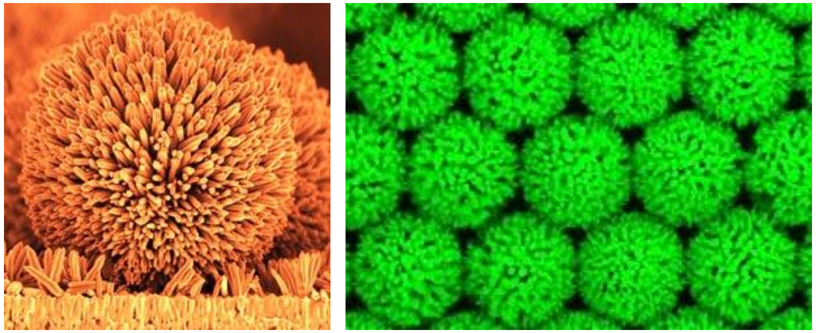
[4] … author's imagination

Technological opportunity – IADF control

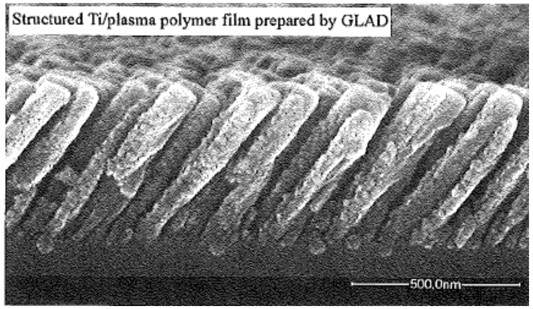
- **polystyrene spheres used as a sort of scaffolding to create 3D nanostructures of semiconducting zinc oxide on various substrates[5]**



- **The principle: spheres a few micrometers in diameter are placed on an electrically conducting surface where they orient themselves in regular patterns**

- **Exploitation: <u>electronic and optoelectronic devices, solar cells, short wave lasers</u>, LEDs and FEDs**
- **<u>excellent light scattering properties</u>**

- **Use of ion-milling to control clustering of nanostructured, columnar thin films**
- **Nanostructured AlN[6] is attractive for the future nanodevice applications – it is possible to direct the growth process by DC toward quasi-3D columnar structures. Similar case – vertically aligned gallium-zinc oxide nanorods[7]**



- **From continuous to nanostructured columnar plasma polymer** [8] Deposition by sequential sputtering of Ti and polypropylen in Ar/hexane mixture at a glancing angles

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[5] Ref. in Advanced Materials by Jamil Elias and Laetitia Philippe of Empa's Mechanics of Materials and Nanostructures Laboratory in Thun, Switzerland, Aug. 2, 2010

[6] Jonathan K. Kwan and Jeremy C. Sit, Nanotechnology 21 (2010) 295301; [7] M. Yan, H.T. Zhang, E.D. Widjaja, and R.P.H. Chang, J. Appl.. Phys. 94, 5240 (2003); [8] A. Choukurov, H. Biederman et al, Plasma Proc. & Polymers 7 (2010) 25-32

Technological opportunity – IADF control

numerical simulations suggested

- **Selective manipulation of ions fluxes can be instrumental in maintaining a steady growth with a predetermined shape[9], reshaping of caved cylindrical nanorods into conical spike-like microemitter structures[10], etc.**

Properties to be influenced:

- ➔Alignment
- ➔Spacing
- ➔Ordering
- ➔Composition
- ➔Stoichiometry
- ➔Crystallinity
- ➔Size
- ➔Shape

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[9] I. Levchenko, K. Ostrikov, M. Keidar and S. Xu, Appl. Phys. Lett. **89**, 033109 (2006); [10] E. Tam, I. Levchenko and K. Ostrikov, J. Appl. Phys. Lett. **100**, 036104 (2006); [11] I. Levchenko, K. Ostrikov, E. Tam, Appl. Phys. Phys. Lett. **89**, 223108 (2006)

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- **Ion fluxes have potential to have impact on the various shapes and structures[11]**

- from “**0 dimensionality**” (ultrasmall quantum dots, …)
- “**1D**” (high-aspect-ratio nanowires or nanotube-like structures, …)
- “**2D**” (nano-wall-like structures, nanowells, …)
- up to “**3D**” (nanoparticles, nanopyramides, nanocones, nanorods, ...)

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Application opportunity for post-processing, coating with nanofilms, functionalization, or doping, …

[9] I. Levchenko, K. Ostrikov, M. Keidar and S. Xu, Appl. Phys. Lett. **89**, 033109 (2006); [10] E. Tam, I. Levchenko and K. Ostrikov, J. Appl. Phys. Lett. **100**, 036104 (2006); [11] I. Levchenko, K. Ostrikov, E. Tam, Appl. Phys. Phys. Lett. **89**, 223108 (2006)

Finding the approach

EEDF	IEDF	IADF
EEDF controls the spatial plasma distribution (uniformity), aimed RF power dissipation into plasma and chemistry	IEDF controls the quantitative and qualitative process performance (processing rates, etch or deposition profile, selectivity, damage, etc.)	IADF is apparently uncontrollable factor (consequence of used pressure and bias, e.g. IEDF)

WYSIWYG?

- **How can one control the EEDF, IEDF and IADF in the plasma?**

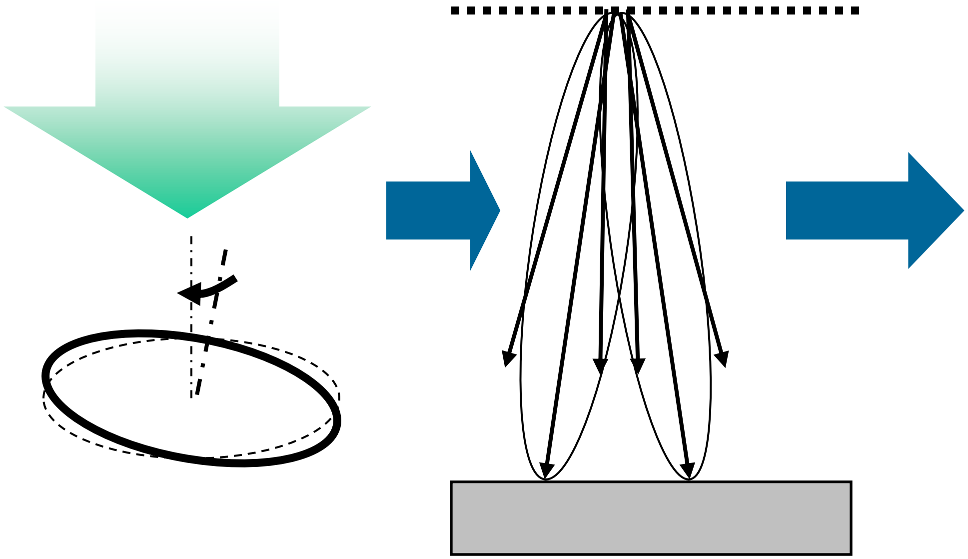
Reactor design, plasma source design, …	**Bias power design, frequency, …..**	**Any independent control knob?, …**

- **Can one design these distribution functions?**

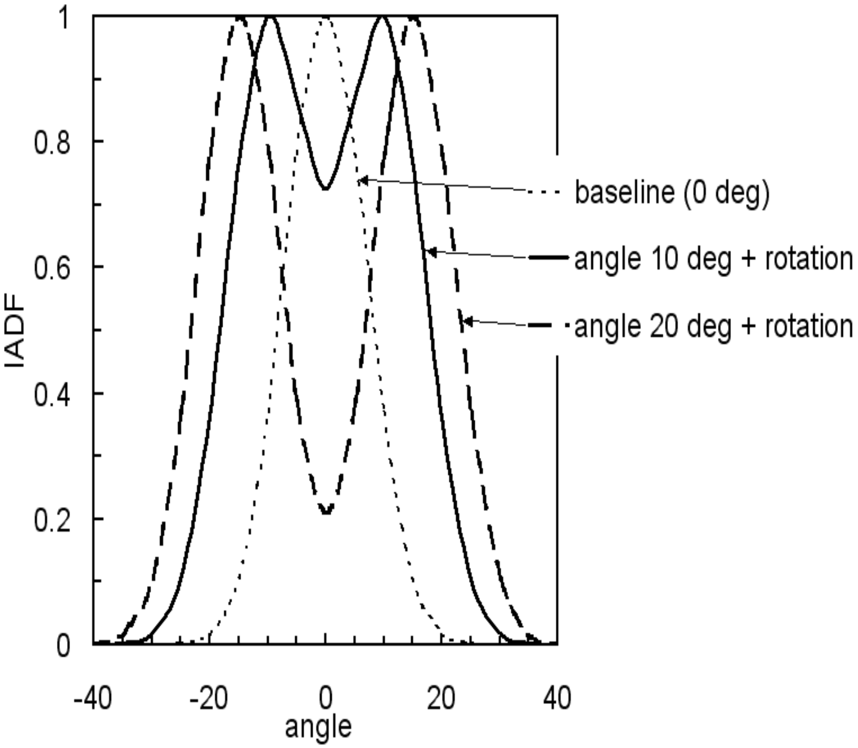
“design at the kinetic level”

Concept: Modification of the IADF

Collimated beam and inclination of the rotating wafer will produce specific IADF



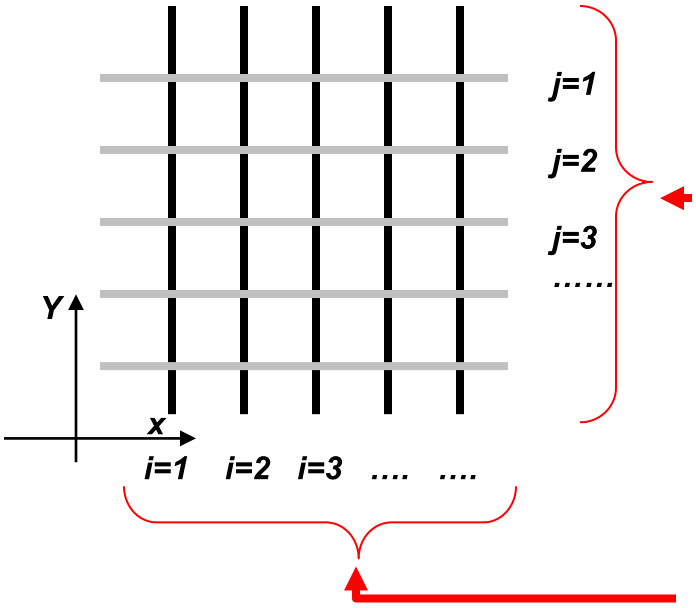
resultant IADF

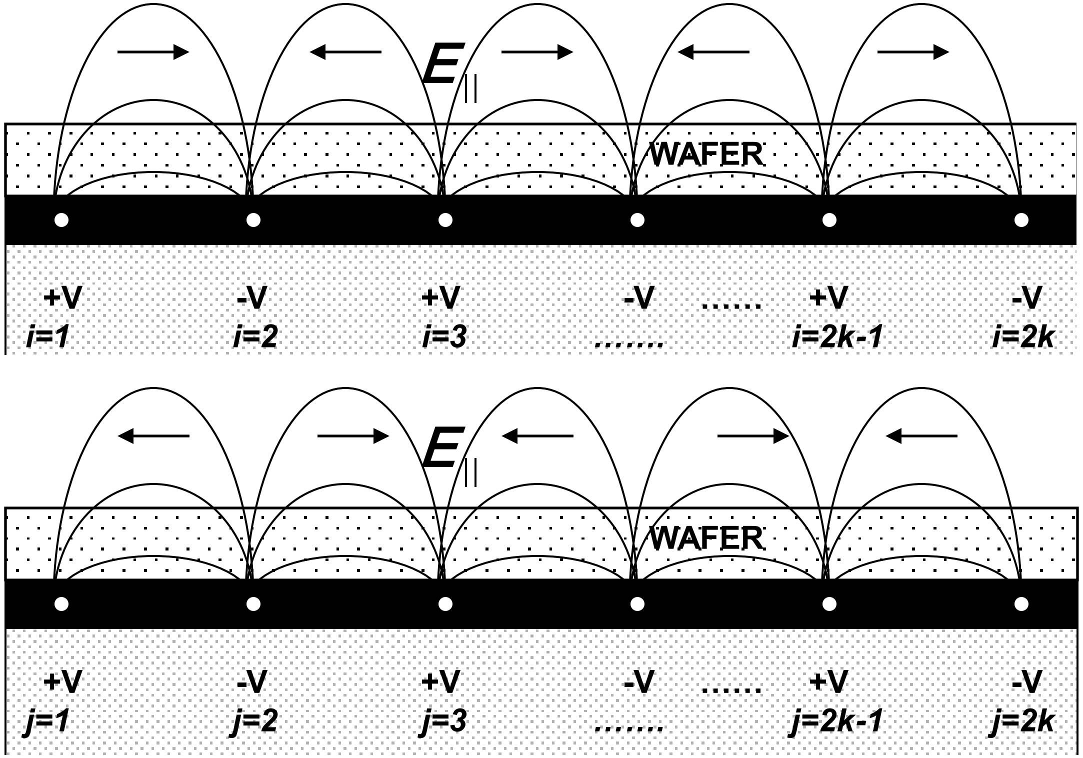


Generate this specific IADF w/o motion and provide its control and variation

Concept

conductive grid structure embedded into a substrate holder



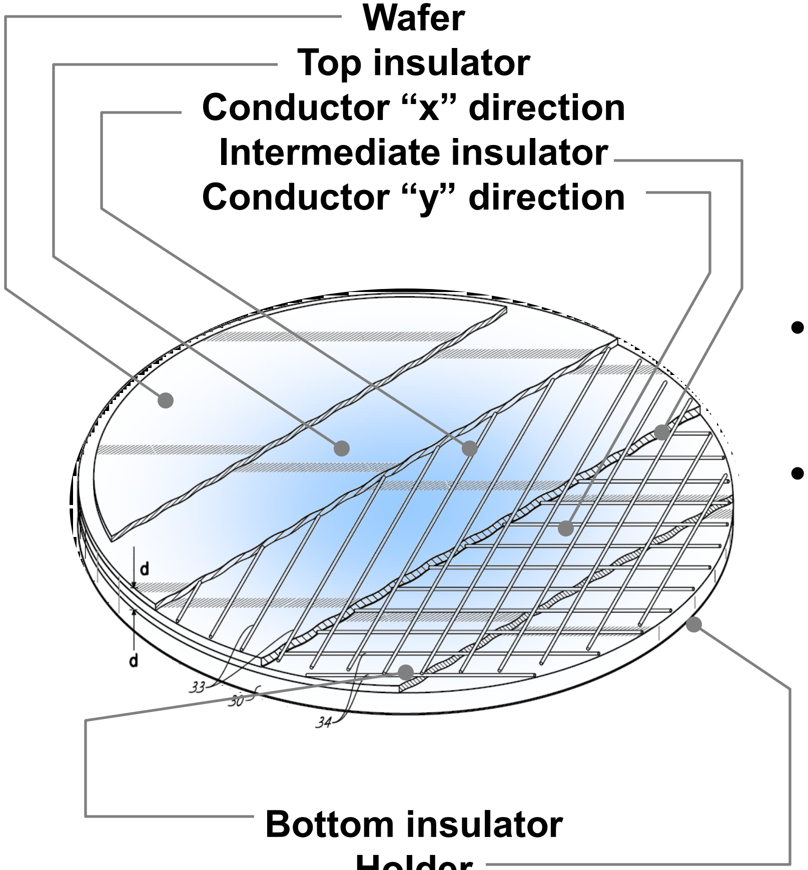


Generation of the E-field parallel to the wafer surface

- Application of ac voltage to grid conductors (cross-section shown is in the y-direction, analogically done in x-direction)

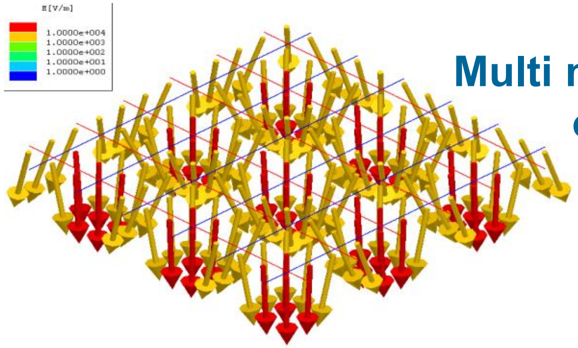
Concept

application for plasma based technology[12]



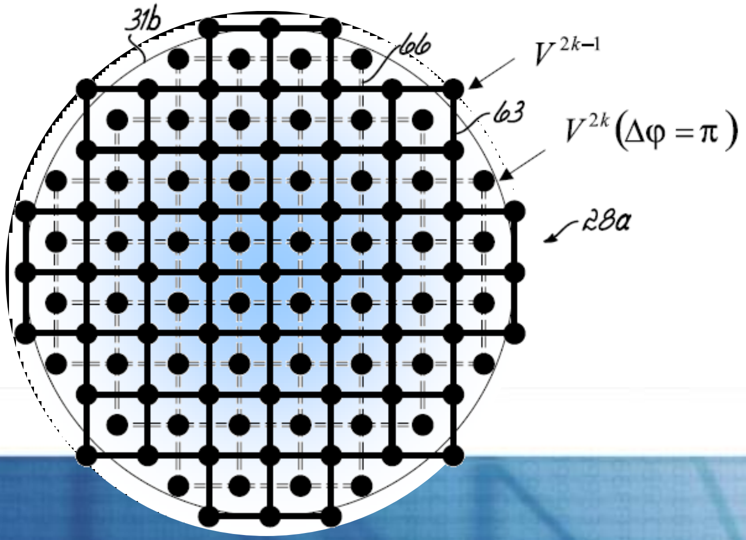
Wafer
Top insulator
Conductor "x" direction
Intermediate insulator
Conductor "y" direction

Bottom insulator
Holder



Multi micro-beams of ions

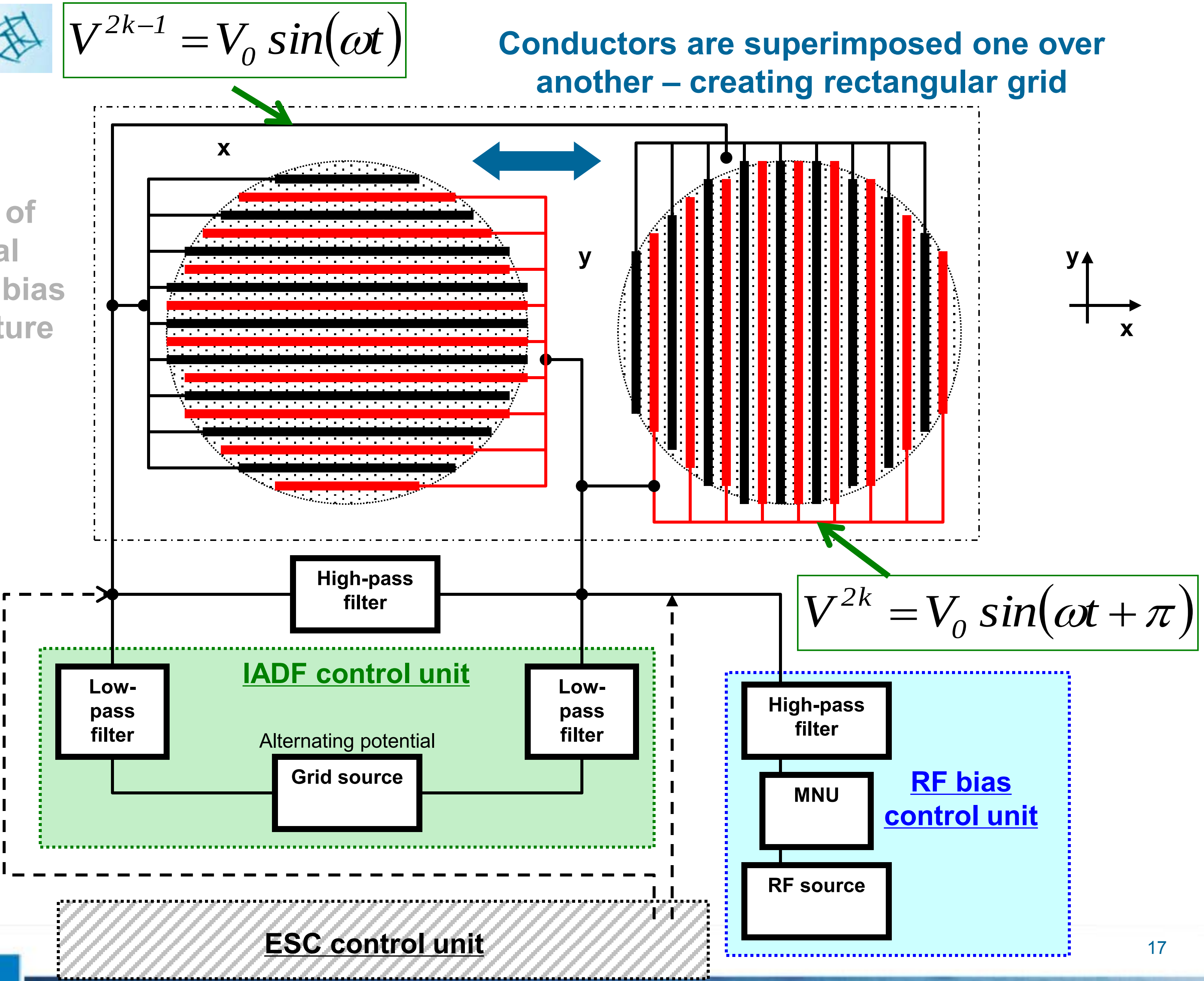
- Resulting effect will depends on the plasma and wafer bias
- Point where E-field is focused is moving on wafer surface in particular pattern



[12] US Pat. Aool. 2008/0242065 (2008)

Conductors are superimposed one over another – creating rectangular grid

Example of electrical scheme to bias grid structure



$$V^{2k-1} = V_0 \sin(\omega t)$$

$$V^{2k} = V_0 \sin(\omega t + \pi)$$

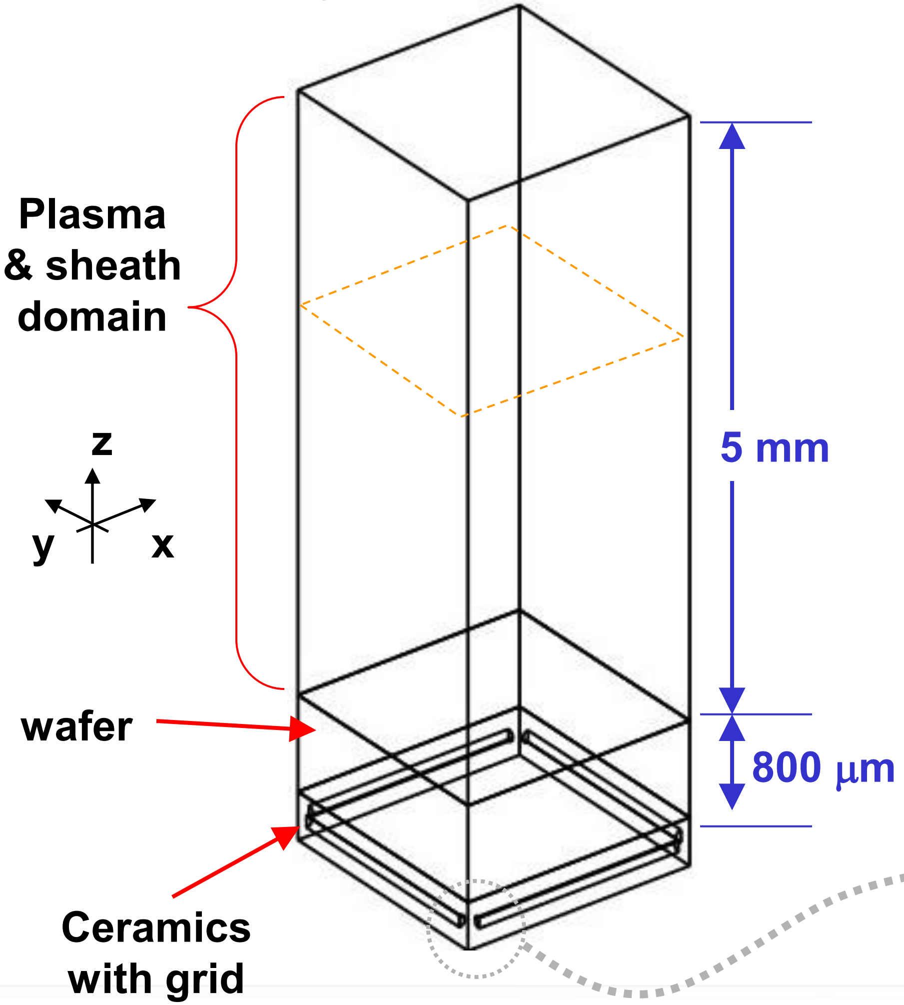
Multiple options to control ion trajectories

Controlling parameters

- **Grid electric field:**
- **Phase $\Delta\varphi_{xy}$ of wires**
- **Amplitudes**
  - V_x and V_y in x and y directions, respectively and/or their ratio
- **Frequency**
  - f_x and f_y and/or their ratio

Multiple options to control ion trajectories

Geometry setup



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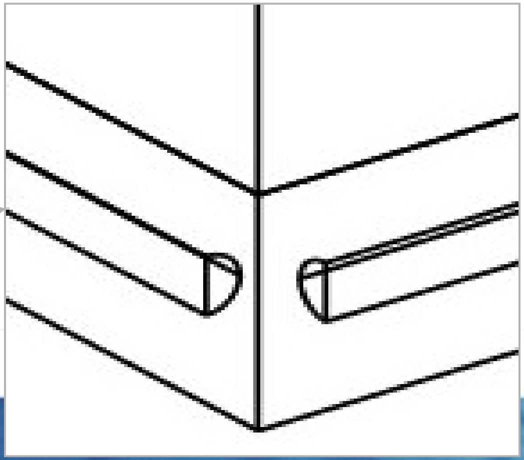
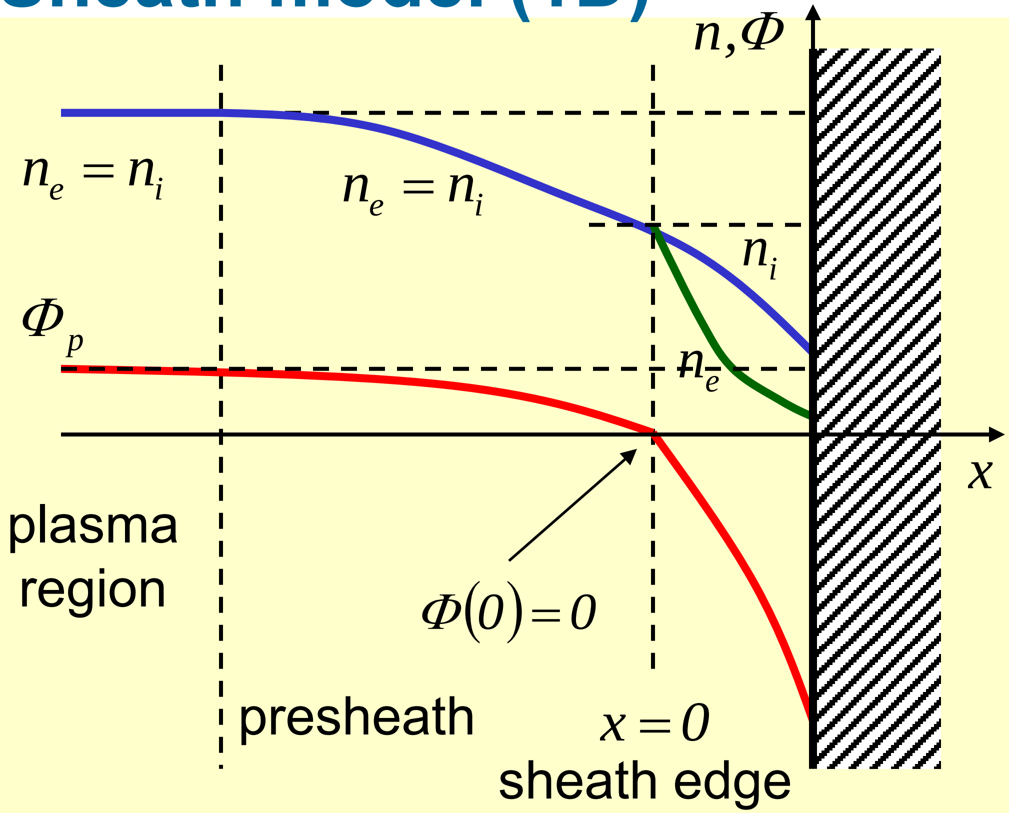


Sheath model (1D)



n,Φ

$n_e = n_i$

$n_e = n_i$

n_i

Φ_p

n_e

x

plasma region

$\Phi(0) = 0$

presheath

$x = 0$

sheath edge

Sheath model (1D)

- We used Lieberman's formulation for collisionless DC sheath[14]
  - **Maxwellian electrons at temperature** T_e
  - **cold ions in bulk domain** $T_i = 0$
  - **quasi-neutrality in bulk plasma**

$$n_e = n_i = n$$

  - **quasi-neutrality in presheath**

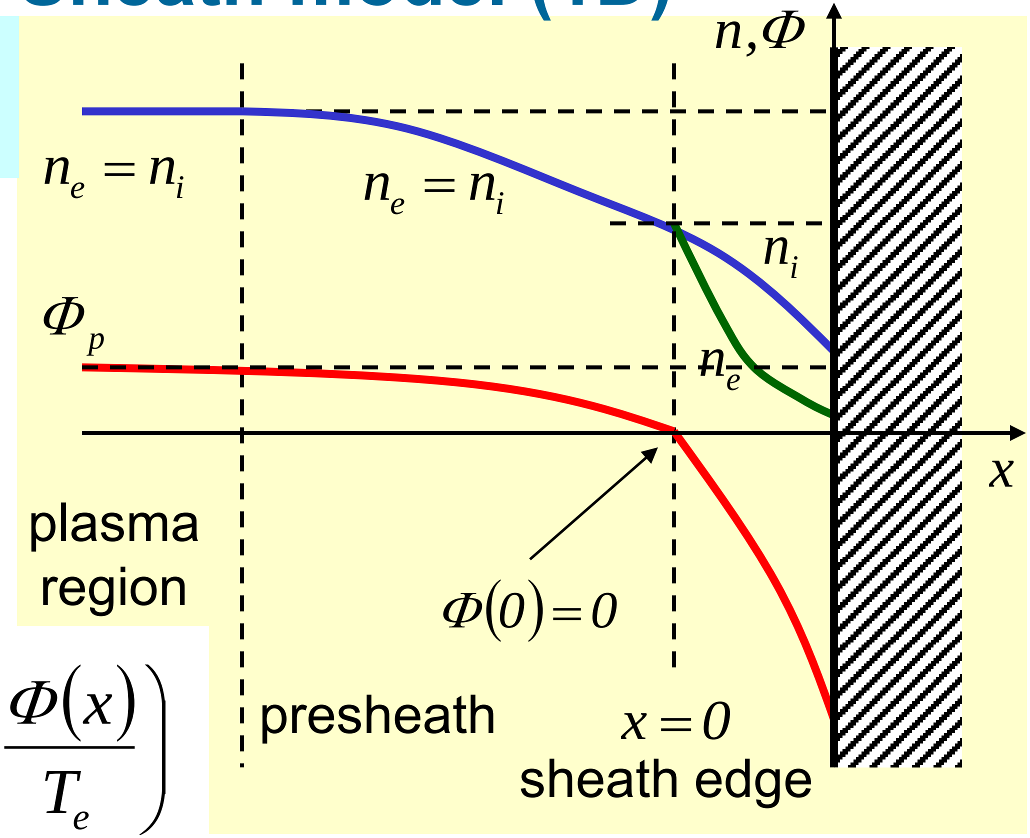
$$n_{es} = n_{is} = n_s$$

  - **Boltzmann relation for electrons in sheath**

$$n_e(x) = n_{es}\, exp\left(\frac{\Phi(x)}{T_e}\right)$$

  - **ion energy conservation**

$$n_i(x) = n_{is}\left(1 - \frac{2e\Phi(x)}{m_i u_s^2}\right)^{-1/2}$$



$$\boxed{\frac{d^2\Phi}{dx^2} = \frac{en_s}{\varepsilon_0}\left[exp\left(\frac{\Phi(x)}{T_e}\right) - \left(1 - \frac{2e\Phi(x)}{m_i u_s^2}\right)^{-1/2}\right]}$$

[14] M. A. Lieberman, A.J. Lichtenberg, Principles of plasma discharges and materials processing, John Wiley & Sons, New York (1994)

Extension sheath model into 2D (3D) and BC

Poisson equation

$$-\nabla \cdot \varepsilon_r \varepsilon_0 \nabla \Phi = \rho = -e(n_i - n_e)$$

Plasma-sheath interface conditions

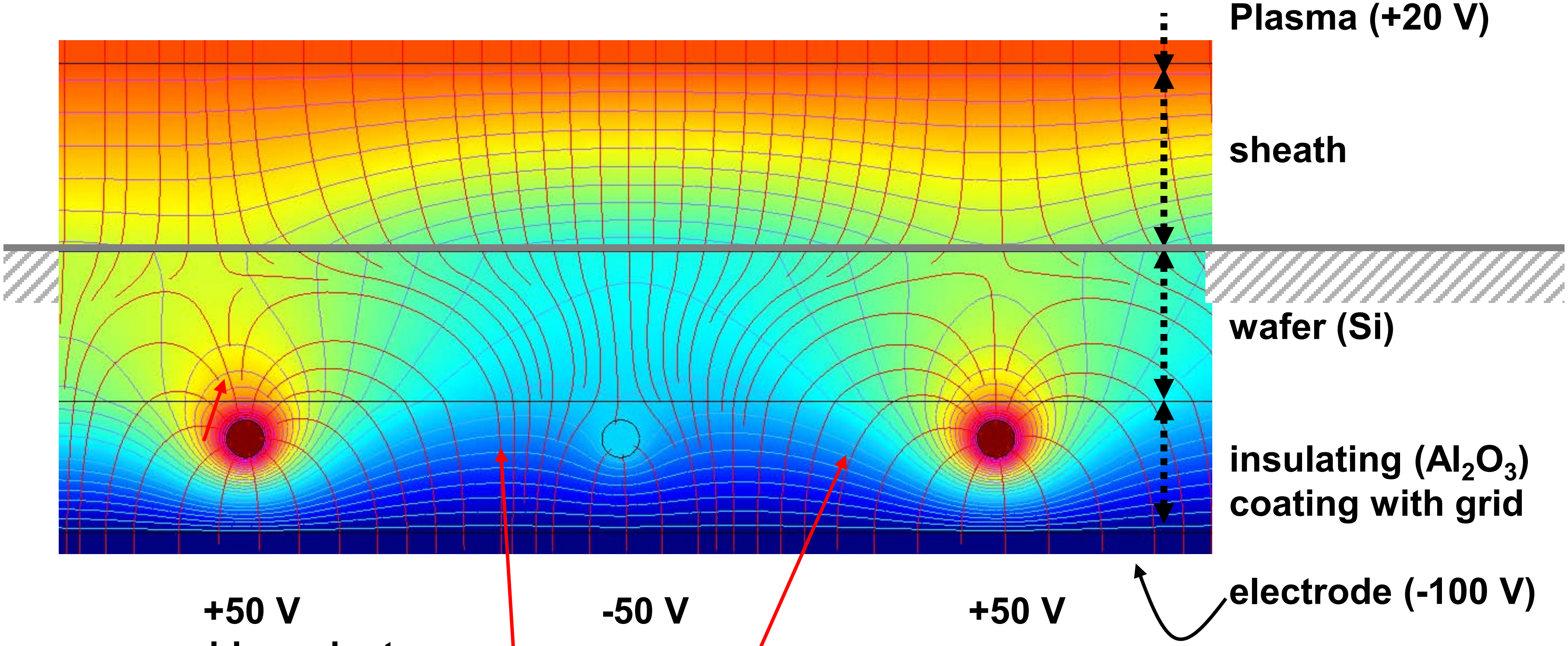
$$n_i = \begin{cases} n_s & when \quad 2\eta > 1 \\ n_s (1 - 2\eta)^{-1/2} & when \quad 2\eta < 1 \end{cases}$$

$$n_e = \begin{cases} n_s & when \quad V > 0 \\ n_s \exp(V/T_e) & when \quad V < 0 \end{cases}$$

$$\eta = eV/(m_i u_s^2)$$

- Under GUI in AC/DC module in Comsol we set following conditions:
  - surface boundary conditions (BC) are set to symmetrical at the vertical sidewalls of each sub-domain
  - top surface boundary is set to relative plasma potential V_{plasma}=0 V
  - surface boundary at electrode are VDC
  - Surface boundary conditions at grid's conductors in dependece on tested potential, Vx, Vy
  - Grid potentials were extended into transient
  - Interior boundaries are represented by continuity BC

2D results from sheath simulation[a] plasma potential @ 20 V, wafer at -100 V



Plasma (+20 V)

sheath

wafer (Si)

insulating (Al_2O_3) coating with grid

electrode (-100 V)

+50 V **-50 V** **+50 V**

grid conductors

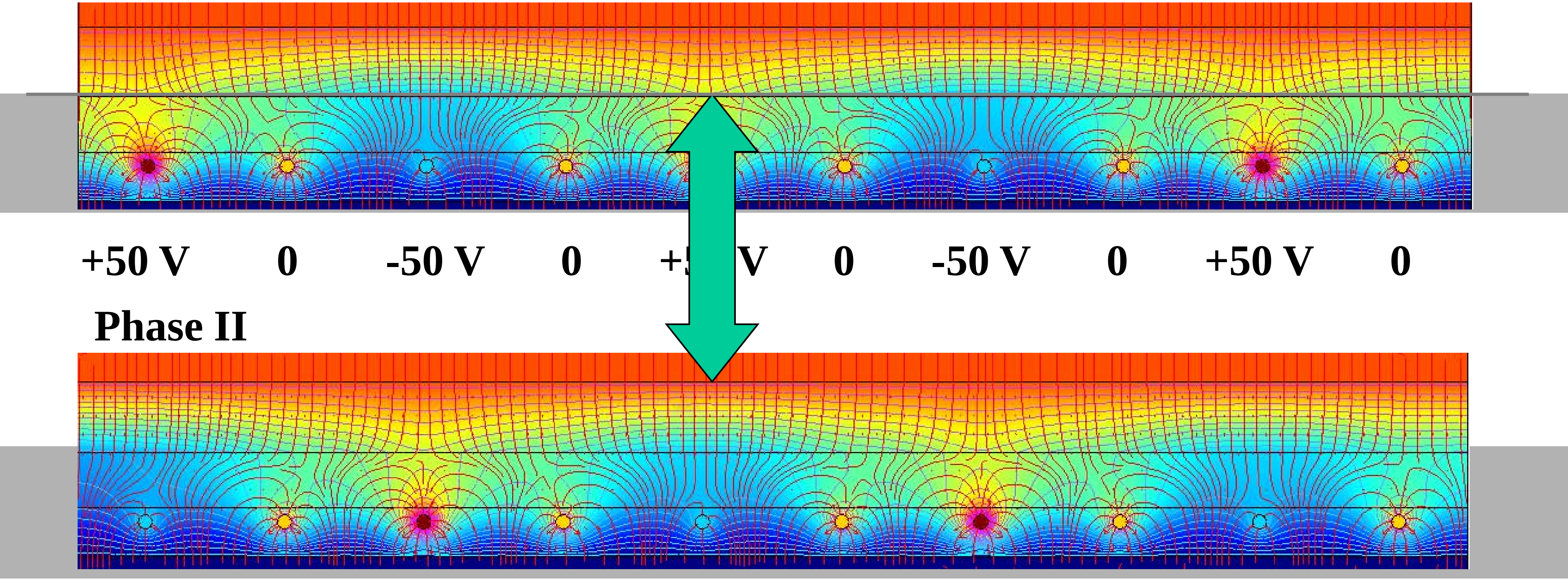
electric field lines (red contours)

electric potential (blue contours, 25 levels) (surface color plot)

[a] Simulation by Multiphysics COMSOL

Sequential biasing the groups of the specific conductor lines

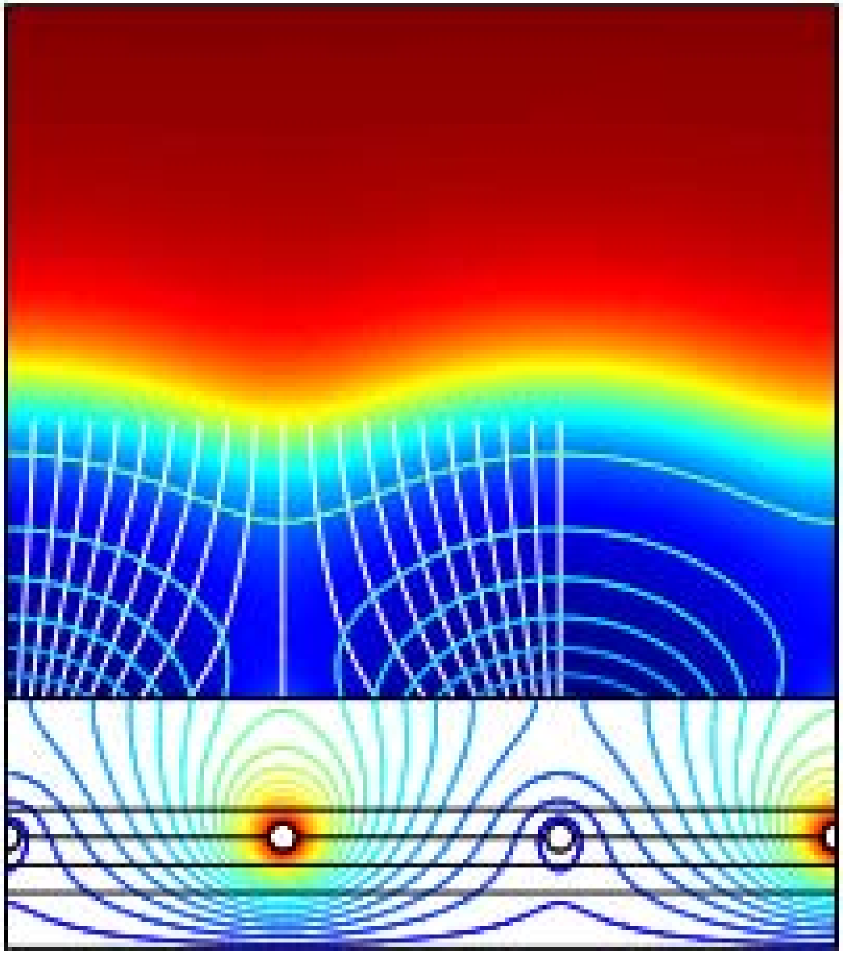
Phase I



- In average overall surface of the wafer will be exposed by ions with specific IADF

Animation object - ionpath200red1.avi

Grid potential



Ion density in plasma

Ion path in sheath

wafer

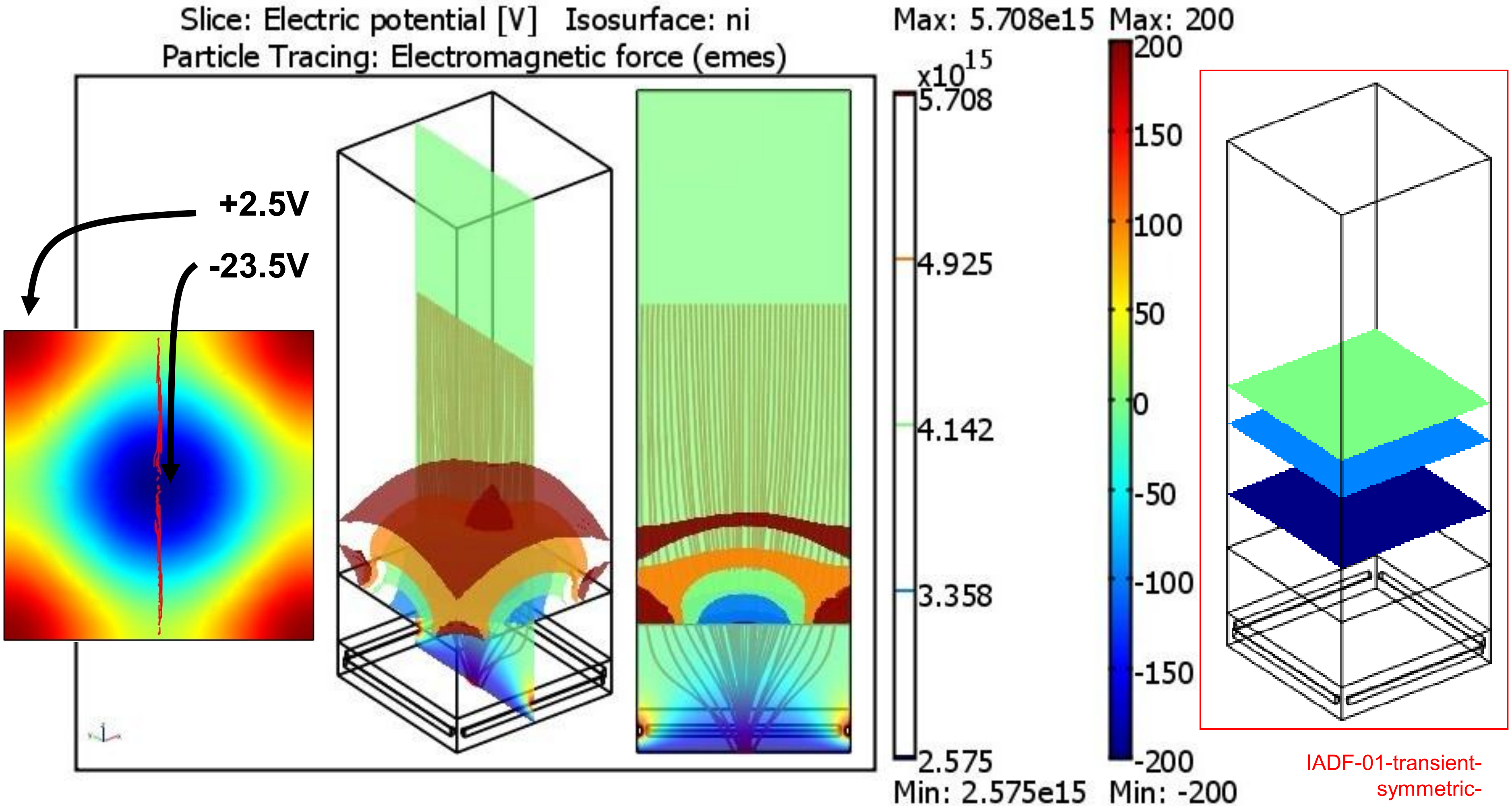
Potential contours

grid

+200 V to -200 V

-200 V to +200 V

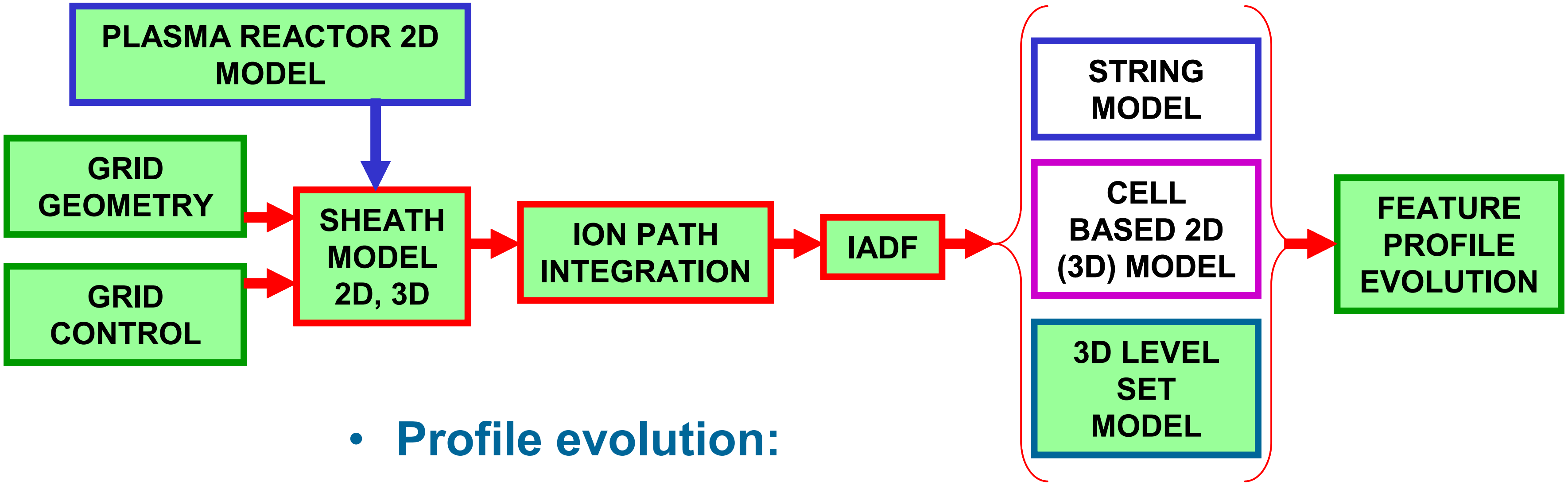
3D grid structures



IADF-01-transient-symmetric-in_phase(red1).avi

Full scale reactor

- **Feasibility stage – virtual prototype for specific plasma reactor**
- **Plasma reactor choice of model**
  - In-house sw for specialty modeling,
  - Plasma module of Comsol



PLASMA REACTOR 2D MODEL

GRID GEOMETRY

GRID CONTROL

SHEATH MODEL 2D, 3D

ION PATH INTEGRATION

IADF

STRING MODEL

CELL BASED 2D (3D) MODEL

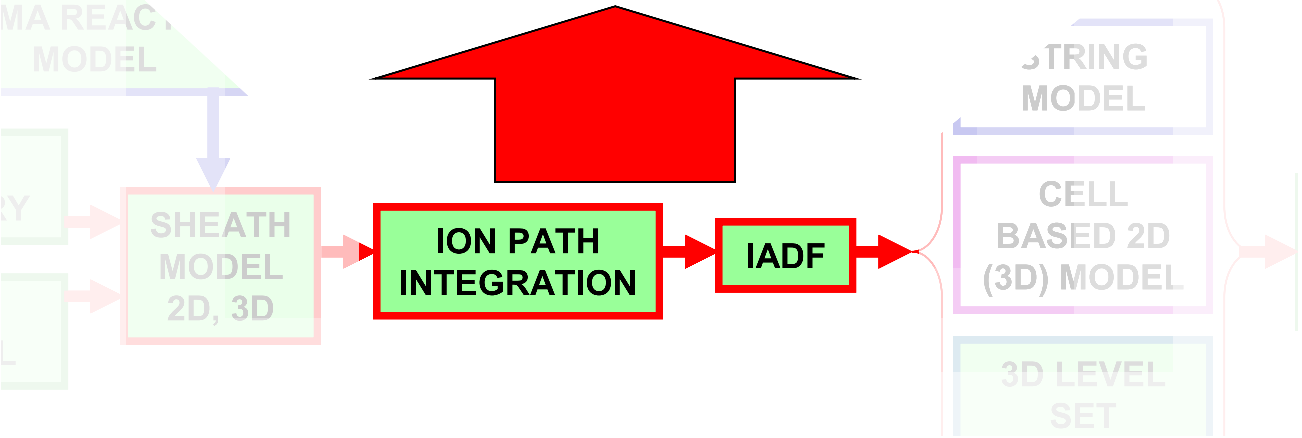
3D LEVEL SET MODEL

FEATURE PROFILE EVOLUTION

- **Profile evolution:**
  - String model, Cell mode, level set model

IADF determination

- **Analytical model**[b]
- **Collisionless rf sheath – cold-ion plasma model**
- **Extended collisional rf sheath model**[a]
- **Monte-Carlo sheath model or hybrid codes**
- **Spatiotemporal sheath electric field**



MA REAC MODEL

RY

L

SHEATH MODEL 2D, 3D

ION PATH INTEGRATION

IADF

TRING MODEL

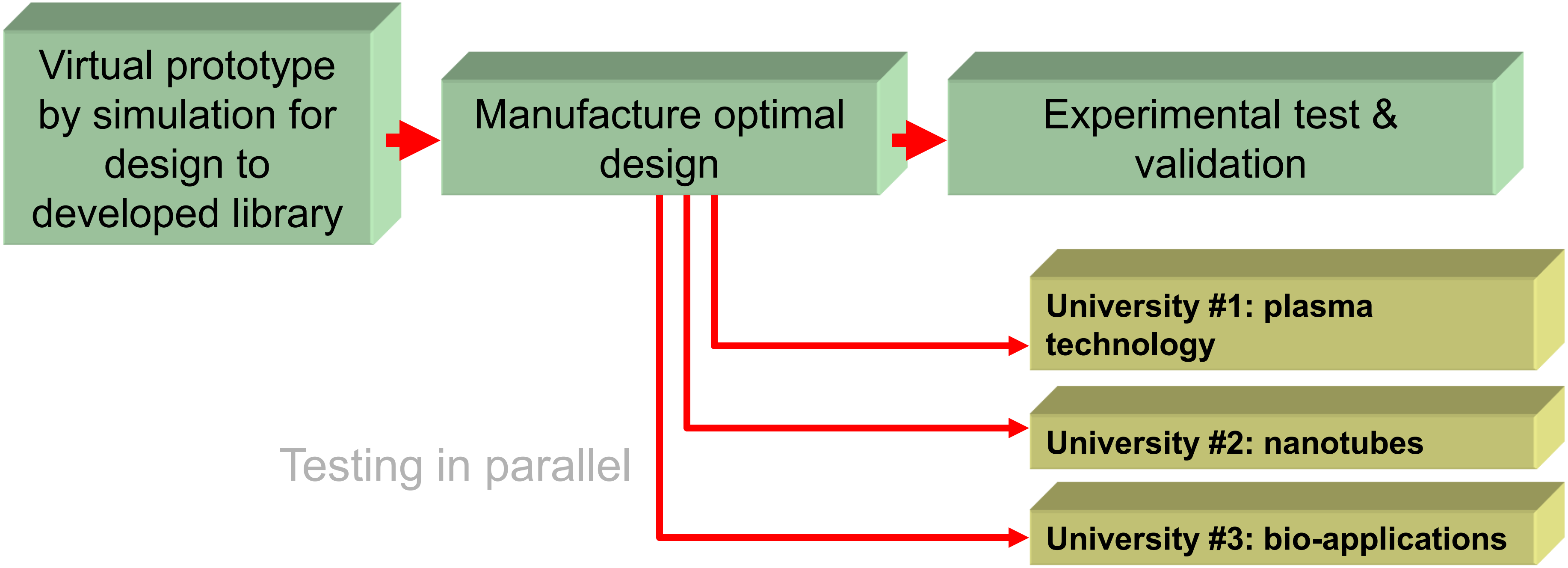
CELL BASED 2D (3D) MODEL

3D LEVEL SET

[a] Zhong-ling Dai You-Nian Wang, Simulation of ion transport in a collisional rf plasma sheath. Physical Review E **69** 036403 (2004); [b] Raja L.,….

Opportunity for collaboration

- **Focus: Application driven R&D**
- **Inside company development (engineering) & partnership with university (computational aspects and experimental evaluation)**



Virtual prototype by simulation for design to developed library

Manufacture optimal design

Experimental test & validation

University #1: plasma technology

University #2: nanotubes

University #3: bio-applications

Testing in parallel

Conclusions

- We introduced idea and described concept on control of the IADF
- Sheath model was developed to investigate properties and performance of such device
- More robust scheme of model is proposed to include input data and output performance, more complex geometry and biasing schemes under same modelling platform
- Several emerging applications were indicated where it can be used and given call for collaboration on this subject