Low energy electron interactions with thin resist films - a new perspective

[1,2]Rudolf M. Tromp, [2,3]Aniket Thete, [2]Daniel Geelen,[3]Ivan Bespalov,
[3]Sonia Castellanos, [2]Sense Jan van der Molen

[1]IBM T.J. Watson Research Center, Yorktown Heights, NY 10598

[2]Kamerlingh Onnes Laboratory, Leiden University, The Netherlands

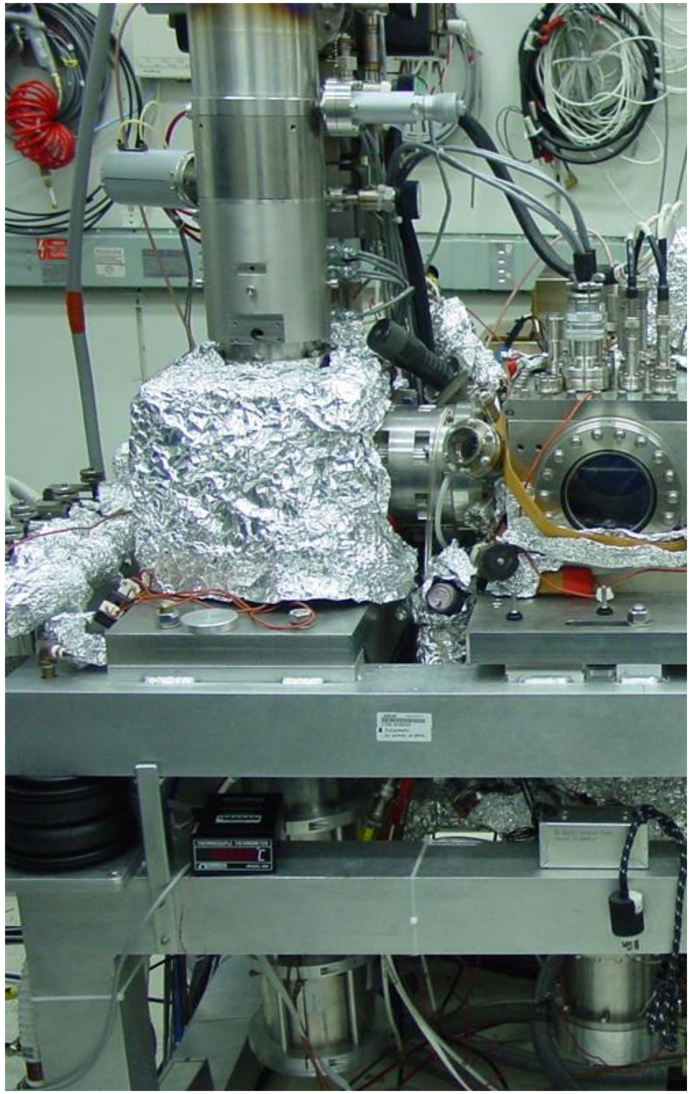
[3]Advanced Research Center for Nano Lithography, Amsterdam, The Netherlands

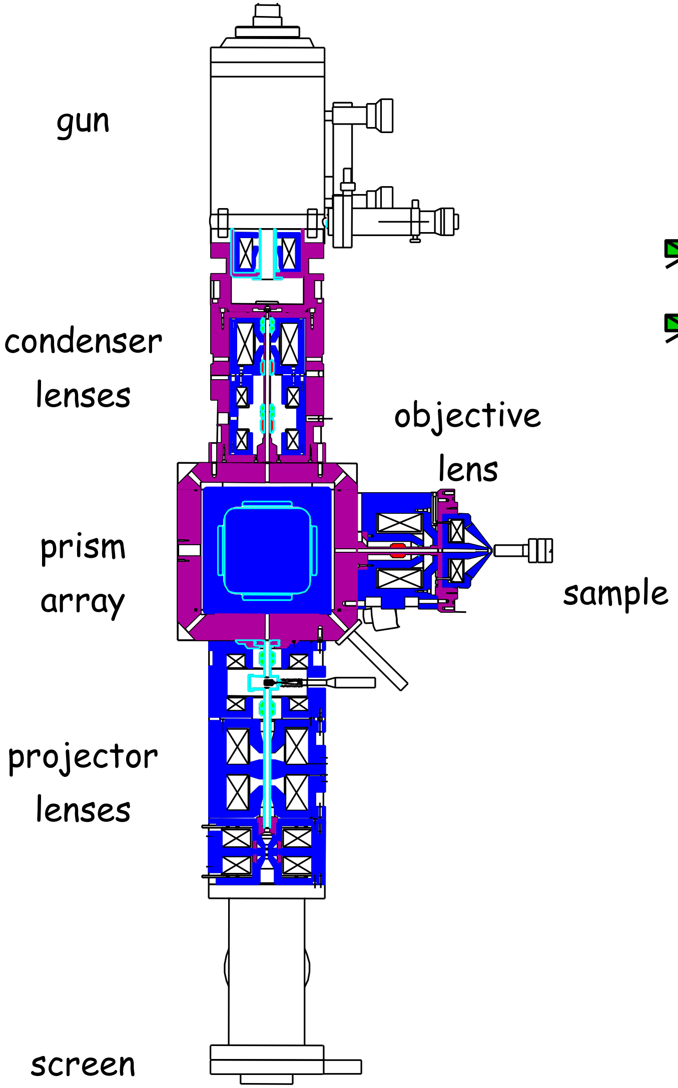
IBM®

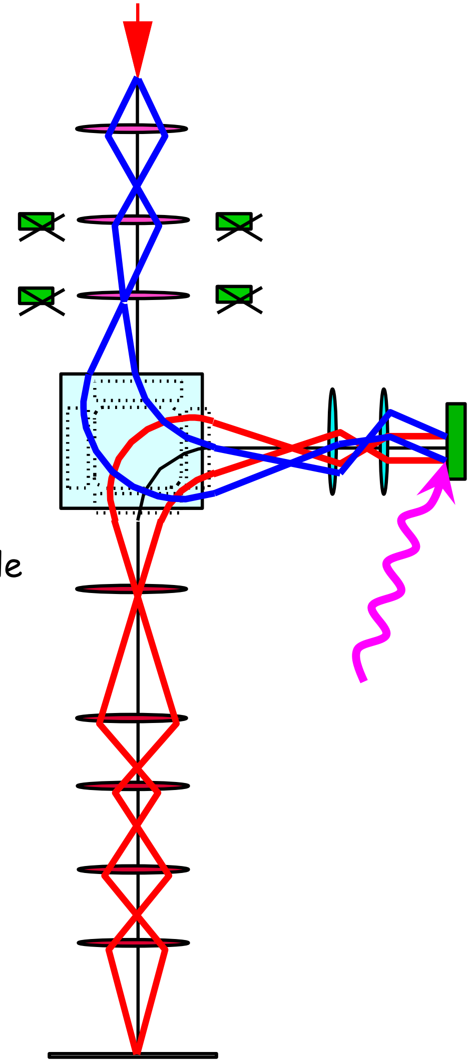
ARCNL
ADVANCED RESEARCH CENTER FOR NANOLITHOGRAPHY

Universiteit Leiden

2nd generation IBM LEEM/PEEM Design: ~30 instruments sold



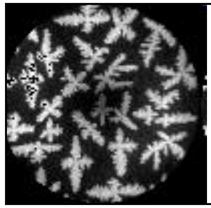
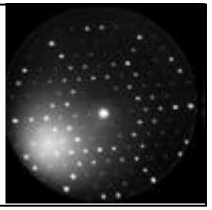
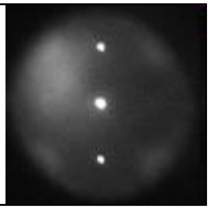
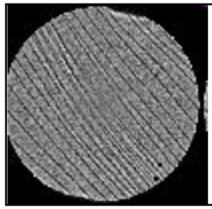
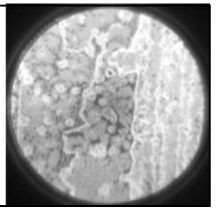
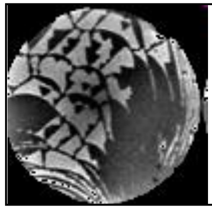
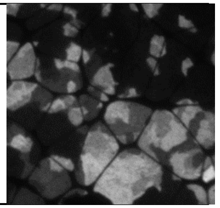
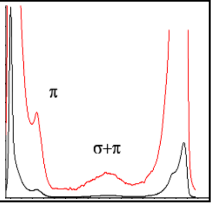




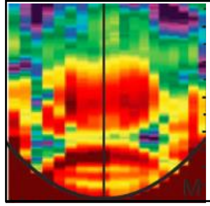
R.M.Tromp, M. Mankos, M.C. Reuter, A.W. Ellis, M. Copel
Surface Review and Letters 5 , 1189 (1998)

SPECS® IBM

Lab-based LEEM/PEEM imaging modes

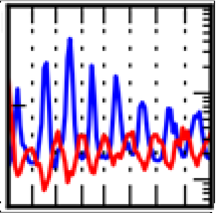
	PEEM imaging Hg light source	LEED Atomic Structure	
	Mirror Microscopy Topography Work Function	Selected Area LEED Local Atomic Structure 200 nm	
	Bright field LEEM Phase contrast	LEEM-EELS Local Electronic Structure Spectroscopy + Imaging	
	Bright field LEEM Reflectivity Structure factor	eV-TEM Transmission imaging without damage	
	Dark field LEEM Structure symmetry	Transmission EELS Low energy loss on the nanoscale	

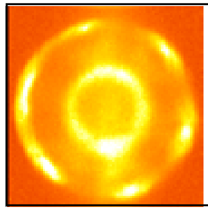
Lab-based LEEM/PEEM imaging modes



ARRES
Empty state
band structure

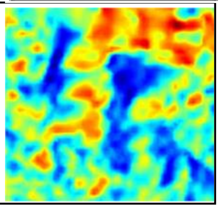
SPA-LEED-PLD
Atomic Layer Oscillations
during PLD growth

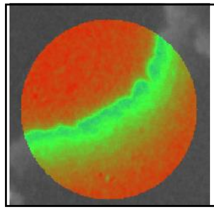




PEEM-ARPES
Filled state
band structure

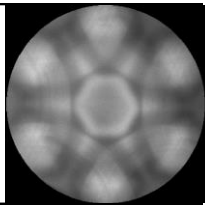
SPA-LEED
Local strain
measurement

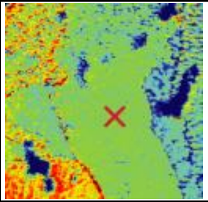




LEEM-IV Imaging
Local Atomic Structure
2-5 nm

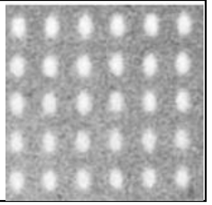
CBED
Local Atomic and
Electronic structure



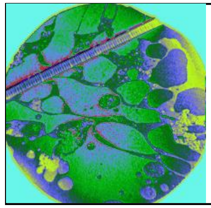


LEEM potentiometry
Contact-less nanoscale
device measurements

LEEM lithography
Structure fabrication
with few eV electrons

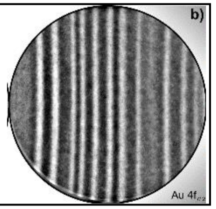


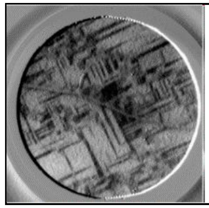
Synchrotron-based PEEM imaging modes



PEEM-IV Imaging
20 nm resolution
Local chemistry

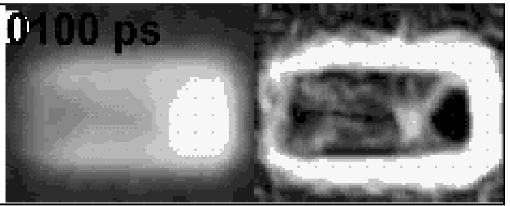
Dynamic Imaging
In-situ processing
Elemental/chemical

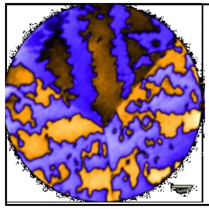




Linear Magnetic
Dichroism
Antiferromagnetism

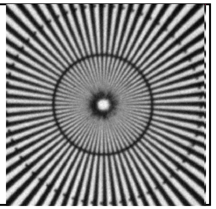
Picosecond
Resolution
Imaging

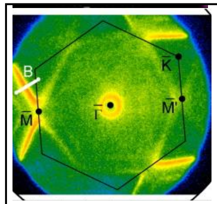




Circular Magnetic
Dichroism
Ferromagnetism

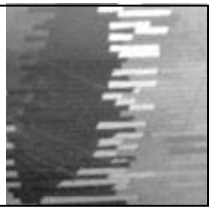
Localized Spectroscopy
Elemental, chemical
Magnetic, Valence

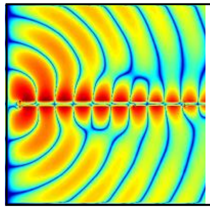




Valence Band Imaging
Surface, bulk
Topological

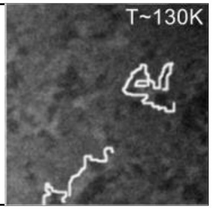
Biological Imaging
Organic, Inorganic
Elemental, chemical



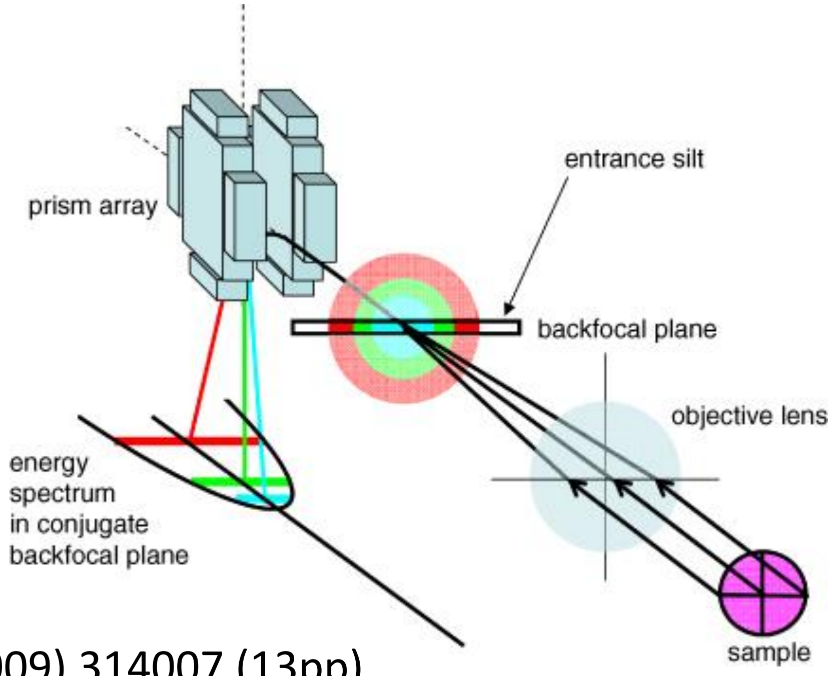


Plasmonics
Dynamics, geometry

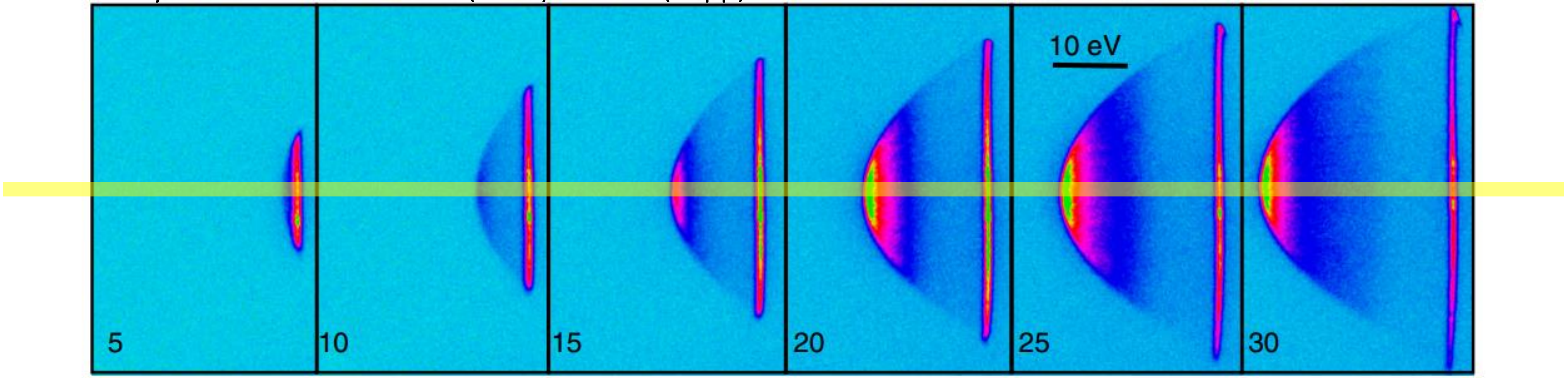
Cryo-PEEM
Solid State
Bio, soft matter



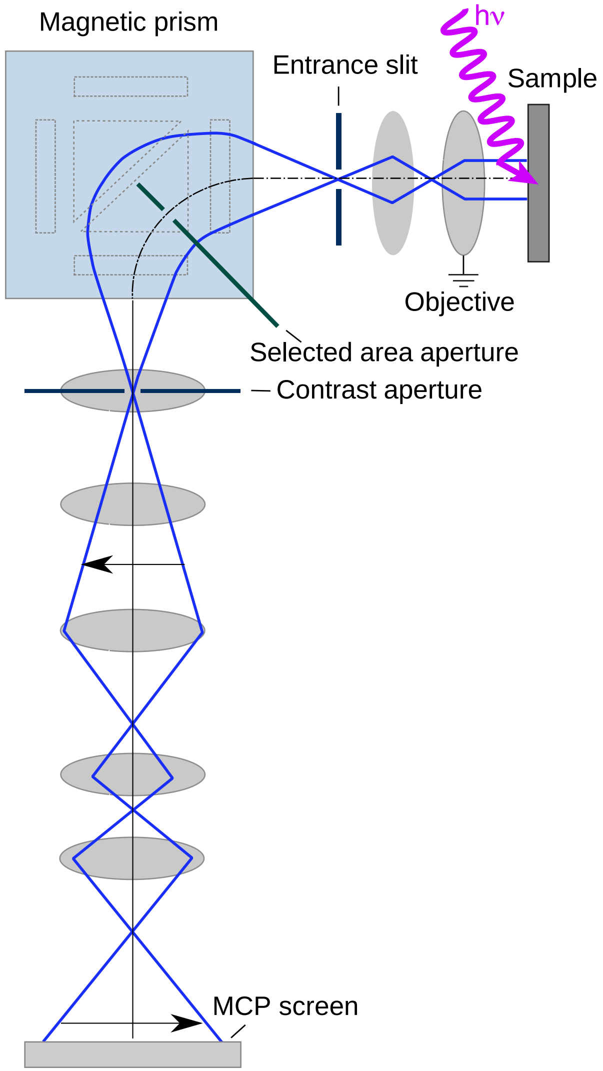
Energy filtering of returning electrons



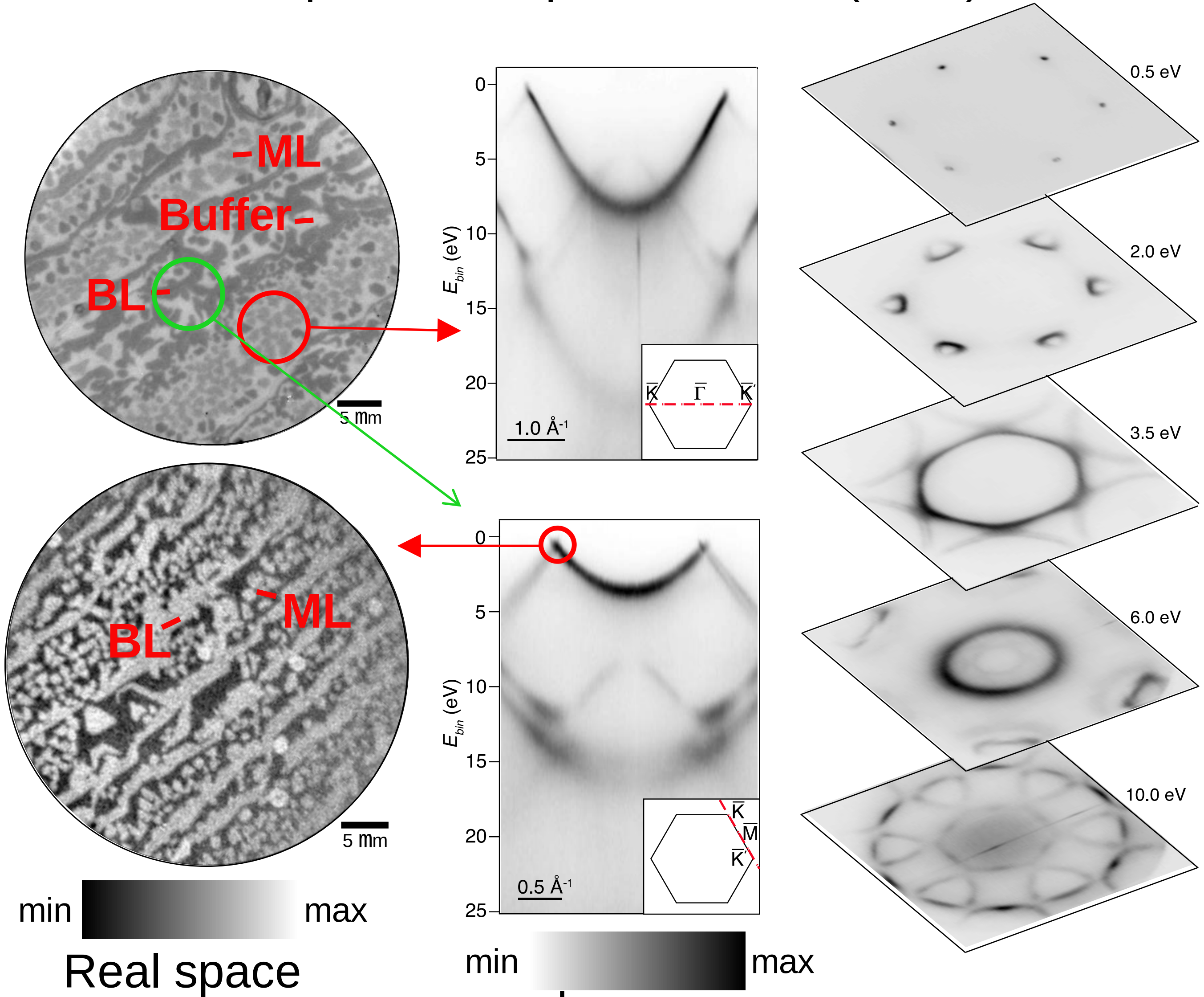
J. Phys.: Condens. Matter 21 (2009) 314007 (13pp)



IBM/SPECS PEEM with an integrated imaging energy analyser



Epitaxial Graphene/6H-SiC(0001)



Dark-field imaging with bands

S. Ulstrup et al., ACS nano 10 (11), 10058-100
R. M. Tromp *et al.*, J. Phys. Cond. Matter **21** 314007 (2009)

Low Energy Electron Microscopy

Illuminate surfaces, interfaces, thin films with low energy electrons

or

Extract low energy electrons by some other means (photoemission, thermo-emission, ion bombardment, etcetera)

THEN

SEE what happens

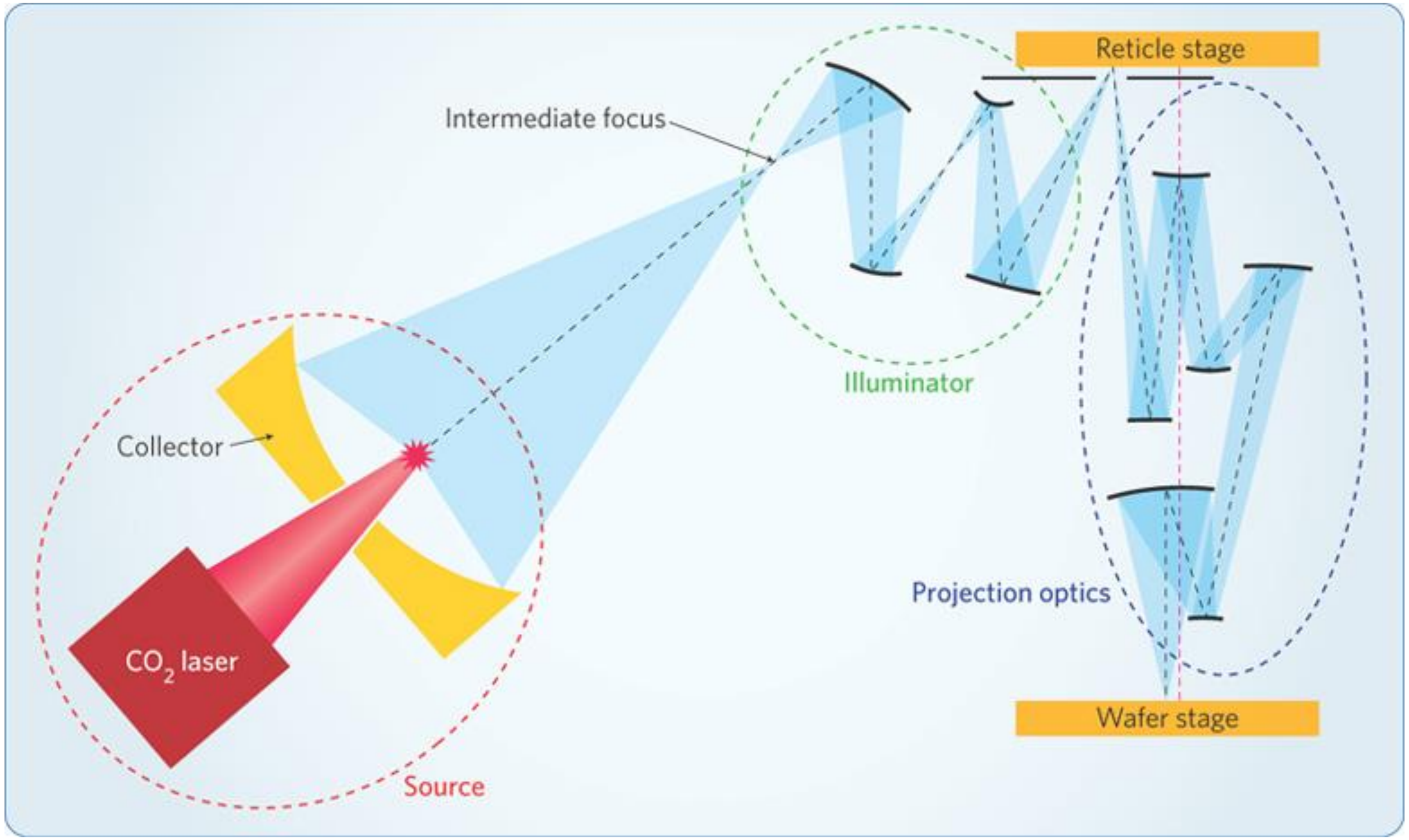
PRL **119,** 266803 (2017) PHYSICAL REVIEW LETTERS week ending 29 DECEMBER 2017

Charge Catastrophe and Dielectric Breakdown During Exposure of Organic Thin Films to Low-Energy Electron Radiation

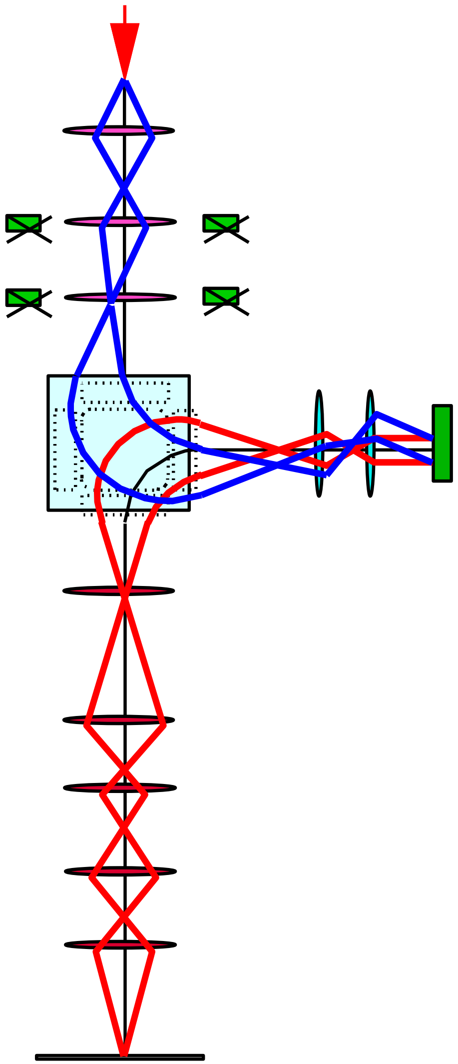
A. Thete,[1,2] D. Geelen,[1] S. J. van der Molen,[1] and R. M. Tromp[1,3]

[1]*Leiden University, Huygens-Kamerlingh Onnes Laboratory, P.O. Box 9504, 2300 RA Leiden, The Netherlands*
[2]*Advanced Research Center for Nanolithography, Science Park 102, 1098 XG Amsterdam, The Netherlands*
[3]*IBM T.J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, New York 10598, USA*

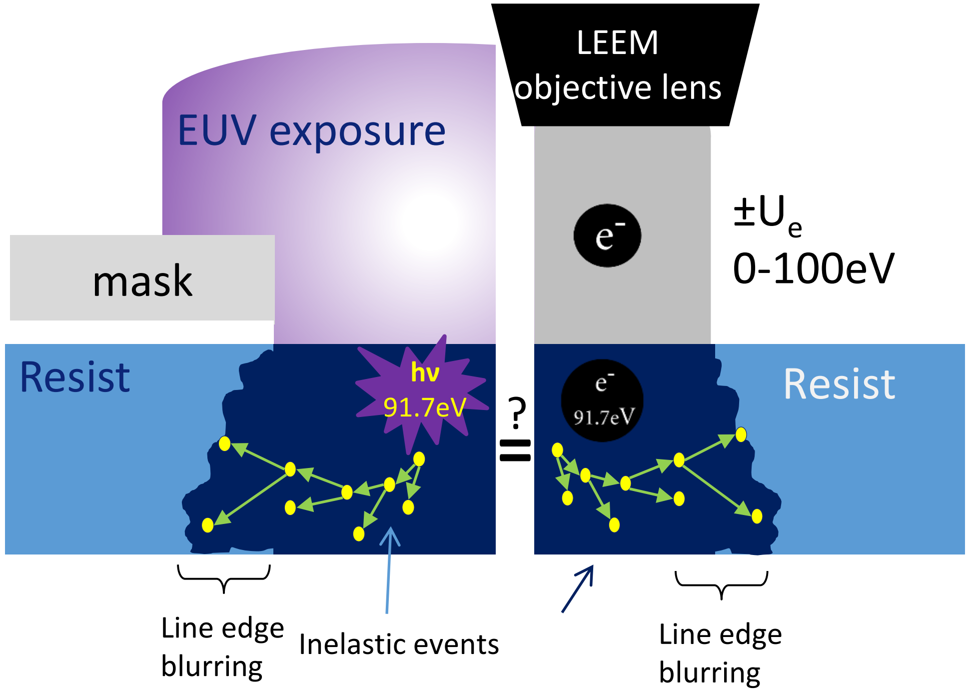
Thin film polymer (resist) exposures with LEEM



EUV lithography: 13.5 nm (91.8 eV) photons

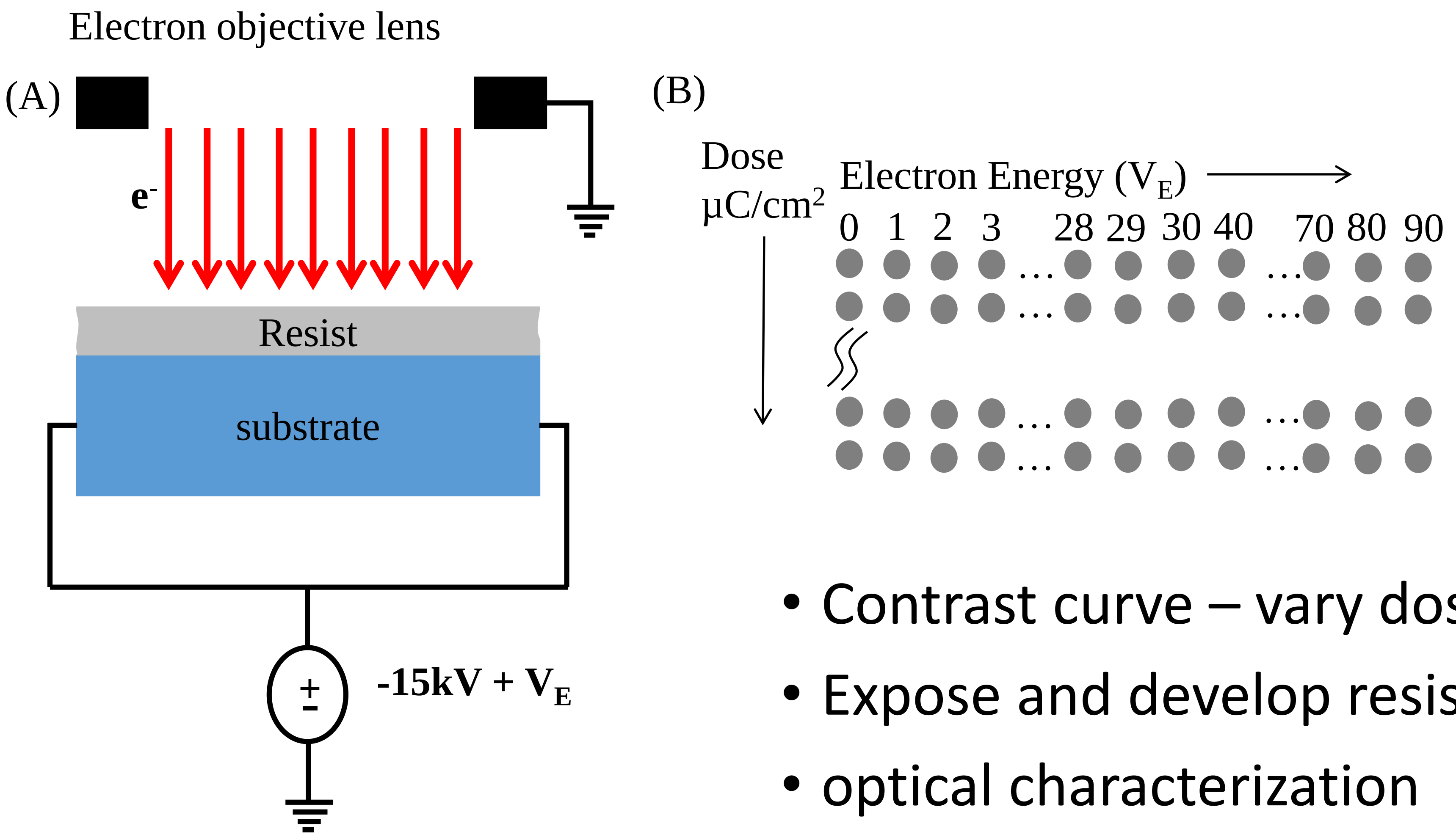


LEEM for EUV lithography research



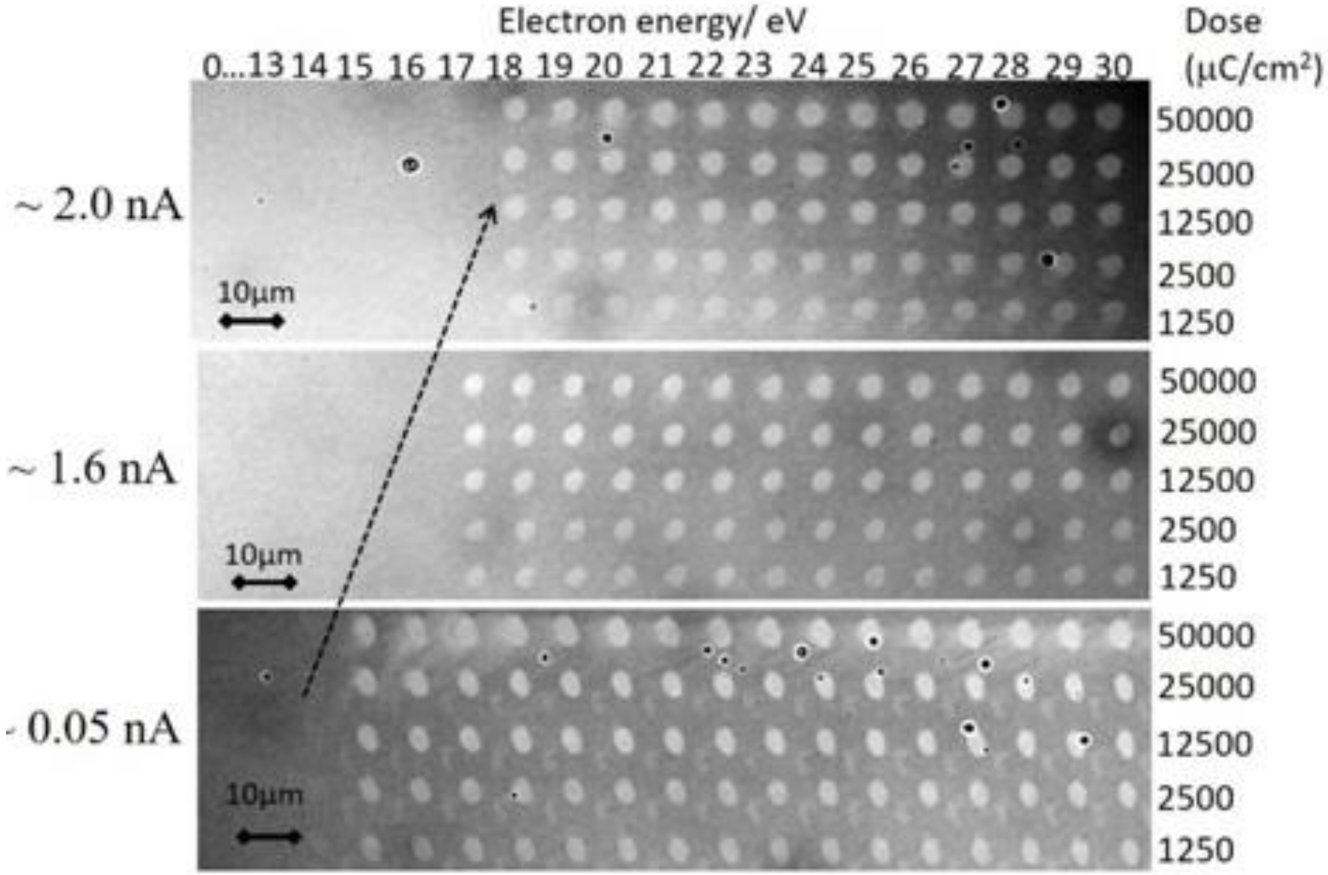
Use low energy electron exposure to mimic EUV exposure

Typical experiment



- Contrast curve – vary dose and energy
- Expose and develop resist
- optical characterization

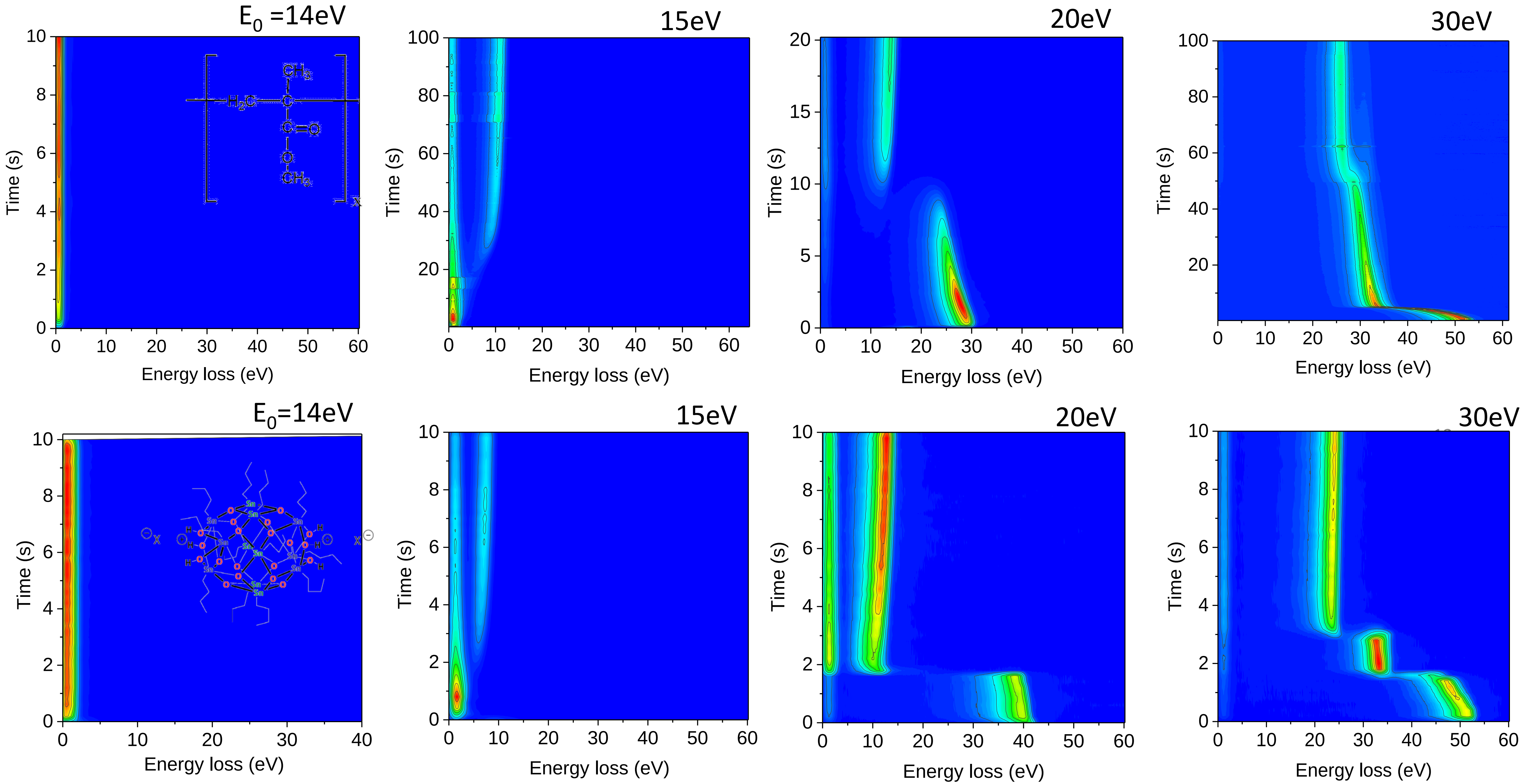
Typical result (20 nm PMMA)



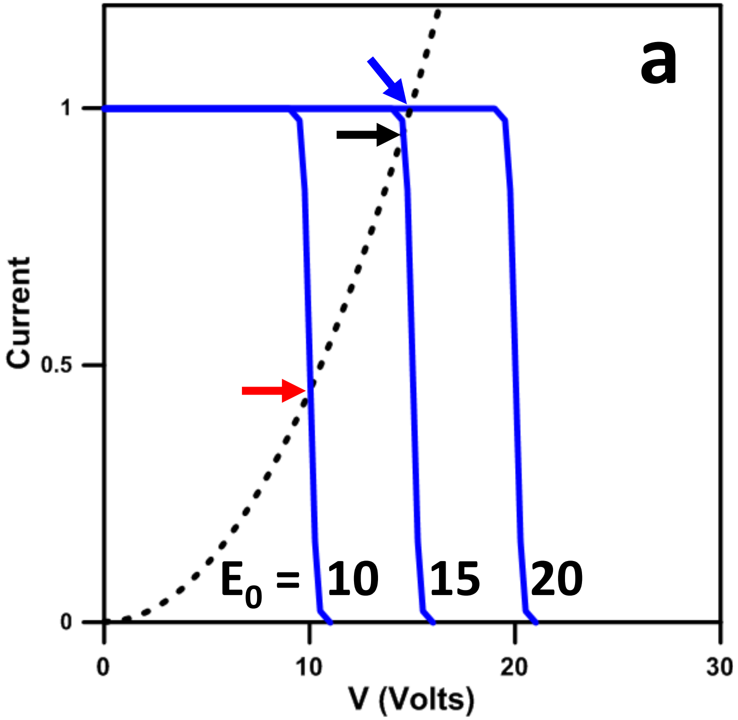
No exposure below threshold (15 – 18 eV)

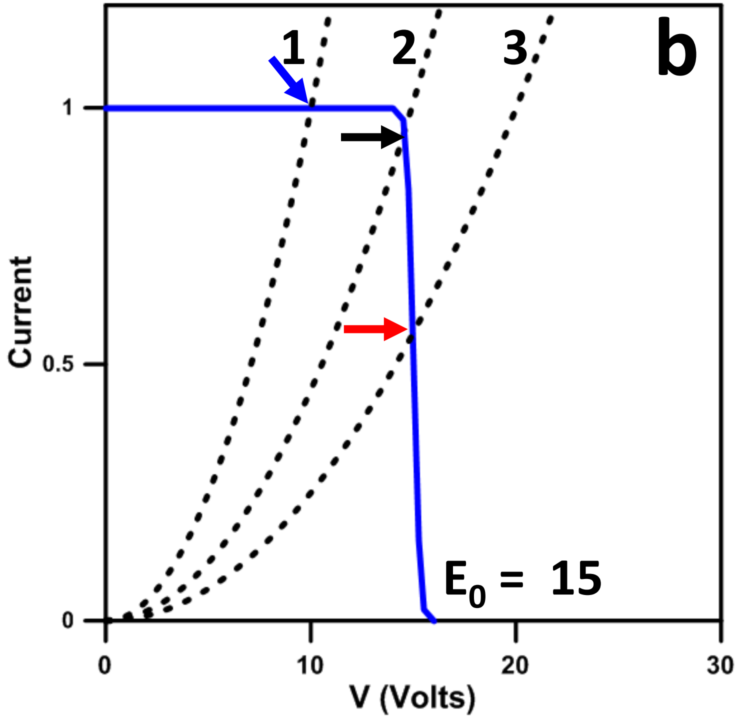
Threshold depends on beam current (5 μm diameter)

Energy spectra vs exposure time

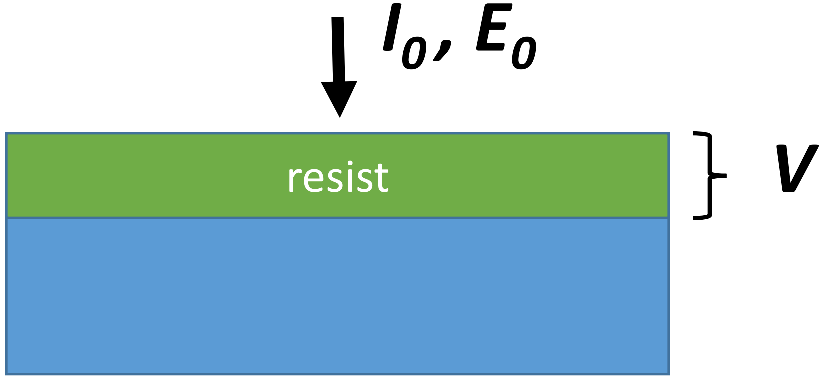


Resist charging during exposure





$$\pm gV^2 = I_0 \int_V^\infty \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(E-E_0)^2}{2\sigma^2}} dE$$

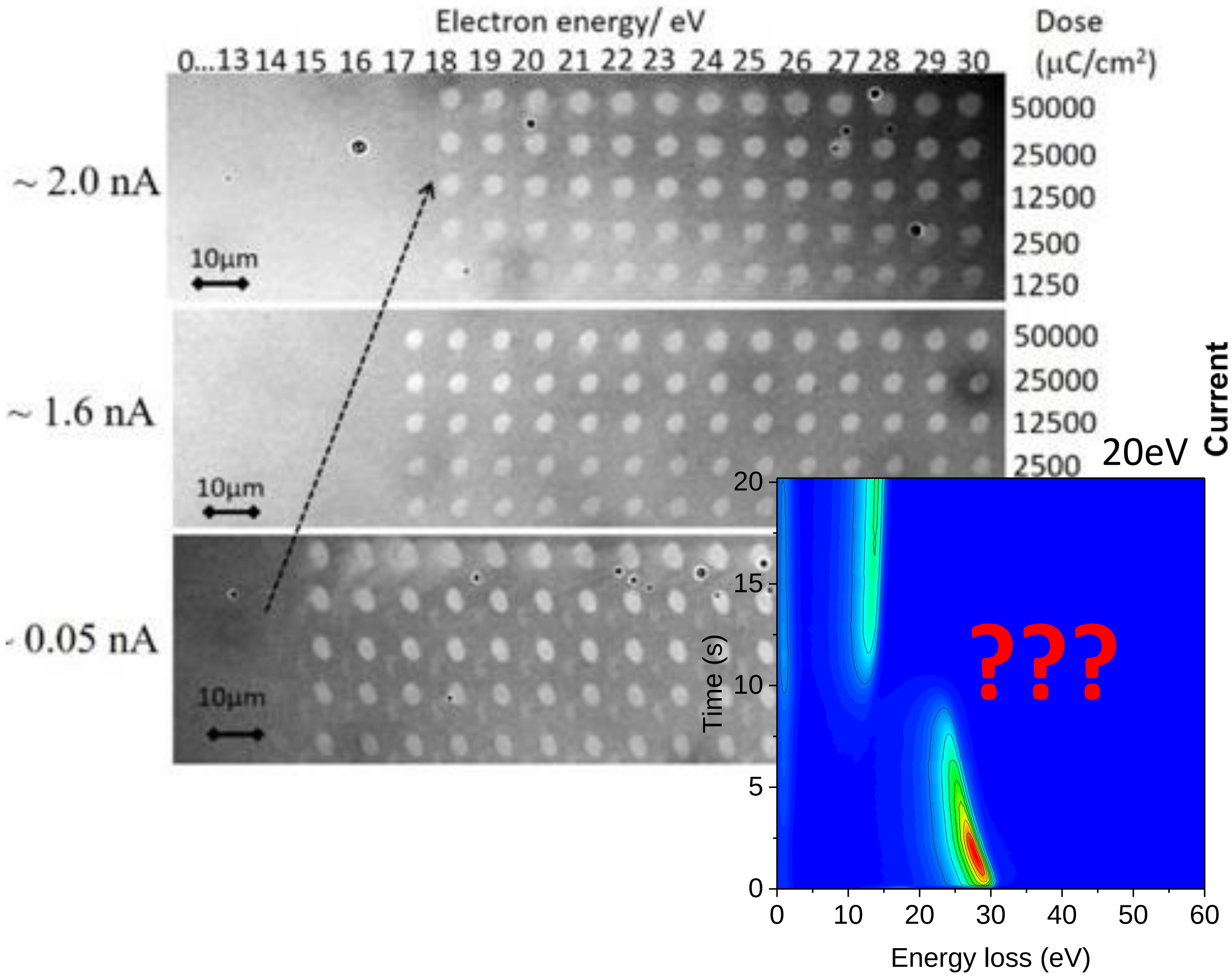


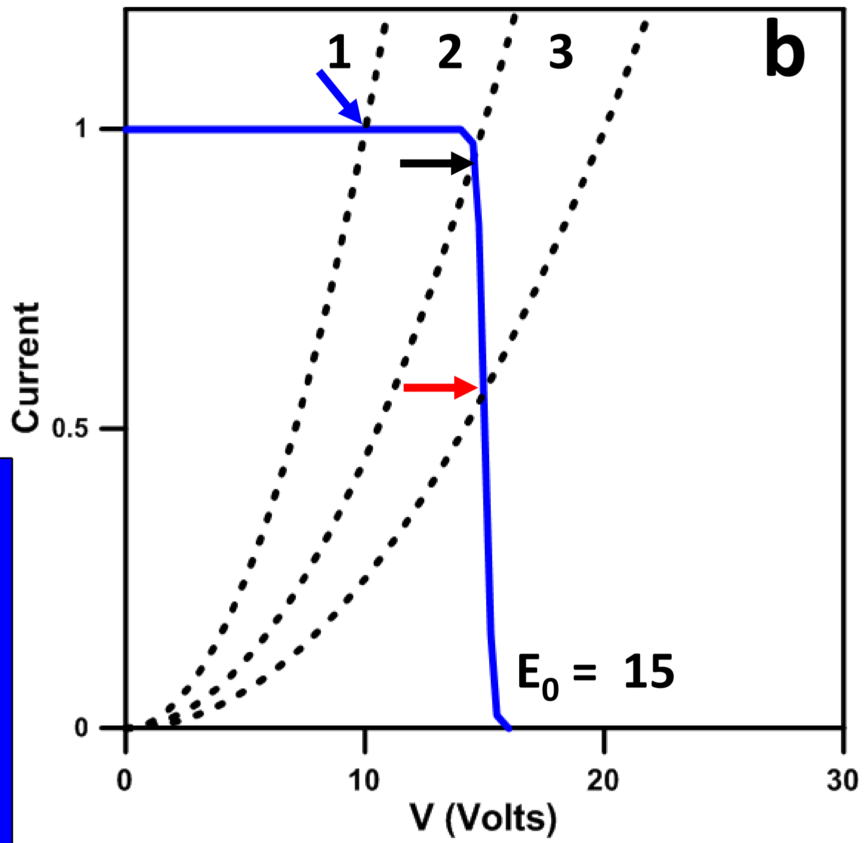
Resist conductance (Mott-Gurney): $I(V) = \pm gV^2$ (black dashed lines)

Electron beam energy distribution: $I_0(E) = I_0 \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(E-E_0)^2}{2\sigma^2}}$

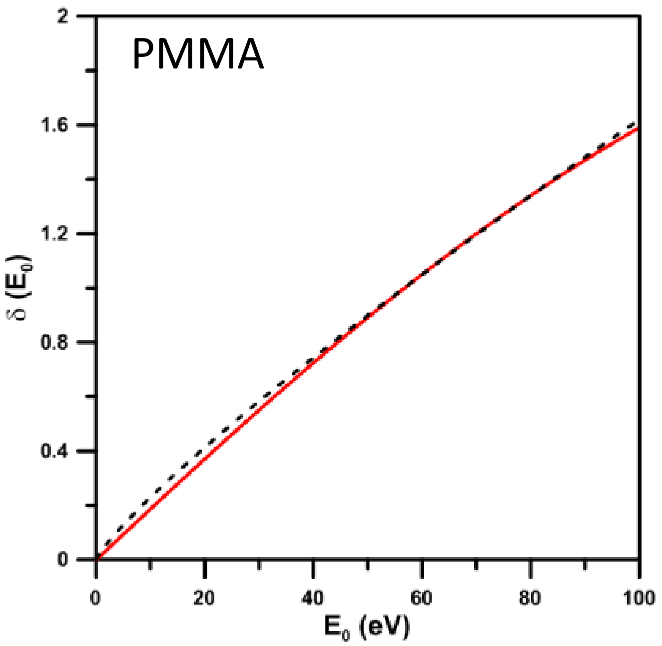
Reaching sample: $I_0 \int_V^\infty \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(E-E_0)^2}{2\sigma^2}} dE$ (blue lines)

Charging explains threshold shift





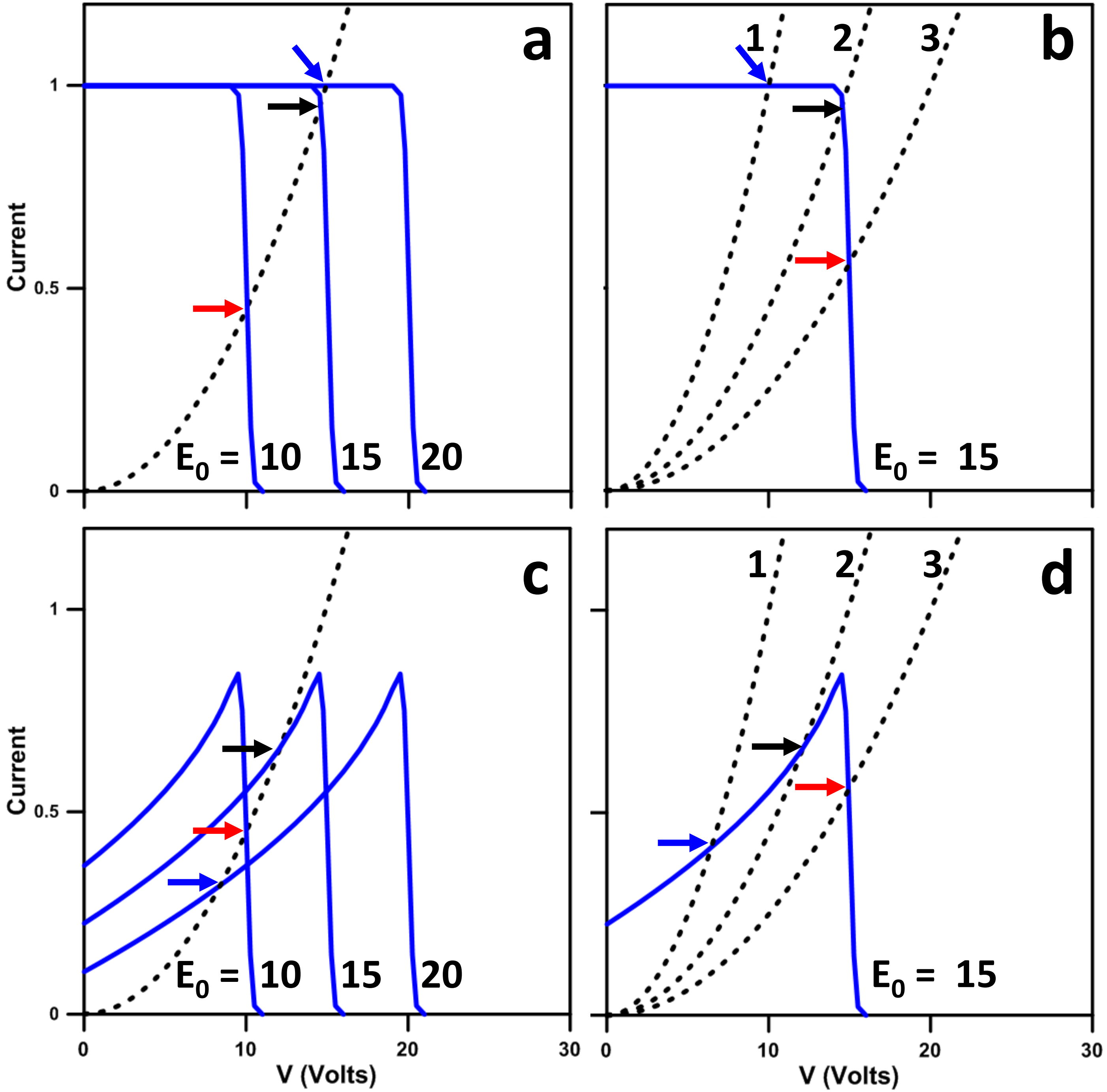
Secondary electrons



$$\delta(E) = \left(\frac{E}{E_1}\right)^{\alpha}$$

Y.Lin, D.C. Joy, Surface and Interface Analysis **37** (2005) 895-900

Incident electrons create secondary electrons that leave the sample.
This decreases the net electron current.



Effect of secondary electrons

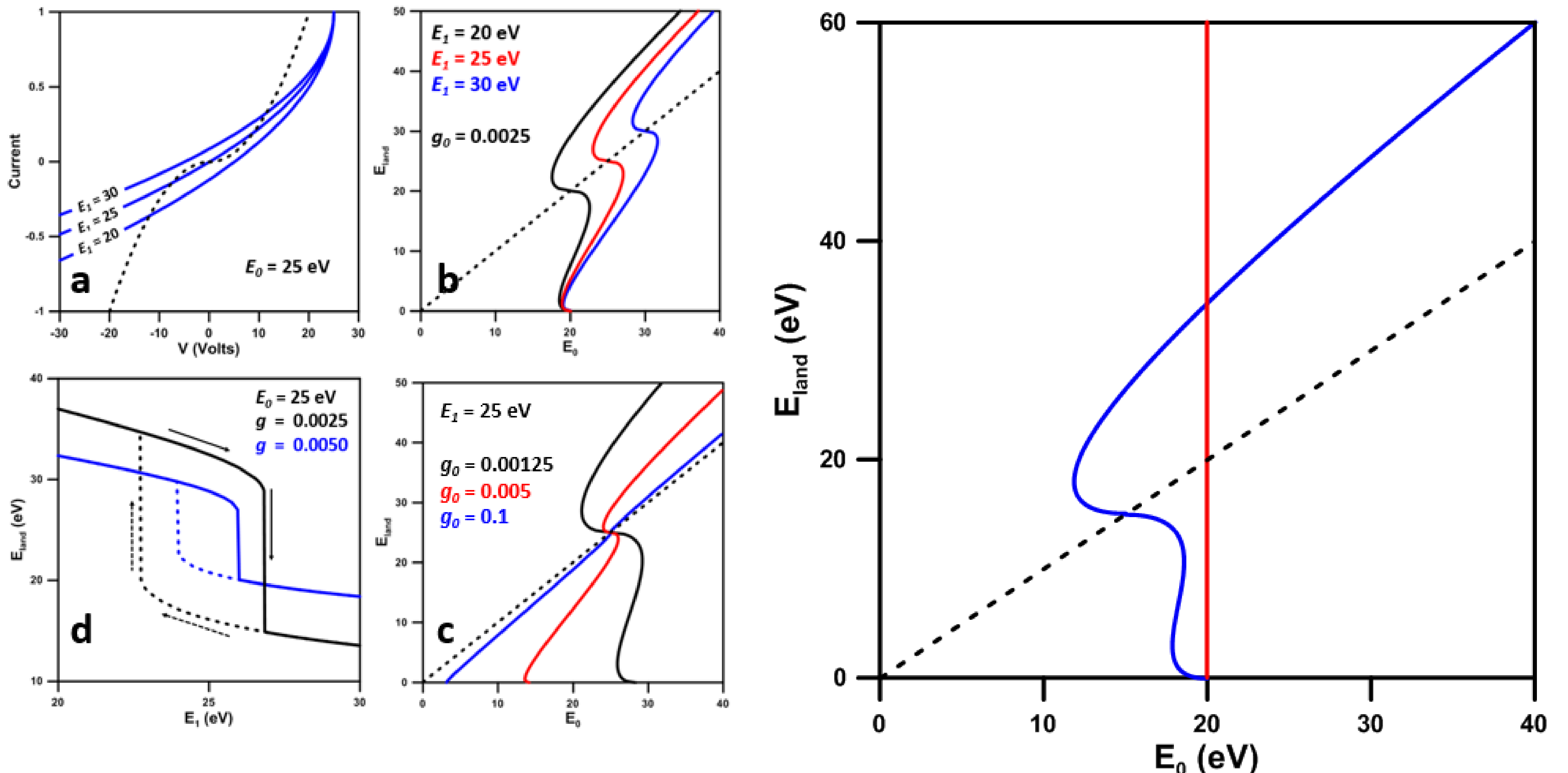
$$\frac{I(V)}{I_0} = \pm g_0 V^2 =$$

$$\int_V^\infty \frac{1}{2\pi\sigma^2}\left(1-\left(\frac{E-V}{E_1}\right)^\alpha\right) e^{-\frac{(E-E_0)^2}{2\sigma^2}} dE$$

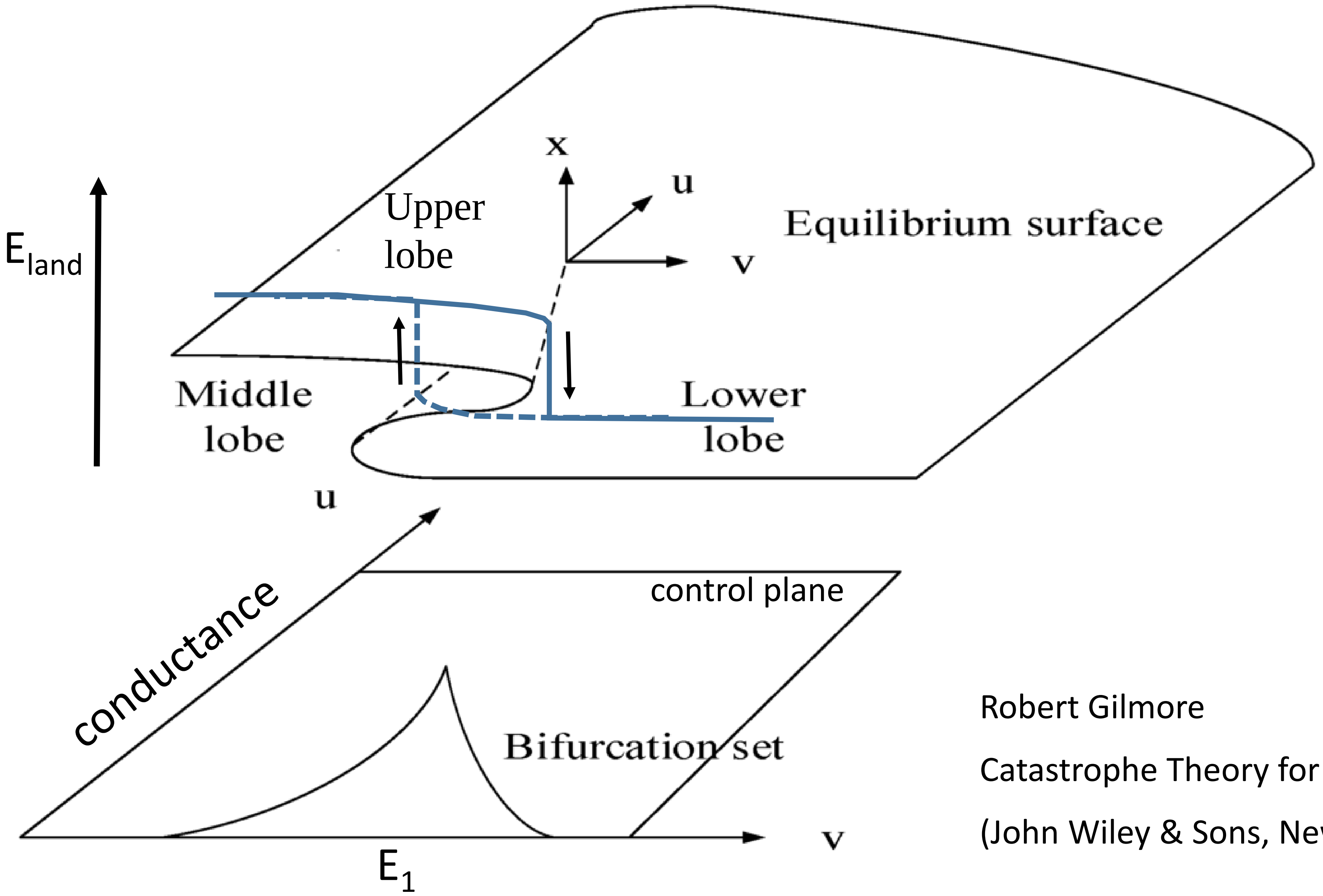
incident secondary

$$\pm g_0 V^2 \approx 1-\left(\frac{E-V}{E_1}\right)^\alpha$$

Big implications!



Catastrophe theory – cusp catastrophe



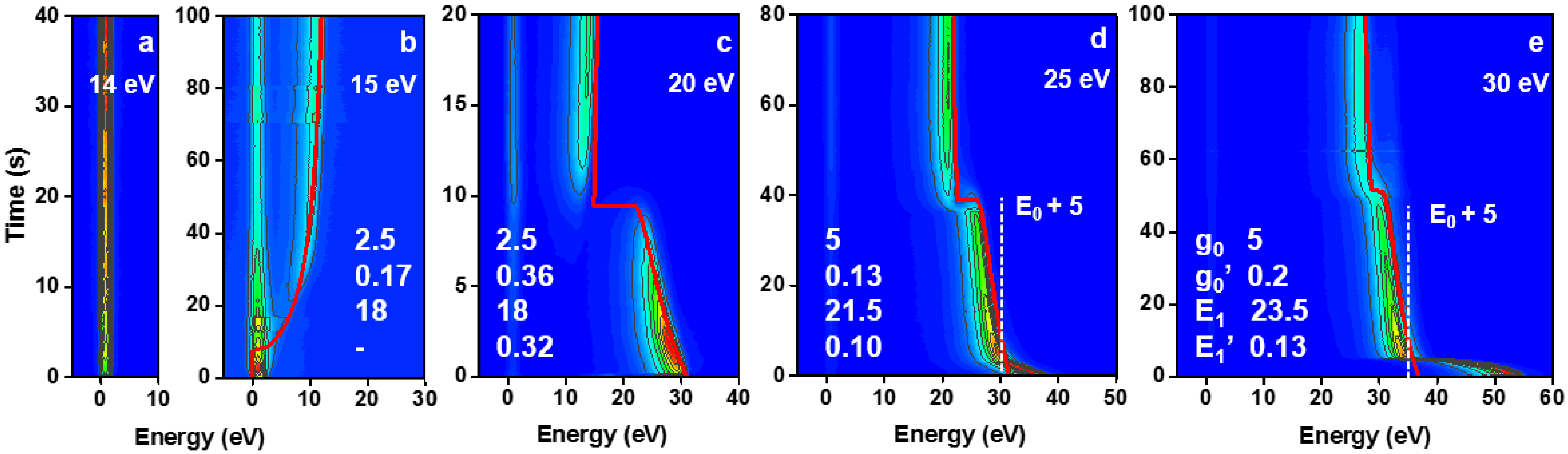
Robert Gilmore

Catastrophe Theory for Scientists and Engineers

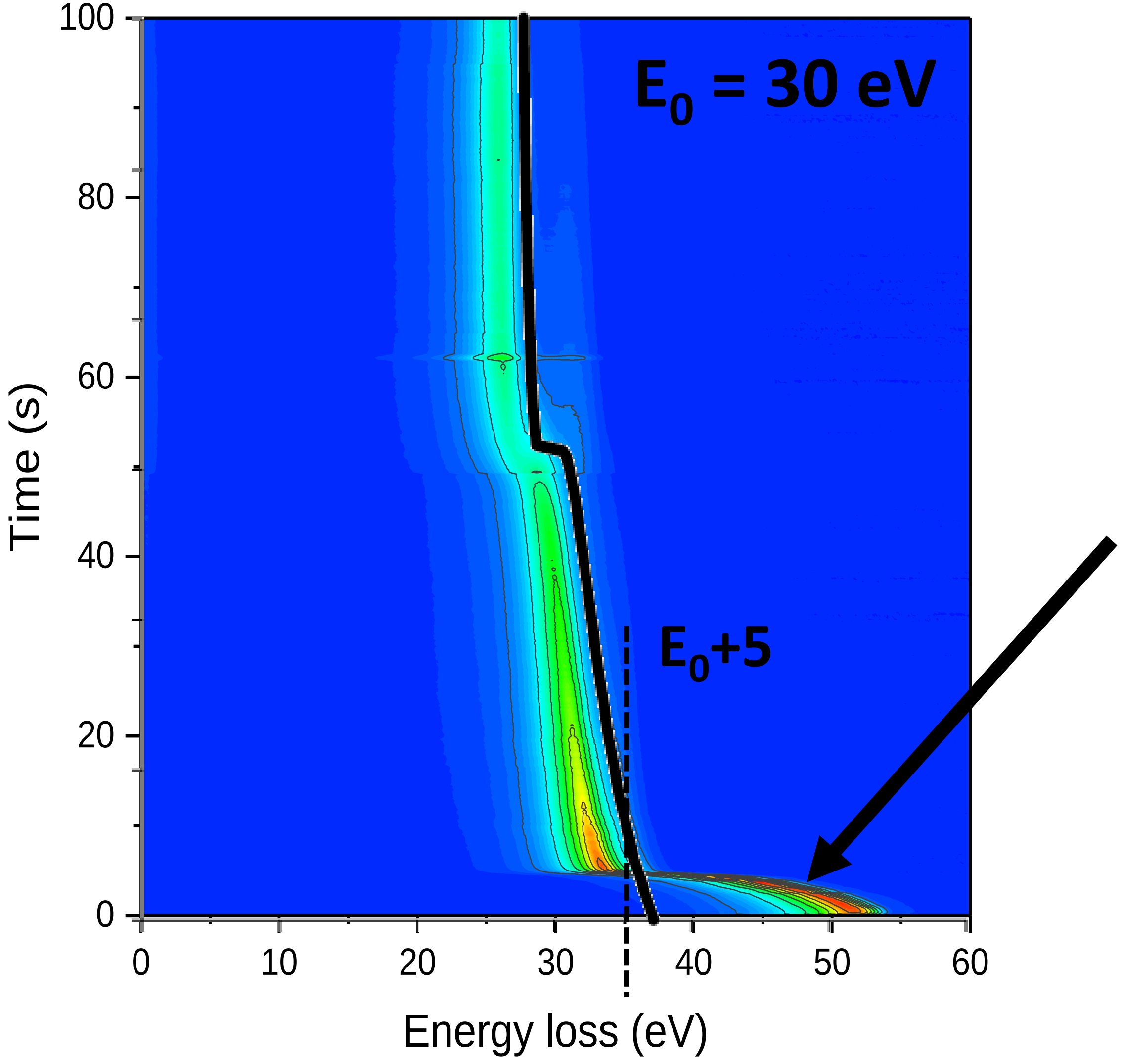
(John Wiley & Sons, New York, 1981, ISBN 0-471-05064-4)

Theory fits the data: **increase** in conductance, **decrease** in secondary electron emission with exposure

(traps!)



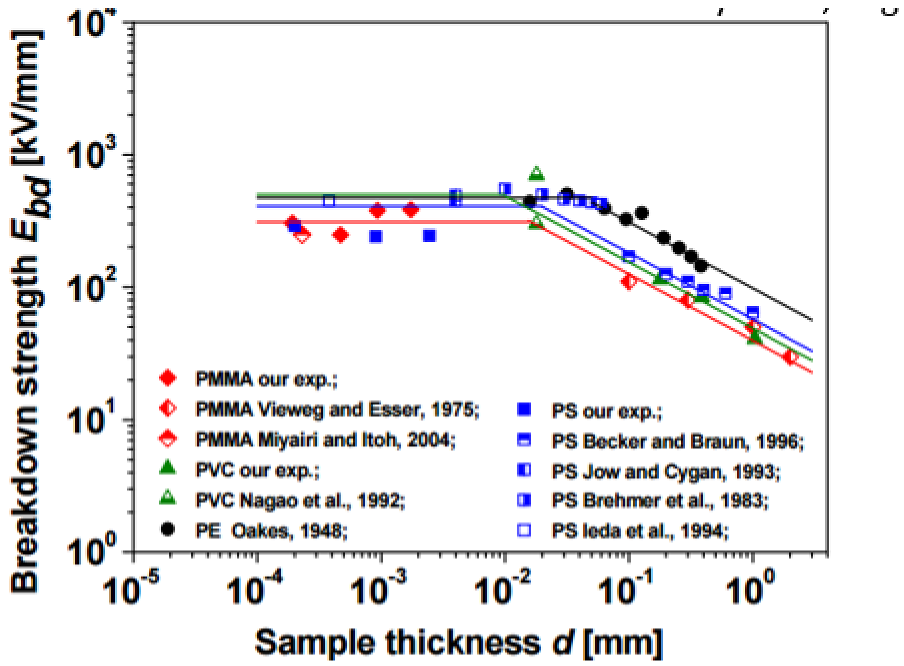
But what about this?



25 V over 20 nm thick PMMA

That is 1.25 MV/mm !

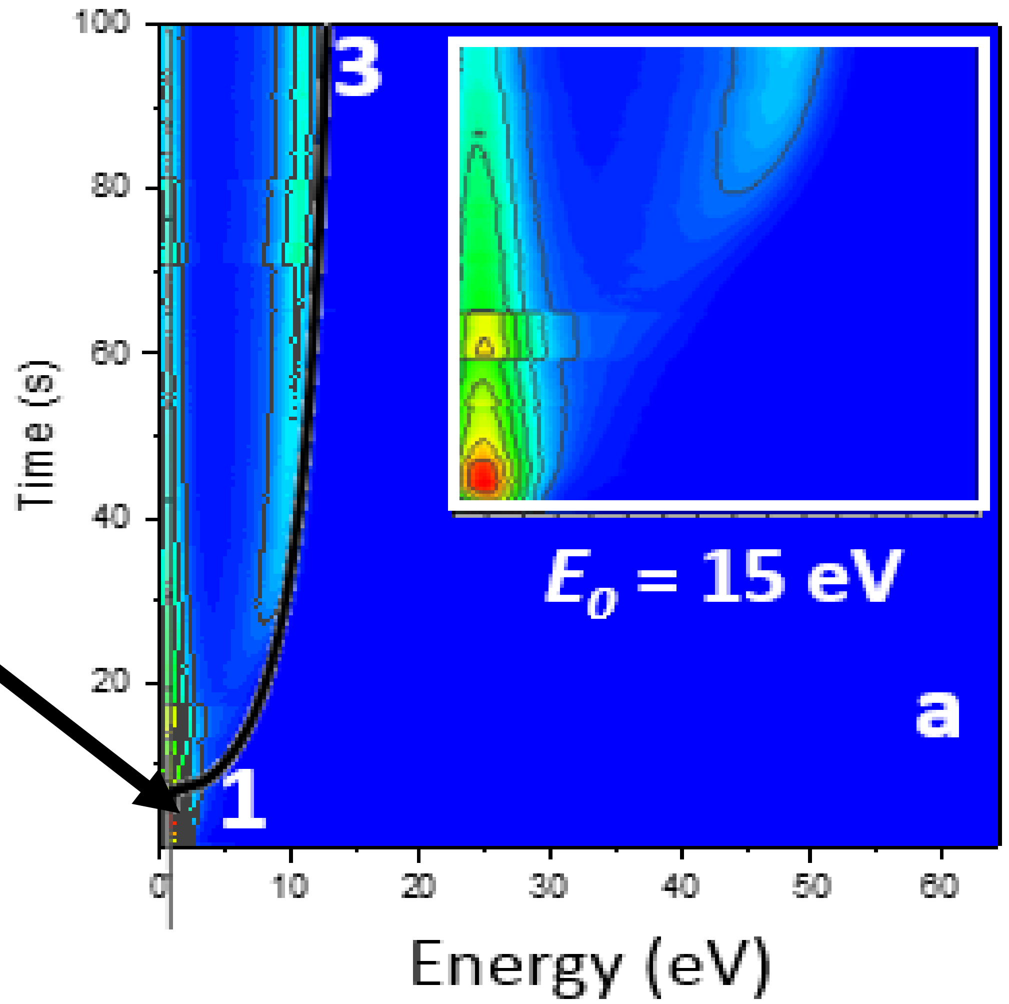
Dielectric breakdown !



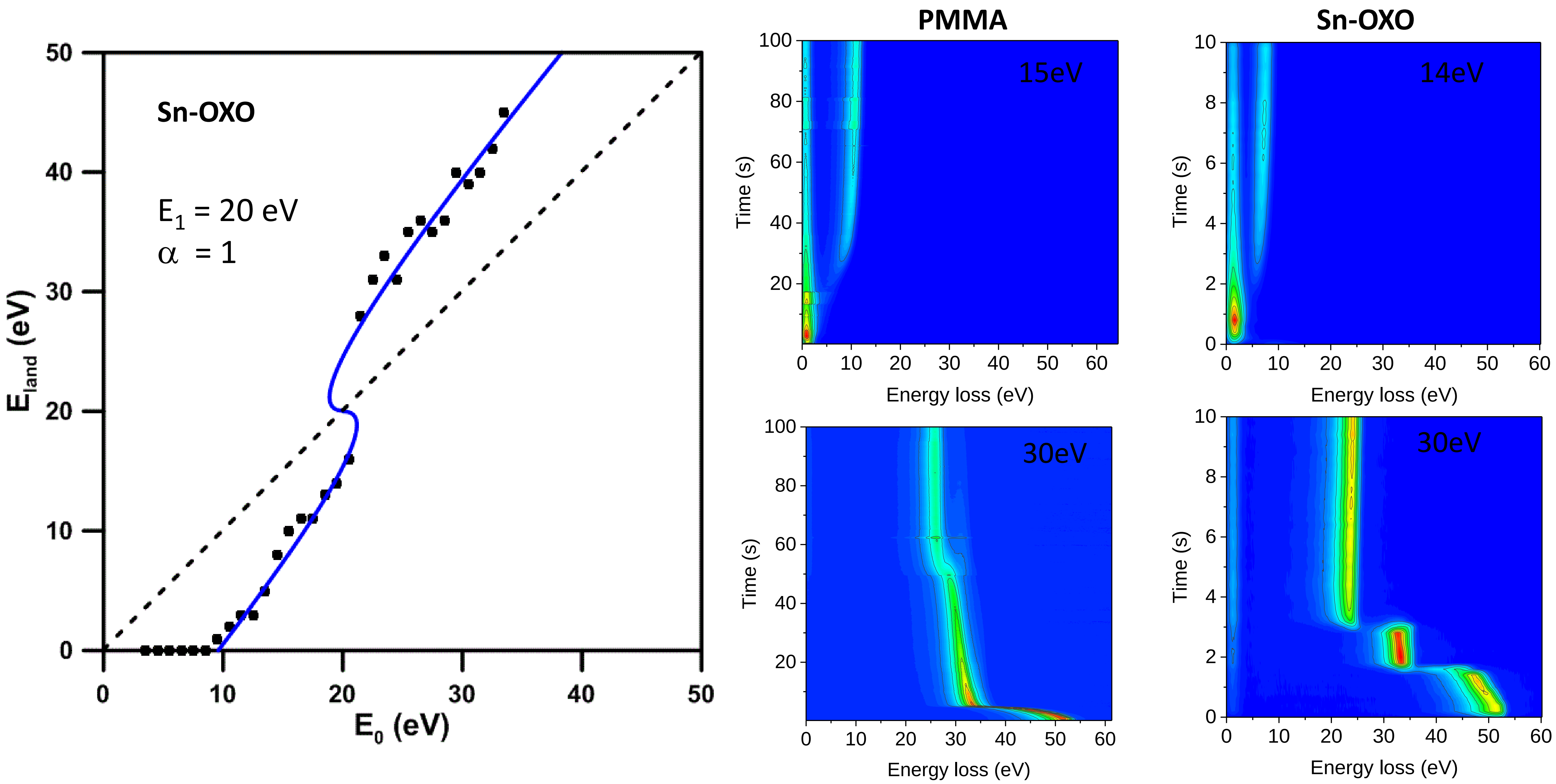
Journal of the Mechanics and Physics of Solids, Vol. 63, February 2014, Pages 201–213,

Or this ?

~ 0 eV electrons expose resist!



And what about Sn-oxo clusters?



Observations

- Resist charges during exposure, either negative or positive
- Exposure threshold due to low conductance
- Conductance increases during exposure
- Secondary electrons play key role; decrease during exposure (E_1 increases)
- Charging instabilities due to intrinsic non-linearities; catastrophe theory
- Charging can be severe enough to cause dielectric breakdown (LER !!!)
- ~0 eV electrons expose resist – no lower threshold (modeling !!!)

- LEEM provides new insight in resist exposure dynamics

A Thete, D Geelen, S Wuister, SJ van der Molen, RM Tromp
Extreme Ultraviolet (EUV) Lithography **VI** 9422, 94220A (2015)

A Thete, D Geelen, SJ van der Molen, RM Tromp
Physical Review Letters **119** (2017), 266803

Thanks:

Aniket Thete

Daniel Geelen

Sense Jan van der Molen

Ivan Bespalov

Sonia Castellanos

STW SPECS™ ASML ARCNL

ADVANCED RESEARCH CENTER FOR NANOLITHOGRAPHY