PureB silicon photodiode detectors for DUV/VUV/EUV light and low-energy electrons

Lis K. Nanver

Delft Institute of Microsystems and Nanoelectronics – DIMES
Delft University of Technology

Keck Institute for Space Studies
California Institute of Technology
Jet Propulsion Laboratory

30th August, 2011

DIMES
Delft Institute of Microsystems and Nanoelectronics

TU Delft
Delft University of Technology

Acknowledgements

PhD students: Lei Shi, Gianpaolo Lorito, Agata Šakič, Francesco Sarubbi, Negin Golshani, Vahid Mohammadi, Lin Qi

Postdocs: Caroline Mok, Jaber Derakhshahdeh

Process technologists: Tom Scholtes, Wiebe de Boer, Silvana Milosalvjevic, Wim Wien, Carel Heerkens

ASML Lithography: Stoyan Nihtianov, Koen Kivits, René de Bruin

FEI Company: Gerard van Veen, Kees Kooijmanns, Patrick Vogelsang

PTB Berlin: Frank Scholze, Christian Lauber, Andreas Gottwald, Ulrich Kroth

ASML FEI COMPANY TOOLS FOR NANOTECH PTB

DIMES Delft Institute of Microsystems and Nanoelectronics

The Dutch Technology Foundation stw

TU Delft Delft University of Technology

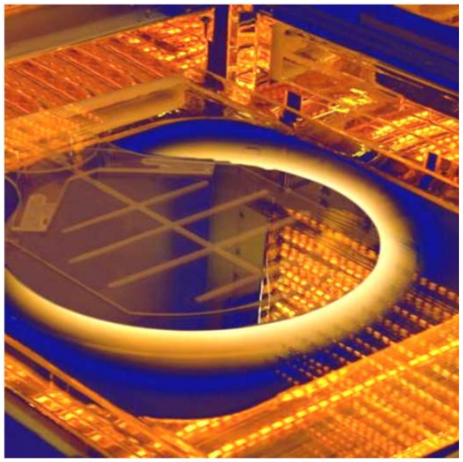
Outline

- Introduction
- Pure boron CVD technology
- Doping from pure boron layers
- Electrical properties of PureB p^+n diodes
- Application as photodetectors for low-penetration-depth radiation and charged particles :
  - VUV, DUV, EUV
  - low-energy electrons
- Conclusions

Outline

- Introduction
- **Pure boron CVD technology**
- Doping from pure boron layers
- Electrical properties of PureB p^+n diodes
- Application as photodetectors for low-penetration-depth radiation and charged particles :
    - VUV, DUV, EUV
    - low-energy electrons
- Conclusions

Pure boron CVD technology



Pure boron deposition from B_2H_6 gas in an AMSI Epsilon One Si/SiGe epitaxial CVD reactor

700°C deposition

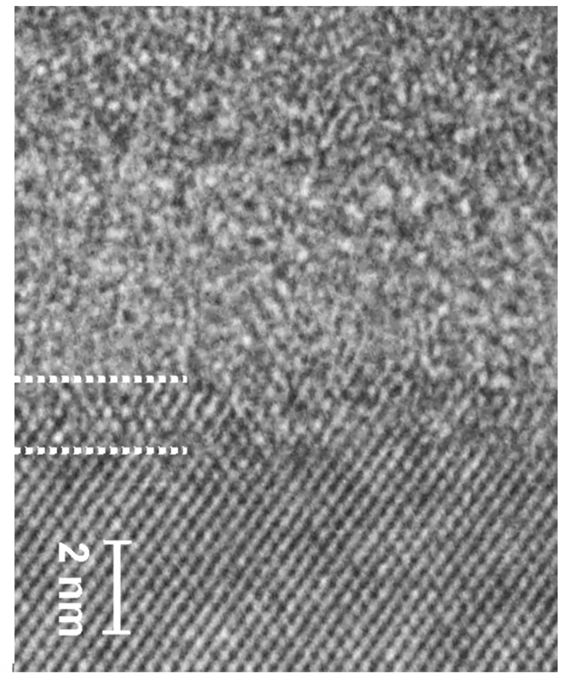
Not visible on the HRTEM:
a few nm B-doping of the c-Si below the B_xSi_y

α-Si

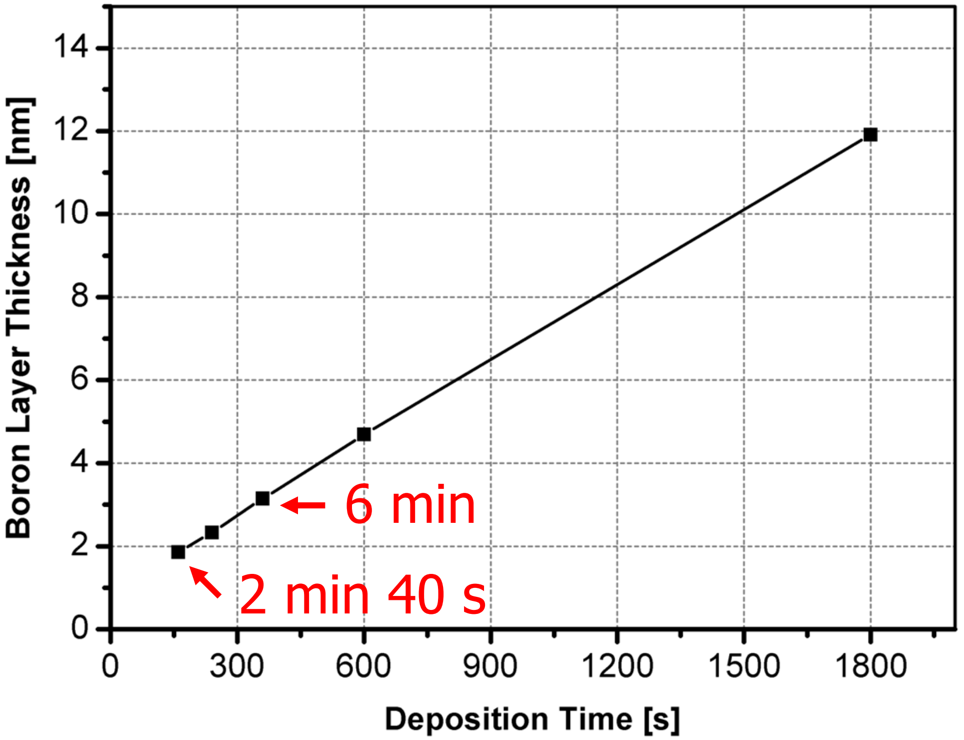
α-B ~ 4 nm

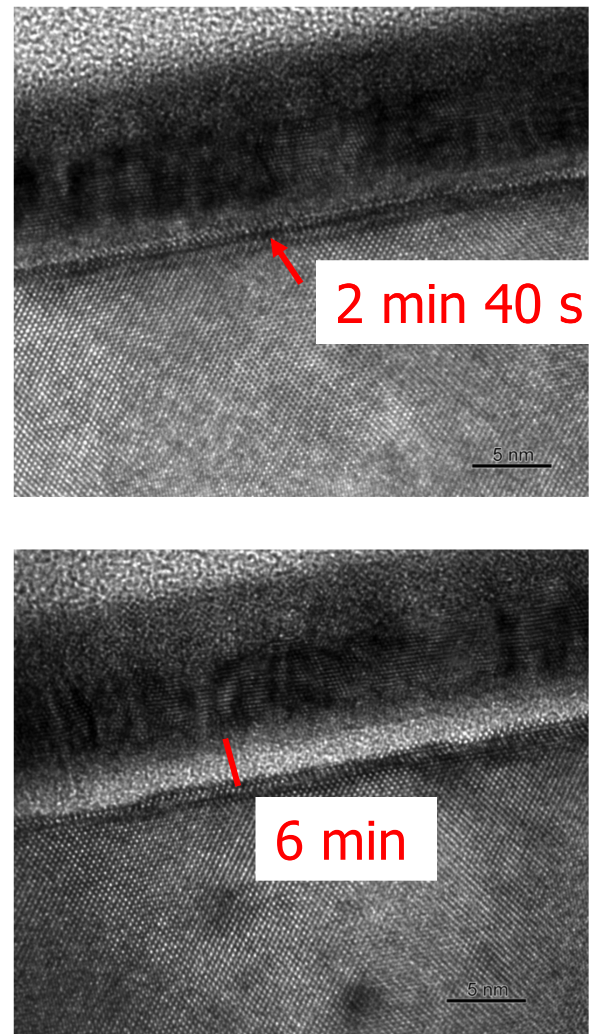
B_xSi_y ~ 1 nm

Crystalline
Si substrate



Constant boron deposition rate





Pressure: 760 Torr

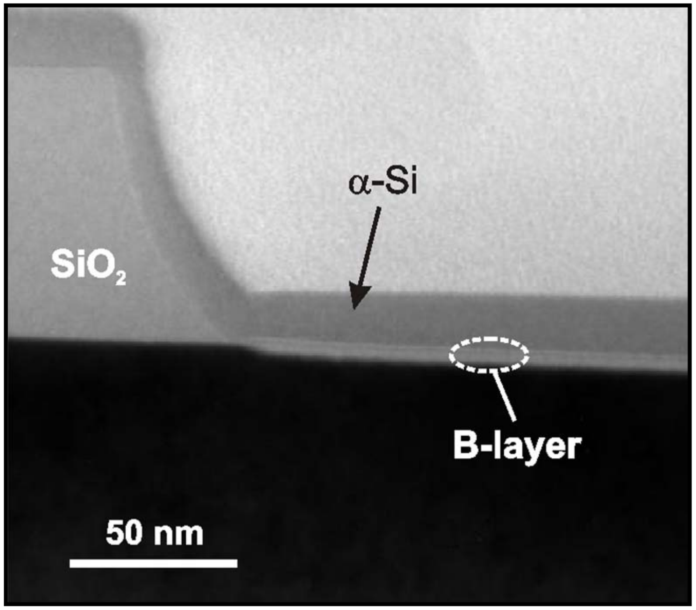
Temperature: 700 °C

B_2H_6 concentration: 2%

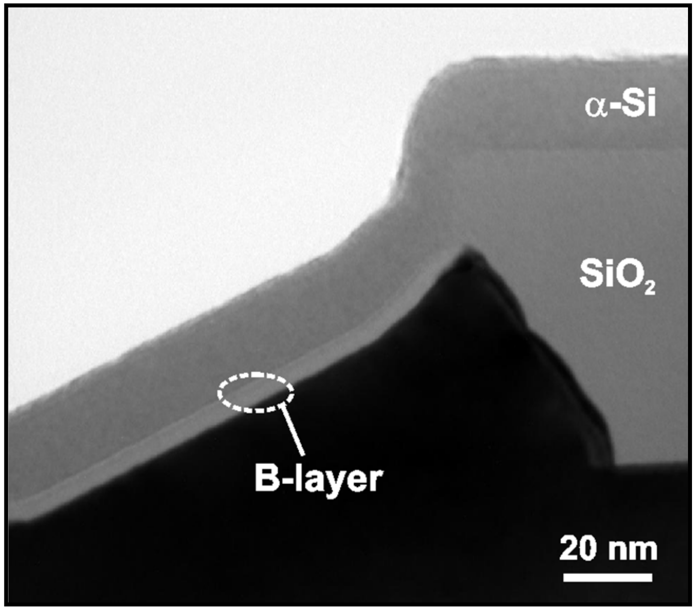
B_2H_6 flow rate: 490 sccm

Other boron deposition properties

Under the right conditions:
- high selectivity to native-oxide-free Si surfaces
- uniform depositions for temperatures: 500 ºC – 700 ºC
- isotropic deposition on Si



Uniform coverage



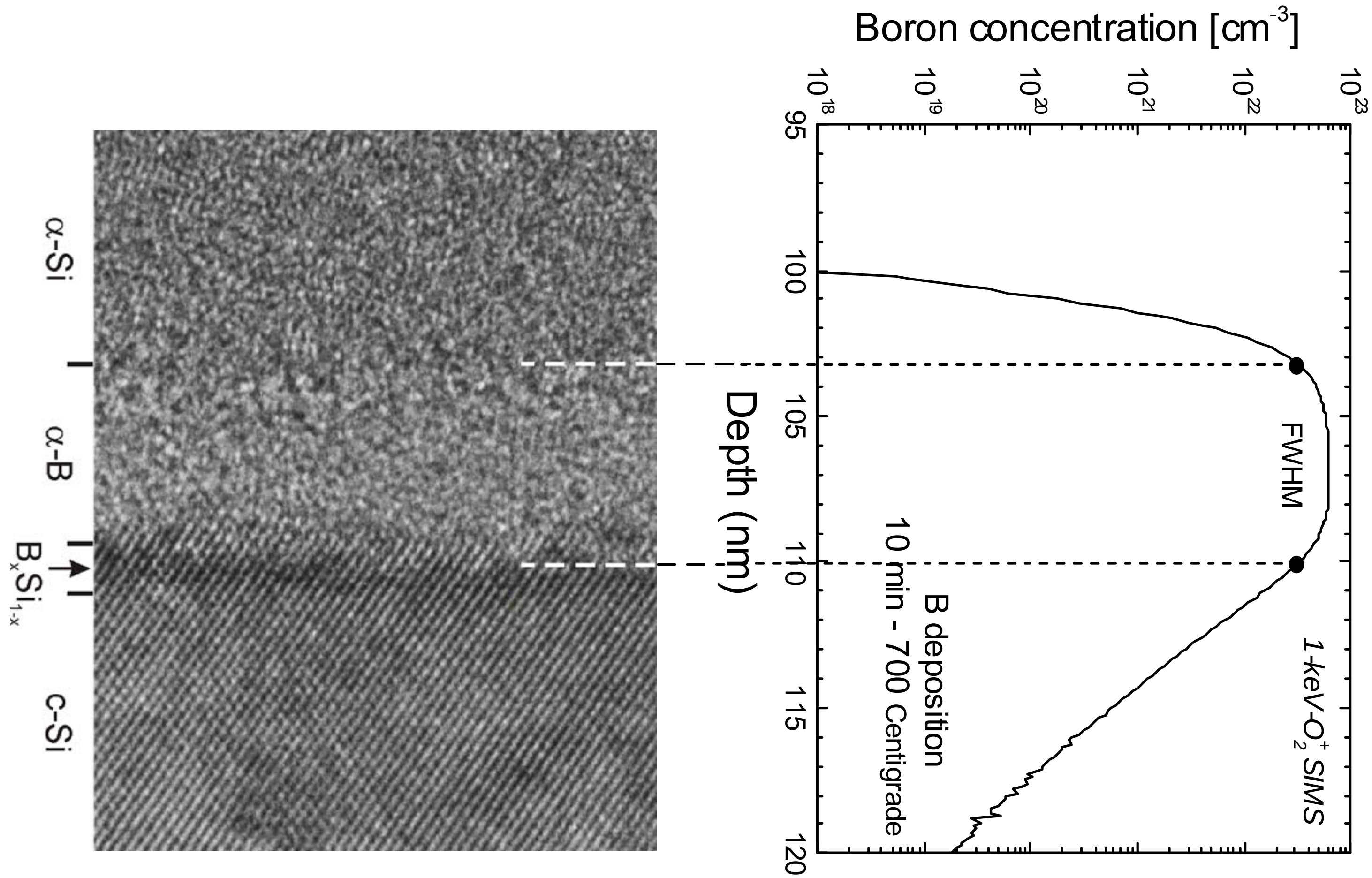
Isotropic deposition

Outline

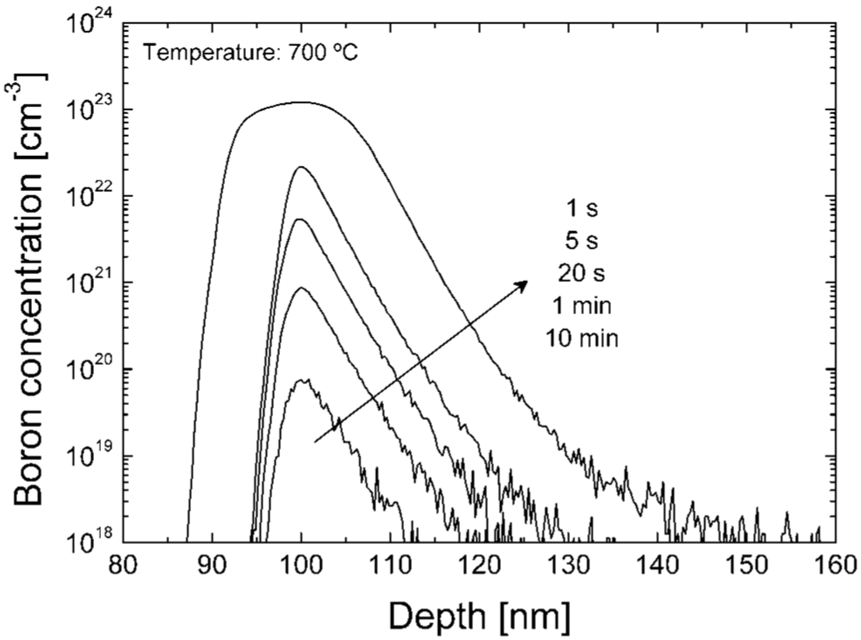
- Introduction
- Pure boron CVD technology
- **Doping from pure boron layers**
- Electrical properties of p^+n diodes
- Application as photodetectors for low-penetration-depth radiation and charged particles :
  - VUV, DUV, EUV
  - low-energy electrons
- Conclusions

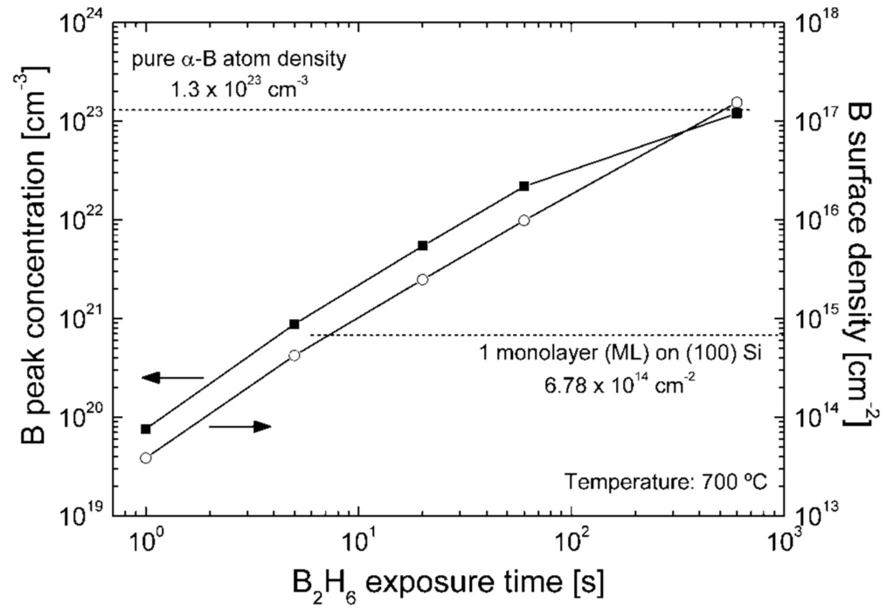
TU Delft

Doping from pure boron layers



Doping from pure boron layers

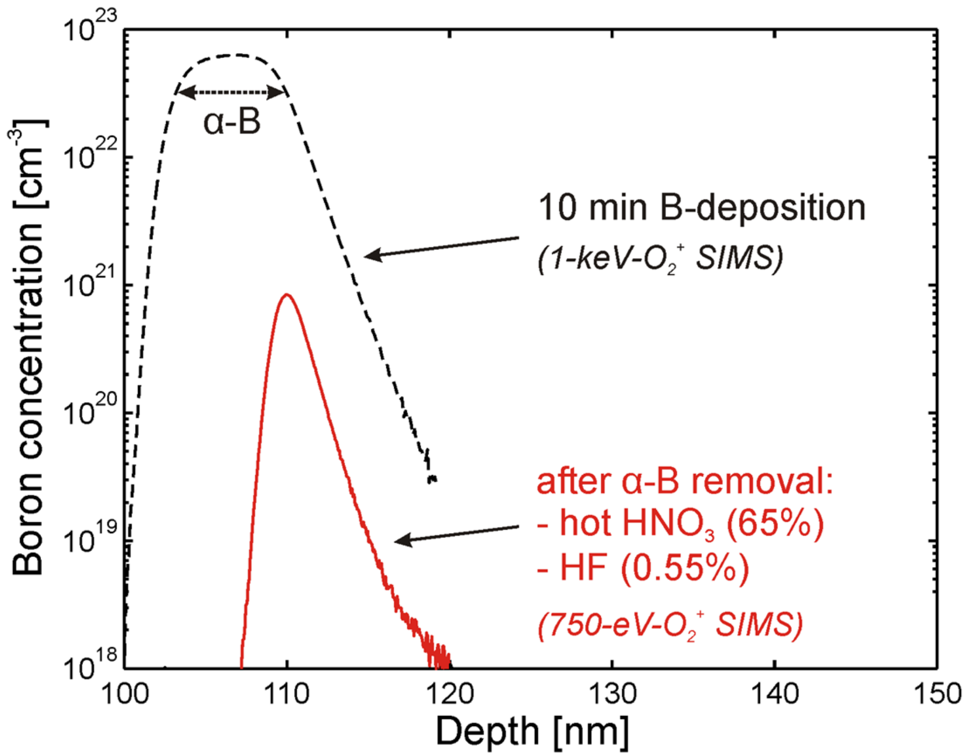




5 s exposure: ~ 1 monolayer = 6.78×10^{14} cm^{-2}

10 min exposure: ~ 10^{17} cm^{-2}

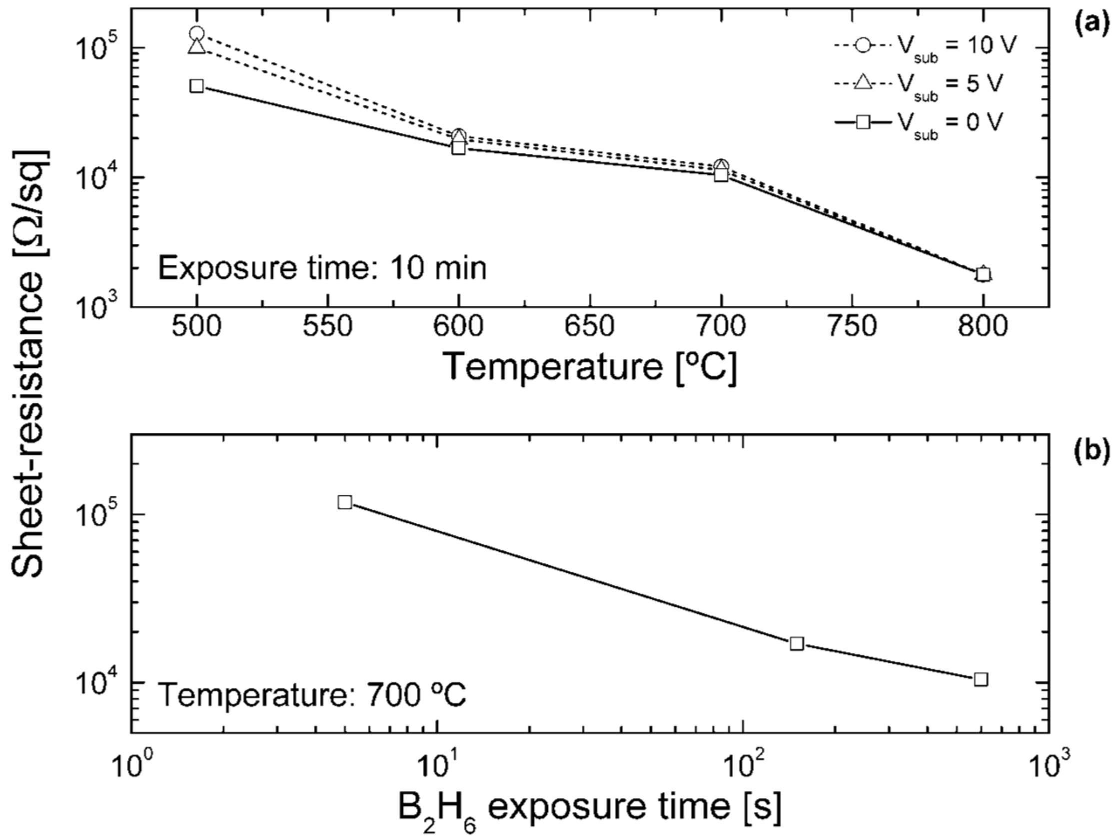
B-layer removal



After B-layer removal: ~ 10^{14} cm^{-2} boron concentration left

This exceeds the solid solubility $\Rightarrow$ some B_xSi_y

Sheet resistance measurements

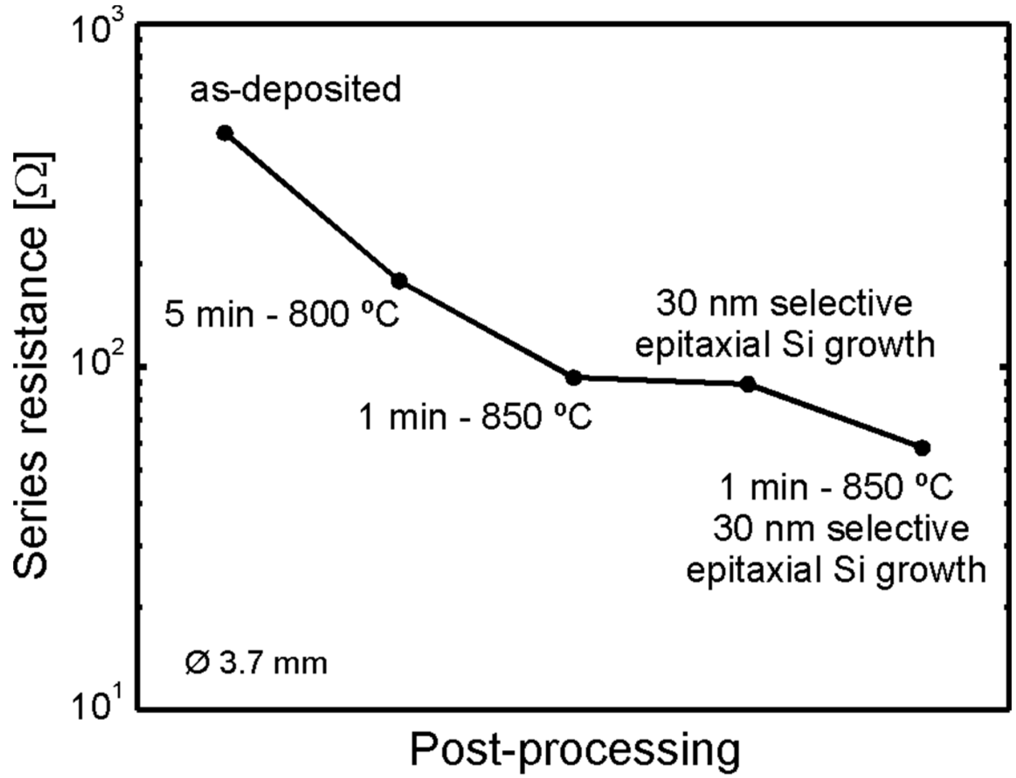


B-layer resistivity very high: 10^4 ohm-cm (semi-metal)

Doping of Si dominates sheet resistance

Post-processing for reduction of series resistance

in-situ thermal annealing and/or selective epitaxial Si/SiGe growth:



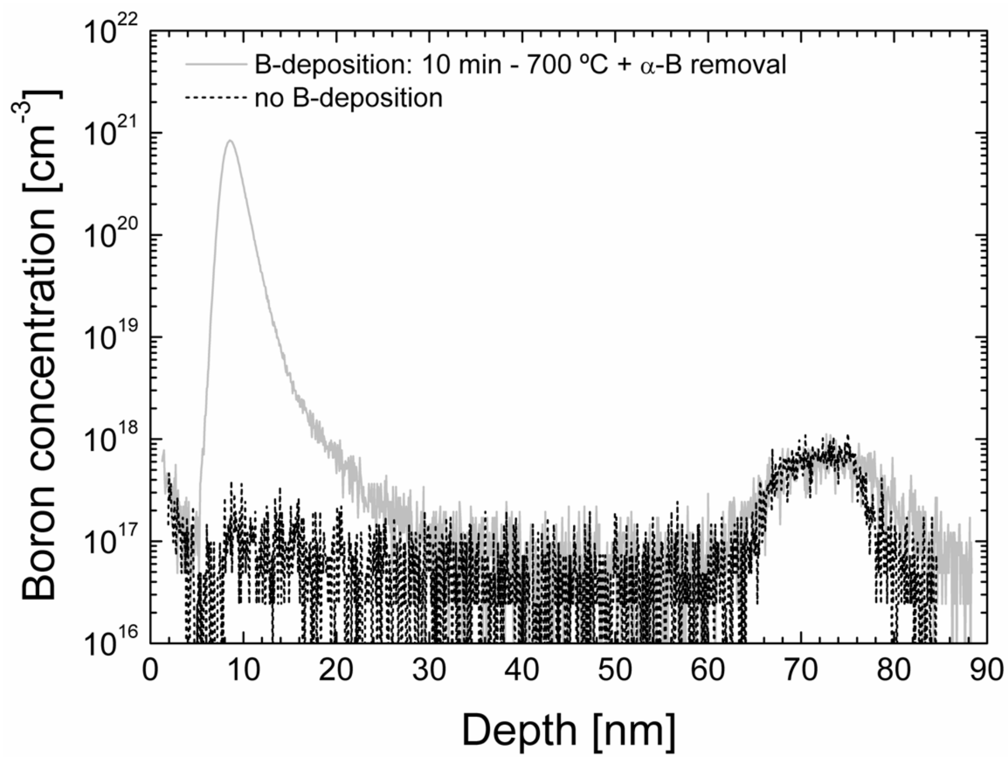
Outline

- Introduction
- Pure boron CVD technology
- Doping from pure boron layers
- **Electrical properties of PureB p^+n diodes**
- Application as photodetectors for low-penetration-depth radiation and charged particles :
  - VUV, DUV, EUV
  - low-energy electrons
- Conclusions

TU Delft

Enhanced diffusion effects

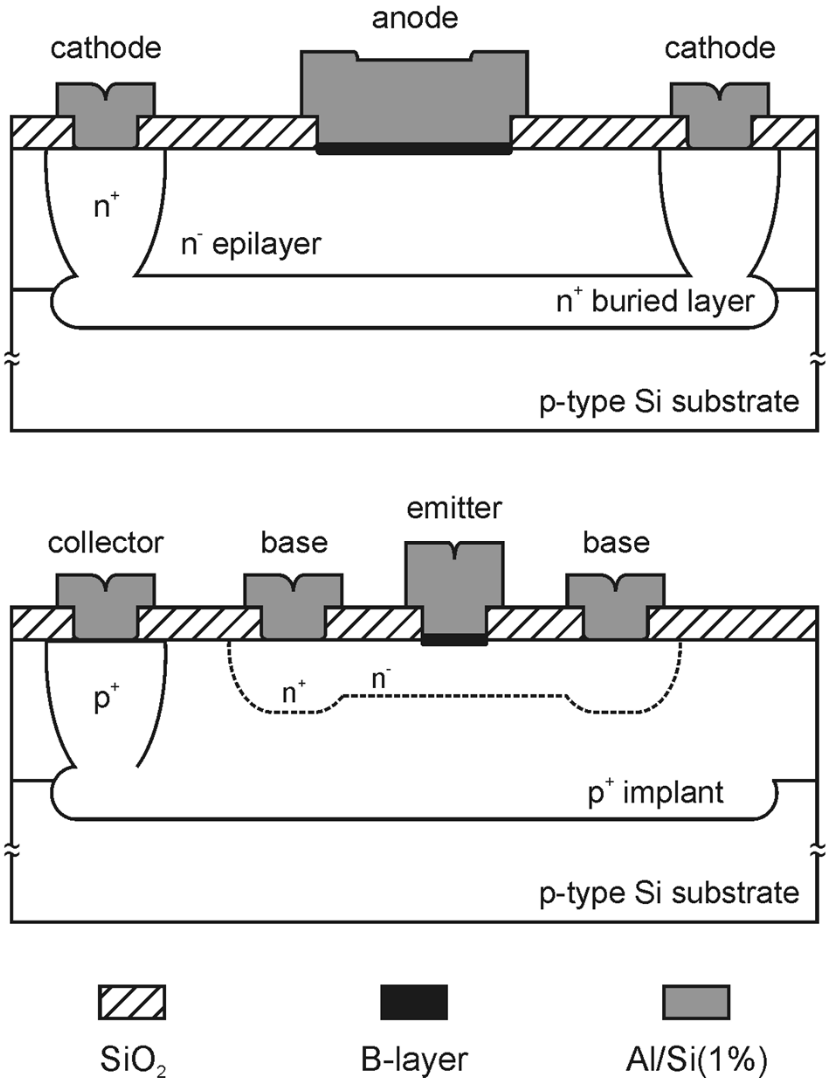
No real evidence of transient or boron enhanced diffusion has been found



Epitaxially-grown boron marker before and after PureB-deposition:

difference within experimental uncertainty

Electrical test structures



(1) p^+n diodes

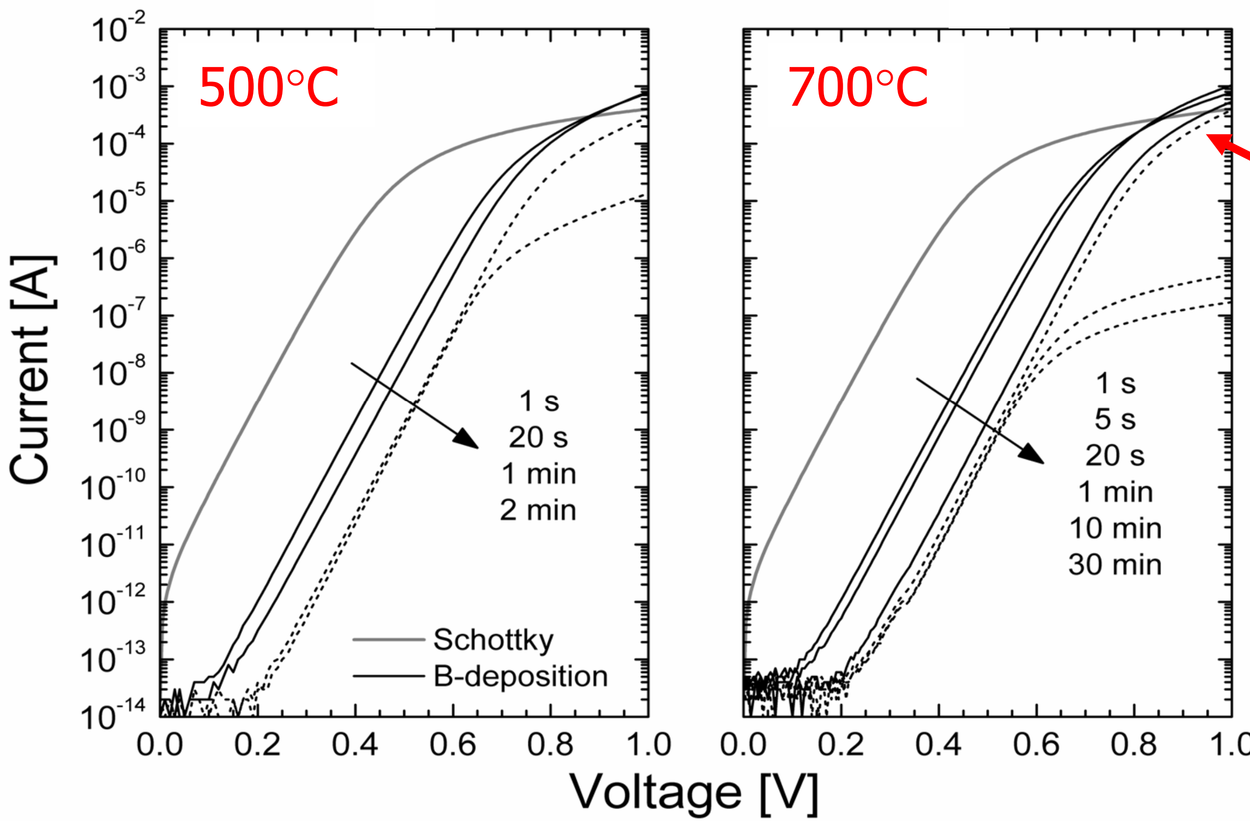
n-doping ~ 10^{17} cm^{-3}

(2) pnp bipolar transistors

emitter = B-layer

B-layer deposited in contact window, metallized immediately with Al/Si(1%)

p^+n forward diode characteristics

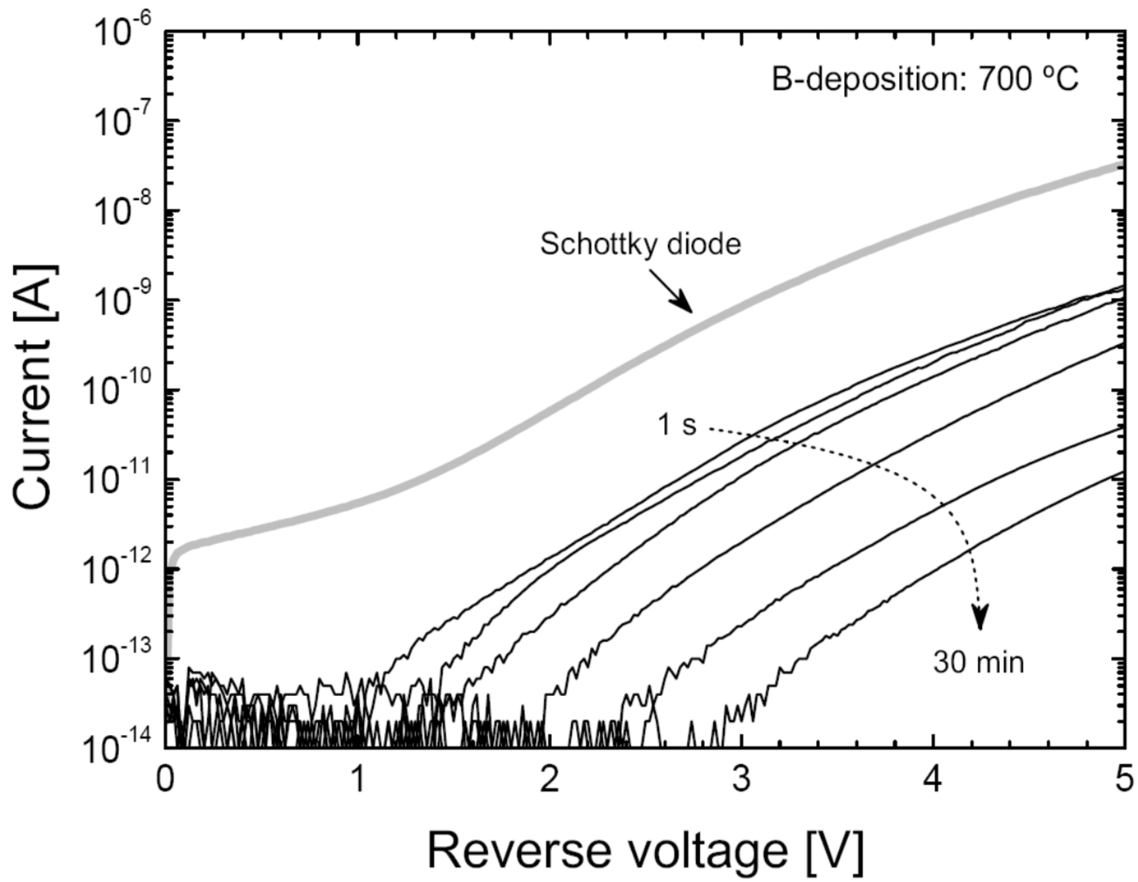


Behaves like conventional deep p^+n junction!

Same behaviour at both temperatures:

- ideal characteristics
- saturation current decreases with deposition time
- series resistance first decreases and then increases

p^+n reverse diode characteristics



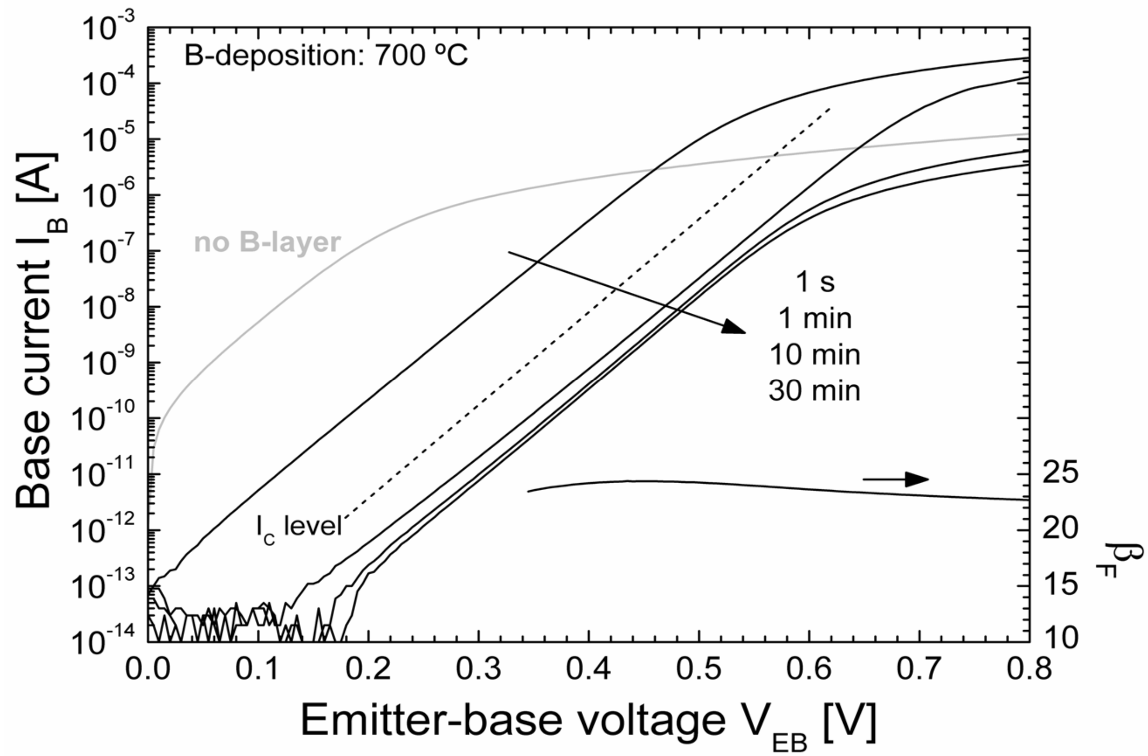
n-doping

~ 10^{17}cm^{-3}

High electric field at perimeter lowers breakdown voltage

Use guard ring, but not seen for low substrate doping

pnp transistor characteristics

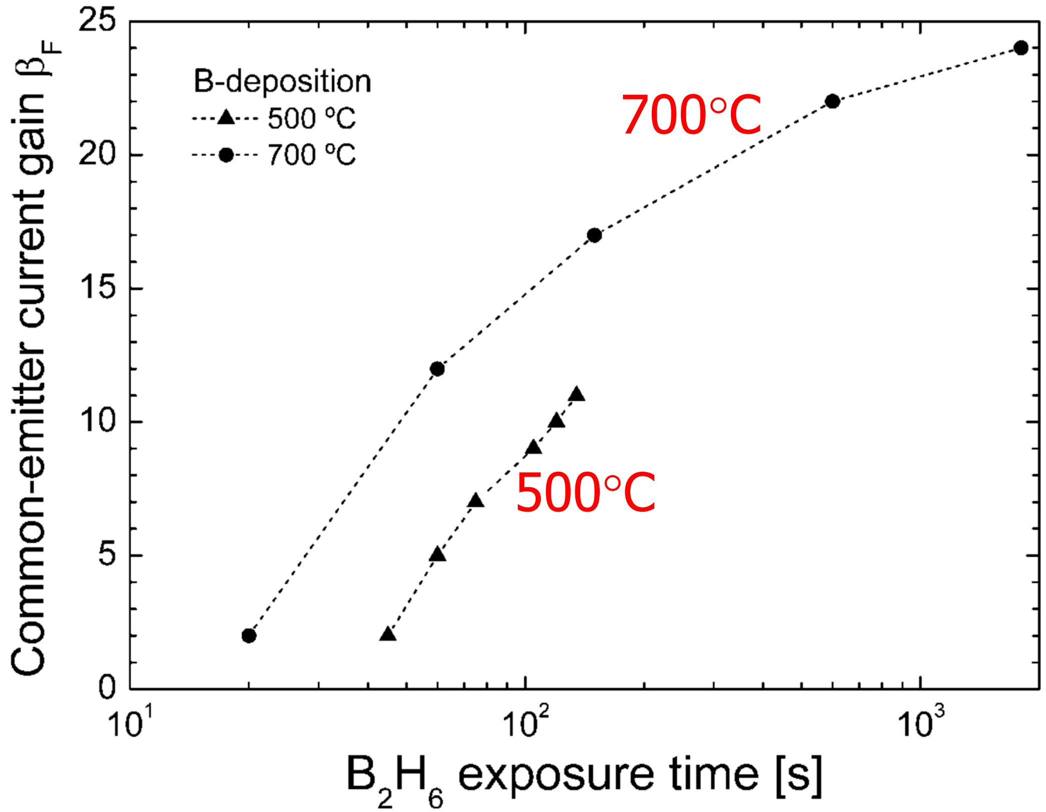


Base current level decreases with deposition time

1 min attractive:

- current gain comparable to conventional implanted-emitter pnp
- series resistance low

pnp transistor characteristics



The B-layer suppresses the injection of electrons from the substrate $\Rightarrow$ B-layer thickness determines the current gain

Sarubbi, IEEE-TED 2010

Outline

- Introduction
- Pure boron CVD technology
- Doping from pure boron layers
- Electrical properties of PureB p^+n diodes
- **Application as photodetectors for low-penetration-depth radiation and charged particles :**
  - VUV, DUV, EUV
  - low-energy electrons
- Conclusions

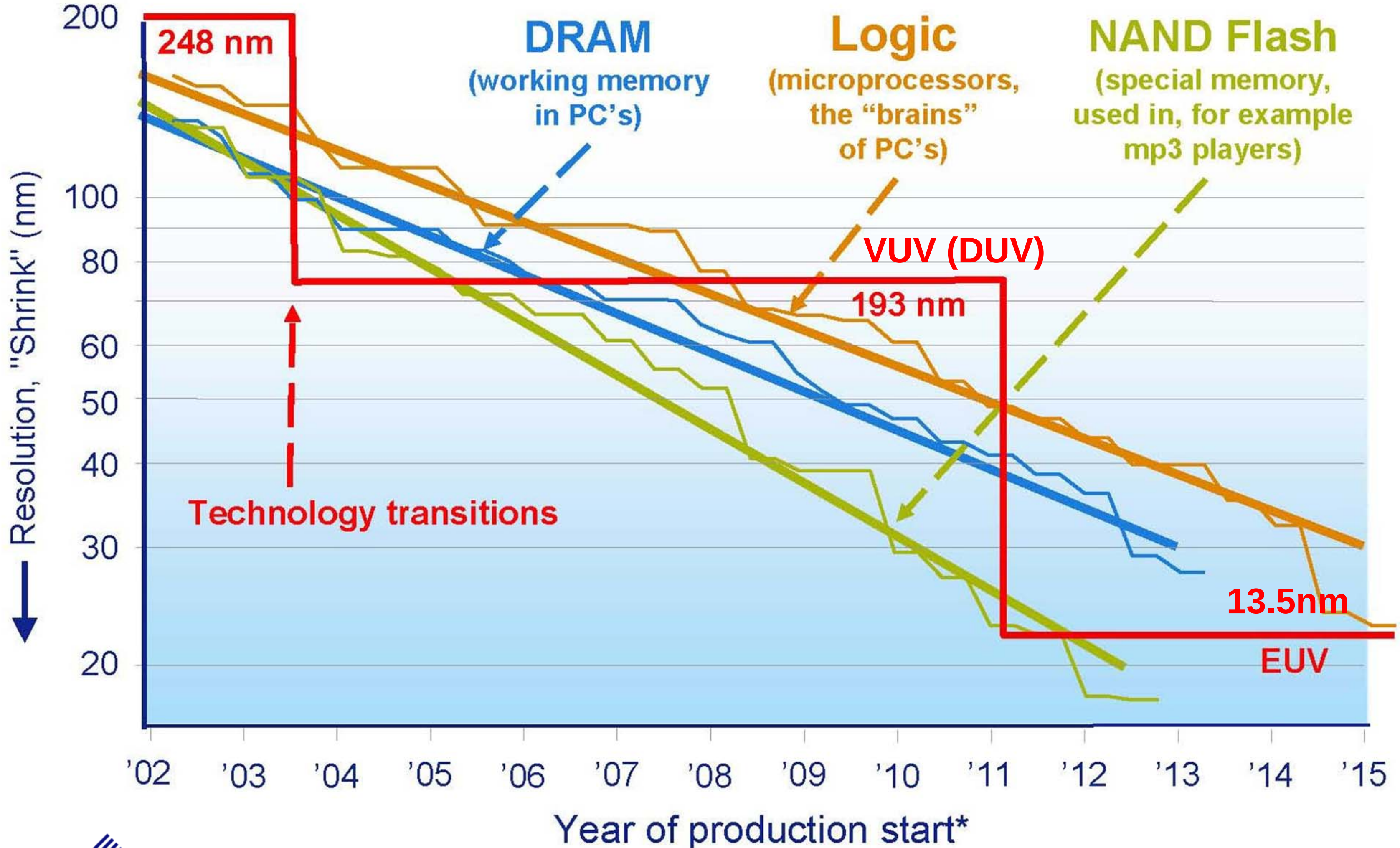
Outline

- Introduction
- Pure boron CVD technology
- Doping from pure boron layers
- Electrical properties of PureB p^+n diodes
- Application as photodetectors for low-penetration-depth radiation and charged particles :
  - **VUV, DUV, EUV**
  - low-energy electrons
- Conclusions

TUDelft

Lithography roadmap down to 10 nm features

EUV: supports 22 nm and 16 nm nodes with a single projection system



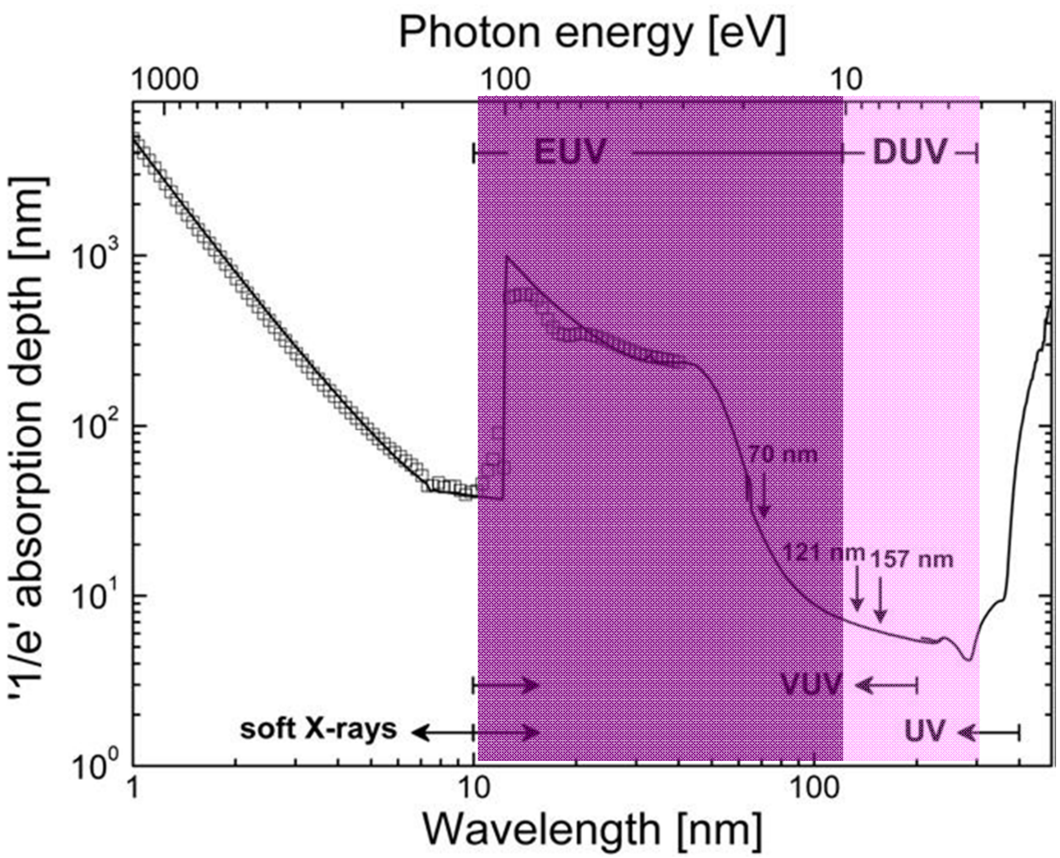
ASML

TU Delft

Challenging DUV / VUV / EUV detection

VUV / EUV

High photon energy

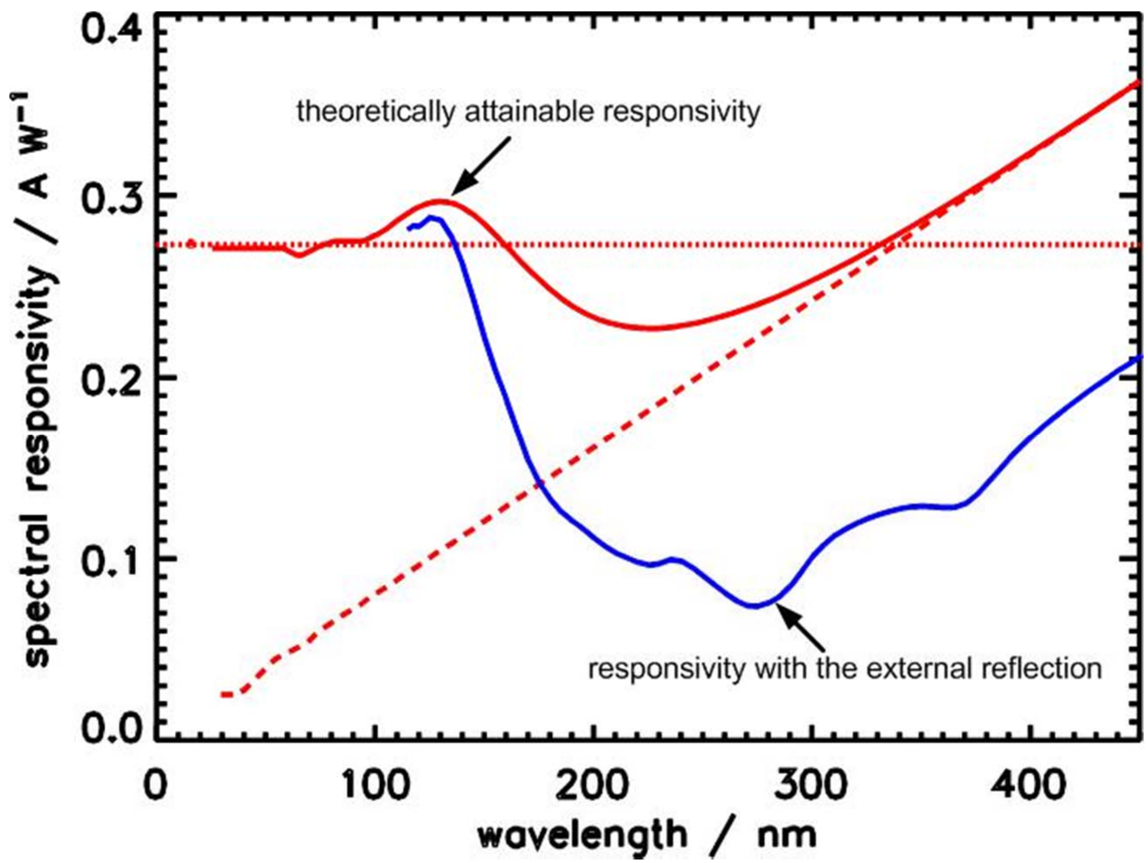


Penetration depth in Si vs. incident radiation wavelength / photon energy.

DUV

Extremely small Penetration depth in Si

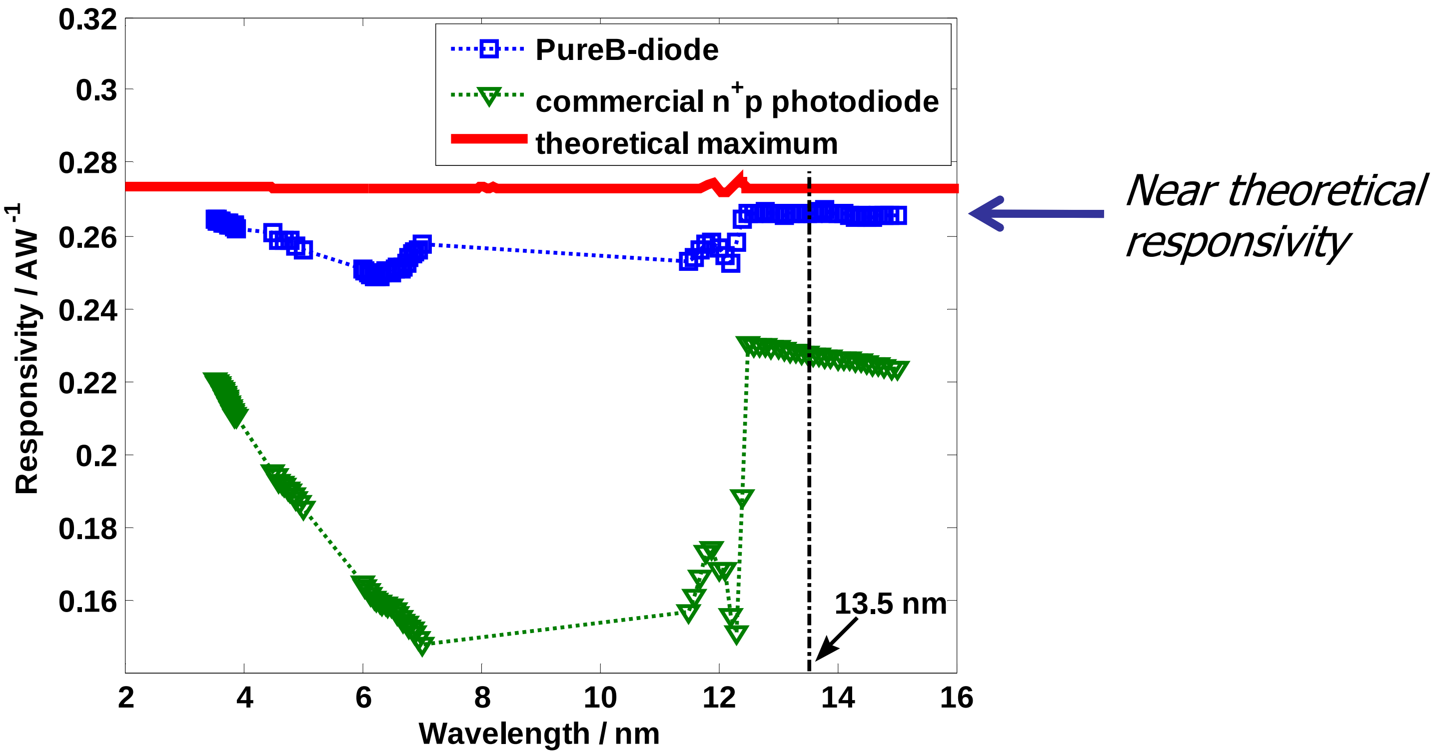
Challenging DUV/VUV/EUV detection



Ideal spectral responsivity of Si-based photodetectors

Optical performance

EUV optical performance

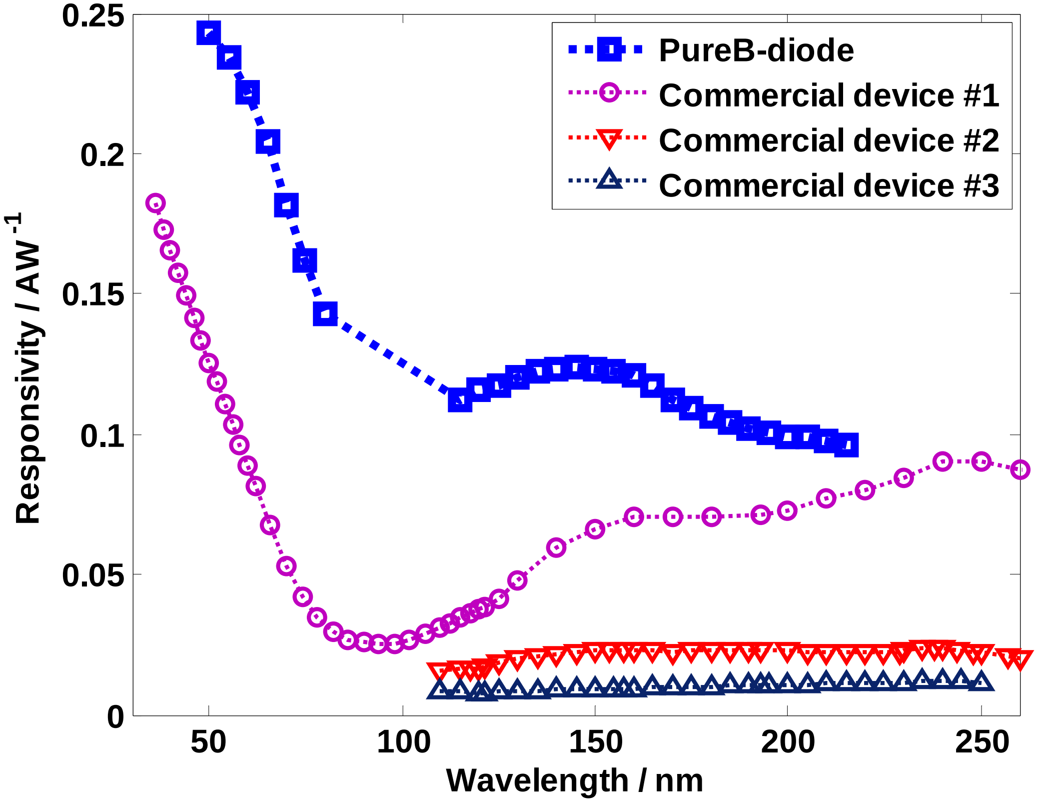


Measured spectral responsivity of EUV PureB diodes with a 2.5 min B-deposition compared with a commercial n^+p photodiode and the theoretically attainable values for an ideal Si-based photodetector.

TU Delft

Optical performance

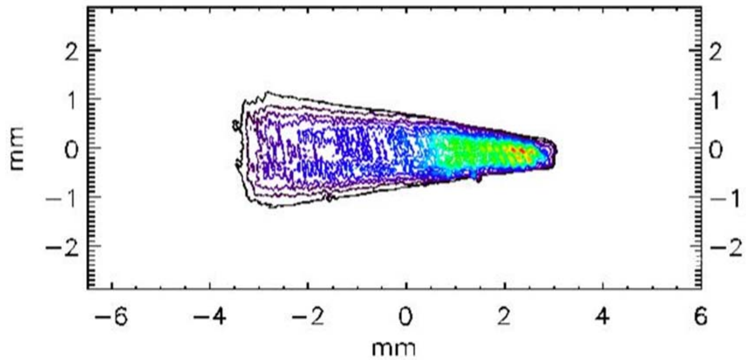
DUV/VUV optical performance

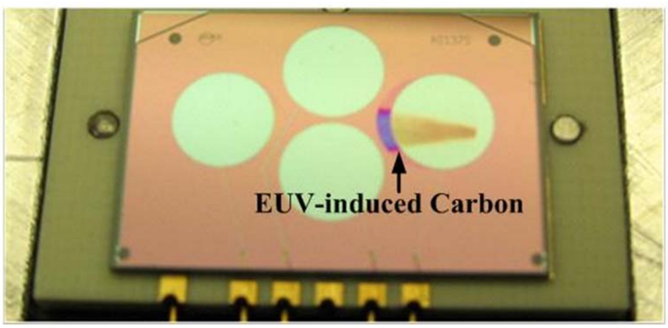


Measured responsivity of PureB-diodes in DUV/VUV spectral range compared with other state-of-the-art photodetectors.

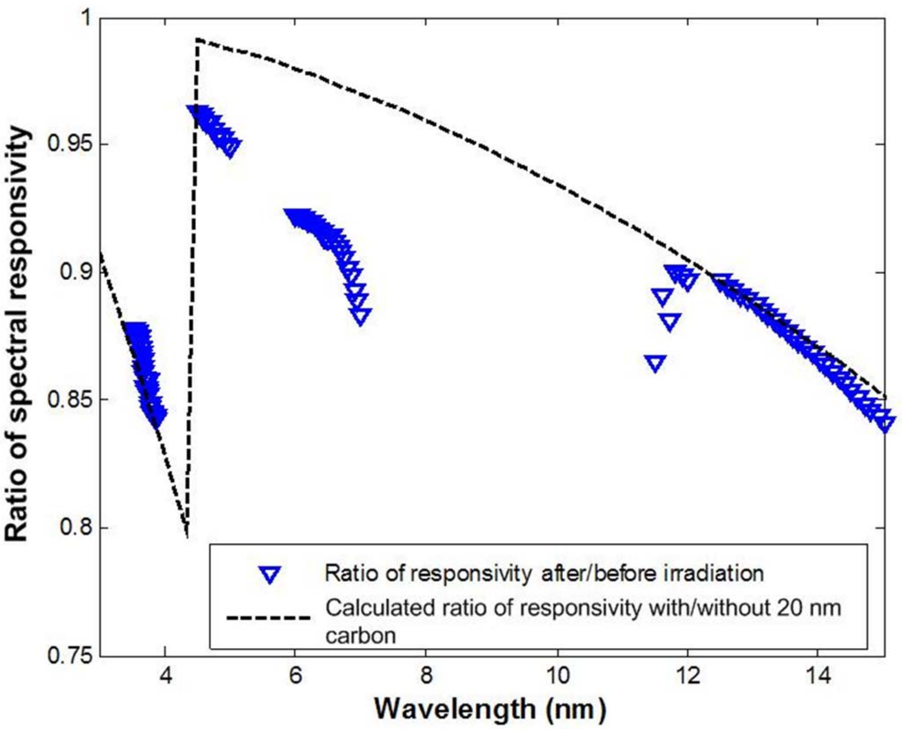
Performance stability

EUV responsivity degradation





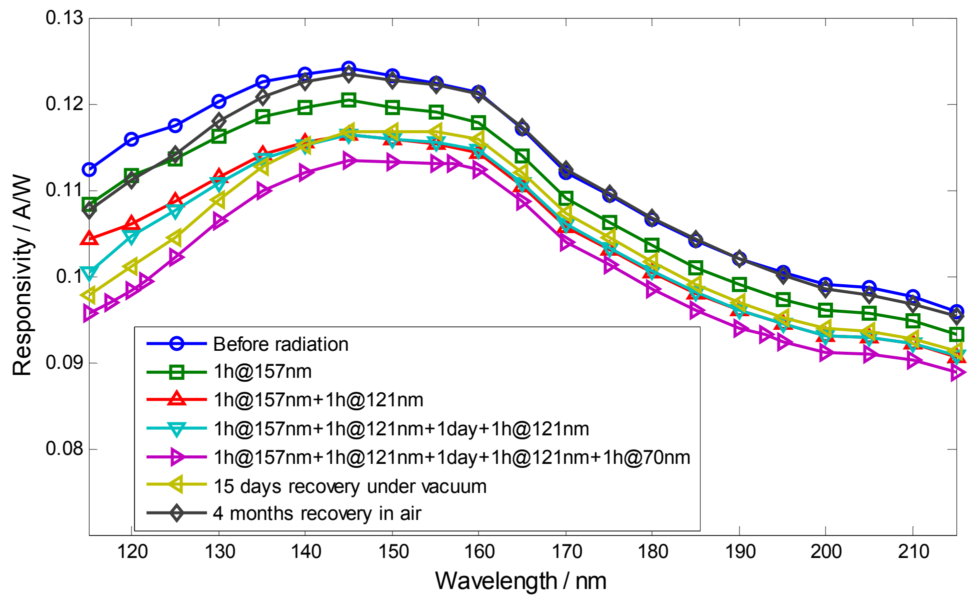
shape of the EUV spot (irradiance in the high power region is 3 W/cm^2 [24]) and the EUV-induced carbon contamination layer.

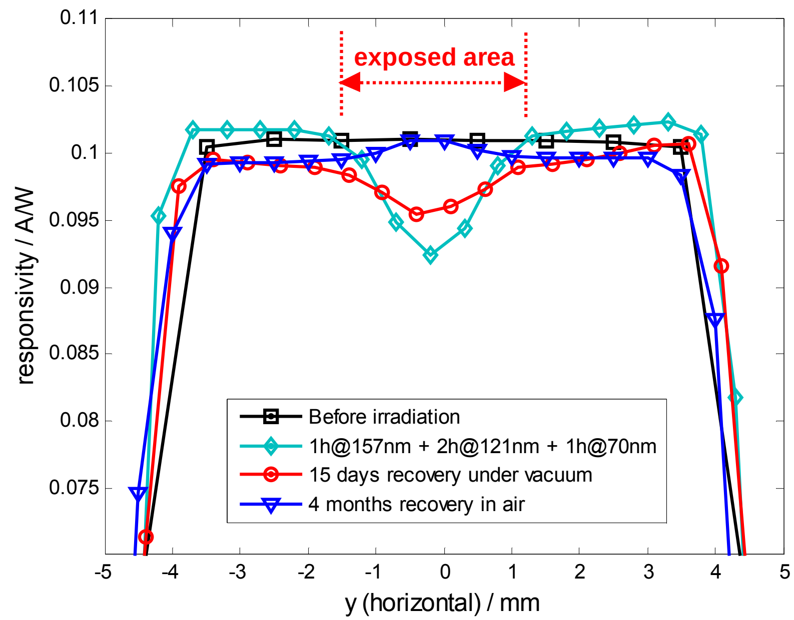


Ratio of measured EUV spectral responsivity after/before intense EUV irradiation (220 kJ/cm^2), compared to the calculated ratio of responsivity based on the same diode with/without a 20 nm carbon layer

Performance stability

DUV/VUV responsivity degradation

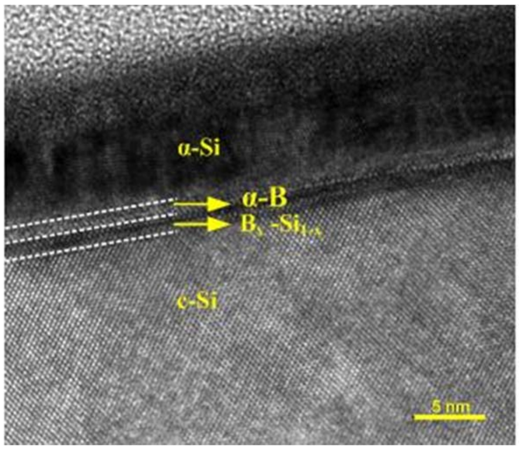


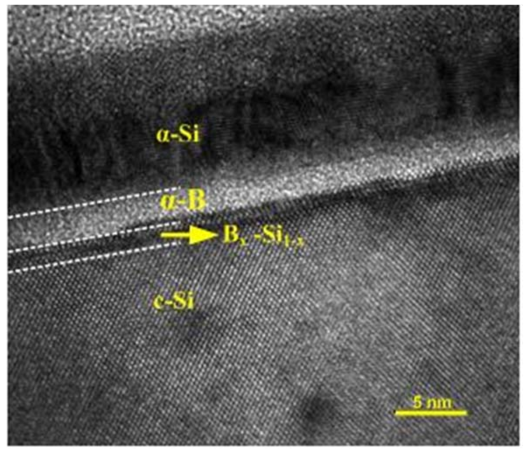


~ 4 nm silicon oxide layer was measured on the diode surface

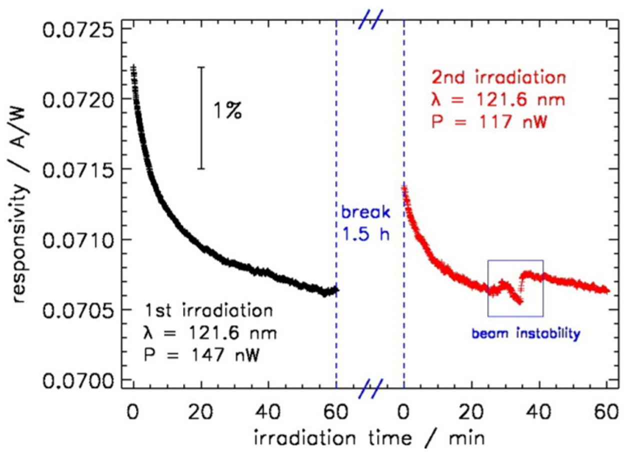
Performance stability

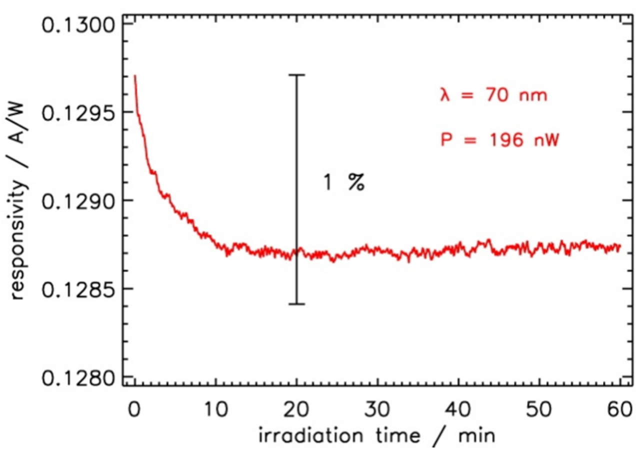
DUV/VUV responsivity degradation





Oxide-free boron surface

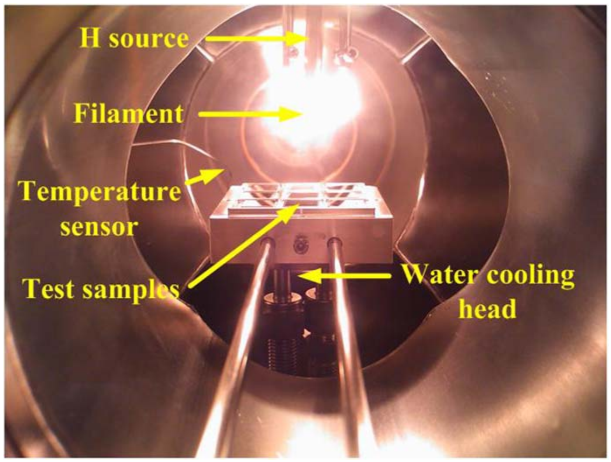




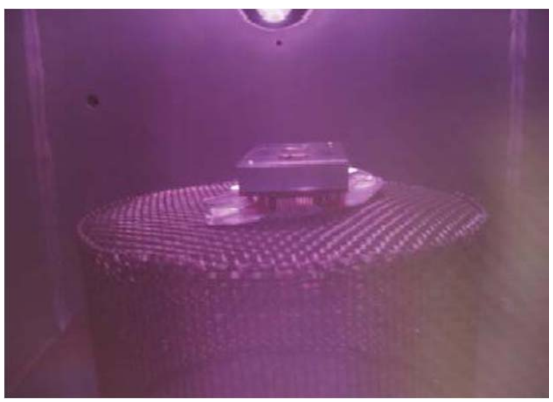
High Stability

Robustness

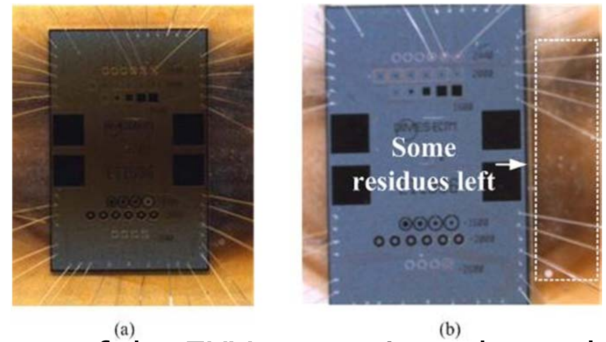
H cleaning*



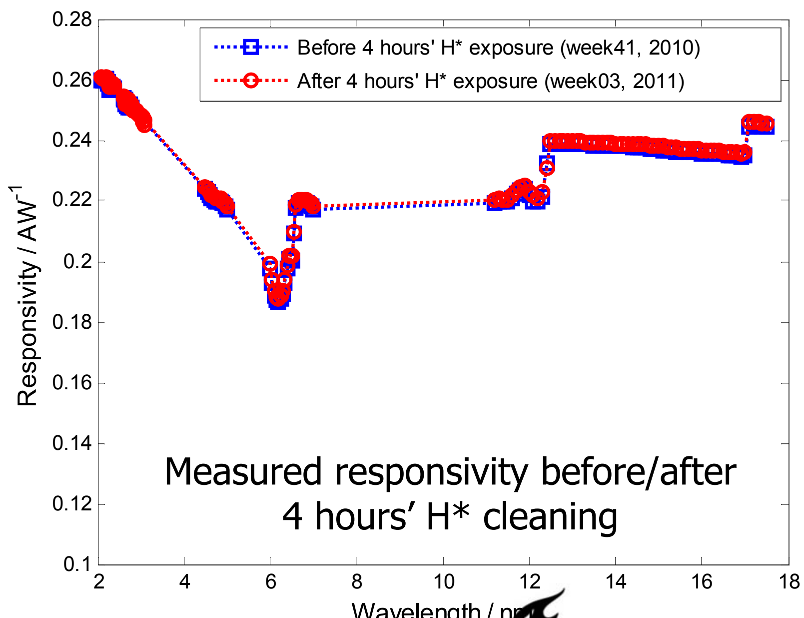
Filament enhanced H* cleaning setup



Plasma-generated H* cleaning setup

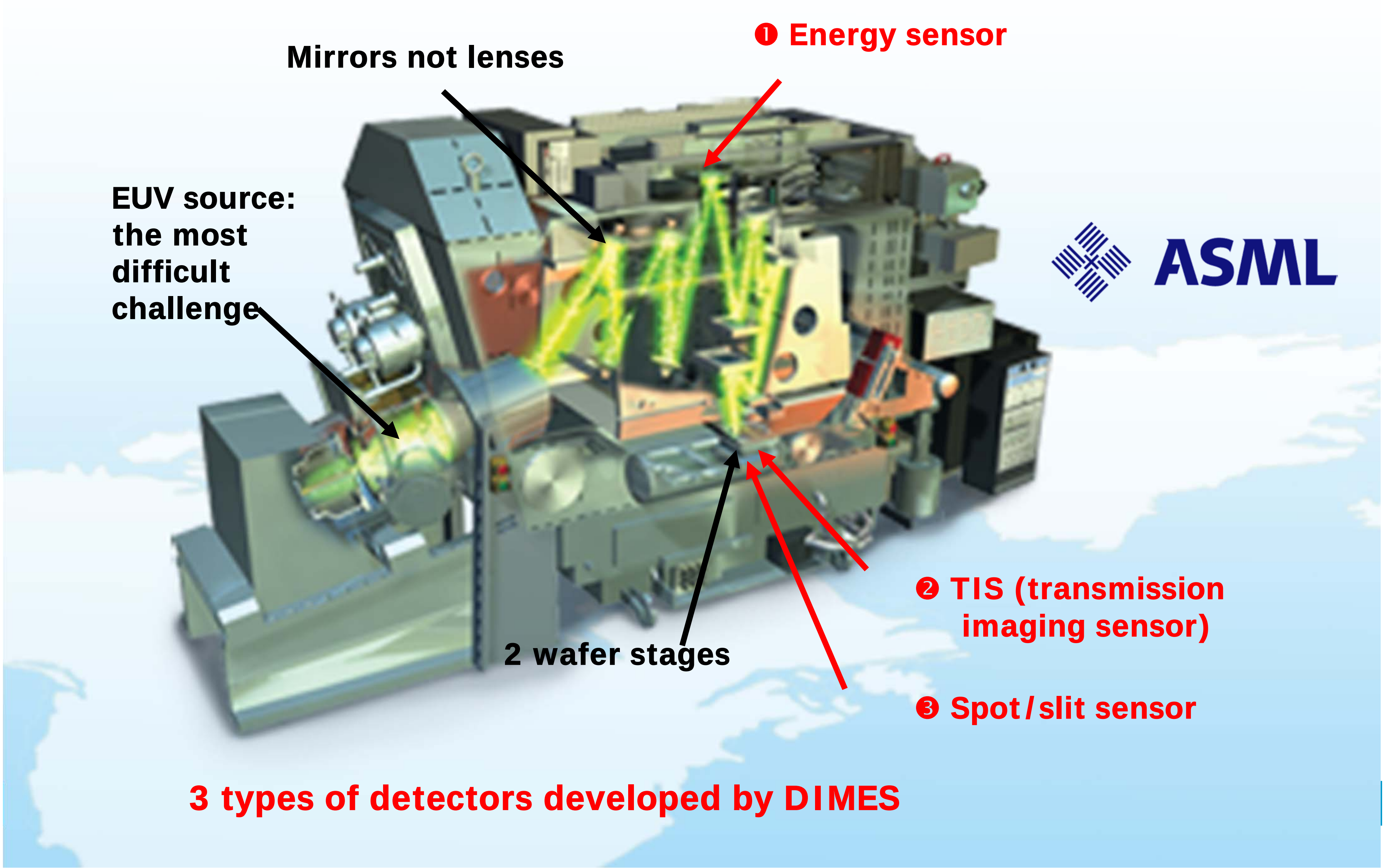


Micro-image of the EUV contaminated sample before / after 2 hours' H* cleaning.



Measured responsivity before/after 4 hours' H* cleaning

Crucial throughput requirement:
100 wafers per hour



EUV Product Roadmap




2006	2010	2012	2013
ADT	**NXE:3100**	**NXE:3300B**	**NXE:3350C**
Resolution = 32 nm	Resolution = 27 nm	Resolution = 22 nm	Resolution = 16* nm
NA = 0.25, σ = 0.5	NA = 0.25, σ = 0.8	NA = 0.32, σ = 0.2-0.9	NA = 0.32, OAI
Overlay < 7 nm	Overlay < 4.5 nm	Overlay < 3.5 nm	Overlay < 3 nm
Throughput 5 WPH	Throughput 60 WPH	Throughput 125 WPH	Throughput 150 WPH
@ 5mJ/cm² ~8W	@ 10mJ/cm2 >100W	@ 15mJ/cm2 >350W	@ 15mJ/cm2 >550W

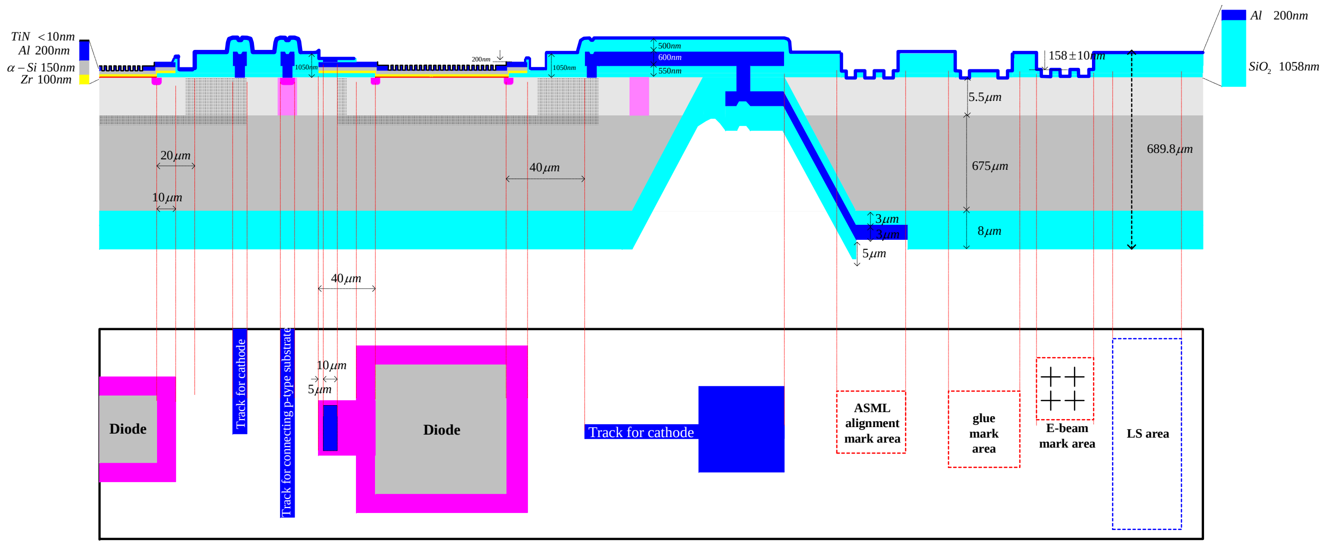
Main improvements
1) New EUV platform :NXE
2) Improved low flare optics
3) New high σ illuminator
4) New high power LPP source
5) Dual stages

Main improvements
1) New high NA 6 mirror lens
2) New high efficiency illuminator
3) Off-Axis illumination option
4) Source power increase
5) Reduced footprint

Platform enhancements
1) Source power increase

** Requires <7nm resist diffusion length*

Extremely complex



Detector elements: photodiodes

temperature sensors

absorber layer stacks

different filter layer stacks

5 different types of alignment marks

two-sided contacting

excruciating electrical, optical and mechanical specifications

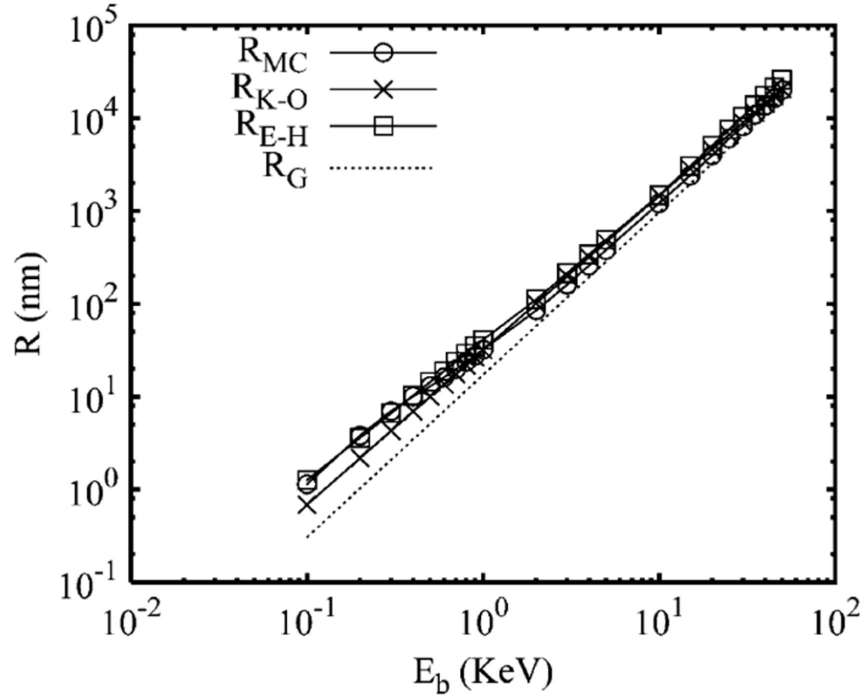
Good manufacturability
- IC processing compatibility
- flexibility

Outline

- Introduction
- Pure boron CVD technology
- Doping from pure boron layers
- Electrical properties of PureB p^+n diodes
- Application as photodetectors for low-penetration-depth radiation and charged particles :
  - VUV, DUV, EUV
  - **low-energy electrons**
- Conclusions

Low-Energy Electron Detection

Challenges: low range in Si



(O. Kurniawan and V.K.S. Ong, in Scanning Vol. 29, 280-286, 2007.)

- 10 keV: ~ 1 µm
- 2 keV: ~ 200 nm
- 1 keV: (10 - 40) nm
- 500 eV: (5 – 15) nm

$\underbrace{\text{Metallization + coating layers + neutral p/n region}}_{\text{DEAD LAYER LOSSES}}$ < 10 nm

DEAD LAYER LOSSES

FEI COMPANY™ TOOLS FOR NANOTECH

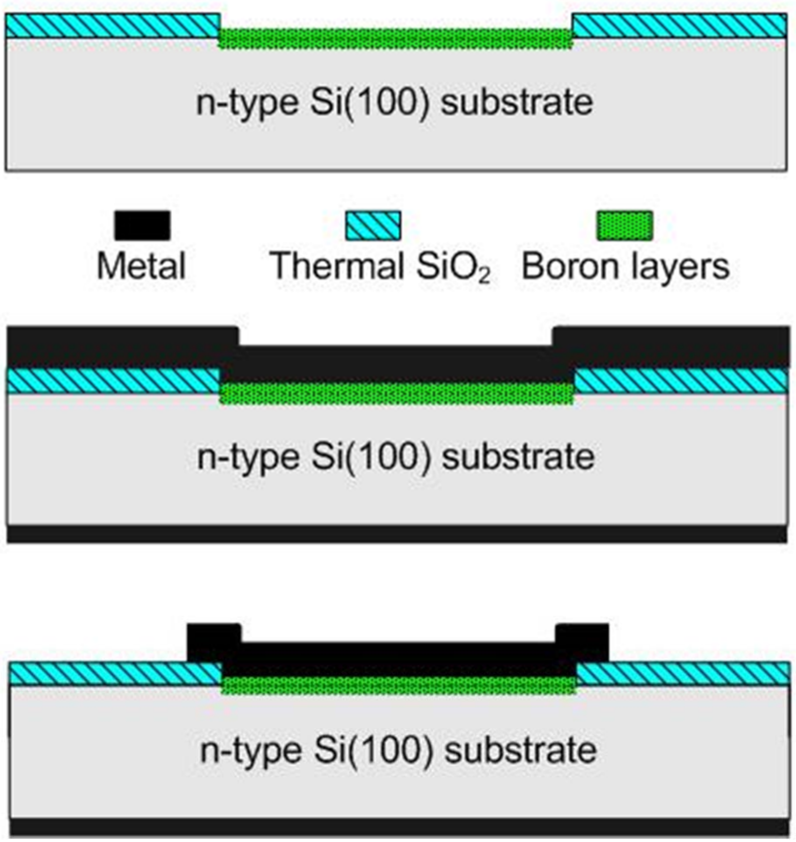
TU Delft

Device fabrication

1)

2)

3)



p^+n junction formation

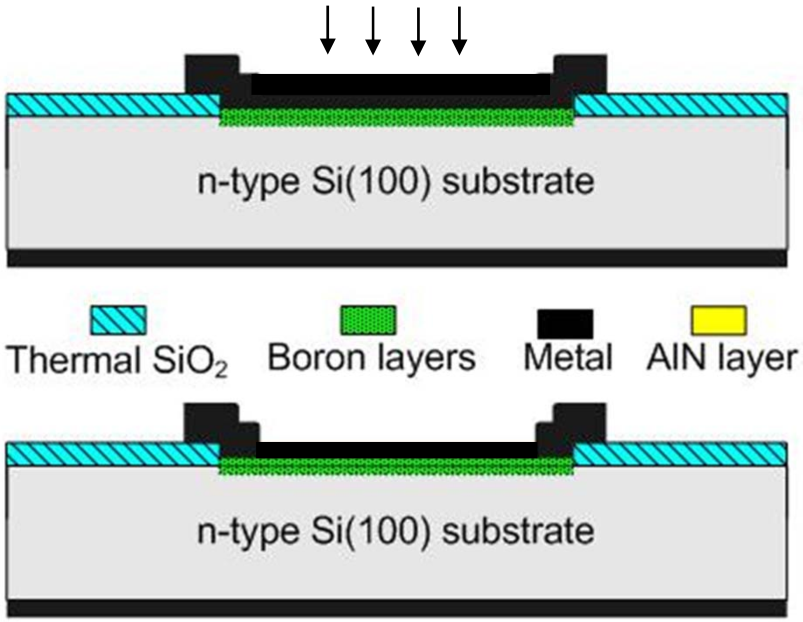
- junction depth controlled with deposition time at 700 °C:
  2′ 40″ for **1.8 nm** and 10′ for **5 nm** B-layer
- OPTIONAL Post-Processing: thermal annealing step for higher dopant activation / epitaxially grown 50-nm-thick B-doped Si layer

Pure Al deposition

- depositing Al with (1-2)% Si would leave Si precipitates when Al is selectively etched

Anode contact definition: diode area, contact ring on the perimeter of the diode, metal track, and contact pad

Device fabrication



4)

5)

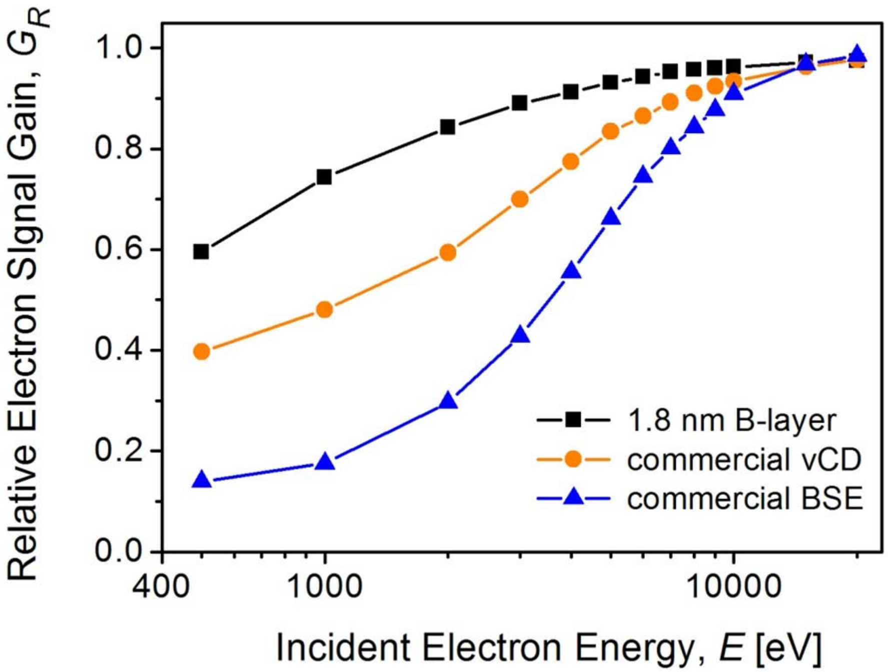
Plasma etching

- Not selective to B-layer
- Promotes anisotropy
- Etching Al to about 100 nm thickness

Dilute HF etch stop

- Wet landing directly to the photosensitive surface
- **B-layer is highly resistant to diluted HF**

Relative Electron Signal Gain



$$G_R(E_{beam}) = \frac{I_{ph} / I_{beam}}{(E_{beam}/e_0)(1-\eta)} = \frac{G_{PH}}{G_{TH}}$$

$$G_R = 0 \rightarrow I_{ph} = 0$$

$$G_R = 1 \rightarrow G_{PH} = G_{TH}$$

State-of-art commercial detectors:

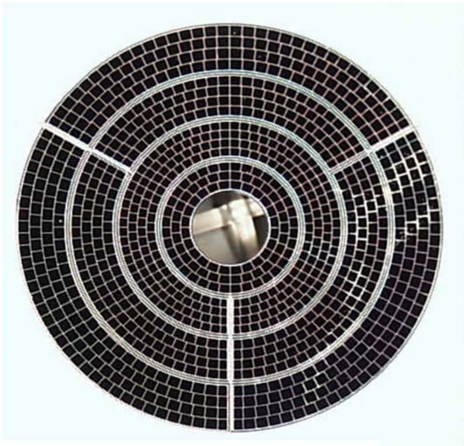
- vCD: low Voltage high Contrast Detector
- BSE: Backscattered-electron detector

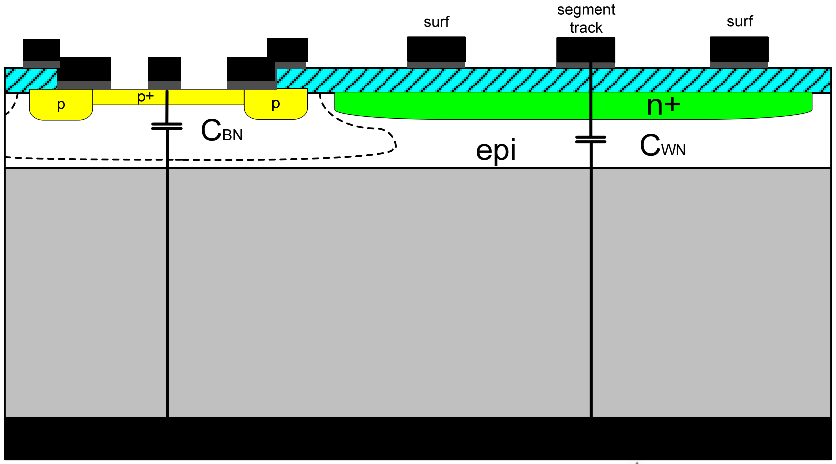
FEI COMPANY
TOOLS FOR NANOTECH
TU Delft

FEI electron detectors

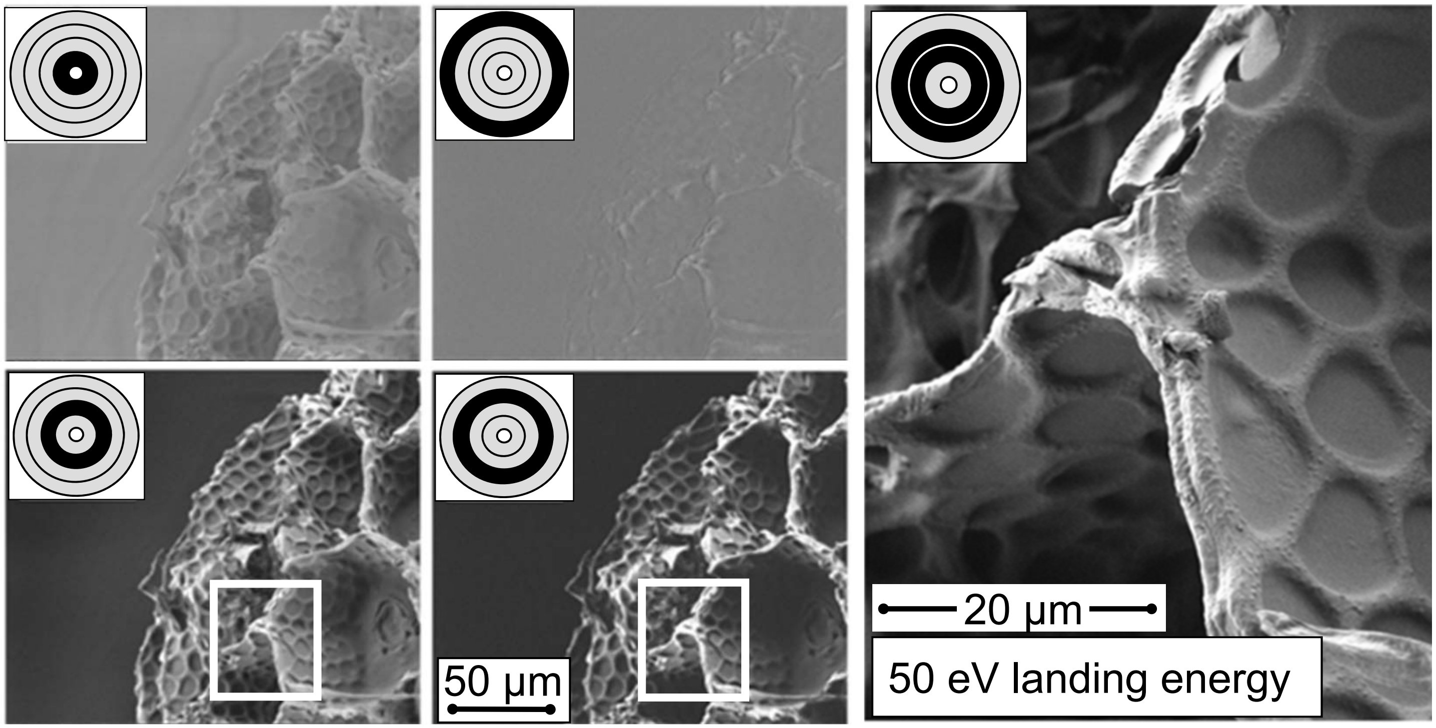
Special requirements: very low capacitance
low resistance
many separated detector segments
through-wafer holes

Solutions: low doped, high-quality, 40 µm thick epi-layers
special metal grid processing
through-wafer deep dry etching





Example of imaging capability (FEI ASB Magellan SEM)



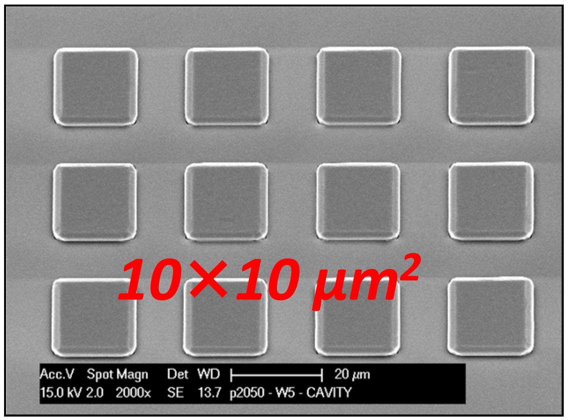
SEM images of pollen taken with B-layer detectors

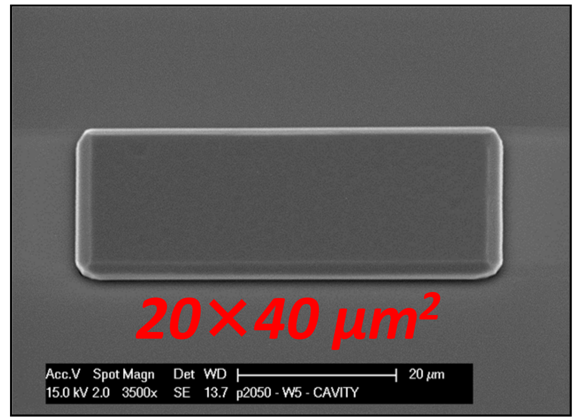
Sakic, IEDM 2010

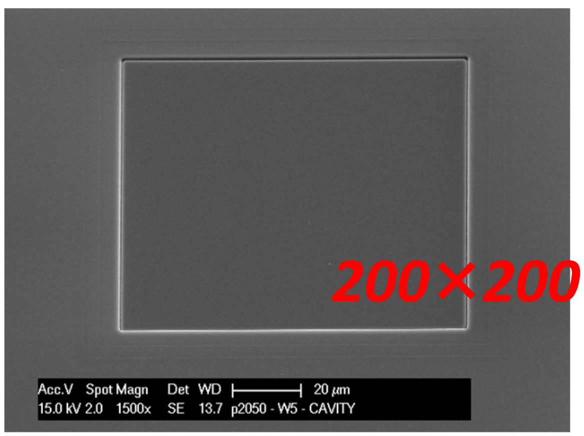
Future processes

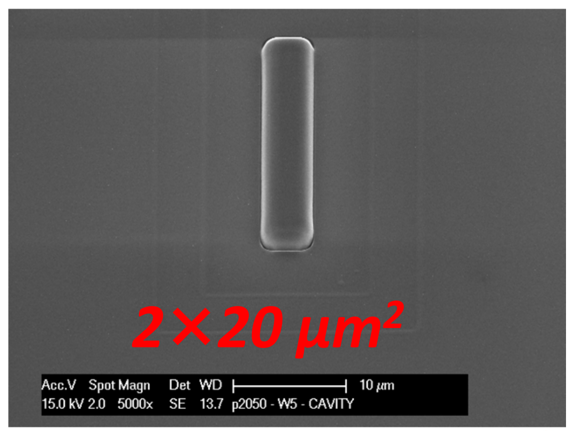
Selective Ge epitaxy on Si

- **Unique feature: Large islands possible with sub-300nm transition at 700˚C**
- **Uniform Ge surface compatible with CMOS planar processing**



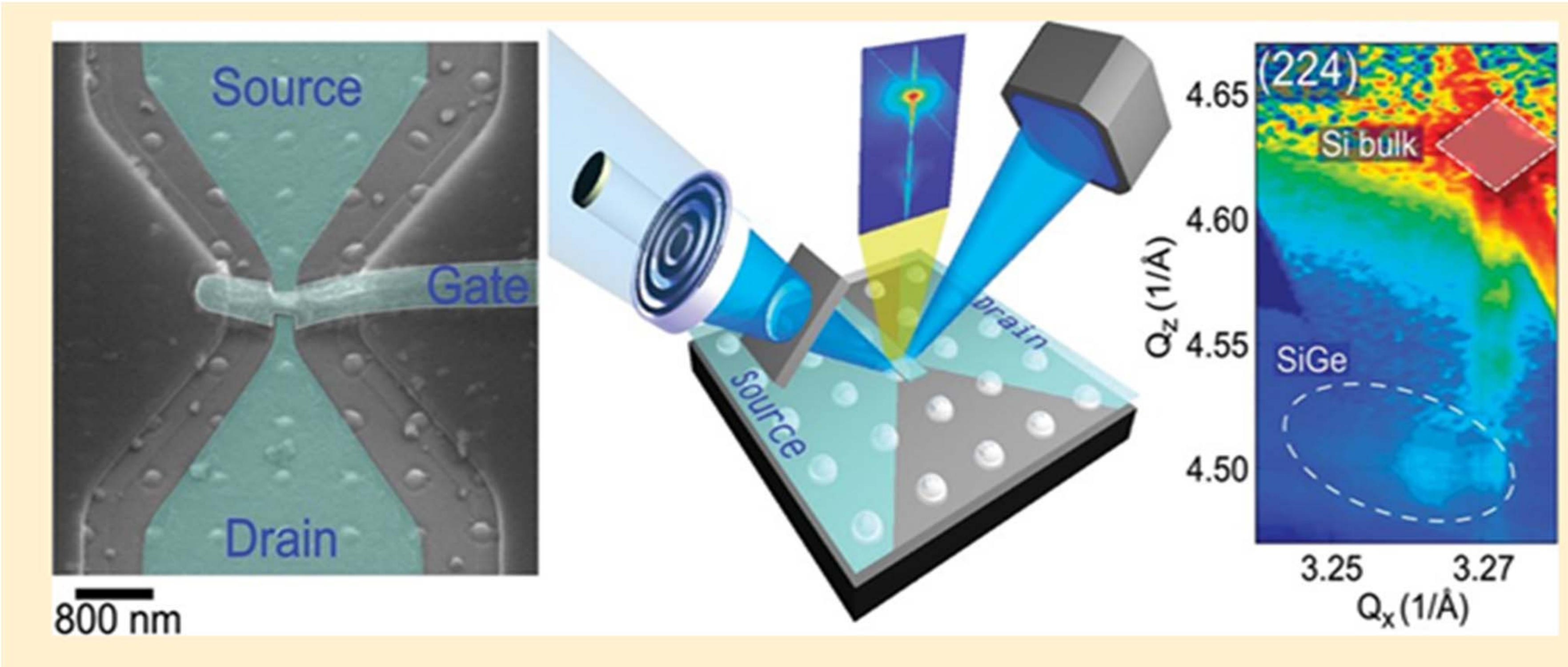






Sammak, ESSDERC2011

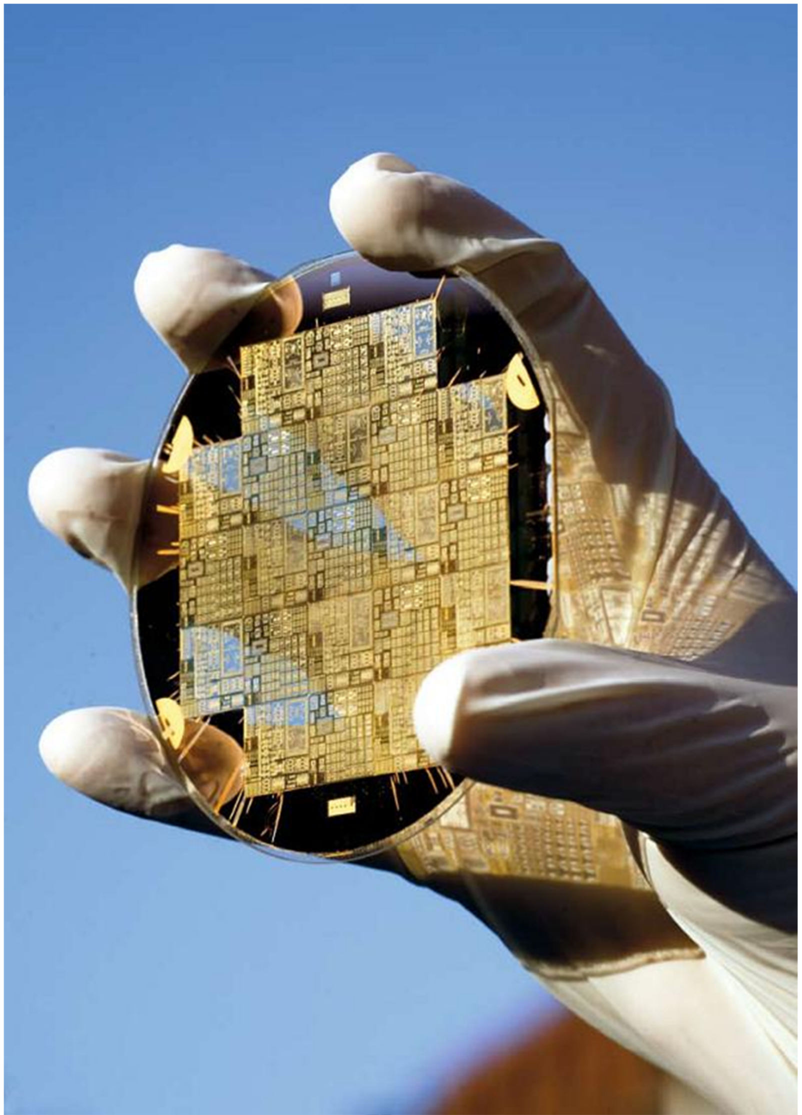
Ge-dots embedded in Si: defect-free



A μ-Raman strain measurement in the silicon above an embedded Ge quantum-dot [2].
Huandra, Nanoletters 2011

The first PureB application:

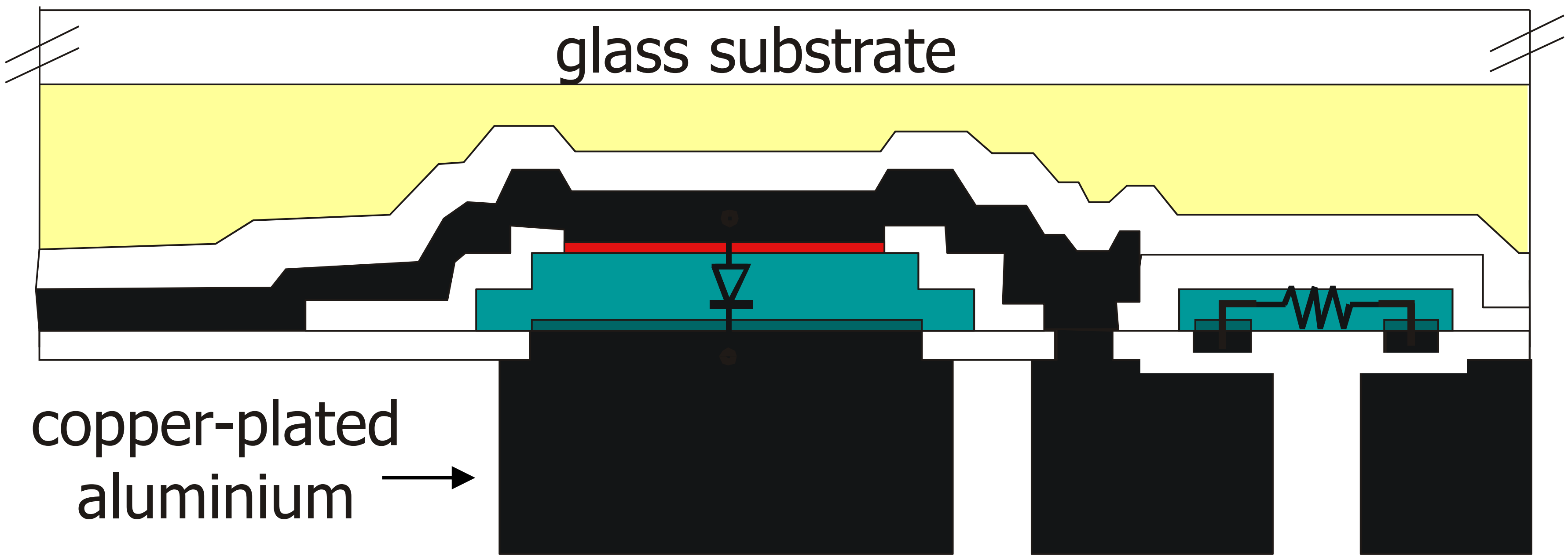
high-Q high-linearity varactor circuits made in silicon-on-glass technology



SOG varactor diodes

True Two-sided contacting: ideal 1-D behavior

eliminate parasitics



Diodes: low leakage, ultrashallow, made at low temperature