The DePFET Pixel Clinic

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HLL Sensor Workshop

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OUTLINE

- Background
  - ESA‘s ATHENA Satellite and the Wide Field Imager
- Defect Search & Handling
  - Optical Inspection
  - Electrical Tests
  - Photonic Analysis
  - Defect Mitigation

ATHENA Advanced Telescope for High ENergy Astrophysics

- ESA Cosmic Vision programme
- L-class flagship mission, total budget 1.3 B€
- launch ~ late 2030s, Ariane-IV carrier
- X-ray observatory
  - ▷ 'hot' objects and energetic processes in the universe
  - ▷ e.g. formation of large scale structures, black hole evolution
- payload
  - ▷ total reflection focusing X-ray mirror
  - ▷ X-IFU (X-ray Integrated Field Unit, cryogenic detector array) ultimate energy resolution, small field of view (4 arcmin)
  - ▷ WFI (Wide Field Imager, Si active pixel sensor) medium energy resolution, full field of view (40 arcmin)
  - ▷ instrument selection by mirror tilt

WFI

focal plane instruments

X-IFU

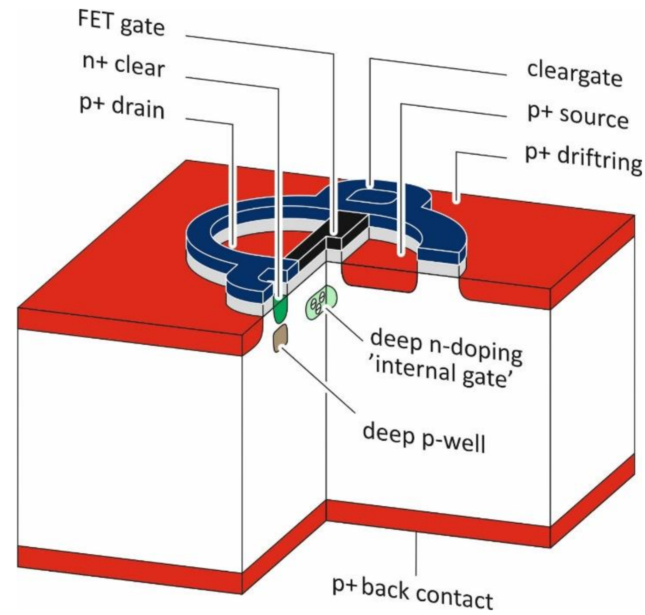
cosine, NL

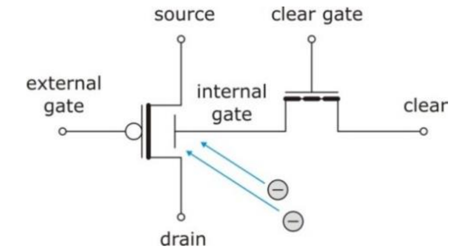
Si pore optics module

• focal length	12	m
• effective area	1.1	m²
• field of view	40	arcmin
• resolution	9	arcsec

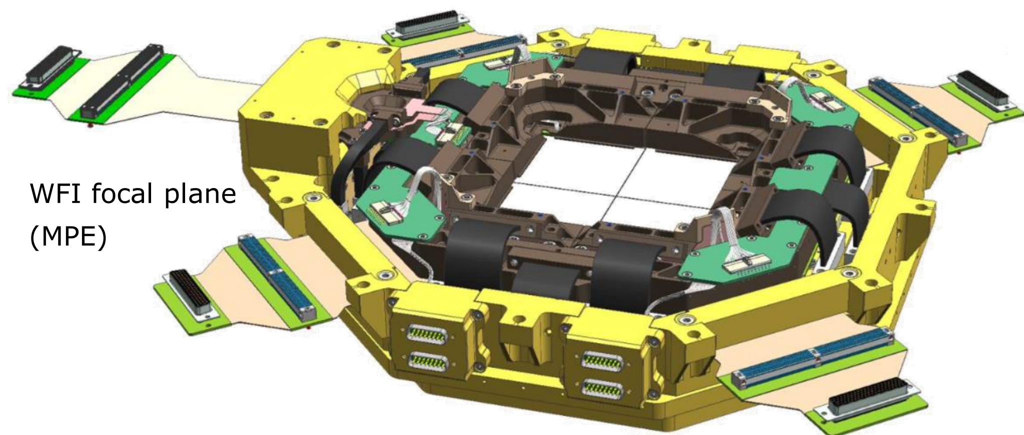
ATHENA WIDE FIELD IMAGER

- Active Pixel Sensor based on DePFET (**DE**pleted **P**-channel **F**ield **E**ffect **T**ransistor)
  - format — 4 quadrants x 512 x 512 pixels
    ~ 14 x 14 cm² ≡ 40 arcmin FoV
  - pixel — 130 x 130 µm² ≡ 2.2 arcsec
  - readout — rolling shutter mode
    5 µsec/row, 2.5 msec/frame
  - resolution — <150 eV FWHM @ 5.9 keV

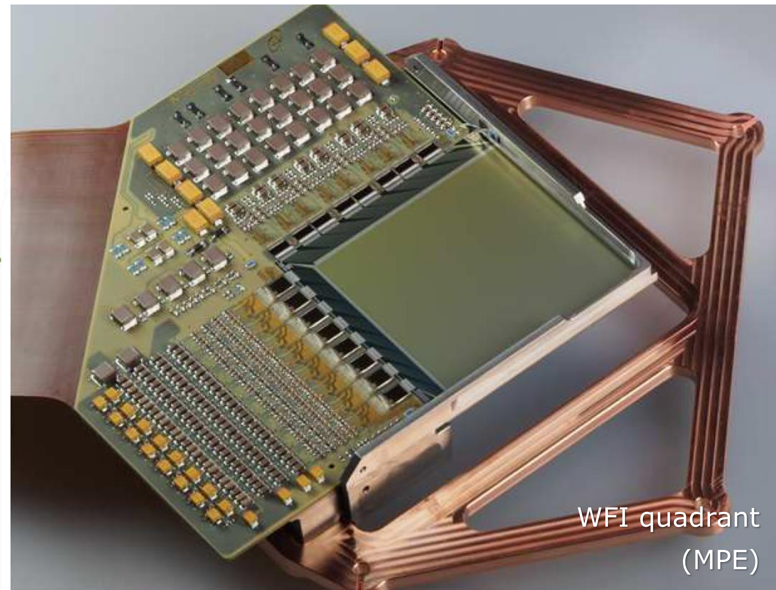




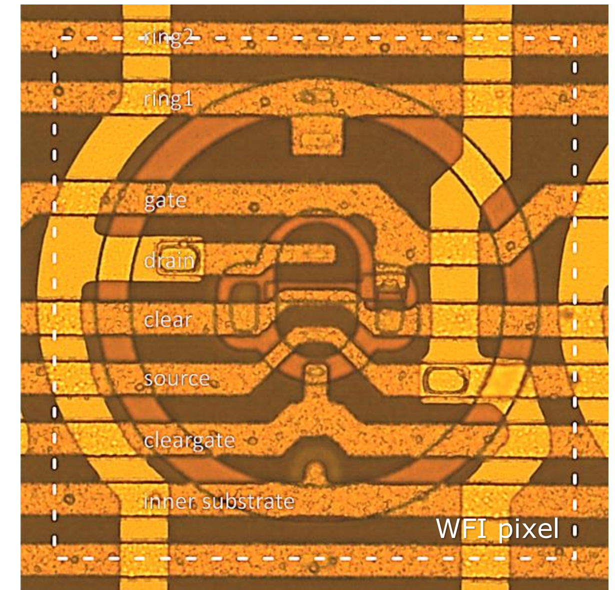
DePFET equivalent circuit



WFI focal plane (MPE)



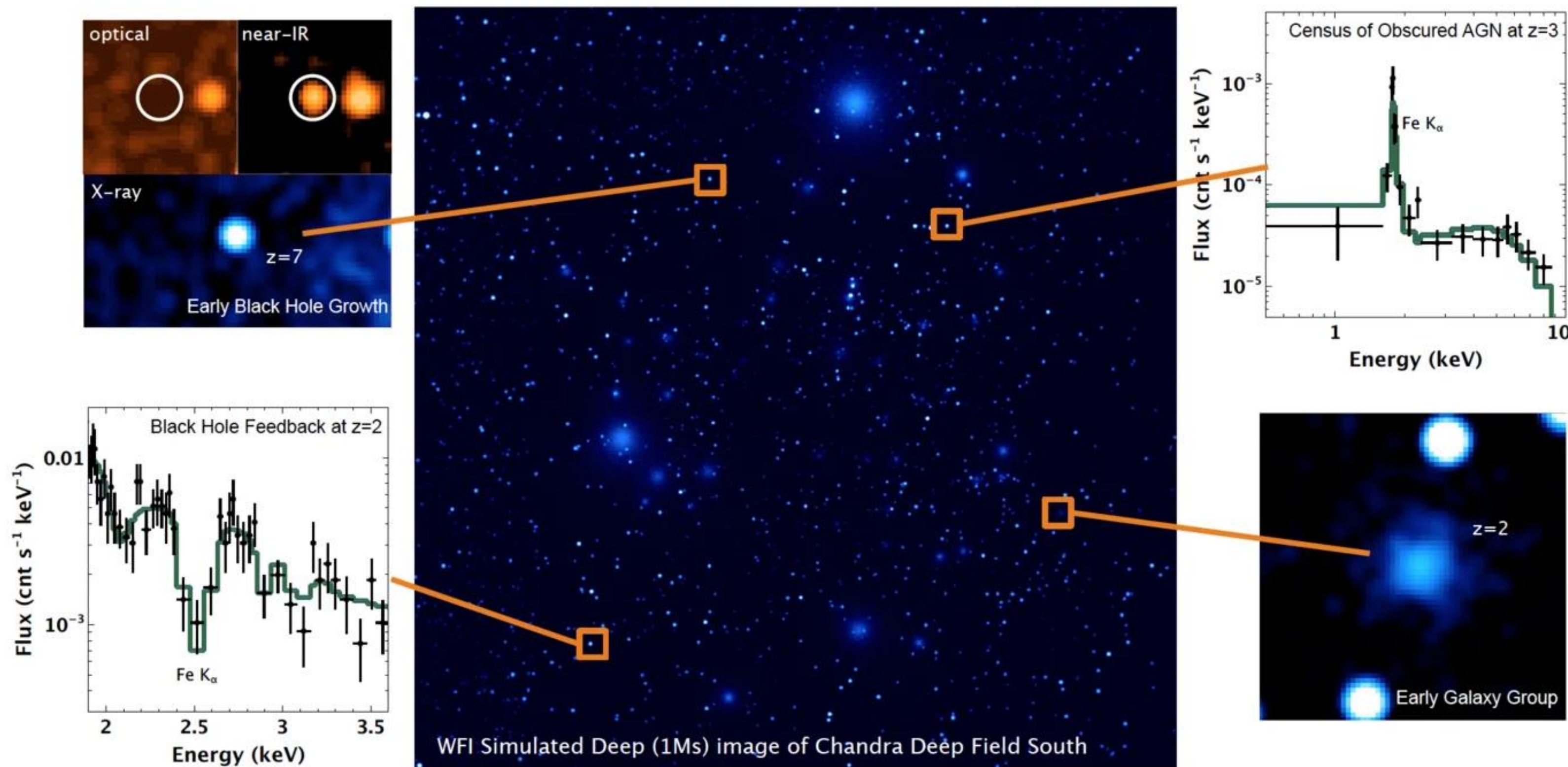
WFI quadrant (MPE)



WFI pixel

ATHENA WIDE FIELD IMAGER

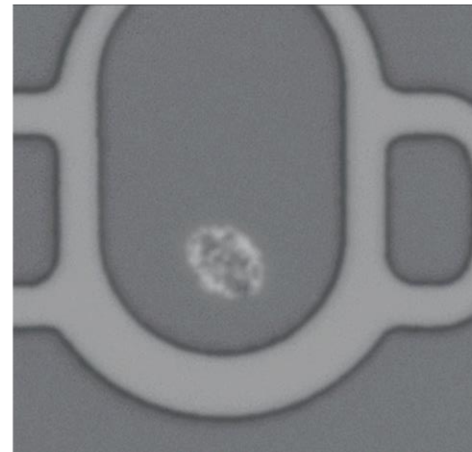
- imaging
  - ▷ intensity map of sky region
  - ▷ structure of extended objects
- spectroscopy
  - ▷ X-ray energy spectrum
  - ▷ continuum
    - → black body, synchrotron emission
  - ▷ characteristic lines
    - → elemental abundance
- timing
  - ▷ transient sources, oscillations
  - ▷ time resolution ≤ 80 µsec



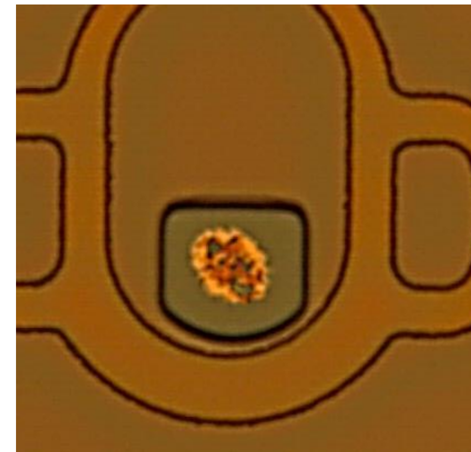
A. Rau / WFI Team
MPE homepage

DEFECT SEARCH & HANDLING

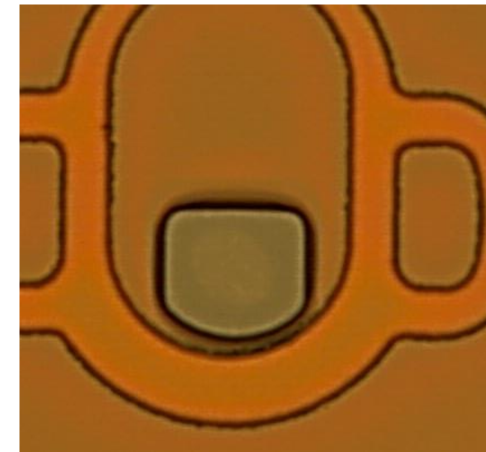
- yield requirement
  - 'defect-free' devices
  - no science penalties
- optical inline inspection
  - µTec Defect Check system
  - pixel-to-pixel comparison
  - each process step
  - visible defects only
  - e.g. ATHENA WFI pixel structure
- repair option
  - point treatment of detected defect
  - on pixel level



polySi leftover,
detected by inspection system



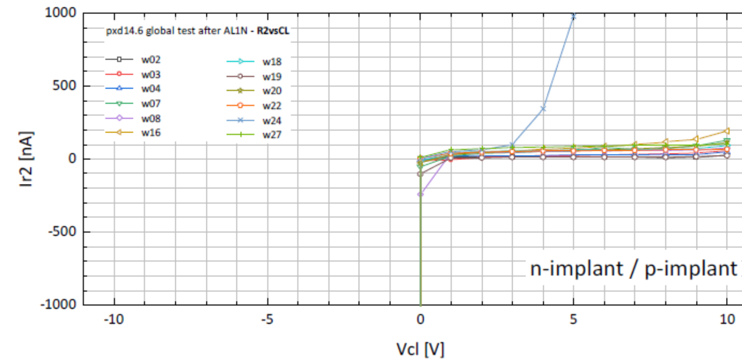
direct wafer lithography
for point repair

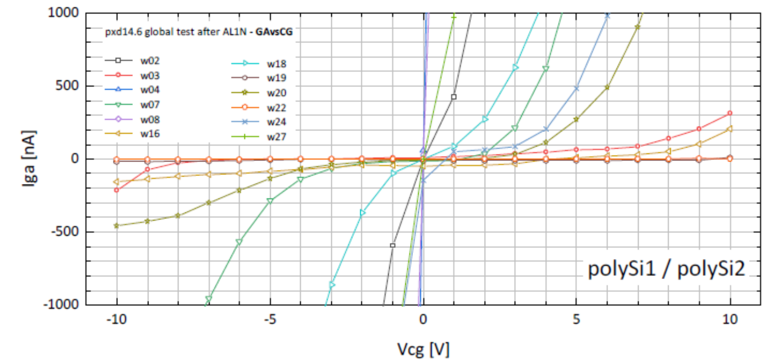


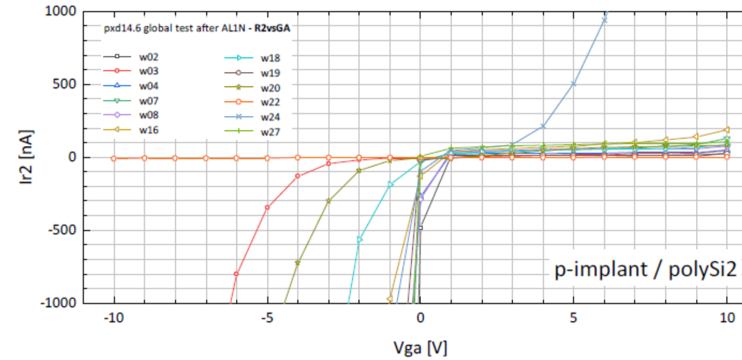
repaired pixel
after polySi re-etching

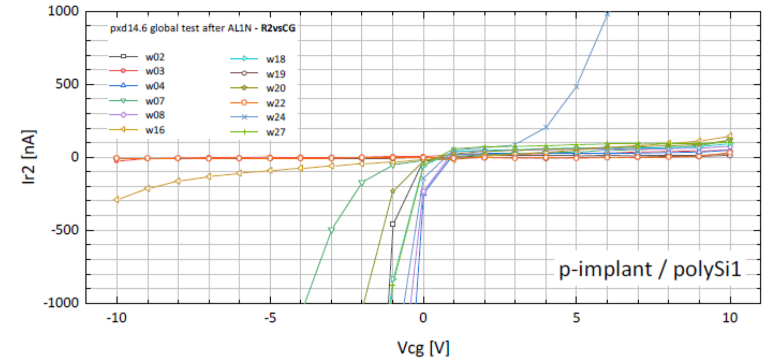
DEFECT SEARCH & HANDLING

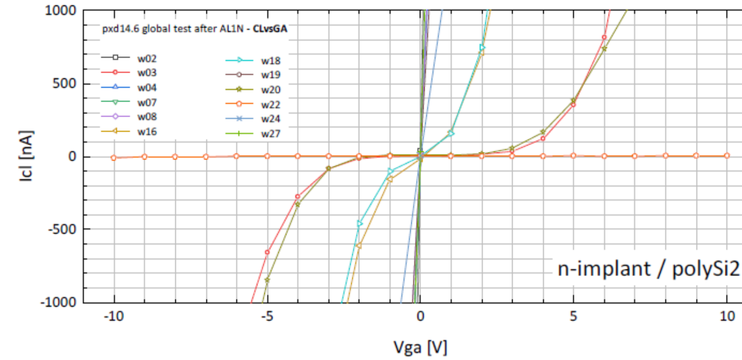
- electrical yield test
  - inline, after 1st metal layer
  - e.g. 12 wafers of ATHENA production
  - use of global test points
    i.e. 512 x 512 pixels in parallel
  - conventional probe station
  - 2-terminal I(V)-tests
  - search for shorts (and breakdowns)
  - no information about number, nature, and location of defect(s)
  - summary
    - 1 device free of defects
    - 10 devices with 1 or 2 defect types
    - 1 device with diode breakdown
      → no further option

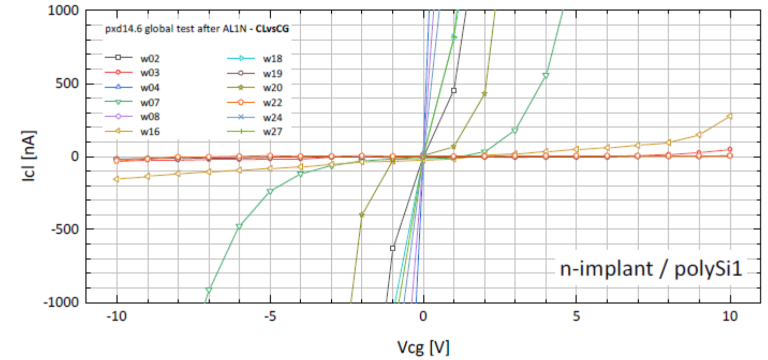








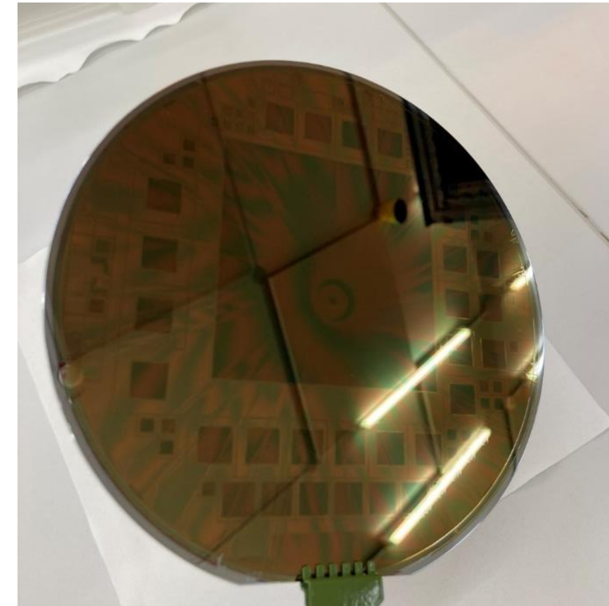




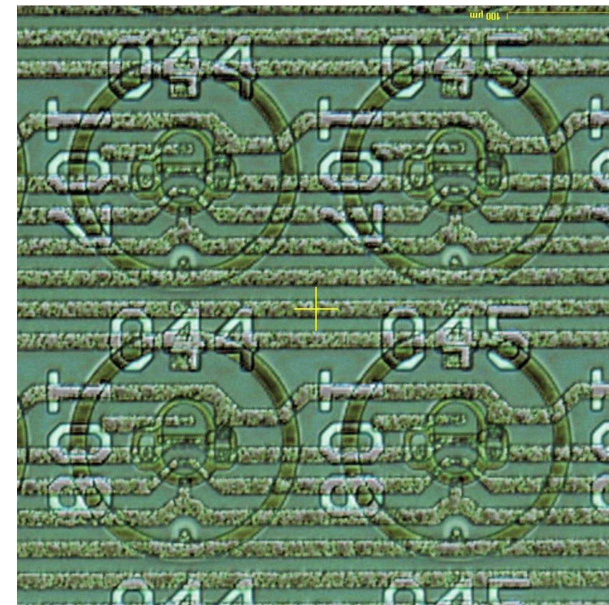
DEFECT SEARCH & HANDLING

- strategy
  - row-by-row short test on probe station
    - → more information on number of defects
    - → identification of defect row(s)
    - → restriction of search area

- wafer preparations
  - protection of entrance window side by 10 µm resist
  - temporary pixel row & column in photoresist



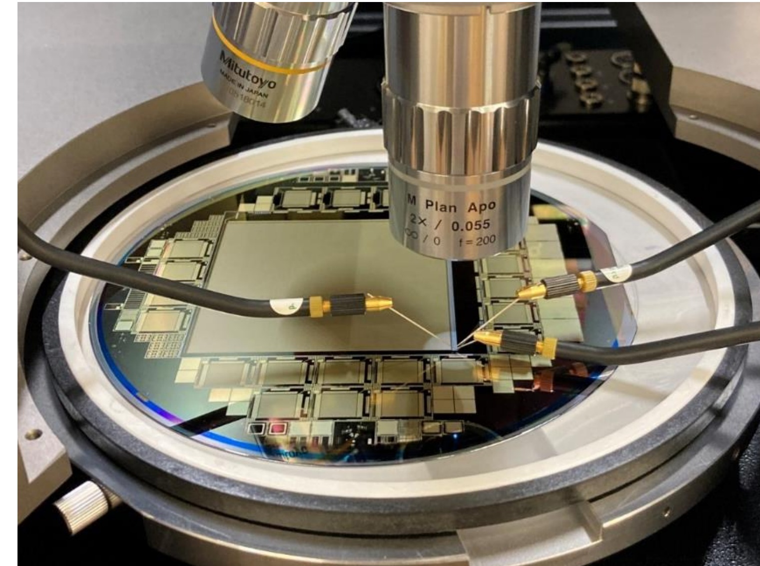
entrance window protection

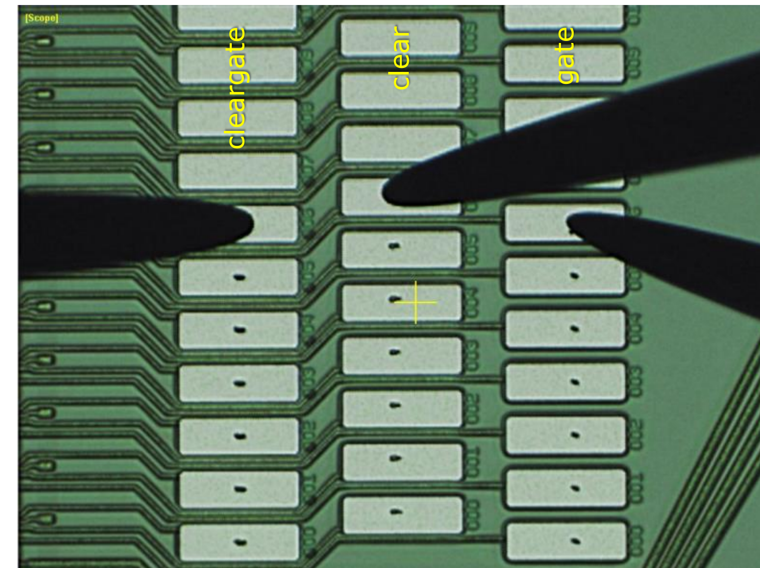


pixel address in photoresist

DEFECT SEARCH & HANDLING

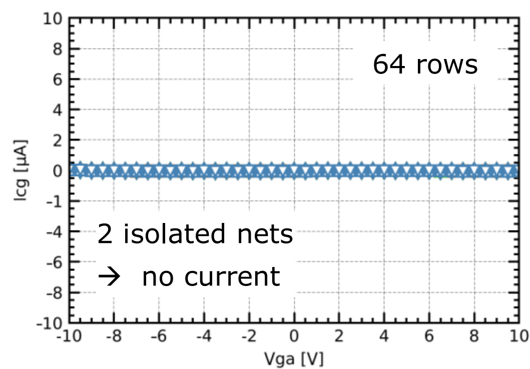
- automatic probe station FormFactor PA200
  - 3 stationary probes, programmable moveable chuck
  - wafer on permeable tissue, fixation by vacuum
- test procedure
  - 3 x 2-terminal I(V)-tests per row
  - measurement time
    - ~ 2.5 min / row
    - ~ 22 h / device

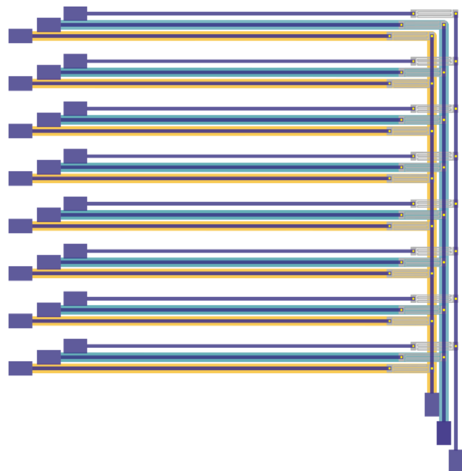




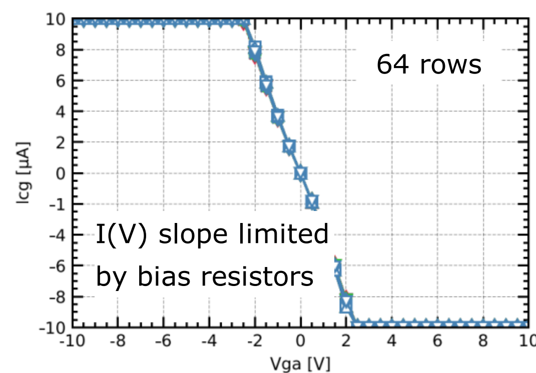
DEFECT SEARCH & HANDLING

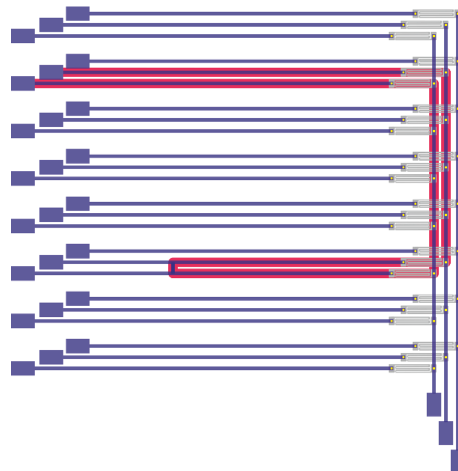
- short detection
  - ▷ no short



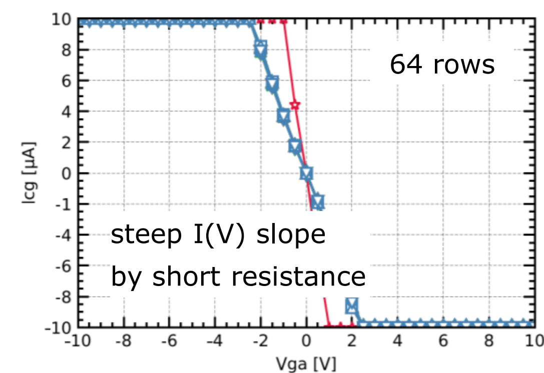


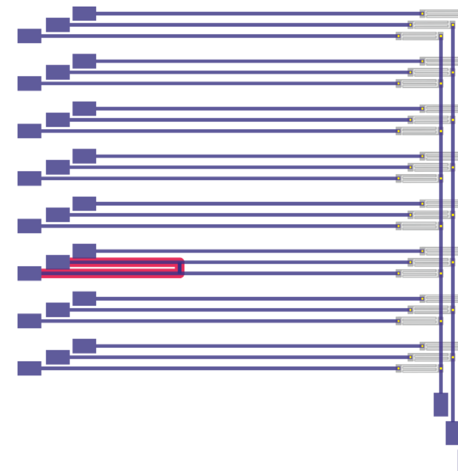
  - ▷ short outside of tested row





  - ▷ short in tested row





  - ▷ summary
    - 10 devices (512 x 512)
    - 6 x 1 defect row
    - 4 x 2 defect rows

DEFECT SEARCH & HANDLING

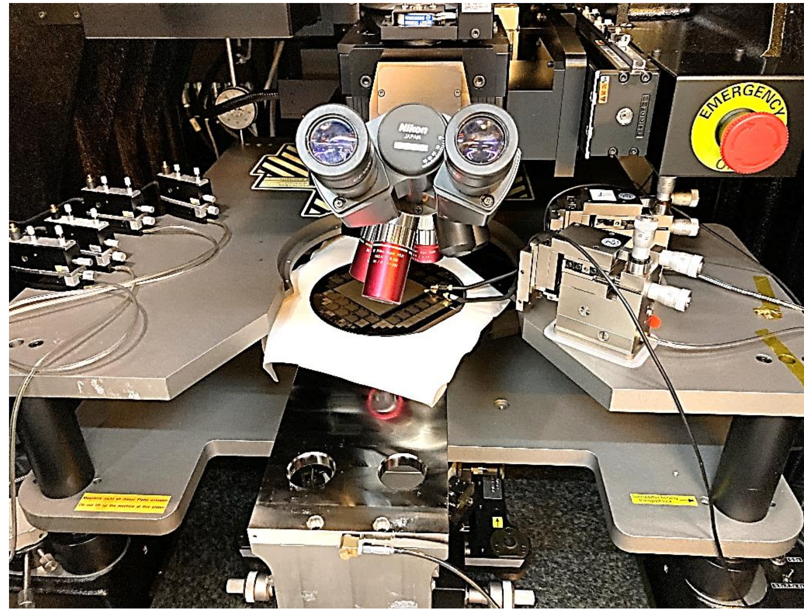
- PHEMOS emission microscope
  - ▷ defect row biased by prober needles
    - → power dissipation @ short
    - → emission of heat & light
  - ▷ detection devices
    - – Si CCD → low level light
    - – InGaAs IR camera → heat
  - ▷ system limitation

    sensor row length (~ 7 cm)

    vs.

    camera/microscope travel distance (~ 5 cm)

    - → wafer twist angle 45°
    - → use full travel distance in X & Y



PHEMOS emission microscope

close-up of chuck & wafer

DEFECT PIXEL SEARCH

- PHEMOS emission microscope
  - row scan with macro lense x0.8
    - field of view ~ 100 x 100 px
    - sequence of 6 images

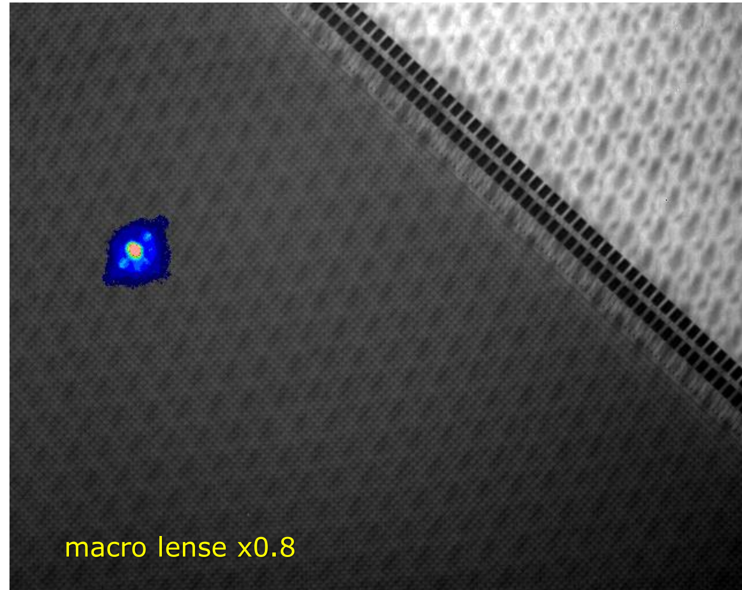
    → defect detection

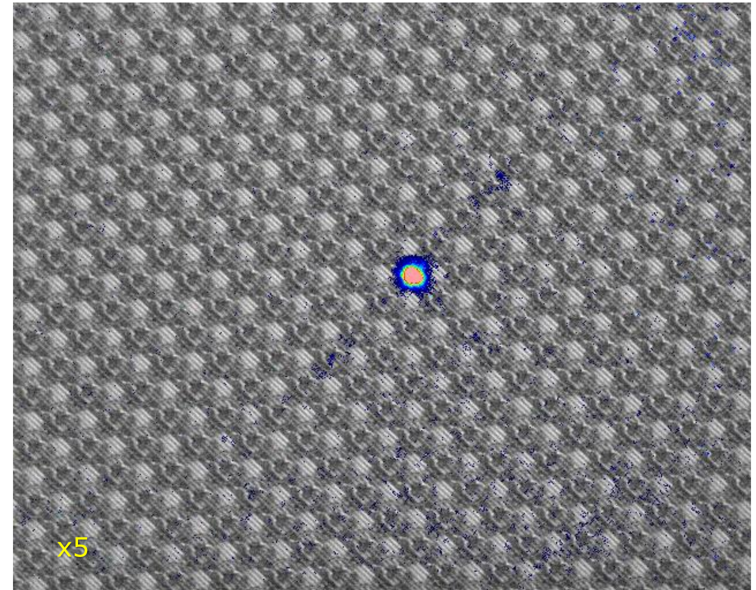
  - successive increase of resolution
    - x5, x20, x100

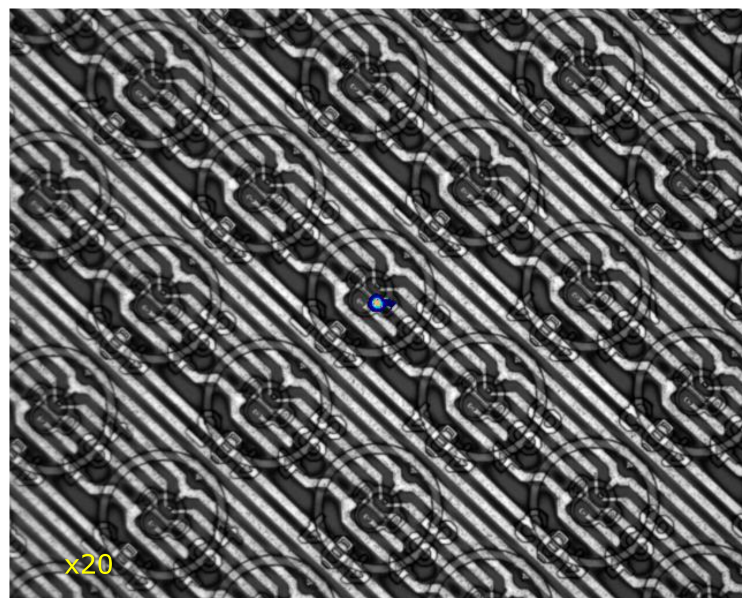
    → pixel identification

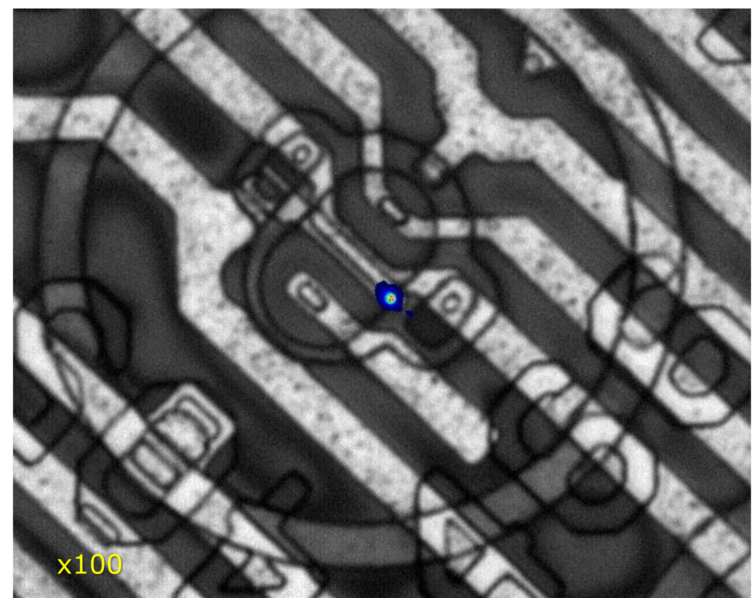
  - statistics (w/o wafer 24)
    - 13 defect pixels on 11 devices
    - pixel yield

    $Y = 1 - 13/(11 \times 512^2) =$
    $= 0.999995$



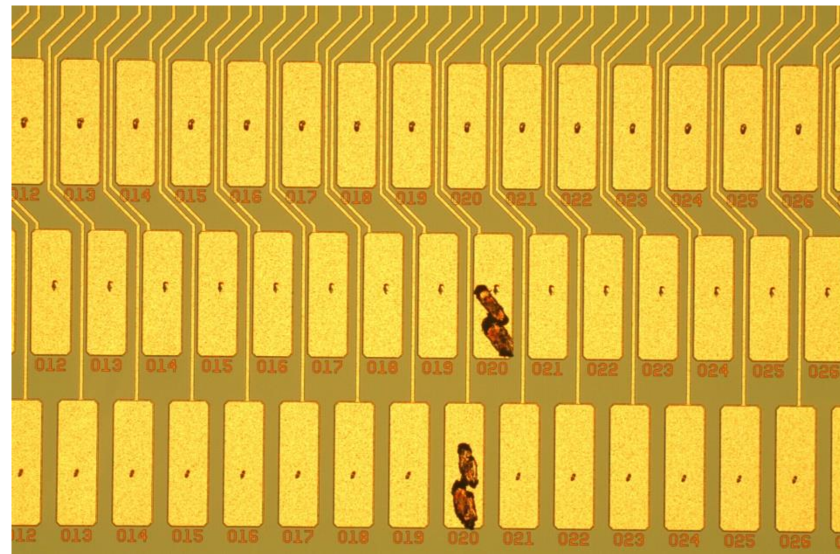




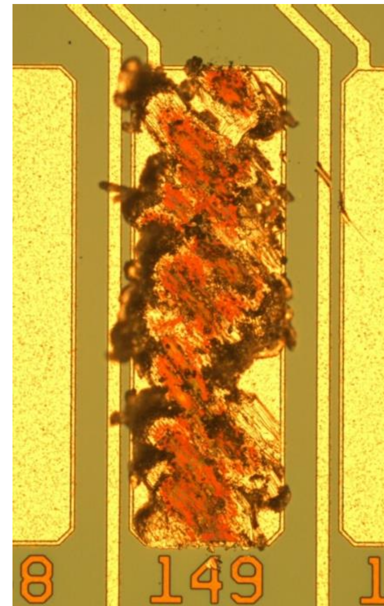


DEFECT SEARCH & HANDLING

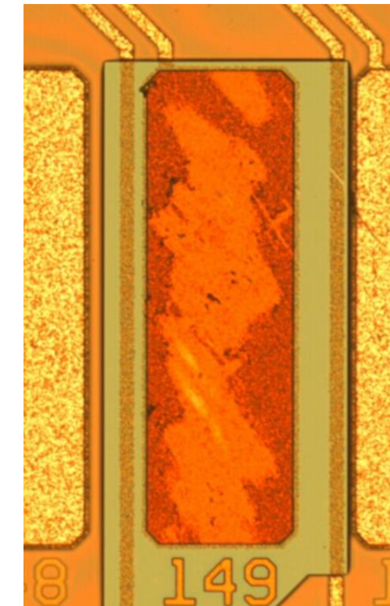
- PHEMOS backdraw
  - mechanically instable system
  - shock/vibration caused by switching camera lense and by door opening/closing
  - frequent loss of contact
  - severe scratching of Al test pads
- forced repair procedure
  - point lithography
  - etching of affected pads (& lines)
  - replace by 2nd metal layer
- remedy?
  - mechanical decoupling
  - manual → automatic probes, liftoff during camera switching



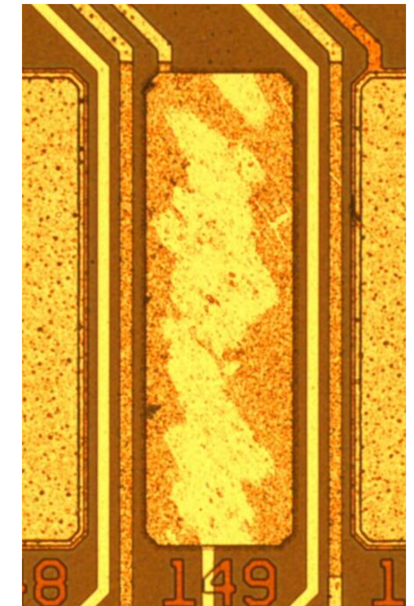
PHEMOS needle traces
vs.
probe station footprints



destroyed test pad,
shorted & interrupted lines



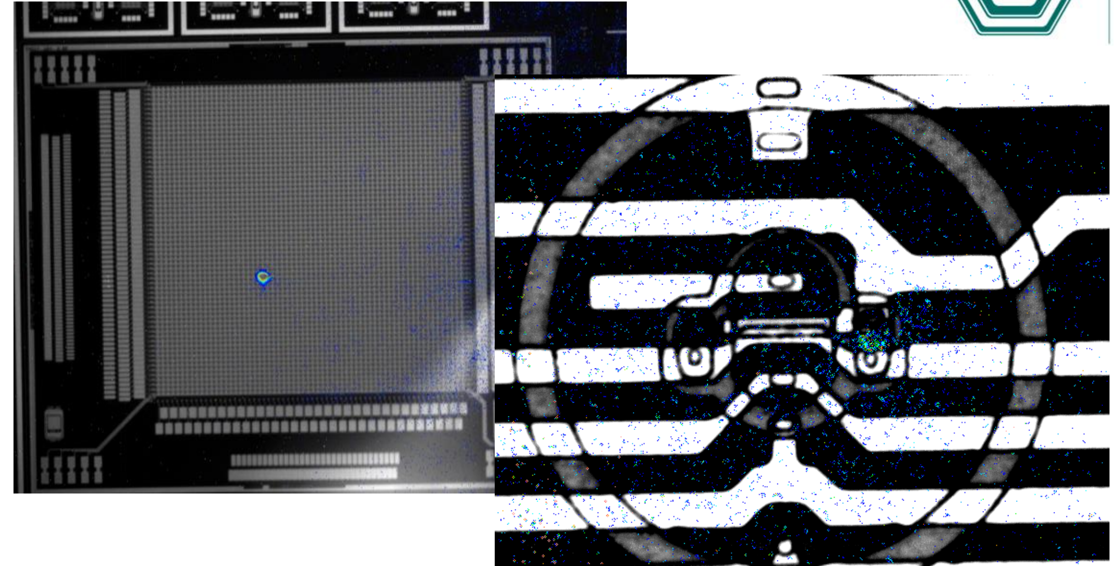
point lithography,
etched Al structures

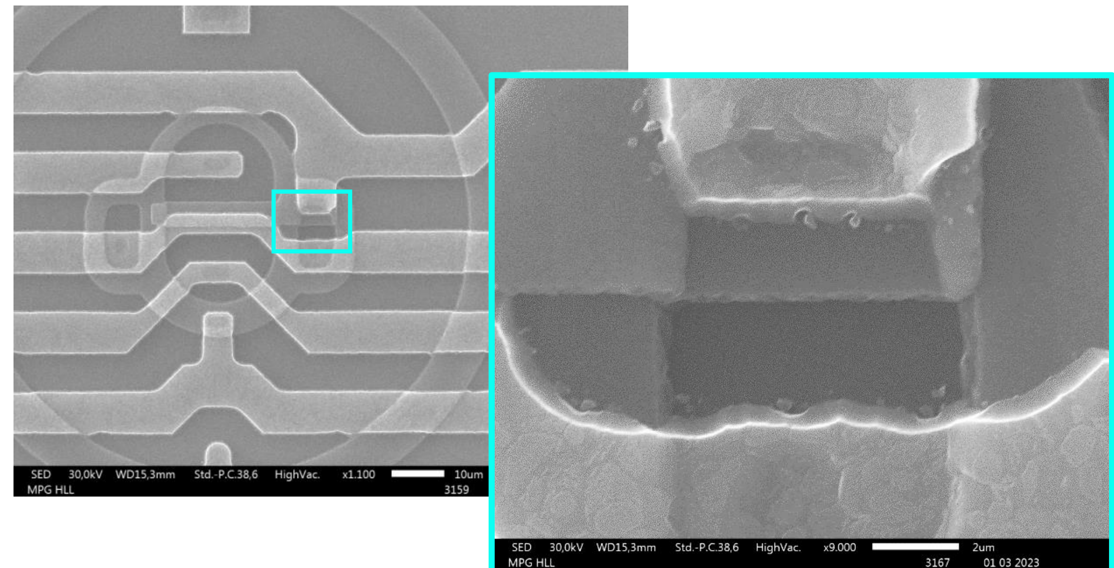


replaced Al pad,
bridged Al lines

DEFECT SEARCH & HANDLING

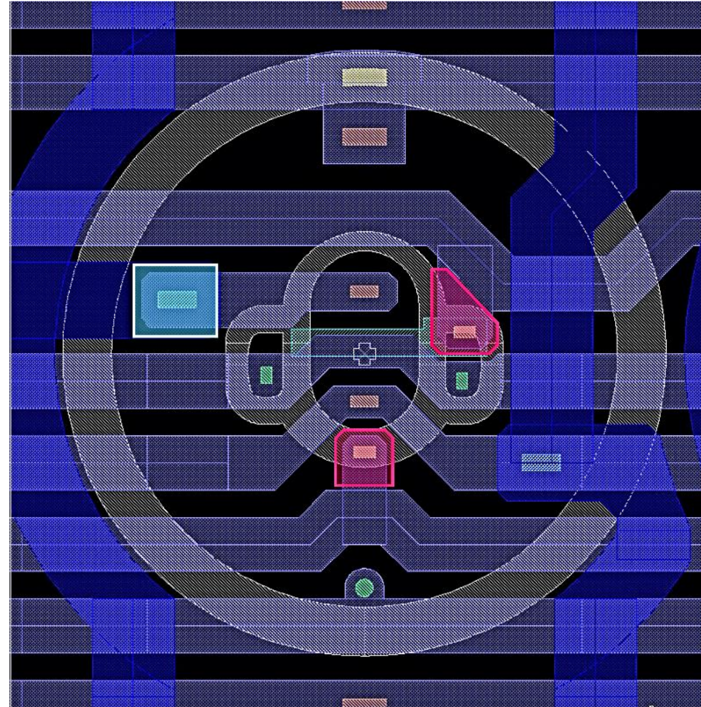
- defect root cause?
  - use of prototype format 64 x 64 as monitor
  - total 216 chips ≈ 0.9 Mpixels ≈ 3½ LDs
  - global test on probe station
    - → 4 defect devices found
  - row-wise test on probe station
    - → identification of defect row
  - PHEMOS emission microscope
    - → identification of defect pixel
    - → identification of defect spot within pixel
  - scanning electron microscope
    - → origin of shorts unresolved
    - → no repair option
  - no further non-destructive diagnostics



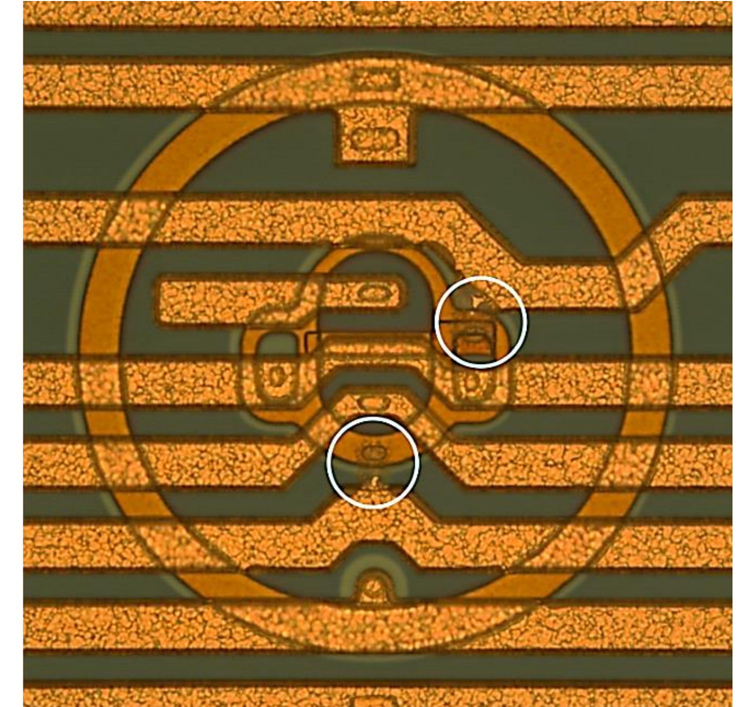


DEFECT SEARCH & HANDLING

- pixel 'blinding'
  - ▷ disconnection of supply lines
    - – lithography @ defect pixel
    - – local etching of metal1
    - – remaining pixels in row stay connected
  - ▷ omission of drain connection
    - – local layout modification in metal2
    - – no extra step, part of standard flow



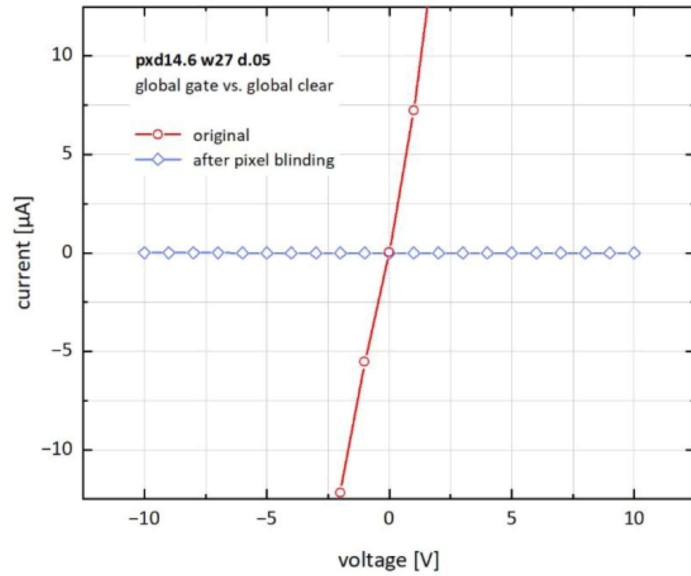
ATHENA WFI pixel 'blinding' layout
- mask for disconnection of gate & cleargate
- omission of drain connection



'blinded' ATHENA WFI pixel
- disconnected gate & cleargate

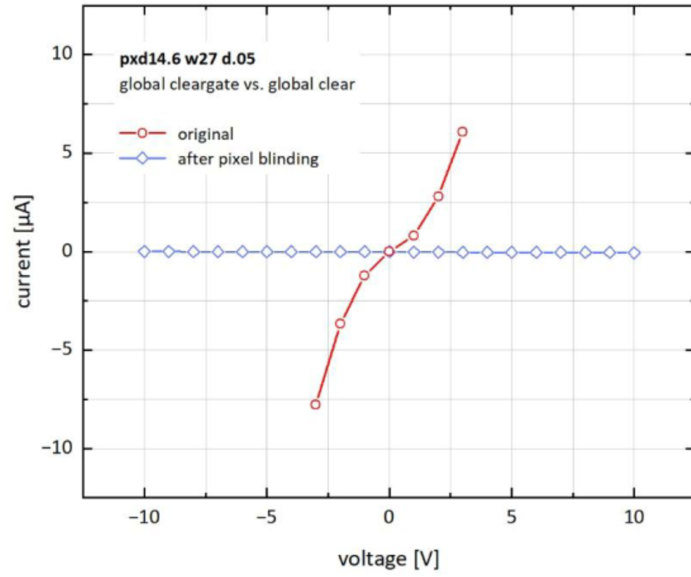
DEFECT SEARCH & HANDLING

- verification of pixel 'blinding'
  - fully processed device
  - repetition of global short test
  - no short(s) visible on 512 x 512 - 1 pixels



global short test before/after pixel 'blinding'

gate vs. clear



global short test before/after pixel 'blinding'

cleargate vs. clear

SUMMARY

- Active Pixel Sensor for the ATHENA Wide Field Imager
  - high yield requirement
  - identification of defect pixel(s) by electrical & photonic inline analysis
  - selective pixel 'blinding' (~ 1 of 512 x 512)
  - flawless operation of the rest of the pixel matrix
  - status: waiting for operation of 1st repaired sample by MPE