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Radiation Effects Studies with Ion Photon Emission Microscopy

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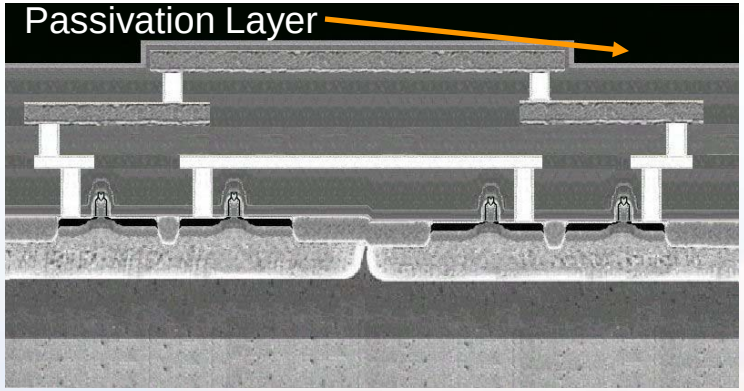
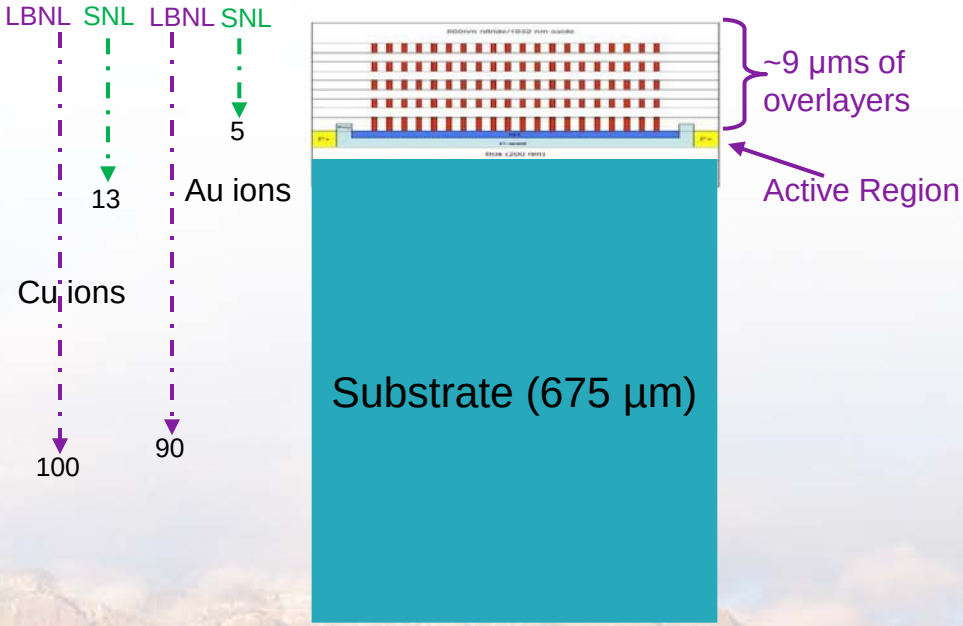
Background and Motivation

Radiation Effects Microscopy (REM) – used in IC design, pinpoints radiation intolerance to single event effects (such as single event upsets)

- Metal, dielectric and passivation layers (as well as flip-chip) → hundreds of microns of material → only high energy ion beams can penetrate
- Current GeV ions from cyclotron: a potential solution, but hard to focus due to high magnetic rigidity and get poor energy resolution



SEM image of CMOS transistor from Analytical Solutions, Inc.

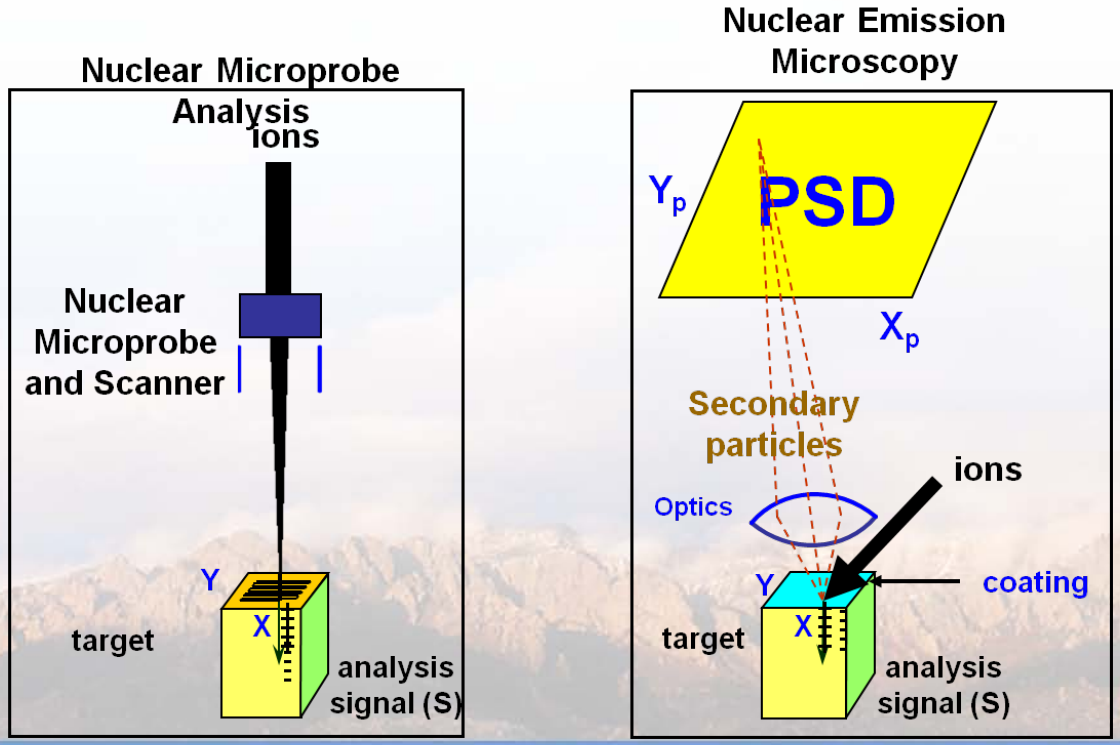


Our approach (IPEM): use photons emitted from the location of the ion impact to determine the position of the ion, and thus rely on these photons and the ion's effect on IC to image radiation sensitivity.

Approach - Proof-of-Principle

This tabletop version of the IPEM was used to study various luminescent materials

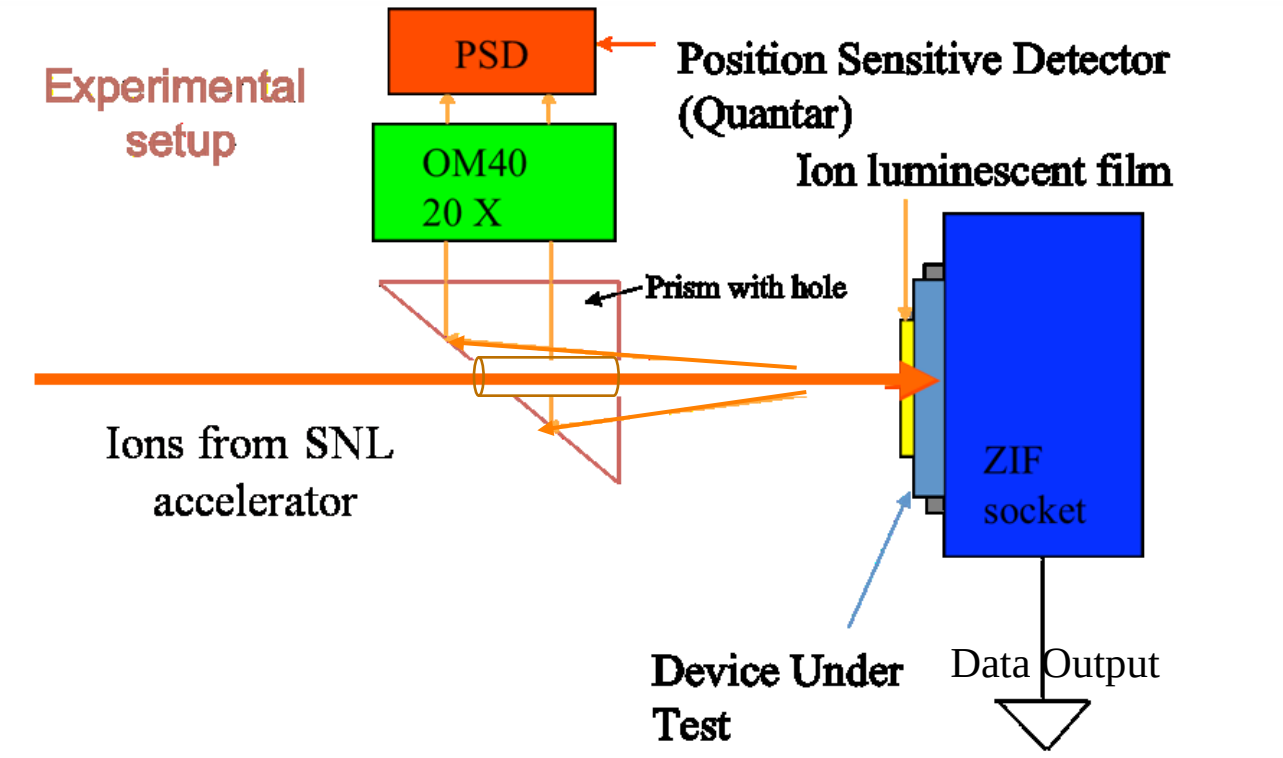
- Ions have two major interactions
  1) Ions hit luminescent film and get ion beam-induced luminescence (IBIL)
  2) Ions hit chip and create ion beam induced charge (IBIC) and possibly upsets
- Photons produced by film detected with single photon position-sensitive detector (PSD)
- However, cannot cause single-event effects with α-IPEM



Approach – Accelerator IPEM

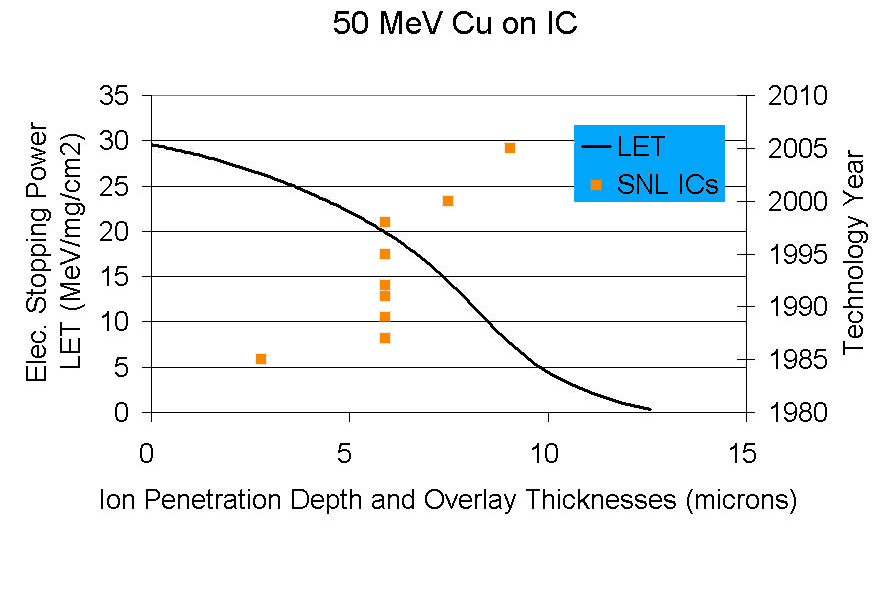
Developed IPEM system on nuclear microprobe line on SNL's tandem accelerator

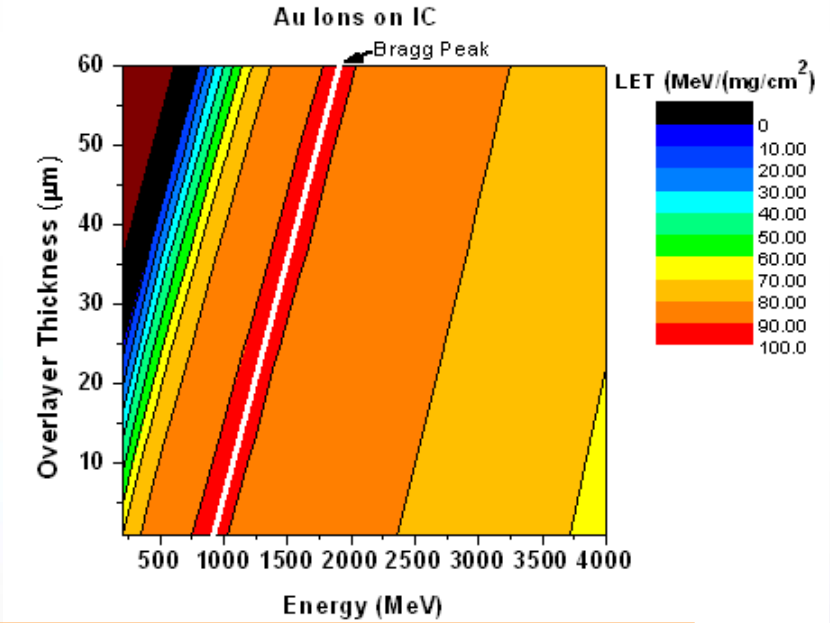
- Availability of various ion species/energies (2 MeV protons to 50 MeV Cu ions)
- Allows us to compare results obtained with traditional nuclear microscopy and IPEM technique



Approach – SNL Limitations

Advancing IC technology is hindering our ability to microscopically study radiation effects, even with ions from the tandem



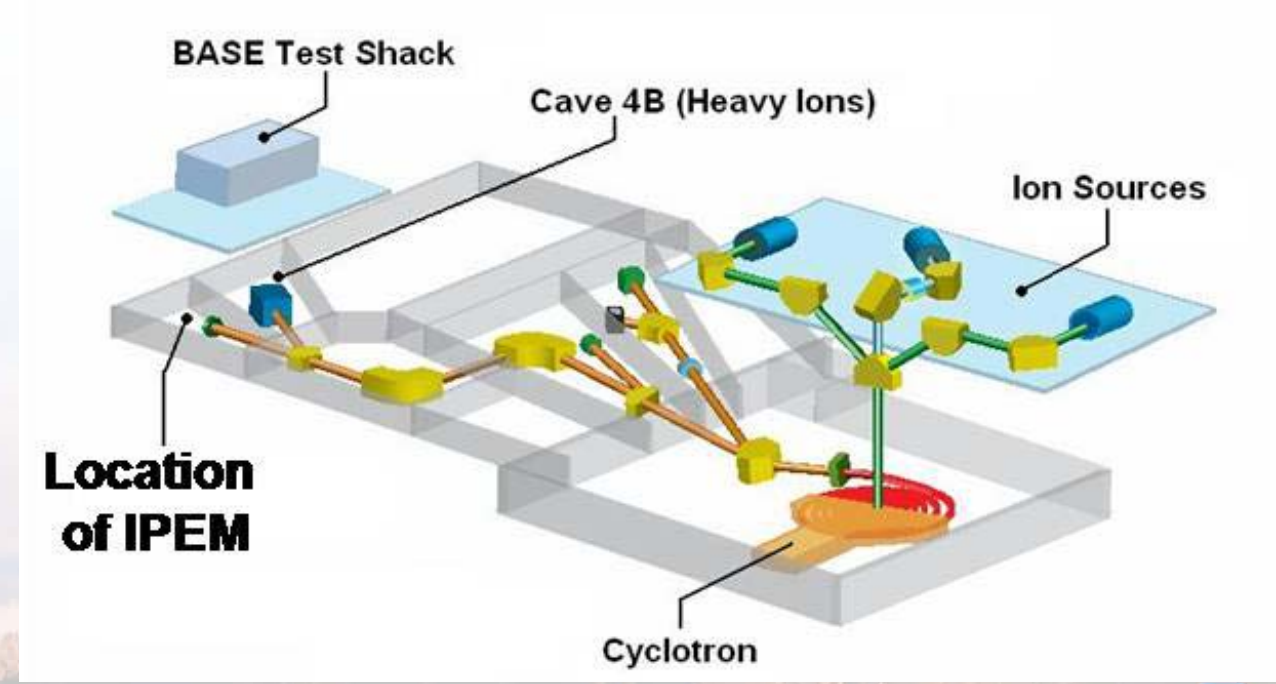


- New technologies continually increase the overlayer thickness on ICs, limiting our ability to probe the active region and study the devices using the tandem.
- Bragg peak for Au ions occurs at 0.9 GeV with an LET of ~90 MeV/(mg/cm^2); With 20 µm of overlayers, 1.2 GeV is required to position the Bragg peak into the sensitive depth.
- If start with lower incident energies, LET will decrease as material is penetrated, and before reaching the silicon active region.

Approach - Newest IPEM Location

In progress: developing an IPEM system on 88" Cyclotron at Lawrence Berkeley National Labs

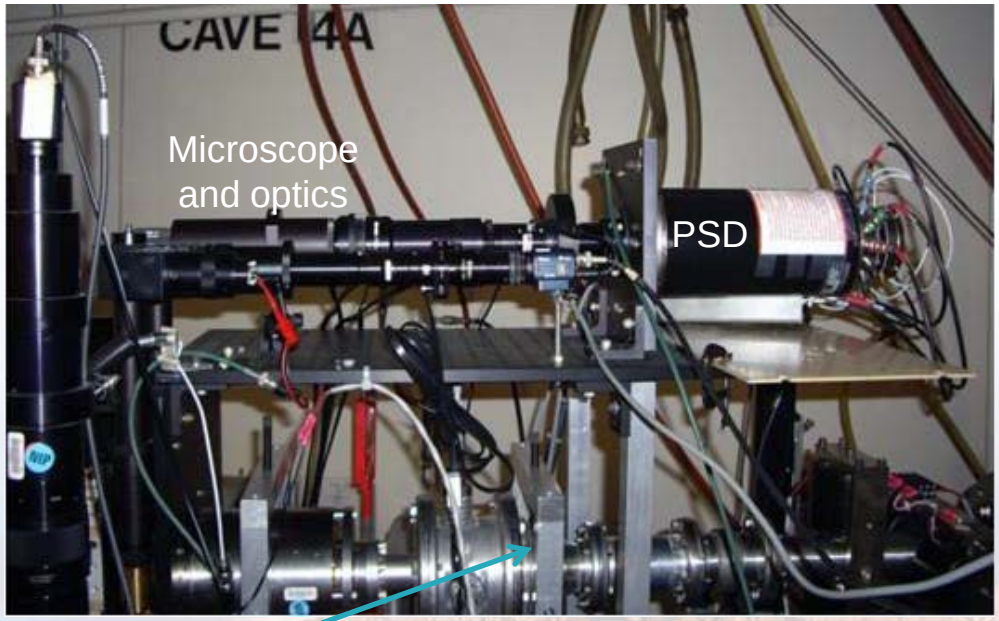
- Availability of various ion cocktails (4.5 MeV/amu to 16 MeV/amu heavy ions)
- Allows us to get ions with sufficient mass/energy to probe modern devices, while still operating externally
- Footprint of IPEM: ~5' X 2' optics and ~2' X 3' electronics
- System ideally will be portable



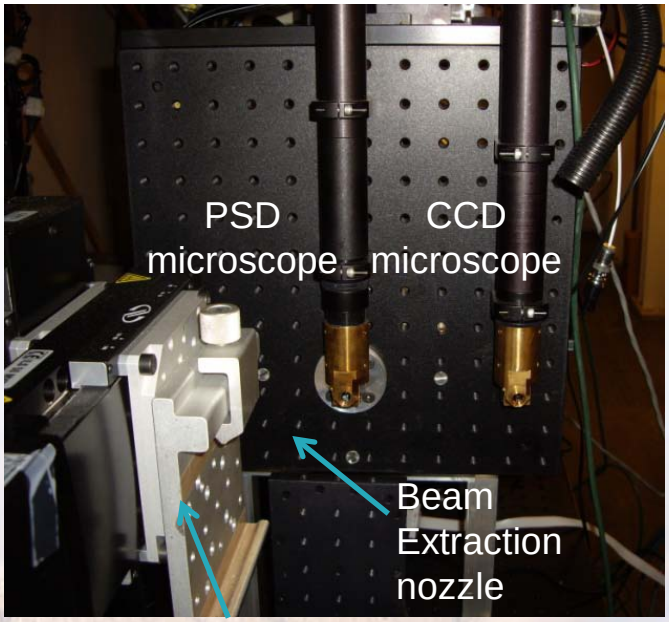
Approach - Design of Cyclotron IPEM

IPEM on LBNL's 88" Cyclotron

- Tandem IPEM was significantly modified for initial attempt at cyclotron capability.
  - Separate optics lines for CCD and PSD imaging
  - Aperture for self-standing GaN
  - Exit foil for in-air operation
  - Remote control of all operations



Cyclotron beamline



3D stage for device board

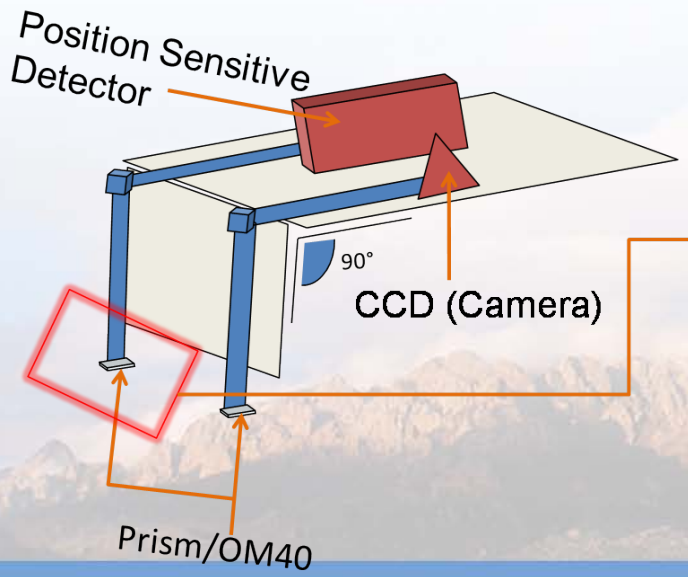
Research - Techniques

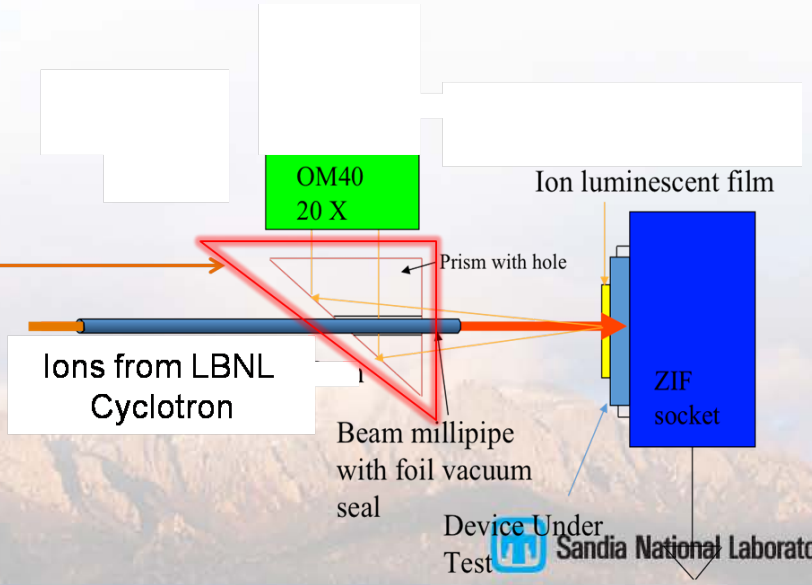
SNL's Tandem Accelerator

- Excitation source:
  - 7.5 MeV α particles
  - 30 MeV C^{5+} ions
  - 35 MeV Cl^{5+} ions
- Focused scanning microbeam
- 5 µm GaN film
- One OM-40 microscope
- Single photon position-sensitive detector
- Two images result

LBNL's 88" Cyclotron

- Excitation source: 10 MeV/amu ion cocktail
  - B^{+}, O^{5+}, Ne^{6+}, Al^{7+}, Ar^{11+}, Cu^{18+}, Co^{16+}, and Xe^{38+3}
- Broad (~ 1mm) beam
- 5 µm Al exit foil for in-air
- Two microscopes (CCD and PSD)
- Single photon position-sensitive detector
- One IPEM image results





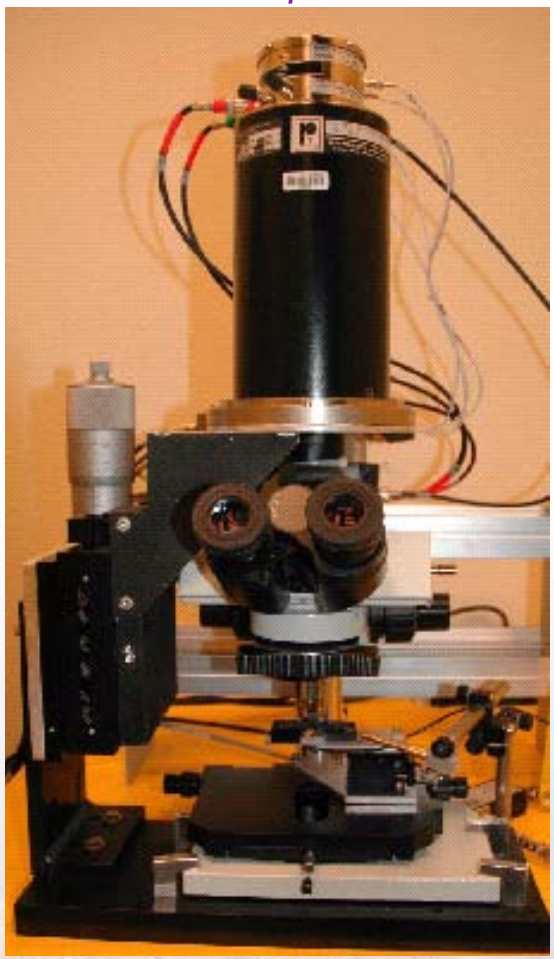
Background – Phosphor Requirements

A variety of parameters need to be met for phosphor to work in IPEM application

To achieve the desired resolution, we need a phosphor that:

1. Provides high enough intensity (> 1 detected photon/ion)
2. Thin enough to minimize blooming and scattering
3. Radiation damage tolerant to last long
4. Easy to handle
5. Provides homogeneous luminescent properties

Tabletop IPEM



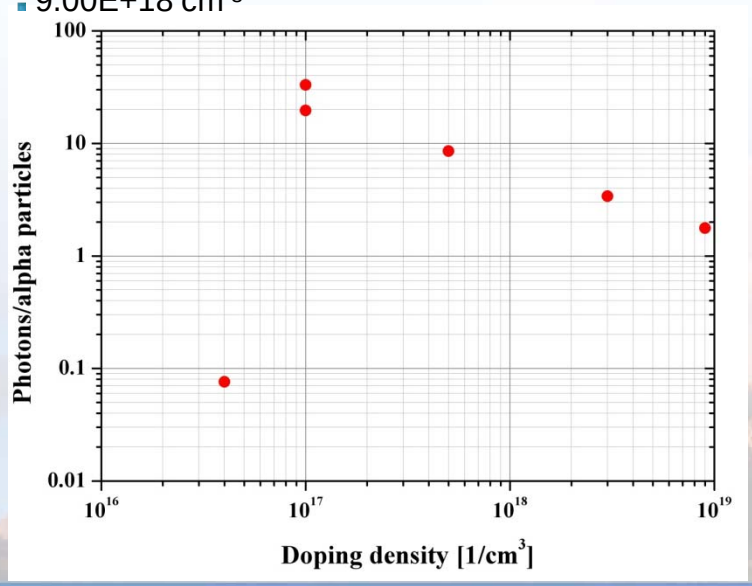
Materials

Various materials are still being studied to find optimum

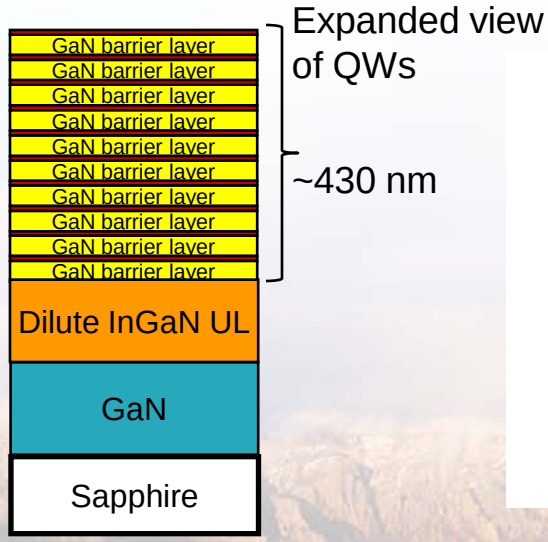
- 3 types of materials are currently the focus of our phosphor research:
  - n-type GaN (lightly doped with Si)
  - InGaN/GaN quantum wells
  - Nanophosphors (YAG:Ce, $Sr_2P_2O_7:Eu^{2+}$, etc.)

n-GaN Materials Studied

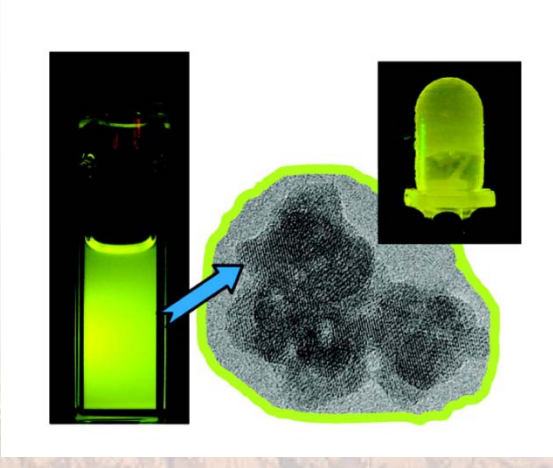
- 4.00E+16 cm^{-3}
- 1.00E+17 cm^{-3} **
- 5.00E+17 cm^{-3}
- 3.00E+18 cm^{-3}
- 9.00E+18 cm^{-3}



Example Quantum Well Structure

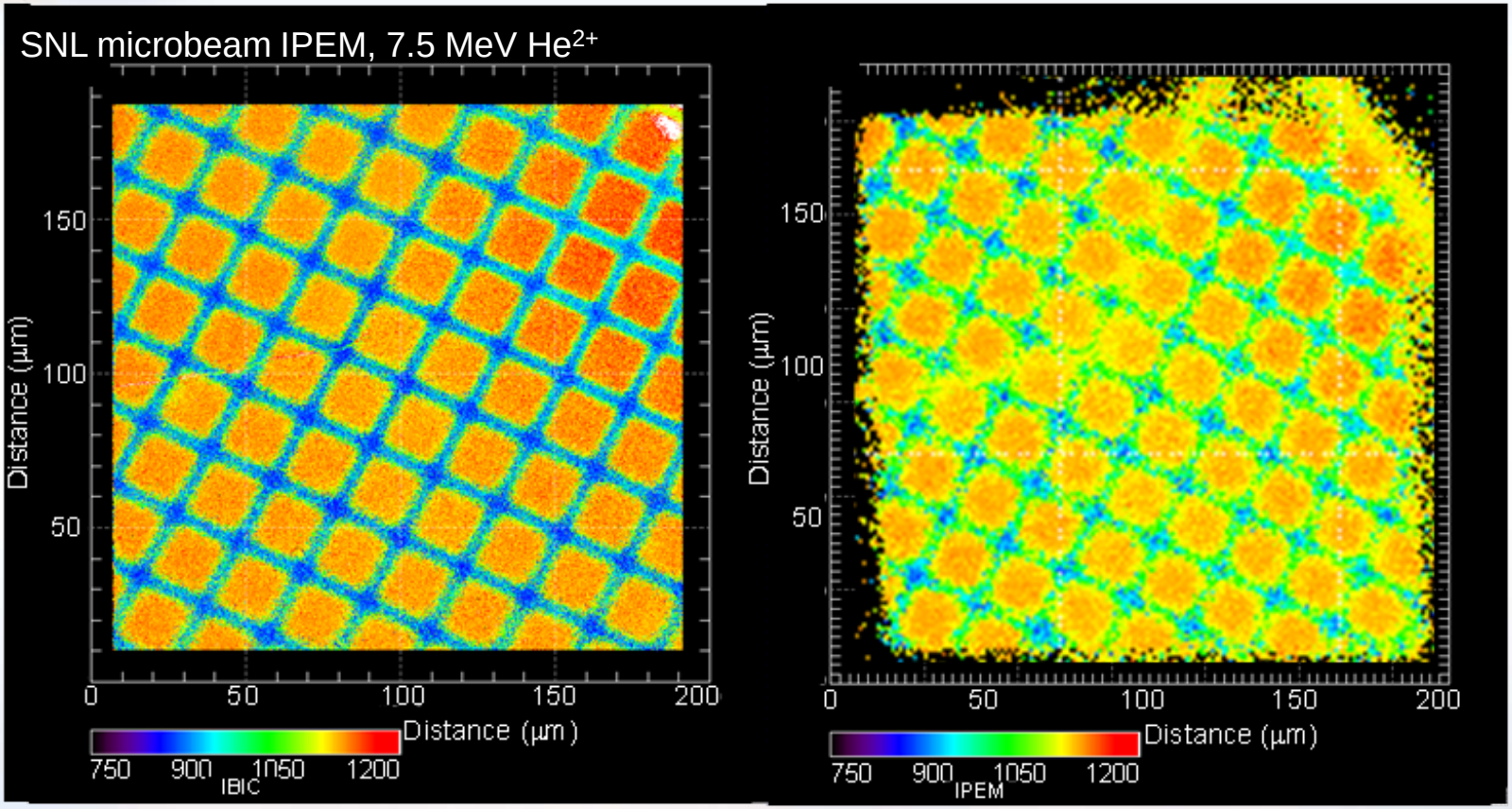


Nanophosphors



Research – SNL Results

Focused beam IBIC and IPEM IBIC from SNL



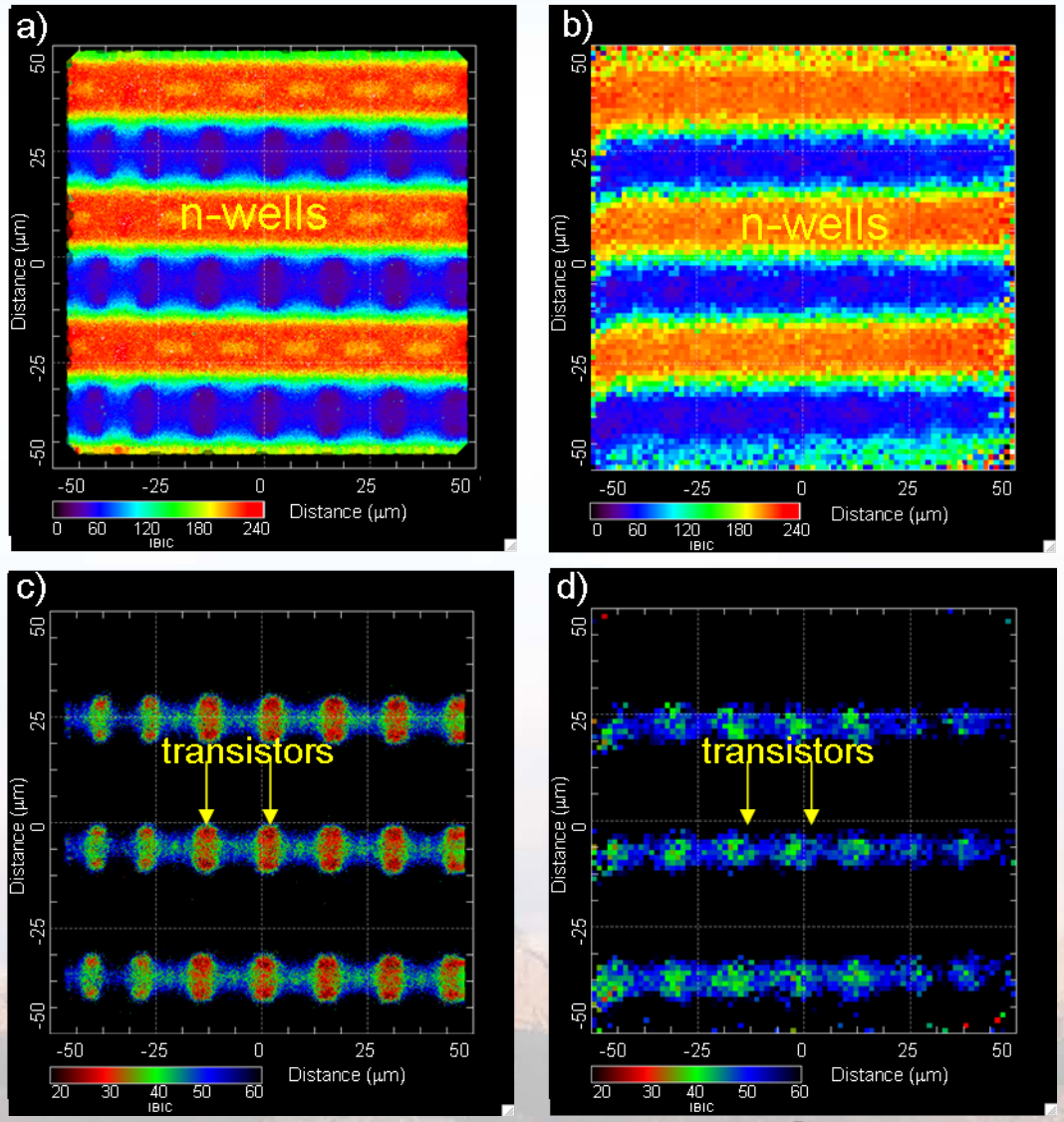
- New IPEM system installed on SNL's tandem accelerator
- IBIC on diode + TEM grid + GaN film

- IPEM IBIC image
- Signal from diode put in coincidence with photons arriving at detector
- See damage, cracks in GaN

Research – SNL Results

Focused beam IBIC and IPEM IBIC from SNL

- IBIC images of TA788 from scanning microbeam of 30 MeV C^{5+} ions
- n-wells easily distinguishable – high charge collection in junctions between n-well and p-substrate
- Intensity range modified in bottom image to resolve details in p-substrate
- IBIC on device + GaN film

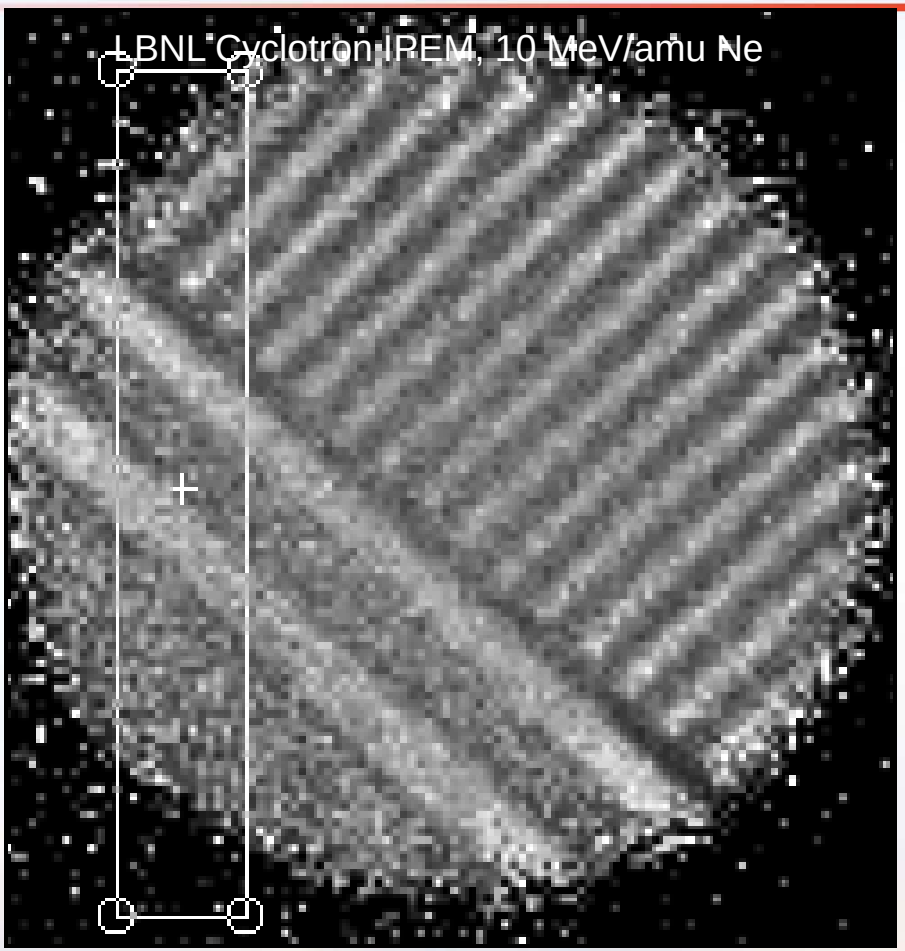


- IPEM/IBIC image of TA788 with 5 µm GaN as luminescent film
- Can still distinguish details, but resolution not comparable to focused scanned-beam IBIC
- Intensity range modified in bottom image to resolve details in p-substrate
- IPEM/IBIC on device + GaN film

SNL microbeam IPEM, 30 MeV C^{5+}

Research – Cyclotron Results

Broad beam IPEM image from LBNL cyclotron



- First IPEM image obtained from LBNL cyclotron
- Device is a Sandia TA788 64k SRAM
- Bright bands at ~10-12 µm
- Current resolution of this system is ~5 µm
- Cyclotron IPEM is not yet optimized

Obstacles/Work in Progress

Many obstacles/difficulties have arisen with development and installation of IPEM:

- Timing: luminescent lifetime and incident ion rate → accidental coincidences
- Radiation damage and luminescent properties of materials
- Alignment of separate portion of beamline – 6-inch beam entering a 1 mm nozzle
- Need to redesign optics/microscope system

Future Work

- Need to optimize various components
  - Find the best phosphor material/composition/thickness/structure
  - Re-design the optics for ease-of-use and reliability
  - Potentially install IPEM in separate cave at LBNL to avoid continual alignment issues
- Need to understand effect of heavier/more energetic ions on materials and how it will affect system performance
- SEU testing of SNL devices with IPEM to prove its potential in radiation-effects testing

Conclusions & Acknowledgements

Conclusions

- Future of heavy ion radiation effects microscopy depends on developing scanned microbeams and/or emission microscopes that can be easily used on cyclotrons
- IPEM provides a reasonable solution, and its continuing progress is promising
- The cyclotron IPEM has been installed and operational, but further research is required to make it efficient and user-friendly
- IPEM will allow us to continue using REM as feature sizes shrink, and thicknesses of IC overlayers increase

Acknowledgements

- Dan Buller – for building and making the systems work; not an easy task
- Jim Knapp – for the tedious work involved with removing the GaN films
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