Development of Large-Size Germanium Detectors for Dark Matter Experiments

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CAGDT Collaboration

- **International Collaborators**
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    - Qian Yue, Associate Professor, Jianmin Li, Professor, Yulan Li, Professor
  - Canberra France (Industry Partner), France
    - Marie-Odile Lampert, Director, General manager for GM specialty detector site Canberra France, Benoit PIRARD, Director, Head of R&D Specialty detector site Canberra France
  - Max Planck Institute for Physics (MPI), München, Germany
    - Iris Abt, Senior scientist and a team leader on germanium detector development, Béla Majorovits, Senior scientist and a project leader on GERDA experiment
  - Institute of Physics, Academic Sinica, (IPAS), Taiwan
    - Henry Tsz King Wong, Senior scientist and Spokesman of TEXONO
  - National Institute of Nuclear Physics & University of Padova (INFN-LNL), Italy
    - Maggioni Gianluigi, Scientist and a team leader on INFN-LNL's materials lab, Daniel R. Napoli, INFN's senior scientist, Spokesman of the INFN's Gamma Collaboration.
- **Domestic Collaboration**
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    - Mary Kidd, Assistant Professor
  - Physics, Black Hills State University (BHSU), Spearfish, South Dakota, USA
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  - Physics, Dakota State University (DSU), Madison, South Dakota, USA
    - Barbara Szczerbinska, Associate Professor
  - Physics, The University of South Dakota (USD), Vermillion, South Dakota, USA
    - Jing Liu, Assistant Professor, Ryan Martin, Assistant Professor, Ryan MacLellan, Assistant Professor, Joel Sander, Assistant Professor, Christina Keller, Professor, Chao Zhang, Assistant Research Professor, Guojian Wang, Assistant Research Professor, Gang Yang, Research Scientist

Exploring Un-Available Techniques

- Relevant to Dark Matter
  - Explore n/γ discrimination at 77 K
  - Develop planar detector with internal amplification to achieve down to 12 eV

Challenges to all Experiments

- Reduce background Events – all about reducing background events
  - External backgrounds – outside the detector volume
    - Cosmic rays
    - Natural radioactivity from environment
  - Internal backgrounds – inside the detector volume
    - Radon and its progenies
    - Small parts and cables
    - Target materials – natural radioactivity
- Scale-up mass exposure and keep discrimination ability
  - Discrimination capability fading away in low energy region

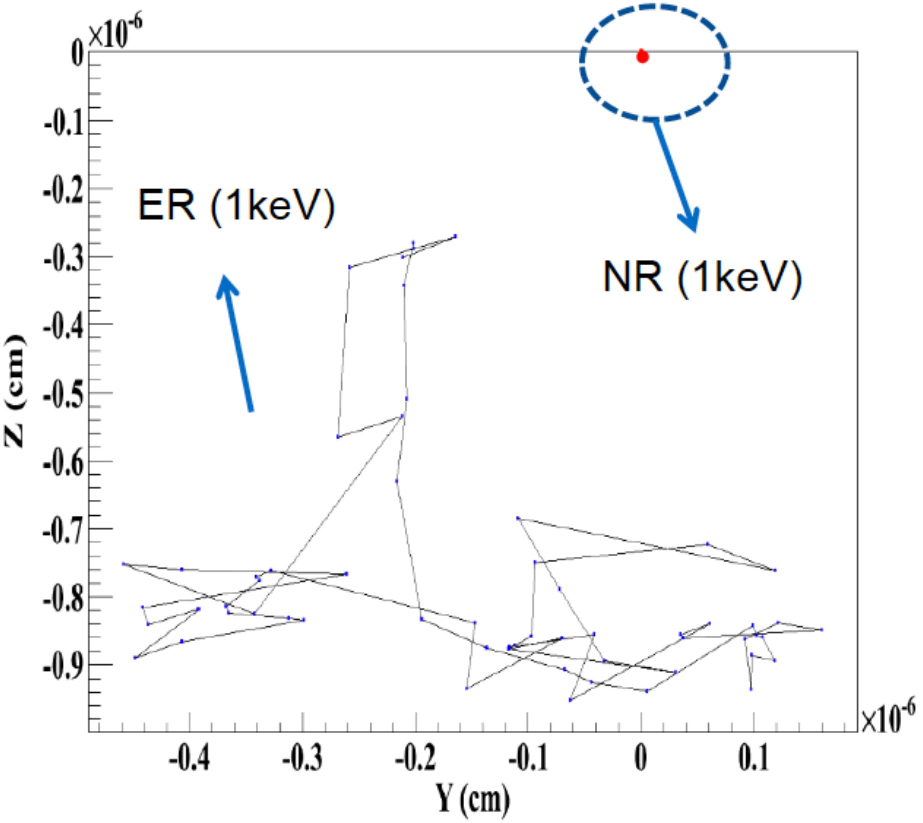
Background Reduction Methods

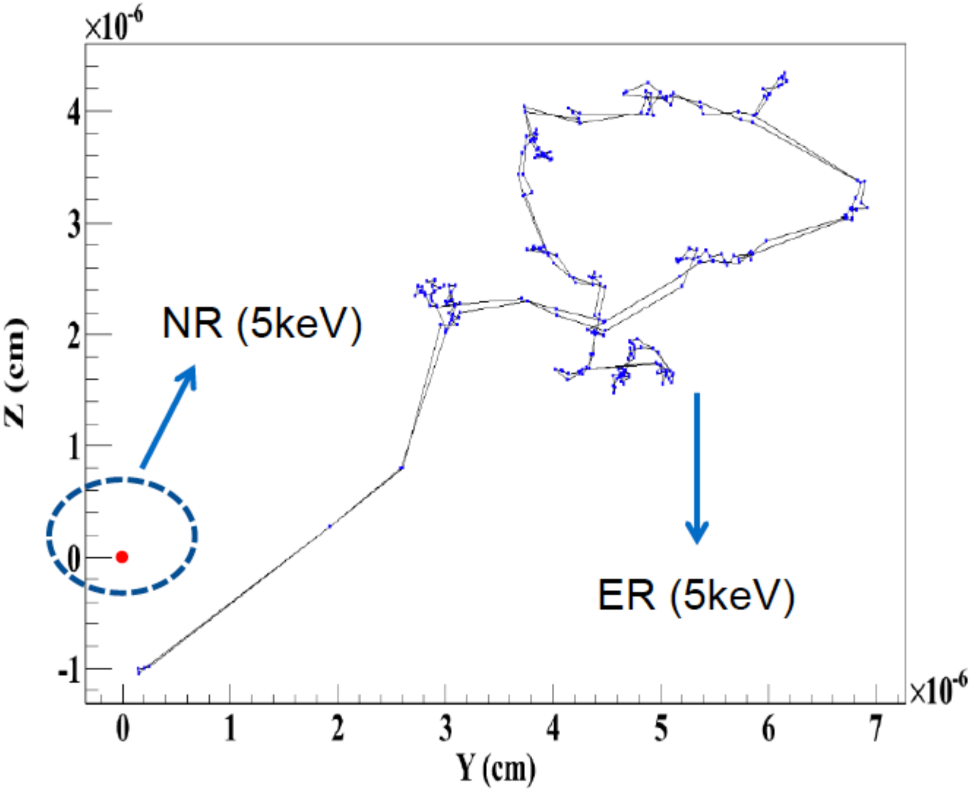
- External Background Reduction
  - Cosmic muons – deep underground lab
  - Natural radioactivity – adequate shielding
- Internal Background Reduction
  - Inner volume - radon control + cleanliness
  - Target - purification + fiducial volume
- Discrimination
  - **Nuclear recoils versus electronic recoils for WIMP searches?**
  - **Must have some handles about signal versus background for light dark matter particles coupling to electrons**

Challenges to a New Germanium Experiment

- **Must be new in technique**
  - **Can we have n/γ discrimination at 77 K?**
    - **Plasma time difference in nuclear recoils and electronic recoils**
      - **Highly innovate – making germanium detector with excellent timing resolution?**
  - **How to get there?**
    - **Requirements**
      - **Amorphous-germanium contact without transition layer**
      - **Uniformity of impurity distribution across entire crystal**
      - **Uniform E-field**
- Must have low energy threshold
  - Internal amplification
    - Amplification factor of 1000
      - Highly innovate – making a extreme low energy threshold down to 12 eV

Ionization Tracks

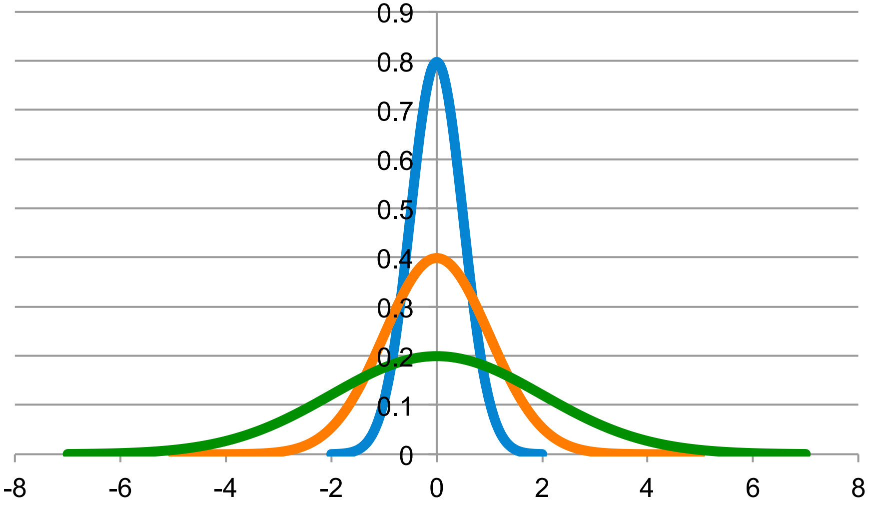




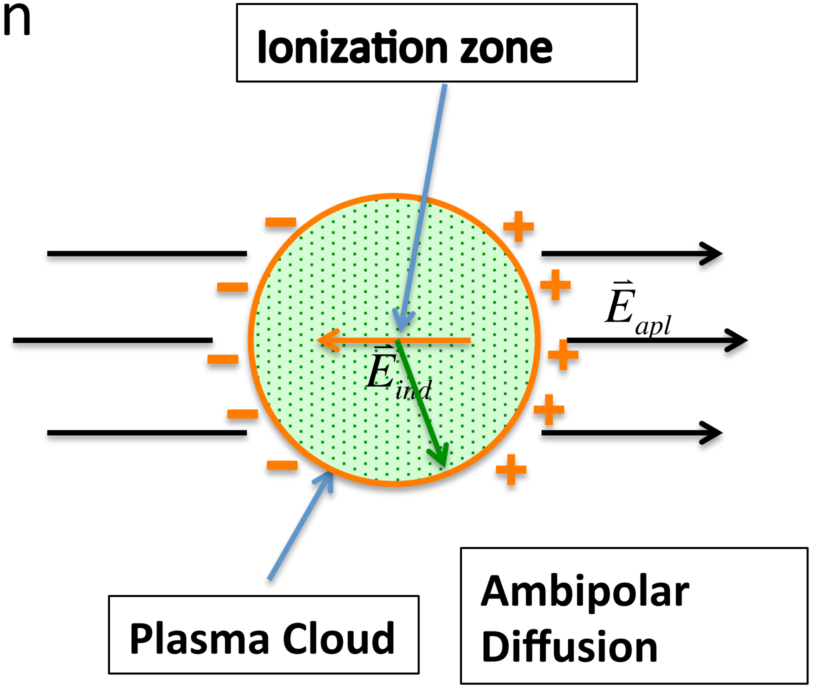
Very different tracks between nuclear recoils and electronic recoils

Principle of Plasma Time

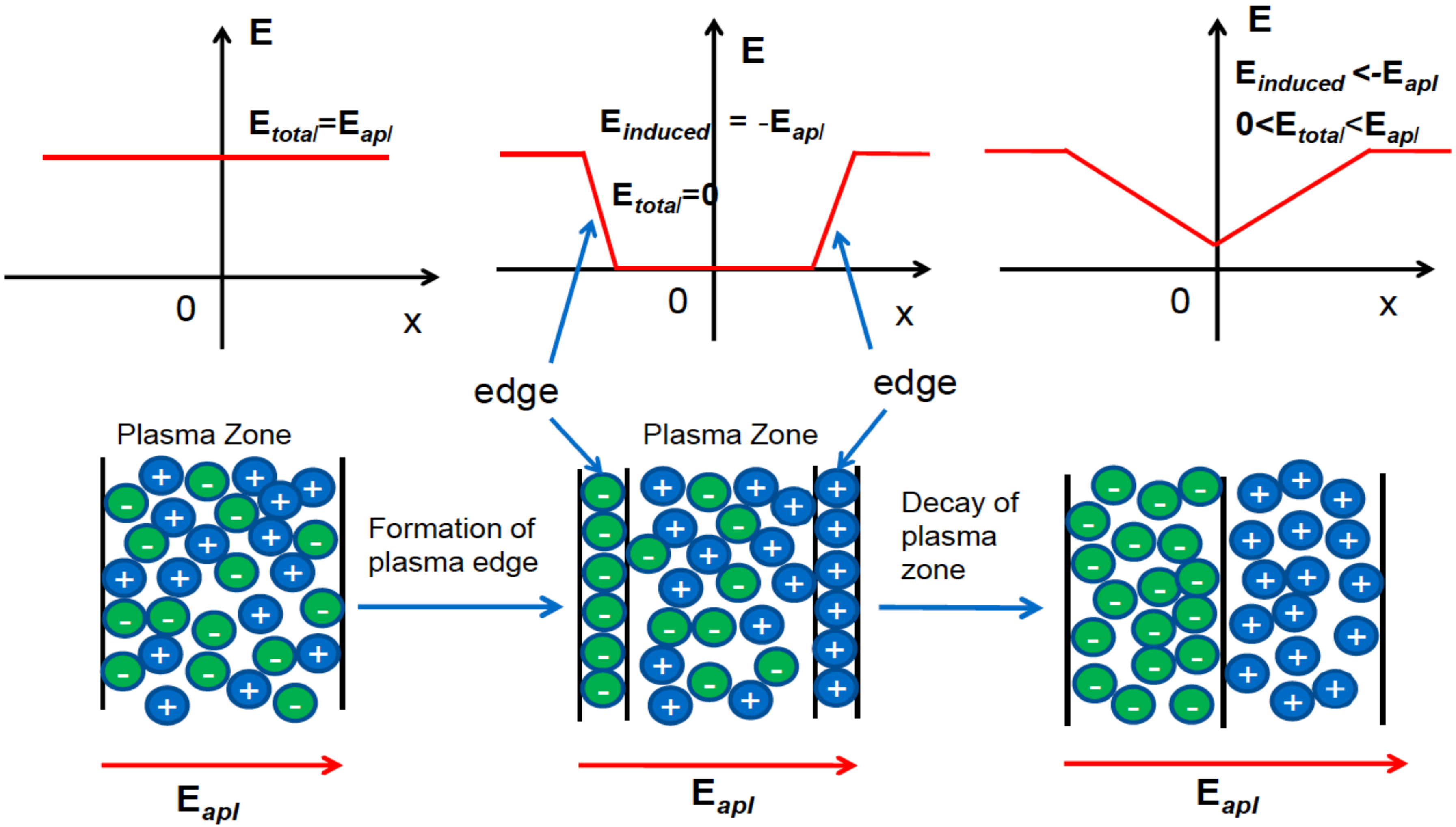
- High density of charge carriers along the ionization track forms a plasma-like cloud
- Outer charges begin to drift due to applied electric field
- Cloud expands radially as the charges diffuse
- Plasma time – time needed for the deterioration of the plasma region



Diffusion over time

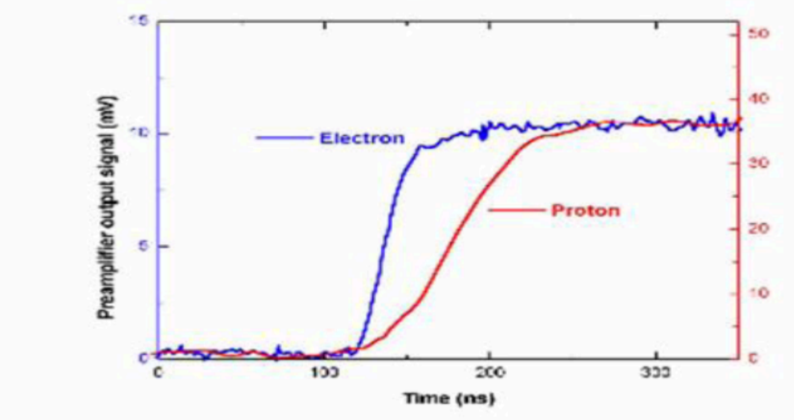


Plasma Effects

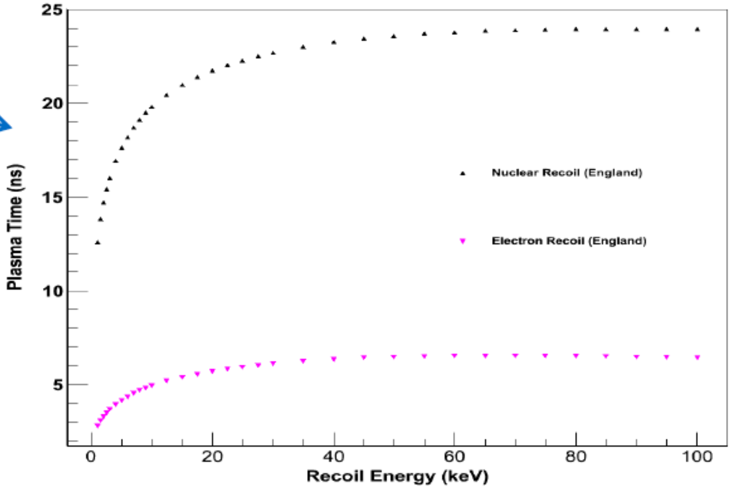


Plasma Effects in Silicon

Year	Authors	Notable Work
1960	G. Miller et al.	Observation of plasma effects
1967	P.A. Tove, W. Seibt	1D & 2D theoretical models
1969	A. Taroni, G. Zanarini	Numeric calculation (agreed with data)
1989	J.B.A England, G. M. Feild	Relate plasma effects to the ionization energy loss of the incident ion
2012	Z. Sosin	Charge distributions are assumed to be Gaussian all the time.



Rise time difference observed in a Silicon Diode detector: Alberto Fazzi et al, 0-7803-8257-9/2004 IEEE



A 3-D Numerical Calculation

$$\begin{cases} \boldsymbol{\nabla j} = -\dfrac{\partial\rho}{\partial t} \rightarrow \begin{cases} \boldsymbol{\nabla j} = -q\dfrac{\partial p}{\partial t} & (for\ holes) \\ \boldsymbol{\nabla j} = q\dfrac{\partial n}{\partial t} & (for\ electrons) \end{cases} & \text{Continuity Equation} \\ \boldsymbol{j} = \dfrac{Q}{At} = \begin{cases} qp\mu\boldsymbol{E} & (for\ holes) \\ qn\mu\boldsymbol{E} & (for\ electrons) \end{cases} & \text{Current density definition} \\ \boldsymbol{\nabla E} = \dfrac{\rho}{\varepsilon_r\varepsilon_0} = \dfrac{q(p-n)}{\varepsilon_r\varepsilon_0}\ (for\ both\ holes\ and\ electrons) & \text{Differential form of Gauss's law} \\ \dfrac{\partial p}{\partial t} = D\nabla^2 p\ (for\ holes) and\ \ \dfrac{\partial n}{\partial t} = D\nabla^2 n (for\ electrons) & \text{Diffusion Equation} \end{cases}$$

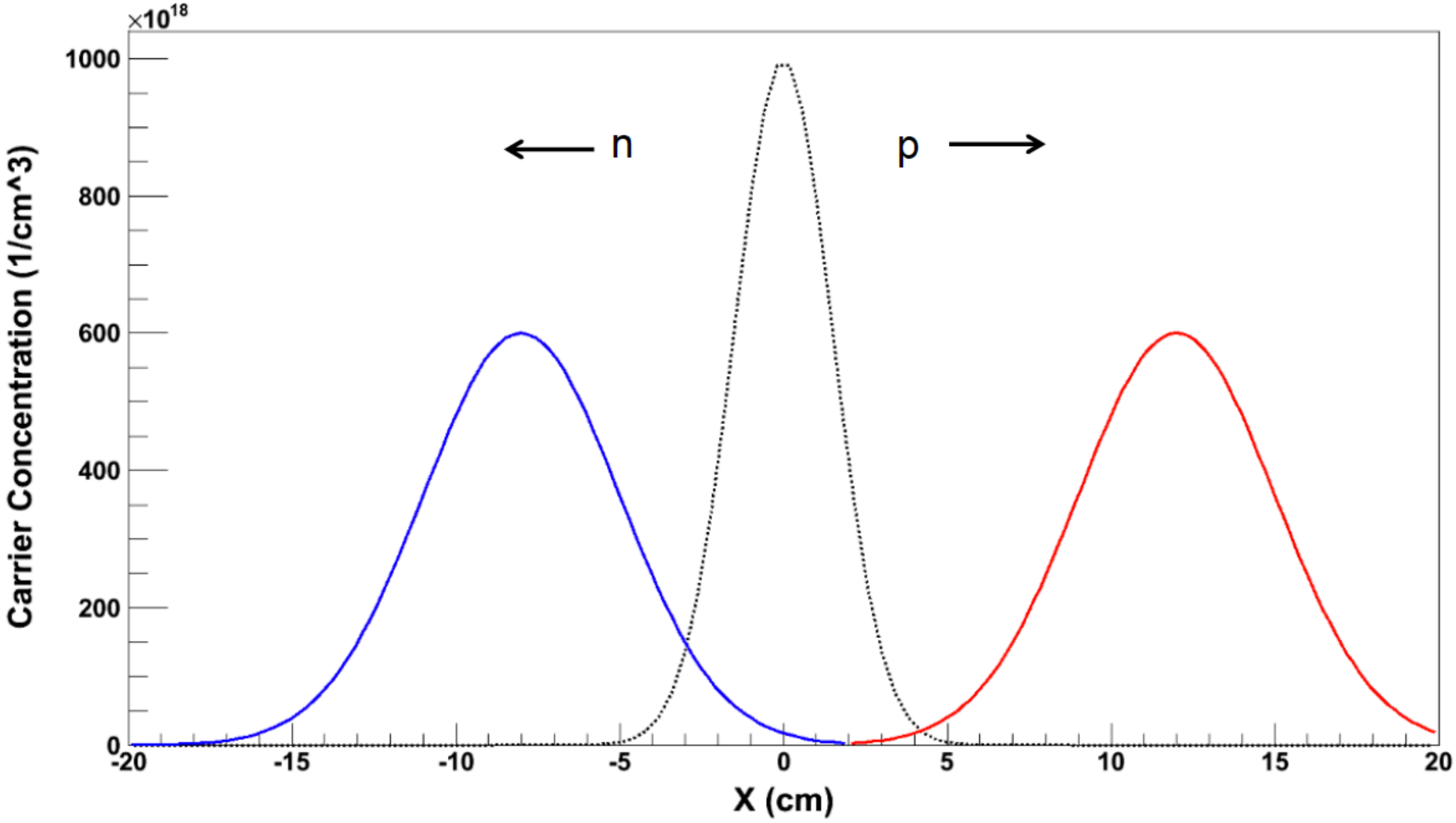
These equations will yield:

$$\begin{cases} \mu\boldsymbol{E}\nabla p + \mu p\boldsymbol{\nabla E} + D\nabla^2 p = -\dfrac{\partial p}{\partial t}, and\ p(t_i) = p(t_{i-1}) + \dfrac{\partial p}{\partial t}dt\ (for\ holes) \\ \mu\boldsymbol{E}\nabla n + \mu n\boldsymbol{\nabla E} + D\nabla^2 n = -\dfrac{\partial n}{\partial t}, and\ n(t_i) = n(t_{i-1}) + \dfrac{\partial n}{\partial t}dt\ (for\ electrons) \end{cases}$$

Critical Parameters in the Model

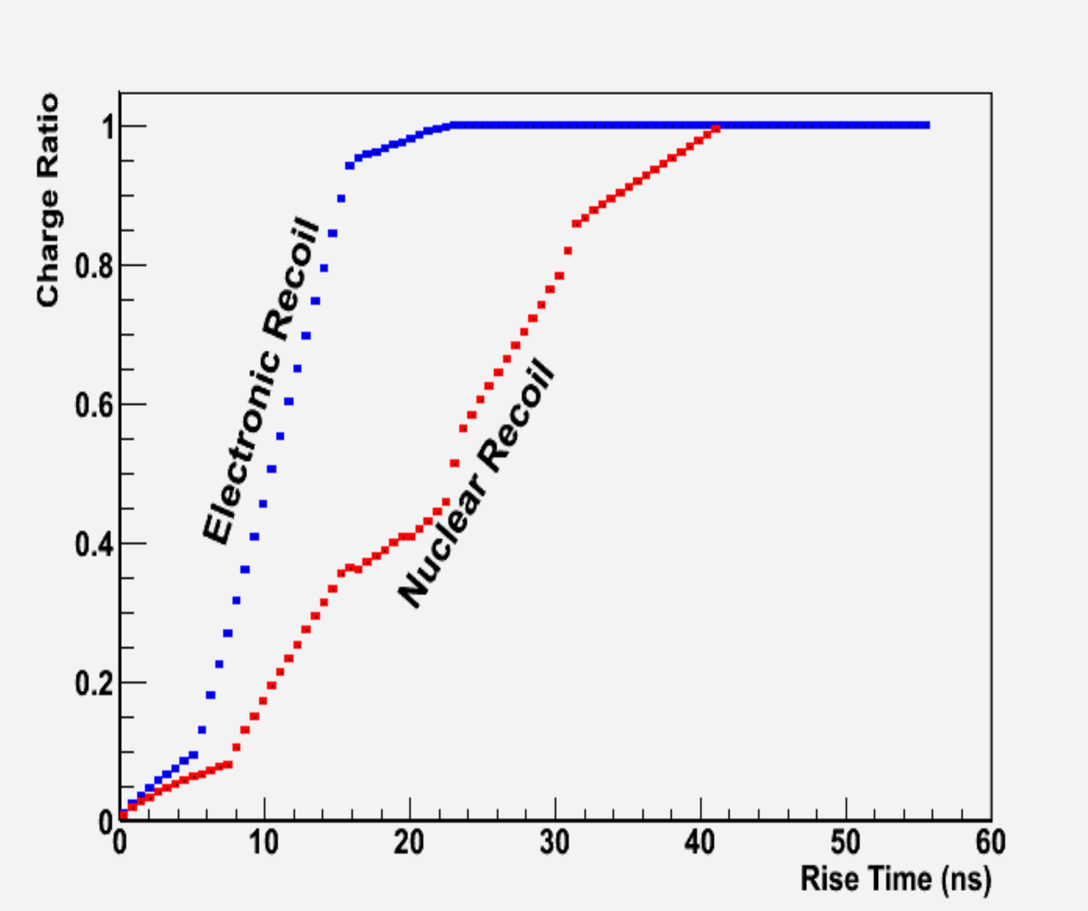
- Ionization density
  - Ionization zone
  - Charge carrier density
- Ambipolar diffusion Coefficient
  - Equation: $D = D_I \times (1 + \frac{T_e}{T_I})$
- Mobility
  - Einstein relation: $D_I = \frac{kT}{e} \mu_I$

Evolution of Carrier Concentration Distribution



Initial condition: electron and hole concentration have the same Gaussian distribution.

Expected Charge Pulses



Three noticeable effects:

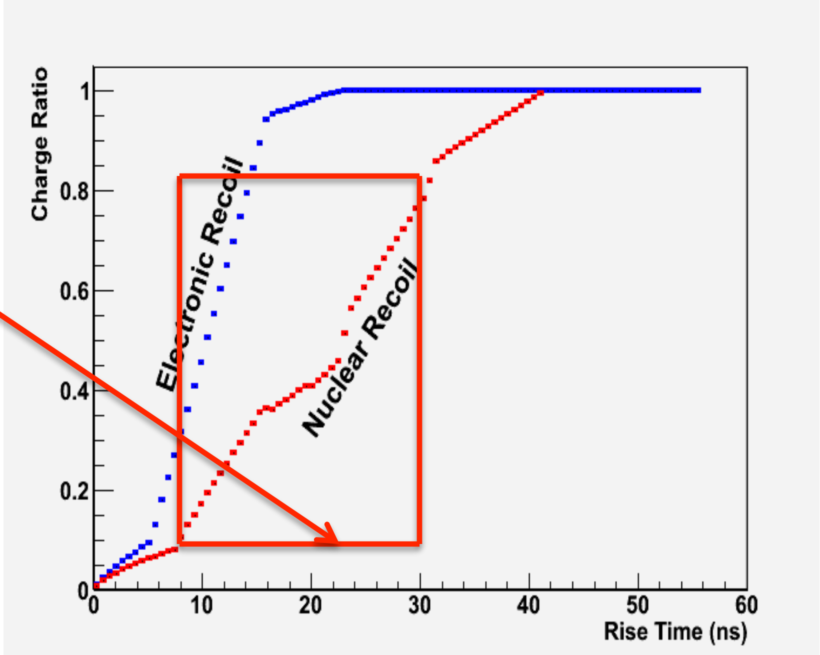
(1) The rise time of the pulse is much slower which results in a delayed charge collection time

(2) During the delay within the plasma zone, electrons and holes have time to recombine so that total collected charge is less than what is created, which leads to pulse height defect

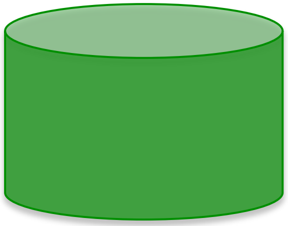
(3) Plasma time is inversely proportional to the external field and is about 5-30 ns at an external field of ~1000 V/cm.

Experimental Measurements

- Timing resolution is key
  - Region of interest



- Generic Ge: Δt~50 ns

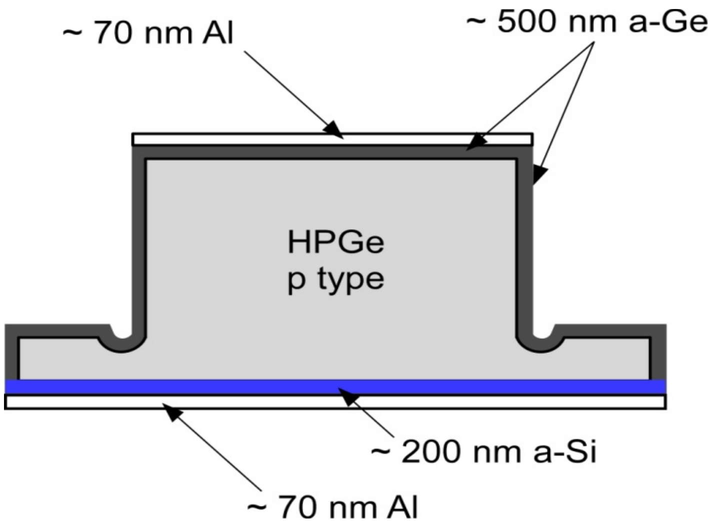


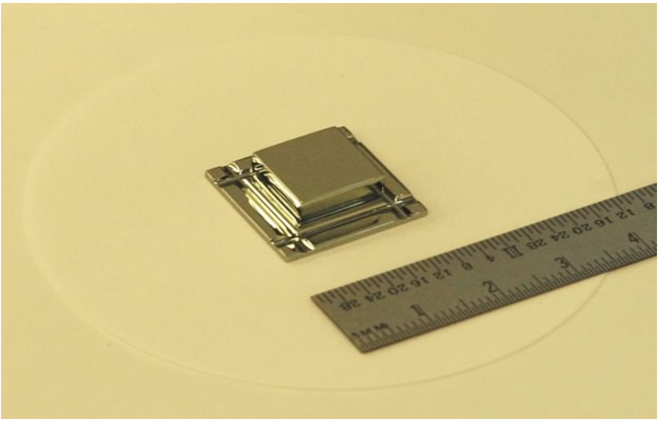
Point Contact
Coaxial

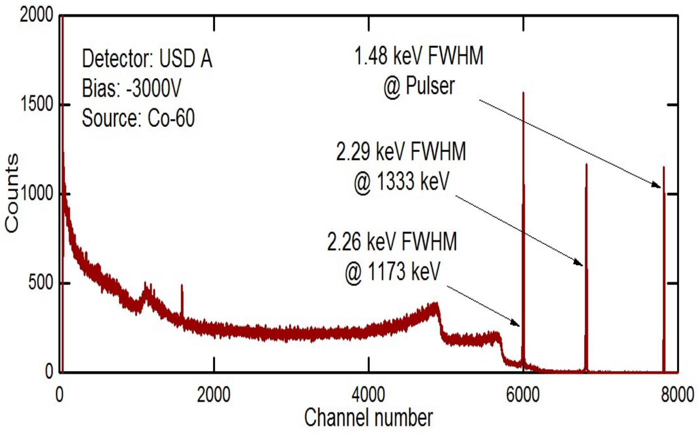
- Planer detector

  - If diameter/thickness >> 1, improve timing resolution to ~1ns
  - Can see a difference in pulse shape

Planning for a Measurement







G. Wang et al., Material Science in Semiconductor Processing V39 (2015) 54-60

1. **A planar detector with Amorphous Ge contacts was made by Mark Ammen at LBNL**
2. **A variable temperature cryostat is planned for measurement**

Detector Requirement

- Depletion length
  - Assume applied field is 1000 V and d = 2 cm

$$d = \sqrt{\frac{2\varepsilon V}{eN}}$$

N = ~1.0 x 10^{10}/cm^3

- Good time resolution
  - Uniform Electric filed
  - Uniform Impurity distribution
  - Uniform mobility (>45,000 cm^2/s) distribution
- Size of the detector
  - Large diameter ~ 15 cm
  - 1.8 kg per detector

Improving time resolution

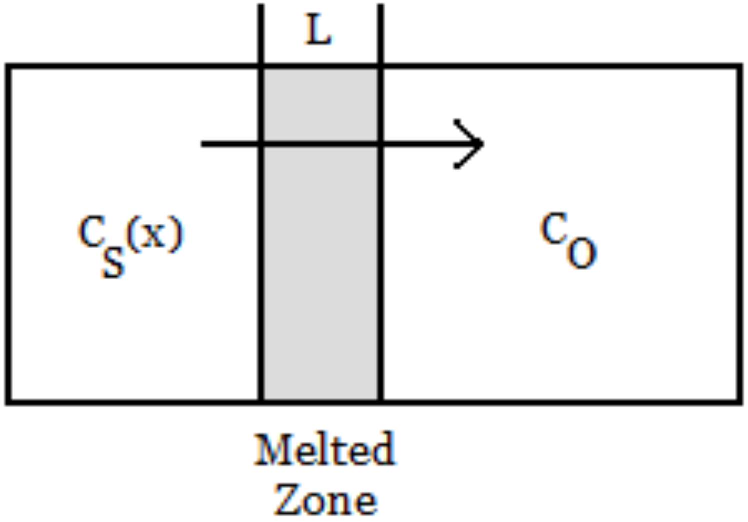
- Work with experts (Mark Ammen) at LBNL to use amorphous germanium to make contacts without transition layer
- Grow crystal with uniform impurity distribution across the entire crystal
  - Use zone refined ingots
  - Control the growth process

Description of Zone Refining

The molten region melts impure solid at its forward edge and leaves a wake of purer material solidified behind it as it moves through the ingot. The impurities concentrate in the melt, and are moved to one end of the ingot.

X: the length of Ge ingot

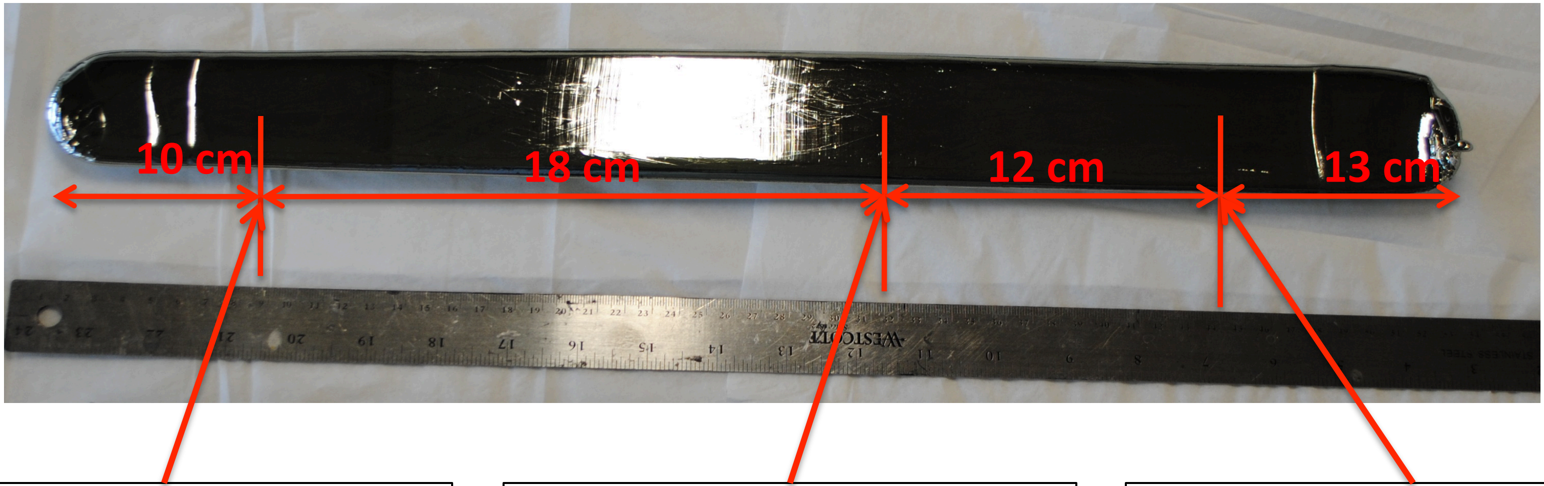
$C_S(x)$: Impurity of the Ge ingot after zone refining



C_0: The initial impurity In the Ge ingot

Liquid move from left to right during the melting in the zone refining process

Zone Refining to achieve a purity level of 0.999999999999



$|N_A - N_B| = 6.04 \times 10^{10}/cm^3$
Resistivity: 2,603 Ohm-cm
Mobility: 39,690 cm^2/Vs

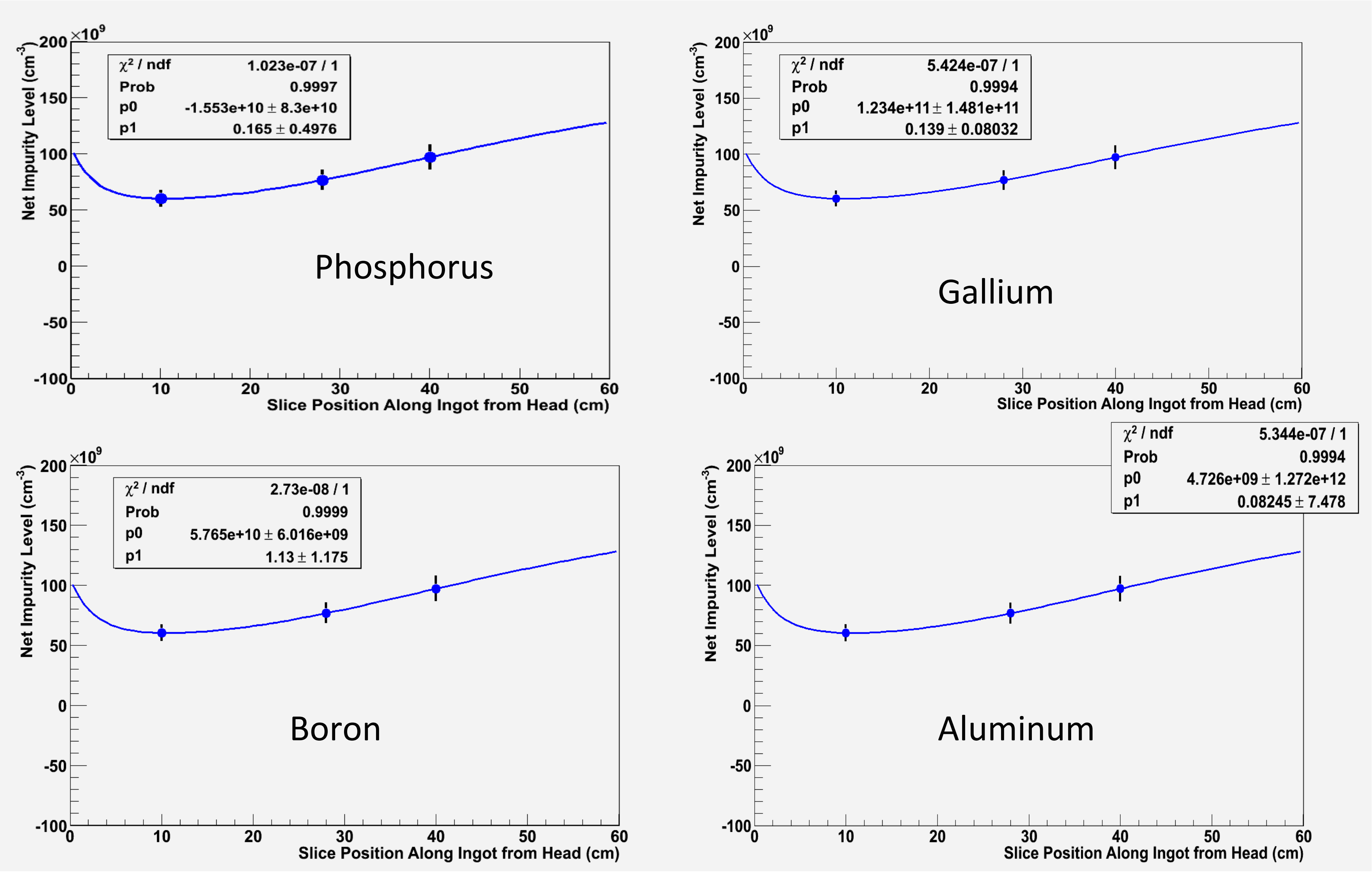
$|N_A - N_B| = 7.68 \times 10^{10}/cm^3$
Resistivity: 1,960 Ohm-cm
Mobility: 41,270 cm^2/Vs

$|N_A - N_B| = 9.72 \times 10^{10}/cm^3$
Resistivity: 1,583 Ohm-cm
Mobility: 40,580 cm^2/Vs

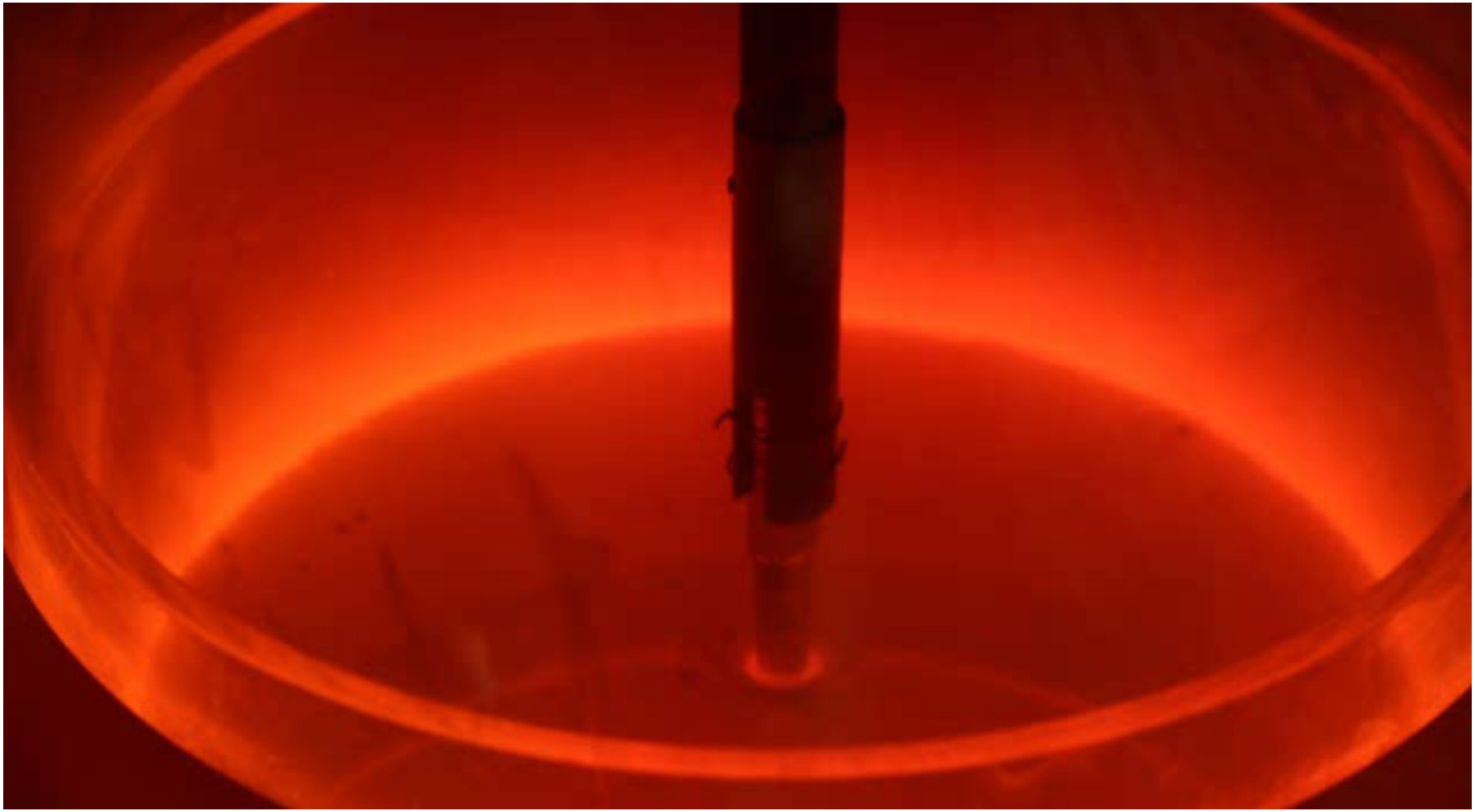
$$|N_A - N_B| = \sum_i C_i \times (1 - (1 - k_{eff}) \times \exp(-k_{eff} \times \frac{L}{\Delta L}))^n$$

$|N_A - N_B|$: Net impurity level; C_i: the level of Impurity species; k_{eff}: the effective segregation coefficient; L: the length of the ingot; ΔL: the width of the melt: n: the number of passes

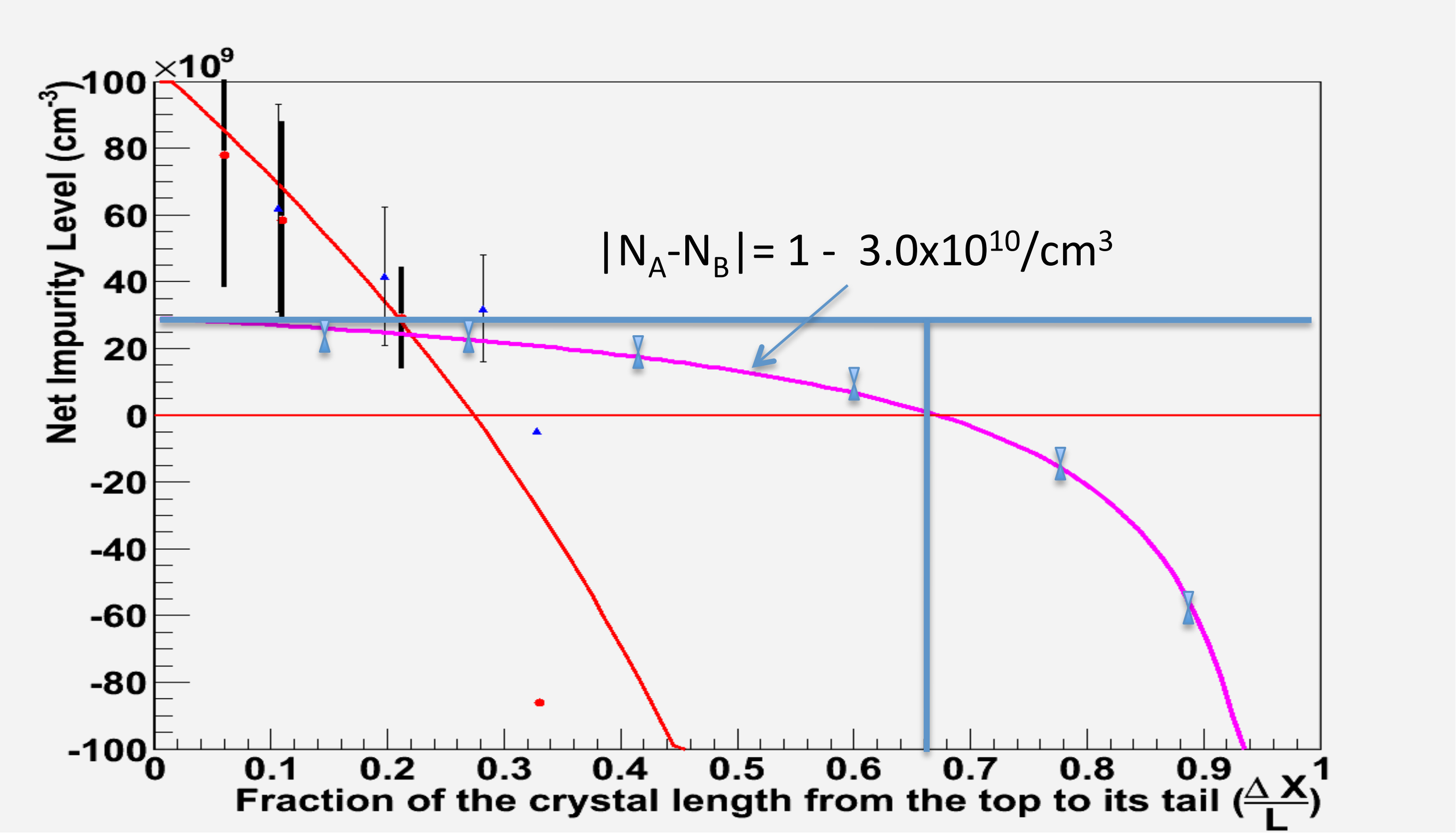
Impurity Components



Large-Size Crystal growth



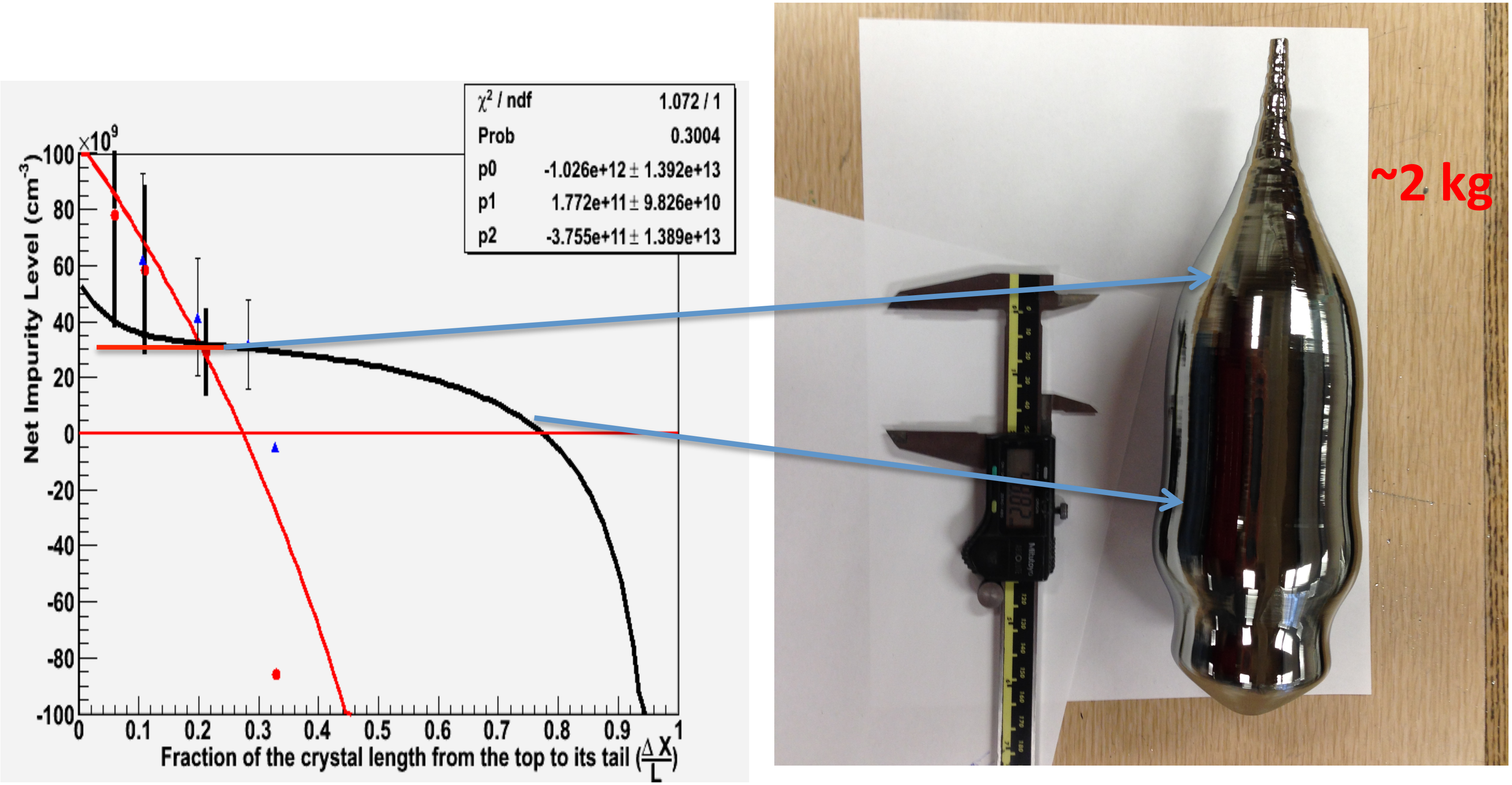
Grow a Crystal with Zone-Refined Ingot



$$|N_A - N_B| = \sum_i C_i \times k_{eff} \times \left(1 - \frac{\Delta x}{L}\right)^{(k_{eff}-1)}$$

$|N_A - N_B|$: The net impurity; C_i: the level of impurity species;
k_{eff}: the effective coefficient; $\frac{\Delta x}{L}$: the mass ratio of a grown crystals

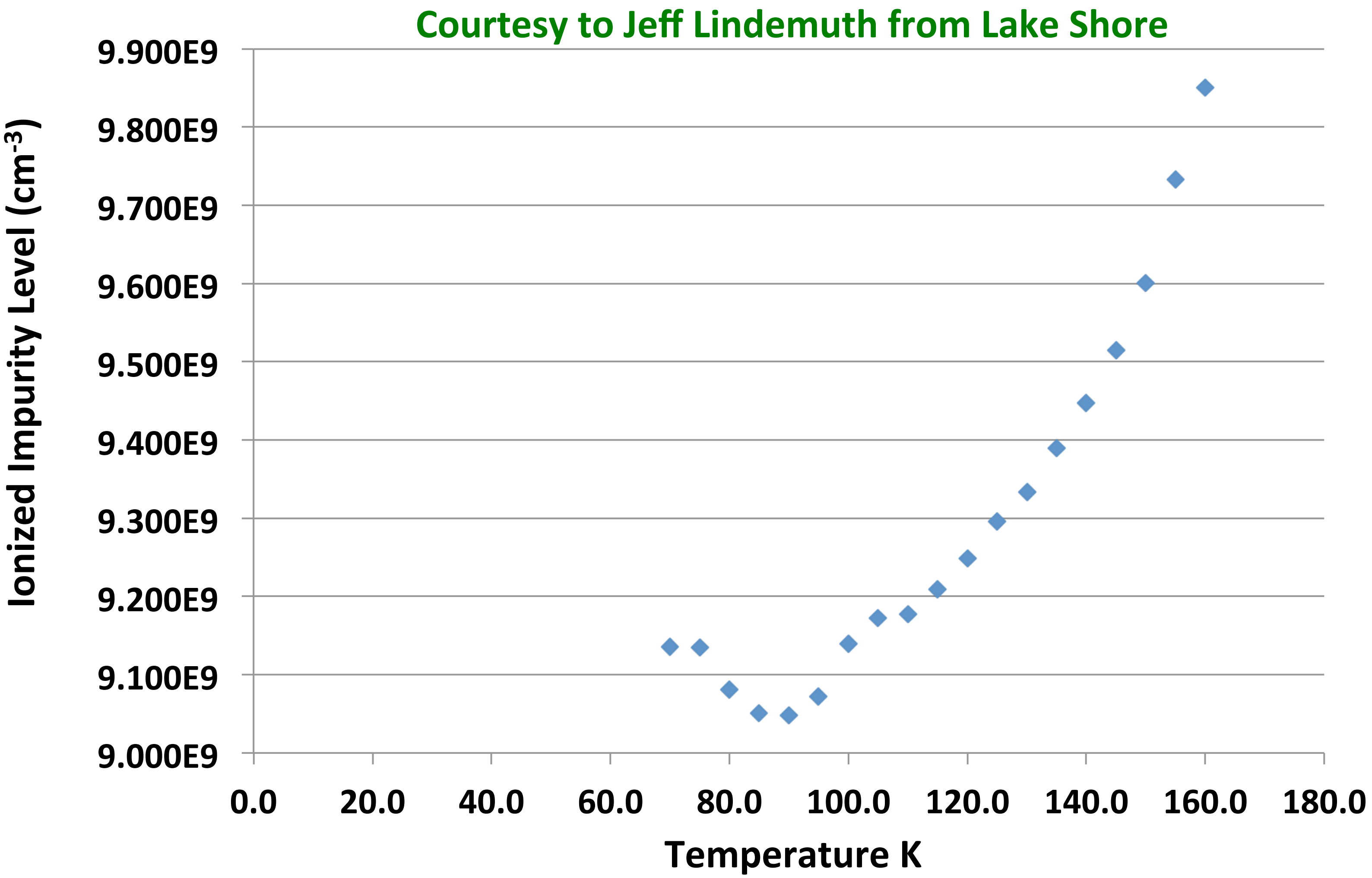
Impurity Control – Achievable



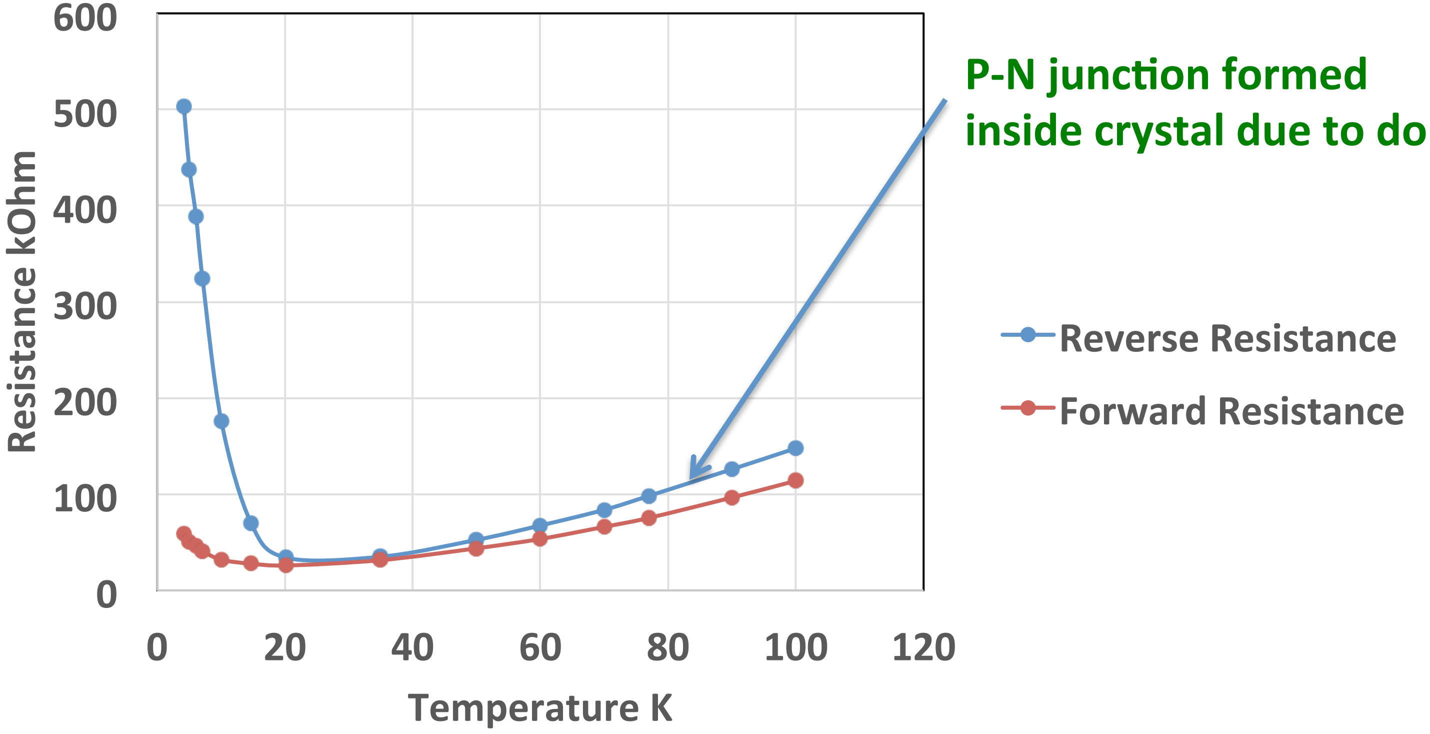
$$k_{eff} = \frac{k}{k + (1-k)\exp(-R\delta / D)}$$

k: segregation coefficient in equilibrium
R: growth rate, δ: the thickness of the growth interface, D: diffusion coefficient

Key: Crystal Quality



Key: Crystal Quality



Ortec Sample: +4.8x10^9 cm^{-3}

P-N junction formed inside crystal due to doping

Pulse Shape Properties

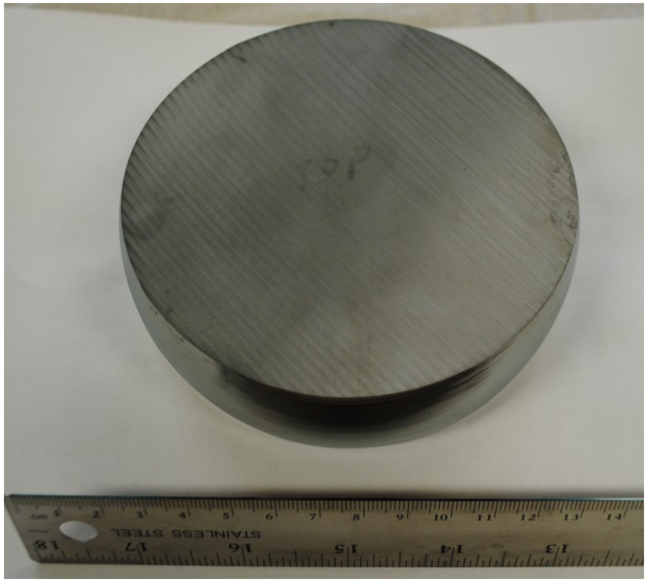
- Variation of drift time
  - $v = E \times \mu$

$$\frac{1}{\mu_{total}} = \frac{1}{\mu_{neutral}} + \frac{1}{\mu_{ionized}} + \frac{1}{\mu_{acoustic}} + \frac{1}{\mu_{optical}}$$

- Mobility
  - Distribution along radial and axial directions
- Charge trapping
  - Dislocation along radial and axial directions

A Crystal from 2014

5.9Kg

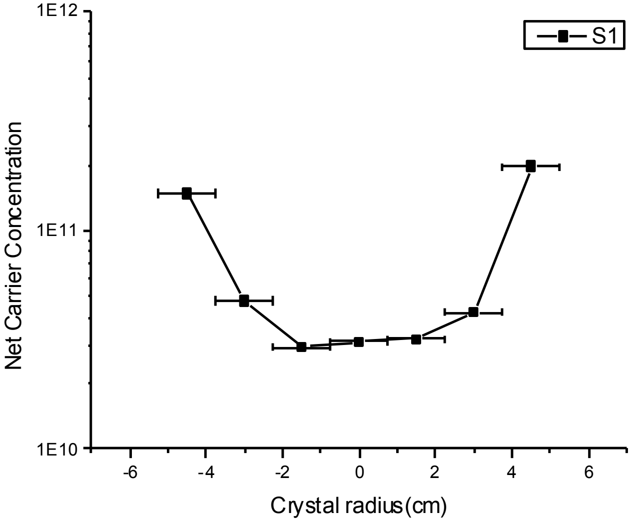


Weight 2.3kg

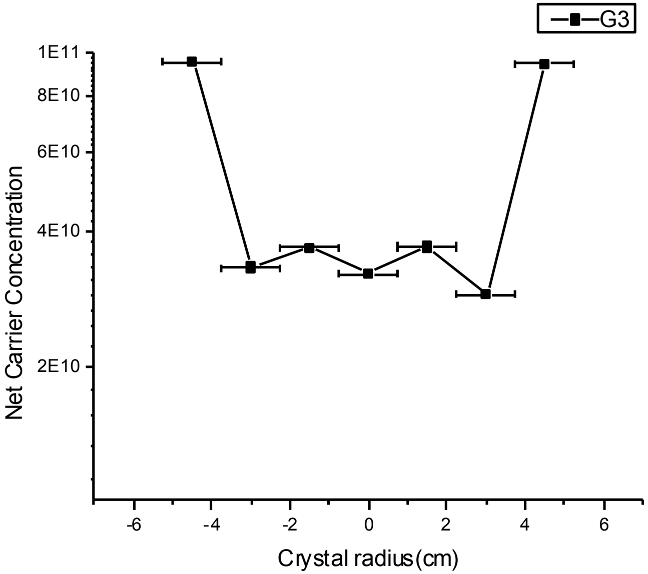
112mm (top) x 115.7mm (bottom) x 41.1mm thickness.

Sample	Carrier Concentration (cm^{-3})	Mobility ($cm^2/V.s$)	Resistivity ($\Omega.cm$)
Top	1.3×10^{11}	4.8×10^{4}	872.4
Bottom	5.8×10^{10}	4.2×10^{4}	2567.3

Radial distribution of P-type impurity



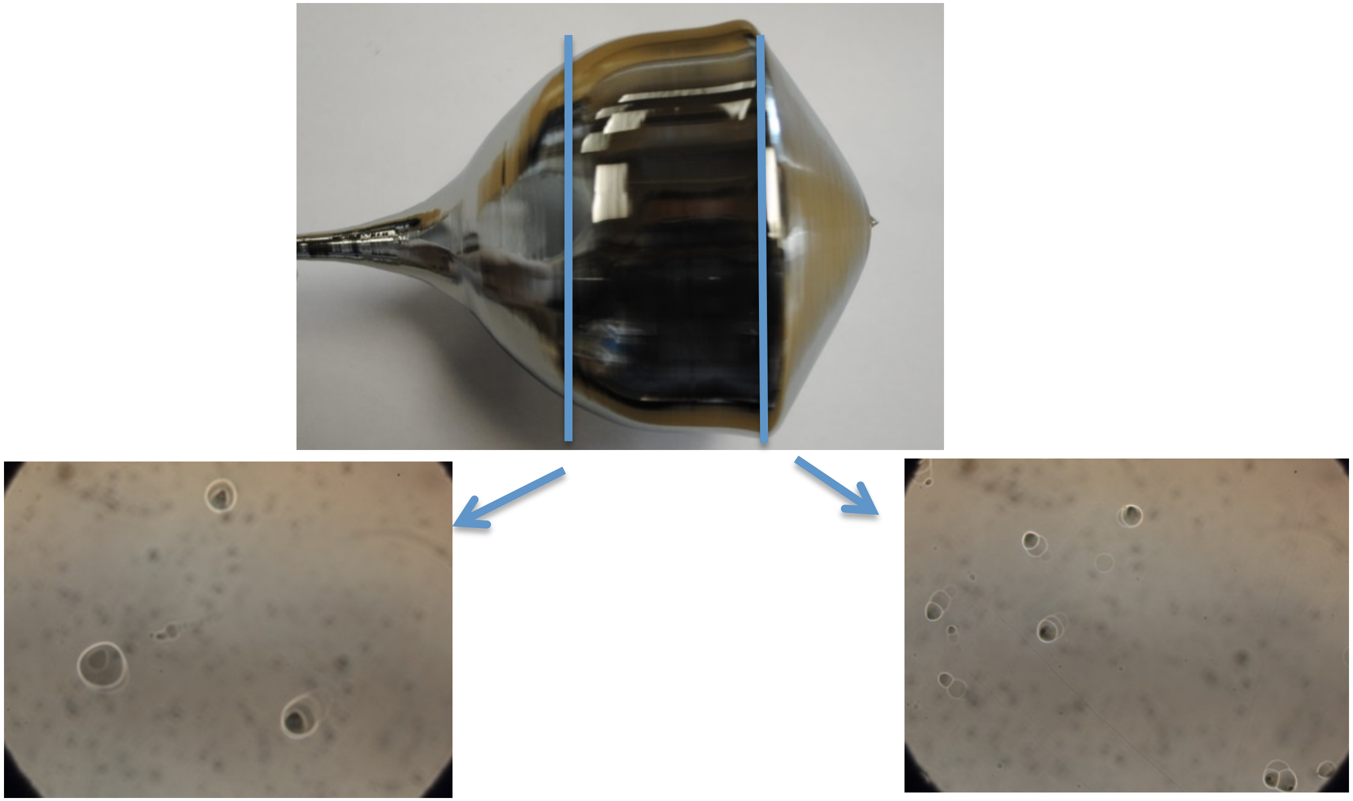
A Crystal from USD



Another Crystal from USD

The edge of the wafer shows higher p type impurity concentration. The 8cm core of wafers presents the impurity is uniformly distributed.

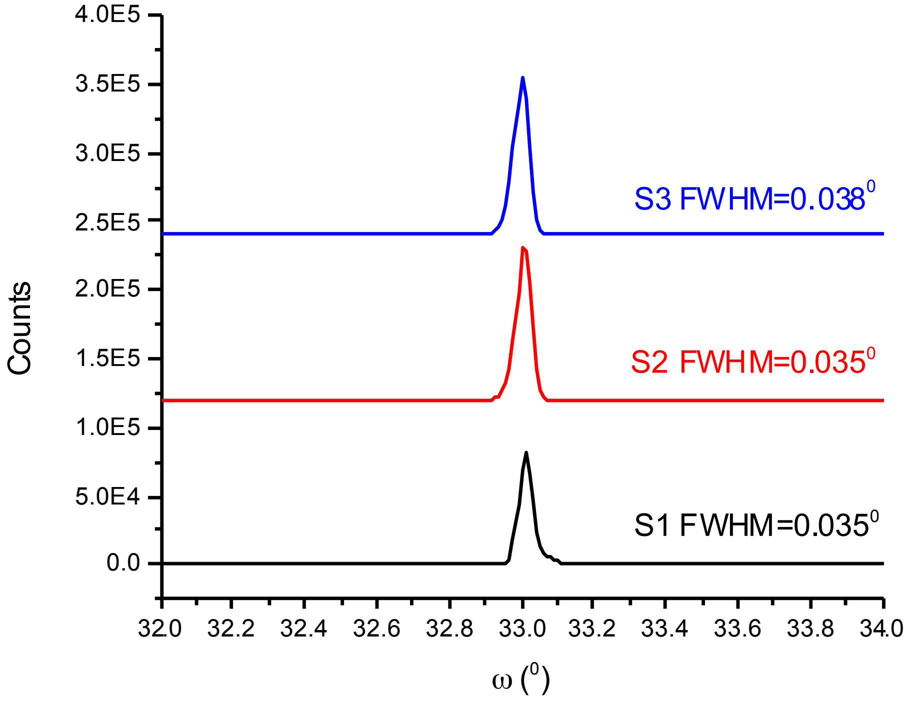
Dislocations of a Ø12cm crystal



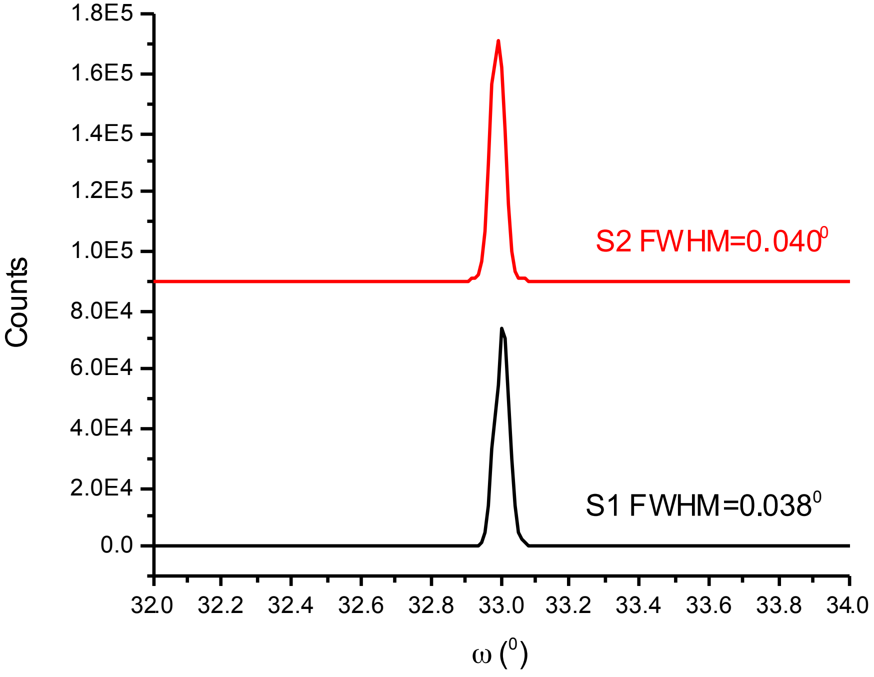
$3000\ cm^{-2}$

$7000\ cm^{-2}$

X-ray rocking curve

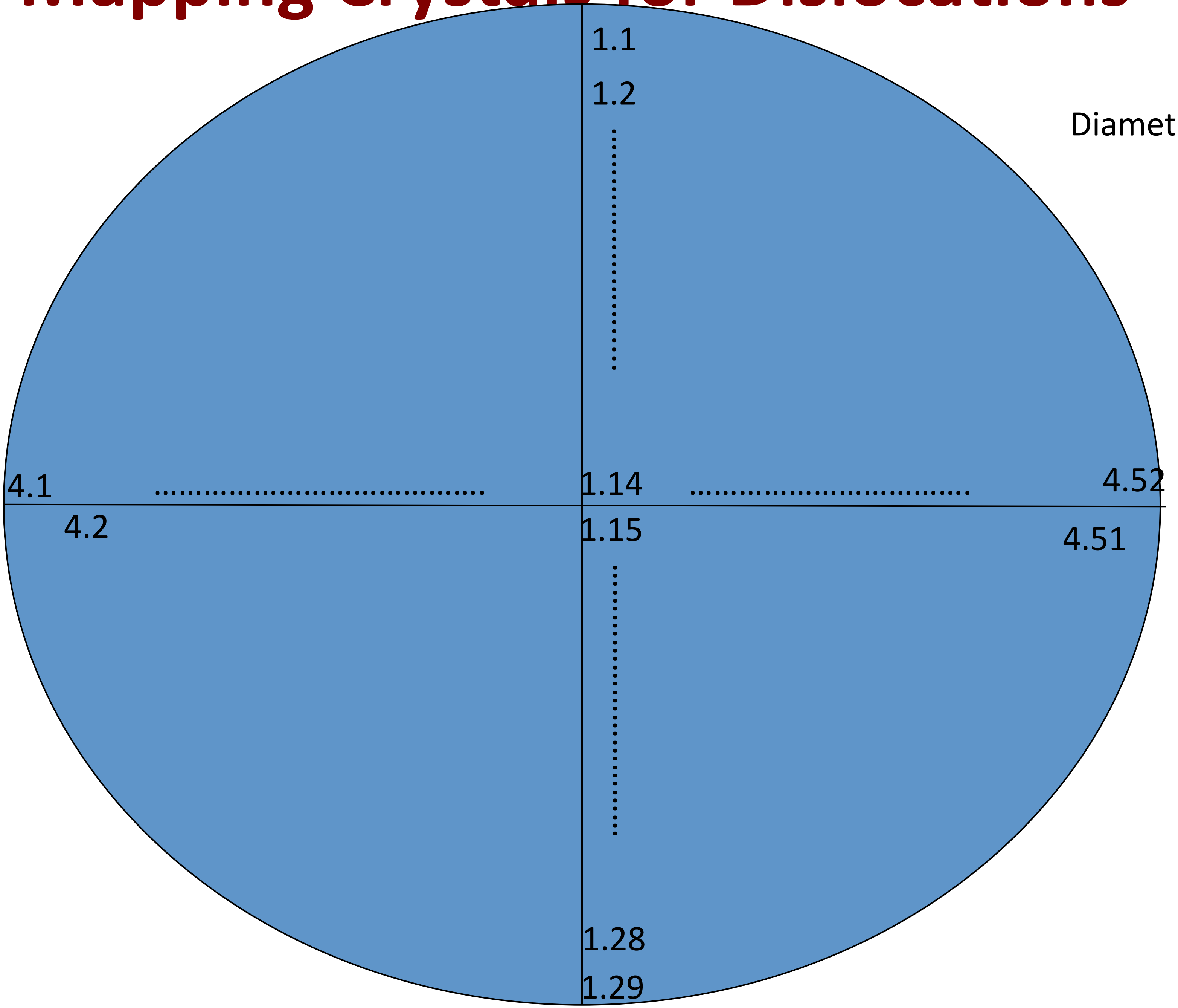


No.5-31-13 crystal Ø3.5cm



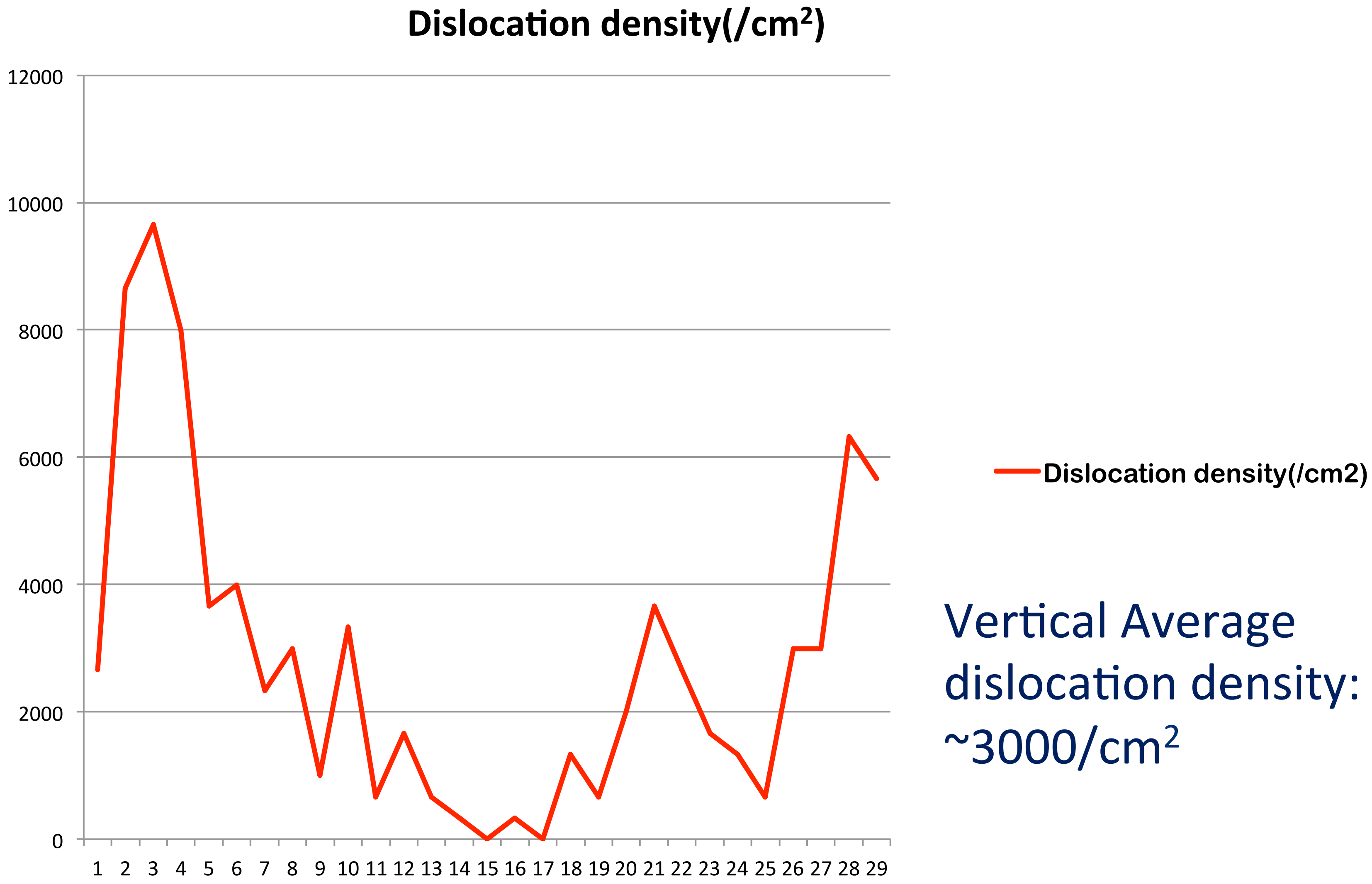
No.20 crystal Ø12cm

Mapping Crystals for Dislocations



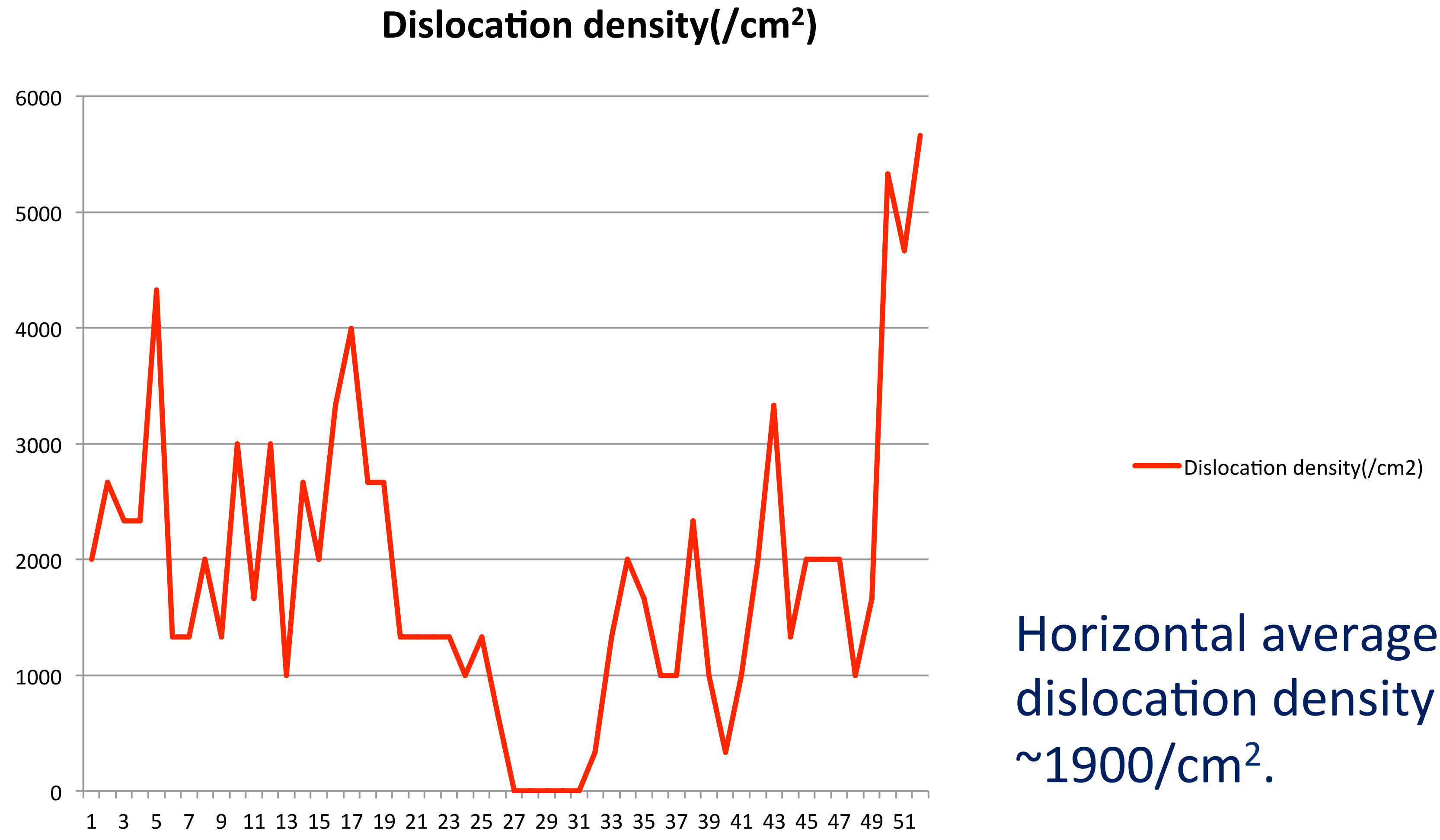
Diameter: ~9cm

Vertical Dislocation Density



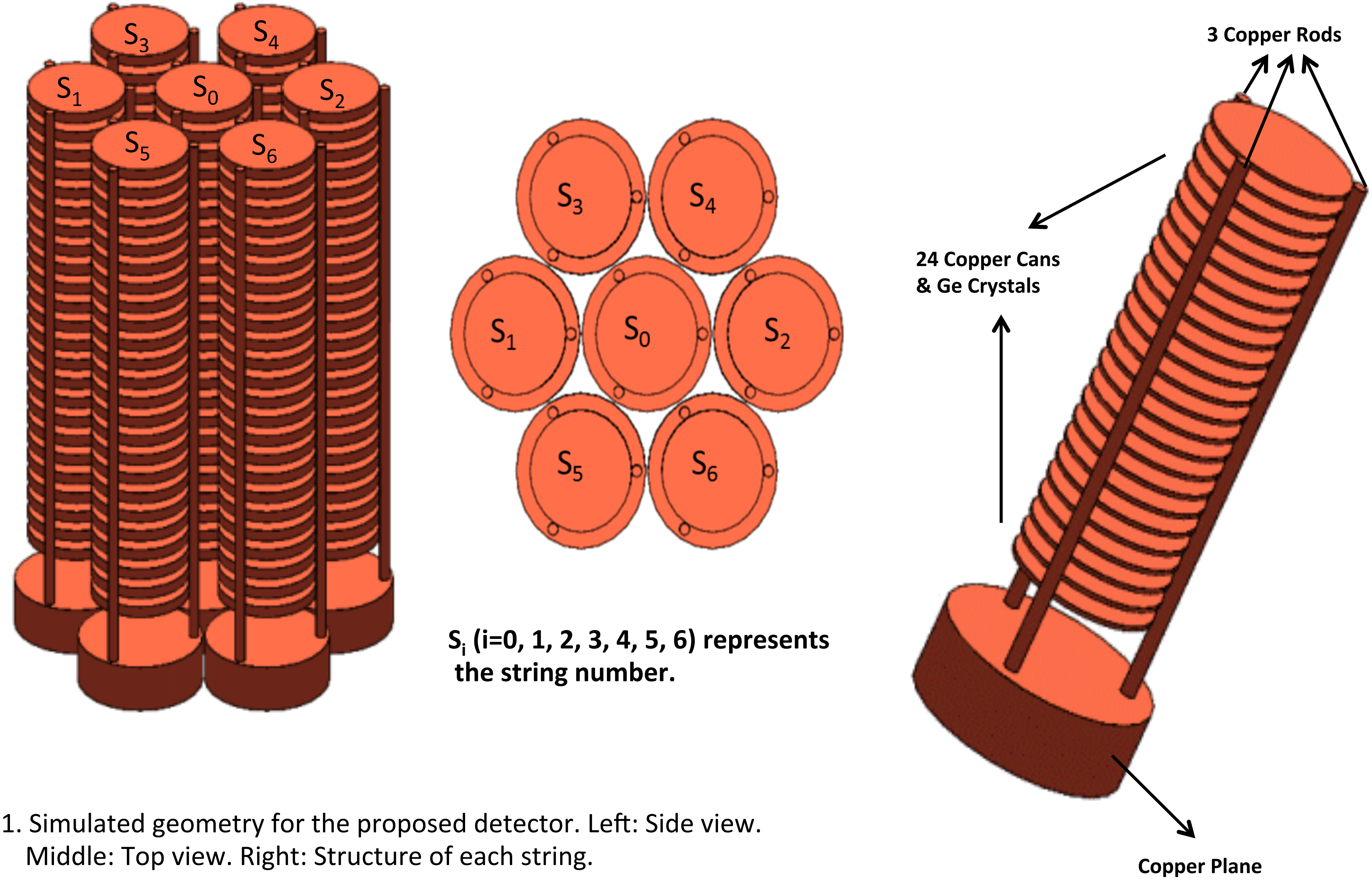
Vertical Average dislocation density: ~$3000/cm^2$

Horizontal Dislocation density



Horizontal average dislocation density: ~1900/cm^2.

Modular Geometry



S_i (i=0, 1, 2, 3, 4, 5, 6) represents the string number.

Fig.1. Simulated geometry for the proposed detector. Left: Side view. Middle: Top view. Right: Structure of each string.

Summary

- Grow large-size crystals for developing novel detectors
- R&D: Developing new detectors in next five years
  - Dark matter, neutrino-nucleus coherent scattering, neutrino magnetic moment
- Build large-scale experiment in combination with some of R&D detectors
  - If R&D is successful, build 100 kg R&D dark matter detector

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- Funding for a Workshop on Germanium Detectors and Technology
  - NSF Award Number: Award No. IIA-1434142