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Ion Beam Induced Charge Collection (IBIC) in channeling direction with keV heavy ions

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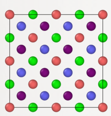
Motivation

Ion Beam Induced Charge (IBIC) measurements can serve as a method to detect single ions implanted. This is an important topic in creating quantum computers, single-photon sources, and other fields. In a current SNL project, we intend to use IBIC to image displacement damage on nm scale due to implanted single heavy ions using our nano-implanter. In this project we face the same challenges as the above-mentioned fields, detecting low energy heavy ions with high energy (e.g. IBIC) resolution. In this energy range for heavy ions (practically anything above He) a large part of the energy loss goes into nuclear processes. That will lower the IBIC signal significantly. We investigate here the idea to use ions incident along a crystal axis rather then randomly. We used the MARLOWE[1] Binary Collision Approximation (BCA) code to calculate the ionization energy loss (which is the source of the IBIC signal) dependent on energy, angle, and oxide thickness for Li and Kr ions.

[1] M.T. Robinson, I.M. Torrens, Computer simulation of atomic-displacement cascades in solids in the binary-collision approximation, Physical Review B, 9 (1974)

Simulation by Marlowe



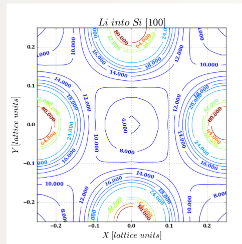
This what the ion sees
red – first plane
blue – second plane
green – third plane
magenta fourth plane

- Exponential sum potential
- ZBL non-local energy loss
- Special code to calculate ionization energy loss for ions and recoils for each cascade
- 5000 ions and their recoils are followed (1 million for maps)

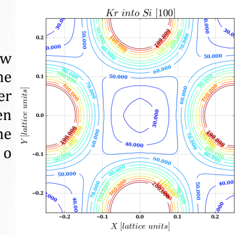
Channeled – 0 degree with 0 degree divergence
Amorphous – target is rotated after every collision

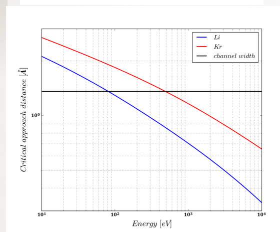
Channeling (analytical theory) [2]

[2] G. Hobler, Radiation Effects and Defects and Effects in Solids, 139 (1996)

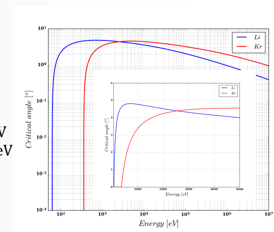


Ions approaching the row of atoms closer than the critical approach scatter out of the channel. When this distances reaches the channel width no channeling is possible.



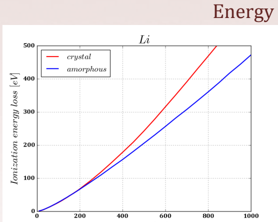


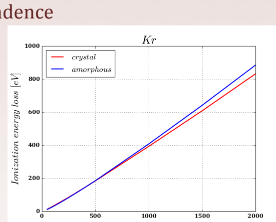
$E_{min}(Li)$ = 81 eV
$E_{min}(Kr)$ = 489 eV



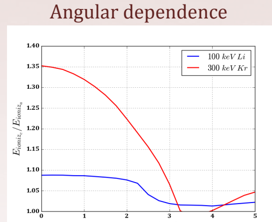
Simulation results

Energy dependence

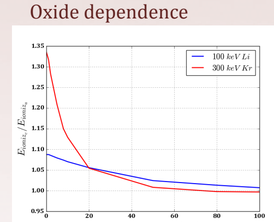


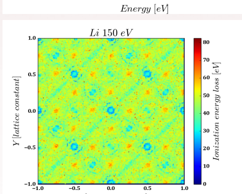


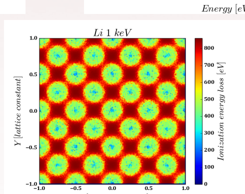
Angular dependence

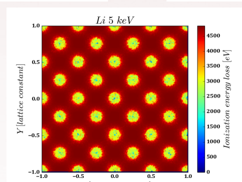


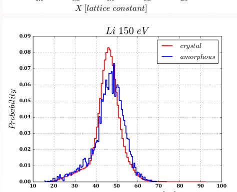
Oxide dependence

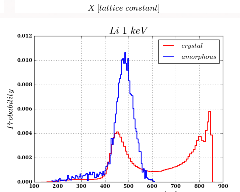


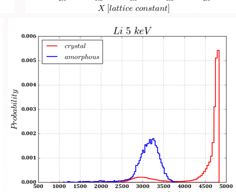












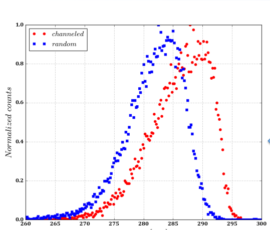
In future experiments 300 keV Kr will be used for damage and 100 keV Li for IBIC analysis

Definition: no channeling when the ionization energy loss becomes the same as for amorphous material.

- Minimum energies ~ 150 eV (Li) and ~500 eV (Kr) are comparable to theory
- Below the minimum energy IBIC spectrum is identical for channeled and amorphous
- Even well above the minimum energy there are many dechanneled ions that contribute to the amorphous peak
- 3 degrees off axis reduces IBIC to amorphous levels
- 40 nm oxide dechannels the Kr beam completely but not the Li

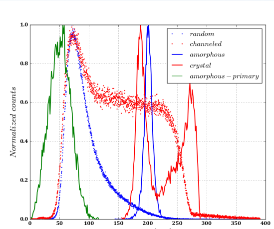
The channeling IBIC is more advantageous for heavier ions because of their lager ballistic deficit. In channeled mode most of the energy goes into ionization and very few recoils are created; therefore, it is easier to detect.

300 keV channeling IBIC in Amptek high resolution windowless X-ray detector



Detector was aligned using a 300 keV He beam

ΔE_{exp} = 5.8 keV
$\Delta E_{Marlowe}$ = 4.5 keV



Channeling edge slightly different – resolution, calibration
Channeling shape different – resolution + effect below
Random peak is much lower than simulation, closer to primary ion energy loss!
Speculation:
Low energy recoils create high density e-h pasma right where the damage is. Large part of the e-h pairs immediately recombine, therefore, the recoils contribute very little to IBIC.

Ionization energy loss fraction:

	Total	Ions	Recoils
Experiment	28.57%		
Marlowe	60.17%	13.60%	46.57%
SRIM	56.62%	18.34%	38.28%

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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