Gamma and x-ray accelerated tin whisker development

Osama Oudat,[1] Vidheesha Arora,[2] E. Ishmael Parsai,[2] Victor G. Karpov,[1] and Diana Shvydka[2]

[1]Dept. of Physics and Astronomy,
[2]Dept. of Radiation Oncology,
University of Toledo, Toledo OH, USA

Outline

- Introduction
- Summary of previous studies
- Experimental details
  - Samples
  - Irradiation sources: gamma-rays of ^{192}Ir and x-rays of medical linac
- Results: SEM images, whisker density/length
- Acceleration factor
- Conclusions

Introduction

- First report of the effect of high-energy photons on whisker kinetics published ~50 years ago
  - Observed delayed whisker growth on Sn-plated surface irradiated under 50keV x-rays, no explanation
- We have investigated the effect of high-energy electrons and photons on Sn and Zn whisker kinetics over the past 5 years
  - Consistent observations of whisker growth accelerated through electric field induced in substrate
- Possibility of developing non-destructive accelerated life-testing tool

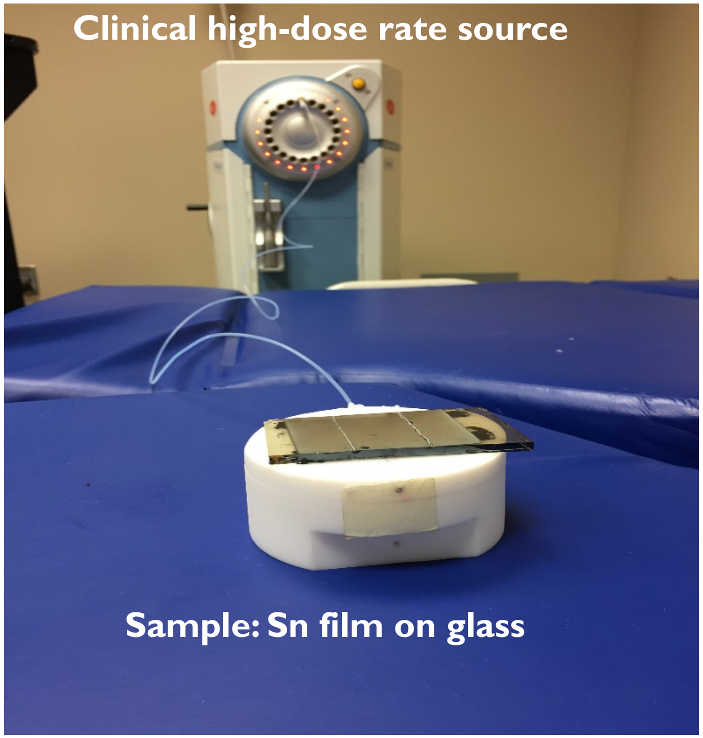
Previous results: irradiation with 6MeV electron beam

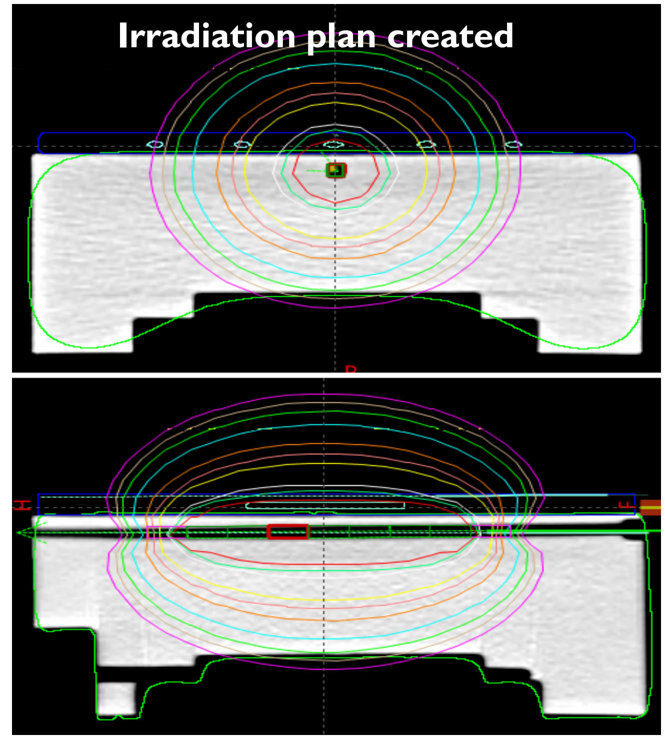
- Samples irradiated under 6MeV electron beam of clinical linear accelerator
  - Sn thin films (~300 nm) on glass
  - Zn-plated steel floor samples (NASA computation center, courtesy of J. Brusse) placed on acrylic slab

Previous results: irradiation with 6MeV electron beam

- Irradiation time 10-20 hours in sessions, to achieve dose 10-20kGy (SI unit of dose 1Gy=1J/kg)
- Observed enhancement in whisker growth and whisker lengths in irradiated samples compared to control samples
- Acceleration ratios ~200 found
- Main mechanism: substrate charging under electron beam
- Electrical measurements showed charging present only during irradiation

Irradiation under Ir-192 source

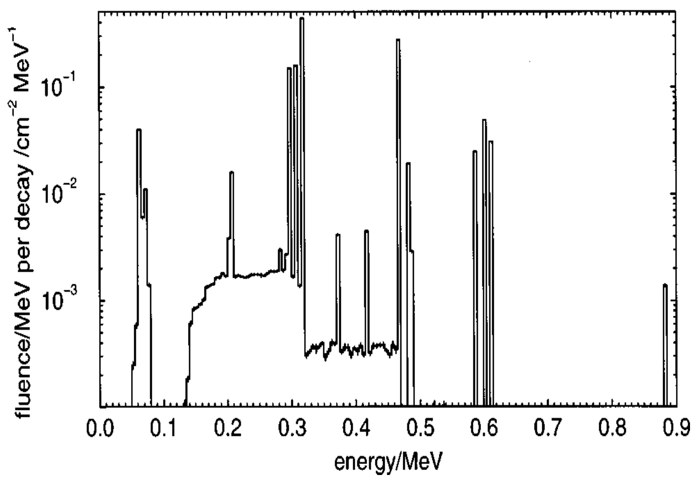




- A small (~5mm) encapsulated radioactive source is attached to a wire and moves along a catheter
- Dwells in pre-planned locations, a line source irradiation geometry
- The dose (up to 30kGy) was delivered in multiple irradiation sessions of 2-4 hours per 1kGy

Irradiation under Ir-192 source

^{192}Ir γ-ray spectrum

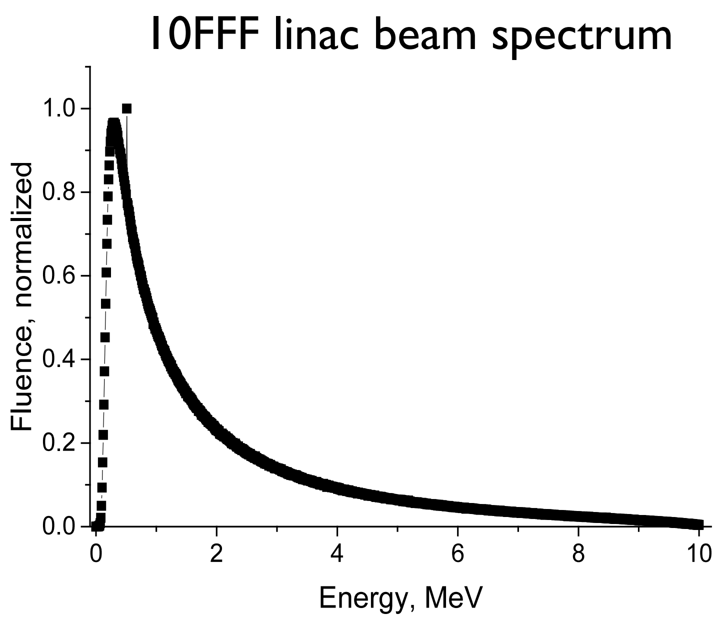


^{192}Ir also emits β-particles, which are absorbed in source encapsulation

γ-ray source average energy ~380keV, maximum energy ~1MeV

- Sn film thickness is too small to have significant number of interactions
- ~7% of γ-rays interact in 3mm thick glass
  - Compton scattering is predominant
  - Some photoelectric effect processes

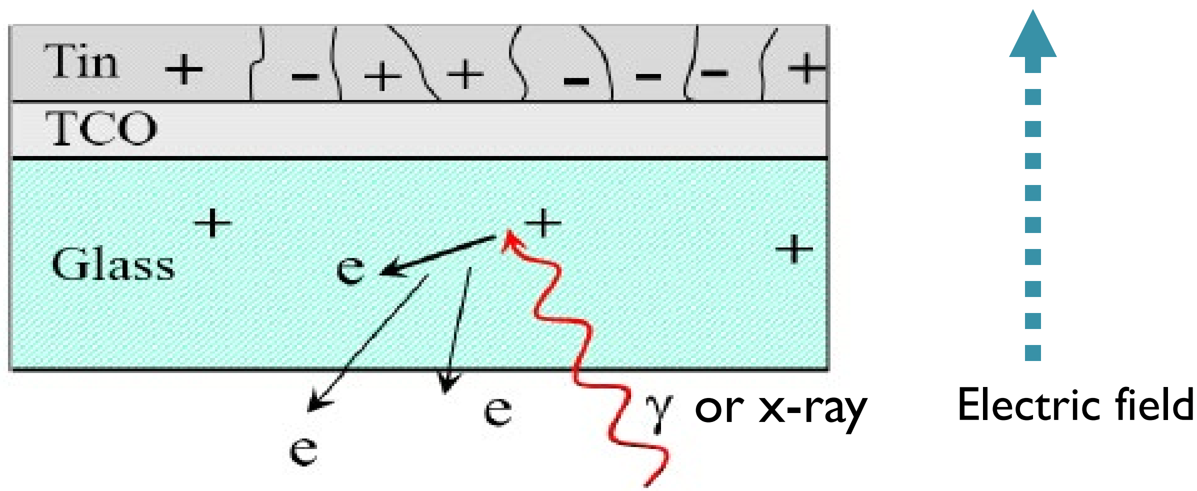
Irradiation under linac source



Medical linear accelerator (linac) photon source average energy ~1.5MeV, maximum energy 10MeV

- Sn film thickness is too small to have significant number of interactions
- ~4% of x-rays interact in 3mm thick glass
    - Compton scattering is predominant
    - Some photoelectric effect processes

Irradiation under both sources



- Interactions take place in 3mm thick glass substrate
- Substrate charging and electric field in direction perpendicular to the film surface

Irradiation energy vs atomic displacements

- The x-rays average energy ~1.5 MeV, the average Compton electron energy is ~50% of the maximum photon energy
- The energy transferred to an atom due to the Compton effect is lower than the electron energy by $\sim 4\times10^{-6}$ (the ratio of the electron to atom masses). Consequently, the atom receives <1eV on average
- While for10MeV photons ~40eV maximum energy can be transferred to an atom, the probability is vanishingly small ($\sim 10^{-7}$)
- Even less energy transferred by the gamma rays (lower average energy ~0.38 MeV)
- The average electron energy is well below the displacement threshold energy estimated for Sn as 22.2 eV
- Other mechanisms of energy transfer are even less efficient

No atomic displacements in Sn film under γ- or x-ray irradiation

Sn film samples

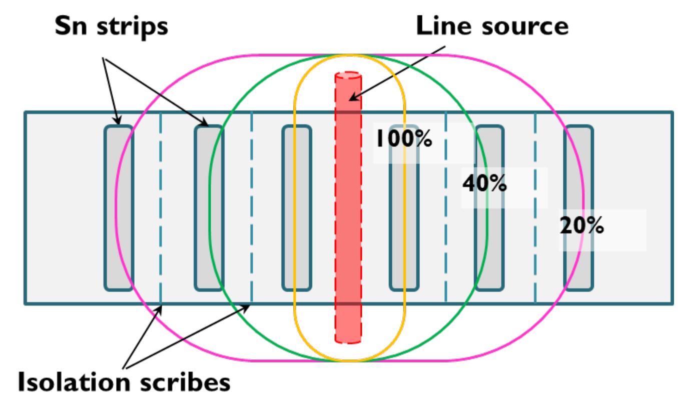
- Sn thin film samples studied
  - Fresh: vacuum evaporated at RT
  - "Mature": RF-sputtered at RT 3 years ago (whiskers were present at 0 dose)
- Sn thickness ~250-300 nm
- Deposited on 3mm-thick soda-lime glass covered with transparent conducting oxide (TCO, specifically, SnO_2:F with nominal 15 Ohm/square sheet resistance; TEC-15 glass from Pilkington)

Sample evaluation

- Evaluated with (SEM) imaging
- Image analysis at 0, 20, and 30kGy of radiation dose, corresponding to initial, and weeks 3 and 4 time intervals for the control sample
- Whisker statistics was collected from 40 images per dose level, grouped by proximity to the source or exposure condition (fully irradiated vs shielded)

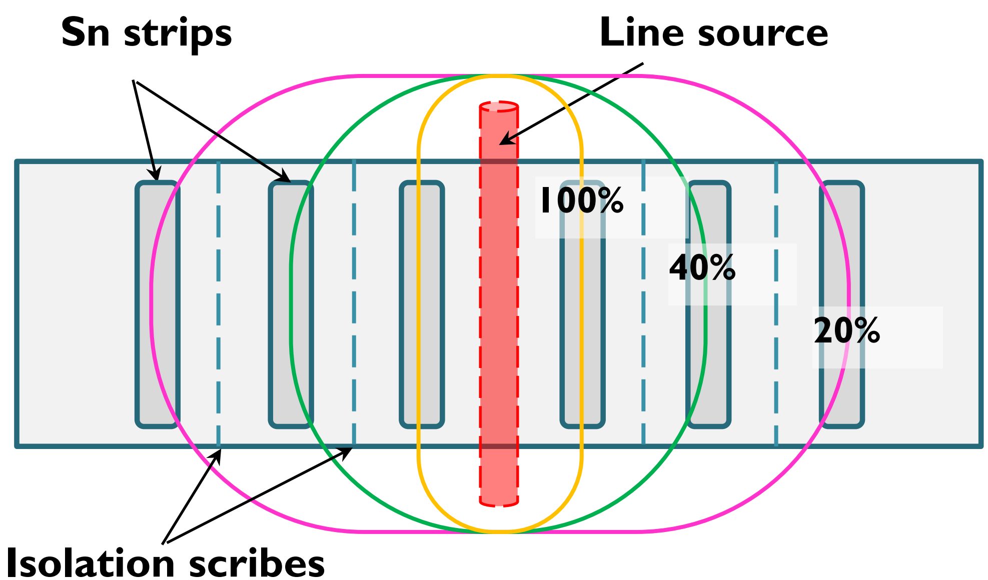
Summary of observed correlations vs. sample type

Sample	Radiation dose: Local dose	Radiation dose: Average dose
Connected strips	No	Yes
Disconnected strips	Yes	Yes



- Average radiation dose correlates with whisker growth through induced electric field
- Field distribution depends on sample: connected cells/strips are equipotential

Sample and γ-ray irradiation geometry

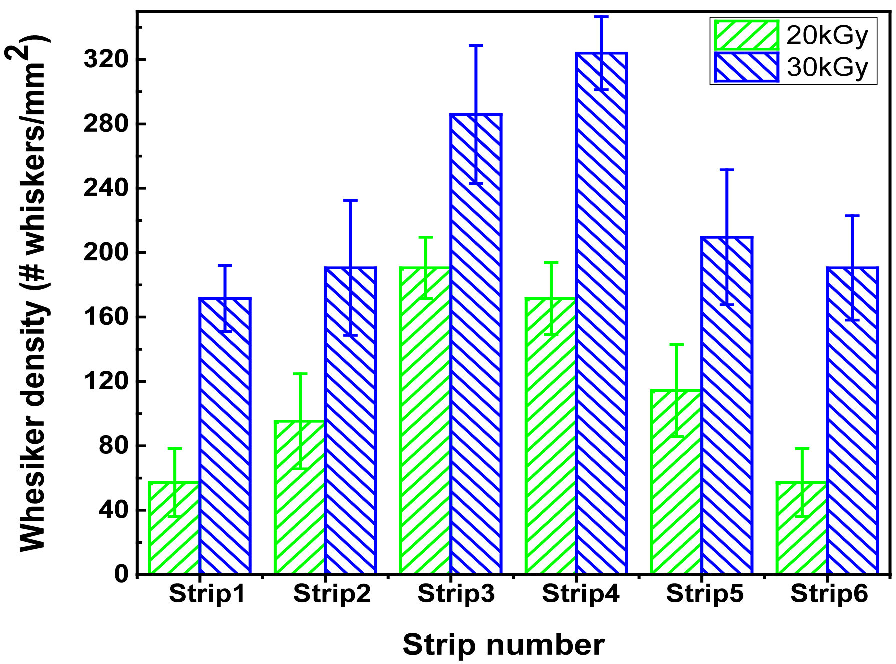


For a line source dose falls off with distance r as 1/r

Sample – Sn strips, isolation scribes through TCO

- Sn film deposited in strips/TCO continuous originally
- Sn strips exposed to 100%, 40%, and 20% dose levels

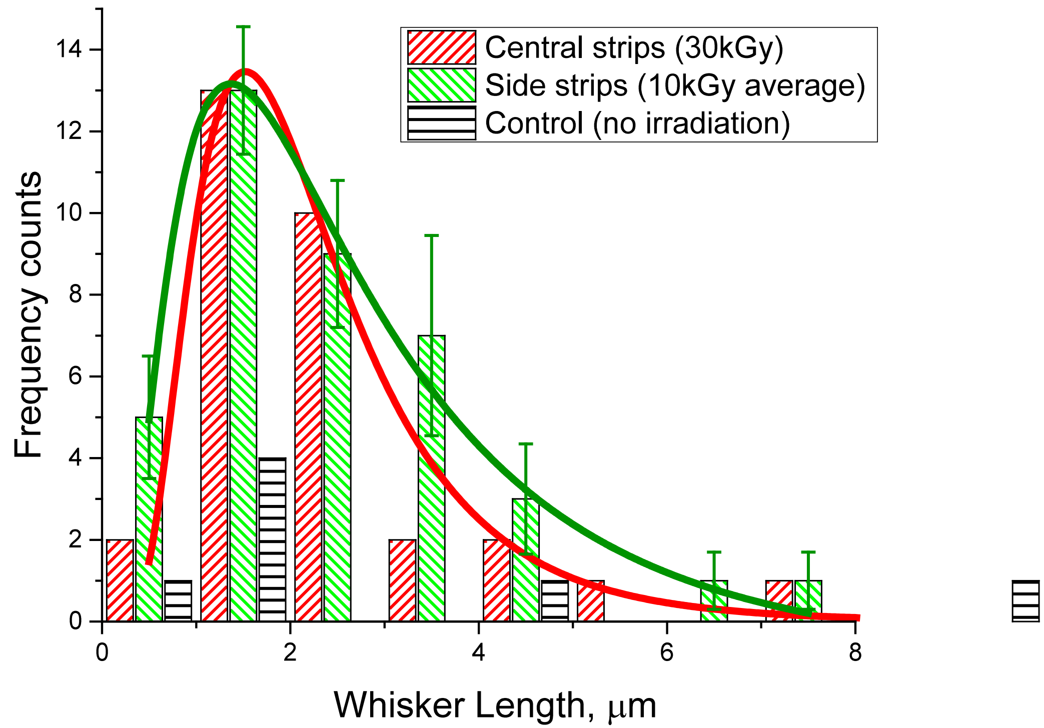
Results: Samples on glass/scribed TCO



0 kGy (not shown here) corresponds to no whiskers in a freshly deposited sample

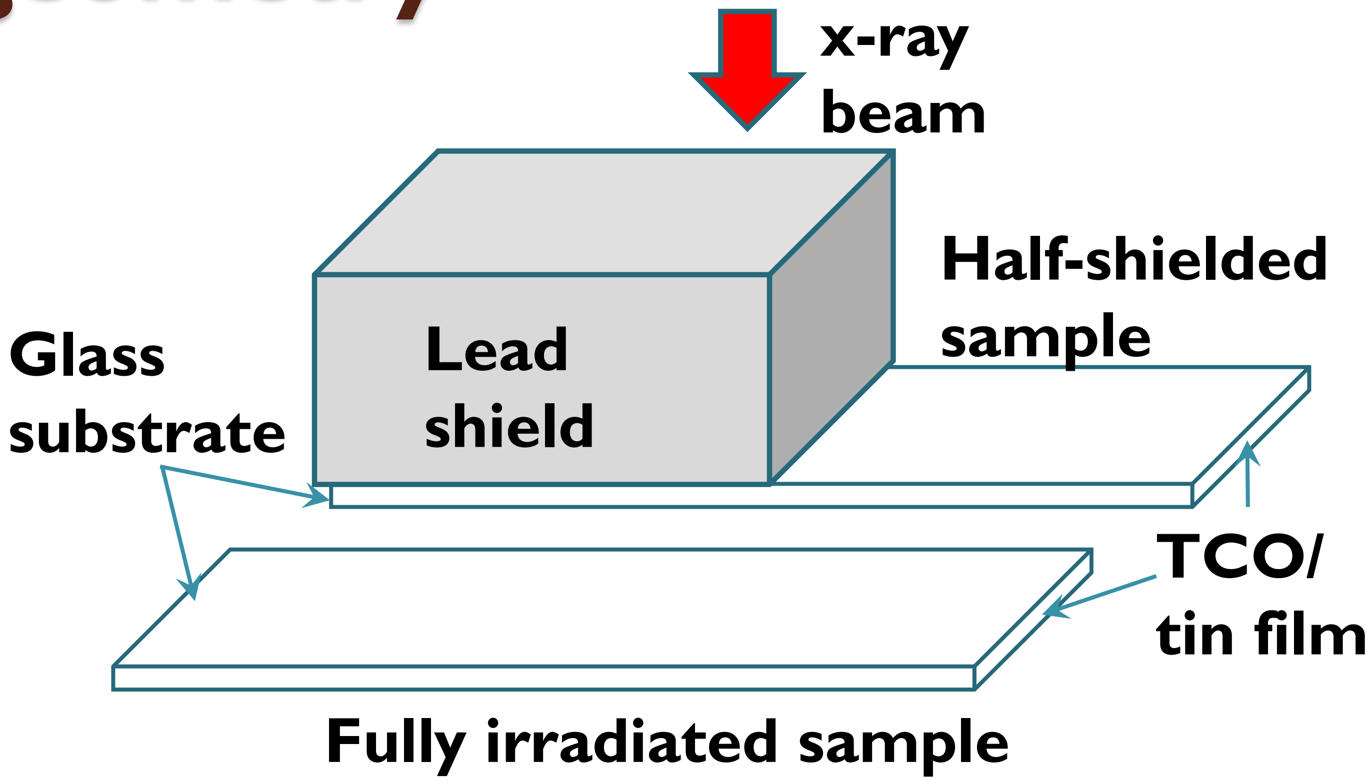
- Summary whisker statistics for the sample irradiated under γ-rays to 20 and 30 kGy doses, grouped by location on a corresponding electrically insulated Sn film strip
- Central strips 3 and 4 received the highest dose of 20 and 30kGy

Results: Samples on glass/scribed TCO



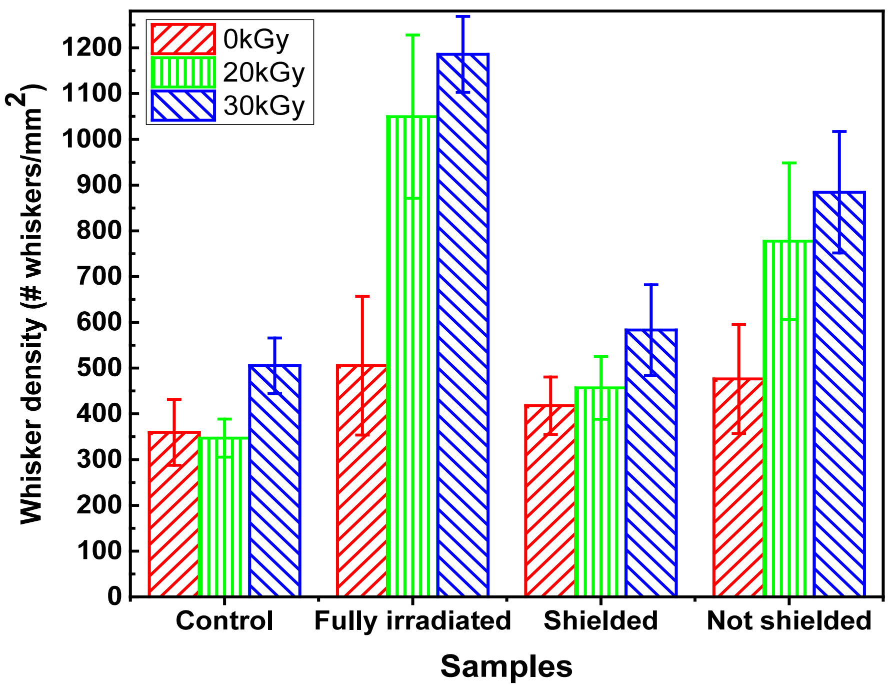
- Whisker length statistics: central region irradiated to 30 kGy, side regions irradiated to the average dose of 10 kGy. Data for control sample evaluated at the same time is included.
- Error bars of comparable magnitudes for central strips and control sample are not shown. The curves correspond to the log-normal fits.

Sample and x-ray irradiation geometry

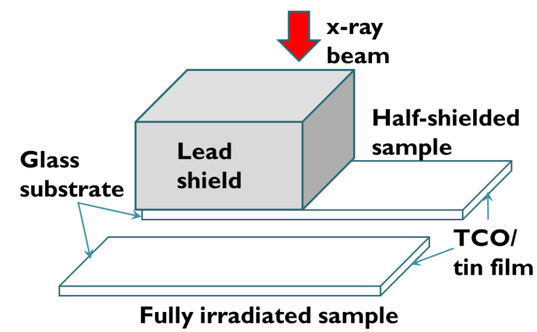


- Lead shield blocks 90% of the x-ray beam over half-shielded sample
- Shielded and exposed parts of half-shielded sample are electrically connected through TCO

Results: Samples on glass/continuous TCO

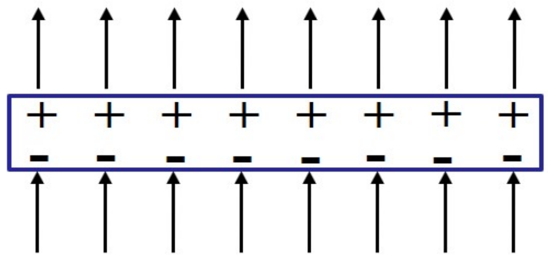


Summary of the whisker density statistics for samples irradiated under 10FFF x-ray beam

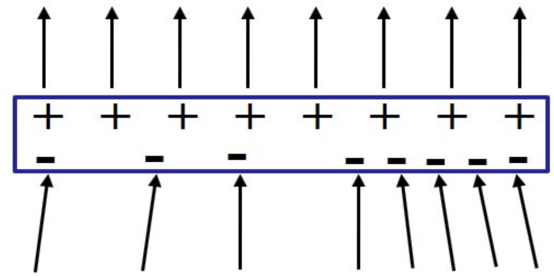


- Control sample, Fully irradiated, and Half-shielded (represented by two data sets labeled as 'Shielded' and 'Not shielded'); "mature" Sn samples
- "Fully irradiated" developed significantly more whiskers
- 'Shielded' and 'Not shielded' were electrically connected through TCO: lower effective electric field

Results: Electric field distribution



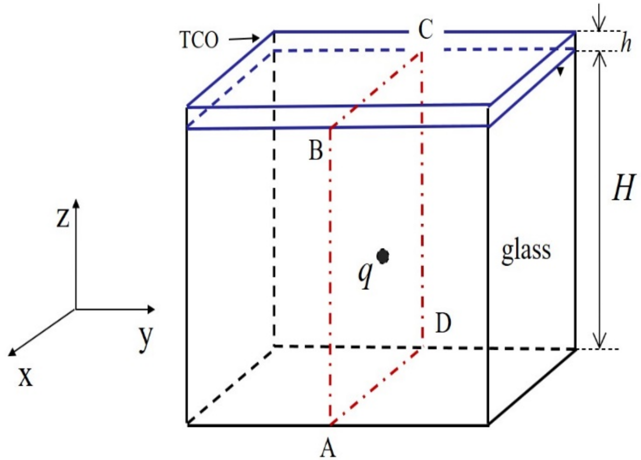
Uniform substrate field



A non-uniform field causing the free carrier redistribution

- Non-uniform irradiation causes non-uniform charging in the glass substrate
- Charge carriers re-distribute in TCO in response to the electric field of the underlying substrate
- The free carriers are chosen to be negative; the positive background remains intact

Results: Electric field distribution



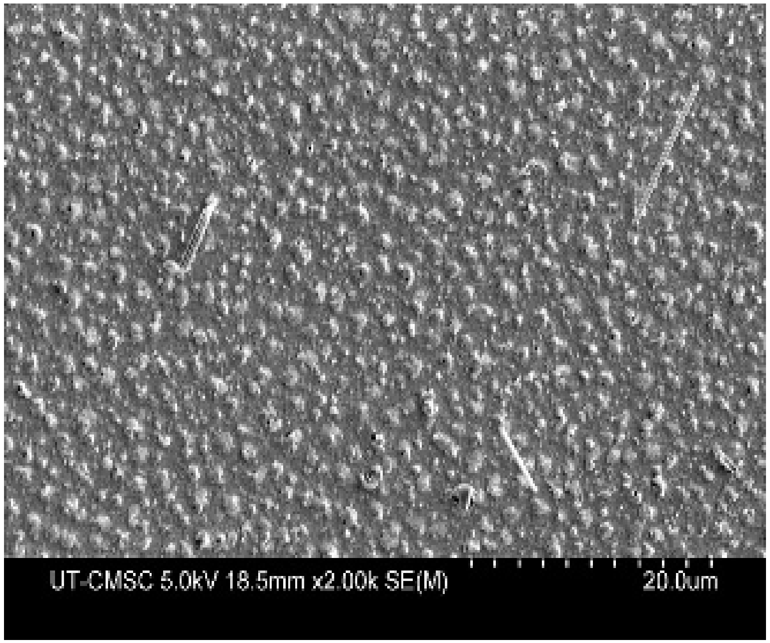
TCO layer is much thinner than glass, h << H

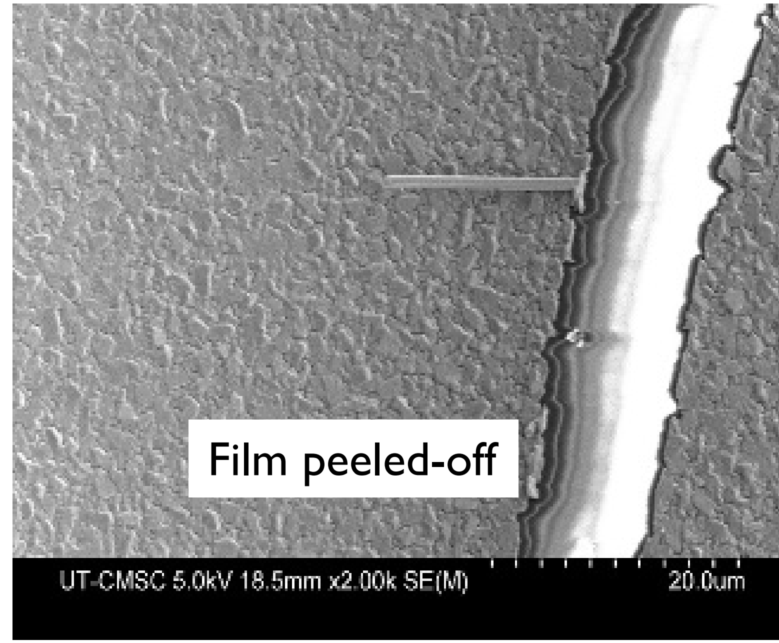
This is true but ignore; described in our ms.

$$\rho(y) = -\frac{1}{2\pi}\int_{L/2}^{L/2} \ln\left[\frac{(y'-y)^2+H^2}{(y'-y)^2}\right] g(y')dy'$$

- Solved electrostatic problem of field distribution due to laterally nonuniform substrate electric charges with and w/o TCO
- The non-uniform component of the electric field is shielded completely by the TCO layer
- The average field not screened depends on average charge concentration– radiation dose dependence; shielding suppression

Results: Samples on glass





- Whiskers grow on Sn film deposited on bare glass after γ-ray irradiation (no Cu culprit)
- Film adhesion is a concern

Acceleration factor

- To quantify the effect of electric field on whisker growth we use whisker creation rate

$$R = \frac{\text{whisker density}}{\text{time}}$$

- Distinguishing between E-field stimulated R_{STIM} and spontaneous R_{SPON} whisker growth rates, define *acceleration ratio*

$$a \equiv \frac{R_{STIM}}{R_{SPON}}$$

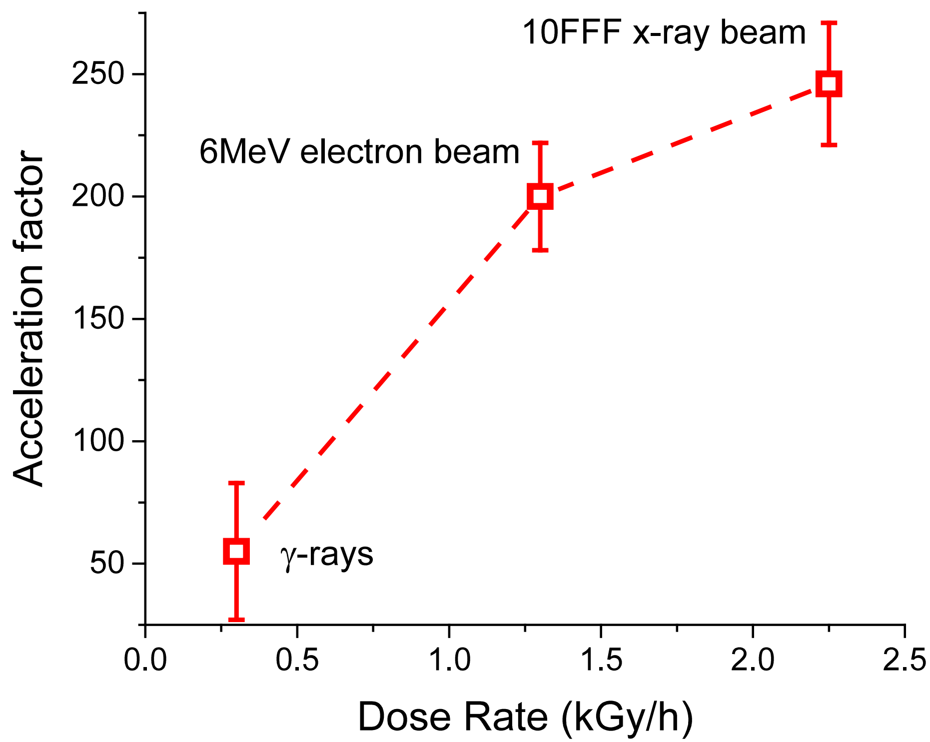
- Evaluate at 30kGy irradiation dose; shelf samples imaged together with those irradiated

Acceleration factor

	Radiation source, 30kGy total dose	
	γ-ray source, central strips	x-ray source, fully irradiated
Dose rate	0.3kGy/h	2.25kGy/h
Acceleration factor	55	246

- Acceleration factor for γ-ray exposed sample is similar to that from previous experiments
- Field distribution depends on sample: connected cells/strips are equipotential

Acceleration factor: summary



- Sn film irradiated with 0.4MeV and 10MeV photons
- Zn film irradiated with 6MeV electrons (previous experiments)

- Acceleration factor calculated based on whisker density
- Three different sources with markedly different dose rates
- Dose rate is possibly an important factor

Conclusions

- Consistently observed effect of accelerated whisker growth under ionizing irradiation sources: both whisker densities and lengths are greatly enhanced
- For all types of sources studied so far (x- and γ-rays, electrons), and both Sn and Zn films, we determined the characteristic range of radiation doses of 20-30 kGy, for which that effect becomes significant
- Attributed to generation of electric charges in the insulating glass substrate supporting thin films. The charges create an electric field perpendicular to the film surface, providing conditions conducive to electrostatically driven whisker growth

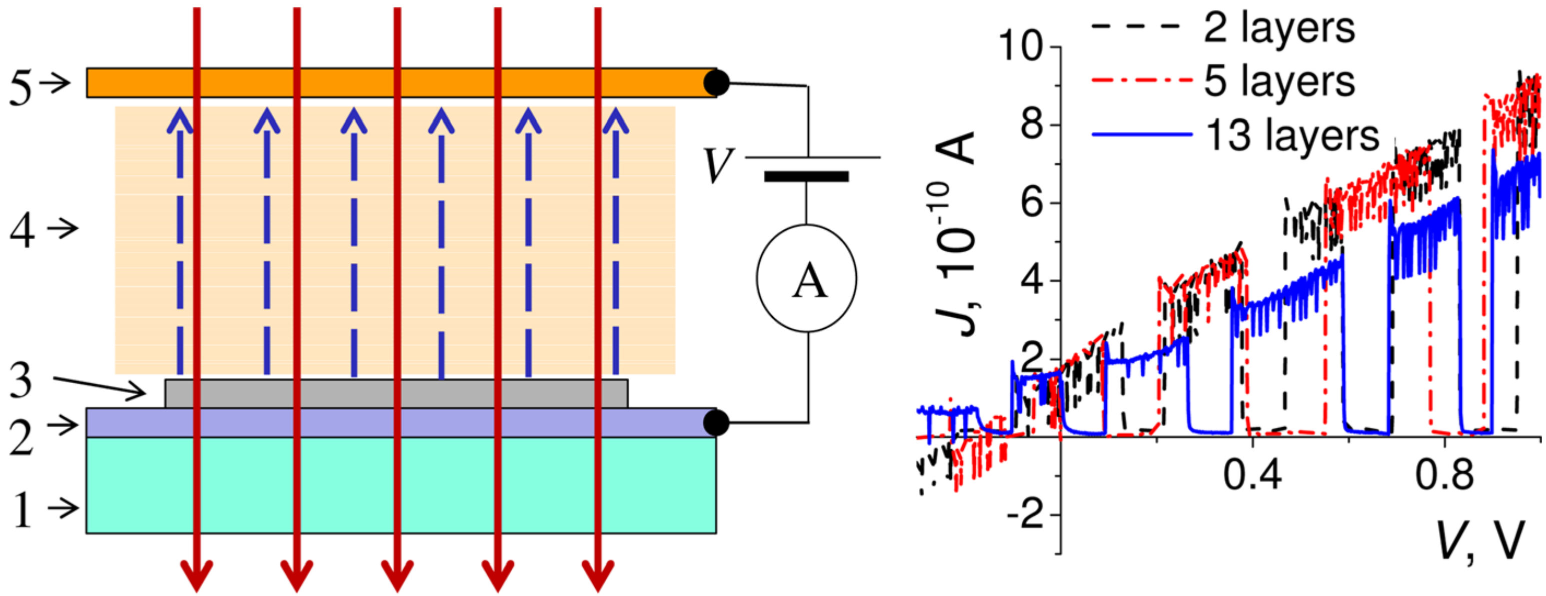
Conclusions

- The field acts mostly at the nucleation stage by diminishing the whisker nucleation barrier
- Field distribution depends on the sample: connected (e.g., through TCO underneath) cells/strips are equipotential
- The observed acceleration factor of up to ~250 were found; higher values correlated with higher dose rates (varied by source or with shielding) and corresponding generated electric field
- Promising as a non-destructive readily implementable accelerated life testing tool for whisker propensity

References

- O. Oudat, V. Arora, E. Parsai, V. G. Karpov, and D. Shvydka, Gamma- and x-ray accelerated whisker development, J. Phys. D: Appl. Phys. 53, 495305 (2020)
- Vamsi Borra, Daniel G. Georgiev, V. G. Karpov, and Diana Shvydka, Microscopic Structure of Metal Whiskers, Phys. Rev. Applied 9, 2018, p.054029-1-9
- Morgan Killefer, Vamsi Borra, Ahmed Al-Bayati, Daniel G. Georgiev, Victor G. Karpov, I. Eshmael Parsai, Diana Shvydka, Whisker growth on Sn thin film accelerated under gamma-ray irradiation, Journal of Physics D: Applied Physics 50, 2017, p. 405302-1-7. V. G. Karpov, Electrostatic theory of metal whiskers, Phys. Rev. Applied, 1, 044001 (2014)
- A. C. Vasko, G. R. Warrell, E. I. Parsai, V. G. Karpov, and Diana Shvydka, Electron beam induced growth of tin whiskers, J. Appl. Physics 118, 125301 (2015)
- D. Niraula, J. McCulloch, G. R. Warrell, R. Irving, V. G. Karpov, and Diana Shvydka, Electric field stimulated growth of Zn whiskers, AIP Advances, 6, 075201 (2016)
- W. C. Ellis, D. F. Gibbons and R. G. Treuting, Growth of metal whiskers from the solid, in Growth and Perfection of Crystals, Proceedings of an International Conference on Crystal Growth, Cooperstown, New York August 27-29, 1958. Edited by R.H.Doremus, B.W.Roberts, and D.Turnbull
- J.Borg, D.W.O. Rogers, Spectra and air-kerma strength for encapsulated ^{192}Ir sources, Med. Physics 26, 2441 (1999)
- F. H. Attix, Introduction to radiological physics and radiation dosimetry, Wiley 1986.

Backup slide:
Previous results: irradiation with 6MeV electron beam demonstrated E-field present only during irradiation



(a) (b)

(a) Sketch of the experimental setup for electrical characterization of sample charging: downward arrows represent the primary electron beam; upward arrows show the measured current of secondary electrons from the sample. The layers represent: 1-glass substrate, 2-conductive oxide, 3-tin, 4-spacer filled with plastic sheets, and 5-second (foil) electrode.

(b) Current-voltage characteristics of the structure in (a) for different insulating spacers. The beam was repeatedly turned on and off, leading to the gaps (beam off) in the plots.