Materials for Enabling Performance of Electronic Devices in Radiation Environments

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Joseph L. Lenhart (1821)
Sandia National Laboratories
Materials and Processing Sciences Center

Acknowledgements / Collaborators

- ***Radiation tolerant polymers:*** Phillip Cole, John Schroeder, Shannon Lacy, Mike Belcher, Robert Klein, John McBrayer, Lothar Bieg, Ginger De Marquis
- ***Proton shielding measurements / calculations:*** Paul Dodd, James Schwank, Diana Wrobel
- ***Electron shielding measurements / calculations:*** Ethan Blansett, Gayle Thayer, Paul Dodd, James Schwank, Diana Wrobel
- ***Thermal Spray Coatings:*** Aaron Hall

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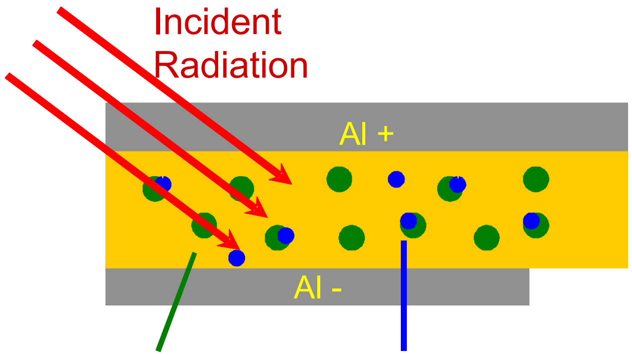
Two Approaches for Radiation Tolerant Devices

1. *Engineer radiation tolerant polymers for the device*

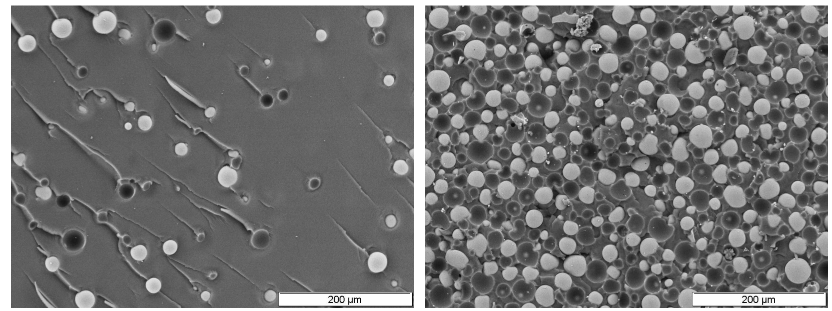


electron acceptor/donor Incorporated in polymer as a small molecule dopant

Radiation induced electrons or holes captured by dopant

- Incorporate small molecules dopants to reduce Radiation Induced Conductivity (RIC)
- Dopants “trap” electrons or “fill” holes
- Focus on polymer films
- Utility for thin films, coatings, encapsulants, underfills, etc

2. *Develop polymeric composites to shield devices from radiation exposure*

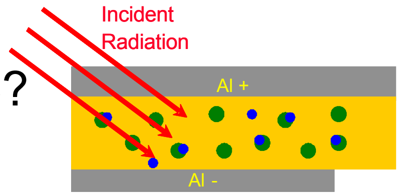


- High-Z particulate fillers with polymeric matrix for shielding composites
- Loadings from 1 to 50 volume % depending on radiation environment and the specific application
- Polymer composites provide processing flexibility for wide range of applications
  - structural composite for system level shielding
  - Localized encapsulant / coating for particularly sensitive devices

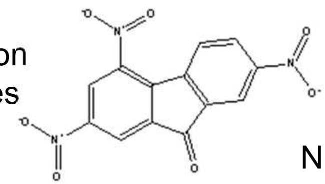
Radiation Tolerant Polymeric films

What causes RIC?

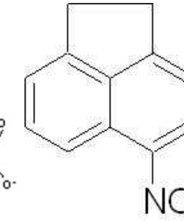
Mobile electrons upon radiation exposure



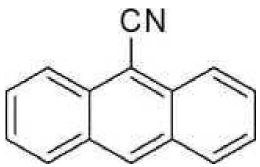
Incorporate electron trapping molecules



Trinitrofluorenone (TNF)



Nitroacenaphthene (NAN)

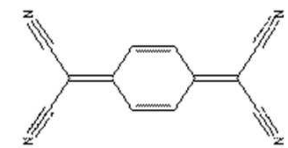


Cyanoanthracene (CAN)

What makes an electron trap?

Aromatic core with pendant electron withdrawing groups

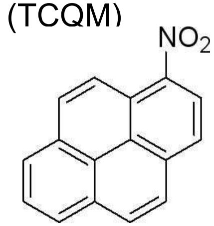
Identify candidates with nitro- or cyano- groups



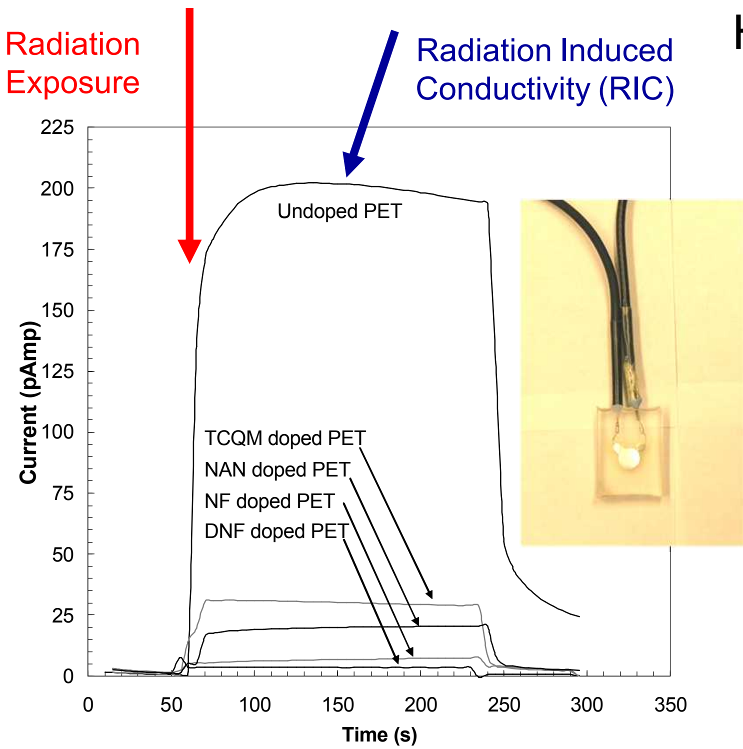
Tetracyanoquinodimethane (TCQM)

How do we incorporate the trap?

Immerse polymer in solvent-dopant solution
Adsorption-diffusion process



Nitropyrene (NP)



- Aromatic core with pendant withdrawing groups are effective (electron traps)
- NO_2 more effective than CN
- Adsorption-diffusion process

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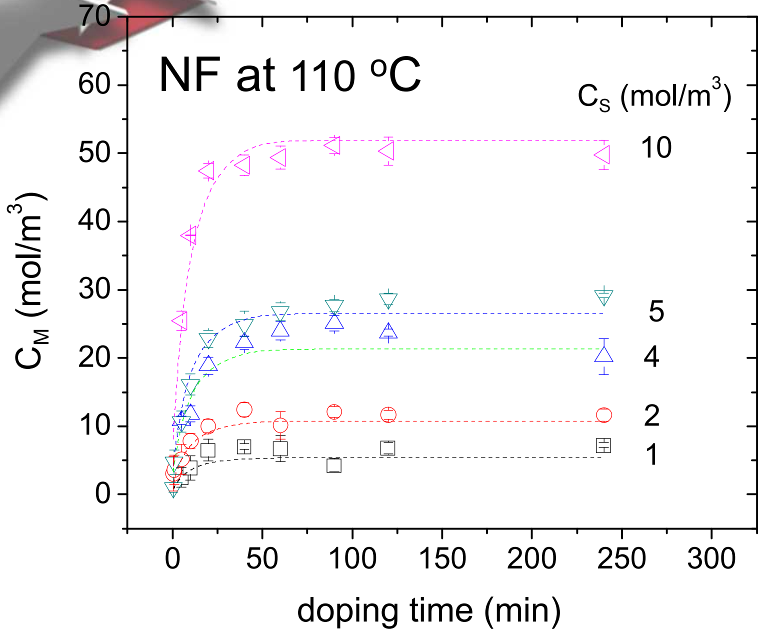
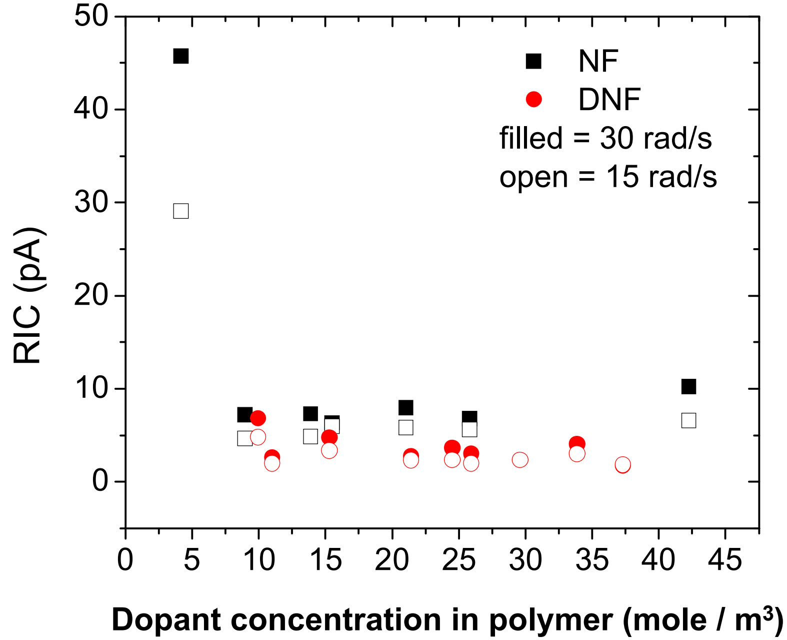
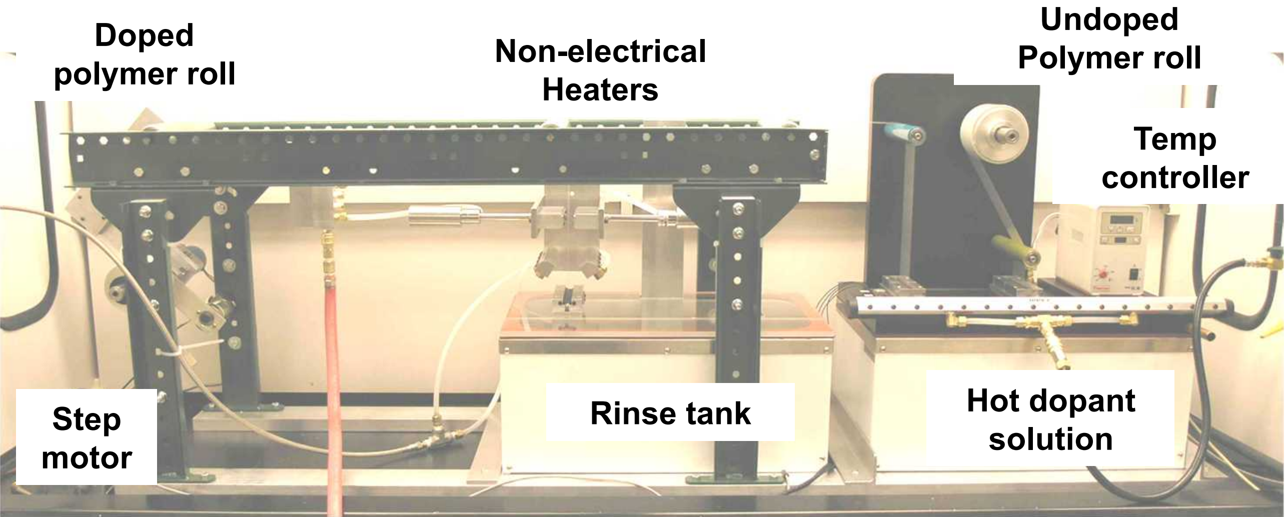
Science to Application





1. Develop adsorption – diffusion model to extract D_{dop} and K_{ads}

2. Investigate concentration dependence of RIC



3. Use information to outline processing windows and design pilot – scale manufacturing operation

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Radiation Shielding with Particulate Filled Polymer Composite Encapsulants, Coatings, Structural Materials

Issue

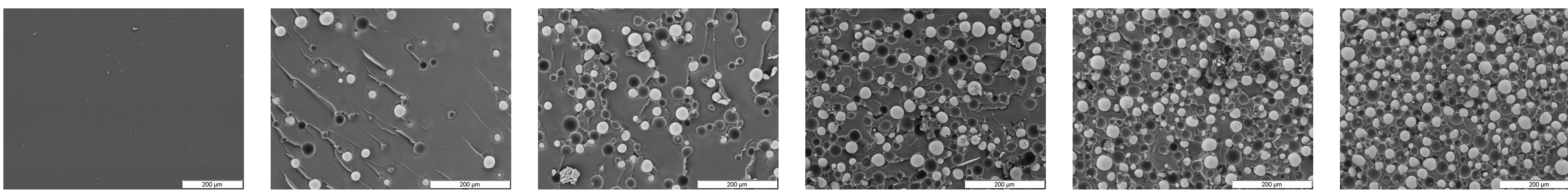
- Need for devices to function in various radiation environments
- Need flexible processing approaches and light weight materials

Objective

- Develop polymer composites composed of high-Z fillers dispersed in polymer matrix
- Verify radiation shielding performance
- Investigate processing approaches

Advantages

- Reduced mass / volume
- Localized shielding
- Simple and flexible processing for wide range of applications
- Complex geometries



0 % | 10 % | 20 % | 30 % | 40 % | 50 %

Electron Shielding

X-ray, Gamma, Proton Shielding

EMI Shielding / Conductivity

Shielding from a variety of radiation environments

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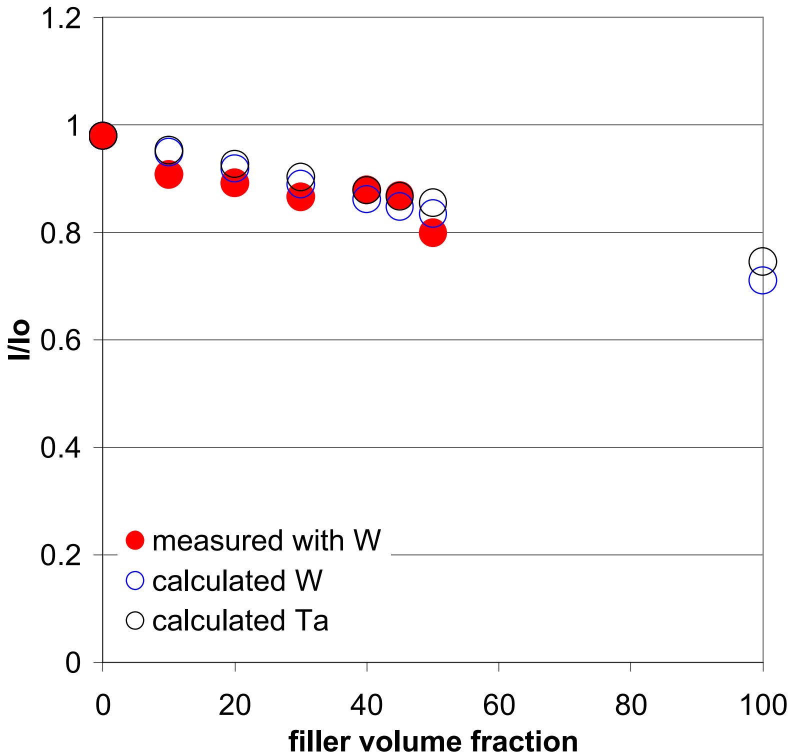
X-ray / Gamma Radiation Attenuation

1. 0 to 50 vol% tungsten loading in silicone
2. Attenuation measured for ~ 1.3 MeV gamma radiation
3. Calculated mass attenuation coefficients from NIST data base
4. Excellent agreement between measured and predicted attenuation



Attenuation as expected with Gamma radiation from Co^{60}

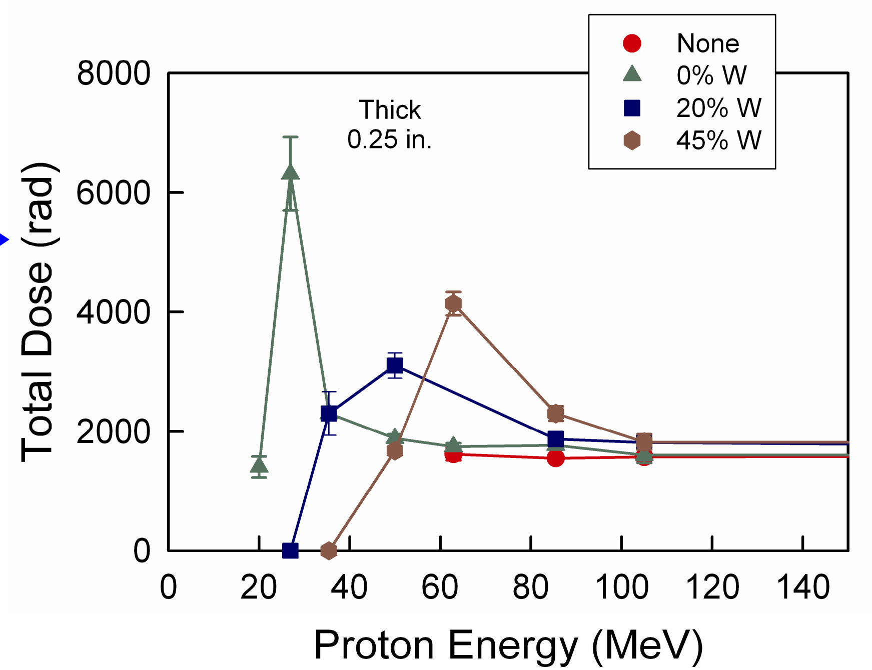
$$\frac{I}{I_0} = \exp\left[-\left(\mu/\rho\right)_{composite}\rho_{composite}x\right]$$

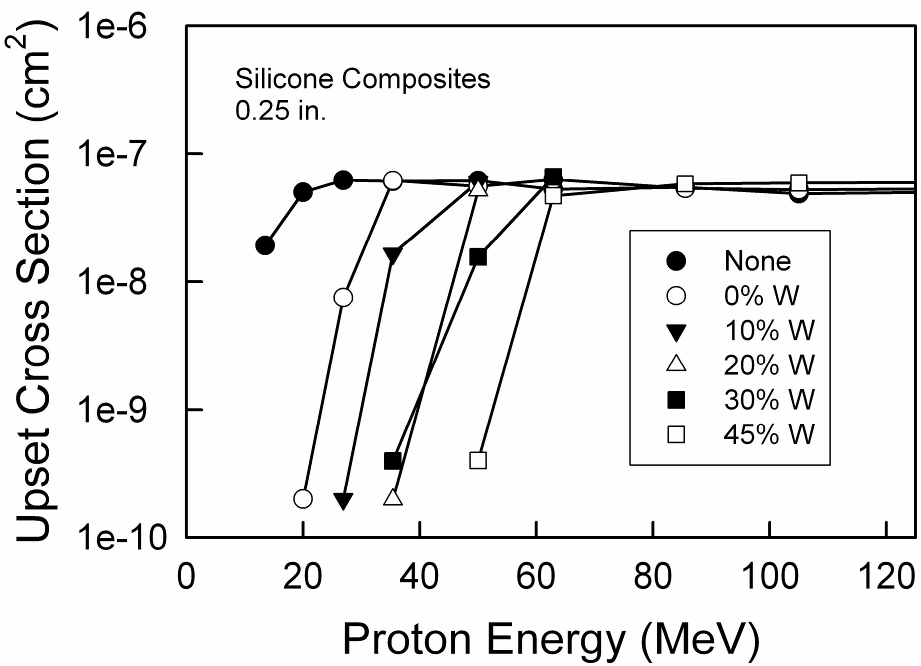
$$\left(\mu/\rho\right)_{composite} = \sum_i w_i \left(\mu/\rho\right)_i$$

- ***Modeling in combination with attenuation measurements will enable us to focus on relevant tungsten loading and coating thickness***
- ***Higher loadings are most effective***

Proton Shielding

- Measure dose with TLD behind composite
- Composite can reduce dose with low energy protons (< 60 MeV)
- High loadings and thick composites are better





- Measure upsets of integrated circuit behind composite
- Composite can reduce upsets with low energy protons (< 60 MeV)
- High loadings and thick composites are better

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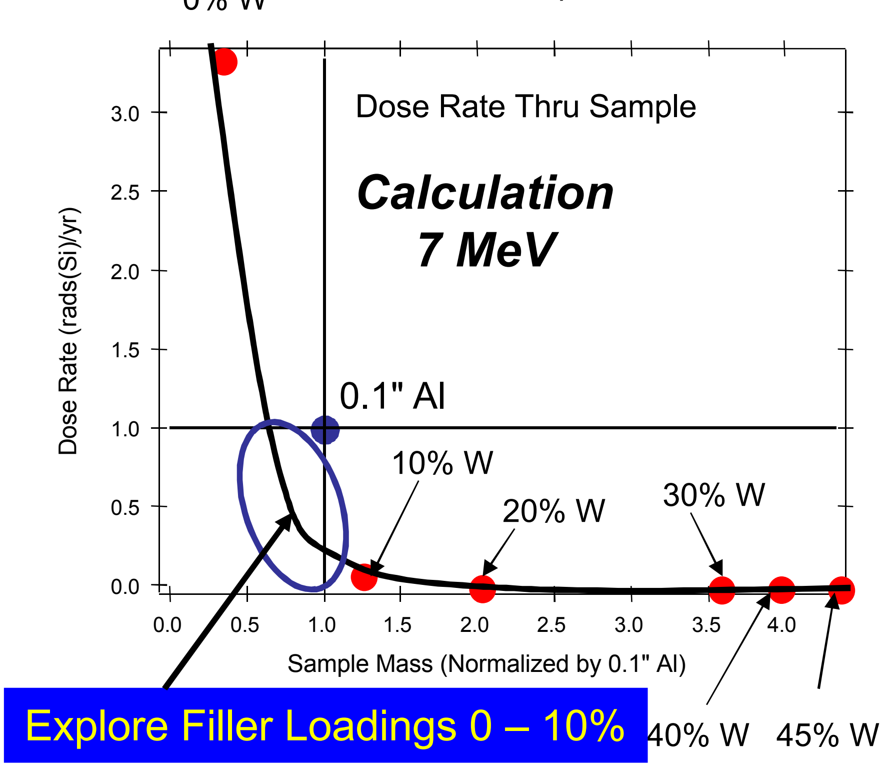
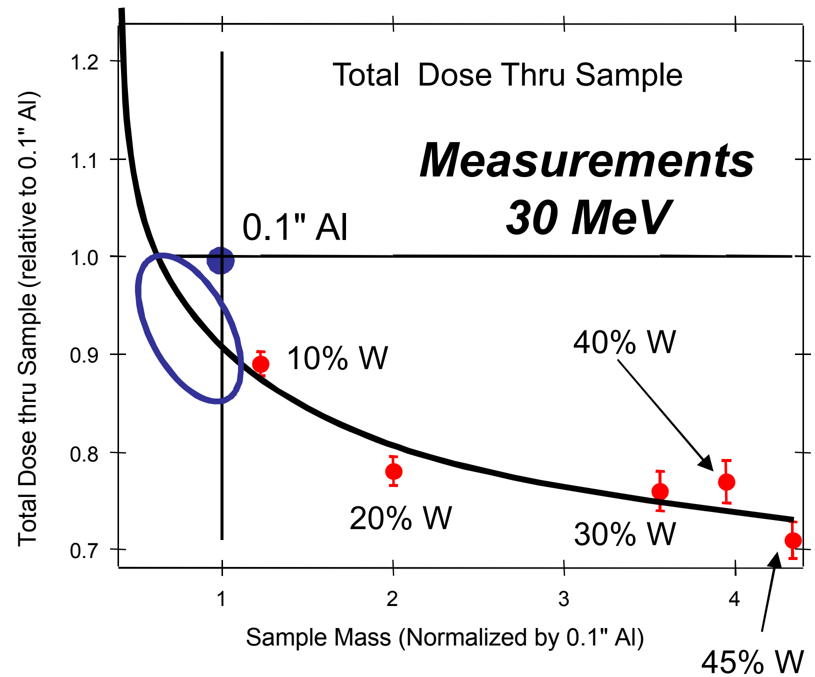
Initial Electron Shielding Results

1. 0 to 50 vol% tungsten loading in silicone polymer resin
2. Calculated electron attenuation at (7 MeV narrow distribution)
3. Measured attenuation for higher energy electrons (30 MeV broad distribution)





Conclusion: It is feasible to design tungsten loaded polymer composite with superior electron shielding ability and lower density than Aluminum (polymer chemistry is flexible ie. epoxy, silicone, others)

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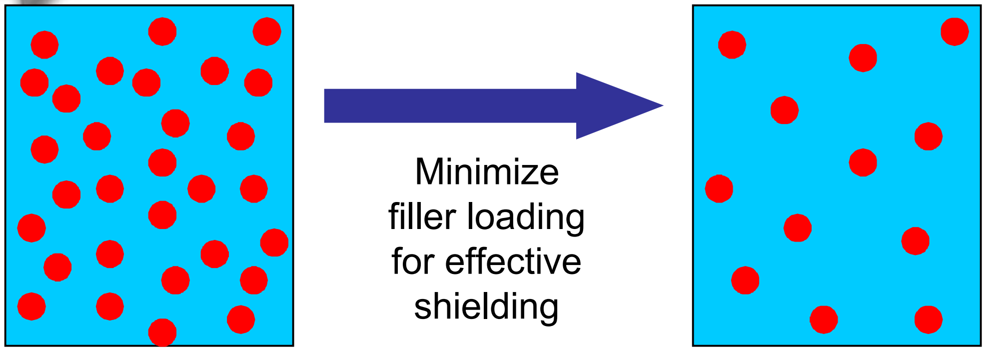
Low Density Composites for Electron Shielding

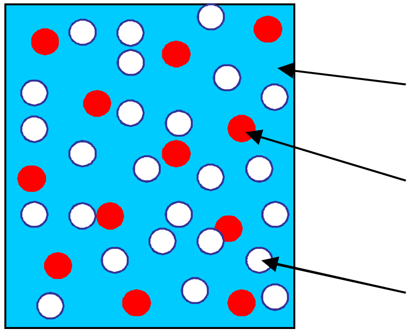


Step 1:

- *Investigate tungsten / tantalum loadings of 0 to 10 vol%*
- *Utilize minimum filler loading to obtain adequate shielding ability*

Step 2:

- *Incorporate mixed filler strategy to further reduce composite mass*
- *Small tungsten / tantalum loading*
- *High loading of glass microballoons (GMB)*



composite volume fractions			composite density (with GMB)	composite density (no GMB)	Percent Change with GMB
GMB	W	silicone			
0.38	0.02	0.6	1.0768	1.415	-24
0.36	0.04	0.6	1.4596	1.78	-18
0.34	0.06	0.6	1.8424	2.145	-14
0.32	0.08	0.6	2.2252	2.51	-11
0.3	0.1	0.6	2.608	2.875	-9

density (g/cc)			
GMB	W	silicone	Al
0.16	19.3	1.05	2.7

- *GMB / Tungsten composites less dense than Aluminum and provide superior shielding (verified with 10%)*
- *How will GMB impact attenuation*
- *40 vol% filler loading is still reasonable polymer viscosity for processing*

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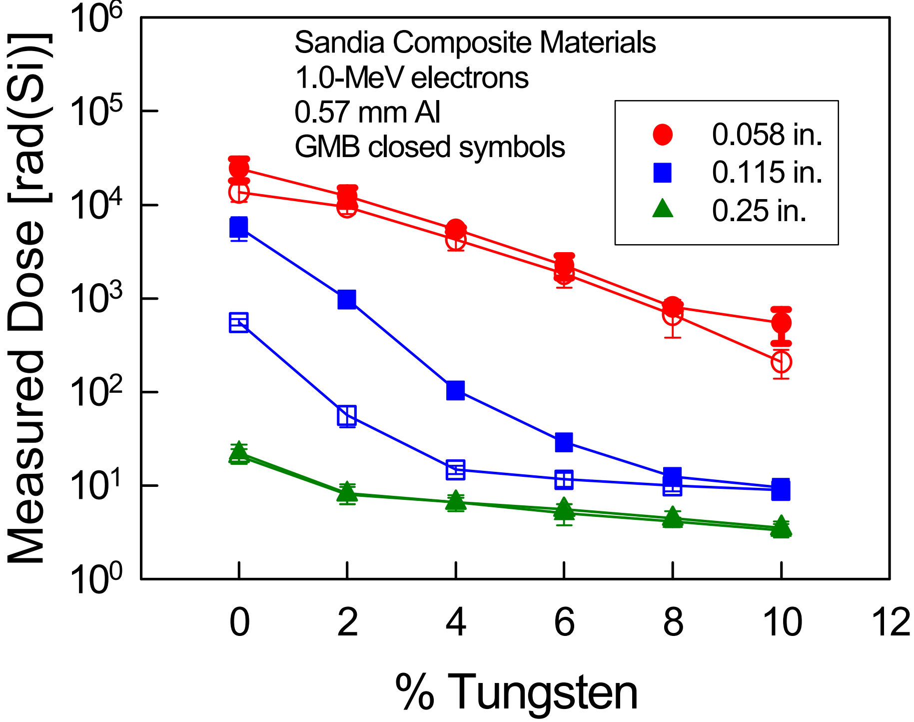
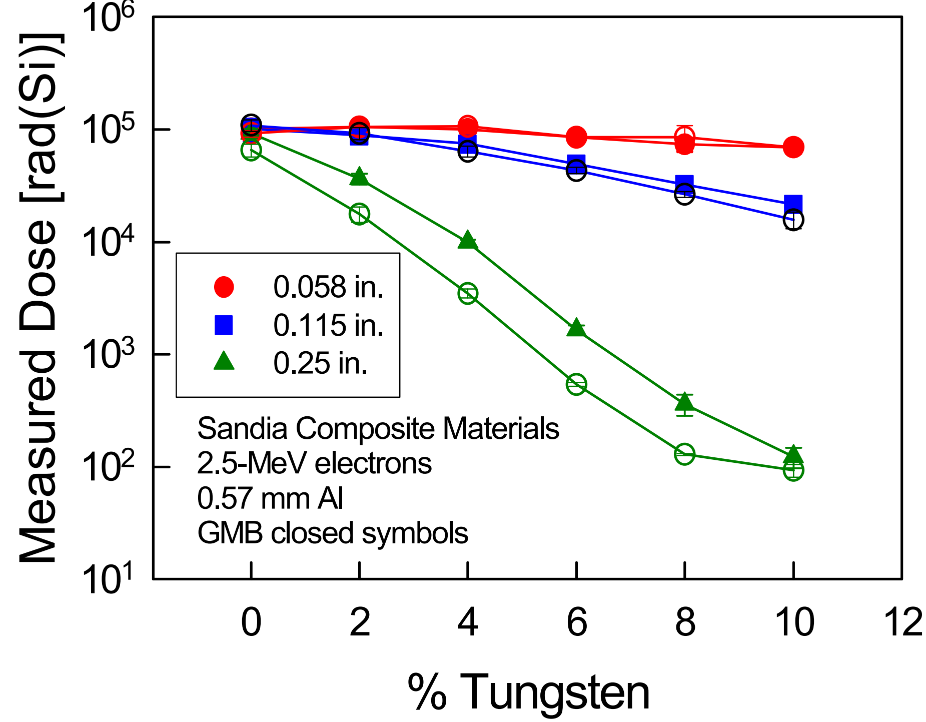
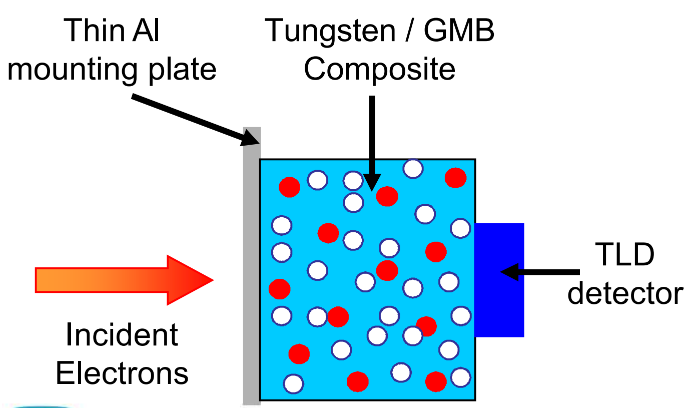
Electron Attenuation with Tungsten / GMB Composites

1.0 MeV incident electrons

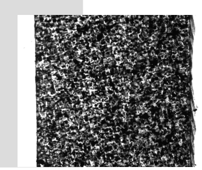


2.5 MeV incident electrons



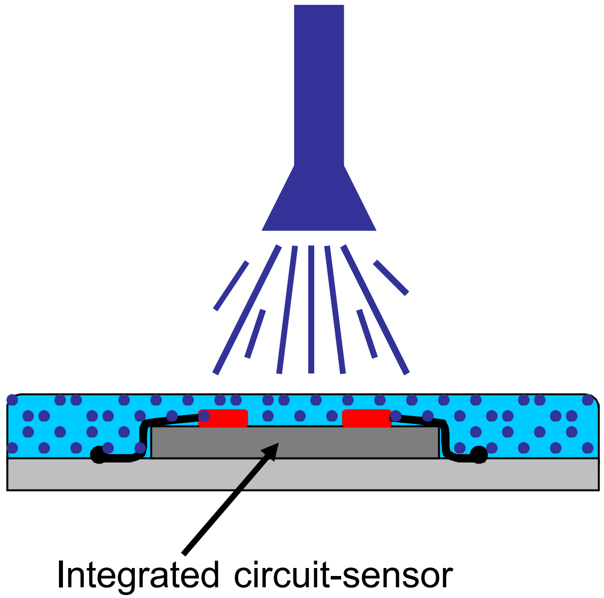


- Thicker composites and higher tungsten loadings increase attenuation
- All thickness and loadings provide some attenuation with 1.0 MeV electrons
- Thicker films and higher tungsten loadings required for attenuation of 2.5 MeV electrons
- Inclusion of GMB decreases attenuation (air verses silicone resin or microstructure?)



Processing Approach

1. Current Approach: Mix, degas, pour, and cure
2. Exploring incorporating fillers into pre-preg for structural composites
3. Need additional processing avenues to enable all potential applications

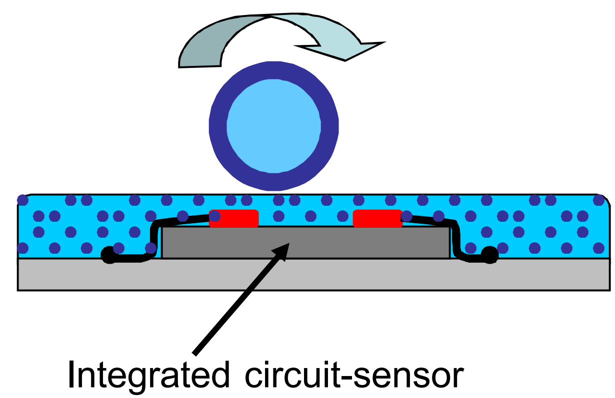


Path 1:

- *Traditional "Spray Applied" coating*
- *Polymer/filler mixture in solvent sprayed onto surface with solvent evaporation*
- *Challenge: Optimizing process to spray uniform polymer-filler coating*

Path 2:

- *Non-traditional "Brush Applied" coating*
- *Polymer/filler mixture rolled or brushed onto surface*
- *Challenge: avoid damaging sensitive electronic devices*



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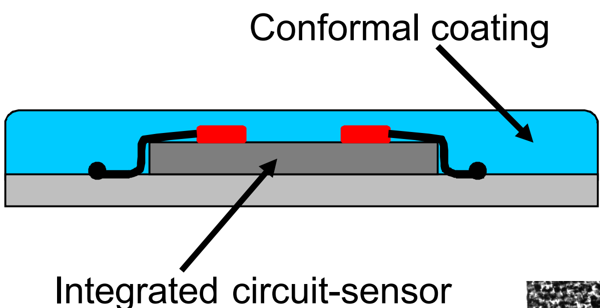
Conformal coatings for localized "spot" shielding offer potential for large weight savings

Uses for Polymer Composites:
- *Structural composites for global shielding*
- *Conformal coatings for "spot" shielding*



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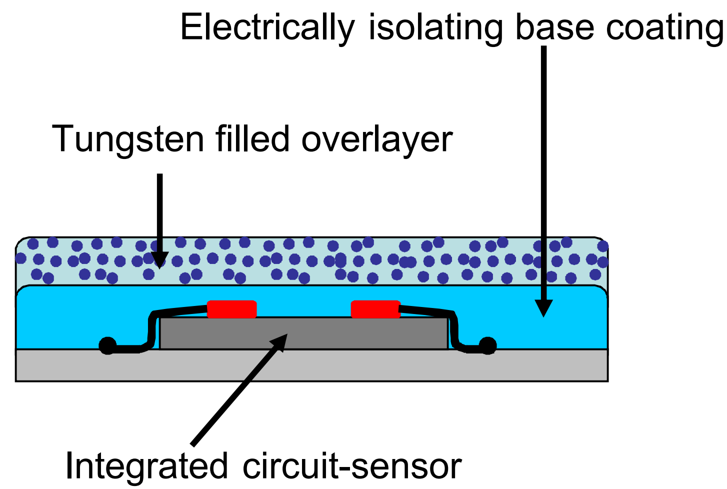

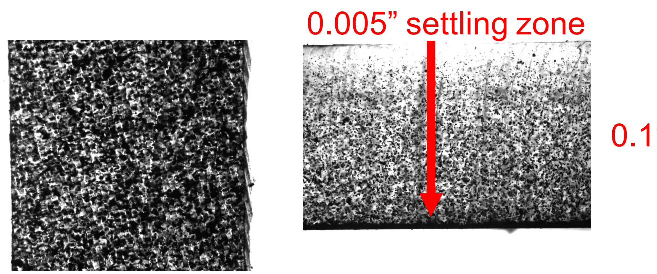

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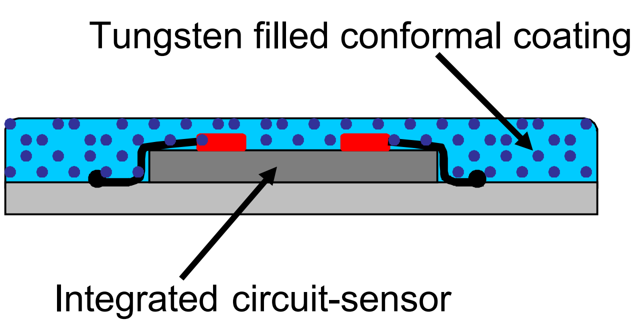

Advantages
- Simple implementation
- Less concerns with particle distribution and layer conductivity

Challenges
- Additional processing step
- Overlayer-base coat compatibility

Issues for Spot Shielding
- Settling
- Transparency

Advantages
- Single step processing
- Integrate with current conformal coatings

Challenges
- Particulate settling
- Conductivity in conformal coating

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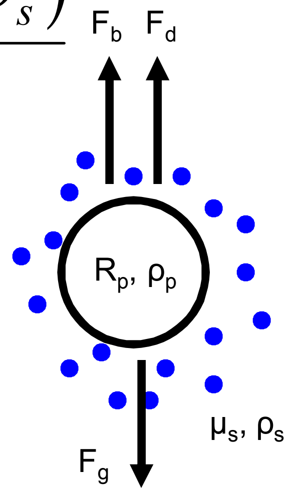
Processing / particle dispersion of composites can be controlled through particle and resin properties.

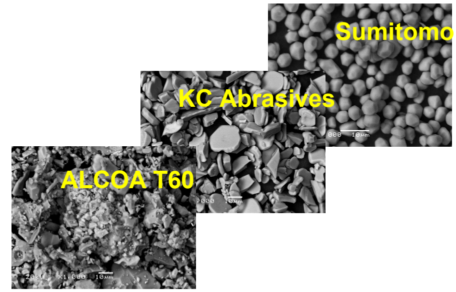
$$V_t = \frac{2gR_p^2(\rho_p - \rho_s)}{9\mu_s}$$

$$\downarrow \rho_p \Rightarrow \downarrow V_t$$

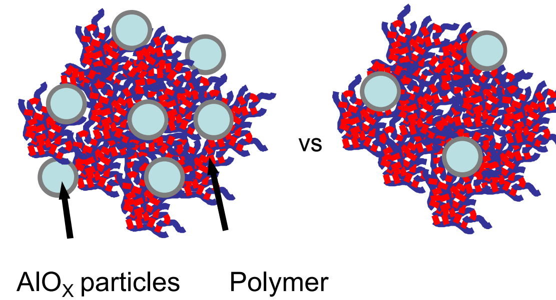
$$\downarrow R_p \Rightarrow \downarrow V_t$$

$$\uparrow \mu_s \Rightarrow \downarrow V_t$$

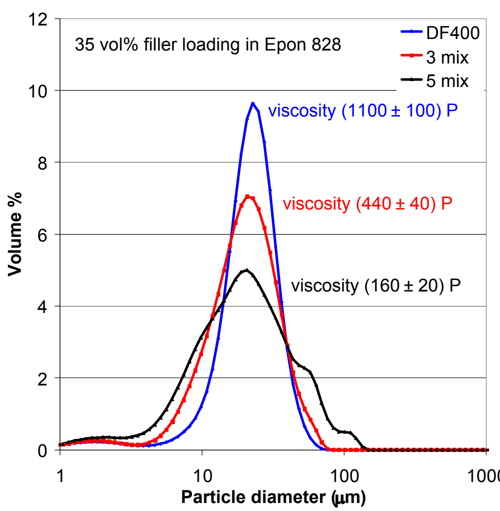


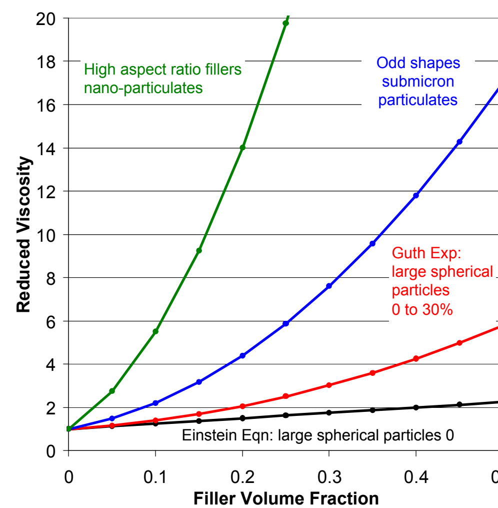


1) Particle shape, size, and size distribution



2) Filler loading





Solutions

- Less dense particles (higher loadings to increase viscosity, smaller V_t)
- Sub-micron to nano-particulates (smaller V_t, less transparency)
- Increase viscosity (longer Mw monomers, narrow particle size distribution, odd-shaped particles)
- High-Z oxide particulates (avoid electrical conductivity)

- Processablility and microstructure can be controlled through particle type, shape, size, size distribution, loading, polymer Mw, processing additives.

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Summary

1. Two approaches for operation of electronic devices in radiation environments

- Radiation tolerant polymers
- High-Z filled polymeric composites

2. Radiation tolerant polymers

- *Incorporate electron traps / donors*
- *Focus on polymer dielectrics*

3. Particulate filled high-Z / polymer matrix composites

- Effective at shielding X-rays, Gammas, Protons, Electrons
- X-rays, Gammas, Protons require higher loadings
- Proton shielding sweet spot (10 to 60 MeV)
- Electron shielding with low loadings (<10 volume %)
- Mixed GMB / tungsten composites for lower density
- Future work to identify and refine potential processing strategies to enable wide range of potential applications