Sandia National Laboratories

Resilient Energy Systems Mission Campaign

Novel E1 Arresters for Electrical Grid Protection

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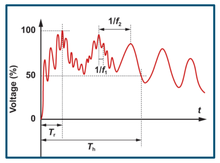
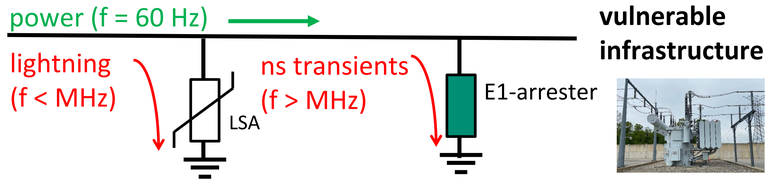
PROBLEM

Nanosecond high-voltage transients, including early-time electromagnetic pulses (E1-EMPs), threaten electrical grid reliability.



Unintended plasma arcs produce very-fast-front overvoltages (VFFOs).[1]

- Gas-insulated substation switching events
- Medium-voltage switchgear restrikes
- Insulation faults



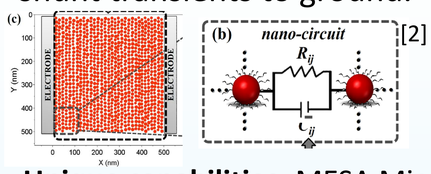
Lightning surge arresters' (LSAs) response time is ~100 ns

An additional ns arrester is needed with

- High breakdown strength (>MV/cm)
- Low conductivity, σ, at grid voltages and frequencies
- High σ at MHz/GHz frequencies and with overvoltages
- Large current carrying capacity (>kA/cm^2)

APPROACH

Granular metals (GMs) offer complementary tunneling and capacitive conduction paths to safely shunt transients to ground.



[2]

R_{ij} is tunneling transport
→ Low σ at grid conditions
→ High σ at overvoltages

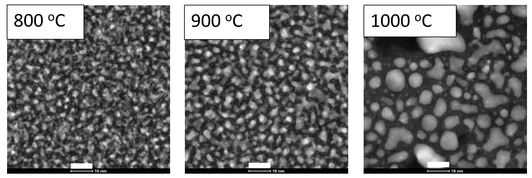
C_{ij} is capacitive transport
→ High σ at MHz/GHz

Unique capabilities: MESA Microfab, simulated E1 pulse testers in the *Electrostatic Discharge Lab*, 3 kV ns-pulse tester in the *Material Physics Lab.*

Technical risks: No commercial package design exists for high-voltage, high-frequency devices. Initial packaged GM devices have increased leakage currents.

Granular metal-based arresters shunt simulated E1 transients

Granular metals comprise a 3D ensemble of metal nanoparticles embedded in an insulating matrix.



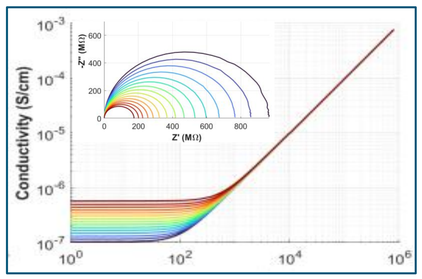
Scanning TEM images of annealed Mo-SiN_x GMs with Mo volume fraction, φ, = 0.4.

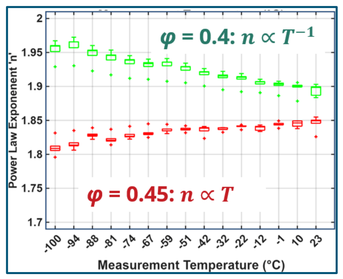
(Scale bar is 10 nm.)

Complementary conduction paths in GMs give rise to universal power law (UPL) response.[3,4]

UPL: $\boldsymbol{\sigma'(\omega) = \sigma_{dc} + A\omega^n}$, where *A* and *n* are temperature dependent fitting parameters; *n* is frequency-dependent as well.[2]

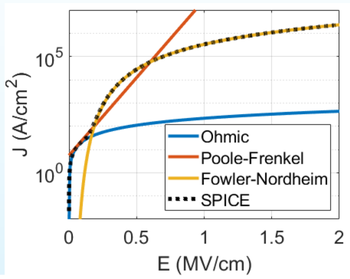
[5]



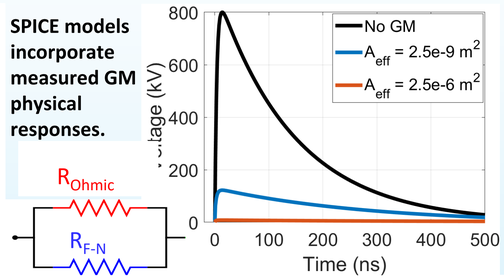


'n' represents tortuosity of charge transport path lengths through GM. Temperature controls the density of energetically favorable hopping sites. Behavior in *n(T)* gives insight on the synergy of trap mediated and direct tunneling transport.

Transport studies provide foundation for improved synthesis as well as device performance simulations.

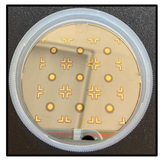


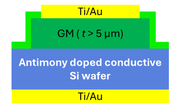
SPICE models incorporate measured GM physical responses.

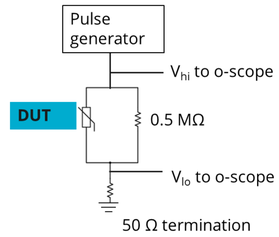


IMPACT

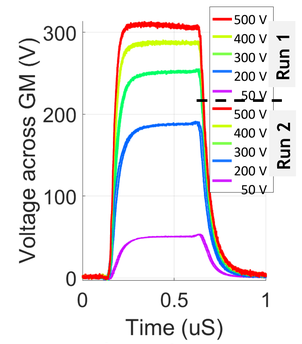
Reproducible voltage clamping of ns transients at >5 MV/cm.



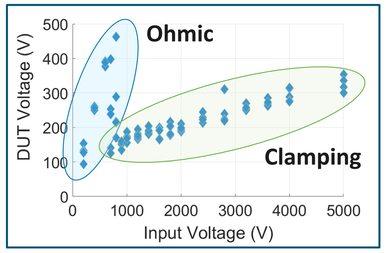




60% V_{input} at input 5 MV/cm



Resistive tunneling at high E-fields supports clamping at fields >0.2 MV/cm, shunting >0.5 kA/cm^2 to ground.



Two-Center Poole-Frenkel[6]

$$\sigma_{PF} \propto \exp(\frac{qE_a}{k_B T})$$

Fowler-Nordheim

$$\sigma_{FN} \propto \mathrm{E}^2 \exp(\frac{1}{E})$$

FUTURE DIRECTIONS

With SNL's PEAK lab, prototype compact arrester packages. Evaluate response of GM devices in parallel with ZnO MOVs.

Commercialization pathways explored through DOE Energy I-Corps interviews

- E1 EMP protection for defense critical electrical infrastructure is a potential beachhead market
- CIGRE and IEEE have identified VFFO-induced degradation of transformers as a growing concern

Future sponsors: ARPA-E, DOE CESER, DHS, DTRA

Other possible applications for SiN_x-based GMs: die/board level circuit protection, rad-hard memory selector devices, high-frequency inductors

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

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[1] IEEE Std 2426-2024, "IEEE Guide for Field Measurement of Fast-Front and Very Fast-Front Overvoltages in Electric Power Systems." [2] L. Merle *et al.*, *J. Appl. Phys.* **132**, 015105 (2022). [3] M. McGarry *et al.*, *J. Appl. Phys.* **136**, 055101 (2024). [4] S. Gilbert *et al.*, *J. Appl. Phys.* **137**, 065101 (2025). [5] M. Landi, *in progress.* [6] A. Calderoni *et al.*, *IEEE Electr. Device L.* **31**, 1023 (2010).

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