Nonlinear Resistive Field-Grading in Medium-Voltage Power Modules

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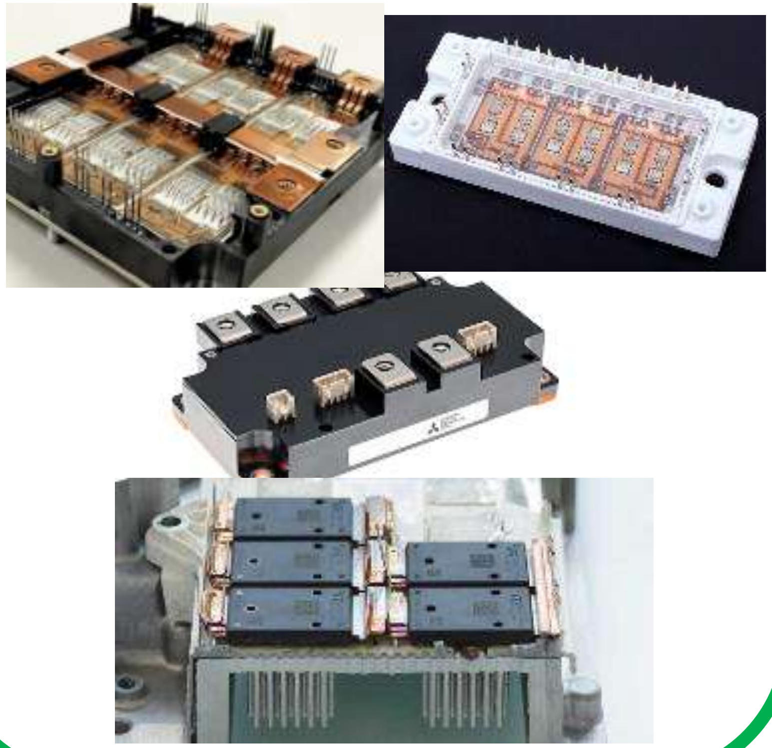
Power Modules – the ”Hearts” of Power Inverters/Converters

Mega-Watt Wind-Turbine Converter

Power Modules



100 – 200 kW EV inverter

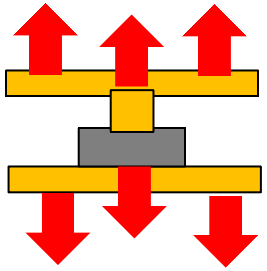
Mega-Watt Solar Inverter

Mega-Watt EV Charging Station

Efficiency, Power Density, Reliability, and Cost!

CPES's Three Strategies for Power Module Packaging

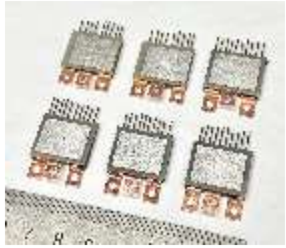
(1) Double-sided cooling: reducing θ_{jc} by > 30%.

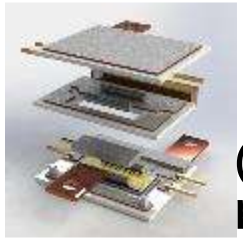


→ increasing q by > 40%.

Examples:

(1.2 kV, 150 A) SiC phase-leg modules





(650 V, 150 A) GaN HEMT phase-leg module

Denso or Mirise

Infineon power modules

(2) Increasing T_j: e.g., from 175ºC to 250ºC.

→ increasing q by > 70%.

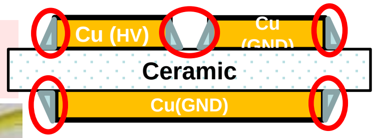
Sintered-Ag:

- Processing T < 250^oC
- Melting T > 961^oC
- Thermal conductivity > 5X
- Electrical conductivity > 5X

Ag paste and preform

Cu paste

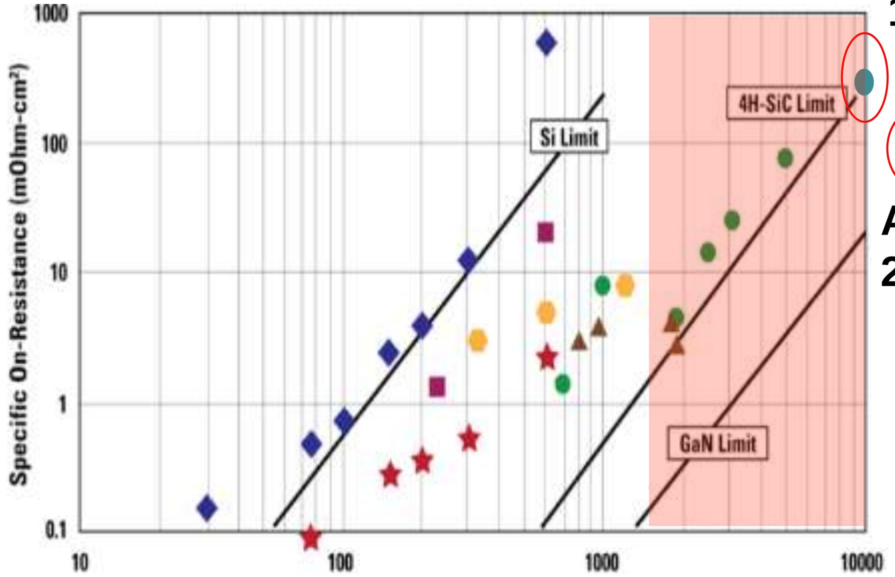
(3) Field-grading at substrate triple points.



→ PDIV ⬆ by 50 – 100% w/o thickening the substrate → q ⬆ by 50 – 100%.

Polymer-nanoparticle composite coating

Medium-Voltage Power Devices/Modules and Applications

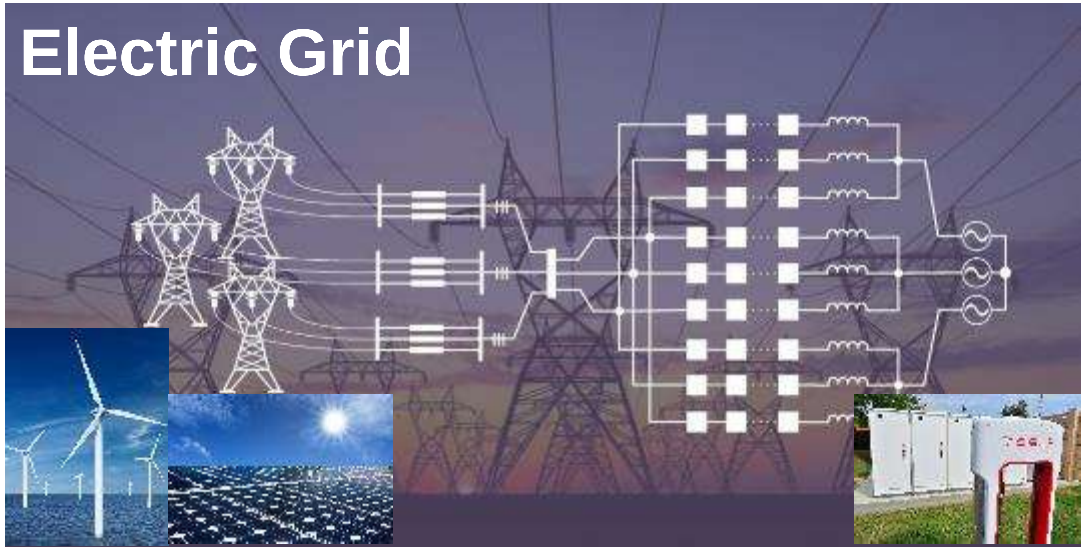


Reverse blocking voltage

Cree's
10-kV SiC

ARPA-E's
20-kV GaN

10 kV SiC
Module



HVDC Thyristor Valve Building in China's 800 kV Power Station

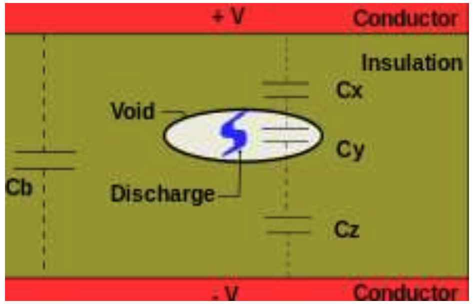
Fraunhofer IIS's 30-kV Modular Multilevel Matrix Converter for DC-AC/AC-DC

Insulation: Key Challenge for Packaging MV Modules

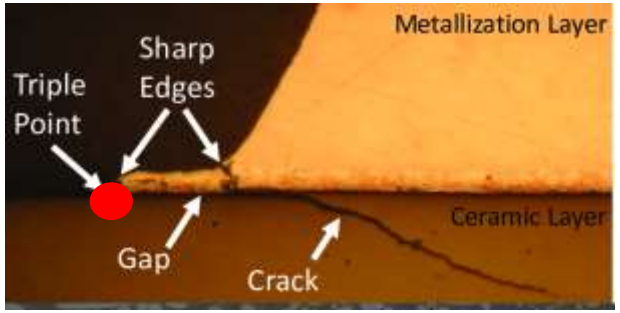
Ionization and Electrical Discharge in Insulator

Gas/fluid exposed to high electric field:

Condensed phase exposed to high electric field:

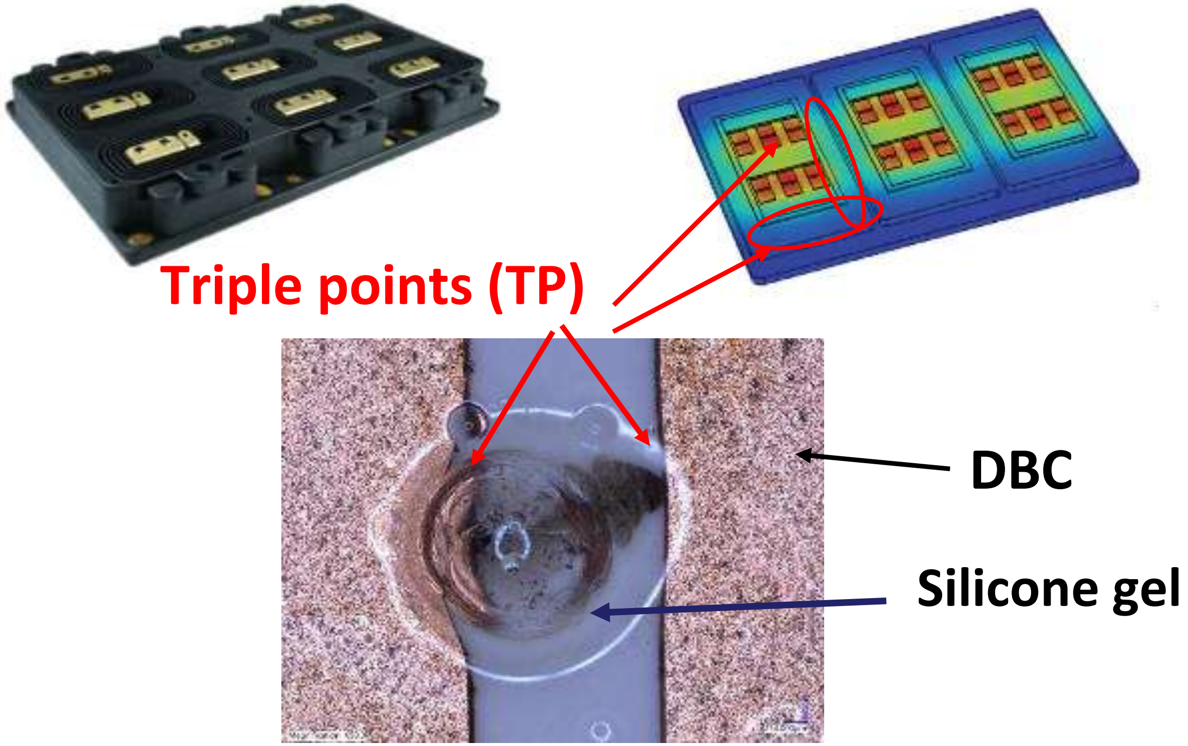


Void in insulation



Field concentration at triple point → PD

Cree/Wolfspeed 10 kV SiC Power Module



PD events degrade the insulation material → dielectric fatigue → dielectric breakdown

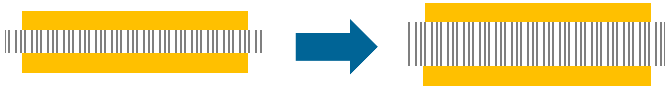
Partial Discharge Inception Voltage (PDIV) and How to Increase

Partial discharge inception voltage (PDIV) of a material or module is the lowest voltage at which partial discharges occur when the applied voltage is gradually increased from a lower value. (Analogous to the yield strength of a material.)

How to increase the PDIV of a module?

Geometric Field-Grading

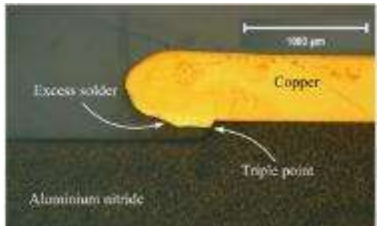
- ○ Thickening or stacking substrates
- ○ Altering the shape of the electrode



~ 70% PDIV increase

(DiMarino, *et al.*)

~ 90% PDIV increase



(Lab of Ampere, France)

~ 26 % PDIV decrease

- × Cost and Tolerance
- × Thermal performance
- × Reliability

Material Field-Grading

- ✓ Capacitive (high *k*), $D = (\varepsilon_o k) E \rightarrow E = D/(\varepsilon_o k)$
- ✓ Resistive (linear or <u>nonlinear</u>).

Cond

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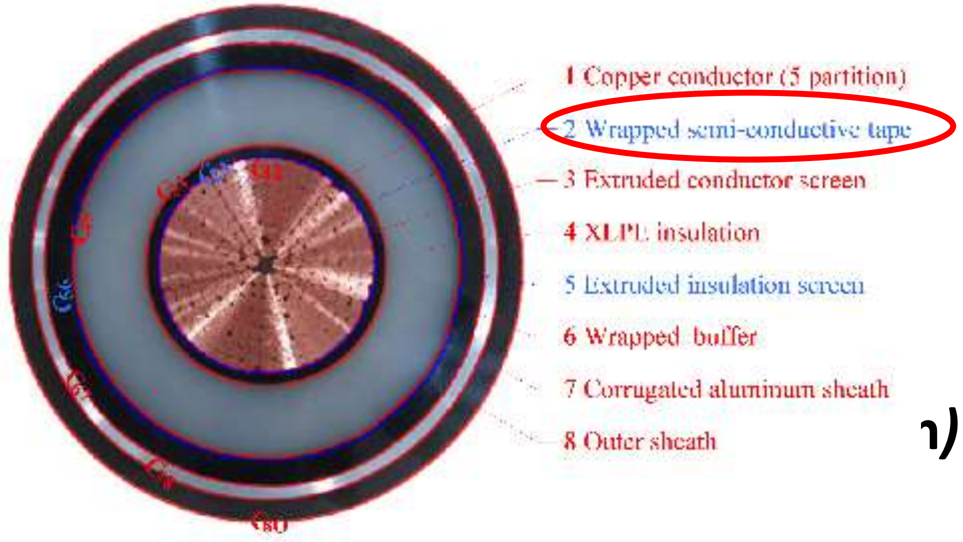


)

Field-Grading by Nonlinear Resistive Materials

Earlier Work:

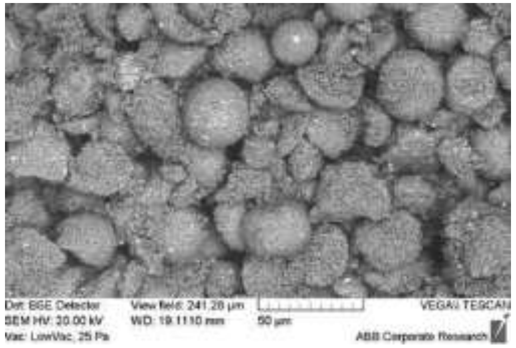
- **Theoretical**
  - ✓ **T. Christen, L. Donzel, and F. Greuter, *IEEE Electr. Insul. Mag*., 2010.**
  - ✓ **L. Donzel and J. Schuderer, *IEEE Trans. Dielectr. Electr. Insul*., 2012.**

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial(\epsilon \boldsymbol{E})}{\partial t}; \quad \nabla \cdot (\epsilon \boldsymbol{E}) = \rho$$

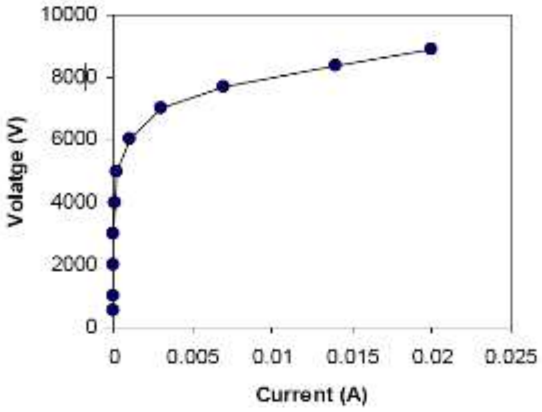
$$\nabla \cdot (\epsilon \boldsymbol{E}) = 0; \quad \nabla \cdot \boldsymbol{J} = 0$$

$$\boldsymbol{J} = \sigma(E)\boldsymbol{E}$$

- **Experimental**
  - ✓ **L. Donzel, F. Greuter, and T. Christen, *IEEE Electr. Insul.* Mag., 2011.**
  - ✓ **K. Li, B. Zhang, X. Li, F. Yan, and L. Wang, IEEE Trans Comp Packaging Manuf Technol., 2021.**



ZnO filled polyimide

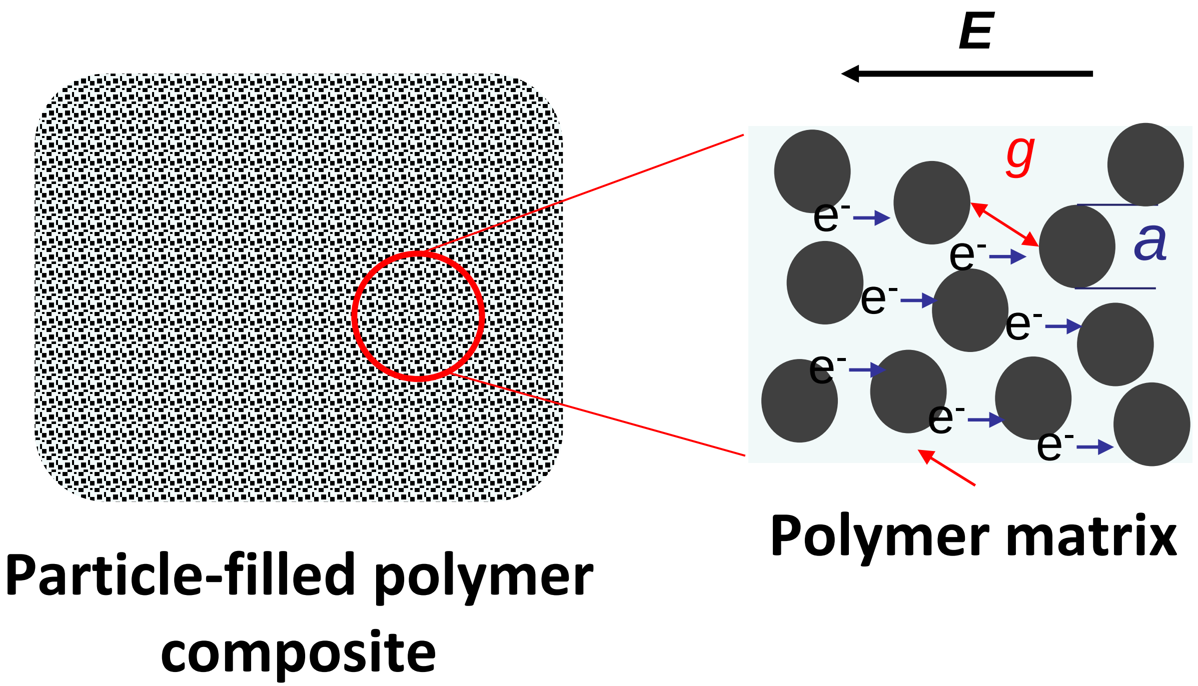


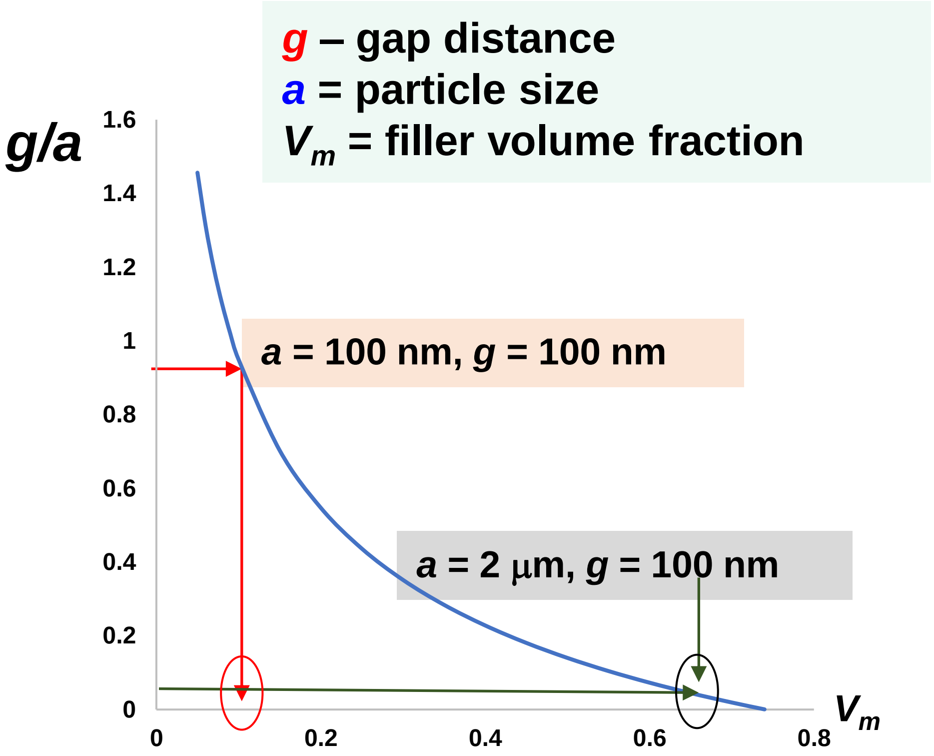
(EP + SiC) composite → 30%

But, only limited success for improving PDIV.

Our Hypothesis and Approach

- Nonlinear conductivity or resistive behavior of polymer-matrix composite comes from thermionic emission and/or tunneling of electrons through the polymer phase.
- Use micron- or submicron-sized conductive particles as fillers in a polymer matrix → high solid loading → high viscosity → air-bubble trapping at the triple point on the module substrate.





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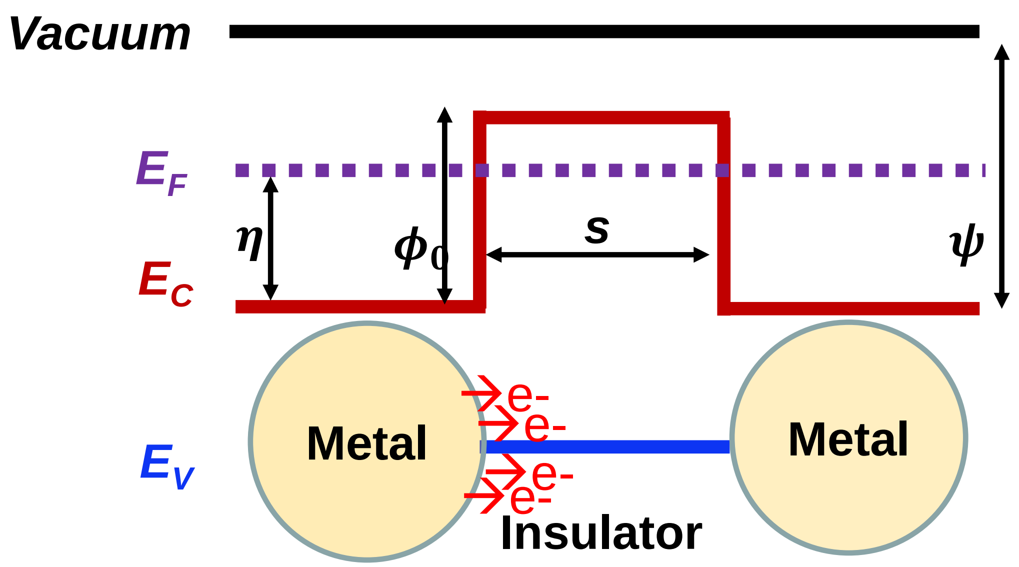
Metal-Insulator-Metal Conduction Model (Simmons, 1960's)

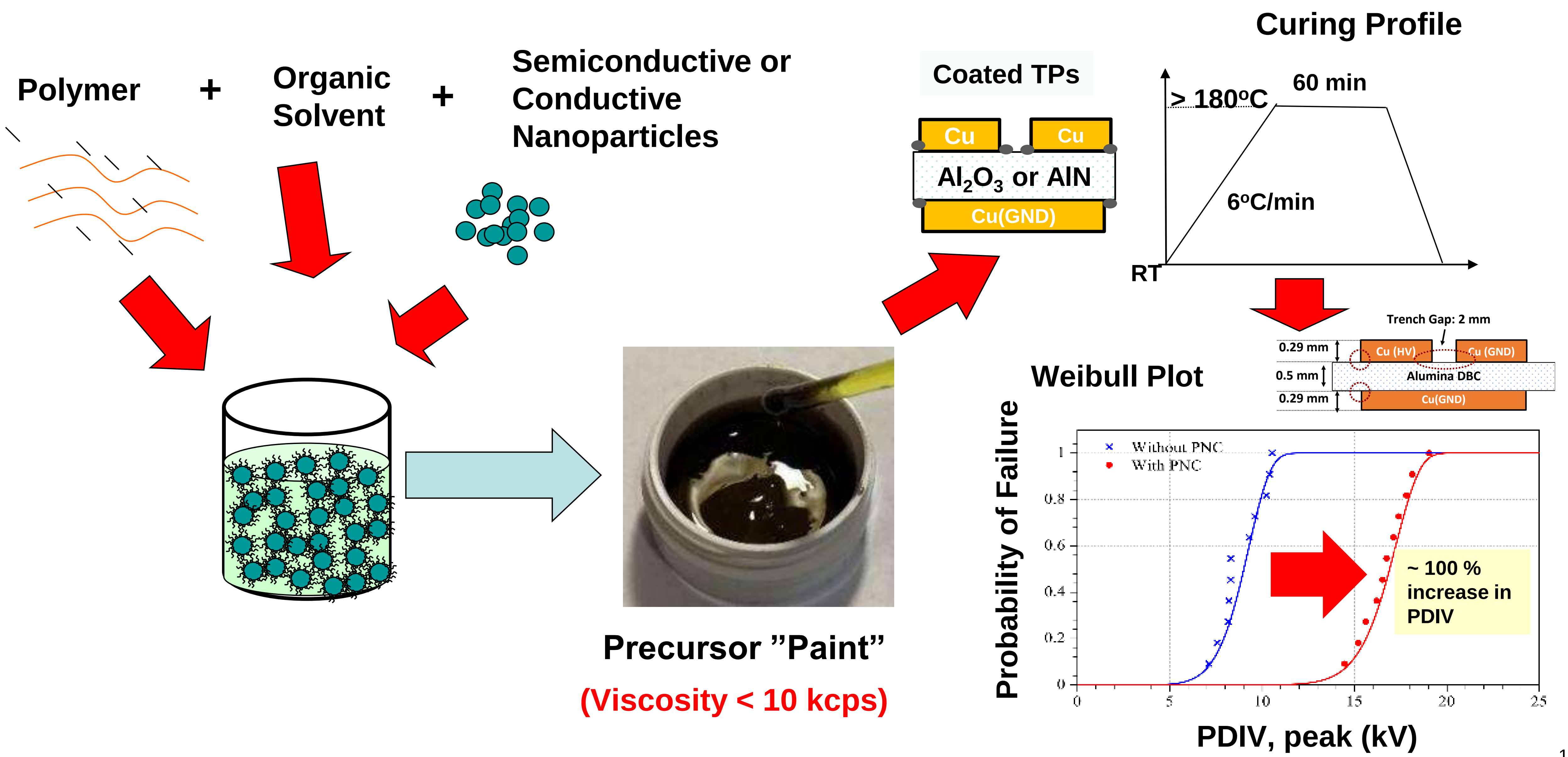


$$J_{\text{MIM}}(E) = J_{\text{Thermionic}} \times J_{\text{Quantum Tunneling}}$$

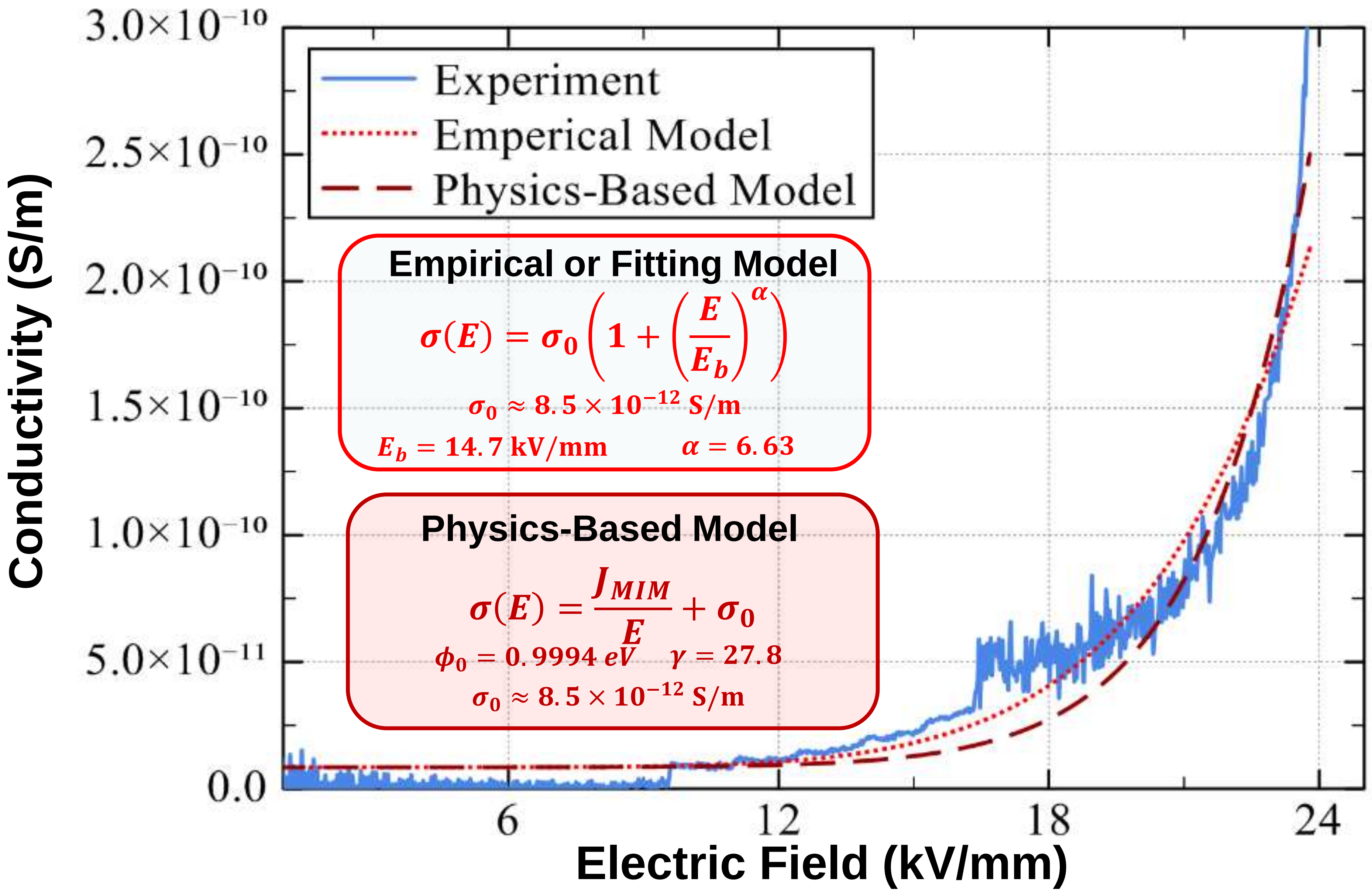
$$= AT^2 \exp\left(-\frac{\phi_0}{kT}\right) \times \exp\left[\left(\frac{14.4E\gamma}{\epsilon_r (kT)^2}\right)\right]^{1/2}$$

$$\sigma_{PNC} = \frac{J_{\text{MIM}}(E)}{E} = f(E)$$

Development of a Polymer-Nanoparticle Composite (PNC)

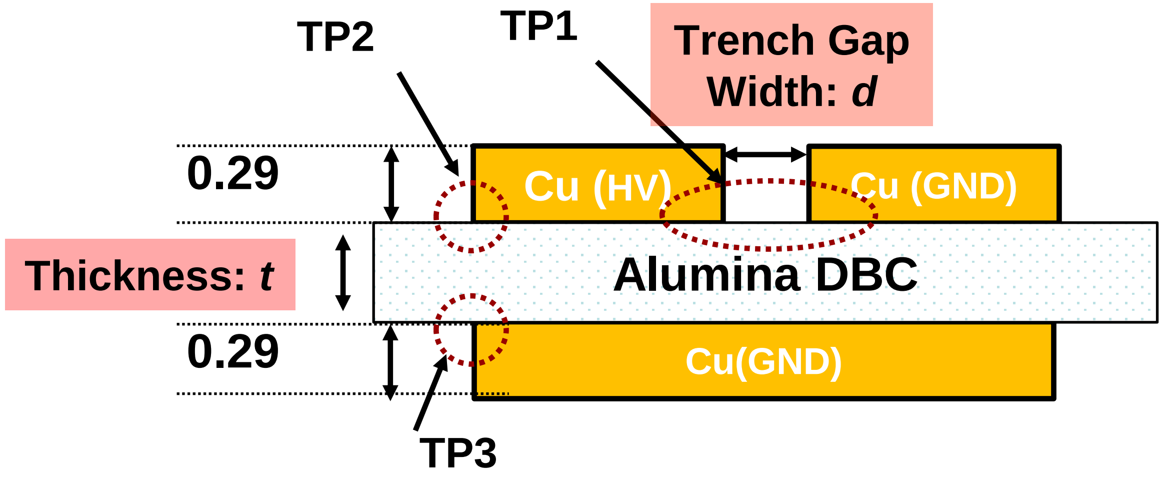


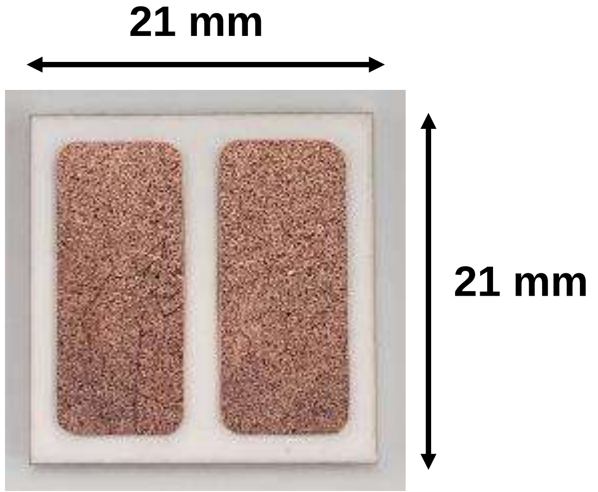
Verification of Nonlinear Resistive Behavior of the Coating



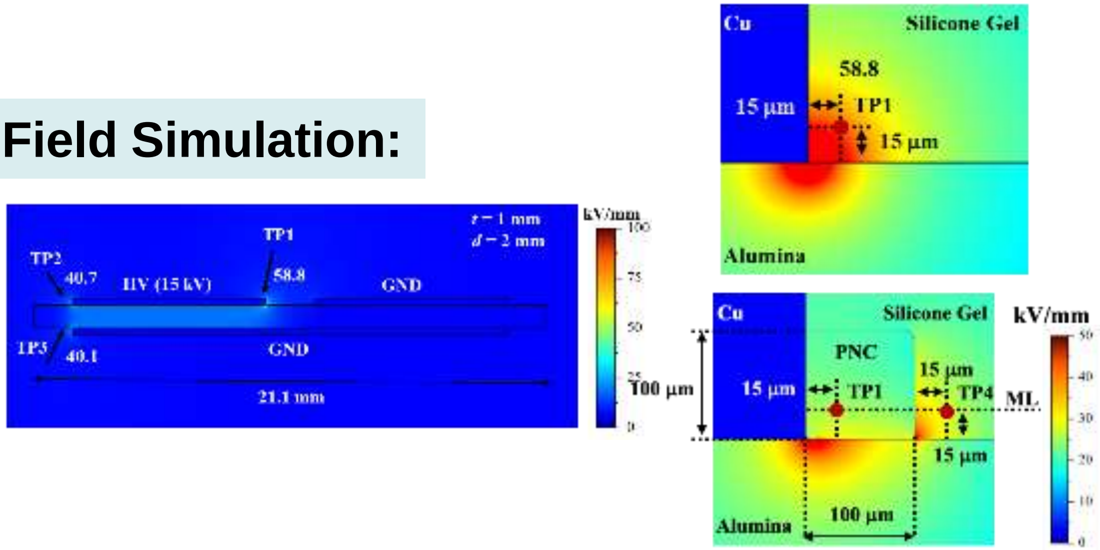
Further Study of the Effect of Coating on PDIV

❖ Effects of: (1) trench gap width, *d*; and (2) ceramic thickness, *t*.





Field Simulation:

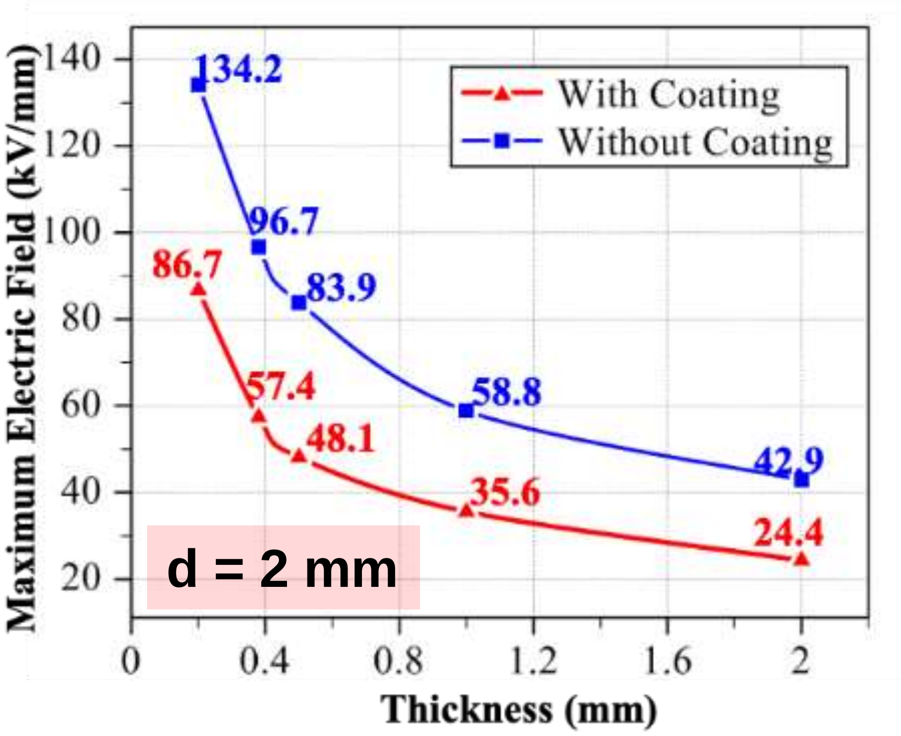


Experiment:

Parameter	Studied Value (mm)
Thickness, t (@ d = 2 mm)	0.38, 0.5, 1.0
Gap width, d (@ t = 1 mm)	2, 3, 5

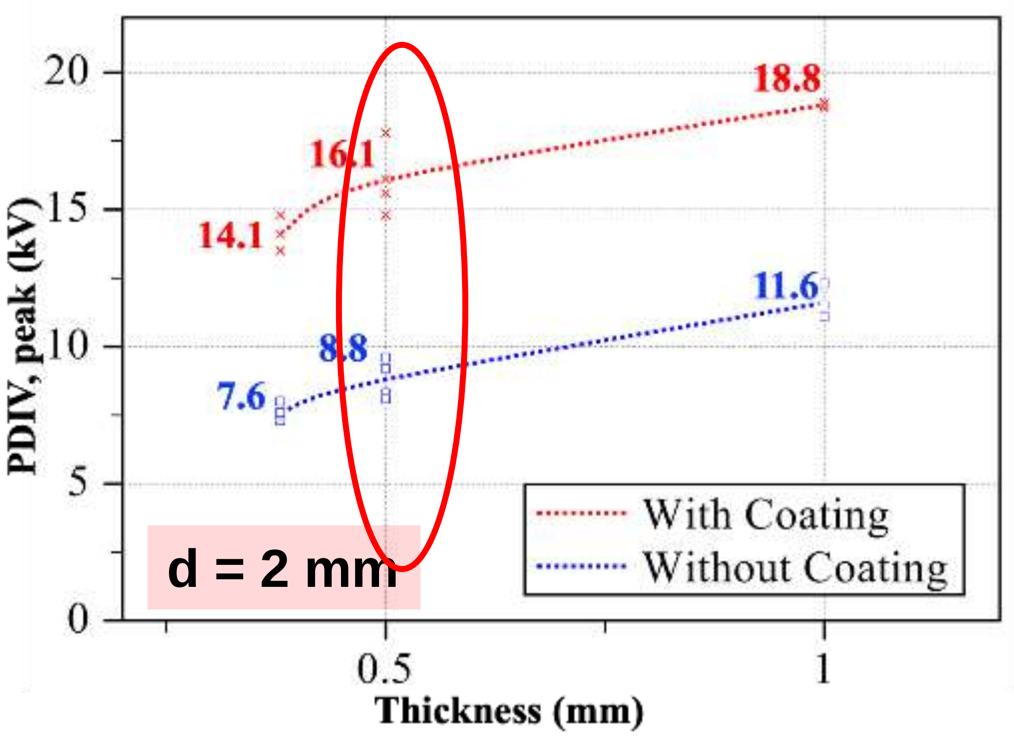
Effect of Alumina Thickness, *t* (@ *d* = 2 mm)

- **Field Simulation:**



- The PNC coating reduces the electric field intensity at the triple point by > 40%.

- **PDIV Measurement:**



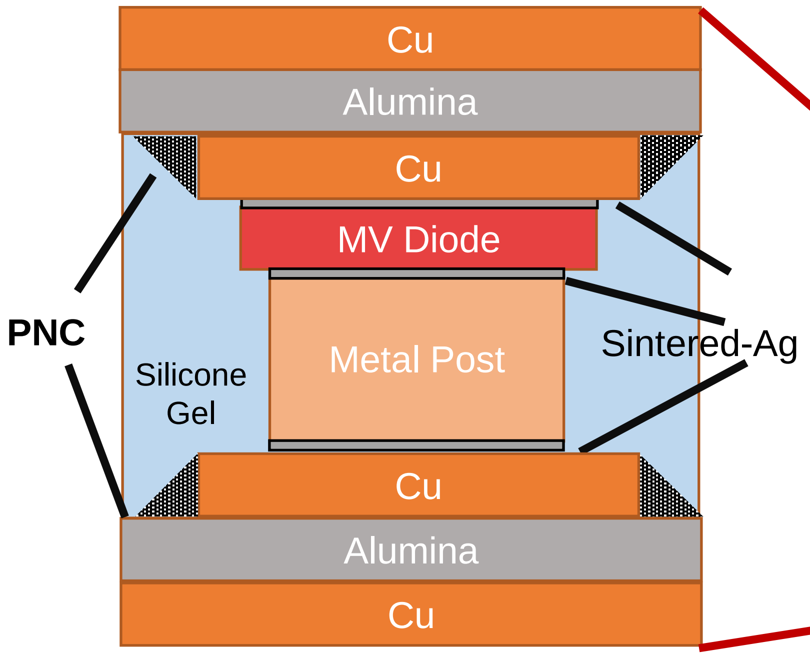
- The PNC coating increased the substrate PDIV by 62% to ~100%.

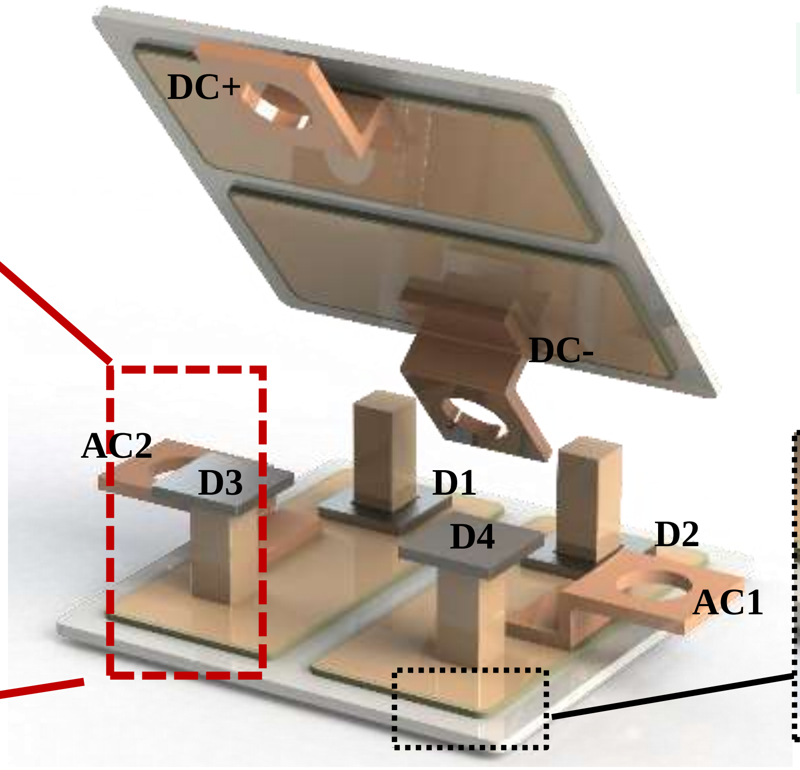
Packaging of a 10-kV SiC Full-Wave Diode Rectifier Module

❑ Key Features:

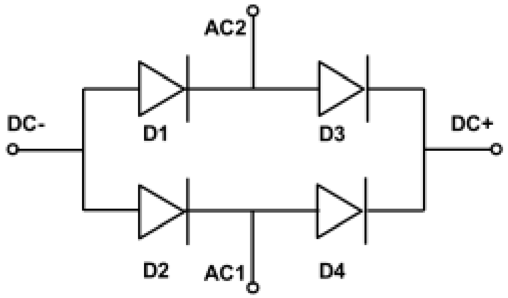
- ❖ Double-sided cooling; → P_d ↑ by > 40 %.
- ❖ T_j > 200°C with sintered-Ag device interconnection; → P_d ↑ by > 70 %.
- ❖ PNC-coated DBC substrates with 50% thinner ceramic (1.0 mm to 0.5 mm). → P_d ↑ by > 40 %.

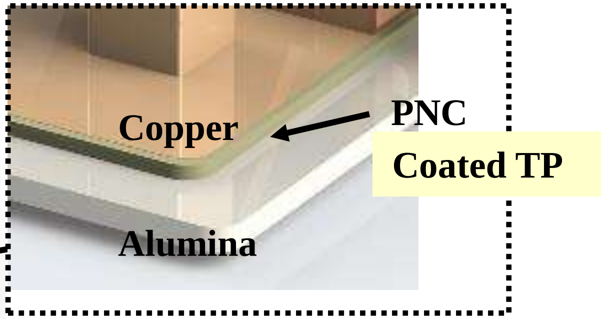
❑ X-Section of the Interconnect





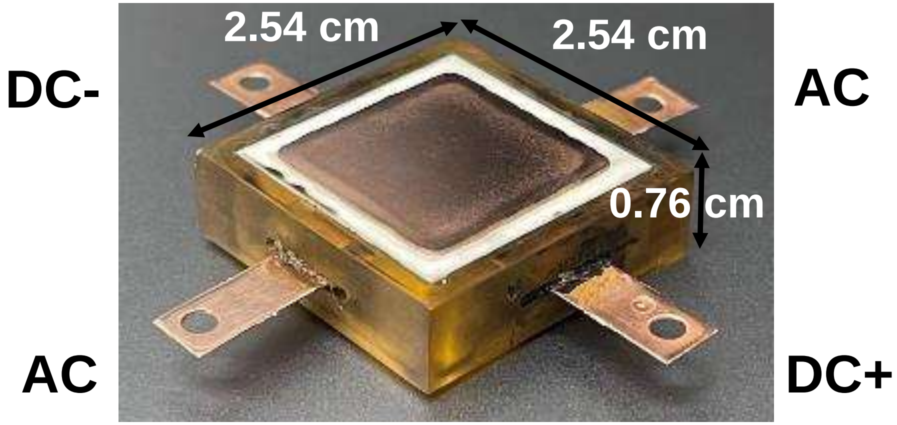
Full-wave rectifier



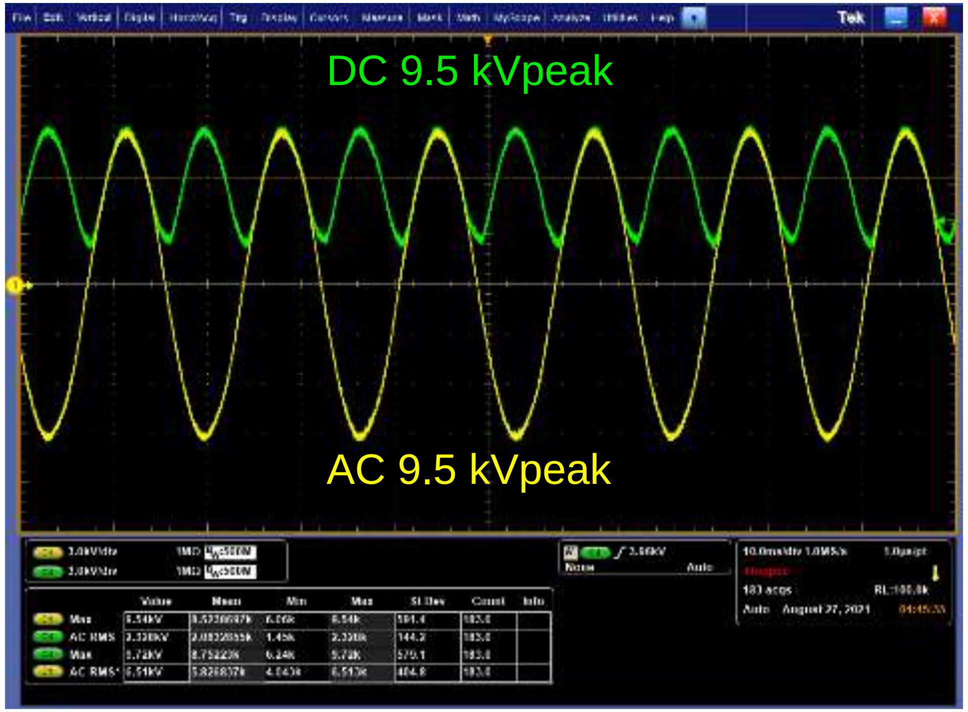


Full-Wave Rectification of the 10-kV SiC Module

10 kV SiC Full-Wave Diode Module

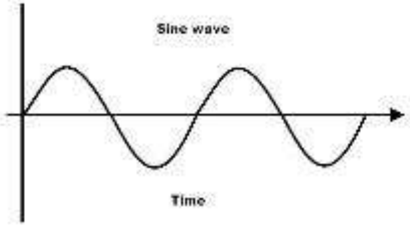


Rectified Waveform



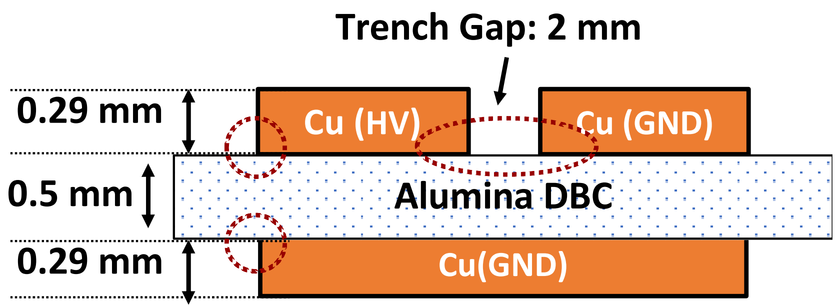
Test Setup

9.5 kV peak, 60Hz AC input



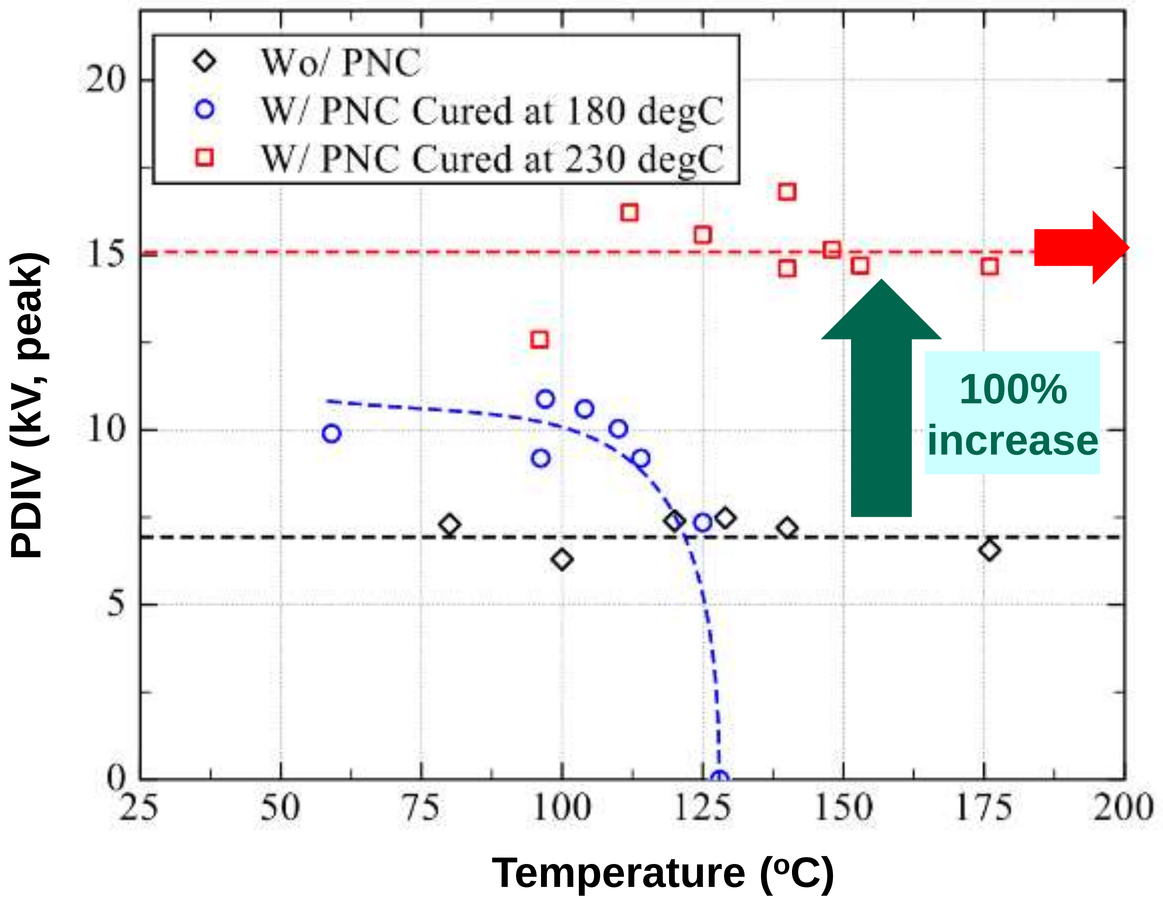
40 kV differential probe (Load)

Effect of Curing Temp on PDIV Improvement at Elevated Temp



Sample	Coating	Max Curing Temp
Group 1	N	N/A
Group 2	Y	180 °C
Group 3	Y	230 °C

Substrates were encapsulated in a silicone gel.

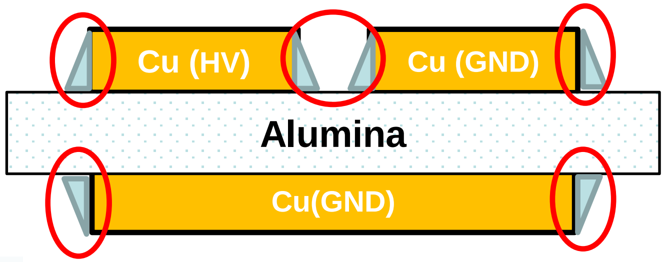


Conclusion: the nonlinear resistive polymer-nanoparticle composite remains effective for field-grading or improving PDIV at > 175 °C.

Summary

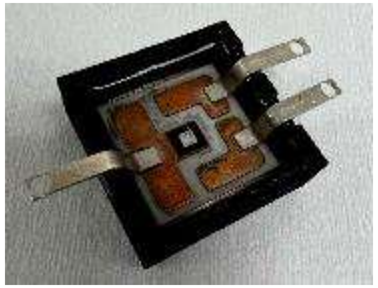
Polymer-Nanoparticle Composite "paint" solution with low viscosity < 10,000 cps

PNC-Coated Substrate Triple Points



~100% increase in the PDIV of the substrate encapsulated in a silicone

15-kV SiC MOSFET Package



Future Work

- ❖ Evaluate the reliability, both thermo-mechanical and voltage endurance, of the PNC-coated substrates.
- ❖ Further understand the physics of the nonlinear behavior and tailor the material properties for different applications.

Thank you for your attention!

Questions or Comments?

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- **Funding from ARPA-E (DE-AR0001008)**
- **Dr. Jiayu Xu and Mr. Carl Nicolas**

VIRGINIA TECH

Climate Change and Power Electronics

- **WHO: “Climate change is the biggest health threat facing humanity, threatening the progress in development, global health and poverty reduction made over the past 50 years.”**


- **“Strong and sustained reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases would limit climate change.”**


- **Power electronics plays a crucial role in the solution to limit climate change by (1) connecting renewable sources to the grid and (2) powering the transportation electrification revolution.**