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Toward Partial Discharge Reduction by Corner Correction in Power Module Layouts

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Motivation

Multi-Chip Power Modules

- High power density
- High switching frequency
- Challenging layout design
- Significant electrical parasitics and thermal effects
- Also, significant electrical stresses, thermo-mechanical strains, and electromagnetic effects causing reliability issues

Application areas

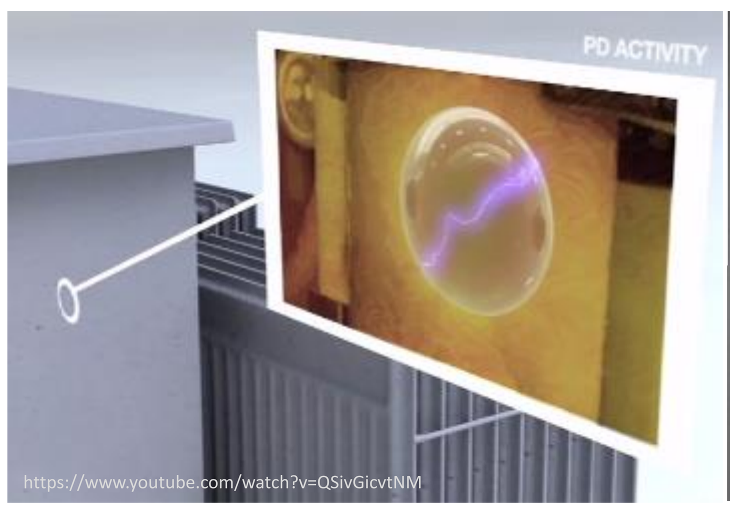
- Hybrid vehicles
- Aerospace
- Defense
- Renewable energy technologies
- Digital computing

The Problem

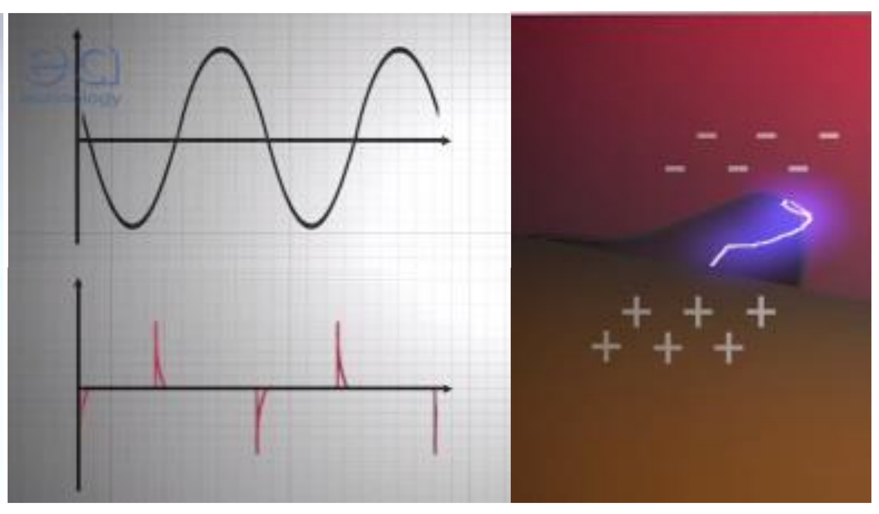
Partial Discharge

Partial discharge (PD) is the localized electrical breakdown of a small portion of insulation between two electrodes, but not the complete electrical breakdown of the insulating material.

PD activity at insulation material interface



PD activity in air bubble inside transformer oil



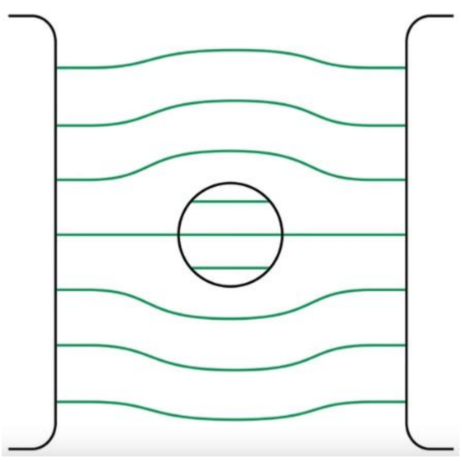
Voltage waveform and PD current spikes

CAUSE OF PARTIAL DISCHARGE:

Concentrated electric field lines (relatively higher electrical stress) in voids where the electrical permittivity is much higher than that of the surrounding area may lead to PD.

The void/gap may be air bubbles, and the insulating material may be solid or liquid.

The discharge phenomena is repeated every cycle and the voids may grow bigger due to charge bombardment during discharge, and high current leading to high temperatures that alter the chemistry of the material in that region.

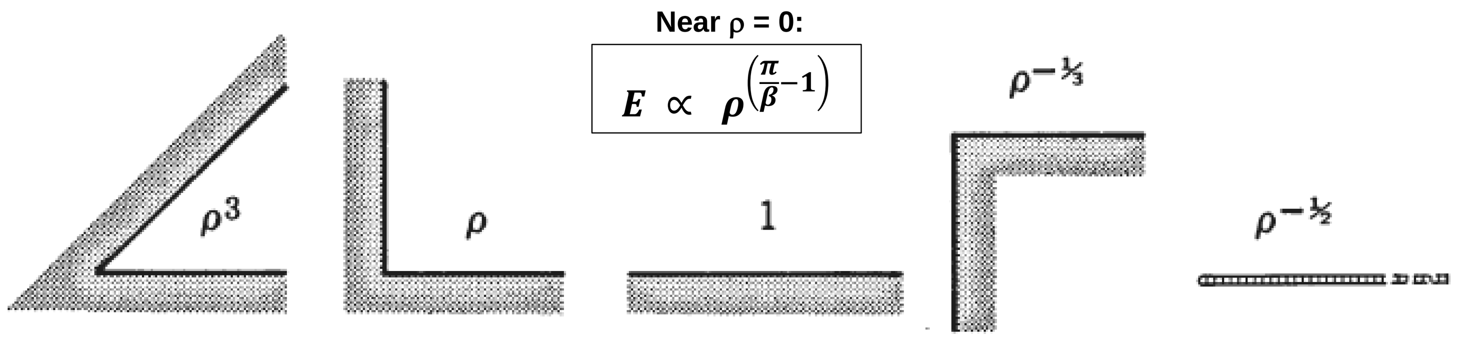


Concentrated E-field lines

E-fields can also concentrate in a region due to local charge densities that are relatively higher than the surrounding material. Example: At sharp corners and asperities in a conductor.

Near ρ = 0:

$$E \propto \rho^{\left(\frac{\pi}{\beta}-1\right)}$$



Theoretical model for E-field and charge accumulation near a corner, where β is the angle of opening between connecting conductors and ρ is the distance from the corner

J.D. Jackson, "Classical Electrodynamics," 2nd Ed., p. 77

EFFECT OF PARTIAL DISCHARGE:

PD within an insulator degrades the material, leading to reduced lifetime of the insulation. This makes power modules less reliable. This effect is exacerbated when operating at higher frequency, power, temperature, and altitude.

Ultimately, PD can cause complete electrical breakdown which may be catastrophic.

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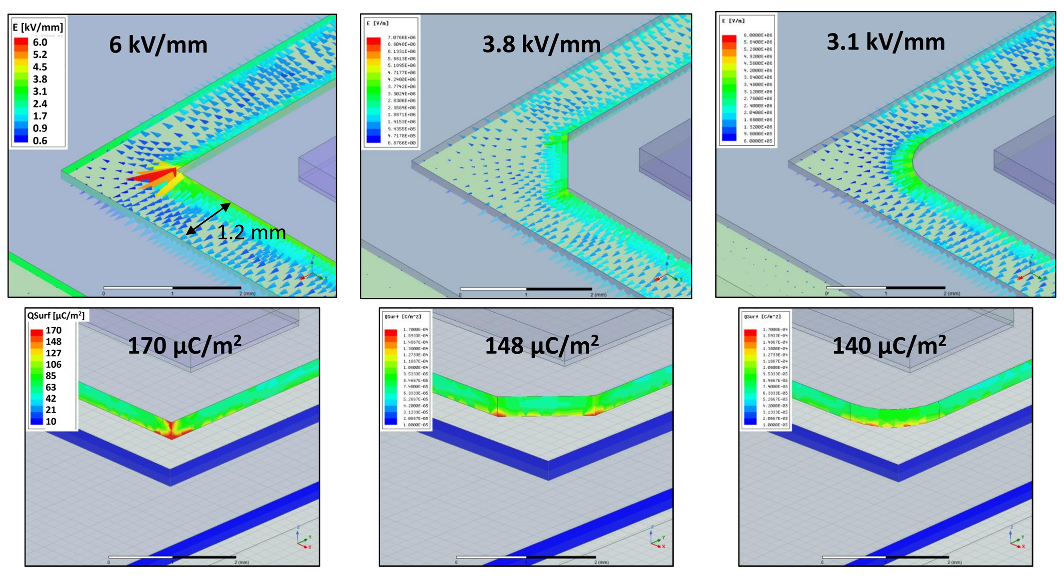
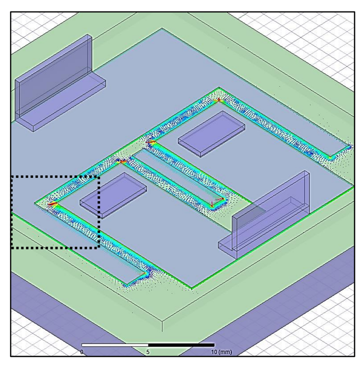
The Solution

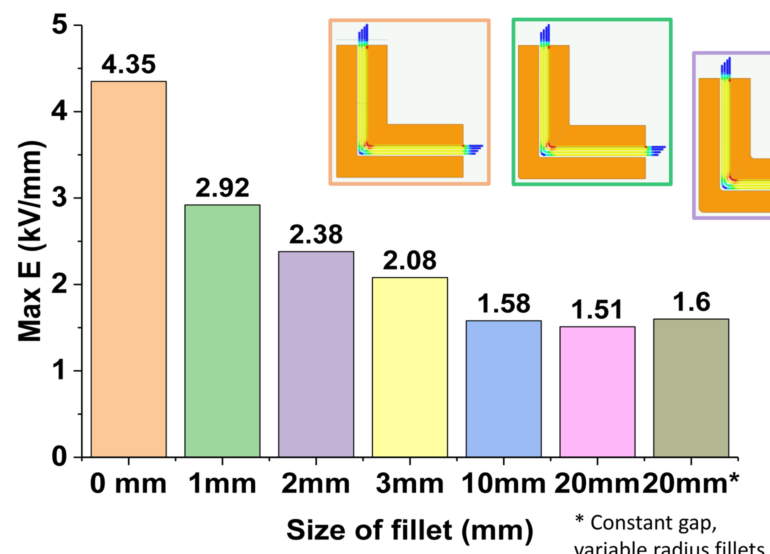
Corner Correction: Observations from Simulations

ANSYS Maxwell simulations showed E-field and charge density are concentrated at sharp corners:

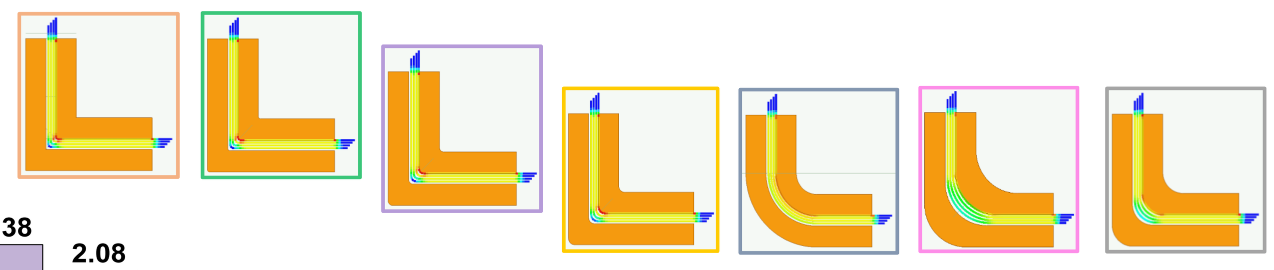




This electrical stress can be relieved by **chamfering** or **filleting** which showed at least 2x improvement.



Impact of filleting



There is significant impact in filleting a sharp corner, but the impact reduces with increase in fillet size.

Near ρ = 0:

$$E_\rho(\rho,\varphi) = \frac{-a_1\pi}{\beta}\rho^{\pi/\beta-1}\sin\left(\frac{\pi\varphi}{\beta}\right)$$

$$E_\varphi(\rho,\varphi) = \frac{-a_1\pi}{\beta}\rho^{\pi/\beta-1}\cos\left(\frac{\pi\varphi}{\beta}\right)$$

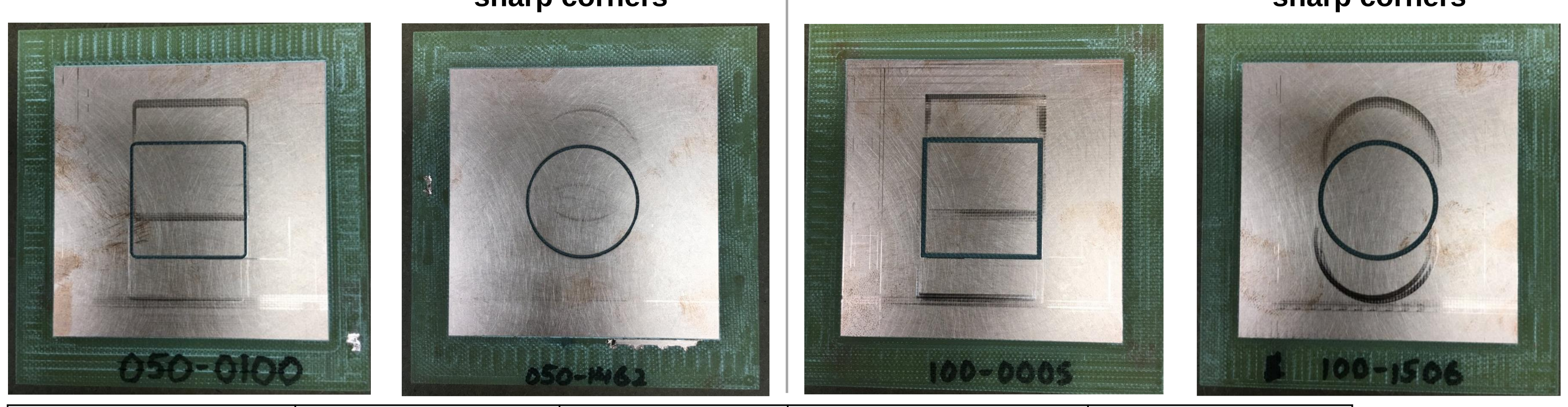
Comparison of Calculated and Simulated E-field Values

No.	Simulation	Simulation result (kV/mm)	Calculated value (kV/mm)
1	Straight traces	1.4	1.4
2	Sharp corner	1.772	1.867
3	Constant radius 10mm fillet	1.440	1.538
4	Constant gap ~10mm fillets	1.476	1.472

Observations from Experiments

Subjecting samples with sharp corners and no sharp corners to increasingly higher voltages confirmed that filleting indeed helps. Samples with no sharp corners could sustain higher voltages compared to those with sharp corners.

Coupon A: Trace gap: 0.50 mm, Square with 1 mm fillet
Coupon B: Trace gap: 0.50 mm, Circle with no intentional sharp corners
Coupon C: Trace gap: 1.00 mm, Square with sharp corner
Coupon D: Trace gap: 1.00 mm, Circle with no intentional sharp corners



Coupon ID:	A	B	C	D
1 μA	570 V	656 V	644 V	630 V
5 μA	903 V	1054 V	1031 V	993 V
Breakdown	1263 V	1435 V	1454 V	1738 V

Lower values for coupon D may be attributed to local asperities due to machining

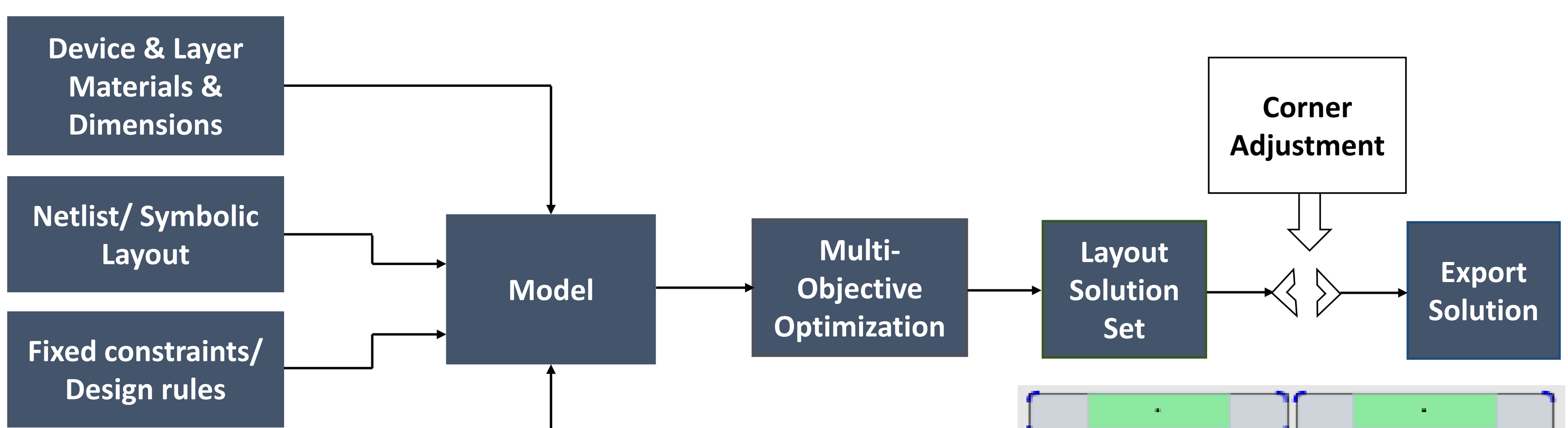
Fabrication and Test Setup:

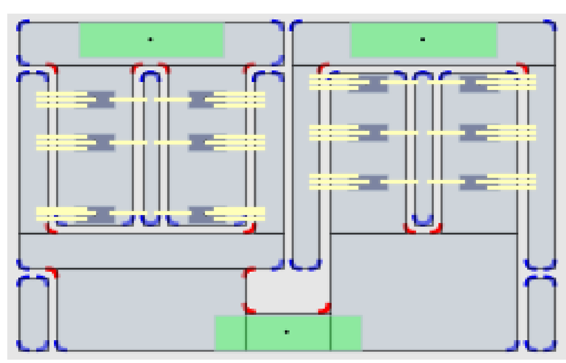
The test coupons were fabricated on single sided copper clad FR4 substrate using a milling machine with minimum tool tip size of 127 μm (5 mils).

The Valhalla Scientific hi-pot tester (5880A Dielectric Analyzer) was used to apply voltage between 100 V and 3 kV.

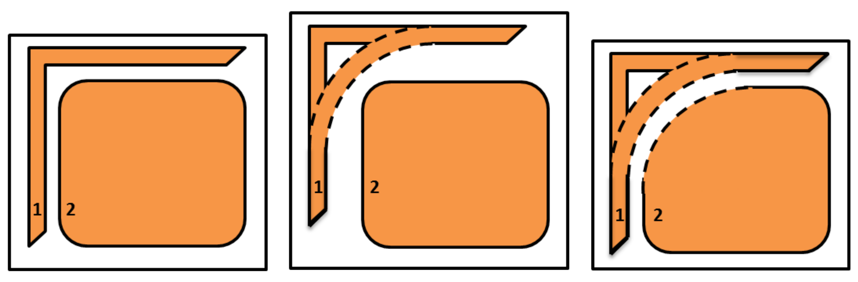
Corner Correction at the Design Stage

Post Layout Optimization in PowerSynth





Applied one-size fillets with minor size adjustments



Impact of filleting on adjacent components and total footprint → Future work.