Electrical and Thermal Finite Element Modeling of Arc Faults in Photovoltaic Bypass Diodes

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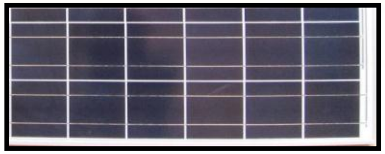
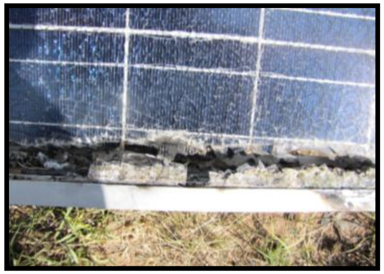
Outline

- **Arc Fault Introduction**
- **Description of the Model**
- **Simulations**
  - – **Normal Operation**
  - – **Solder Corrosion**
  - – **Burn Time**
- **Conclusions**


Polycrystalline Module Design


X-ray image of a Junction Box with Two Bypass Diodes


Burned Module after Arc Fault


Junction Box after an Arc Fault



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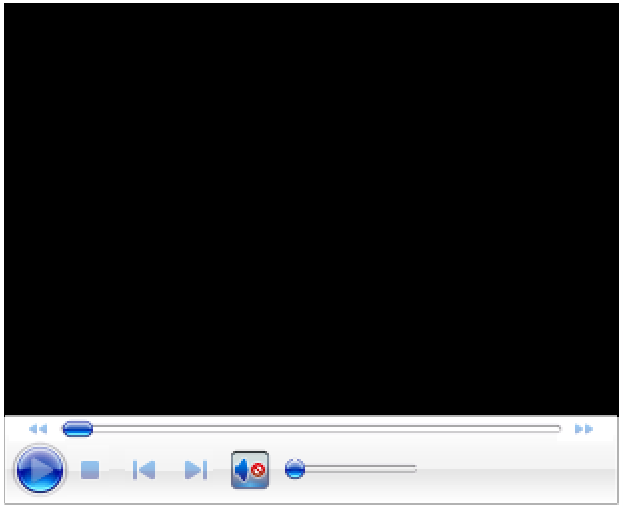
Arc Faults in PV Systems!

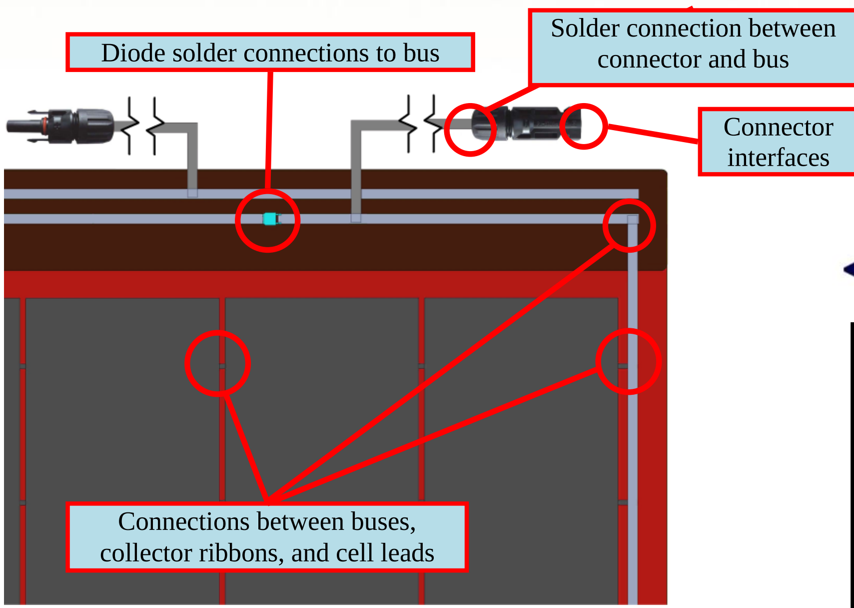
- **Arc: Luminous discharge of electricity across an insulating medium**
- **Arc faults ionize the atmosphere to create a high temperature plasma**
  - **5000+ °C**
  - **Melts metals, burns plastics**
- **Rare but some examples exist:**
  - **Bakersfield, CA**
  - **Mount Holly, NC**
- **Article 690.11 in the 2011 *National Electrical Code* requires arc fault circuit interrupters on rooftop installations**



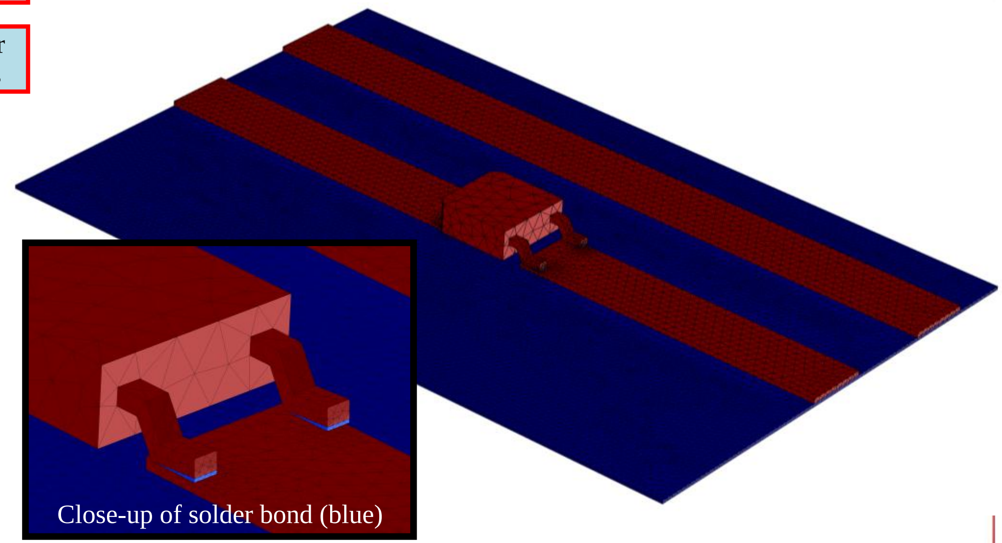
Arc fault video courtesy of John Wohlgemuth at NREL

Selection of Subdomain for Simulations

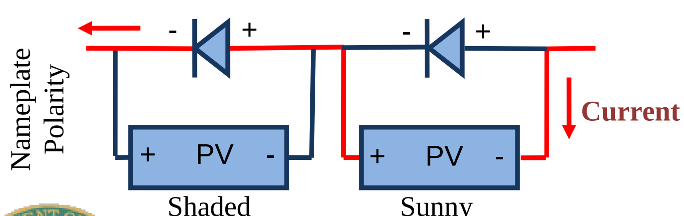
Series Arcing Locations



COMSOL Modeling Domain



Bypass Diode Operation

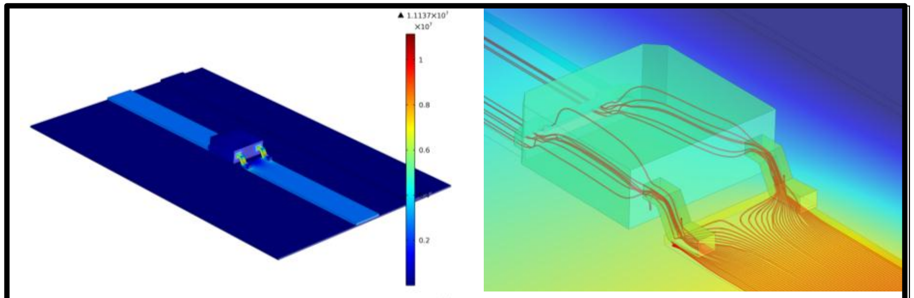


Material Properties

Material	Electrical Conductivity σ [S/m]	Relative Permittivity ε_r [-]	Thermal Conductivity k [W/m-K]
Thermoplastic	0.004	2.25	0.5
Sn-plated Cu	3.43×10^{7}	1.00	234
60Sn-40Pb Solder	6.67×10^{6}	1.00	50

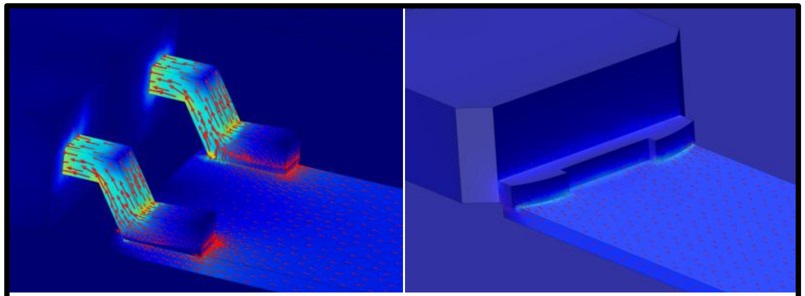
Normal Bypass Diode Operation

- **Diode Heating = Semiconductor Heating + Joule Heating**
- **High-power Si Schottky diodes**
  - **Internal Semiconductor Heating = (turn-on voltage) x (module current) = 0.45 V x 5 A = 2.25 W generated by the diode**

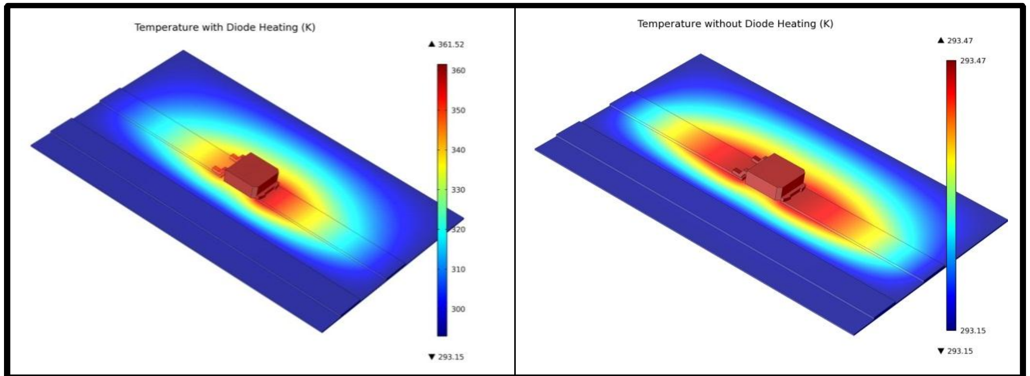


Normal current density (A/m²)

Electron traces through the diode



Current vector field



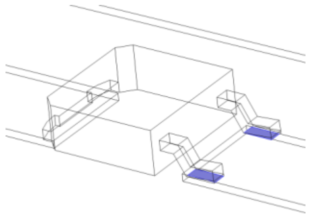
(a) Joule heating with diode heating
Diode temperature: 88.37 ºC

(b) Joule heating without diode heating
Diode temperature: 20.32 ºC

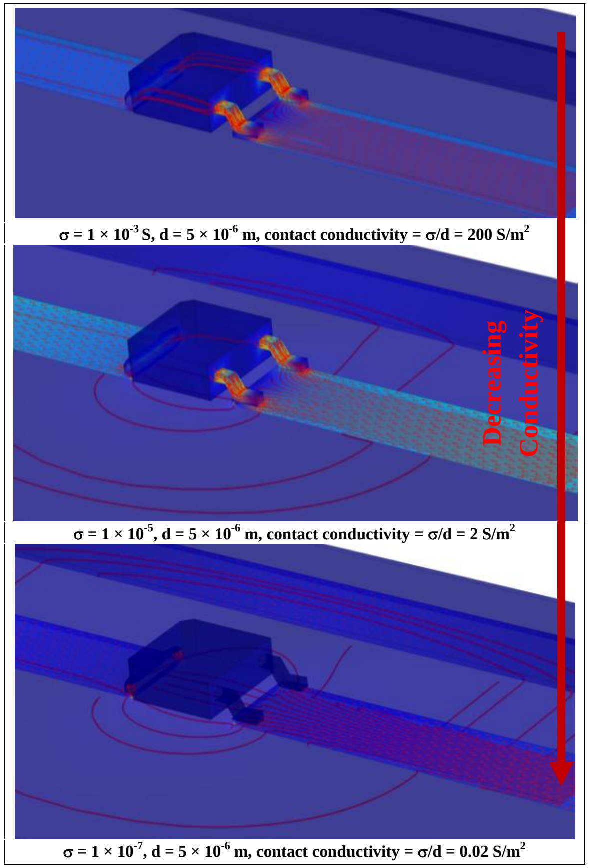
Warm, but no arcing.

Corrosion in Diode Leads

- **What level of corrosion is required to generate the gap voltage required to cause an arc fault?**

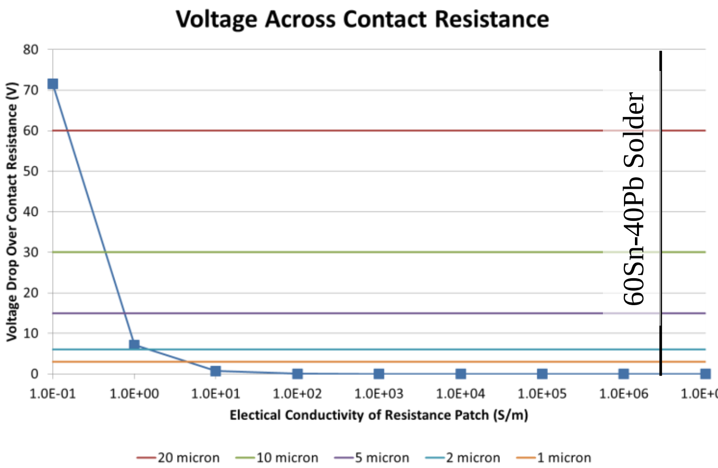


Location of contact resistance from corrosion



Transition from diode acting as a conducting path to the plastic back sheet.

Dielectric strength of air is 3000 V/mm or 3 V/μm.



Significant reduction in conductivity is required to establish an arc.

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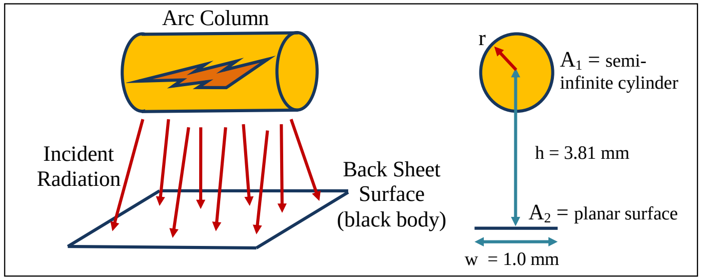
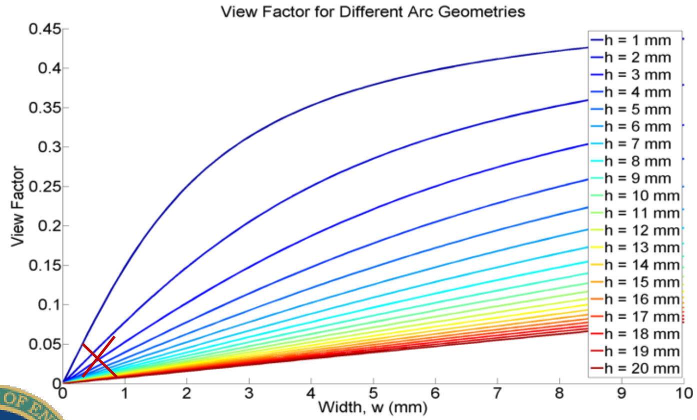
Burn Times

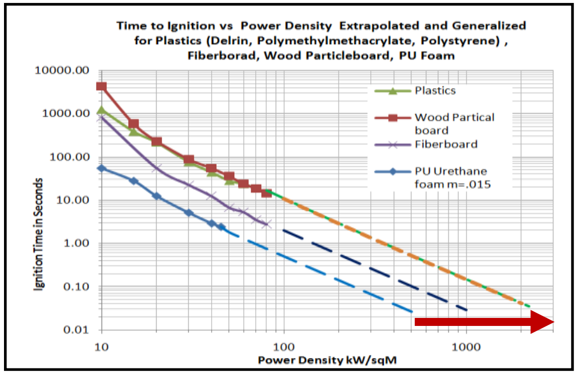
- **Back sheet burn time calculated with radiation model**



View factor = % of radiation absorbed by surface = 4.1%



Assuming arc fault power is 100 W, the 1x1 mm surface would experience **4100 kW/m²** of incident radiation.



J.K. Hastings, et al., A study of ignition time for materials exposed to dc arcing in PV systems, 37th PVSC, Seattle, WA, June 19-24, 2011.

Back sheet ignition time is less than 0.1 seconds.

Conclusions

- **Arc faults in PV systems are rare, but do happen.**
- **Arc fault circuit protection is now required by the *National Electrical Code*.**
- **Ignition of arcs at the solder connection of a bypass diode was simulated:**
  - **Normal operation is warm (68 K above ambient), but will not melt the surrounding materials.**
  - **With large (6 orders of magnitude) reductions in conductivity from corrosion or solder fractures, micron-scale gaps will establish an arc**
  - **Once the arc fault has initiated, it will take less than 0.1 seconds for a polymeric back sheet to ignite.**