Solid-State Protection: Dual-Use for Microgrids

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'More' Electric Crafts: for Air, Land and Sea

Programs in:

- All Electric Aircraft, e.g Joint Strike Fighter
- All Electric Ships
- All Electric Tanks

Other areas:

- All Electric Vehicles
  - Consumer EVs, Fleet Trucks, Busses, …

…In common

Smart Grids, MicroGrids

and the need for Protection

Needs in Protection Systems

Air Force has identified Solid State Protection as the No. 2 Priority for the All Electric Aircraft. (Weight is No. 1)

Solicitation example OSD08-EP6, 2008

TITLE: Scalable Solid-State Circuit Breaker (SSCB)

OBJECTIVE: Develop scalable high-current (50 - 500 Amps), high voltage (270-700 Volts) DC SSPCs (solid-state power controllers) and SSCBs

- *Presently addressed using electromechanical contactors available at high power levels, but have long trip response times, 15 – 110 ms.*
- *Today have SSCBs with fast response times, 5 - 15 micro seconds, but only available up to approximately 25 Amp.*
- *More Electric Aircraft (MEA) electrical loads typically ($270V_{dc}$) range from 5 to 200 A.*
- *Hybrid electric ground vehicle electrical loads typically ($700V_{dc}$) range from 50 to 500 A.*

Needs in Protection Systems(con'd)

Navy is now soliciting for second level of solid-state protection, with first level still under development.

Solicitation example N103-203, 2010

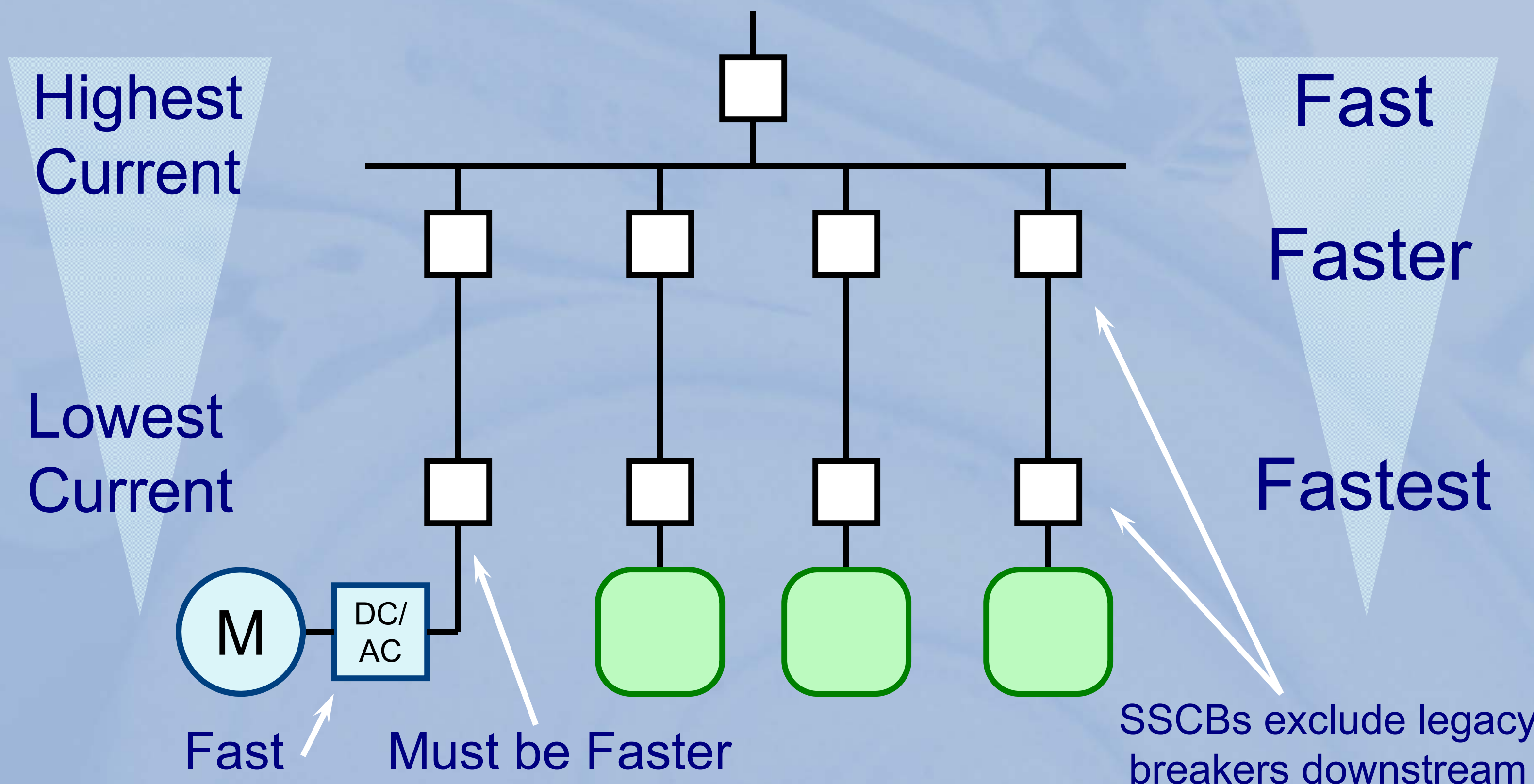
TITLE: Intelligent, Fault Tolerant, and Robust Power Management for Aircraft Applications

PROGRAM: F-34 Joint Strike Fighter Program

- *New generation power line contactor and relay technology is required to improve upon current electromechanical and solid state technologies*
- *Focus on development of replacement technologies for main-line contactor power levels between 250 and 300 A steady-state.*
- *The use of wide temperature power electronics/components, prognostics health management (PHM), and/or 270 VDC arc fault detection may be considered.*

Initial Hierarchy for Solid-State Protection

- *Presently addressed using electromechanical contactors available at high power levels, but have long trip response times, 15 – 110 ms.*
- *SSCBs have fast response times, 5 - 15 microseconds*



Advantages of SS-Protection

Fast response allows for much lower line currents

- Cabling capacity design is reduced
  - e.g. mechanical 150 A_{ac} Molded-Case Breakers has 25,000 A rated breaking capacity (T3N150TW from ABB)

Solid State has no Arc-Flash

- Plasma exists in solid material v. gaseous

Much smaller size, less weight and planar form-factor

Greater compatibility with a Smart Grid

- Inherent electronic interface
- Provides for integrated sensing and easy communications
- Easy to include prognostic inquiry

Re-Settable and reconfigurable for Microgrids, e.g.

- Alternative E-Sources, Microgrids, Islanding, Ring bus, etc.

Disadvantages of SS-Protection

Solid Sate provides only dielectric isolation

- Air break is needed for lock-out, but can be isolating breaker

Higher base cost, but can be reduced through functional integration

- Current-handling capacity scales with area
- Voltage-handling capacity scales with technology (e.g. packaging)

May need isolated external electrical power supply for embedded electronics

Why now? What will it look like?

Confluence of Technologies

Need for "Smart Power" to command and interrogate

- The SMART GRID movement…

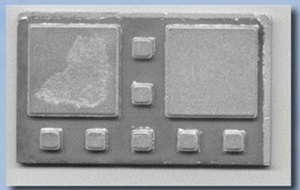
High-Temperature Power Semiconductors

- Silicon Carbide transistors (>350˚c) and thyristors
- E.g. GeneSiCSemiconductor

V_R=6.5kV, I_F=80A

Advanced Thermal Management Materials

- Al metal matrix composites
- Hi-temp organics

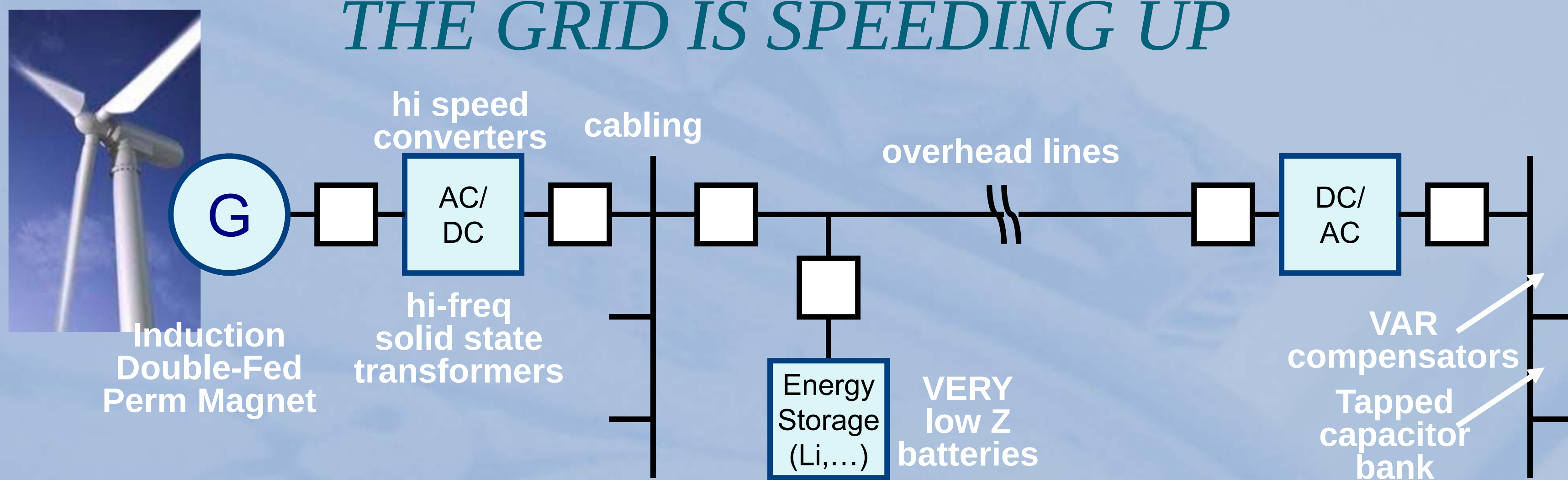


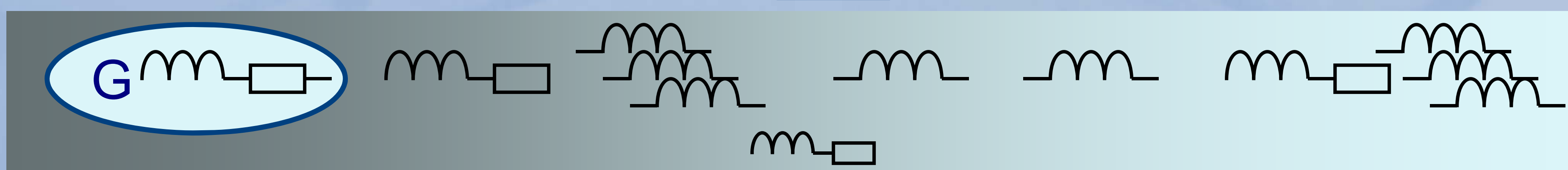
Improved Analysis and understanding of Reliability and Aging issues

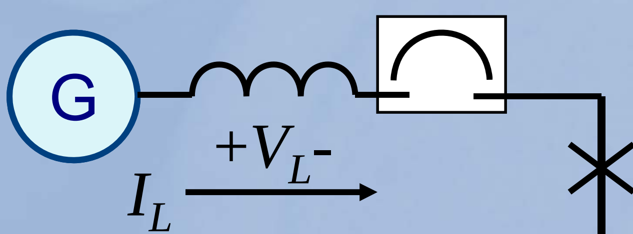
- Last decade(s) exploration of new materials: organic & inorganic

The Technical Challenge

THE GRID IS SPEEDING UP







$$V_L = L\ di/dt$$

For fixed voltages, the lower 'L' causes higher I and *di/dt*

For higher *di/dt* disconnect, causes higher system voltages.

How to build a SiC Solid State "Circuit Breaker"

Bring Technologies Together

SiC Solid State Circuit Breaker

Pre-Testing: Thermal shock

(module, no die)

- Mil Spec 883 method 1011
  - Condition A: 0˚C to 100˚C
  - liquid to liquid, 10 cycles
- (Comfortable to meet Condition B: -55˚C to 125˚C, probable to meet Condition C: -65˚C to 150˚C.)

Additional 'top-cap' gate drive and power routing circuitry customizes the SSPC/SSCB.

DensePower has developed the FLIPS* product line for aerospace and well-drilling applications

*Fault Limiter with Intelligent Power Screening

Transient Thermal Performance Results

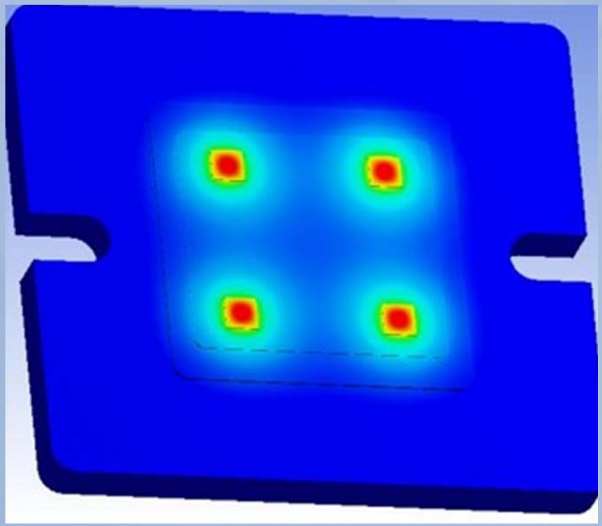
Thermal loading

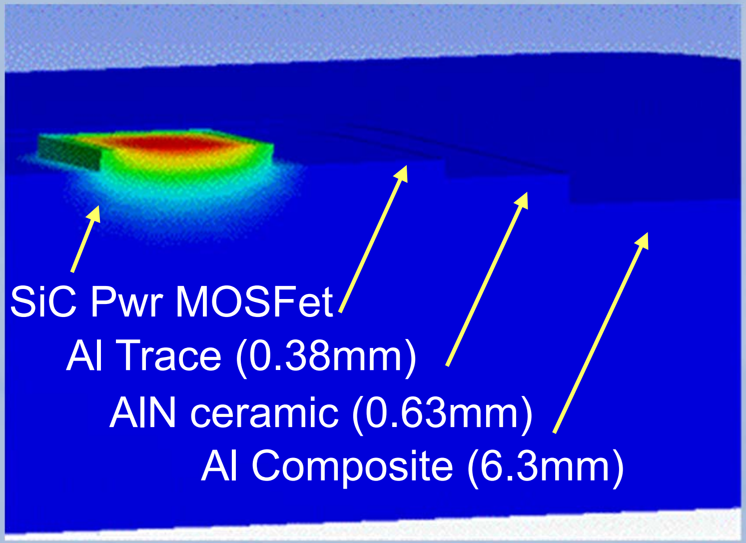
- Nominal 7.5A per die
  - Thermal drop 109.3˚C hot spot with 105˚C thermal ground
- Optimum spacing
  - 0.166 ˚C/W per module steady state (0.665 ˚C/W per die)

Critical Transient Loading:

Dynamic loading of 75 A (fault) per chip causes 56.2 W/mm^2 to 103 W/mm^2 from 0 - 5.15 ms to reach 350˚C max junction

Max Trip Pt.: 75A, 5ms





High-Temp Module Substrate - MOSAIC

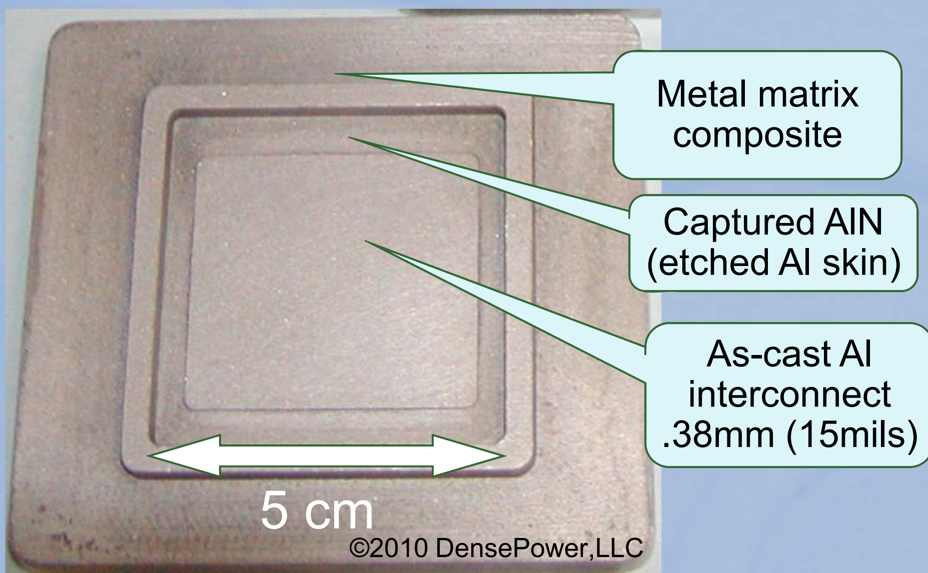
Development platform:

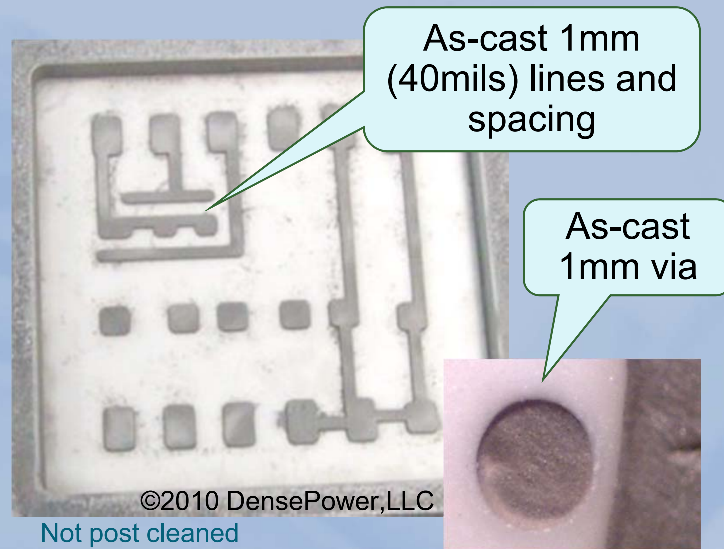
MOSAIC

"MOdule baSeplAte

with Integrated Ceramics"

A lightweight building block for very-high-temperature power modules





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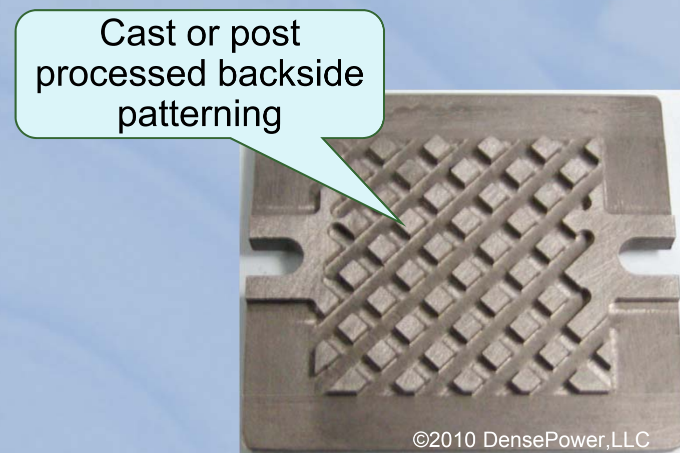


Why Very High Temperature ?

An i^2t *constant* is determined from a well accepted adiabatic temperature rise formula given in standards, etc. [8][9]

$$i^2t = K^2 S^2 \ln\left(\frac{T_2+\beta}{T_1+\beta}\right)$$

where

i -short-circuit current (rms over duration),A

t -duration of short circuit, s;

S -cross-sectional area of conductor, mm^2;

T_2 is final temperature of conductor, ° C;

T_1 is initial temperature of conductor, ° C;

β is reciprocal of TCR(α) for conductor material at *0° C*, ° C.

K -constant depending upon the conductor material, $As^{0.5}/mm^2$;

$$K^2 = \frac{C\,(\beta+20)}{\rho_{20}}$$

where

C is volumetric specific heat of the conductor at *20° C, J/° C mm³*; ρ_{20} is resistivity of conductor metal at *20° C*,Ωmm. Values of *K* and *β* are *226* and *234.5* for Cu, and *148* and *228* for Al.

Hence, an i^2t *module constant* is *~2.9* higher for the aluminum operated at *350° C from 105° C* versus *to 175° C (for Si)*.

In this development the pulsed capability of SiC to operate to 350° C is used and the packaging is developed for >450° C.

Critical Minimum High Voltage Design

For two cylindrical conductors in close proximity, the critical disruptive voltage [1] is,

$$E_0 = g_0 \delta^{2/3} r\ m\ \log_e D / r$$

where g_0 is critical gradient in *kV/cm* (g_0*=21.1kV/cm* is commonly accepted in power systems for open air.)

r is radius of conductor in centimeters

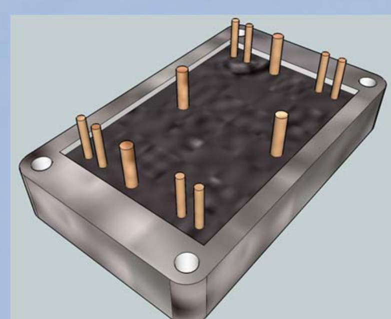
D is the distance in centimeters between conductor

m is surface factor (common value is 1 for solid surface)

δ is air density factor

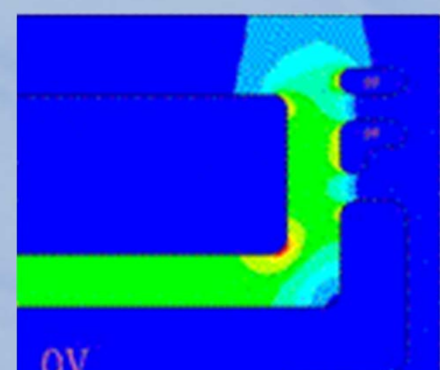
$$\delta = 17.9b / 459 + {}^{\circ}F$$

and *b* is barometric pressure in inches of mercury



Round Corners in Layout

After increasing the critical corner radius from *1.59 mm (0.0625 inch)* to *5.08 mm (0.2 inch)*, the maximum electric field decreased from *1.40 kV/mm (35.5 kV/in.)* to *1.03kV/mm (26kV/in.)*.



1. “Electrical Transmission and Distribution Reference Book,” Central Station Engineers of the Westinghouse Electric Corp., E. Pittsburgh, PA, circa 1950

Conclusions

Aluminum-based packaging has been developed for high temperature SiC applications >350˚C

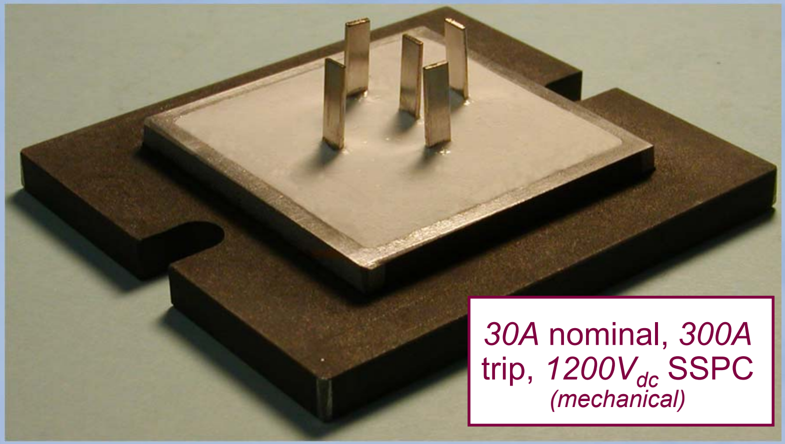
- Al interconnects cast onto AlN ceramic, captured in Al composite
- 1 mm (40 mils) cast lines and spacing resolution demonstrated for flip-chip mounting of die
- 1 mm (40 mils) diameter via demonstrated
- Successful preliminary thermal shock testing Mil Spec 883 method 1011, Condition A: 0˚C to 100˚C; comfortable to meet Condition B

A lightweight building block for very-high-temperature power modules & test bed has been developed

- *MOSAIC* (MOdule baSeplAte with Integrated Ceramics)
- Building block for customer application development (e.g. converter development and devices testing)

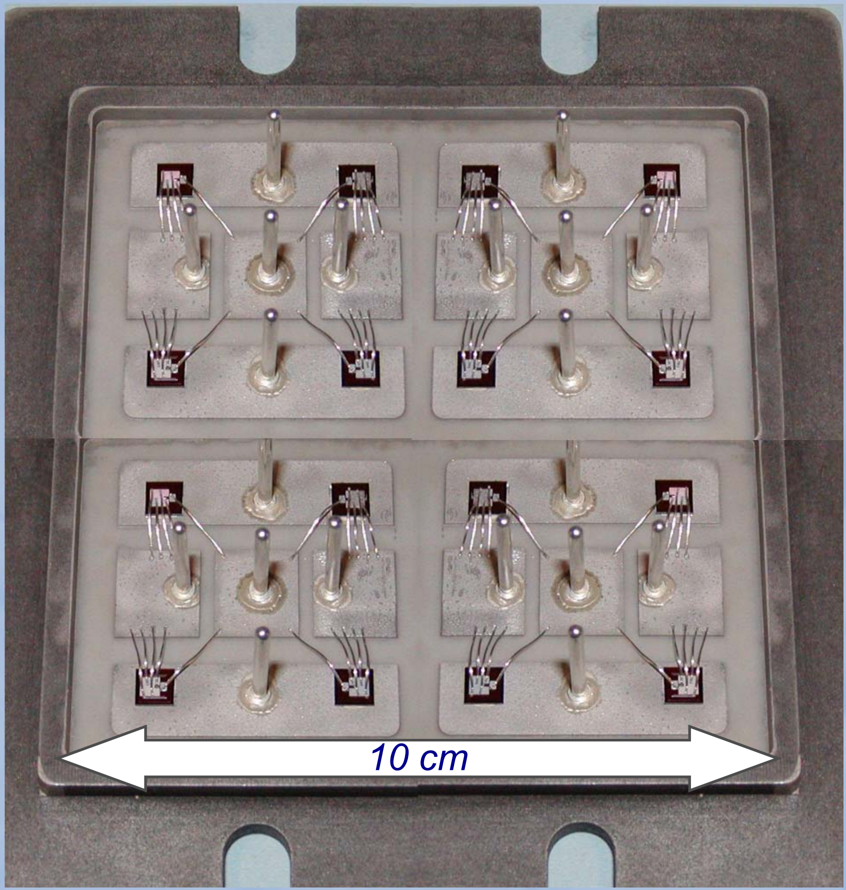
Packaging has been leveraged for demonstration of high-current, high-thermal-transient application to Solid-State Circuit Breakers (SSCBs)

- The *i2t* energy equation can be used for both system wiring and the SSPC design.
- Design to $120\ A_{dc}$ nominal, $1200\ A_{dc}$ fault



30A nominal, 300A trip, 1200V_{dc} SSPC
(mechanical)

Rendition of 120A nominal, 1200A trip, 600Vdc SSPC power test module.



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