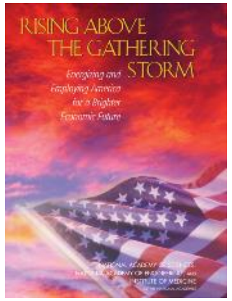
Power Devices for Improved Grid Control, Resilience, and Reliability

Olga Spahn, ARPA-E Program Director
(olga.spahn@hq.doe.gov)

April 30, 2024

History of ARPA-E

In 2007, The National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund advanced energy R&D.



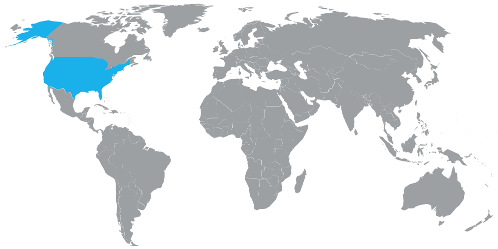
2007

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

2009

American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects



2024

1,560+ Awards
84+ Programs

Current Funding:
$470M
(FY23)

CHANGING WHAT'S POSSIBLE

ARPA-E Mission

REDUCE
imports

REDUCE
emissions

IMPROVE
efficiency

IMPROVE
radioactive waste management

IMPROVE
energy infrastructure resilience

ARPA-E Impact Indicators 2024

Since 2009
ARPA-E has provided
$3.76 billion
in R&D funding to
more than **1,560 projects**
+ 54 selected projects

230 projects
have attracted more than
$12.1 billion
in private-sector follow-on funding

154 companies
formed by
ARPA-E projects

29 exits
market valuations worth
$21.9 billion
from mergers, acquisitions, and IPOs

340 projects
have **partnered with other government agencies**
for further development

7,318
peer-reviewed
journal articles
from ARPA-E
projects

1,120 patents
issued by
U.S. Patent and
Trademark Office

405 licenses
reported from
ARPA-E projects

As of January 2024

Evolving Grid - Needs Better Technologies

- **Aging grid**

100+ years old

ASCE infrastructure grade ***C-***

- **Changing weather patterns**

8+ hours/customer/ year

- **Changing threat patterns**

High risk

- **Changing usage patterns**

Constant Power Loads
Dynamic interactions

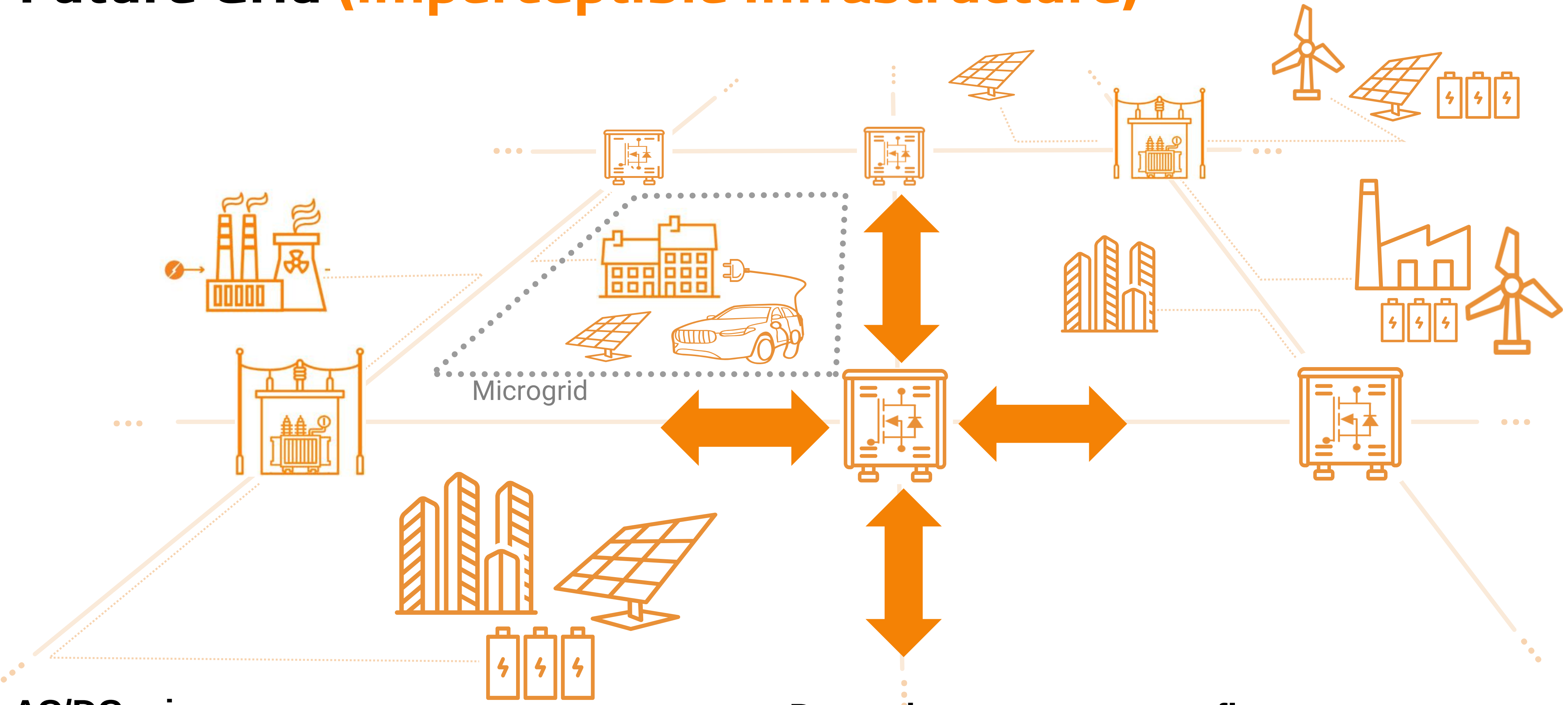
- **Changing generation patterns**

Intermittent Sources
DER Control Coordination

DER and industry electrification are transforming the grid

arpa·e
CHANGING WHAT'S POSSIBLE

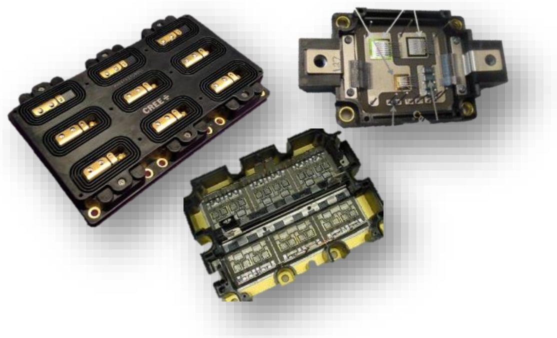
Future Grid (Imperceptible Infrastructure)



- AC/DC mix
- Solid-state and traditional substations
- Distributed mixed generation (and storage)
- Dynamic, two-way power flow… Everywhere
- Prosumers
- Microgrids
- …And much bigger (~4x)

arpa·e CHANGING WHAT'S POSSIBLE

Power Electronics Are a Key Enabler



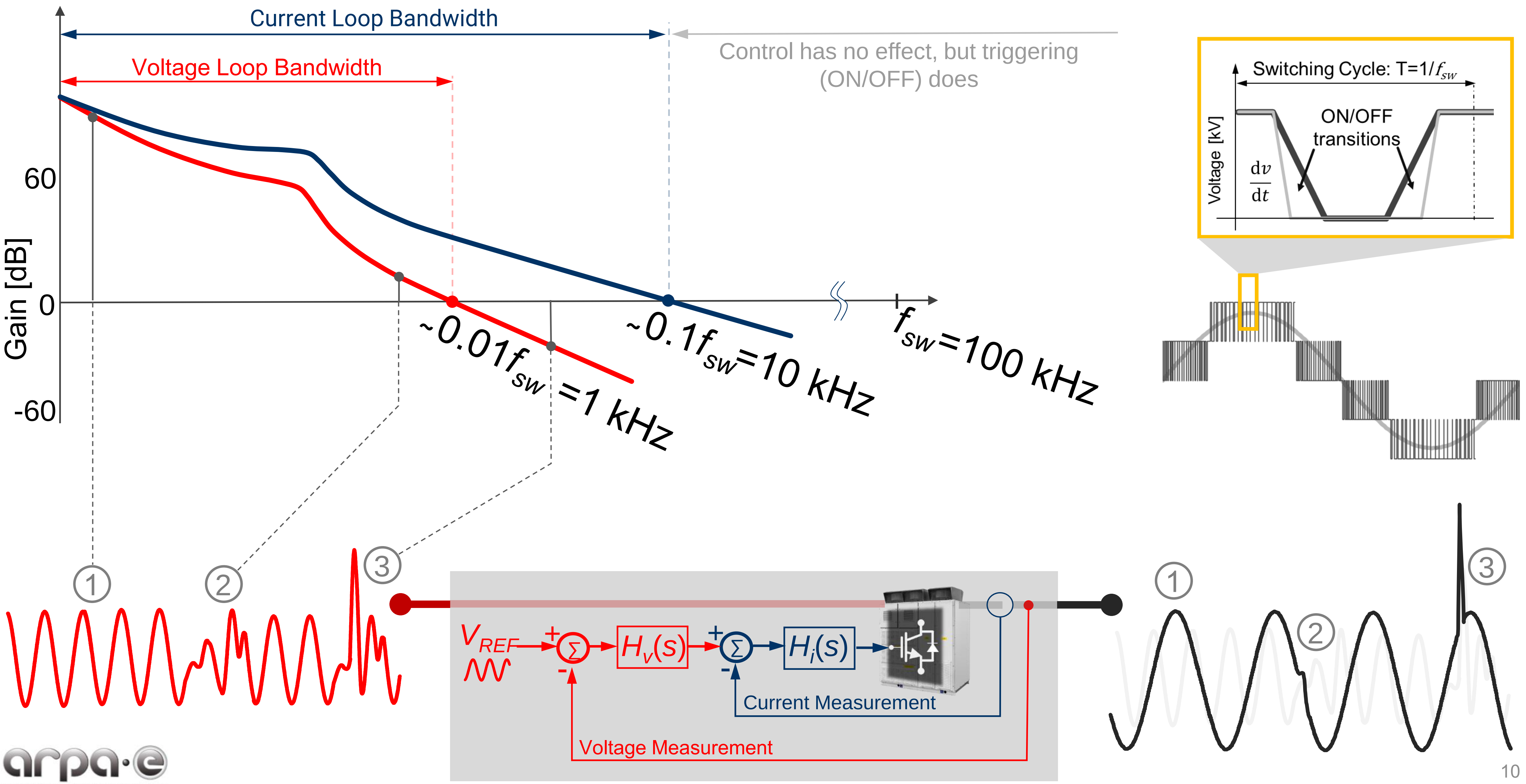
"**Universal adapters**" for grid to function like a standard bus allowing generic connections

- Continuously controlled bidirectional power flow
- Decoupled dynamics between loads, generators and the grid
- Intrinsic protection, faults actively limited to a nominal value or interrupted

But it's not only power grid:

CHANGING WHAT'S POSSIBLE

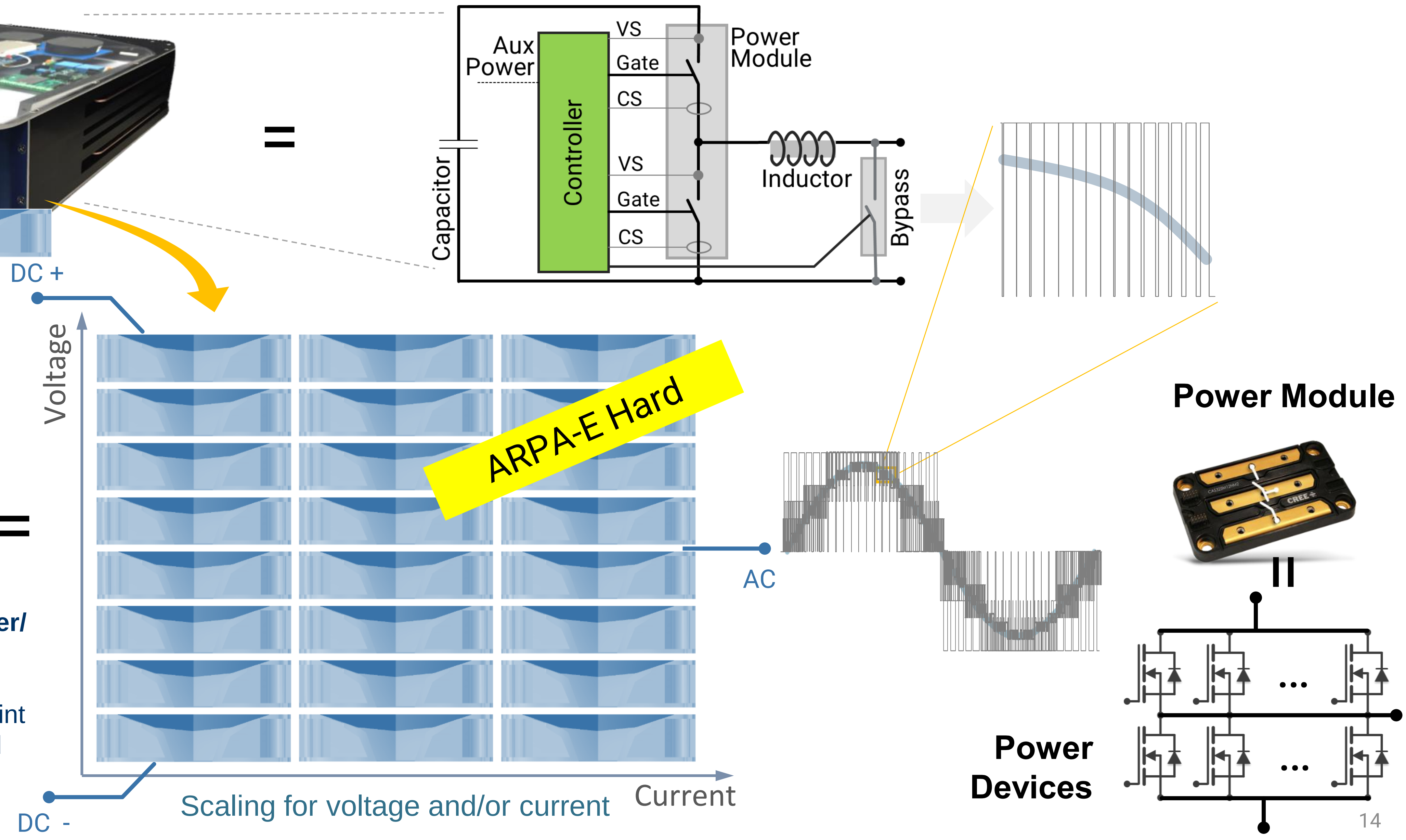
Electronic Energy Router: Control and Protection Bandwidth



arpa·e
CHANGING WHAT'S POSSIBLE

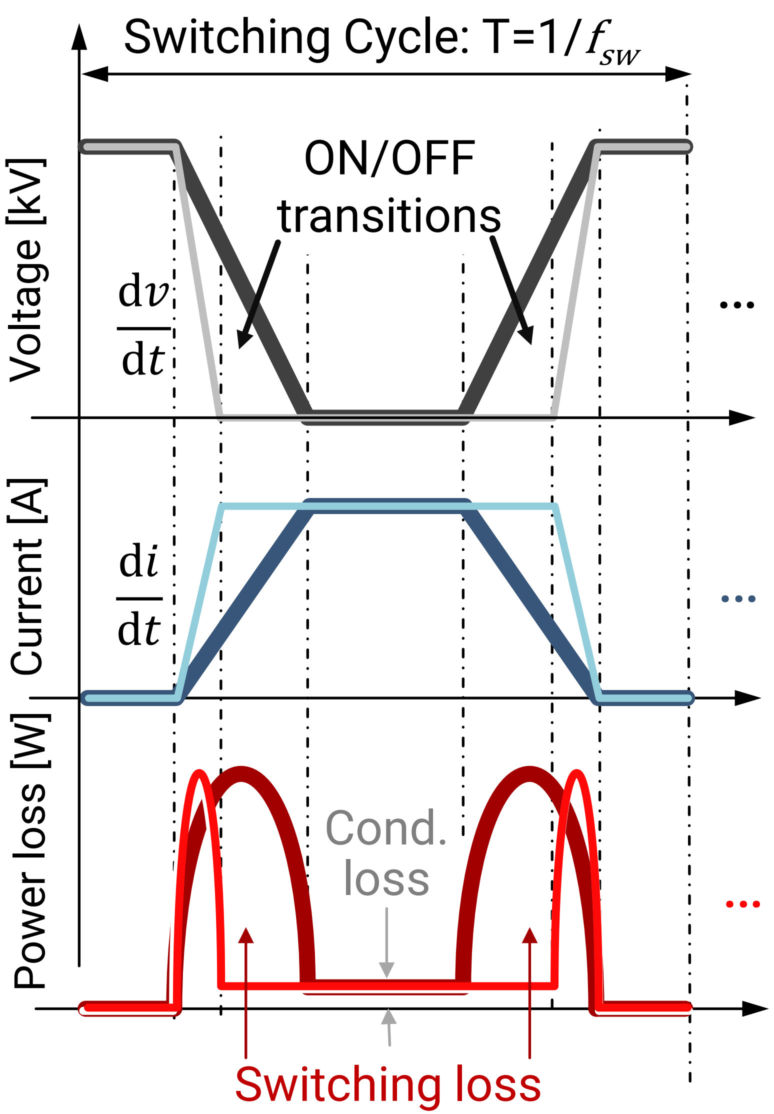
Modular, Scalable Universal Adapter (Modular Multi-level Architecture)

Power Cell

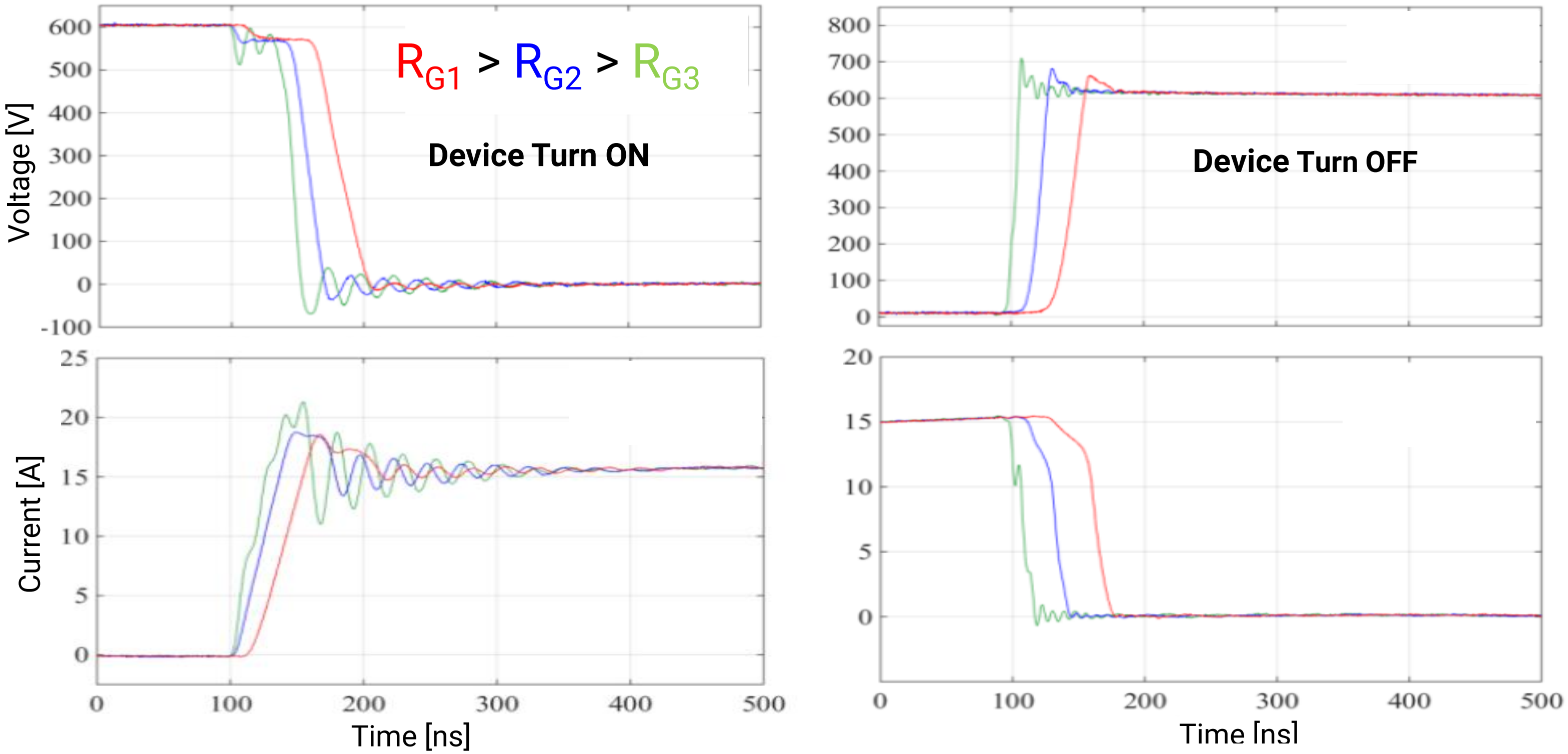


Electronic Energy Router/ Universal Adapter
Bidirectional power converters for point-to point energy flow control and integral protection

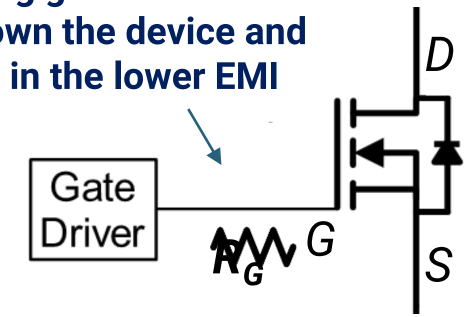
Switching Transients, Loss, and EMI

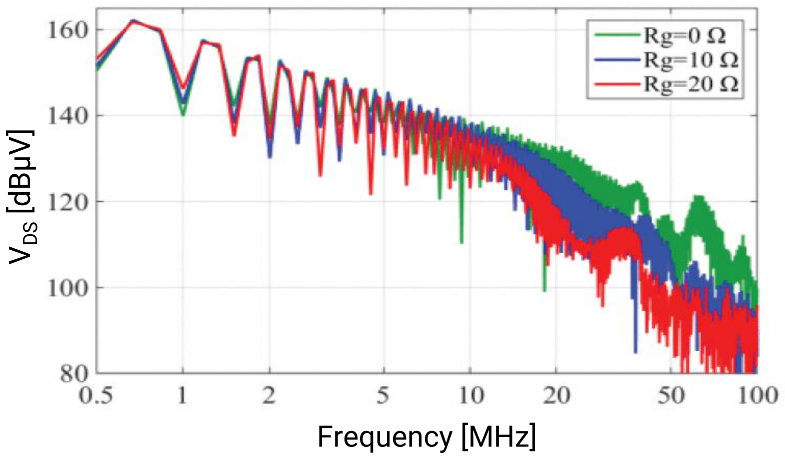


F. Zare, EMI Issues in modern power electronics systems, QUT, 2009



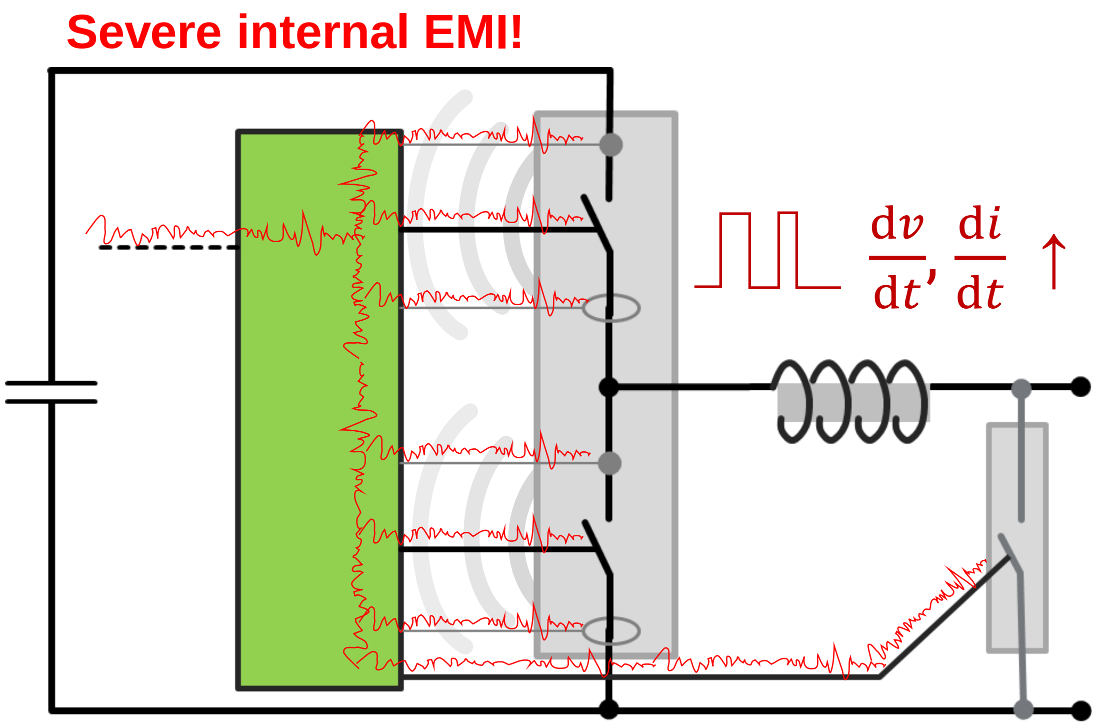
Increasing gate resistance slows down the device and results in the lower EMI

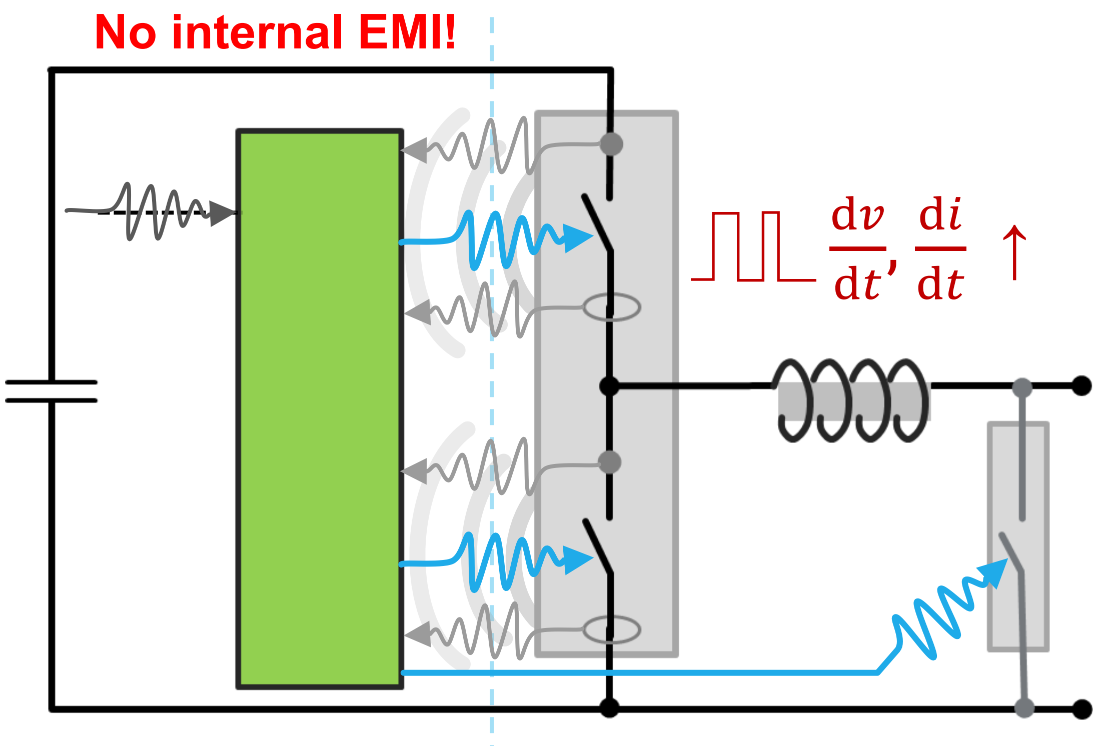




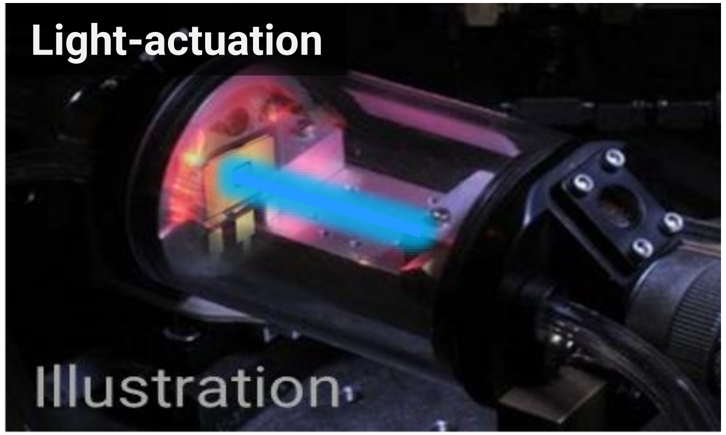
W. Ma, et. al., "Investigation of the Gate Resistance and the RC snubbers on the EMI Suppression in Applying of the SiC MOSFET," IEEE ICMA, 2019

Improved Control and Protection Through Optical Actuation



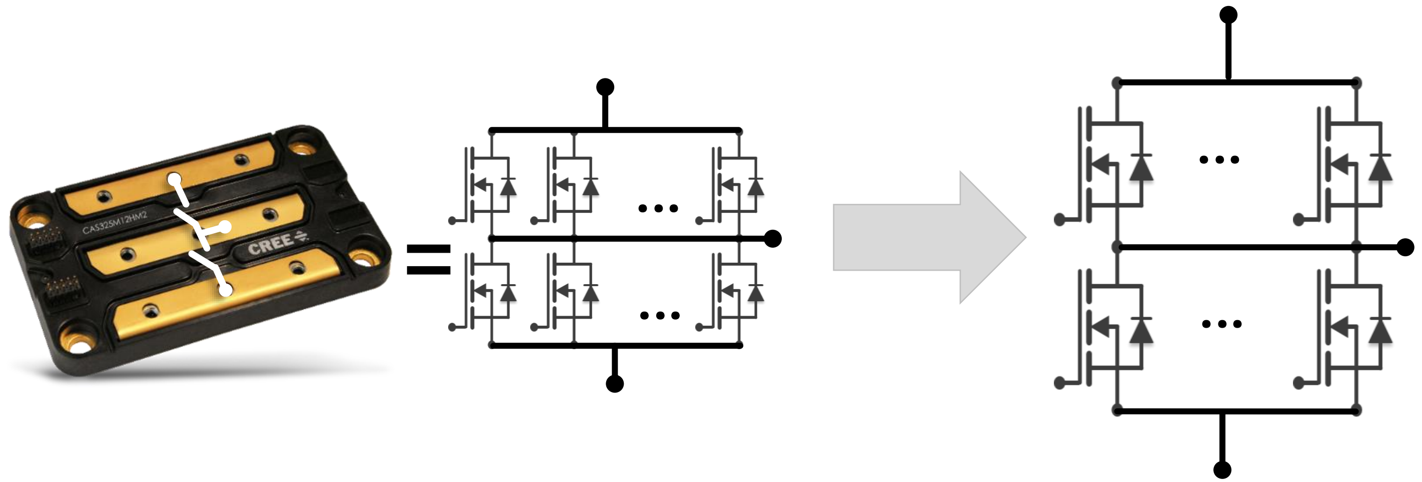


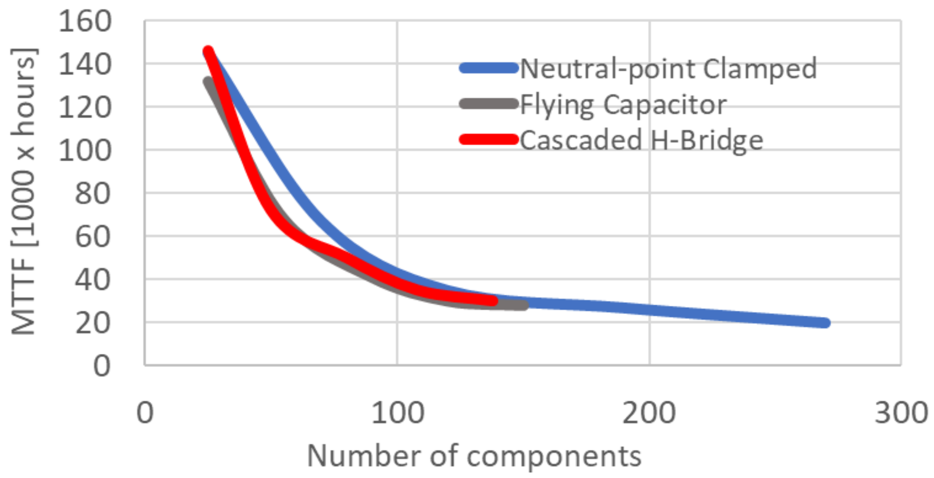
- EMI mitigation - improved reliability
- New functionality for protection and control
- Faster, more efficient actuation
- Improved scalability (I, V balancing)

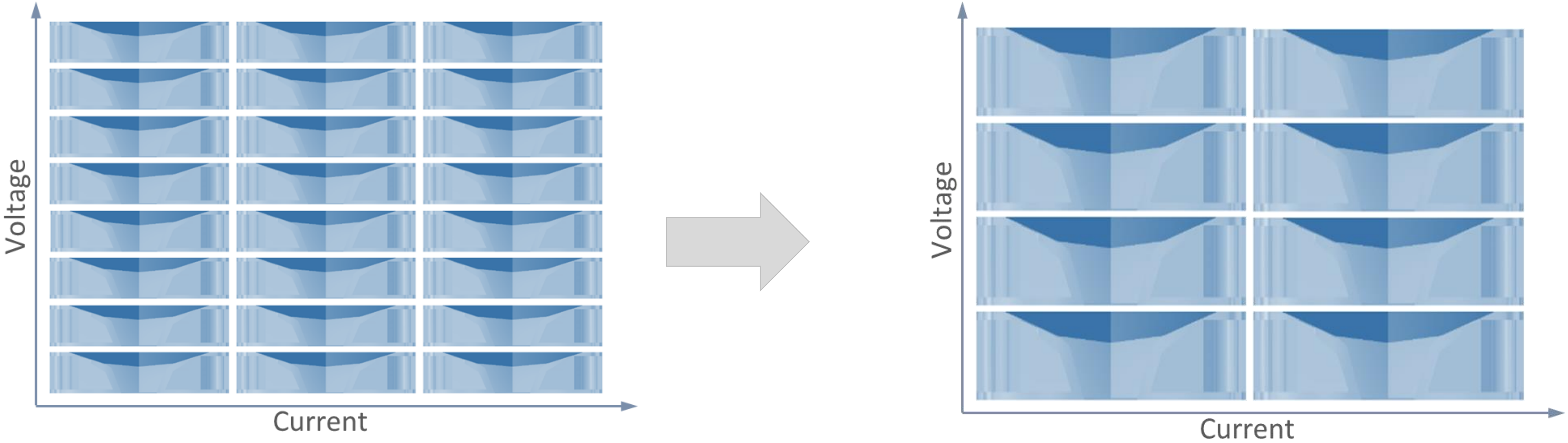


arpa·e CHANGING WHAT'S POSSIBLE

Higher Voltage, Current, and Speed Individual Devices

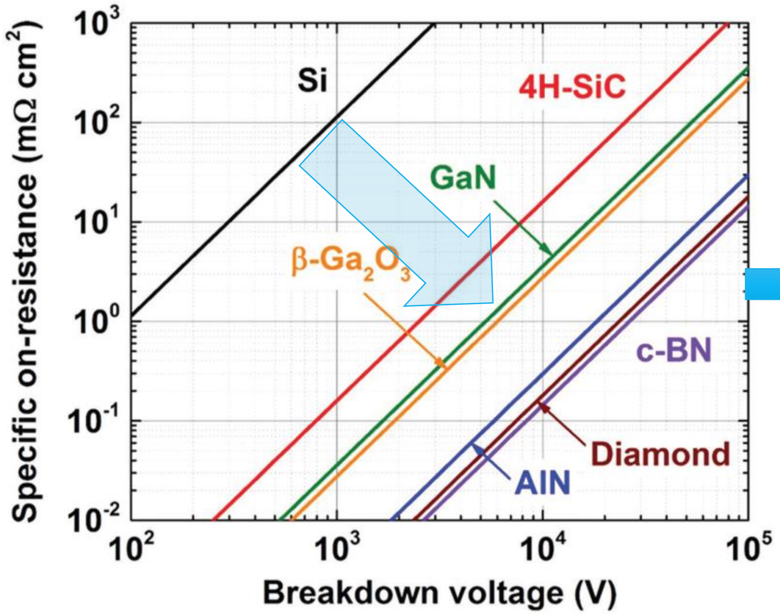


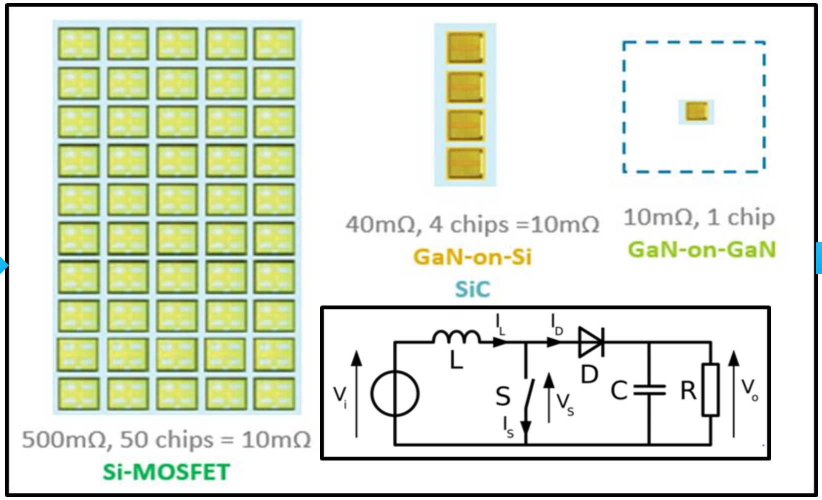




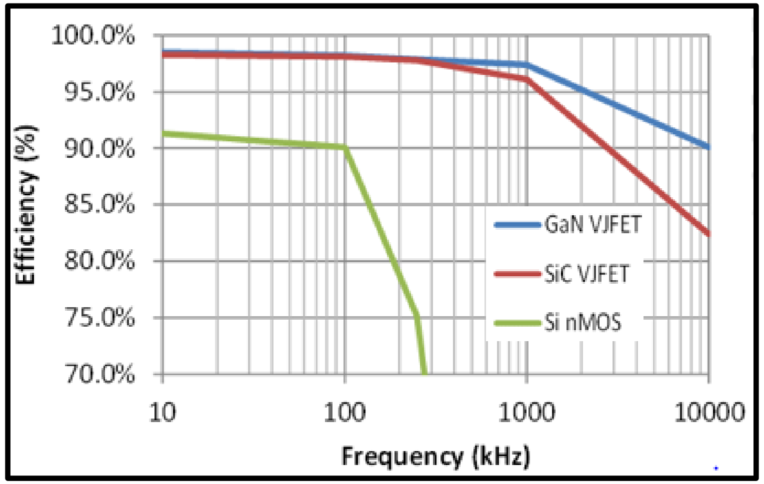
- Improve/simplify Electronic Energy Router realization with fewer higher voltage/current devices/modules

UWBG Advantage in Power Electronics Devices and Systems

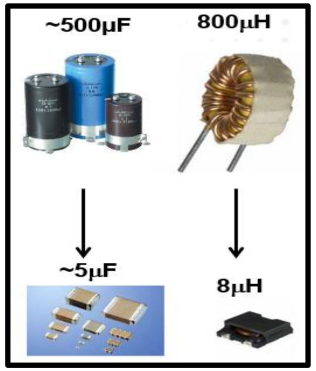




Smaller devices with better performance



Faster switching with lower loss

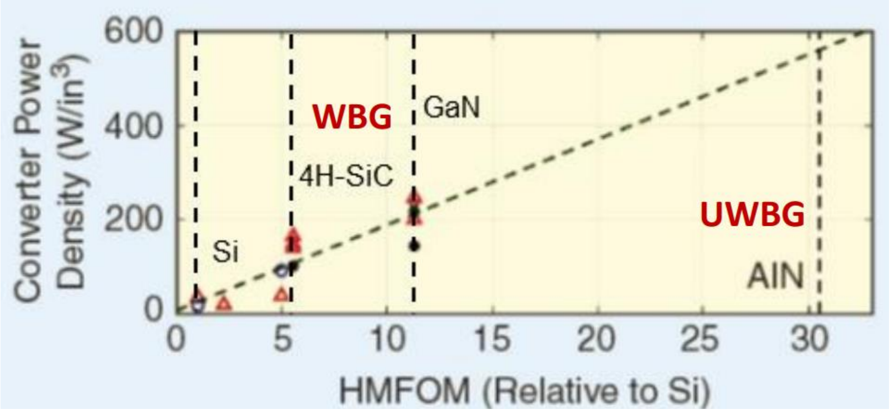


Smaller passives

Need high frequency passives!

Smaller power electronic systems

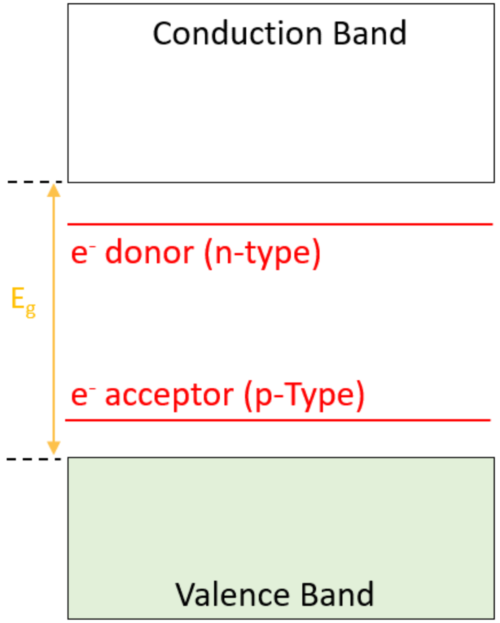
UWBG>WBG>Si

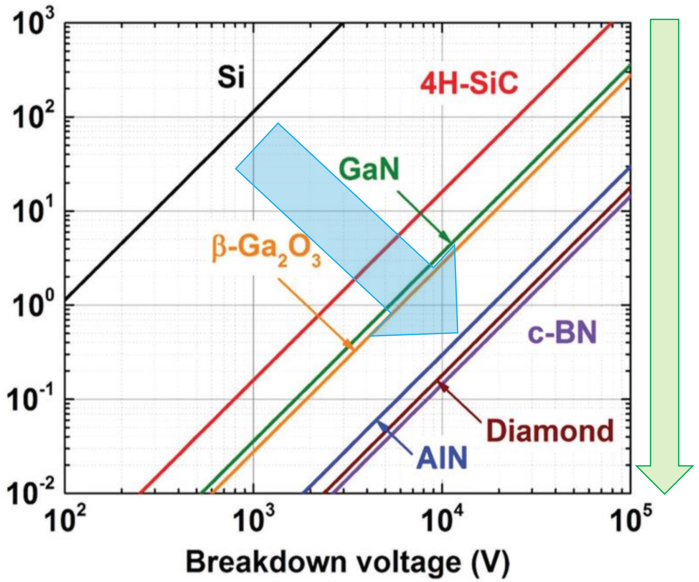


UWBG semiconductors enable even *smaller, lighter, higher temperature, more efficient, reliable, and lower* cost power electronic systems

CHANGING WHAT'S POSSIBLE

Ultra Wide Bandgap (UWBG) Materials – Potential Solution





UWBG semiconductors enable *higher-temperature, more efficient, reliable, better SWaP* power electronics

UFOM: $V_B^2/R_{on,sp} = \varepsilon \mu_e E_c^3$ ($E_c \sim E_g^n$)

UWBG > WBG > Si

However, must solve: Doping, Material quality, Maturity/Manufacturability/Cost …

Could we solve UWBG semiconductor doping problem optically ?

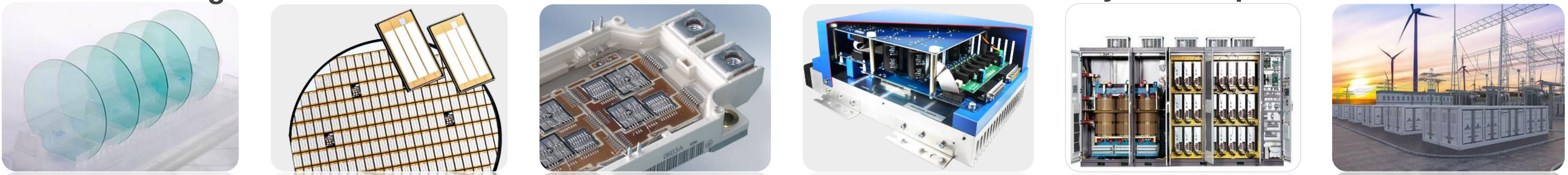
	Si	GaN	4H-SiC	AlGaN/AlN	β-Ga_2O_3	Diamond	h-BN
		WBG		UWBG			
Bandgap E_g (eV)	1.1	3.4	3.3	< 6.0	4.9	5.5	~5.9
Thermal Conductivity (W m^{-1} K^{-1})	150	253	370	253–319	11 – 27	2290 - 3450	~750 (in-plane)
State-of-the-art substrate diameter (in)	12	8 (on Si) 4 (Bulk)	8	2	4	1	4
p - type dopant ionization energy **(acceptor)**	0.055	0.16 - 0.25	0.2	0.53	⊗	0.37	0.3
n - type dopant ionization energy **(donor)**	0.045	0.03	0.06	0.5 - 1	0.011	0.6	0.86 – 1.2

arpa·e CHANGING WHAT'S POSSIBLE

Power Electronics Programs

>$300M investment

Program Domain — **System Impact**



Materials › Devices › Modules › Power Cells › Converters › System

Power Grid

Microgrids

Electric - Vehicles, Aviation, etc..

ULTRAFAST: 2023 - , $42M

SWITCHES: 2014-2019, $35M, 14 projects

CIRCUITS: 2017-2023, $38M, 21 projects

PNDIODES: 2017-2022, $18M, 10 projects

BREAKERS: 2019 - , $23M, 7 projects

GENI: 2012-2017, $43M, 15 projects

OPEN: 2009 - , ~$95M — 2009,2012, 2018, 2021

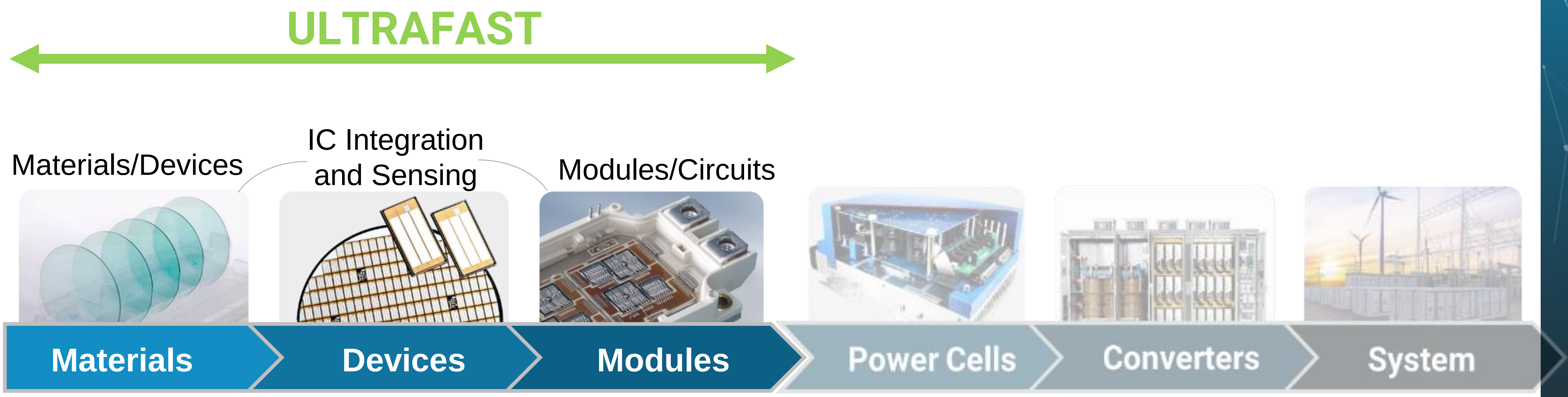
IDEAS, CREATE, SEED, SPARKS

+ Relevant Cohort Programs:

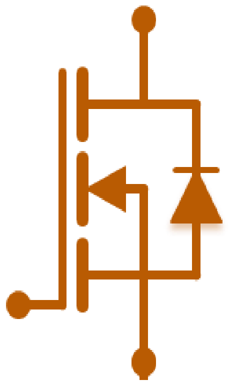
- SF_6-FREE: 2021 -, $10M
- INSULATE: 2021 -, $3.5M
- SUBSURFACE: 2021 -, $16M
- CABLES: 2021 -, $10.5M

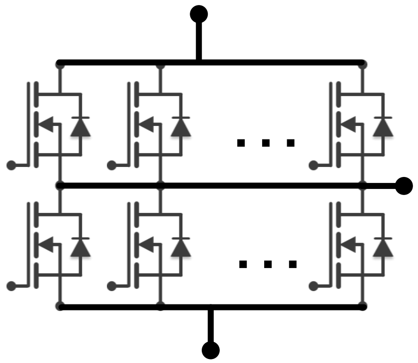
arpa·e CHANGING WHAT'S POSSIBLE

ULTRAFAST Project Types



Risk: novel material/devices

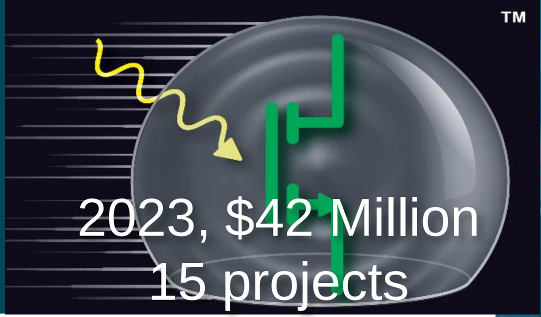




Risk: integration complexity

ULTRAFAST

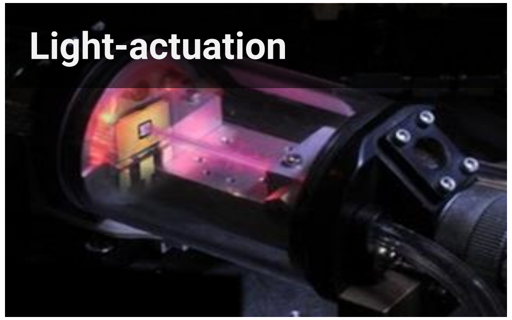
Program Director: Olga Spahn

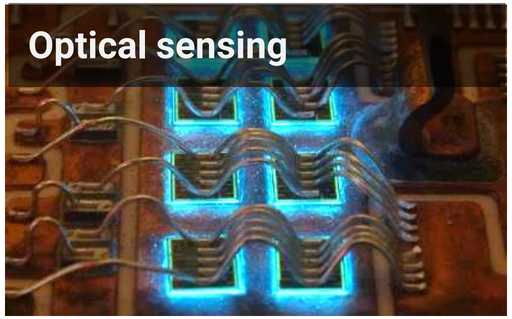


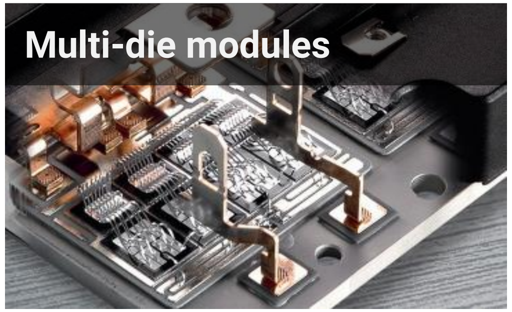
Unlocking Lasting Transformative Resiliency Advances by Faster Actuation of power Semiconductor Technologies

Next generation material, device and module technologies for improved power distribution and control in future grid applications

- **Ultra Wide-bandgap materials for higher power individual devices and modules**
  [protection > 20 kV, > 250 A | continuous switching > 3.3 kV, > 10 A]
- **EMI mitigation for improved stacking reliability**
  [wireless/optical actuation, control and sensing]
- **Faster actuation – improved protection, better control, lower losses**
  [1-100 kHz | > 250 V/ns, > 100 A/ns | > 99% efficiency]
- **Better Size Weight and Power (SWaP)**
- **Supporting enabling technology – sensing, passives, packaging, gate drive technology**







Link: ULTRAFAST FOA

Link: ULTRAFAST Program Announcement

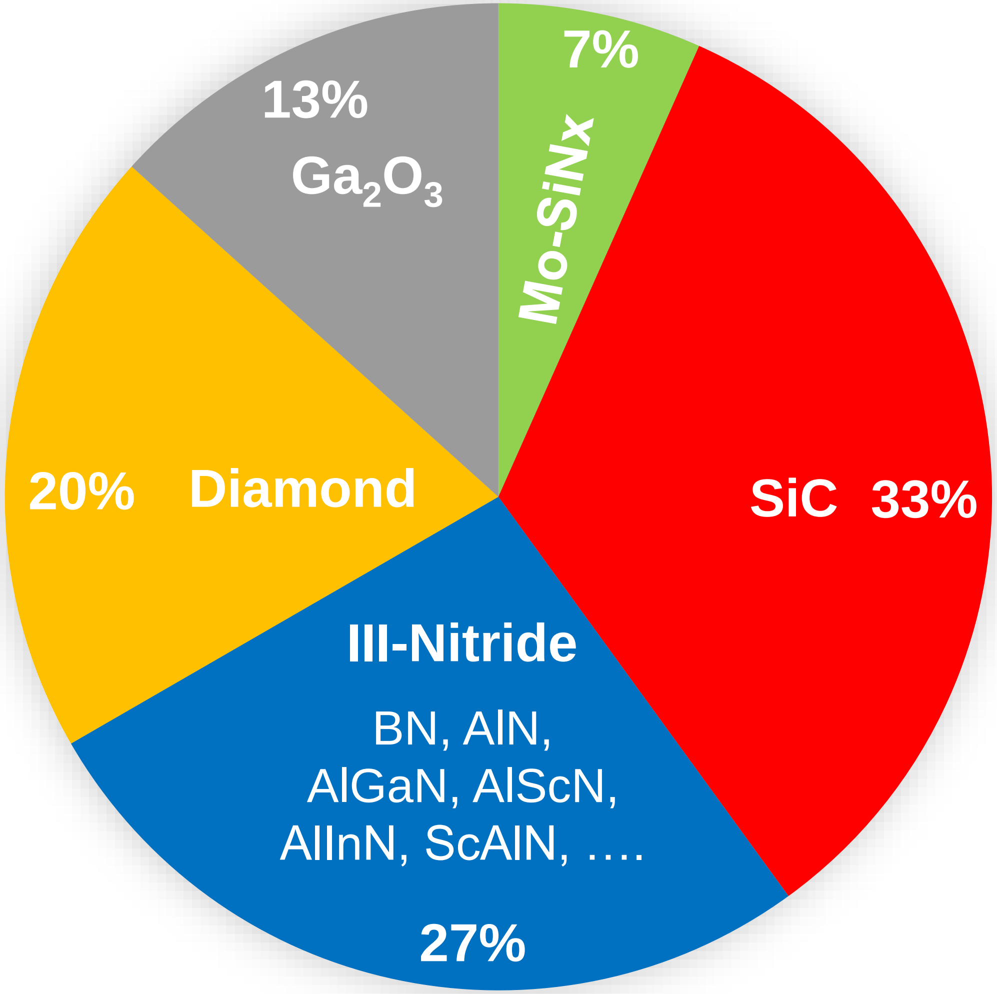
Link: Power Magazine News

Link: ARPA-E Website Info

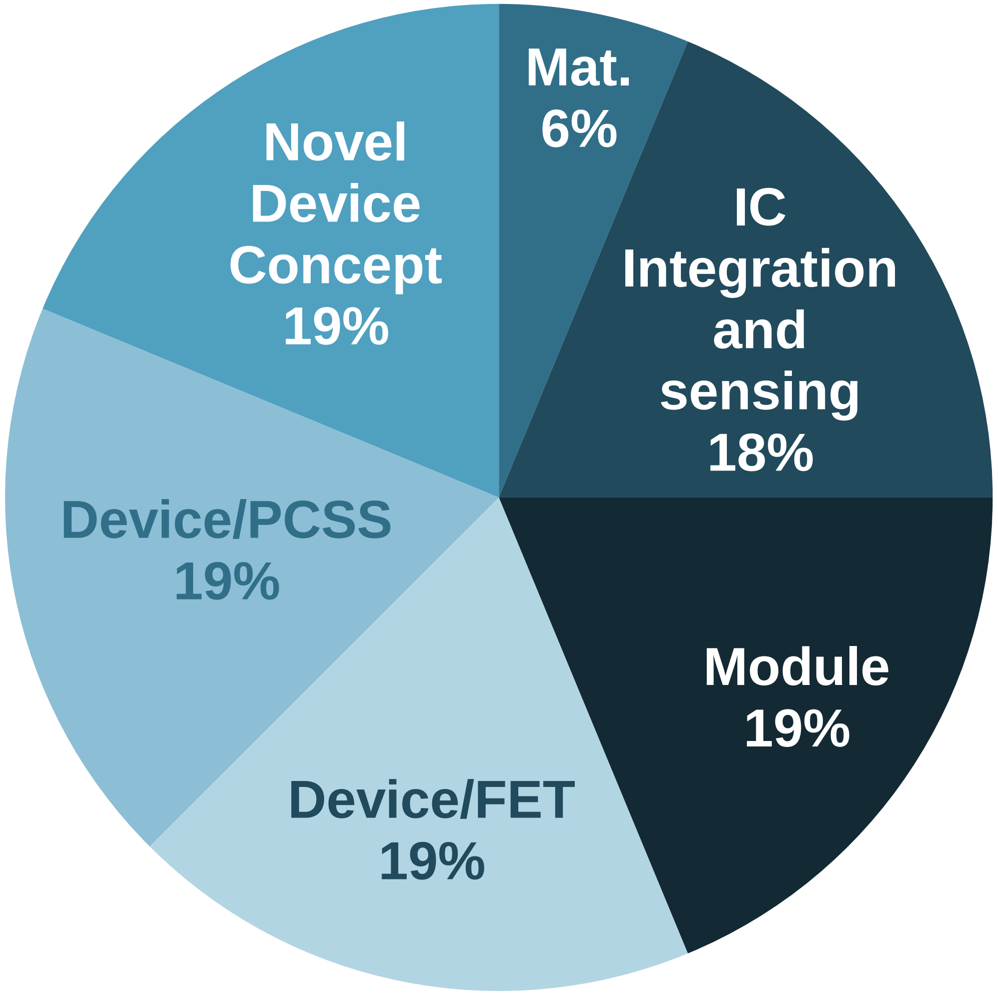
arpa·e CHANGING WHAT'S POSSIBLE

ULTRAFAST Statistics

Semiconductor Materials



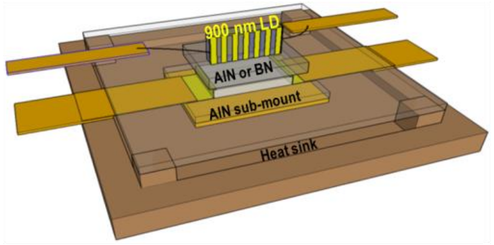
Project Types



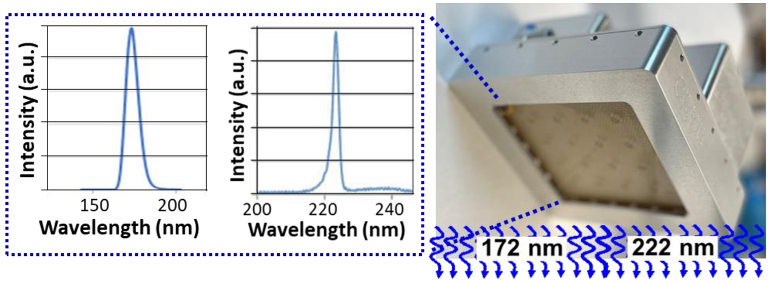
Link: ULTRAFAST Kickoff Meeting Agenda and Presentations

arpa·e
CHANGING WHAT'S POSSIBLE

A Brief Project Summary for *Devices*

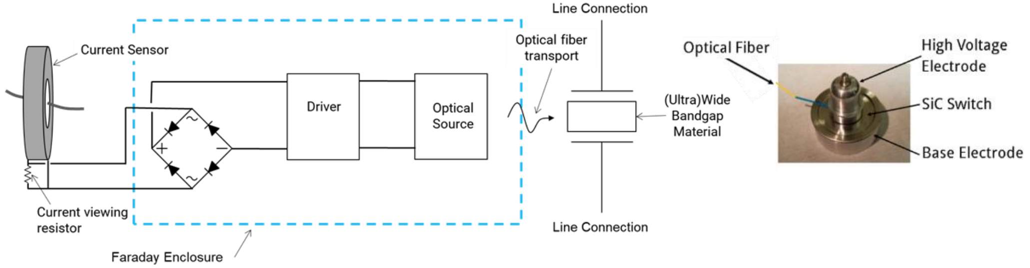


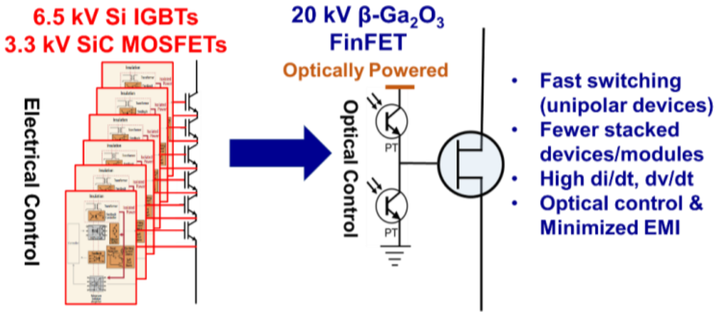
- **UWBG Semiconductors for Extrinsic Photoconductive Switching Devices -** based on ~1 eV deep simple impurity doped AlN and h-BN UWBG crystals for hold-off voltage > 3.3 kV, current > 10 A and switching frequency > 100 kHz.
- Outperform SiC by 10 x and GaN by > 3 x in terms of resistive and switching losses for the same device size



- **Diamond PCSS: Diamond PhotoConductive Semiconductor Switches -** Novel ≥ 20kV, ≥ 250A, ≥ 500 V/ns, ≥ 200 A/ns diamond PCSS devices with buried, metallic p+ current channel, fast fall and rise response (≤ 2.5ns) and linear current scaling with increasing light (intrinsic p- absorber)
- High on/off ratio (i.e., ≥ 1011), high optical efficiency (≥ 3%), linear current scaling with increasing light intensity.

- **Ultrafast, Autonomous Grid Protection Using Linear Photonic Switching** - > 20 kV, >2,500 A peak autonomous grid protection device with matching impedance to prevent reflected transients using Controllable impedance of the Optical Transconductance Varistor

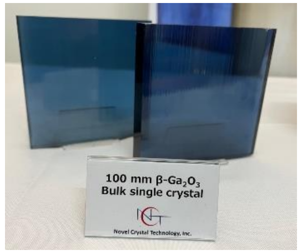


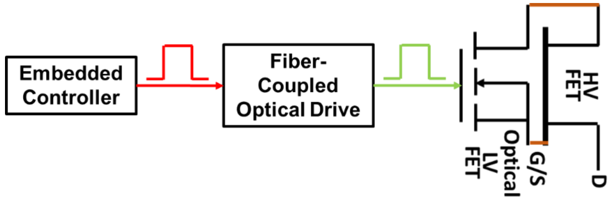


- **Optically Controlled 20 kV Gallium Oxide Power Switches for Grid Resiliency** -3.3 kV -20 kV β-Ga_2O_3 integrated SBD and FinFET with optical gate powering and control
- High field strength (4-8 MV/cm) high quality epitaxial β-Ga_2O_3 layers for 3.3 kV- 20 kV vertical FETs and SBD

arpa·e
CHANGING WHAT'S POSSIBLE

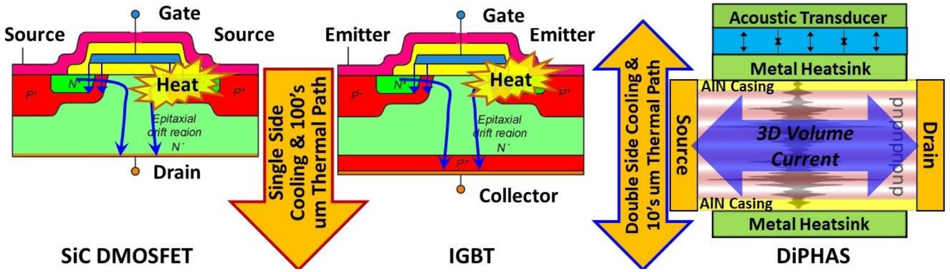
A Brief Project Summary for *Devices* (cont'd)

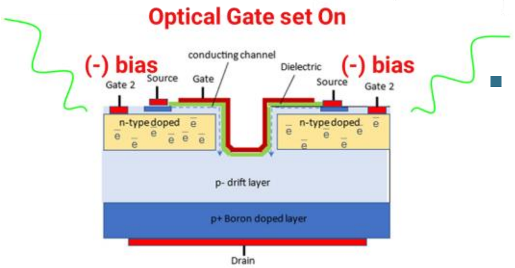




- **Optically Cascoded Ultrahigh Voltage Gallium Oxide Devices for Modular Multi- converter** - design, fabrication and demonstration of Ga_2O_3 20 kV, 25 A vertical transistors with low on-resistance
- Develop an optical cascode architecture for high slew rate operation and EMI immunity, and demonstrate optically cascoded Ga_2O_3 sub-model (SM) based MMC prototype

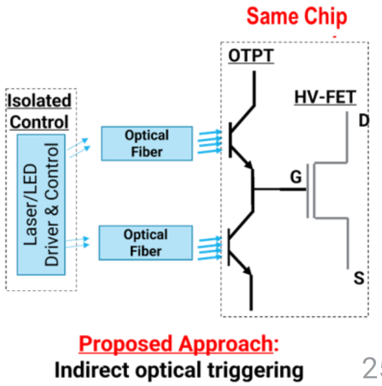
- **Scalable Wide-Bandgap III-Nitride Switch (SWiNS)** - New Device: disappearing polarization, hetero-superjunction acoustic switch
- 10 KV / 10A switching as tested in convertor circuit at >100kHz with design toolkit ready for tech transfer.





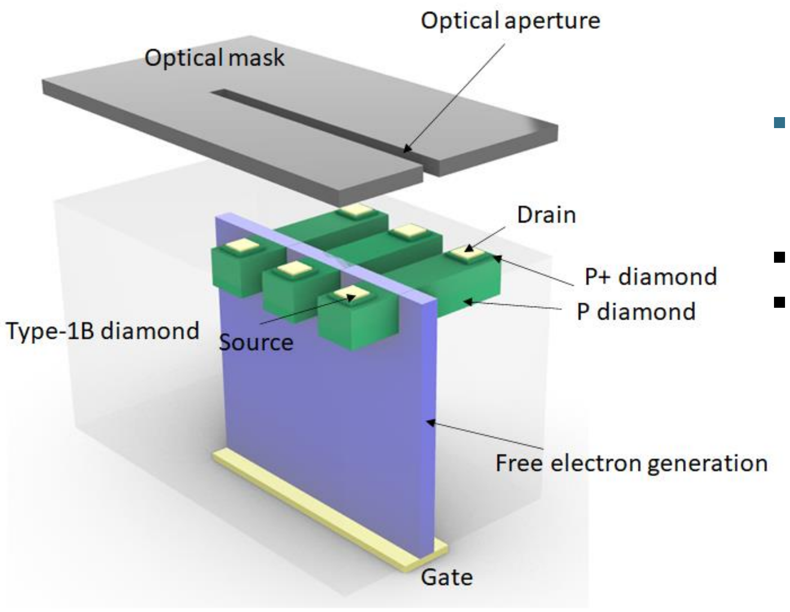
- **High Power Diamond Transistors with Electrical and Optical Gate Control** - Develop ultra high-power 3. 3 kV diamond transistors that includes an electro-optical gate control, to overcome the EMI interference barrier problem and unleash the potential of ultra high-power electronics to dramatically improve the efficiency and resilience of the electric grid applications, and more.

- **Optically Triggered Ultra-Wide Bandgap (UWBG) Power Electronics** - 3.3 kV AlGaN Transistor; AlGaN OTPT with deep UV optical drive
- Reduces power conversion losses by 52% compared to SOTA; Reduces foot-print by 5x; High temperature operation up to 250° C;



A Brief Project Summary for *Devices* *(cont'd)*

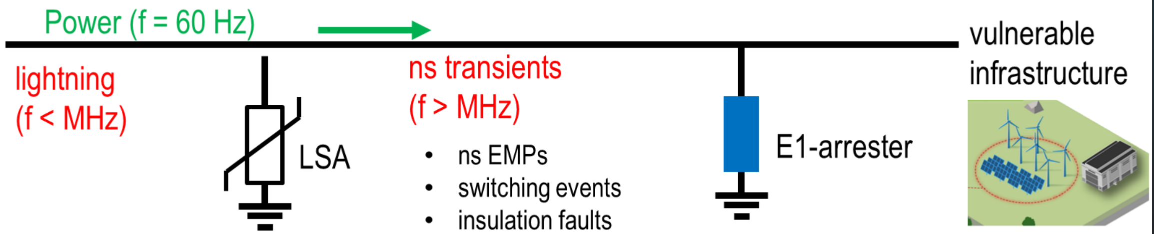
Lawrence Livermore National Laboratory



- **Diamond Optically Gated JFET (DOG-FET)** – > 6 kV, >10 A optically gated junction field effect transistor with optically isolated gate from the channel by the substrate
- Unique memory effect allows for pulsed light triggering on/off
- Allows benefits of optical gating (fast, high switching speed, low EMI) while reducing optical intensity

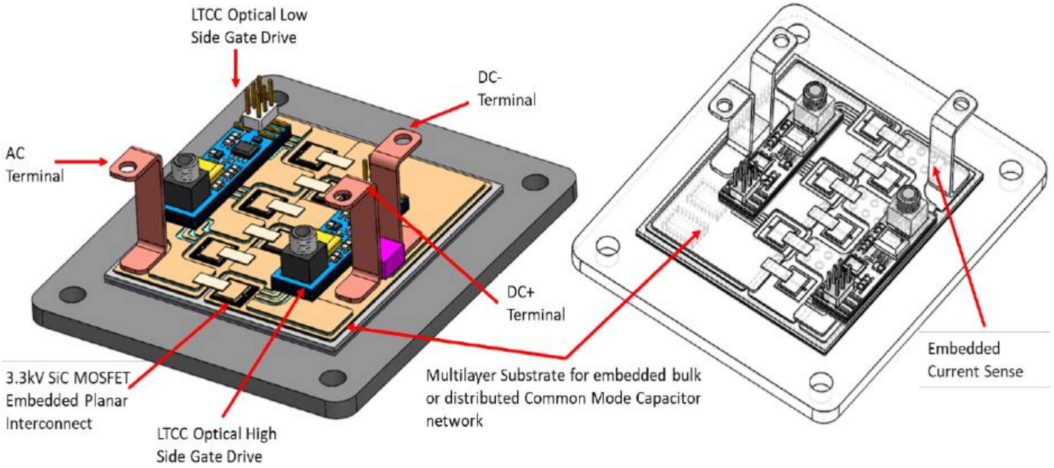
Sandia National Laboratories

- **E1-Arrester for Improved EMP Protection** – takes advantage of the composition of molybdenum nanoparticles in a silicon nitride matrix - to divert sudden and short-lived high-voltage and high-current surges of energy safely away from the grid.
- The proposed 10 kV arrester responds on a nano-second timescale, which is faster than existing lightning surge arresters currently on the grid.



A Brief Project Summary for *Modules*

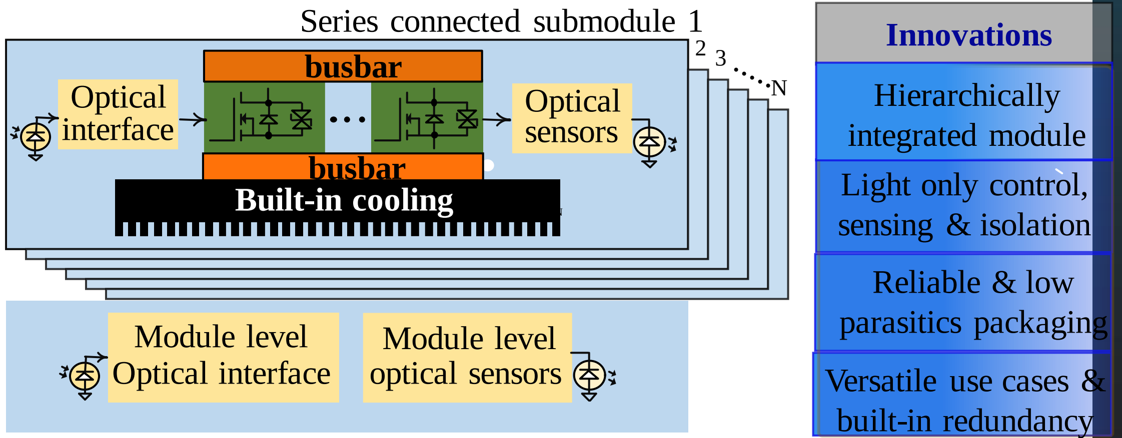
UNIVERSITY OF ARKANSAS



- **Heterogeneously Integrated Power Modules (HIPM)** – 3.3 kV , ≥120 A, 50-75 kHz @ 250 kW
- Utilize advances in multi-layer substrates, embedded passives, field dampening materials, wire bondless interconnect and heterogeneous integration of components to achieve a minimal parasitic, fast-switching power module capable of handling a range of power device switch technologies.

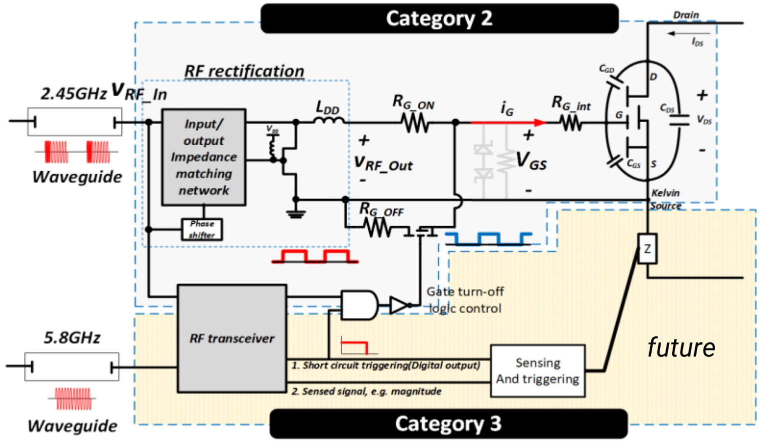
THE UNIVERSITY OF TENNESSEE KNOXVILLE

- **A UNIVERSAL (Ultrafast, Noise-free, Intelligent, Versatile, Efficient, Reliable, Scalable, and Accurate Light-controlled) Switch Module** - Modular design with commercially available low-cost low-voltage low-current fast-switching SiC devices in series and parallel to achieve the desired voltage, current (20 kV/250A) as well as high dv/dt and di/dt
- Sufficient number of paralleled SiC devices with built-in cooling to achieve an efficiency (99.95%) close to mechanical switches and 10X overcurrent capability



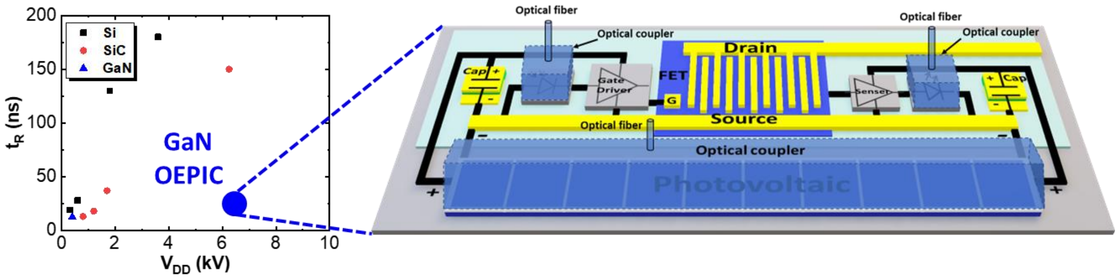
arpa·e CHANGING WHAT'S POSSIBLE

A Brief Project Summary for *IC Integration and Sensing*

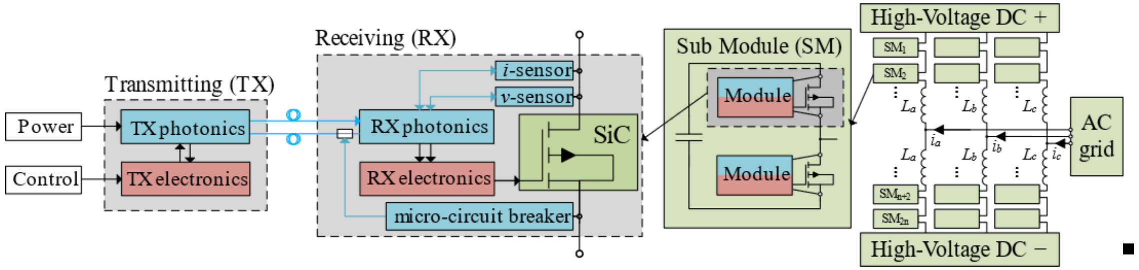


- **TRIGER: Timed RF Integrated Gating for Energy Regulation** - Direct RF triggering of high power SiC FETs; Isolates control from load to enable fast, efficient switching with EMI mitigation
- High-pulsed power RF rectification, GaN MMIC realization, 260 V/ns switching @10 kV / 10 A
- Critical enabler for hybrid-electric propulsion, a key element of RTX roadmap to more sustainable aviation

- **Medium-Voltage Optoelectronic Power IC Building Block** - 10-kV/10-A GaN super-heterojunction technology; Monolithic integration of MV power switches and driving/sensing IC switching at 250 V/ns and 10A/ns
- Chip-scale integration of optoelectronic components and > 5X faster medium voltage switching, with 5X lower power loss

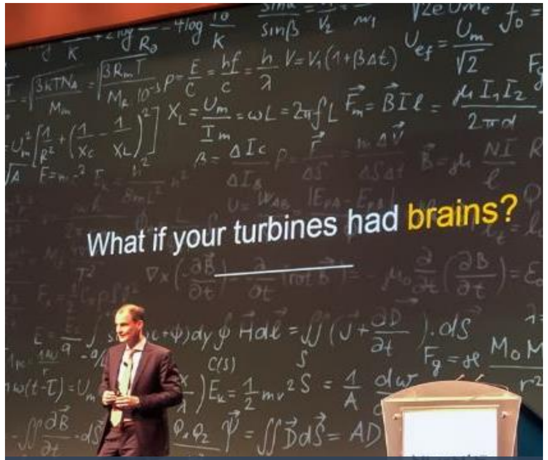


- **All-Optical Control of Isolated High Voltage Power Systems Using Integrated Electronic, Photonic, and Microfabricated Sensing and Breaker Technology** - Scalable, low-noise integrated module for actuating 3.3 kV, > 10 A WBG & UWBG devices with ≥ 100 kHz; Integrated optical power & signal transmission; Optically isolated I/V sensing; Magnetic micro-circuit breaker
- Improving energy efficiency, grid control resilience, and reliability, high noise immunity, efficient high-frequency operation and control



arpa·e energy innovation summit

Highly Selective Technology Showcase



Inspiring Keynotes

Unparalleled Networking

Fast-Paced Technology Pitches

arpae-summit.com

May 22-24, 2024 | Dallas, TX

[Student Program (arpae-summit.com)](arpae-summit.com)

Join the Team that is Transforming the Energy of Tomorrow

Program Directors | Technology-to-Market Advisors | Fellows

Learn more and apply: **www.arpa-e.energy.gov/jobs** or **arpa-e-jobs@hq.doe.gov**

If it works…

will it matter?

Dr. Olga Spahn
Program Director
Advanced Research Projects Agency – Energy (ARPA-E)
U.S. Department of Energy
olga.spahn@hq.doe.gov

arpa·e
CHANGING WHAT'S POSSIBLE