MITSUBISHI ELECTRIC
UNINTERRUPTIBLE POWER SUPPLIES

The Silicon-Carbide Revolution

7x24Exchange-Northwest Chapter

By: Anthony Pinkey
National Accounts Manager

5.11.2021

Today's Agenda

There Are Four Parts To Today's Story

Part One: What is the "*Revolution*" ?
Part Two: Where Is The Battleground?
Part Three: Who Is Funding The Revolution?
Part Four: Two Stories From Inside Revolution

Revolutionary Guide

Anthony Pinkey, National Accounts Manager at Mitsubishi Electric

- Born, raised and educated in New York City
- BEE Degree in Electrical and Electronics Engineering, Manhattan College
- 35 years of Mission Critical experience: sales, product management, marketing, company owner
- Author, speaker
- Represented the United States playing rugby in 10 countries

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PART I

Welcome to The Revolution!

Some Technological Revolutions are

It’s Easy to See the Flashy Ones

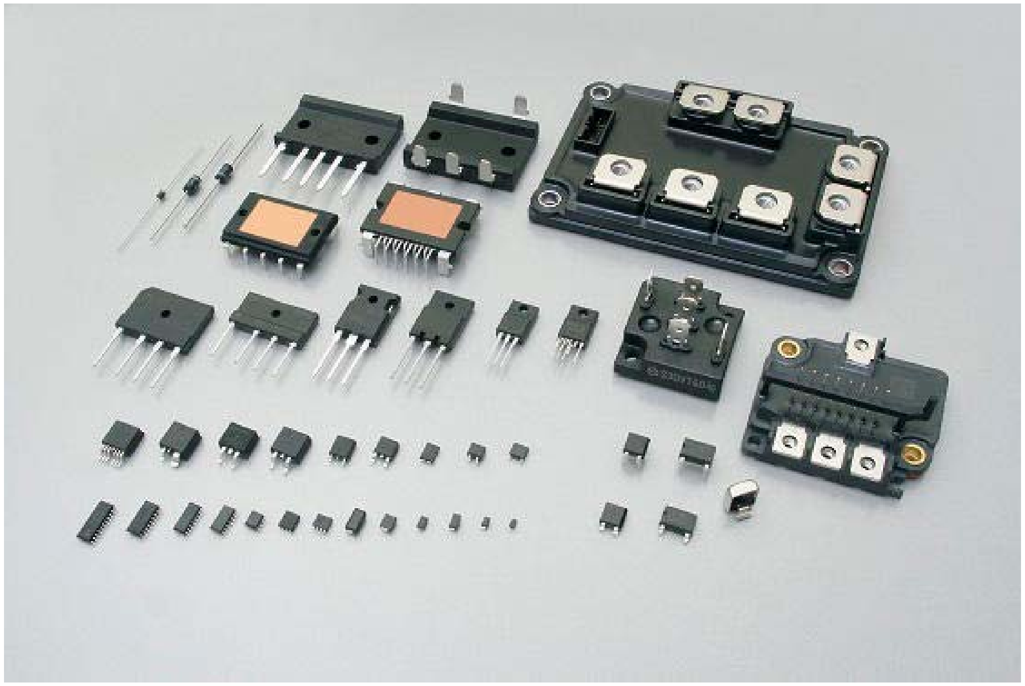
- Your phone recognizes you!
- Augmented Reality!
- 3D screens!
- Your phone is your bank!

Hollograms!

It’s Easy to See the Flashy Ones

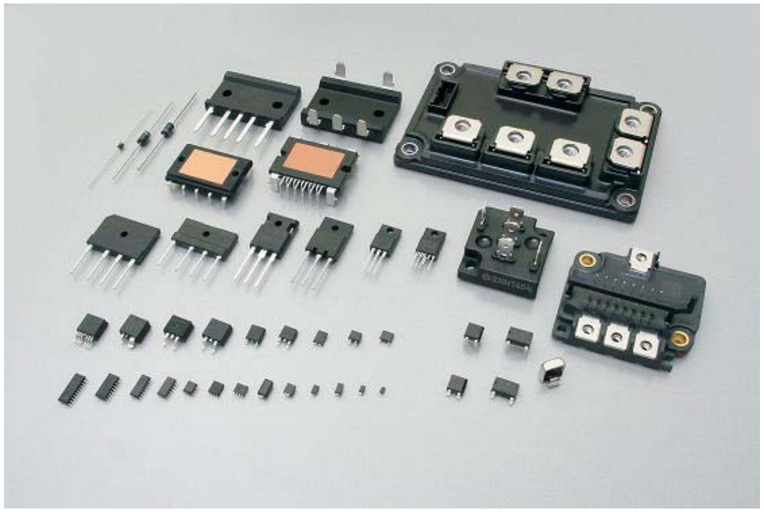
- Products are faster, more efficient, environmentally friendly
- They all embellish cost, size and weight reductions

Some Technological Revolutions are very subtle…



…the *behind-the-scene* Revolution in Power Electronics

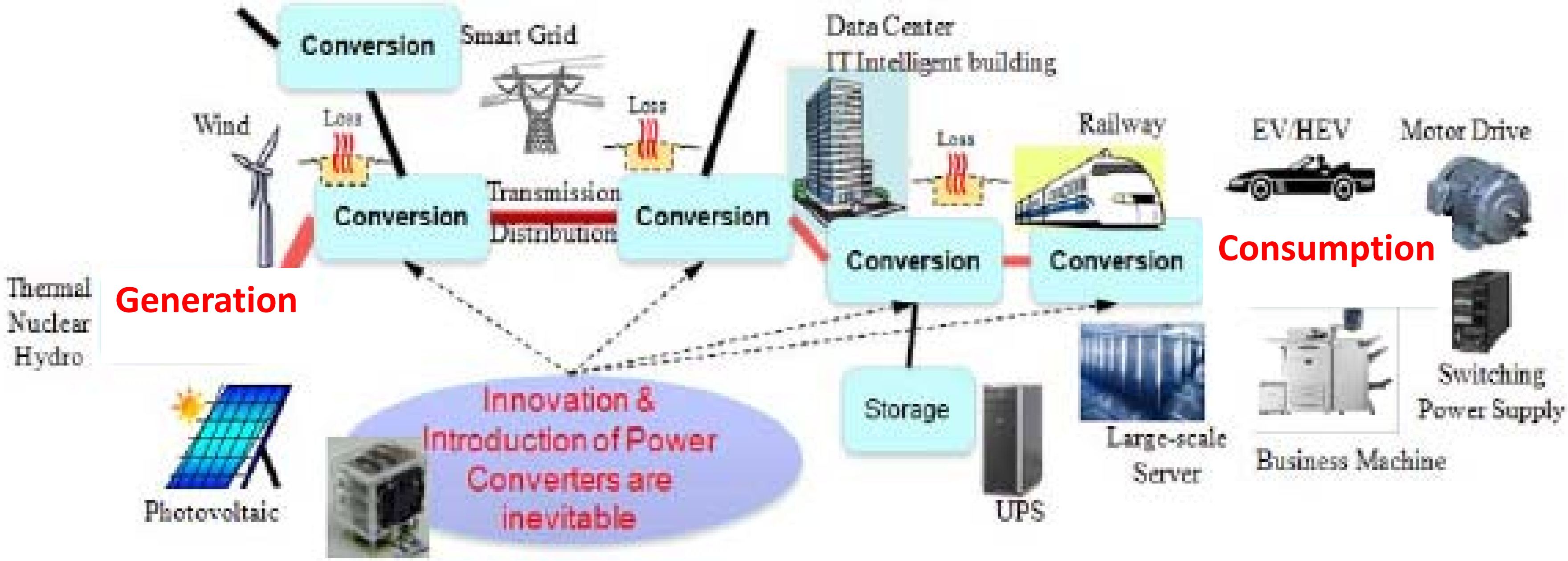
Devices: Semiconductors, transistors, converters, inverters…



Advancements to these devices provide us with more efficient ways to manipulate, regulate, and convert electricity from one form to another…

(THIS is the real Revolution)

Power Electronics Devices at work in the Smart Grid



Currently, > 60% of generated electric power passes through power electronics between generation and use

Power Electronics Devices

Semiconductors, transistors, converters, inverters…

…for the past 60 years, the material used to conduct electricity inside these devices has been Silicon…

…as a material, we have pushed Silicon electrons to their limits…

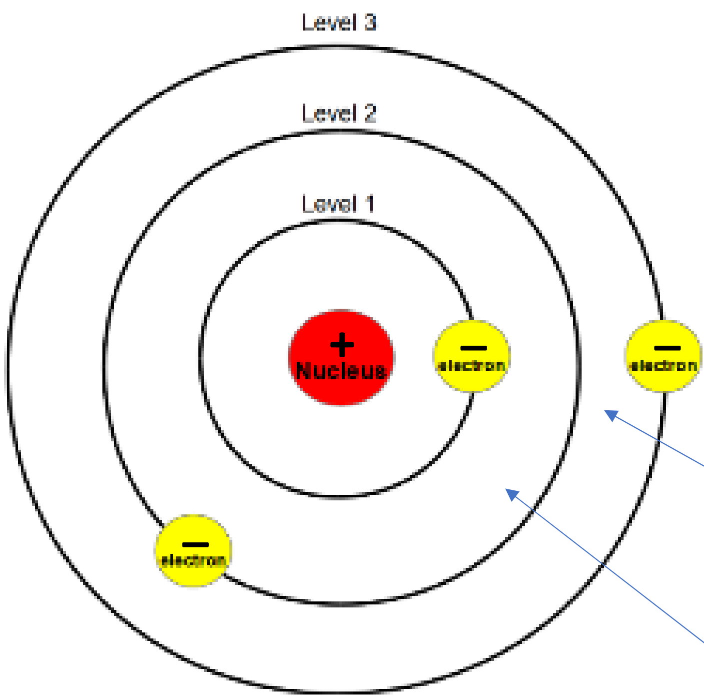
…time for a revolution…

As with all Revolutions, someone or something is going to make an exit…

…you can say goodbye to Silicon…

…good old number 14 on the Periodic Table…

How did this Happen?



- It all starts with the atom
- Every atom has a positively charged nucleus and negatively charged electrons orbiting the nucleus in Bands

- Bandgaps separate the electron Bands
- Electrons cannot exist in Bandgaps!! (No Man's Land)

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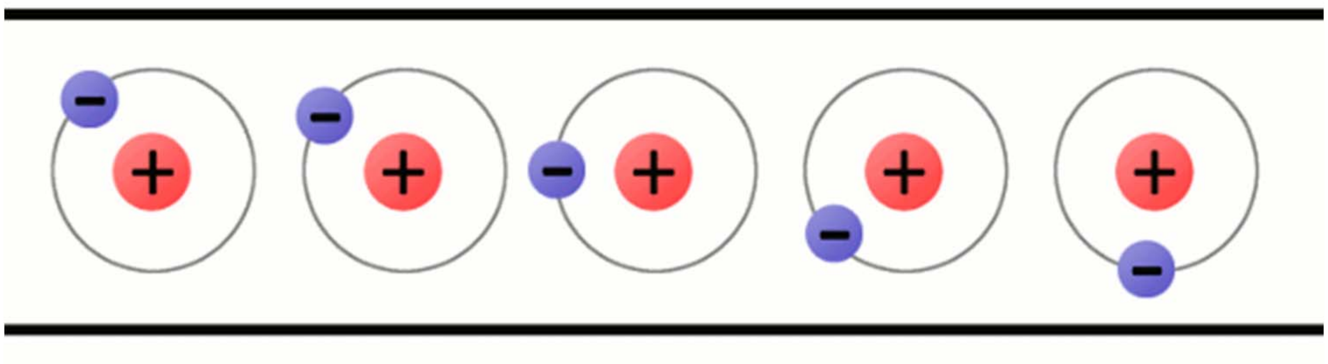
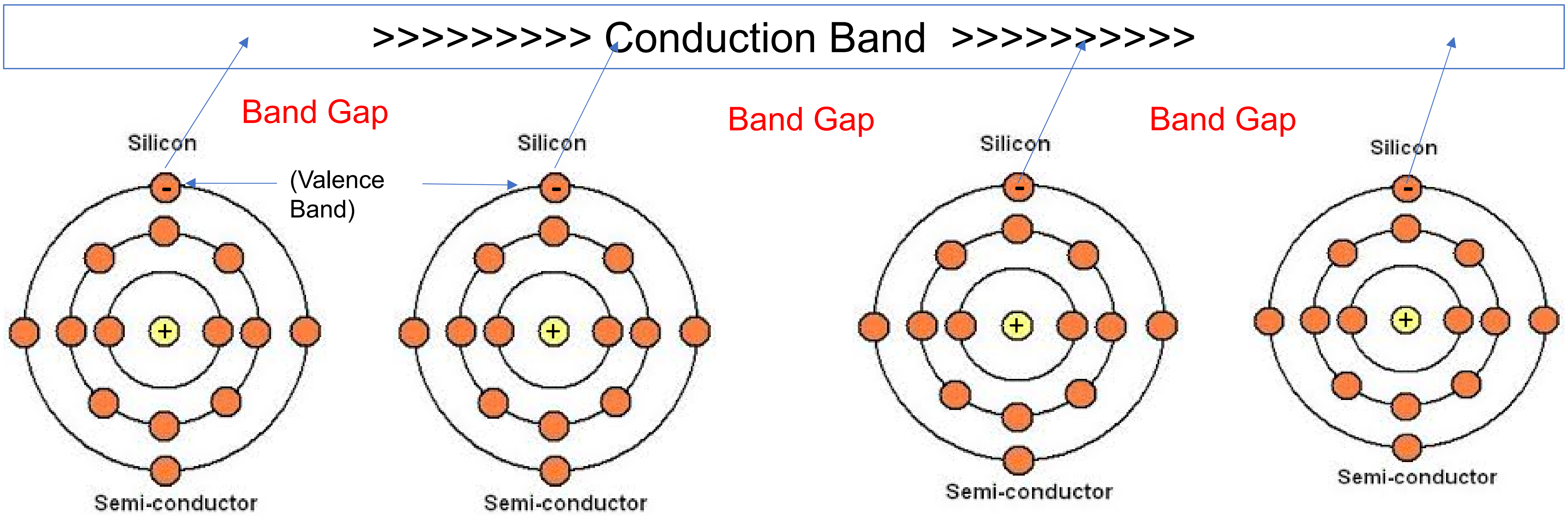
How do we make Electric Current?

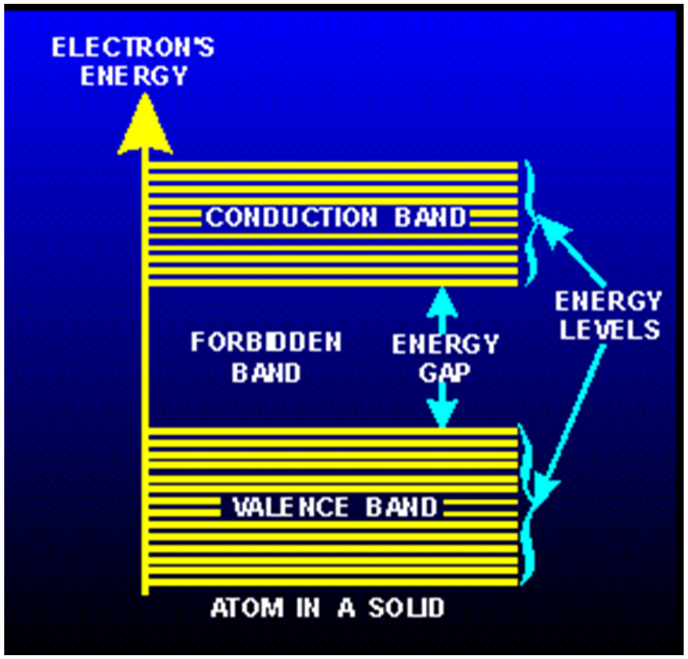


- The movement of charged electrons from one atom to another makes electricity.
- The electrons are not tied to a particular atom, they are on the move in what is called the Conduction Band.

Electrons Must Cross a Bandgap



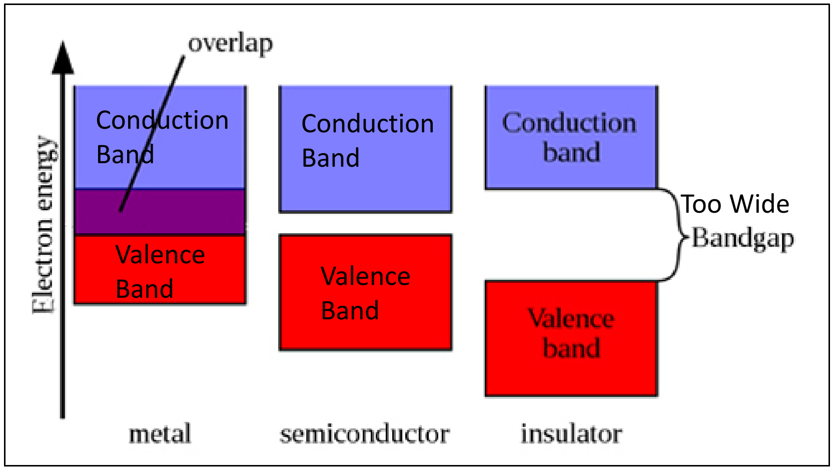
Crossing the Bandgap to Conduction



- You need energy to move electrons to the Conduction Band
- Not all Bandgaps are the same

Bandgaps in Different Materials

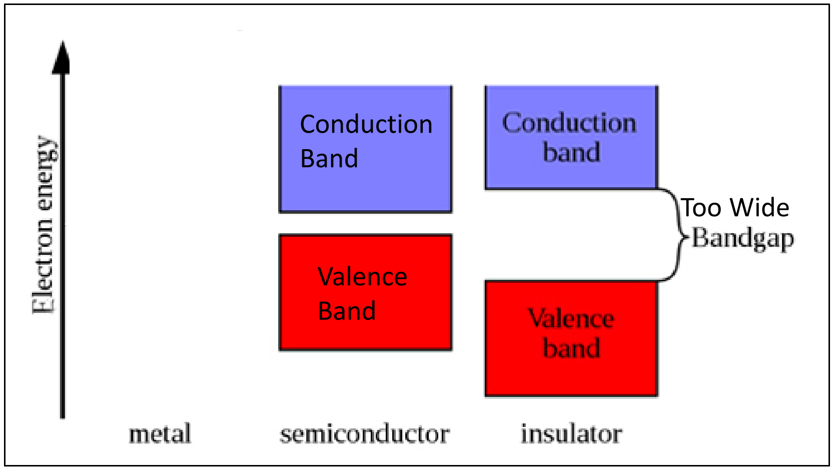
A Look At Different Materials And Their BandGaps



- **Metals** have overlapping electron bands (Valence & Conduction)

Bandgaps in Different Materials

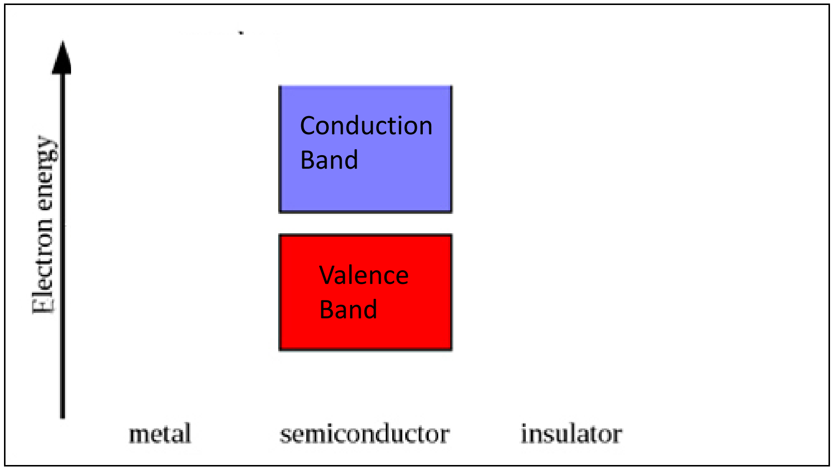
A Look At Different Materials And Their BandGaps



- **Metals** have overlapping electron bands (Valence & Conduction)
- **Insulators** have a Band Gap that is too wide

Bandgaps in Different Materials

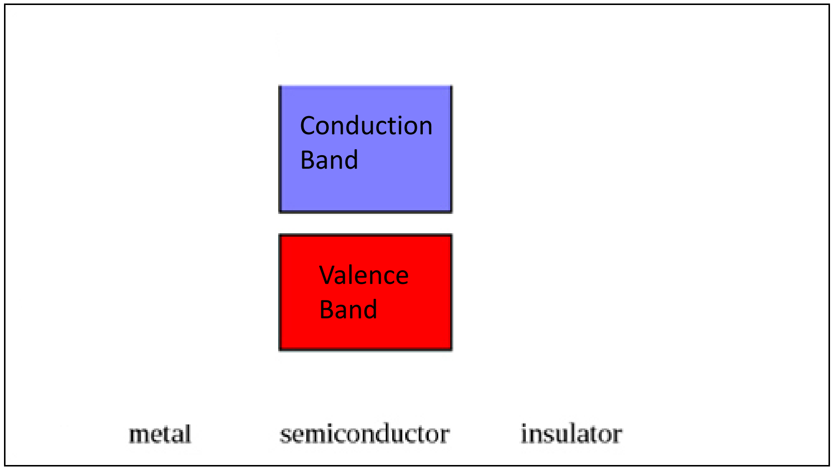
A Look At Different Materials And Their BandGaps



- **Metals** have overlapping electron bands (valence & conduction)
- **Insulators** have a wide band gap between the bands
- In a **semiconductor** the Band Gap is just right; we will **control** the flow of electrons from the valence band to the conduction band by adjusting the size of the Band Gap.

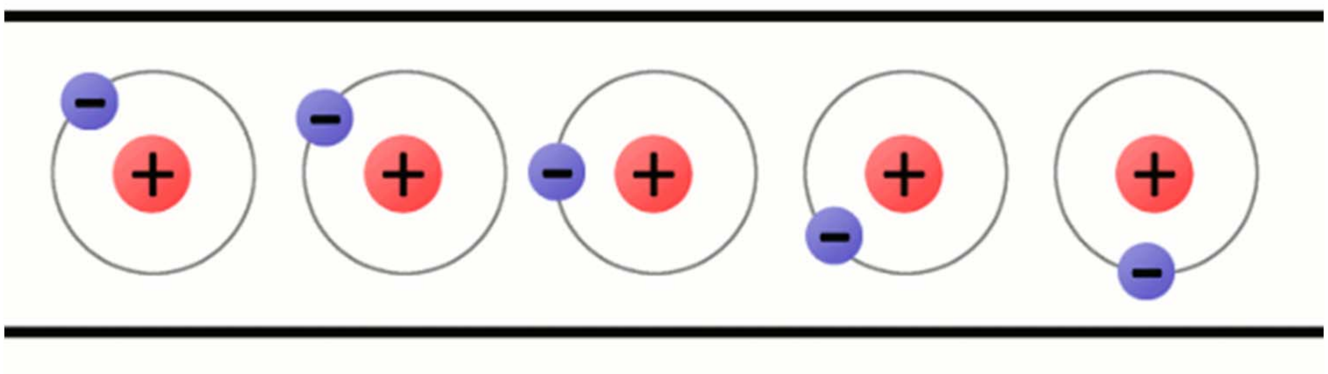
Bandgaps in Different Materials

A Look At Different Materials And Their BandGaps

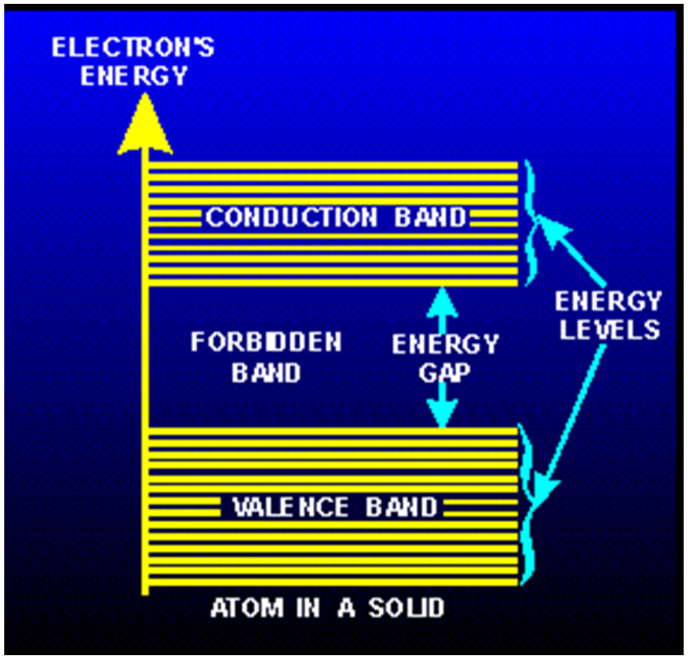


- **Metals** have overlapping electron bands (valence & conduction)
- **Insulators** have a wide band gap between the bands
- In a **semiconductor**, we can **control** the electrons moving from the valence band to the conduction band
- Silicon was chosen as the material best suited for conduction

How Do We Get Electrons To Cross The Bandgap Into the Conduction Band?

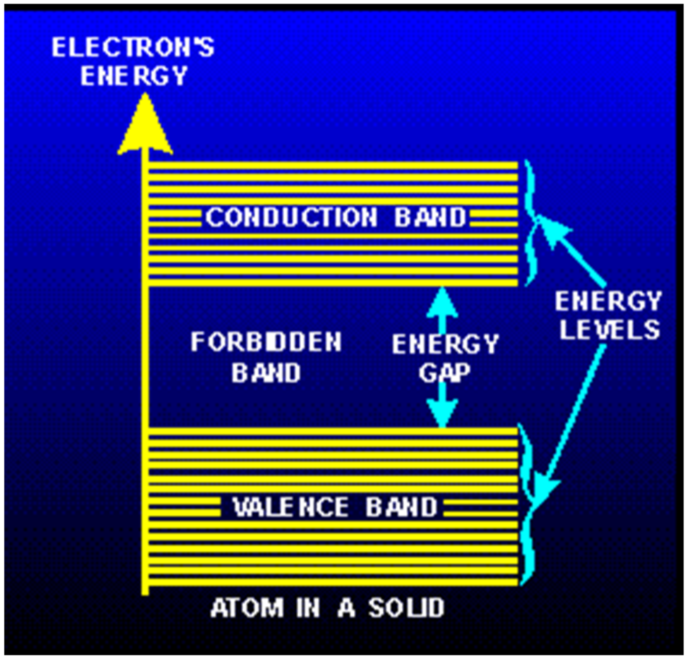


Crossing the Bandgap to Conduction



- You need energy to move electrons to the Conduction Band
- Energy = Voltage, Light, Heat

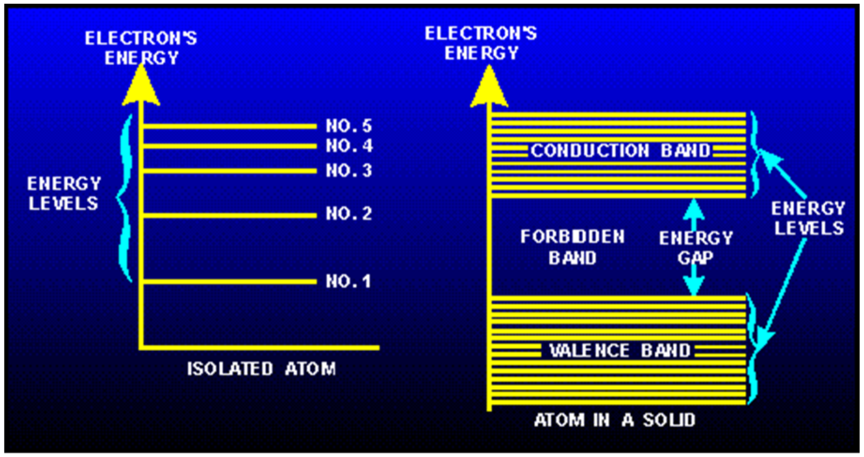
Crossing the Bandgap to Conduction

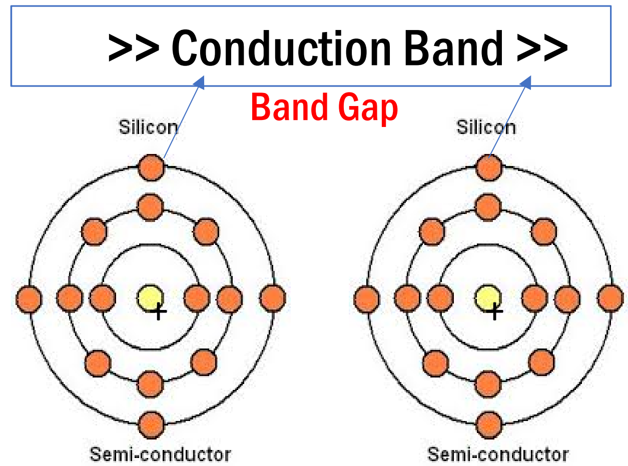


MATERIAL	BANDGAP ENERGY (eV)	APPLICATION
Silicon (Si)	1.11	Lasers, LEDs, Photo-voltaic cells, Power electronics
Silicon Carbide (SiC)	3.25	LEDs, Power electronics, new emerging technology

- Silicon Carbide is a Wide Bandgap material
- Its Bandgap is 3X wider than Silicon

Crossing the Bandgap to Conduction





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- **Bandgaps** determine how a material's electrons behave as electric current

Advantages of Silicon Carbide Over Silicon

Because it can get across the Wider Bandgap:

1. It can sustain 10X higher voltages than Silicon and 10x the breakdown voltage
2. Carry 5X higher currents
3. Withstand 3X higher temperature
4. Exhibit 3X Higher thermal conductivity
5. Switch 10X faster

(...you can see why Silicon-based devices have approached their material limits)

What People in our Industry are saying about Silicon Carbide (SiC)

- "SiC is to the 21st century what Silicon was to the 20th century." – IEEE
- "Wide Bandgap (WBG) semiconductors are a foundational technology that will transform multiple industries, resulting in billions of dollars of savings." – US Department of Energy
- "SiC technology is a disruptive technology that has changed the trajectory of future semiconductor innovations."
  – Oxford University Press

A Technological innovation that creates a new market and eventually disrupts an existing market and value network, displacing established market-leading firms, products, and alliances.

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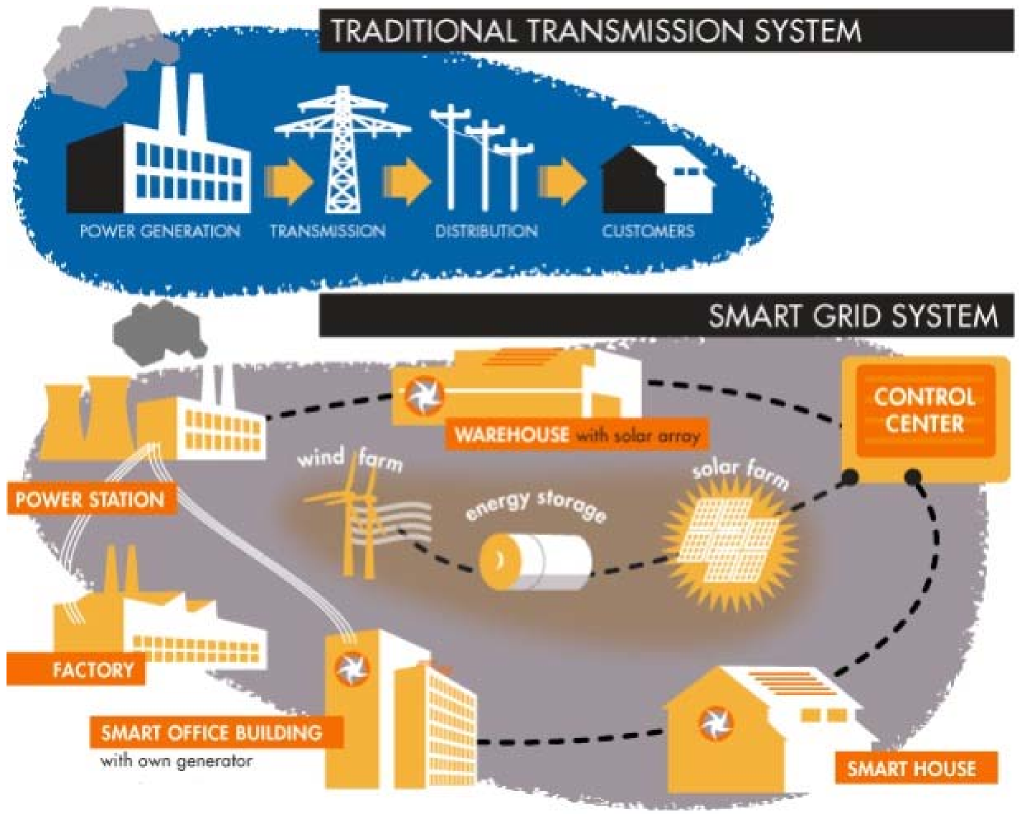
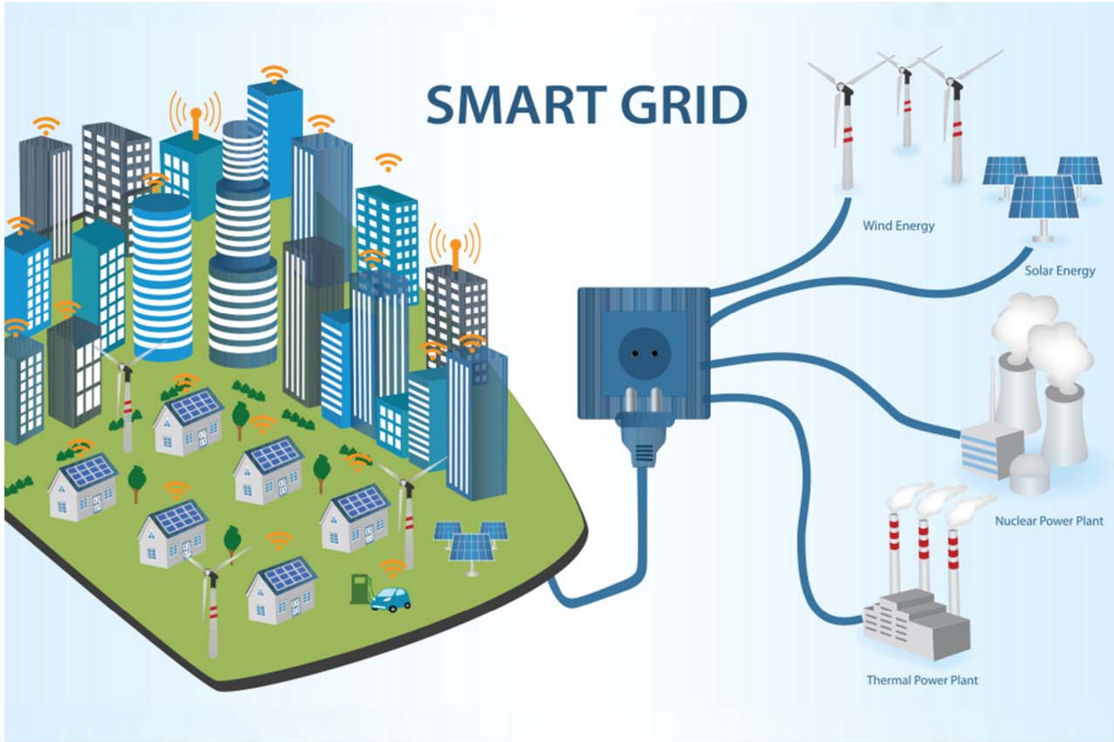
PART II

Where Is The Revolution?

The Revolution Is All Around Us



...the never ending Revolution in Power Electronics Devices

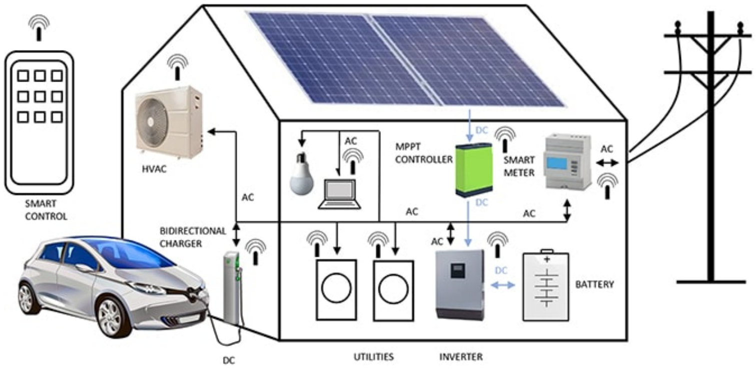


Smart Grid is an **Electrical Grid** with Automation, Communication and IT **systems** that can monitor **power** flows from points of generation to points of consumption (even down to appliances level) and control the **power** flow or curtail the load to match generation in real time or near real time.

Advances in Power Electronics and Control Systems Drive Efficient, and Reliable Electric Grids

Electric Grid Applications

- HV DC Interface (AC to DC)
- Microgrids
- MV Motor Drive
- Solar Interface
- Wind Interface
- Energy Storage Interface



Distributed energy (solar panels, wind turbines, combined heat & power, generators) that produce a self-sufficient energy system that serves a discrete location. Features:

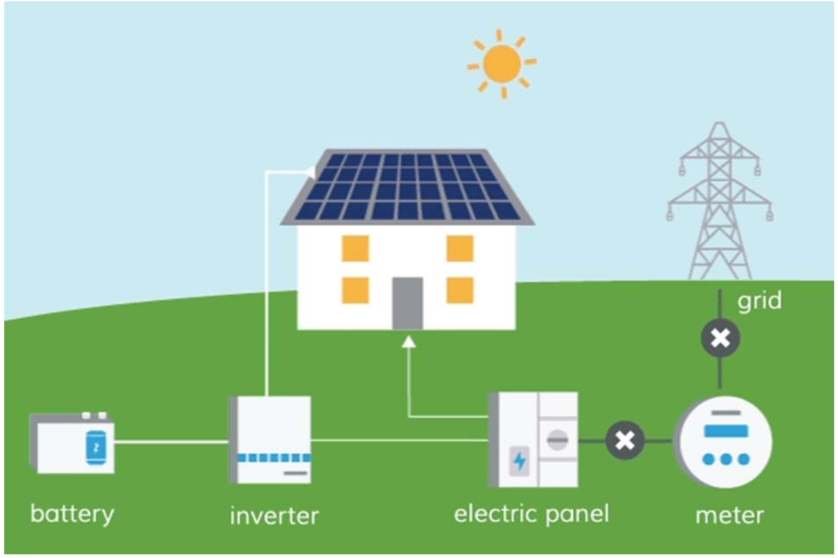
1. A microgrid is local, 2. A microgrid is independent, 3. A microgrid is intelligent

Solar (Photovoltaic) Power

Did You Know:

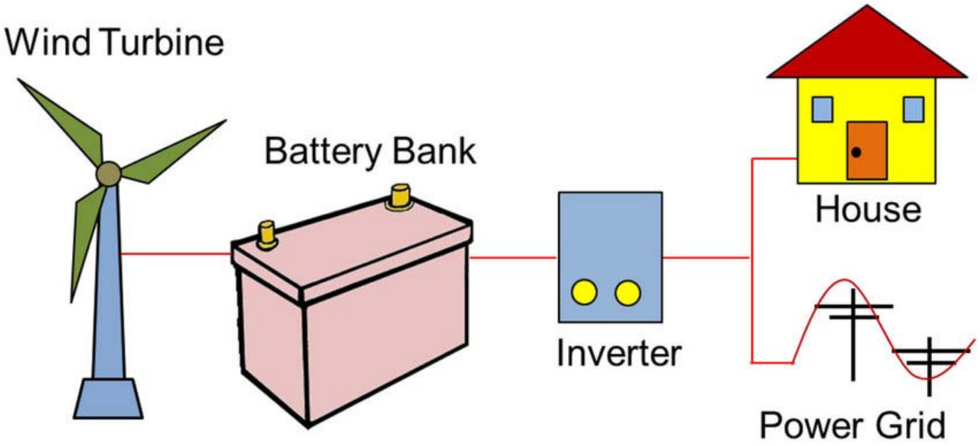
- The Earth receives more energy from the sun in one hour than is used in the entire world in one year.
- 0.3% of the Earth's land area covered in solar panels could supply all of the world's electricity needs.
- The cost that goes into creating solar panels is paid back through clean (renewable) electricity production within anywhere from 1-2 years.

Solar (PV) Power



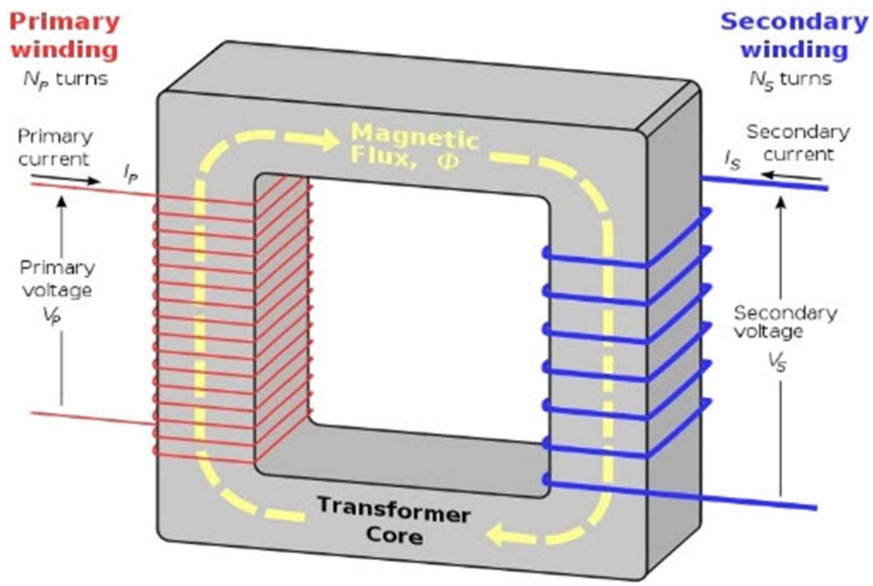
1. Photon particles carry light energy from the sun
2. The photons collide with Silicon (or Silicon Carbide) atoms inside solar panels to create the flow of DC electricity
3. An inverter converts the DC current to AC current that you use in your home, charge batteries or put onto the grid

Wind Power



- Wind is a form of solar power created by the uneven heating of the Earth's surface.
- Prices for power contracts are as low as 2 cents per kilowatt-hour. These prices are recorded by the U.S. Department of Energy.

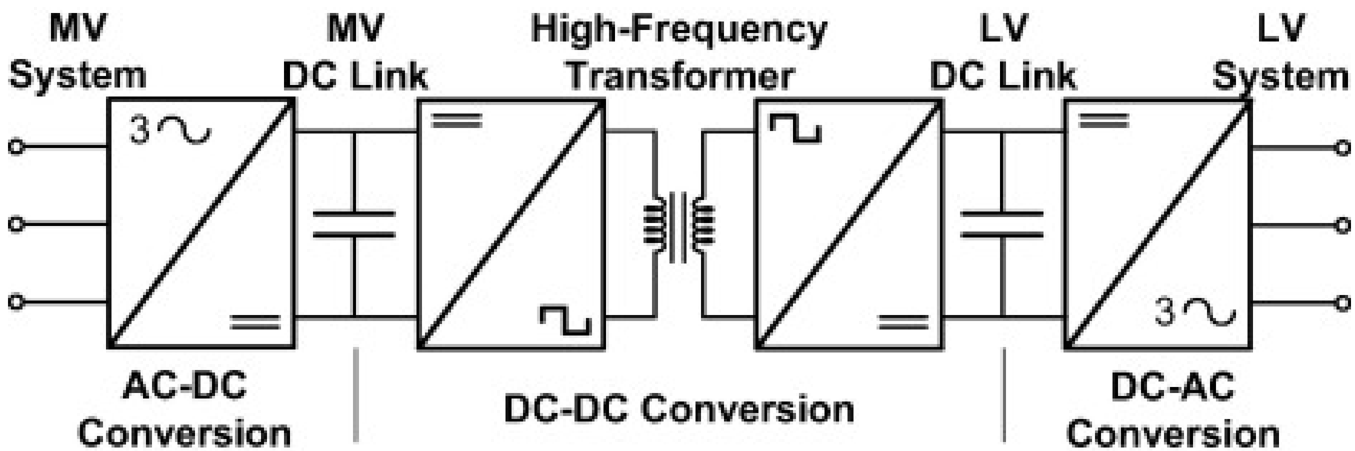
The Transformer



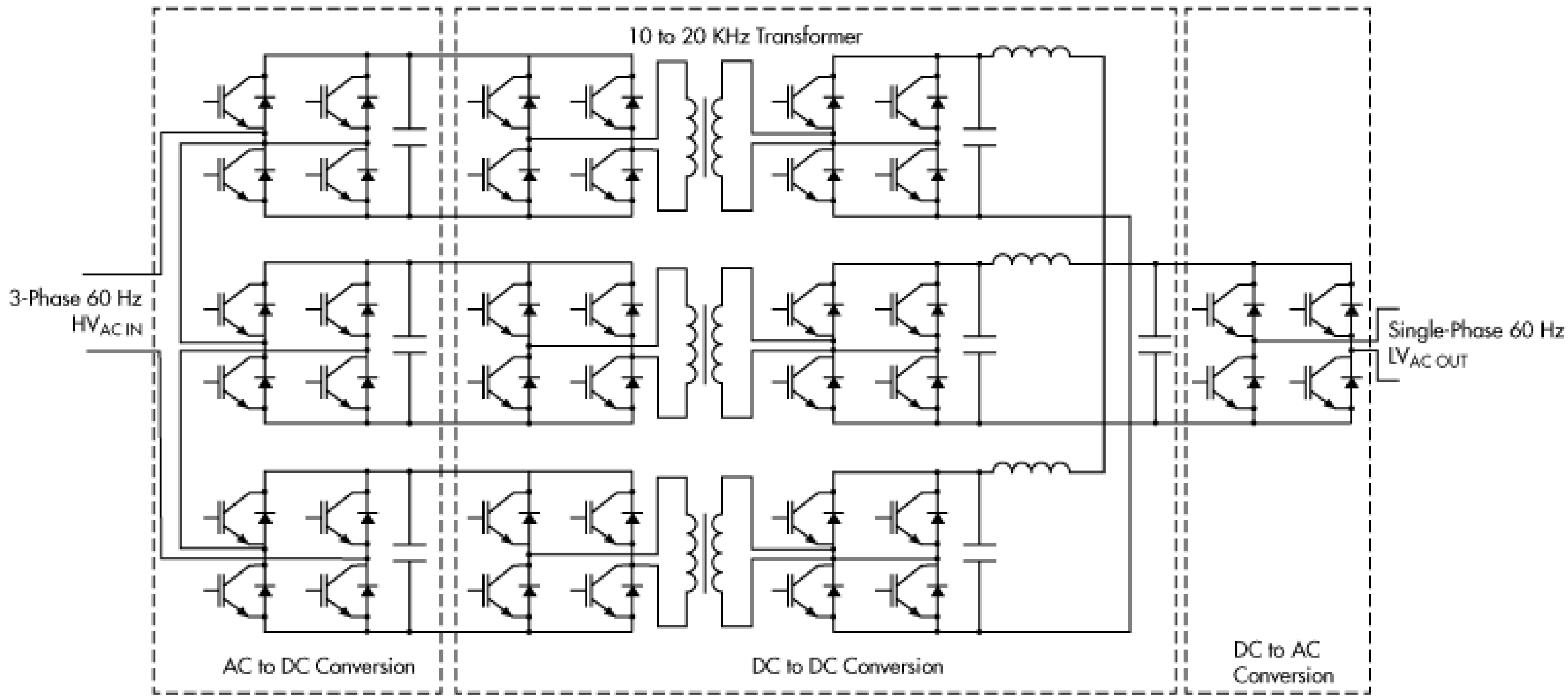
We are using the same design since 1882!

Improvements have been limited due to heat and frequency constraints

The *Solid State* Transformer (SST)

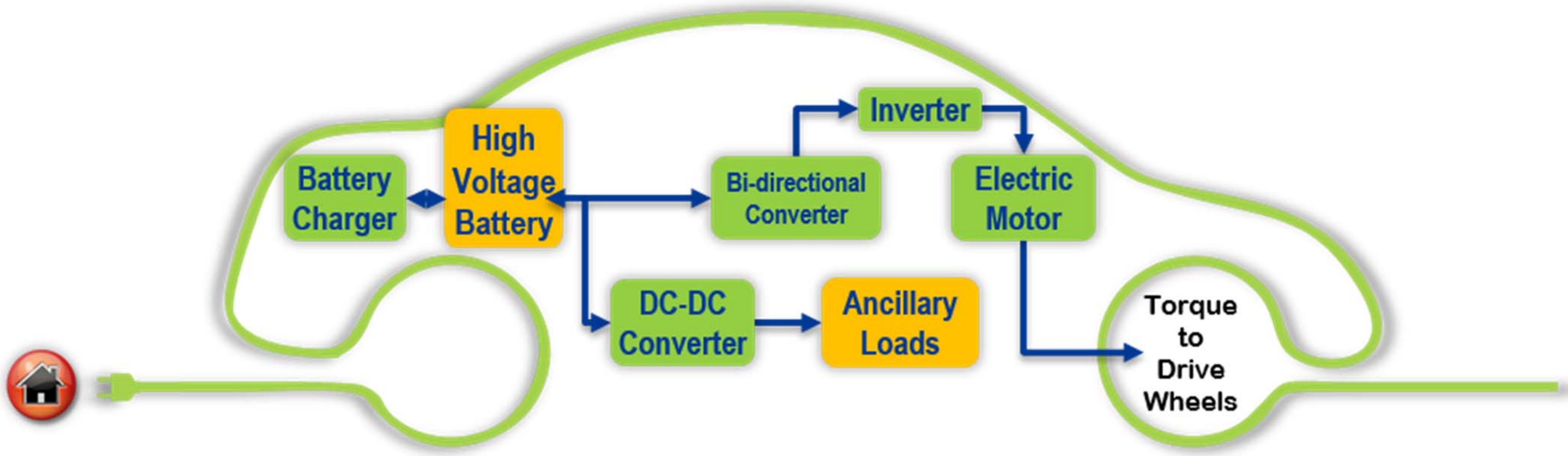


The *Solid State* Transformer (SST)



Three Phase to Single Phase
or
Single Phase to Three Phase

Power Electronics Devices In A Hybrid Electric Vehicle (EV)



SiC MOSFET Modules in NEW Tesla Model 3 EV

"It is now confirmed that Tesla is integrating SiC MOSFET based power modules in Model 3 inverters…

24 SiC MOSFET modules are used in each Model 3 inverter, this represents almost 2 Million SiC MOSFETs on our roads

https://www.pntpower.com/tesla-model-3-powered-by-st-microelectronics-sic-mosfets/?from=singlemessage&isappinstalled=0

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PART III

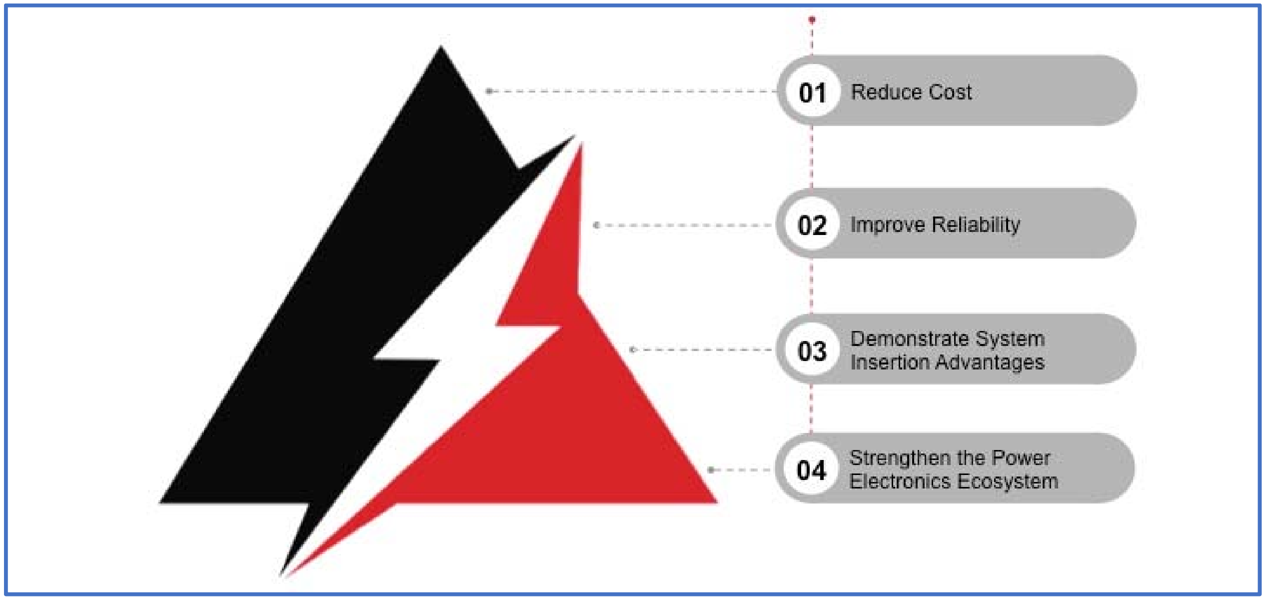
A Revolution Must Have Funding

U.S. DEPARTMENT OF ENERGY

- The U.S Department of Energy launched PowerAmerica, a Manufacturing Institute to Accelerate Adoption of Wide Bandgap power electronics.
- PowerAmerica addresses technology needs in the development of WBG systems to enable US manufacturing job creation and energy savings by US Industries.

PowerAmerica

Mission: Accelerate Commercialization of WBG Technology



Supporting US manufacturing is a priority for all PowerAmerica activities

US Department of Energy

Industrial Motors: WBG materials enable higher-efficiency, variable speed drives in pumps, fans, compressors, and HVAC systems.

Electronics: WBG materials are already used in large, high-efficiency data centers (UPS).

Grid integration: WBG-based inverters can convert the DC electricity generated from solar and wind energy into the AC electricity used in homes and businesses — reducing losses by 50%.

Utility applications: WBG materials can reduce transformer size by a factor of ten or more and accelerate development of high-voltage DC power lines.

Electric vehicles and plug-in hybrids: WBG materials will reduce battery recharging losses by 66%, and reduce the size of the cooling system by 60%. They offer greater efficiency in converting AC to DC power.

Military: WBG semiconductors are used in high-density power applications, satellite communications, and high-frequency radar.

Geothermal: WBG-based electronic sensors can withstand the harsh, high-pressure, and high-temperature environments of geothermal wells.

Circuit Breakers: WBG materials are being used in circuit "switches" that open in 700 nanoseconds.

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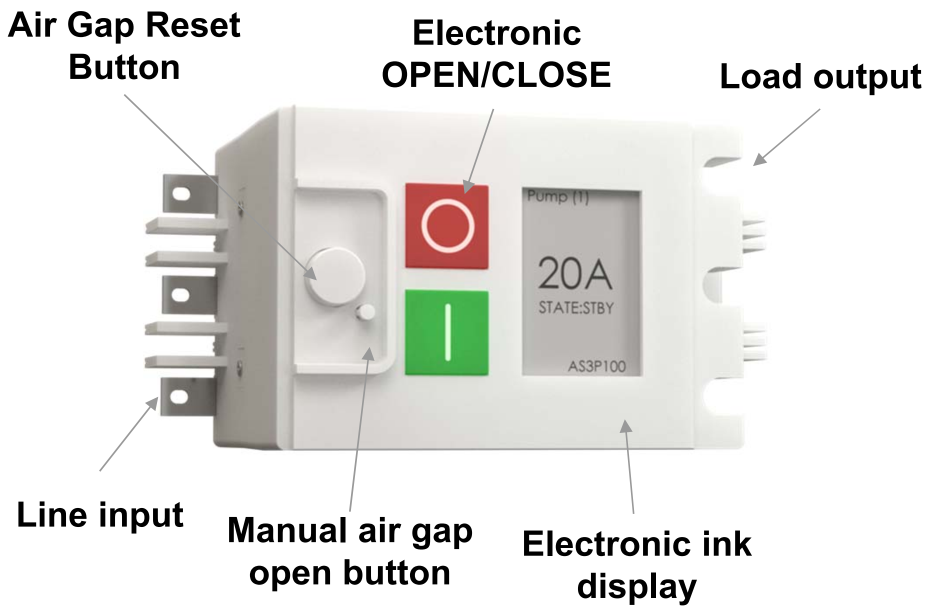
PART IV

Revolutionary Leaders:

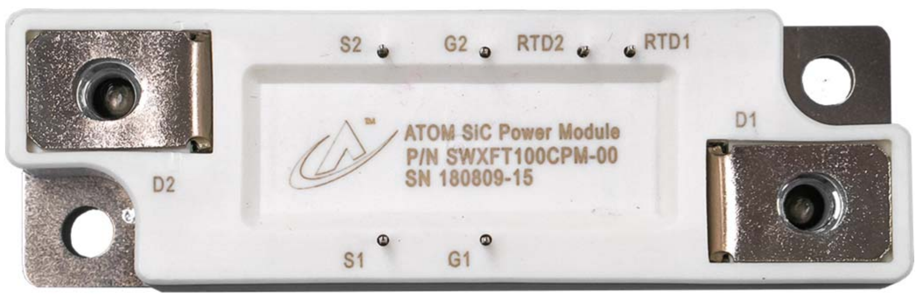
- Atom Power - SiC Solid State Circuit Breaker

Solid State Circuit Breaker (SSCB)

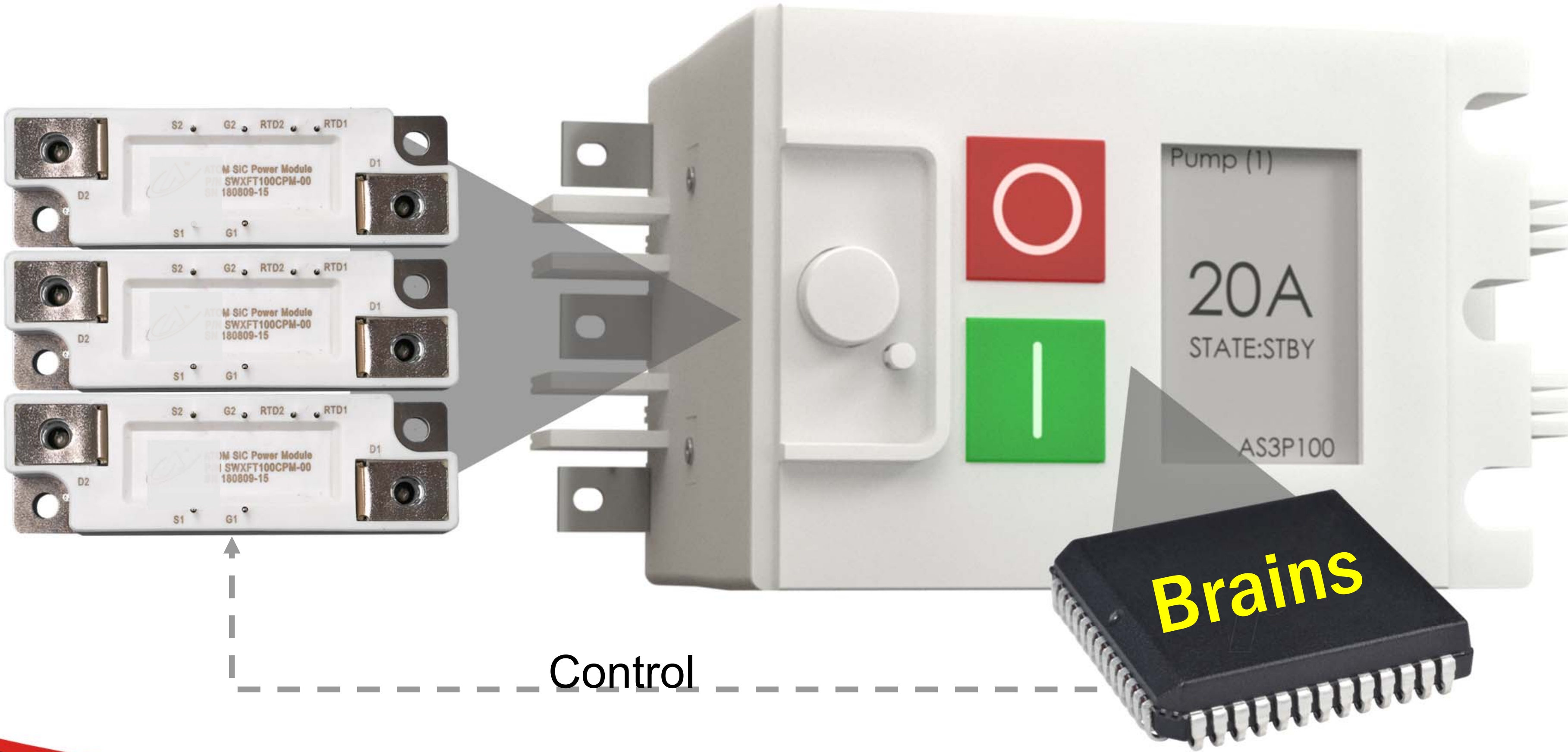


- **Solid-state (SiC) Switch**
- **Safer than any molded case breaker**
- **Intelligent & Self-aware**
- **Dynamic**

Current is interrupted using Silicon-Carbide (SiC) semiconductors

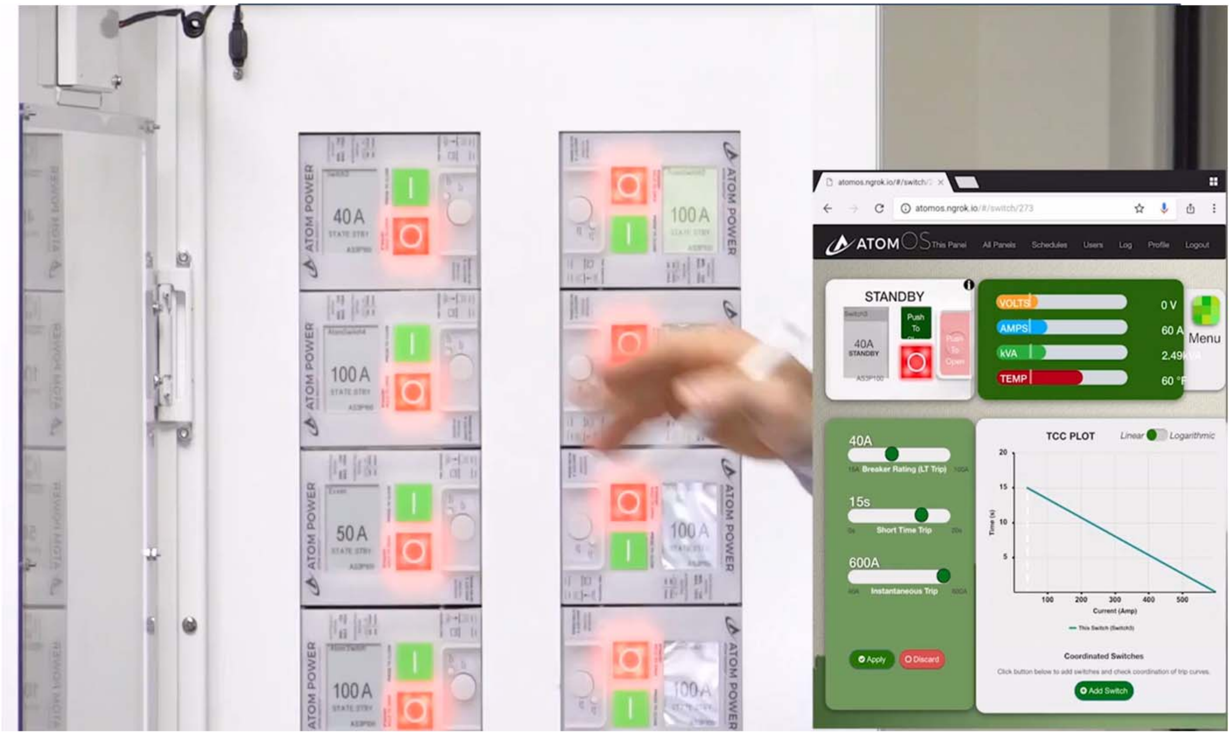


3-Phase SSCB


S2
G2
RTD2
RTD1
M SiC Power Module
SWXFT100CPM-00
180809-15
D1
D2
S1
G1
Pump (1)
20A
STATE:STBY
AS3P100
Brains
Control

Let’s Talk Control

- Digital Remote Control
- Unlimited Operations
- Dynamic Time-Current Curves



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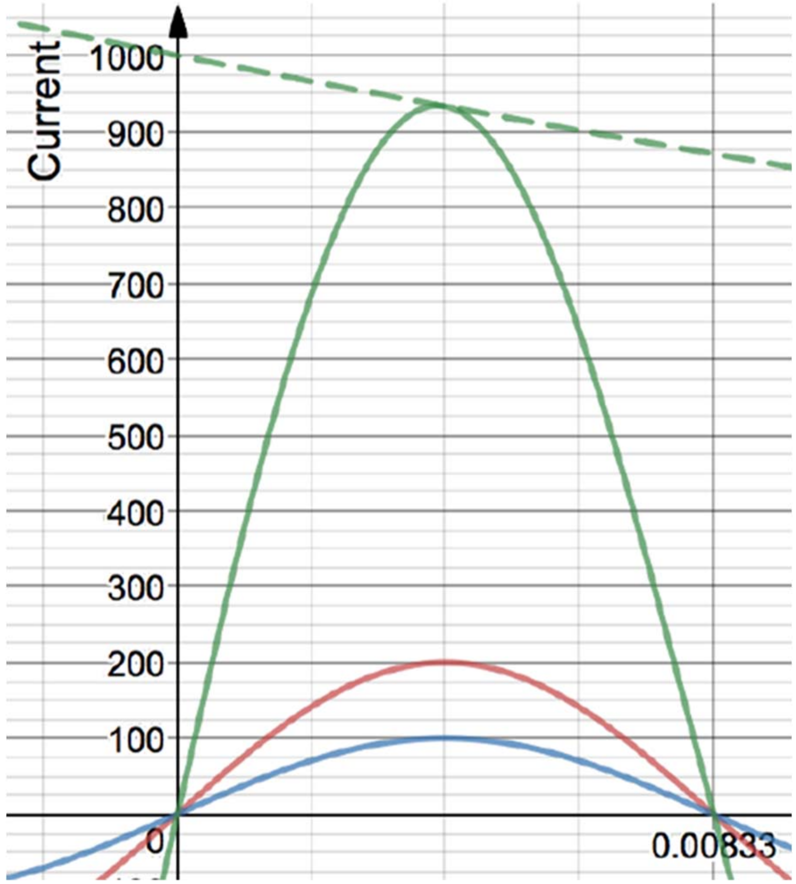
Let's Talk Speed

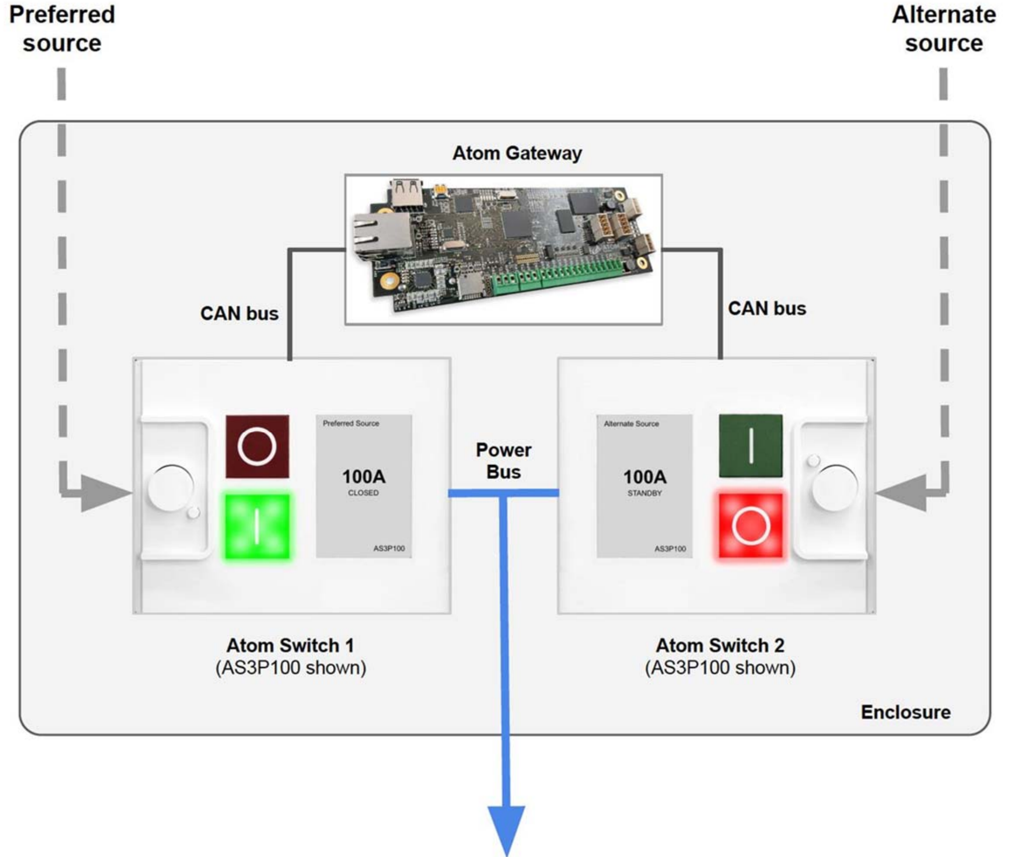
- ~3 microsecond round-trip time fault detection
- ~ Opens 16,000x faster



100,000-amp Interrupting Capacity

- 100 A Switch Opens in 700 nsec
- 1200 A Switch Opens in 2 μsec
- Arc flash energy is reduced by 3,200x

Fast Transfer Switching



80 microsecond transfer time
(amperage does not matter)

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A Summary of things a SSCB can do…

- **Arc flash mitigation**
- **Ultra fast circuit protection** - 3µs round trip fault detection
- **100,000-amp** interrupting capacity
- **Remote Dynamic time-current curve adjustment** of Switch from 15-1200 amps
- **Surge Protection**
- **Thermal memory**
- **Remote firmware update capability**
- **Easily networked** with one (1) IP address for the whole thing

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PART IV

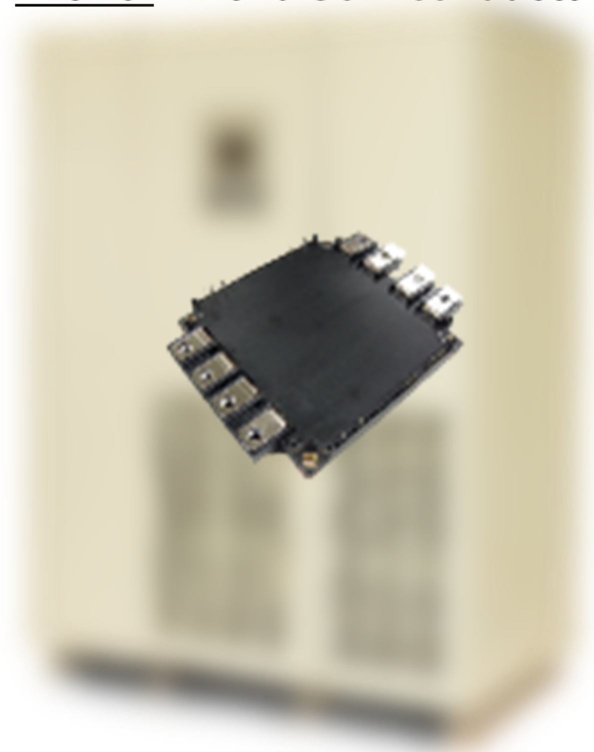
Revolutionary Leaders:

- Mitsubishi - SiC UPS

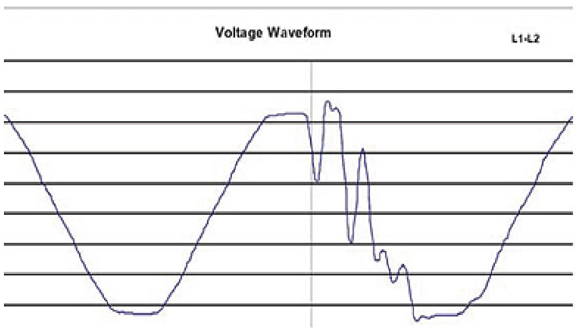
How does a UPS generate Reliable power?

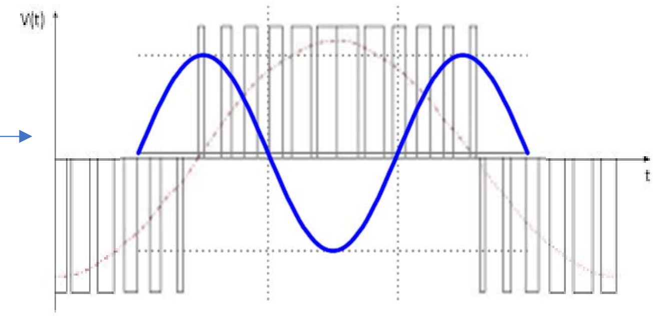
How does a UPS generate Reliable power?

Answer: With a Semiconductor



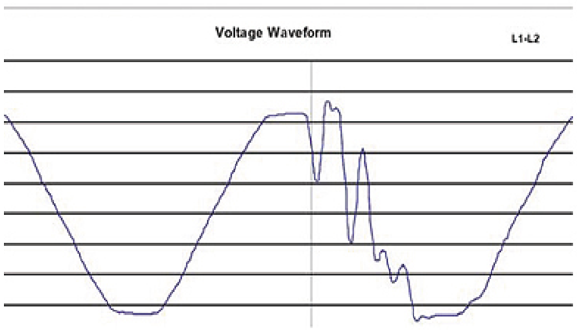
The Semiconductor is the Heart and Soul of the UPS

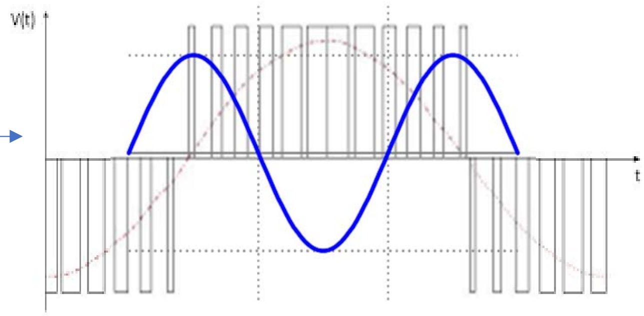




The Semiconductor is the Heart and Soul of the UPS

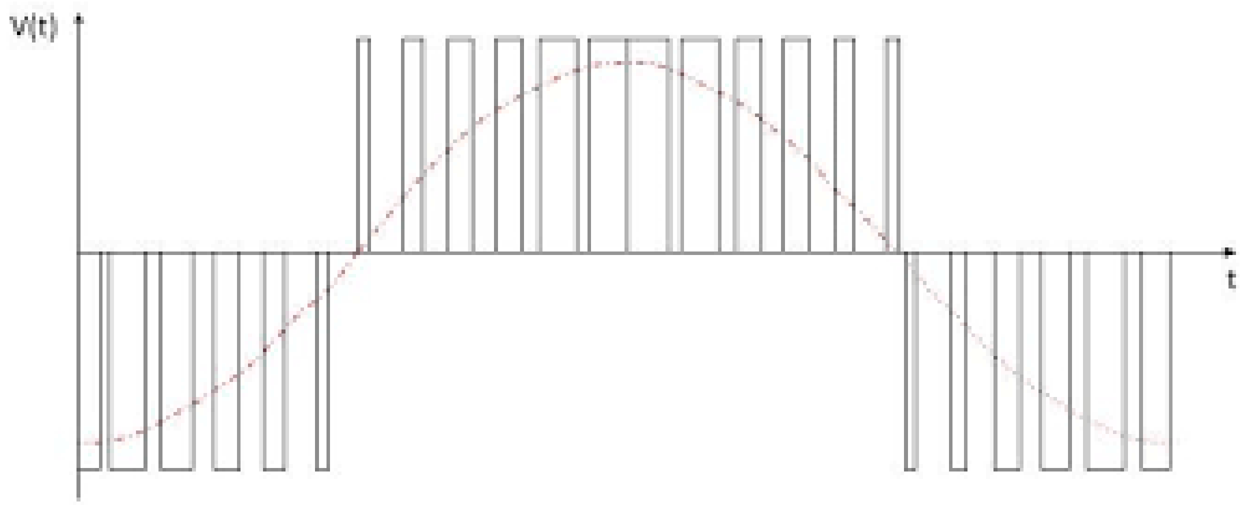
The better the semiconductor…the better the output waveform





How does a UPS semiconductor device work?

- UPS controls turn the semiconductor on and off to create the flow of electricity



Moving Semiconductor Electrons

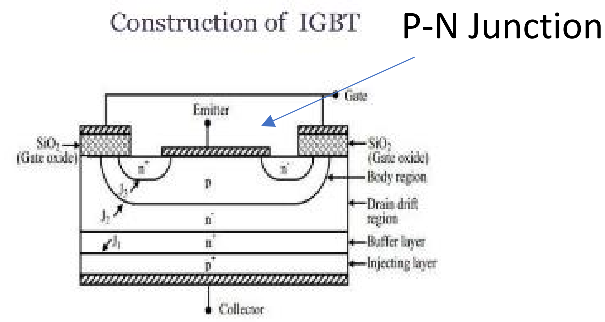


Fig.1

Insulated Gate Bipolar Transistor

Every Cycle Matters!

MOVING SILICON ELECTRONS

Construction of IGBT

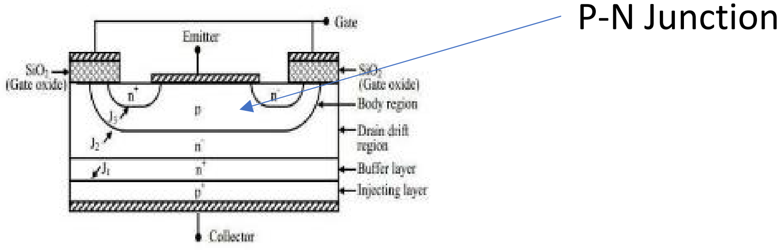
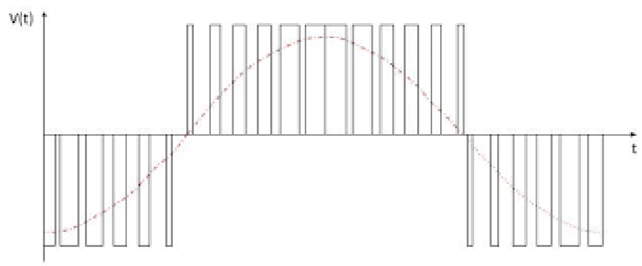
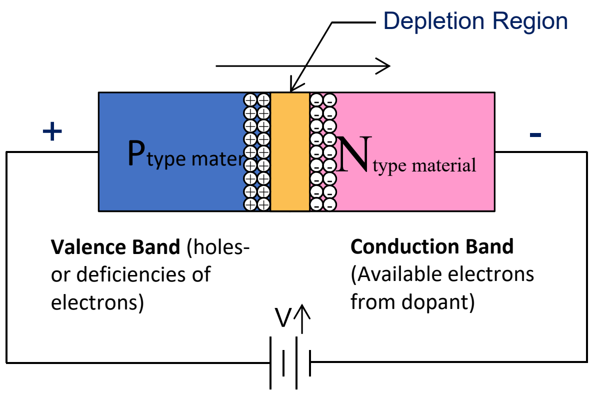


Fig.1

The IGBT P-N junction shapes the UPS output waveform by creating pulses of electricity and spaces with no electricity.



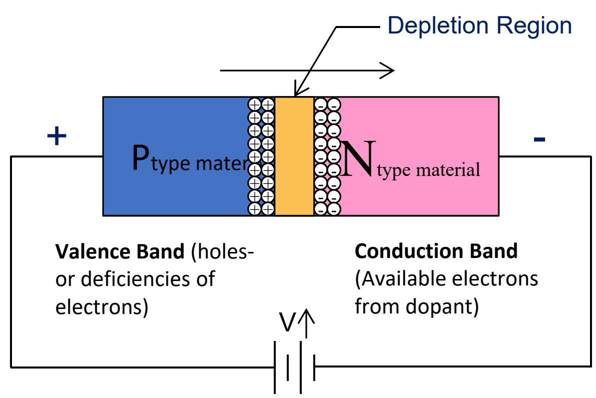
Moving Semiconductor Electrons



Forward Bias

A **p–n junction** is a boundary between p-type and n-type particles.
The "p" (positive) side contains an excess of electron holes, while the "n" (negative) side contains an excess of electrons.

Moving Semiconductor Electrons

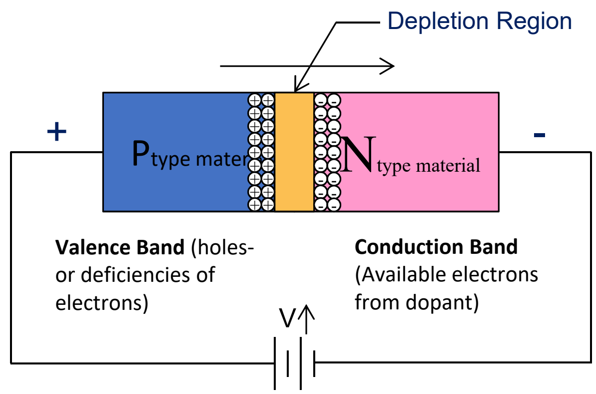


Forward Bias

A p–n junction is a boundary between p-type and n-type particles that are created by doping.

The "p" (positive) side contains an excess of electron holes, while the "n" (negative) side contains an excess of electrons that are created by “*doping*”.

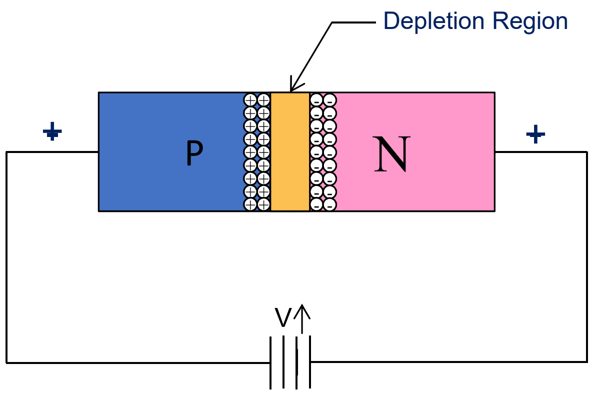
Moving Semiconductor Electrons



Forward Bias

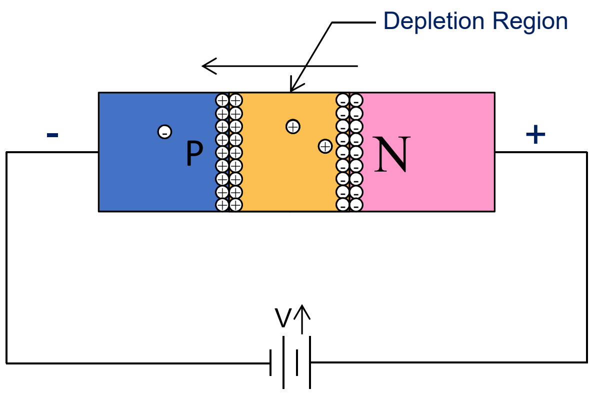
We apply voltage (forward bias)…

Moving Semiconductor Electrons



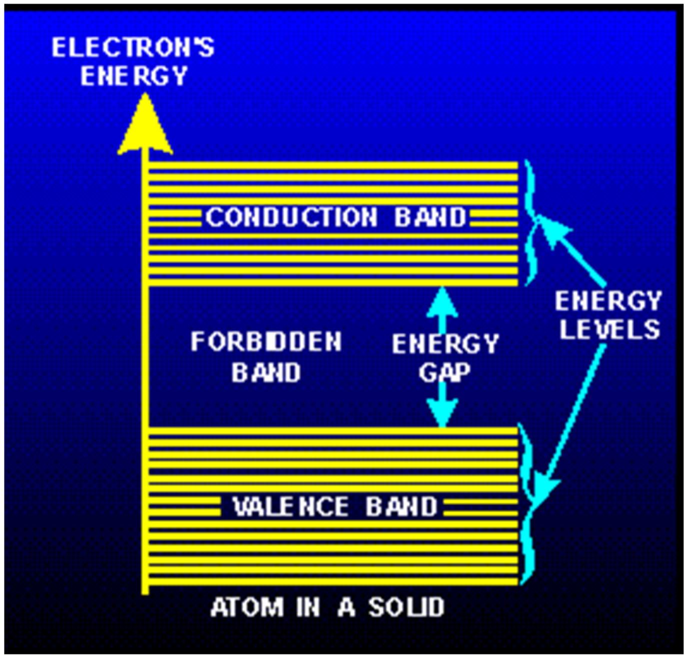
Forward Bias / Reverse Bias

Moving Semiconductor Electrons



Breakdown Voltage

Addition of SiC



- Using Silicon Carbide (a Wide Bandgap material) enables a UPS semiconductor to exceed the limitations of Silicon

Si Based IGBTs Give Way To SiC Based MOSFETs

Silicon Carbide permits manufacturers to replace slow Silicon Bipolar Transistors with single-carrier, or unipolar devices called MOSFETs. They can be switched quickly and far more *efficiently*. These faster devices have the added benefit of more-compact and less-expensive packaging because they require smaller control circuitry. (Equipment shrinks in size...power density increases)

SiC MOSFET

"New" Semiconductor of Choice:

- Simpler (Unipolar)
- Smaller
- Faster
- More efficient

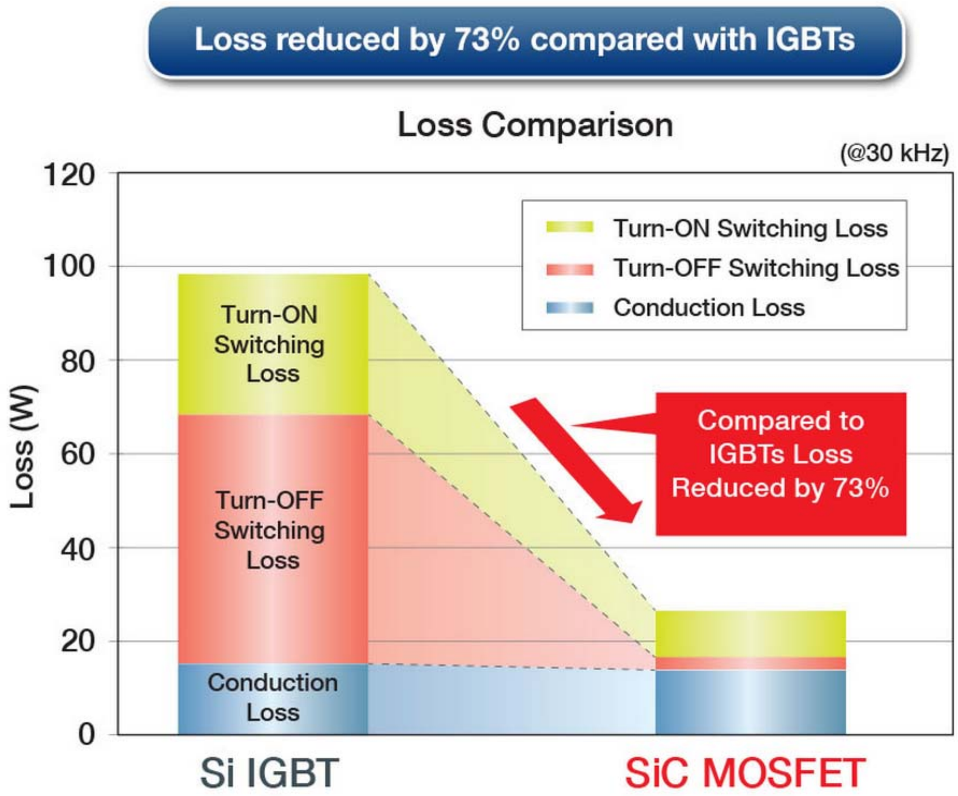
UPS Benefits with Silicon Carbide

1. Higher Efficiencies
2. Less Heat Rejection
3. Less Cooling Requirements
4. Smaller Footprint

Let's take a look at the improved Metrics using Silicon Carbide

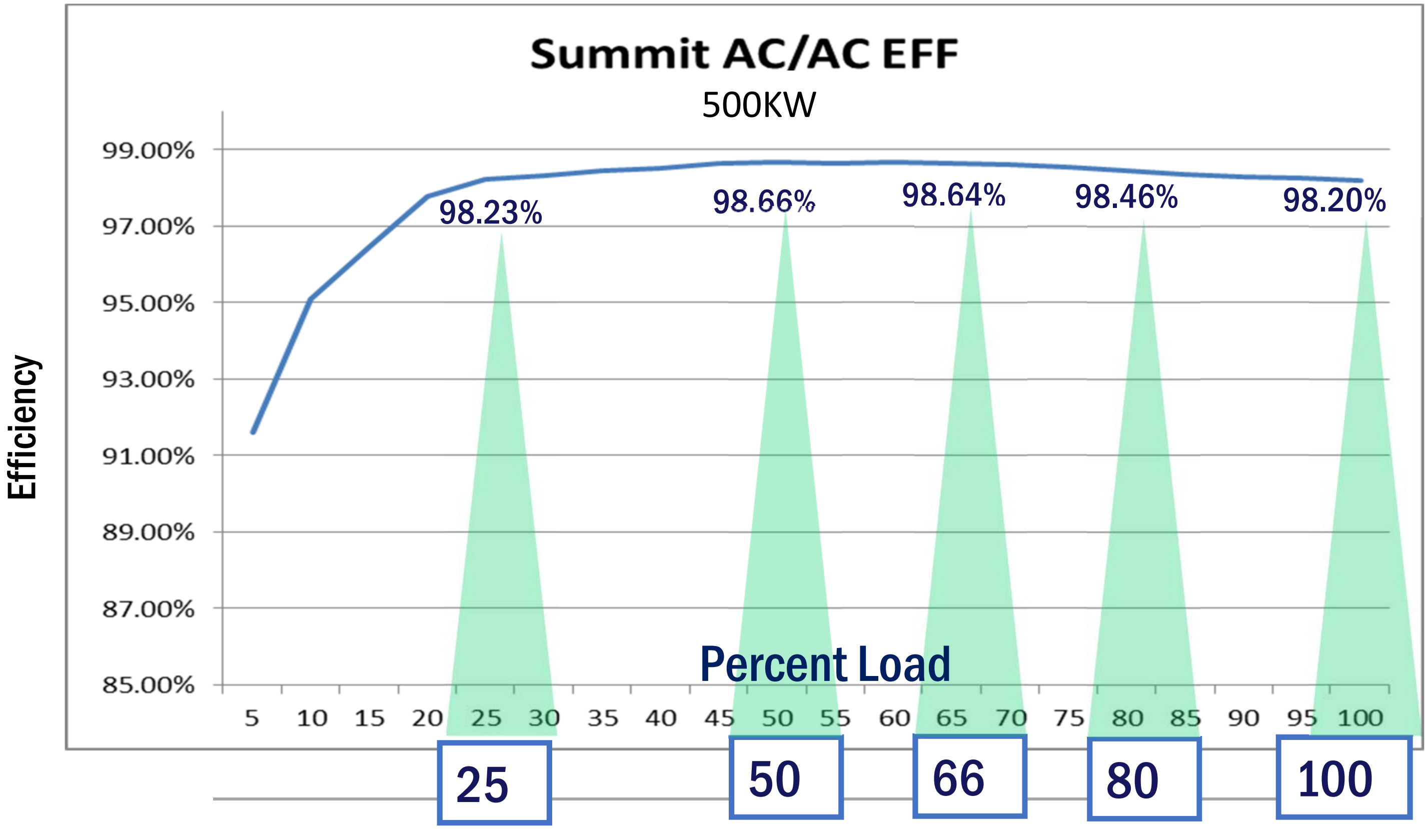
1. Efficiency

SiC: Less Power Losses



- There is a 73% Reduction in Power Losses
- Increases Efficiency

SiC Efficiency Metrics



SiC Factory Test Metrics @ 400kW

#1

Table 4: Efficiency

Load	Power Factor	Input kW	Output kW	Calculated Efficiency
0%	Unity	2.59	-	-
25%	Unity	98.7	96.7	98.0
50%	Unity	203.5	201.4	99.0
75%	Unity	307.7	305.3	99.2
100%	Unity	401.5	398.5	99.3
25%	0.95 lag	99.5	96.6	97.1
50%	0.95 lag	194.7	190.7	98.0
75%	0.95 lag	299.3	294.0	98.2
100%	0.95 lag	387.6	380.4	98.1

#2

Table 4: Efficiency

Load	Power Factor	Input kW	Output kW	Calculated Efficiency
0%	Unity	3.07	-	-
25%	Unity	98.92	96.47	97.52
50%	Unity	197.7	195.2	98.73
75%	Unity	296.2	293	98.91
100%	Unity	405.6	401.2	98.91
25%	0.95 lag	99.7	97.3	97.59
50%	0.95 lag	199.3	196.7	98.69
75%	0.95 lag	292.6	288.9	98.78
100%	0.95 lag	386.5	381.1	98.60

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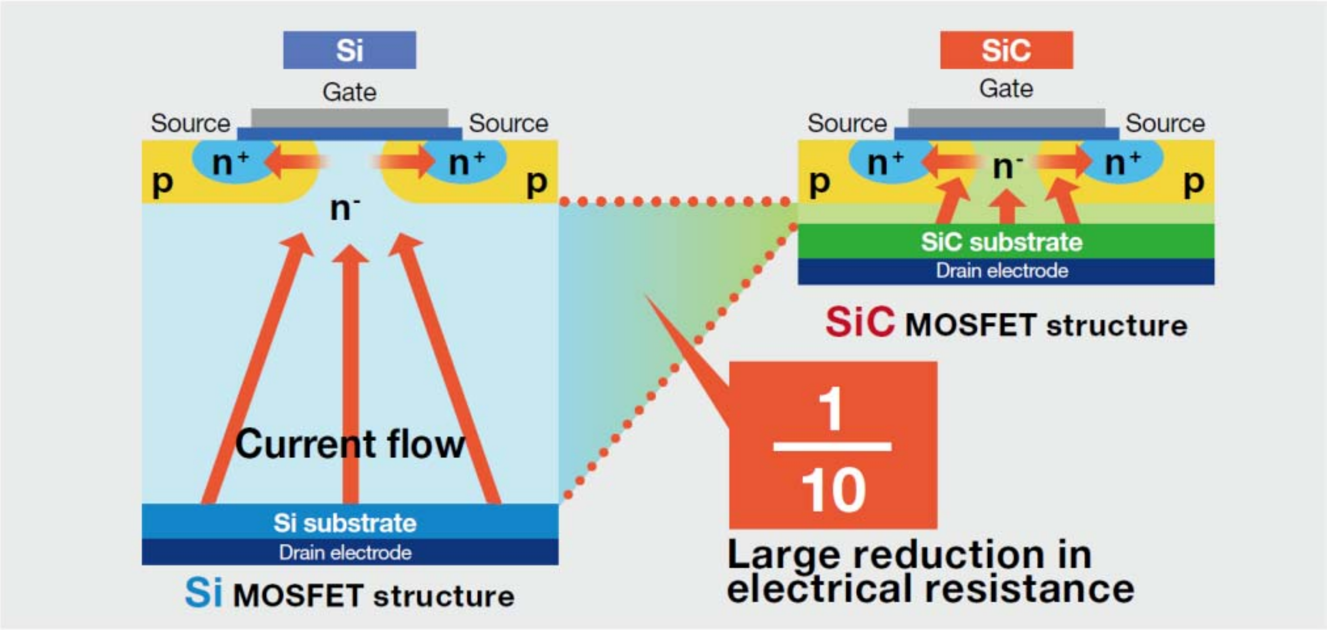
Let's take a look at the improved Metrics using Silicon Carbide

1. Efficiency
2. Heat Rejection

SiC Uses 1/10 The Material

- SiC requires 1/10 the material needed by Si to operate
- Thinner devices are faster and boast less resistance



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SiC Heat Metrics

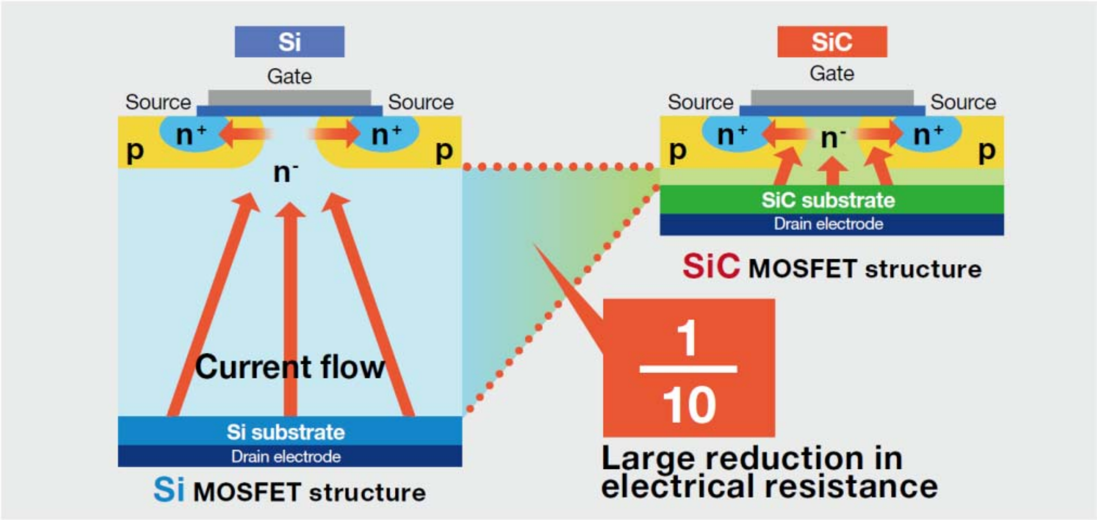
At 100% load Si has a heat rejection of 69.2 kBTU/hr, whereas SiC based UPS has a heat rejection of 42.0 kBTU/hr.

UPS LOAD (%)	SiC UPS ENERGY SAVINGS (%)
100	39.4%
75	49.9%
50	46.9%

Let's take a look at the improved Metrics using Silicon Carbide

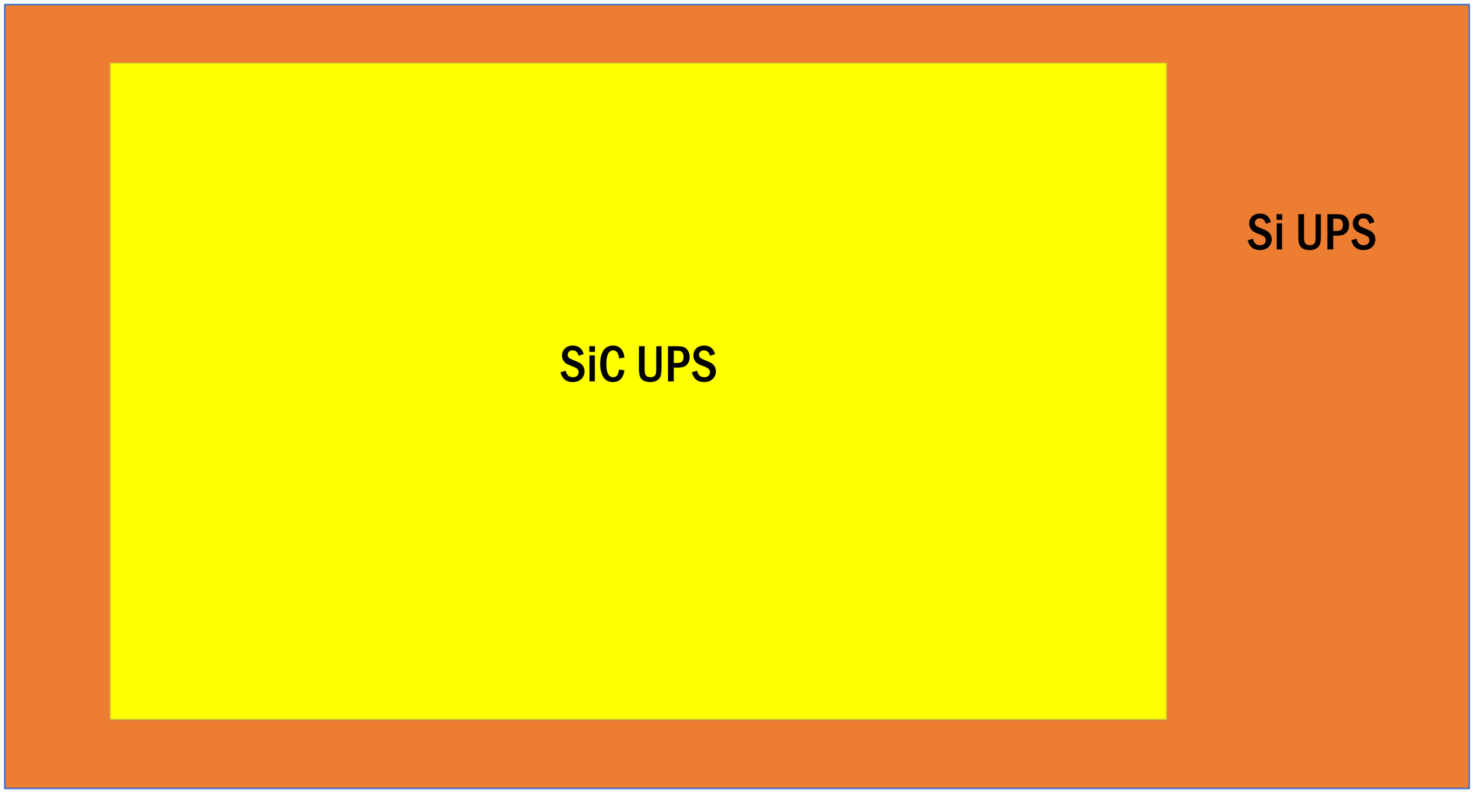
1. Efficiency
2. Heat rejection
3. Footprint

SiC Size Metrics



Faster devices have the added benefit of more-compact and less-expensive packaging because they require smaller control circuitry, heatsinks, inverters...and filters!

SiC Size Metrics

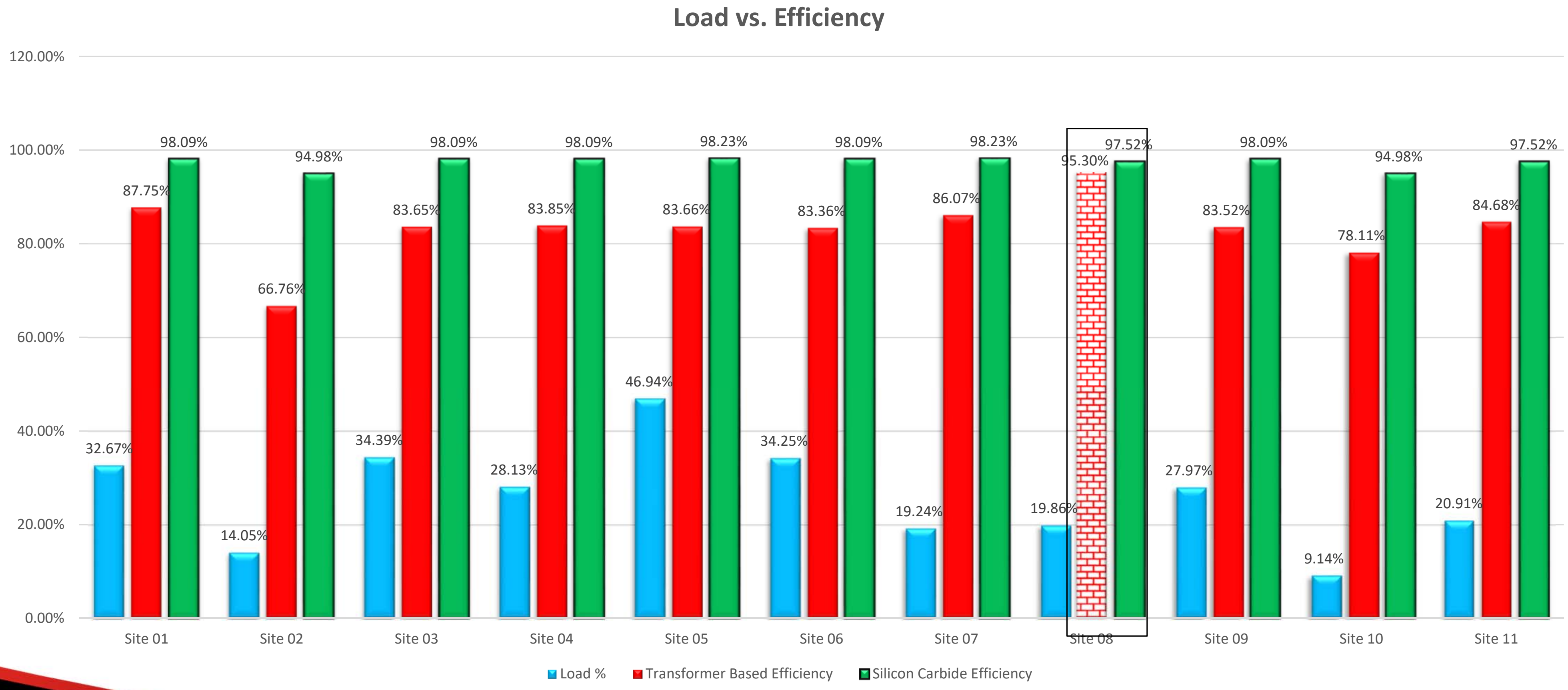


Average 35% Reduction in UPS Footprint

Metrics Summary

- Efficiency > 98-99%
- Heat Rejection > 50% less cooling @ 75% load
- Footprint > 25-30% smaller

Transformer Based vs. Silicon Carbide



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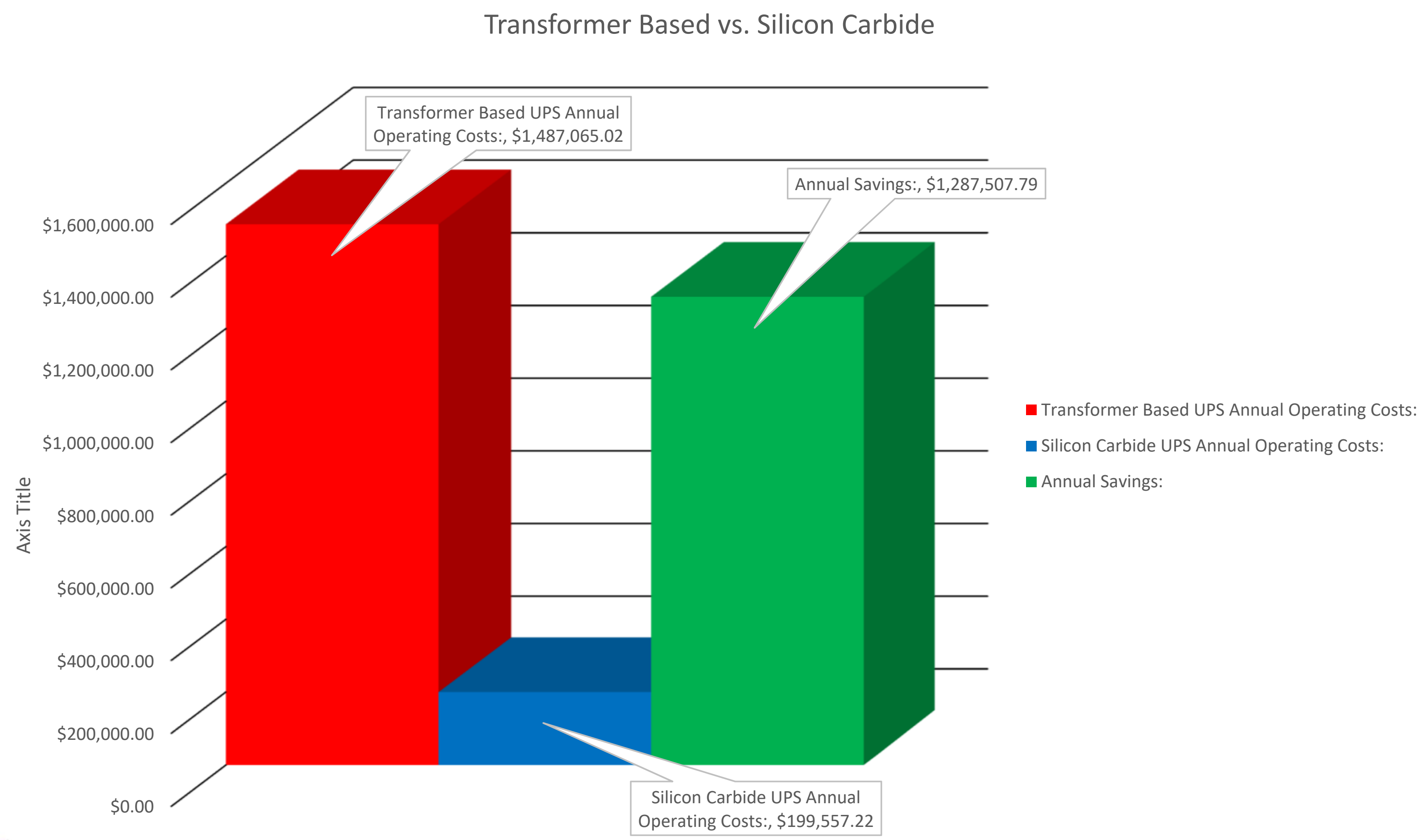
Annual Expense Loss Comparison



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Thank you!