Seamless on-wafer integration of GaN and Si devices for the next generation of power management chips

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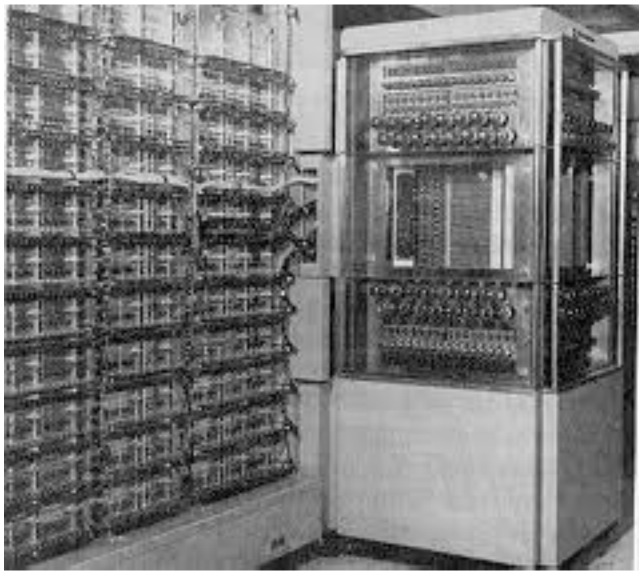
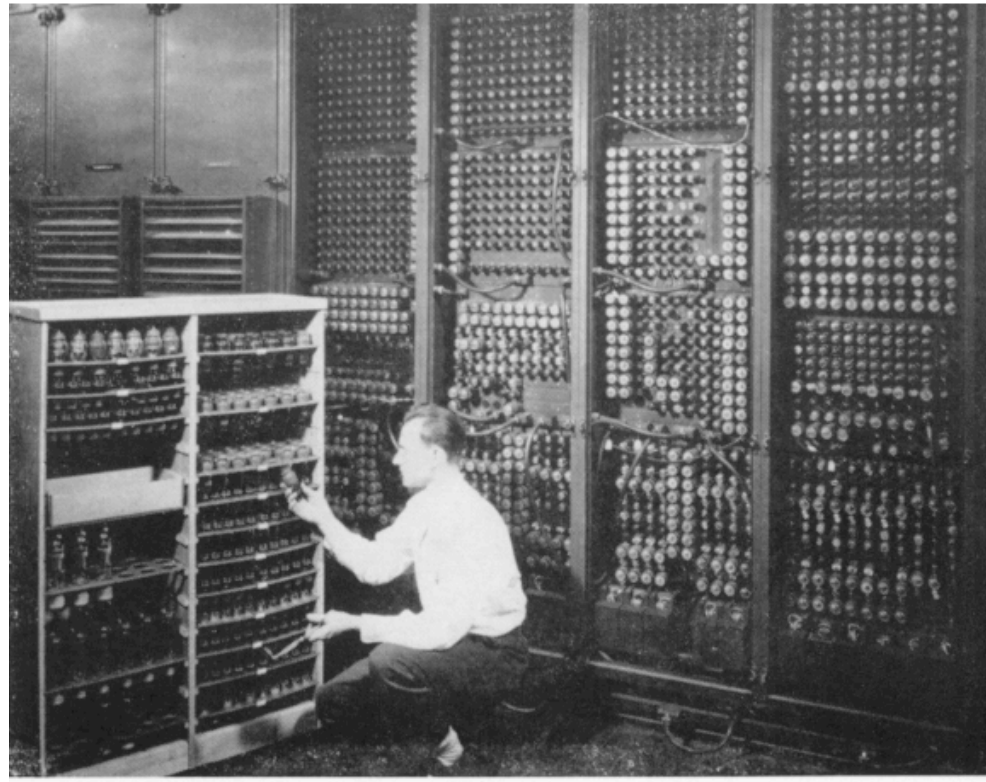
70 years ago, Silicon came to solve a challenge…





Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.

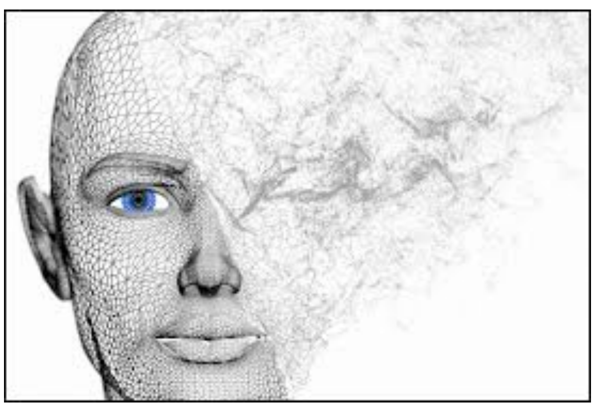
tp

70 years ago, Silicon came to solve a challenge *and start a revolution*…

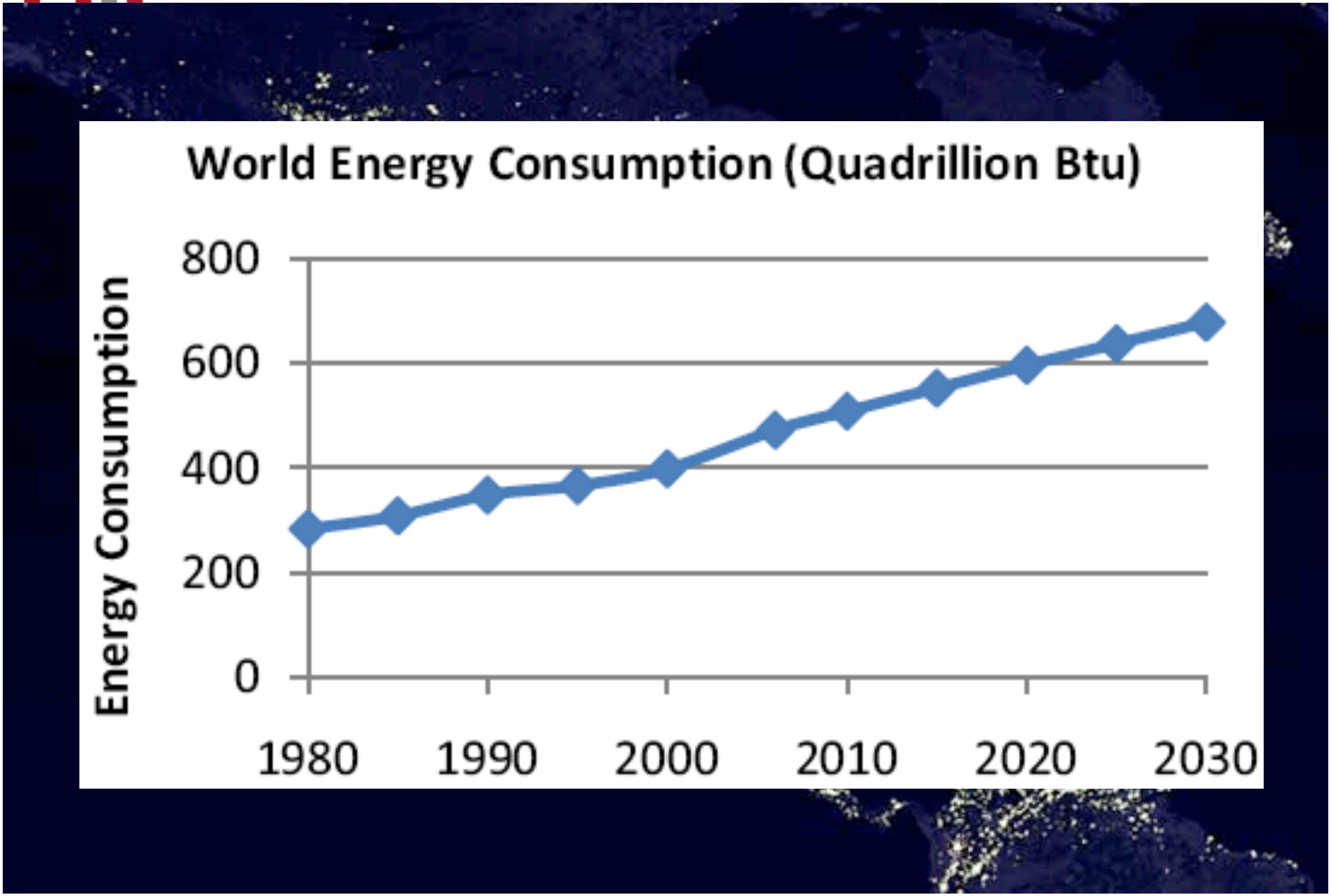




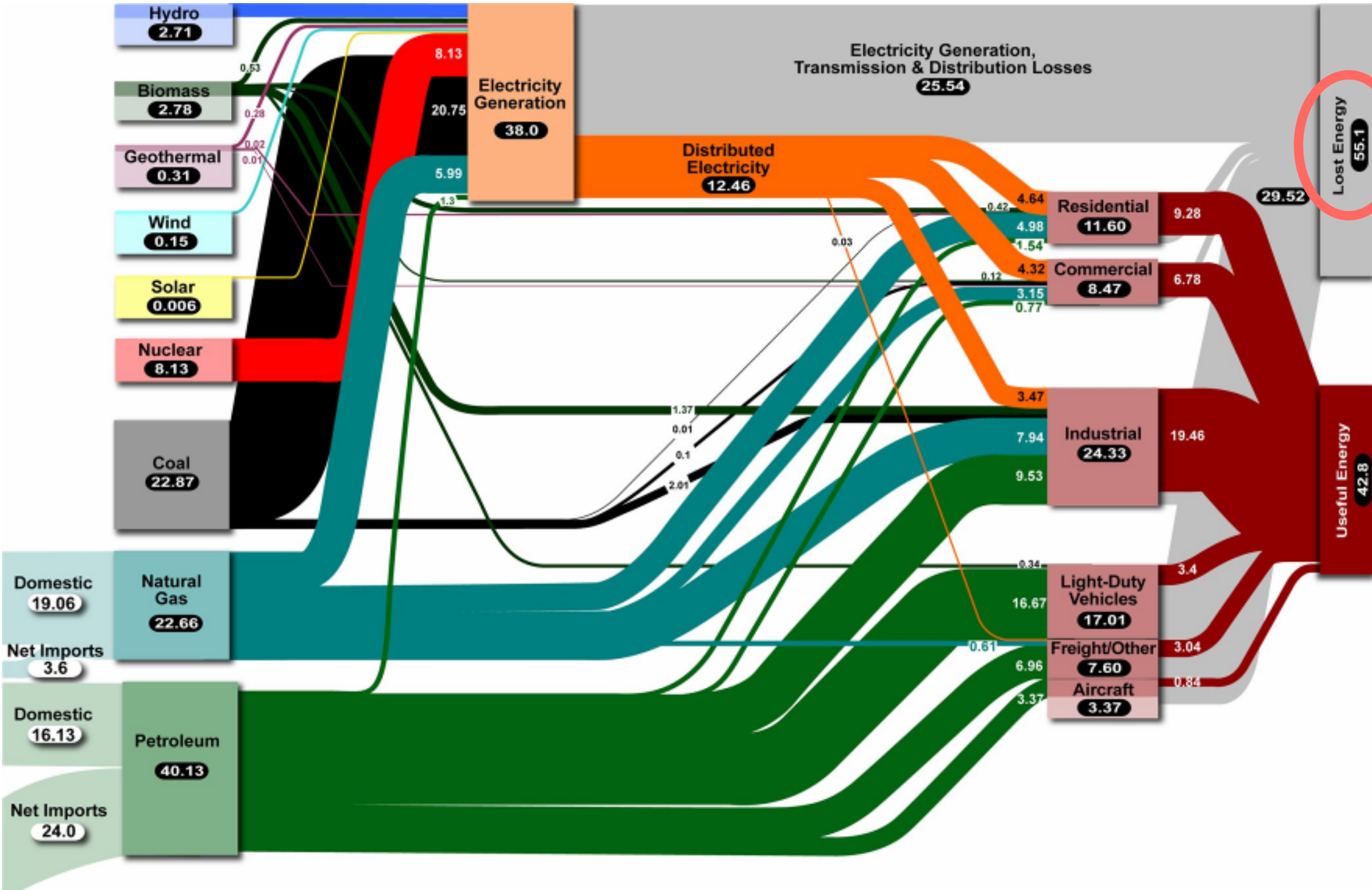




Today's Challenge: *Energy*



The Energy Challenge:
"The good news"



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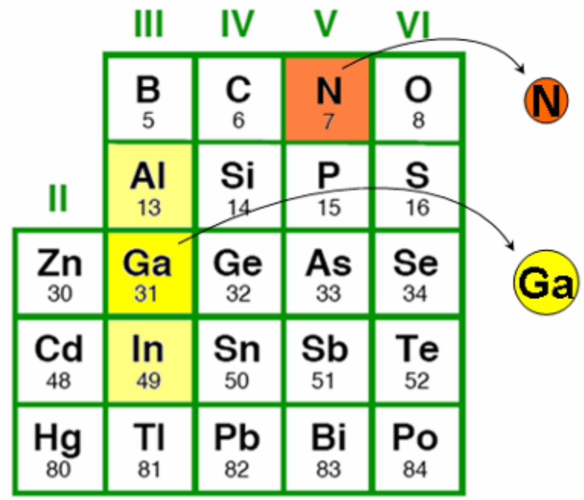
https://eed.llnl.gov/flow/images/LLNL_Energy_Chart300.jpg

Nitride semiconductors

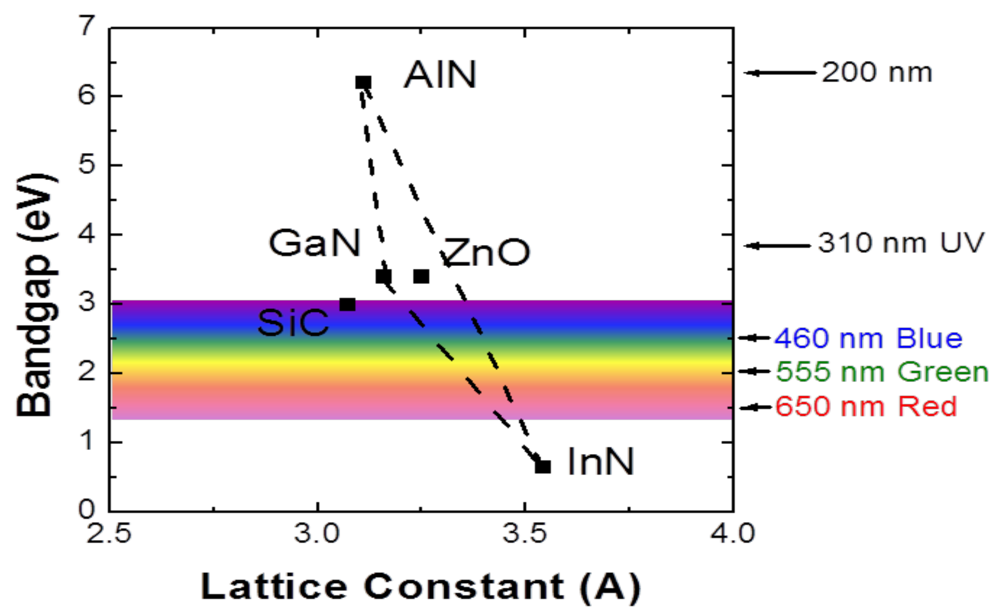
Nitride-based Semiconductors will be key to reduce energy consumption



Outstanding nitride properties:

The highest electron velocities!
(x2-3 than in Si)
The highest electric fields!
(x15 than in Si)
The highest temperatures!
(>x2 than in Si)
The highest electron densities!
(>x3 than in Si)
The highest output powers!
(>x40 than in Si)
The highest light intensity!

(The highest design flexibility)



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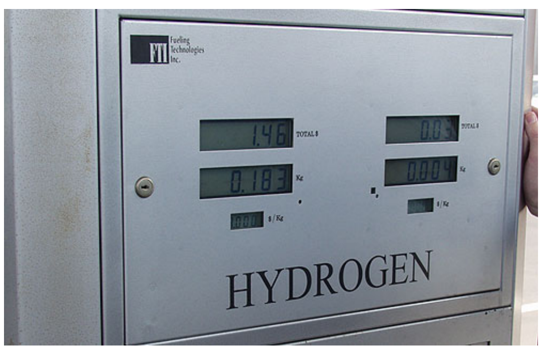
Nitrides and the *Energy Challenge*

Nitrides: the most versatile semiconductor family to address the Energy Challenge…

Solid state lighting

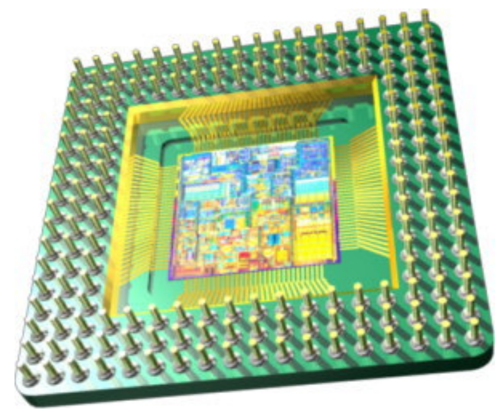
Power electronics

High efficiency solar cells



Hydrogen generation
for fuel cells

Wireless
communication



Efficient computation

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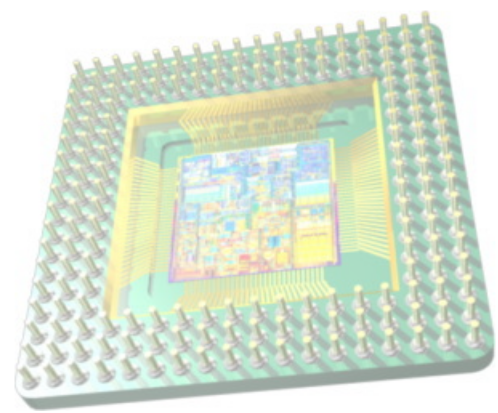

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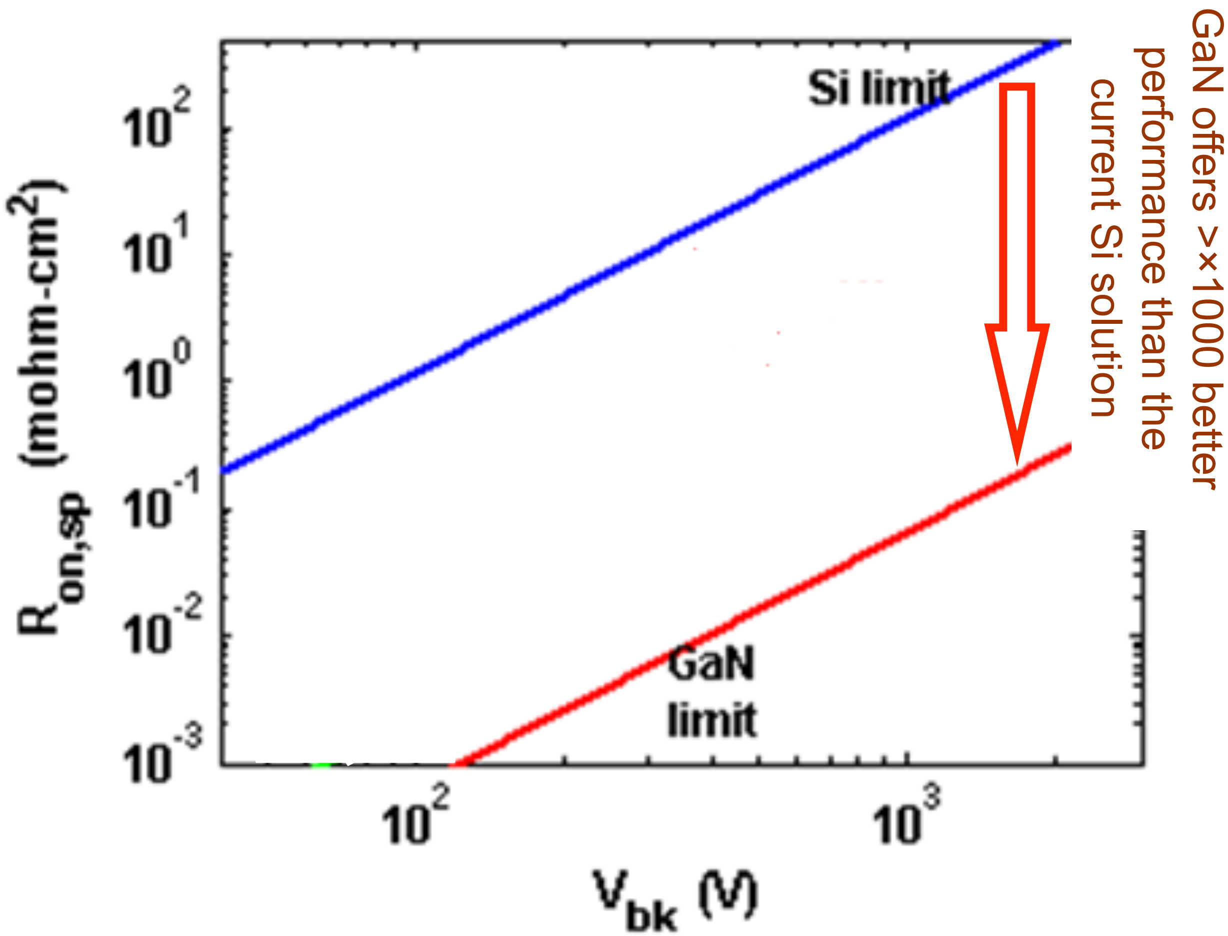
GaN for Power Electronics

Main parameters in power electronics:

- •Breakdown voltage
- •Specific On-resistance

} Efficiency and size



GaN vs Si

For the same breakdown voltage…

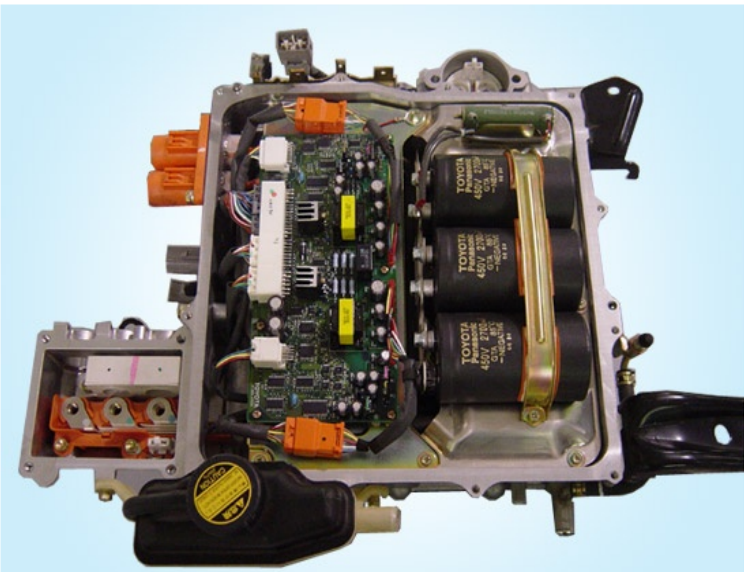
~1000 better resistance …

~Much higher frequency …

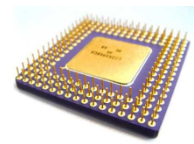
T_{max} ~ 175C: Reduced cooling requirements

Much smaller size and higher efficiency than traditional power electronics!!

Future of Power Electronics



GaN-enabled Future



- Much smaller (cheaper) integrated systems at the same performance
- Reduced cooling requirements
- More efficient energy use
- Cheaper → new applications

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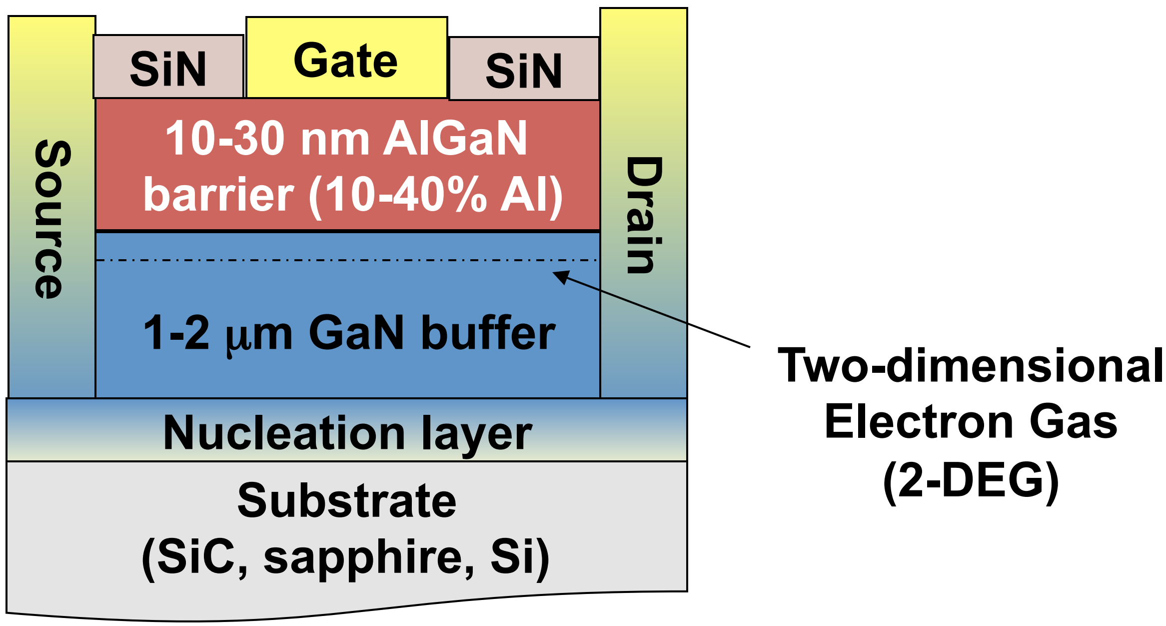
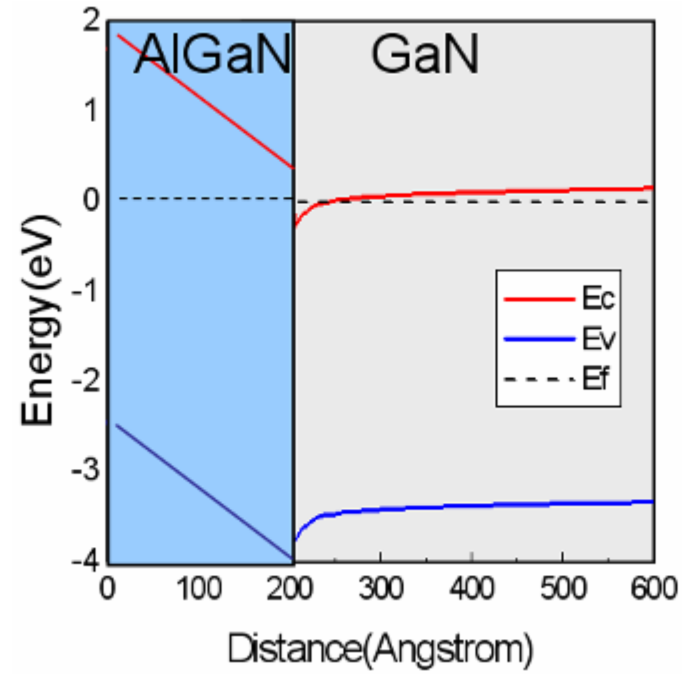
Basic Structure of AlGaN/GaN HEMTs





Main differences with Si MOSFETs…

Heteroepitaxy (no cheap GaN bulk substrate) → Si substrate

No doping needed: electrons induced by *polarization*

AlGaN barrier instead of gate oxide

Non self-aligned gate device

Heterostructures and polarization give new flexibility

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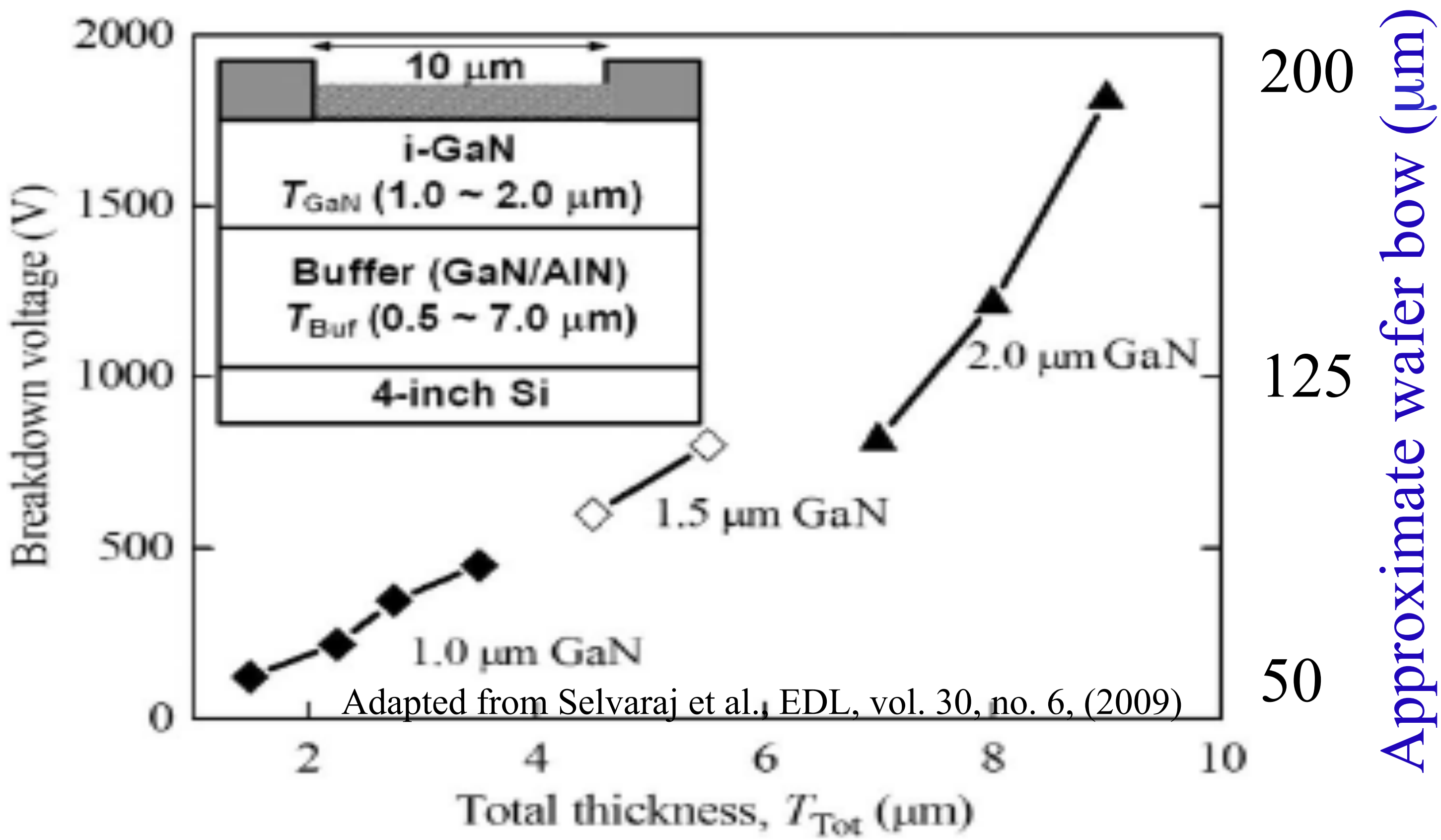
GaN on *Si* for Power Electronics: *Challenges*

-Low breakdown on Si substrates:



-Wafer bow in thick GaN buffers

-Normally-off (Enhancement-mode) devices

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Substrate transfer technology

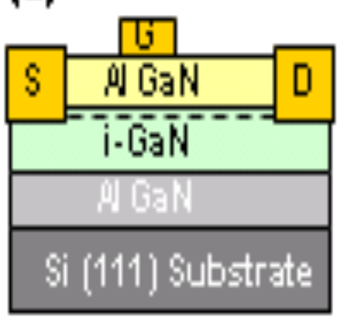
AlGaN/GaN on SiC with 2 μm buffer: 1.9kV

v.s.

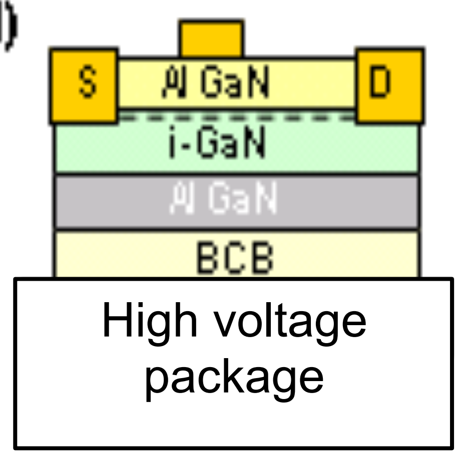
AlGaN/GaN on Si with 2 μm buffer: ~ 500V

If the Si substrate limits the breakdown, let's remove the substrate and integrate the GaN transistor with the high voltage package directly…

(a)



(d)



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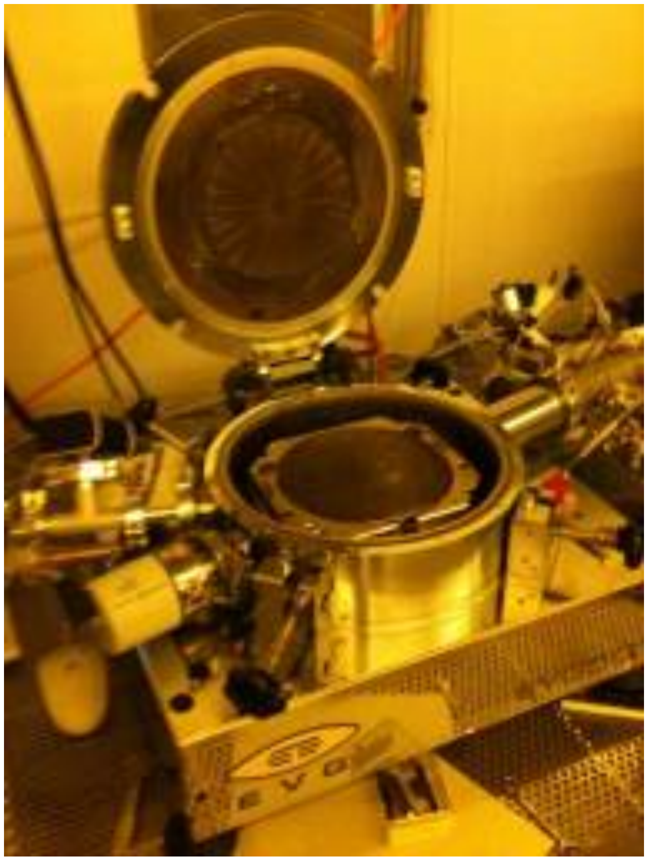
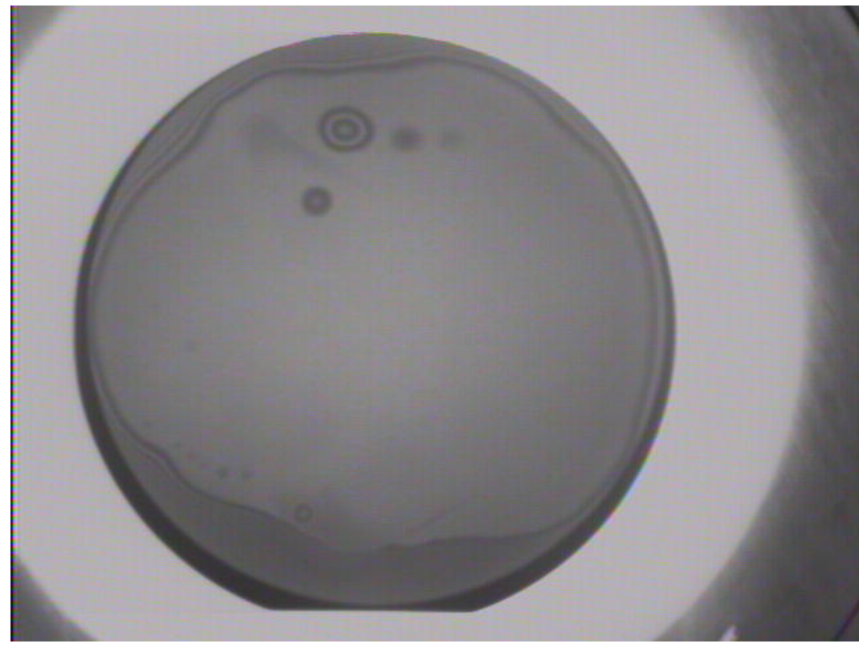
4” GaN-Si Hybrid Bonded Wafer





IR image

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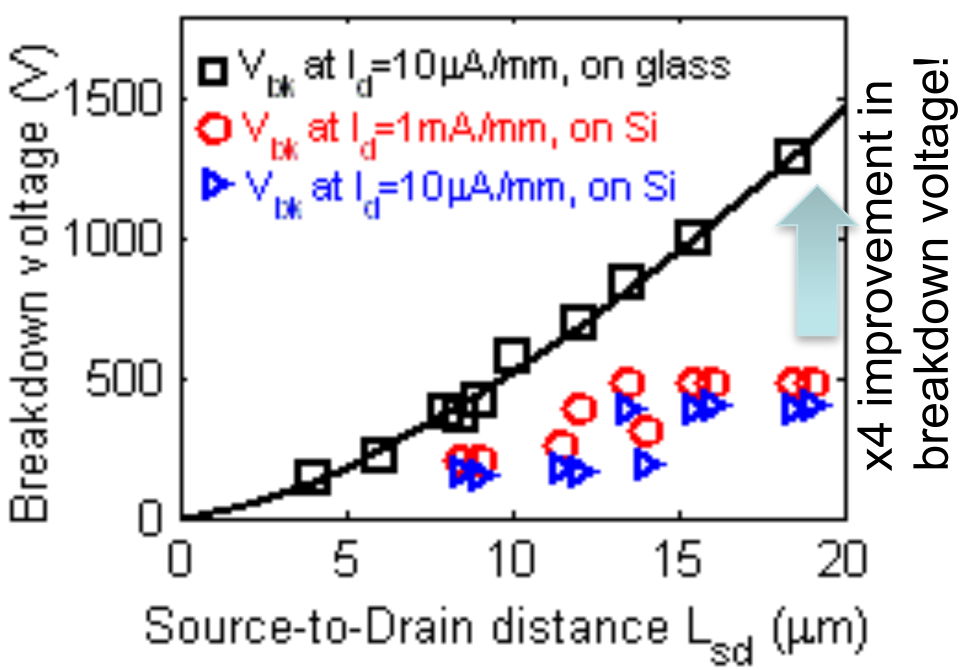
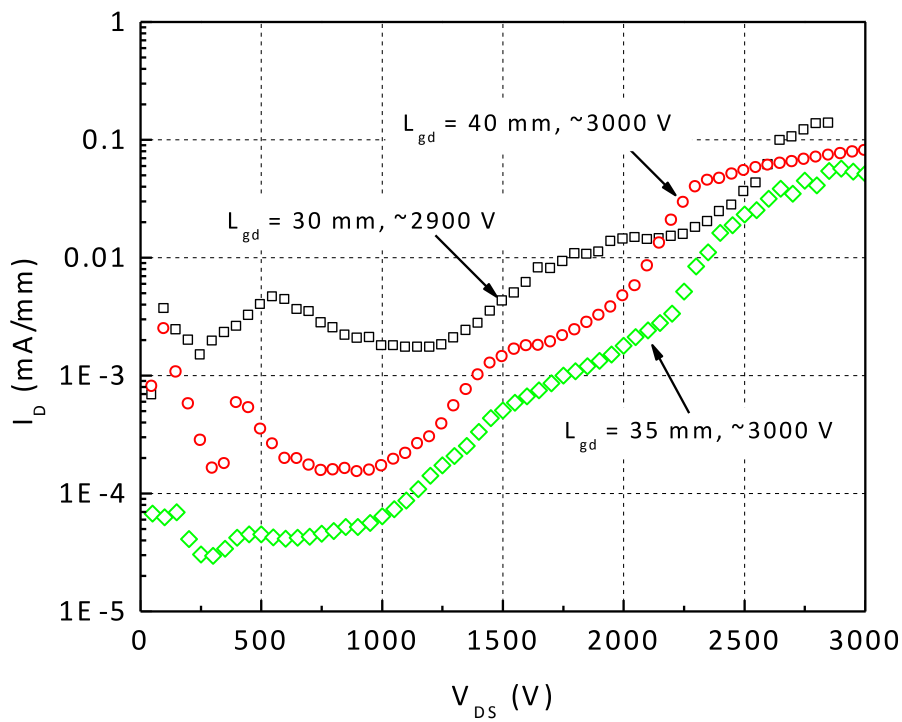
Breakdown voltage





More than 3kV breakdown can be obtained from GaN HEMTs originally designed for 500 V operation

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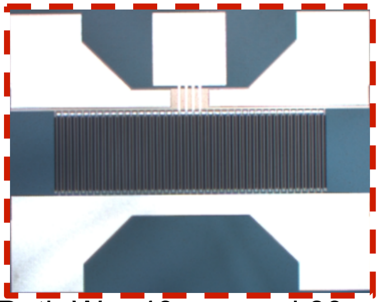
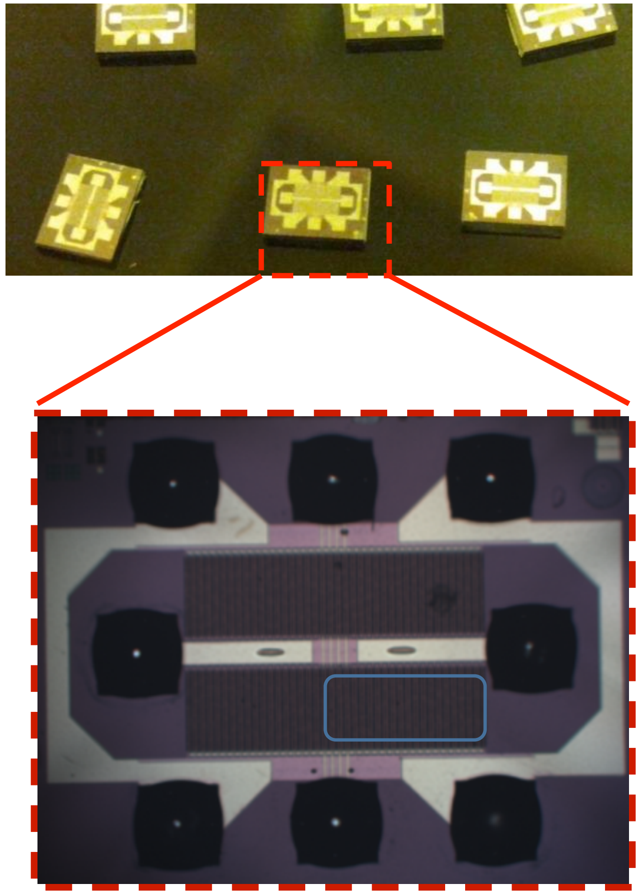
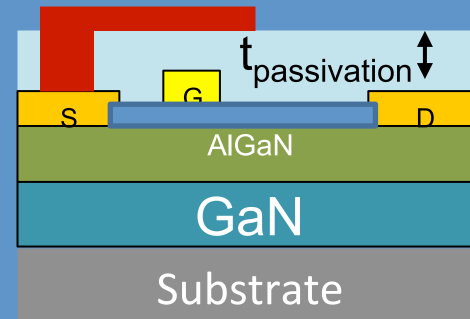
Scaled GaN HEMT Technology



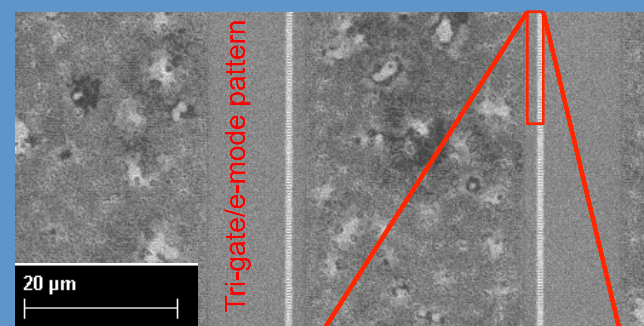
Both Wg=40 mm and 80 mm devices fabricated



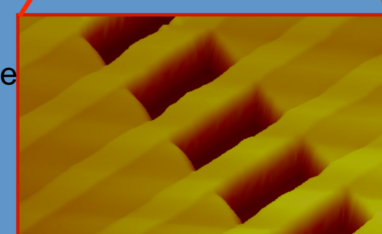
Discrete, Packaged devices for circuit integration



Passivation/Field-plate optimization



Tri-gate recessed technology for enhancement mode operation in wide-periphery devices



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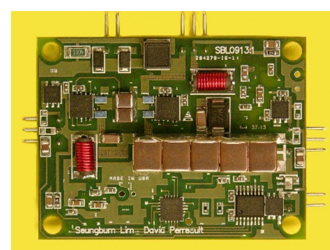
System Demonstrator: Power Electronics for Solid State Lighting

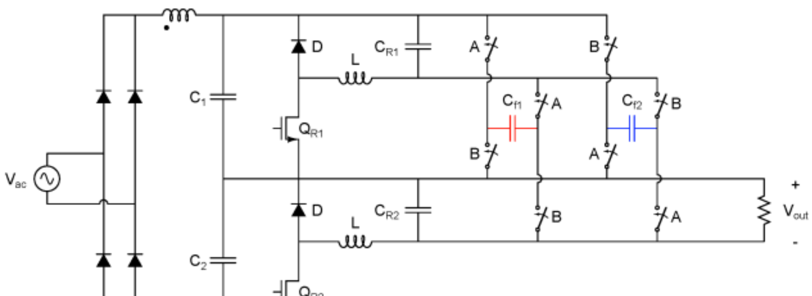
- **Magnetic components largest elements in present designs**
  - (unreliable) electrolytic capacitors 2nd-largest parts
- **Present designs and components yield low switching frequencies (~ 100 kHz) and low power density (< 5W/in³)**
  - Must simultaneously address semiconductor device, magnetic component and circuit design issues

	Commercial	ARPA-E ADEPT PowerChip
Efficiency	64 - 83 %	93 %
Switching Frequency	57 - 104 kHz	5-10 MHz
Power Factor	0.73-0.93	0.89
Power Density	< 5 W/in³	> 50 W/in³

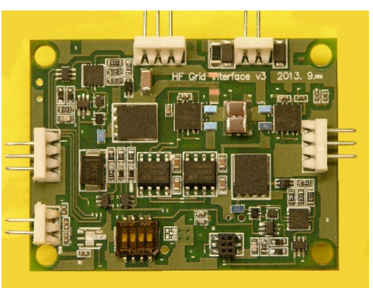


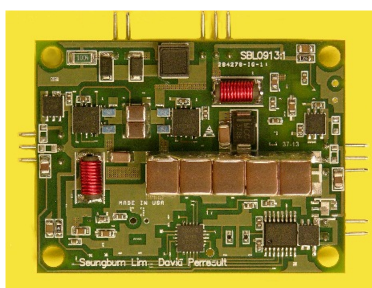
Circuit Architecture, System Demo

- **New circuit architecture for HF grid-interface conversion**
  - Facilitates high frequency and miniaturized magnetics
  - High power factor *without* (unreliable) electrolytics
- **Key targets achieved (>10x frequency, > 10x power density)**



120 Vac in, 35 V dc out





	Commercial	PowerChip
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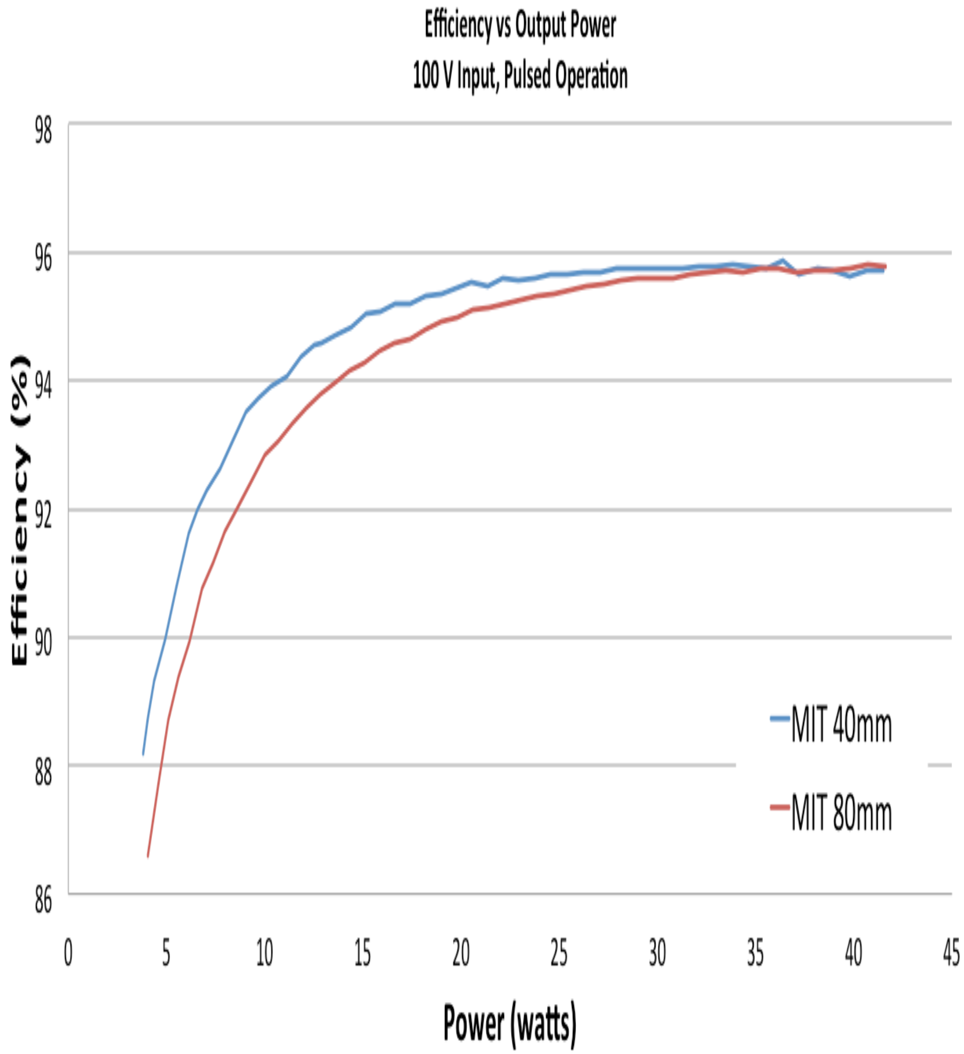
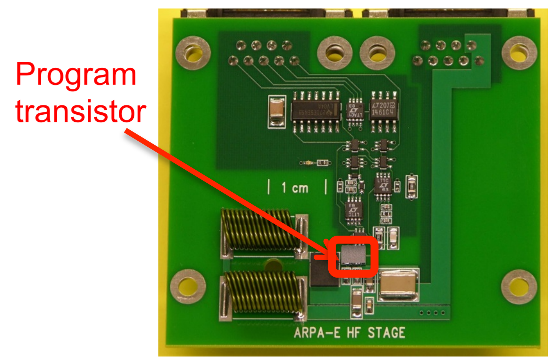
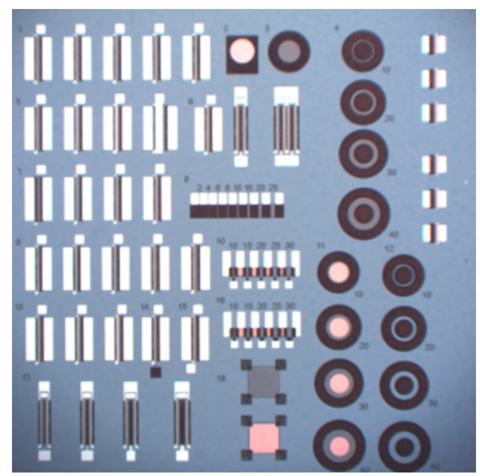
Switching Frequency	57 - 104 kHz	**5-10 MHz**
Power Factor	0.73-0.93	0.89
Power Density	< 5 W/in^3	**>50 W/in^3** (to 130 W/in^3)

Collaboration with Prof. David Perrault's group (MIT)

Final System Performance







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How to achieve higher miniaturization?

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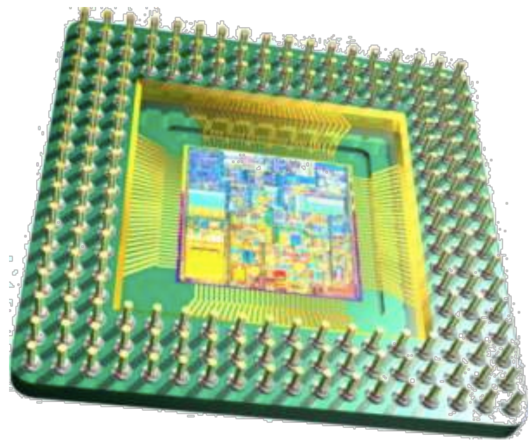
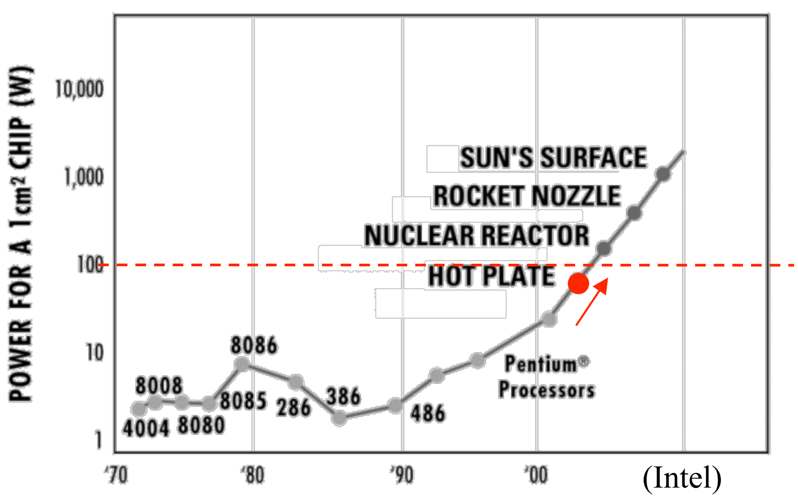
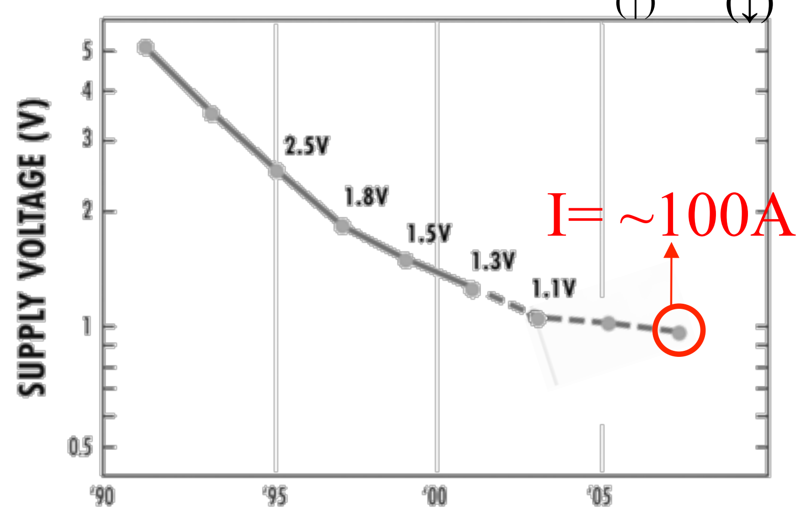
Heterogeneous integration:

Microprocessor Power Distribution





$P = I_{(\uparrow)} \times V_{(\downarrow)}$



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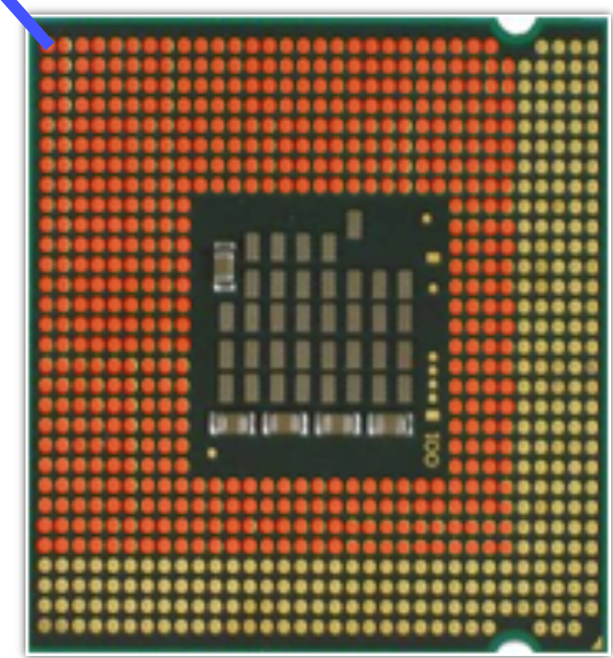
Challenges in Microprocessor Power Distribution

1. Conduction losses



I= ~100 A

2. 50~70% I/O pins in microprocessor

More efficient power distribution scheme is necessary

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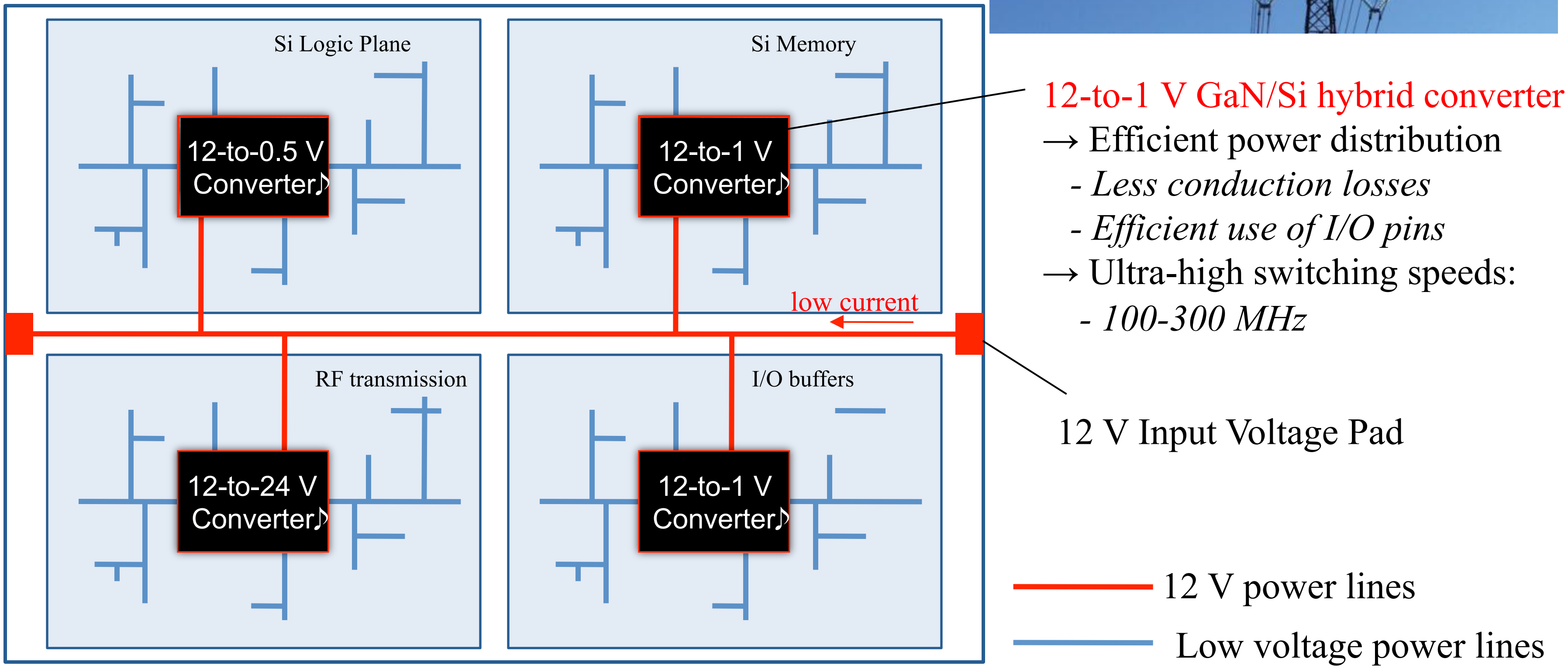
New Architecture for Power Distribution in Si Microprocessors

Power distribution at high V & low I
→ Local conversion to low V & high I
(Si cannot do it: breakdown & low switching speed)



Microprocessor

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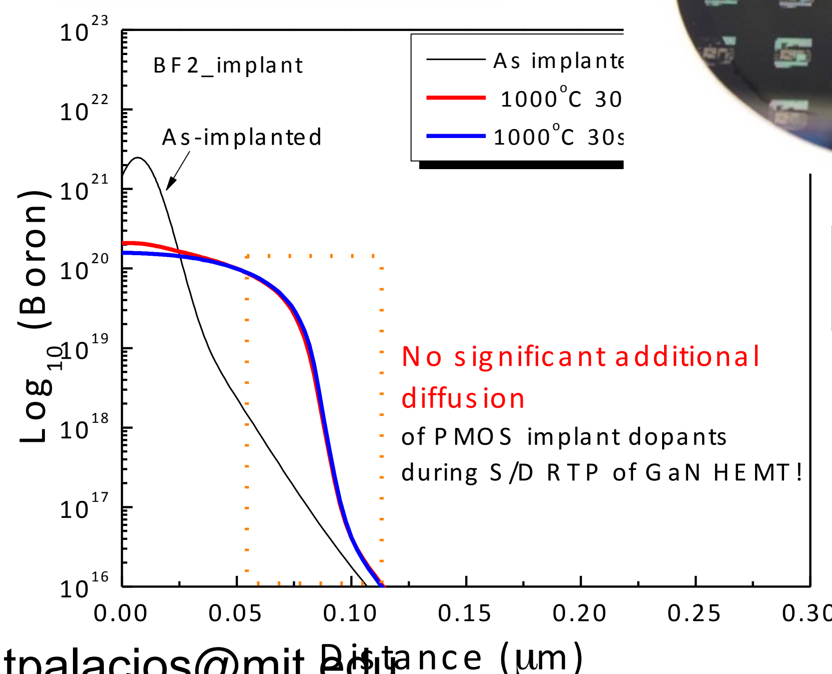
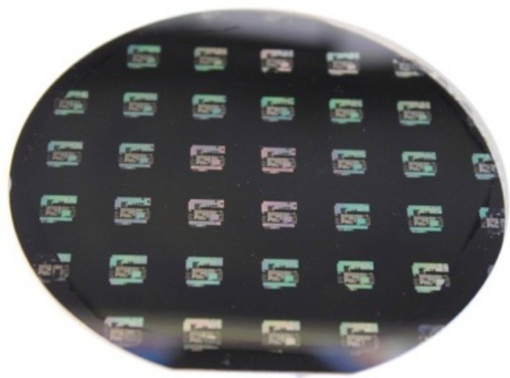
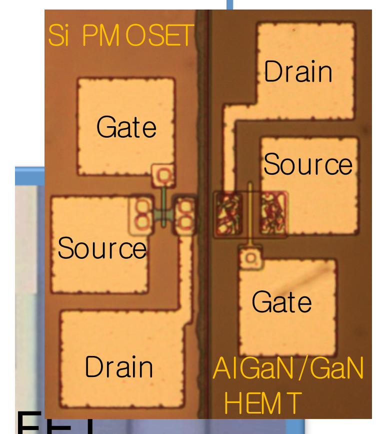
Process Flow for GaN-Si Integration

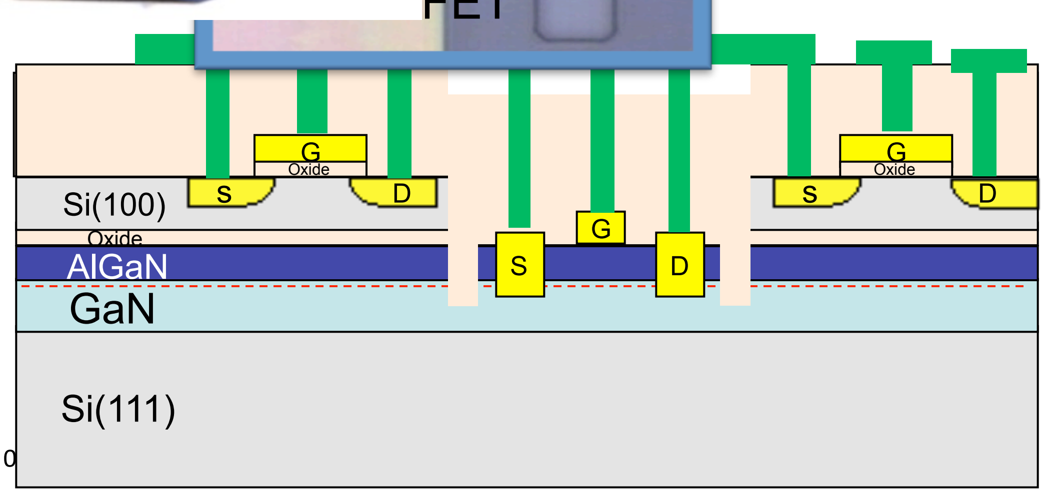
- Starting material
- PMOS process
- GaN HEMT process
- Interconnect process

- ILD/Planarization
- contact via (Dry etch + wet etch) : Si/GaN
- Ti/Al metal connect









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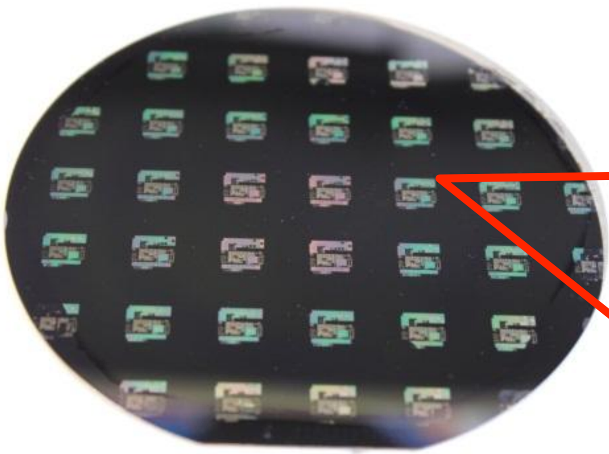
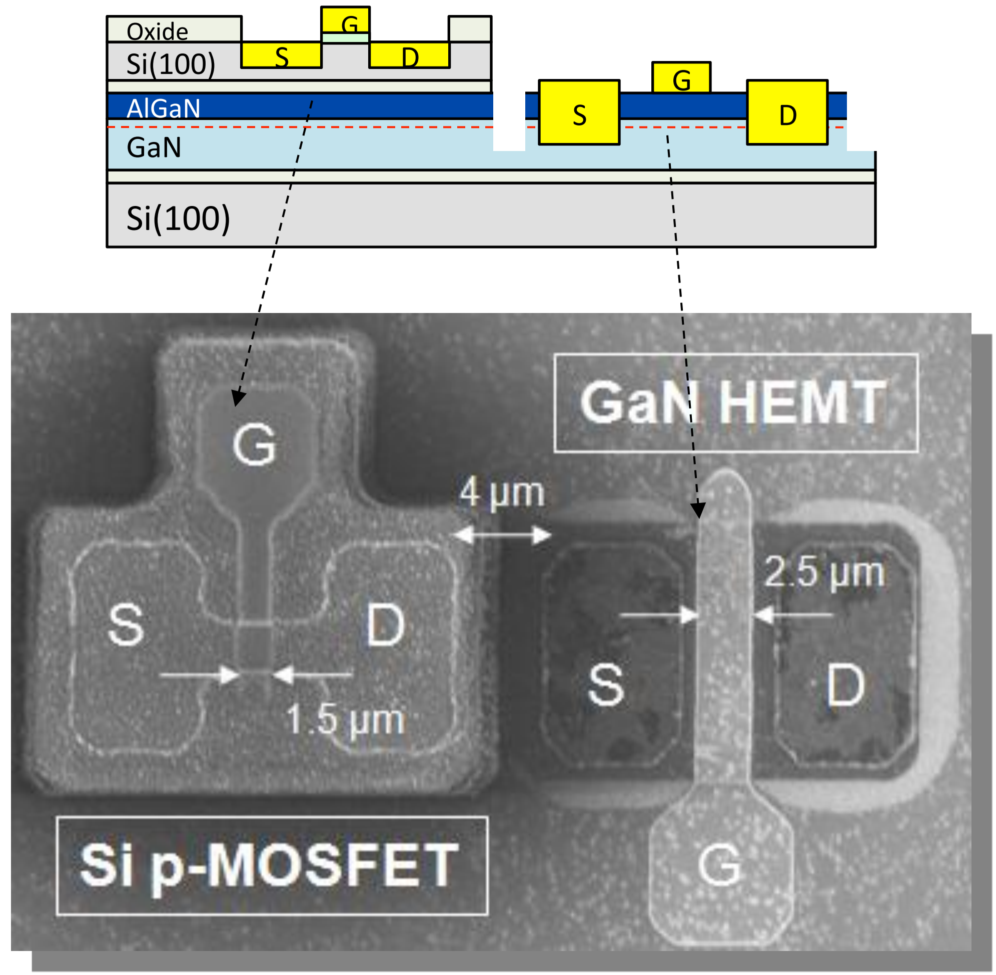
Integration of Si (100) MOSFET and GaN HEMTs





Integration of III-V HEMTs and Si (100) MOSFETs on 4" hybrid wafer !

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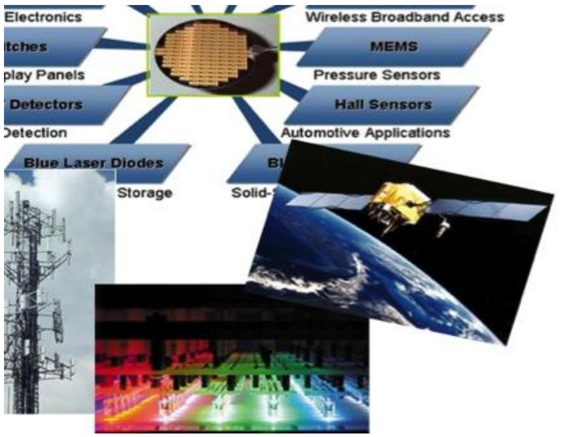
Heterogeneous integration:

Advanced hybrid circuits



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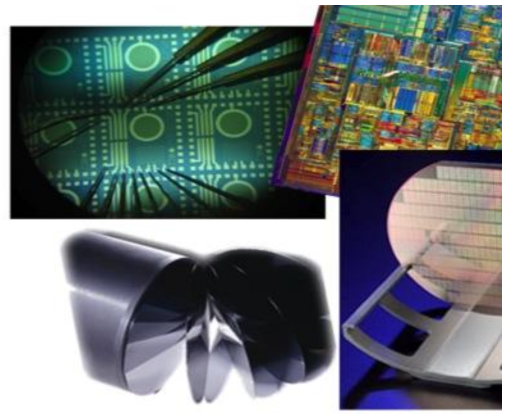
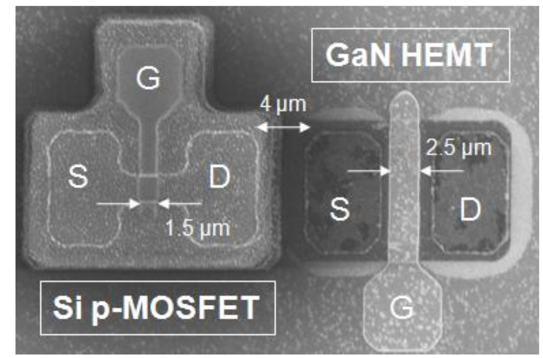
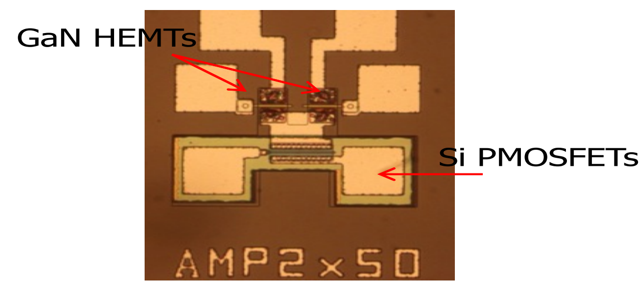
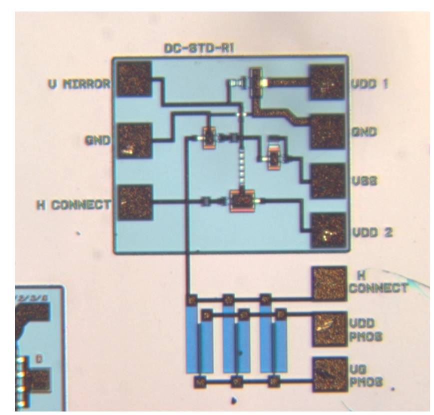




Unprecedented flexibility for advanced circuit design:



- *High power digital-to-analog converters* (DACs)
- On-wafer wireless transmitters
- *Driver stages for on-wafer optoelectronics*
- *Power amplifiers coupled to Si linearizer circuits*
- *High speed (high power) differential amplifiers*
- *Normally-off power transistors*
- *New enhancement-mode power transistors*
- *Buffer stages for ultra-low-power electronics*
- *Power distribution network in Si electronics*



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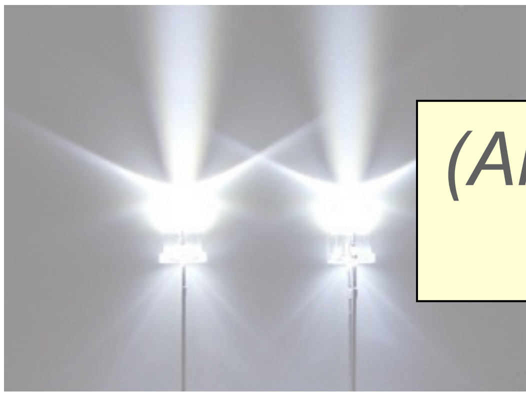
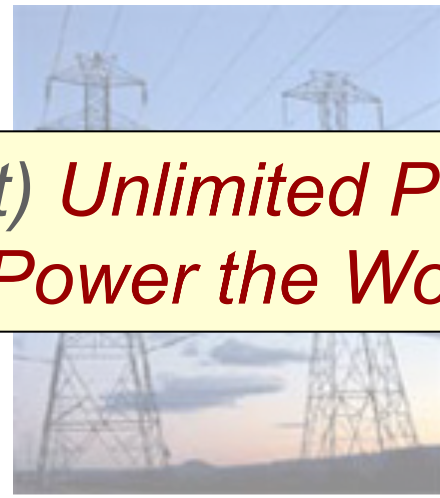
Nitrides and Energy…

Nitrides: the most versatile semiconductor family to address the Energy Challenge
+ Easily integrated in a Si platform + ~$15B industry today

(Almost) Unlimited Potential to Power the World



Solid state lighting

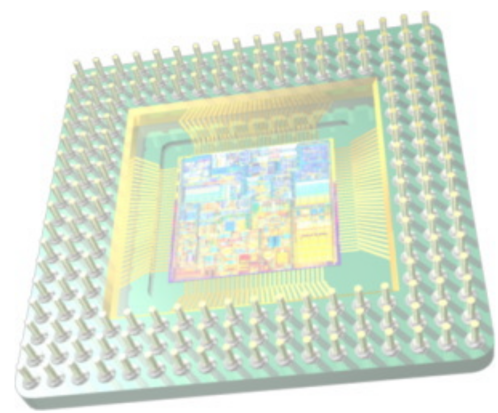


Power electronics

High efficiency solar cells

Hydrogen generation for fuel cells

Wireless communication



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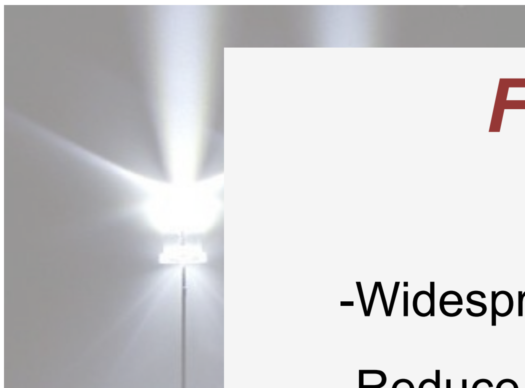
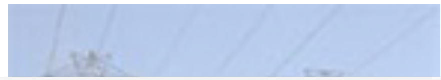


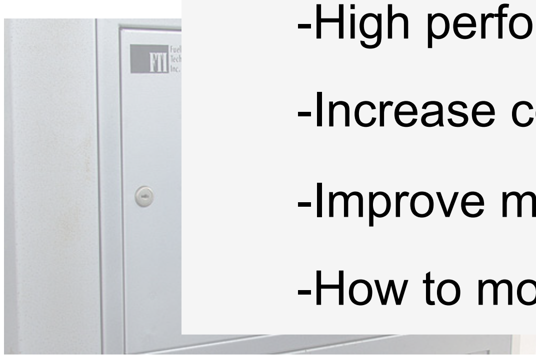
Solid s…



…olar cells

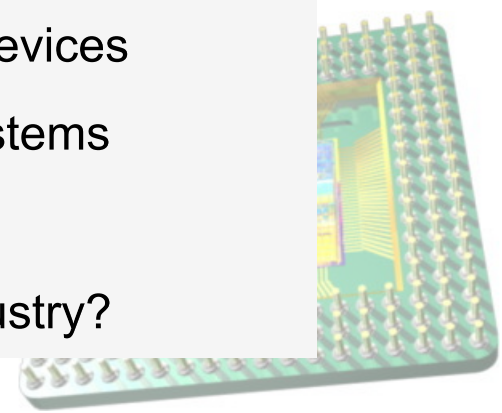
Future Challenges for GaN

- -Widespread use of GaN-on-Si wafers
- -Reduce dislocations from 10^8 cm^{-2} to <10^3 cm^{-2}
- -Take full advantage of extreme materials: AlN and InN
- -High performance vertical GaN electronic devices
- -Increase complexity of GaN circuits and systems
- -Improve magnetic materials
- -How to move from a ~$15B to a $100B industry?



Hydrogen generation for fuel cells

Wireless communication



Efficient computation

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A Technology Overview of the PowerChip Development Program

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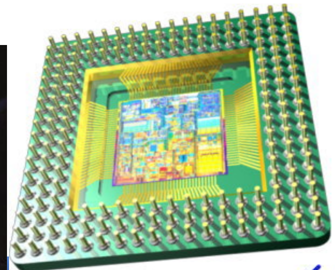
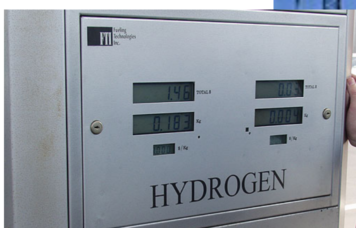
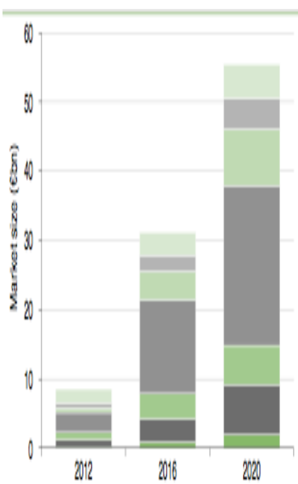
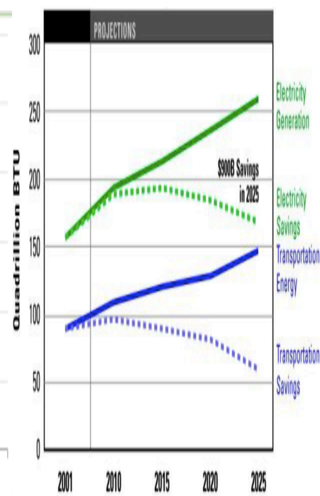
Gallium Nitride:
The Si of the 21st Century?





Critical mass…

Governor Cuomo Announces 100 Businesses Led by GE to Join $500 Million Partnership

North Carolina Is Home to America's Newest High-Tech Manufacturing Hub

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Absolutely, yes!! However...

The future $100B GaN industry is made of wafers that are 99.5% Si…

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