Gallium Nitride (GaN) Technologies

עולם הגליום ניטריד ליישומי אלקטרוניקת הספק

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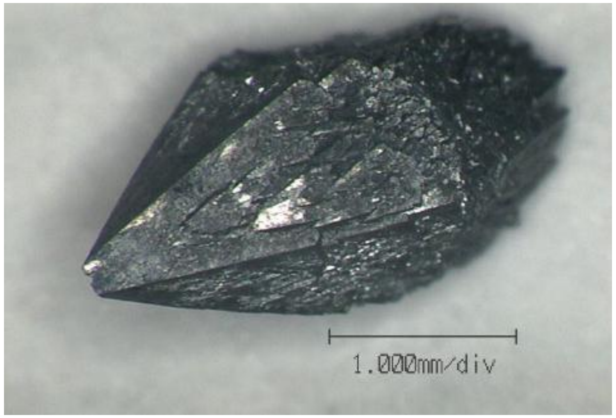
Gallium Nitride (GaN)

- Introduction
- Properties
- Crystal Structure
- Bonding Type
- Applications

Introduction



http://www.phy.mtu.edu/yap/images/galliumnitride.jpg

- **GaN is the next important semiconductor material after silicon.**
- **Can be operated at high temperatures, high power and high speeds.**
- **It's The key material for the next generation of high frequency and high power transistors.**
- **GaN is a Wide band-gap device.**

Properties

PROPERTY / MATERIAL .	Cubic (Beta) GaN .	Hexagonal (Alpha) GaN .
Structure	Zinc Blende	Wurzite
Stability	Meta-stable	Stable
Lattice Parameter(s) at 300K	0.450 nm	a_0 = 0.3189 nm c_0 = 0.5185 nm
Density at 300K	6.10 $g.cm^{-3}$	6.095 $g.cm^{-3}$
Nature of Energy Gap E_g	Direct	Direct
Energy Gap E_g at 293-1237 K		$3.556 - 9.9x10^{-4}T^2 / (T+600)$ eV Ching-Hua Su et al. 2002

Properties

Energy Gap E_g at 300 K	3.23 eV Ramirez-Flores et al 1994 . 3.25 eV Logothetidis et al 1994	3.44 eV Monemar 1974 . 3.45 eV Koide et al 1987 . 3.457 eV Ching-Hua Su et al, 2002
Energy Gap E_g at ca. 0 K	3.30 eV Ramirez-Flores et al1994 Ploog et al 1995	3.50 eV Dingle et al 1971 Monemar 1974

Properties

Comparison between Common Semiconductor Material Properties and GaN

Material	Bandgap (eV)	Electron Mobility (cm2/Vs)	Hole Mobility (cm2/Vs)	Critical Field *Ec* (V/cm)	Thermal Conductivity σT (W/m•K)	Coefficient of Thermal Expansion (ppm/K)
InSb	0.17, D	77,000	850	1,000	18	5.37
InAs	0.354, D	44,000	500	40,000	27	4.52
GaSb	0.726, D	3,000	1,000	50,000	32	7.75
InP	1.344, D	5,400	200	500,000	68	4.6
GaAs	1.424, D	8500	400	400,000	55	5.73
GaN	3.44, D	900	10	3,000,000	110 (200 Film)	5.4-7.2
Ge	0.661, I	3,900	1,900	100,000	58	5.9
Si	1.12, I	1,400	450	300,000	130	2.6
GaP	2.26, I	250	150	1,000,000	110	4.65
SiC (3C, b)	2.36, I	300-900	10-30	1,300,000	700	2.77
SiC (6H, a)	2.86, I	330 - 400	75	2,400,000	700	5.12
SiC (4H, a)	3.25, I	700		3,180,000	700	5.12
C (diamond)	5.46-5.6, I	2,200	1,800	6,000,000	1,300	0.8

Crystal Structure

- GaN grown in
  - Wurtzite crystal structure
  - Zinc-blende crystal structure
- The band gap, Eg, is affected by the crystal structure

Applications

- Gallium Nitride Typical Applications:
  - Power Electronics
  - Laser diodes
    - High-resolution Printings
  - Microwave Radio-Frequency power amplifiers
  - Solar Cells

Power Devices - Silicon vs. New Materials

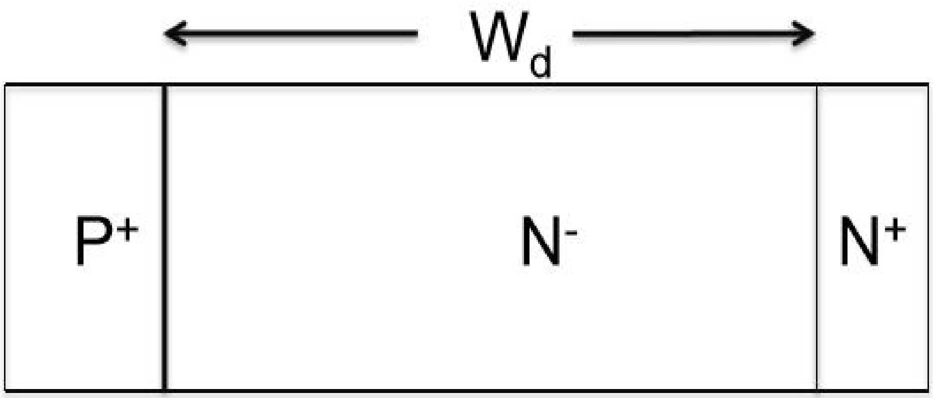
	Si	GaAs	GaN	4H-SiC
Bandgap energy (eV)	1.12	1.4	3.49	3.26
Breakdown field (MV/cm)	0.3	0.4	3.5	3
Electron mobility at 300 K ($cm^2/V \cdot s$)	1400	8500 *10,000	900 *2000	700
Saturated (peak) electron velocity (10^7 cm/s)	1.0 (1.0)	1.3 (2.1)	1.3 (2.7)	2.0 (2.0)
Relative dielectric constant	11.8	12.8	9	10
Thermal conductivity (W/cm·K)	1.5	0.5	1.7	3.5
Thermal expansion (10^{-6}/K)	2.6	5.7	5.6	5.1
Lattice constant (Å)	5.43	5.65	3.19	3.07

* Values of corresponding heterostructures.

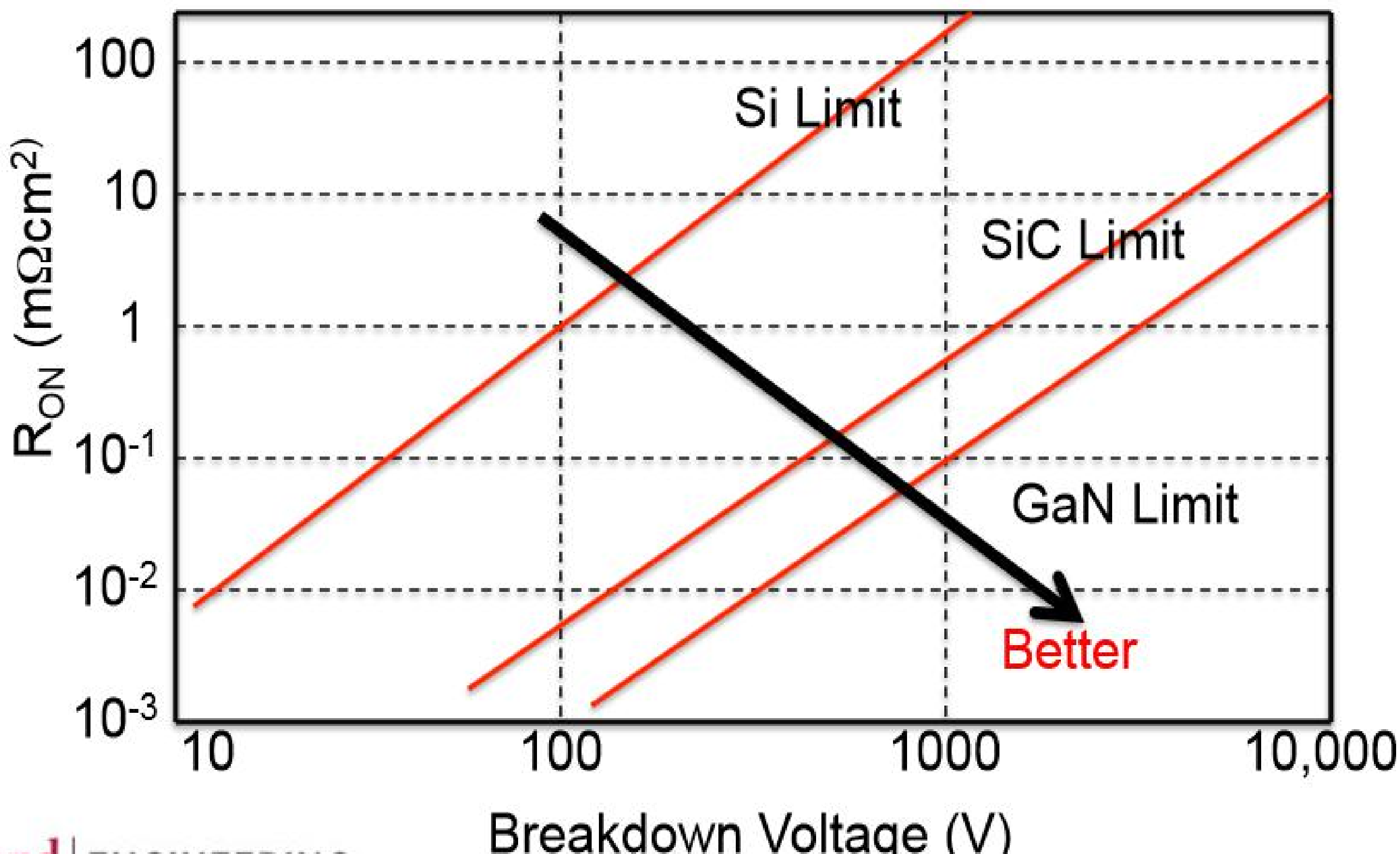
(F. Iacopi et al., MRS Bulletin, May 2015, pg. 390)

The opportunity for major advances occurs primarily because of the higher bandgap and breakdown fields in GaN and SiC.

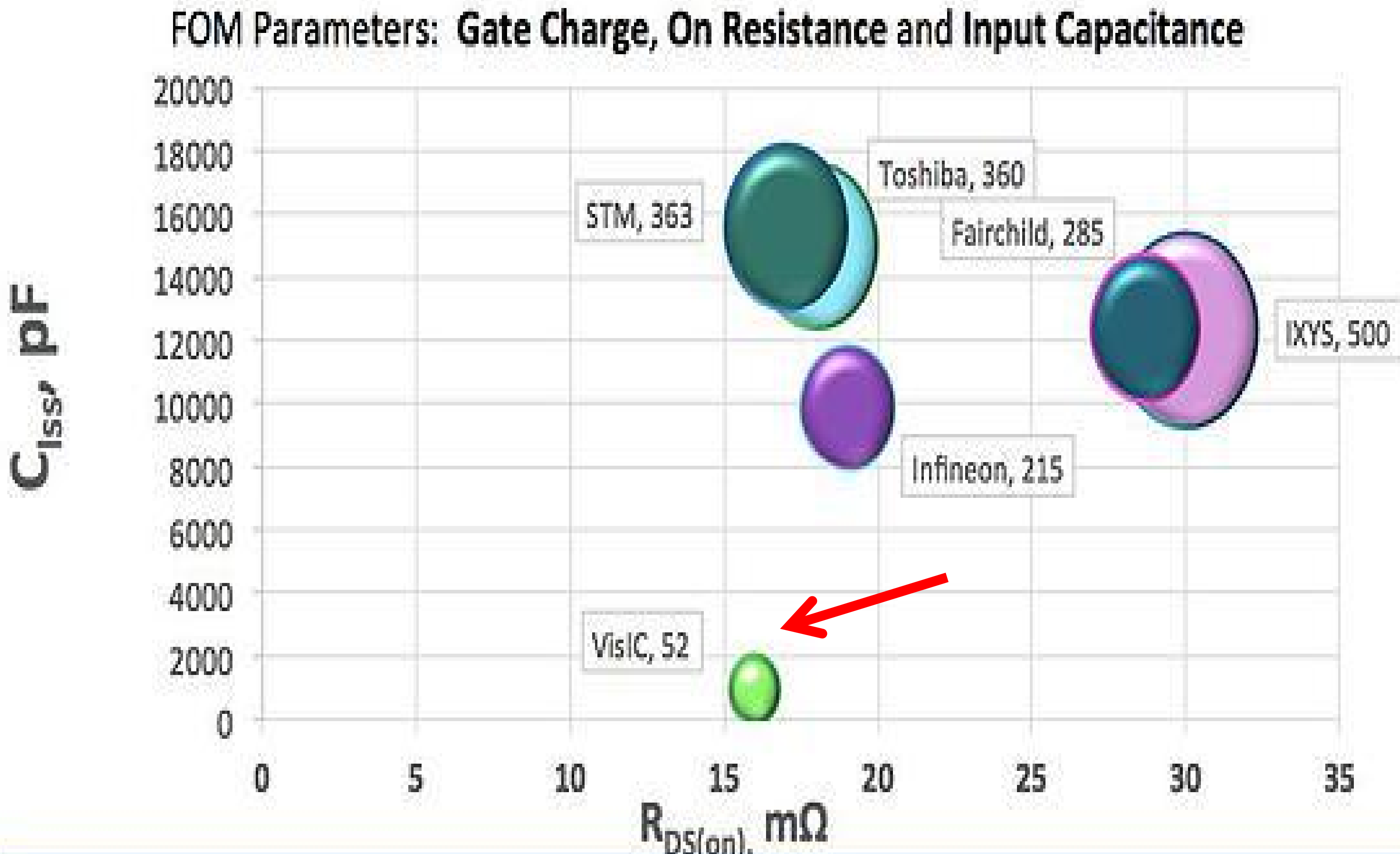
Basic Materials Comparison – Unipolar Limit



$$R_{on} = \frac{W_d}{q\mu N_D} = \frac{E_{cr}\kappa\varepsilon_o}{\mu q^2 N_D^2} = \frac{4V_{bv}^2}{\mu\kappa\varepsilon_o E_{cr}^3}$$

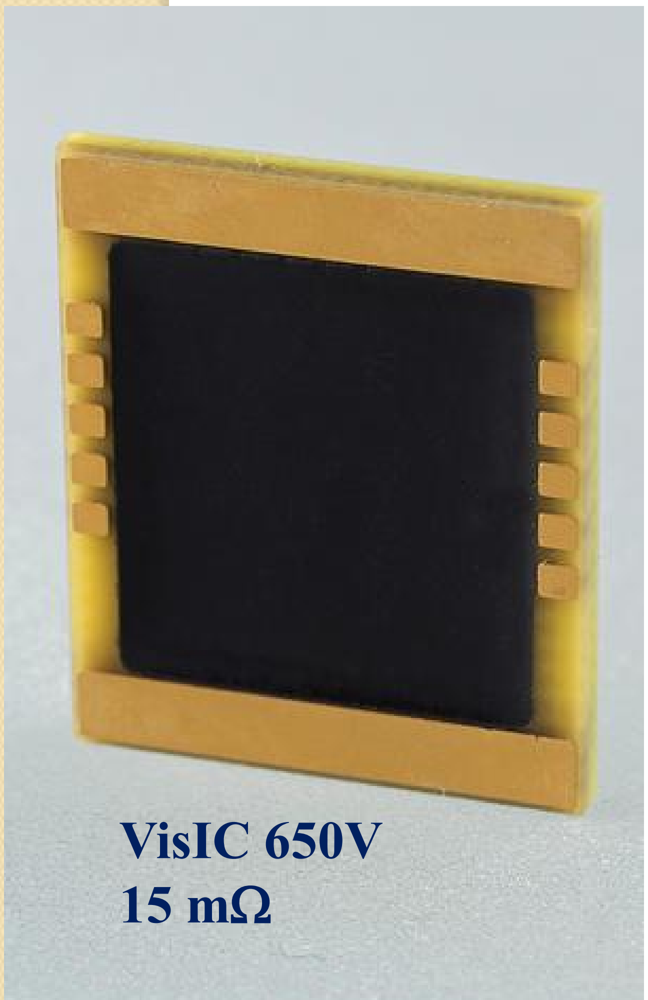


LOW RDS(on) MOSFETs Figures of Merit (FOM)



The best transistors have the lowest FOM (bubble size).

Commercial GaN Power Devices

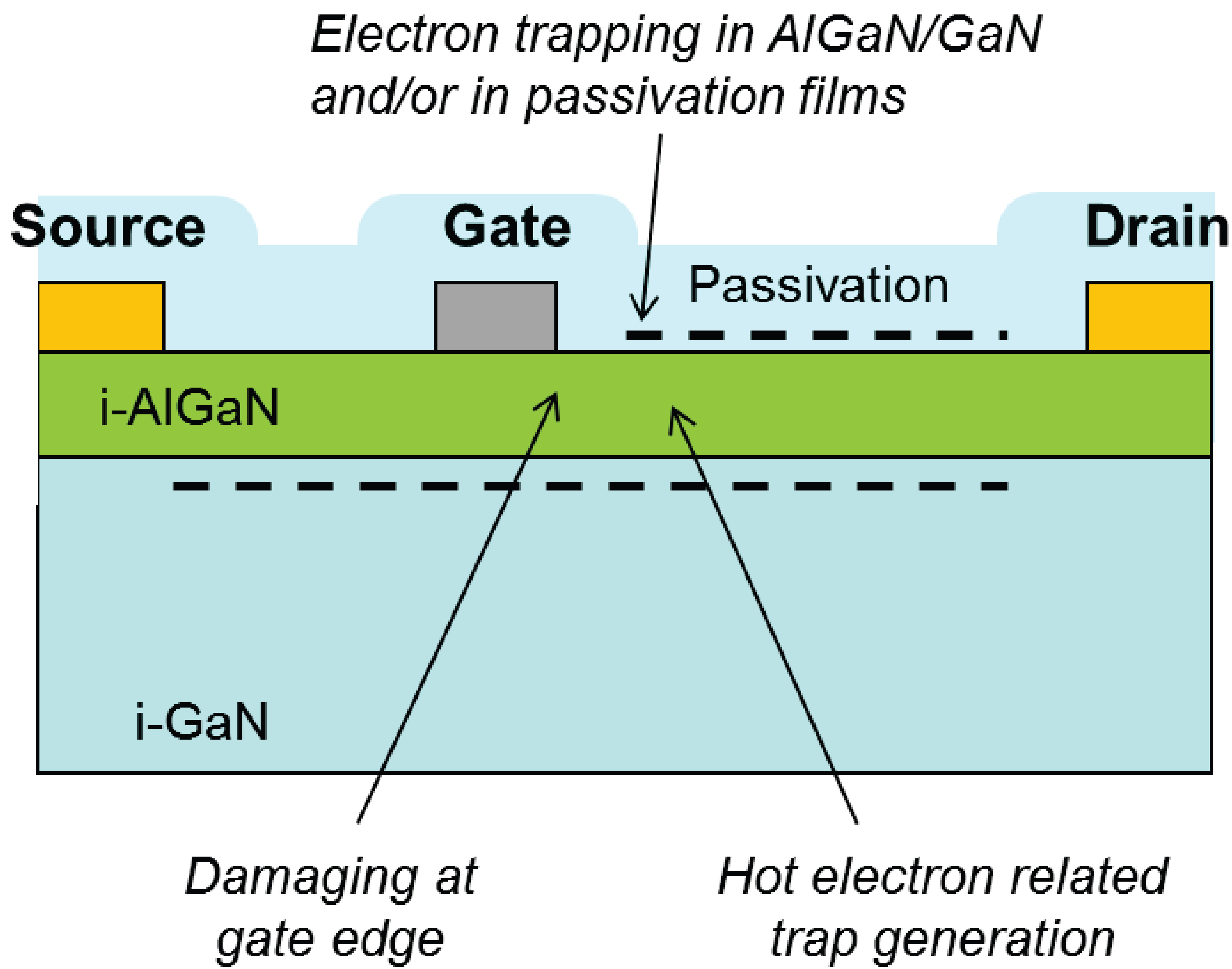


40V
10A
12 mΩ

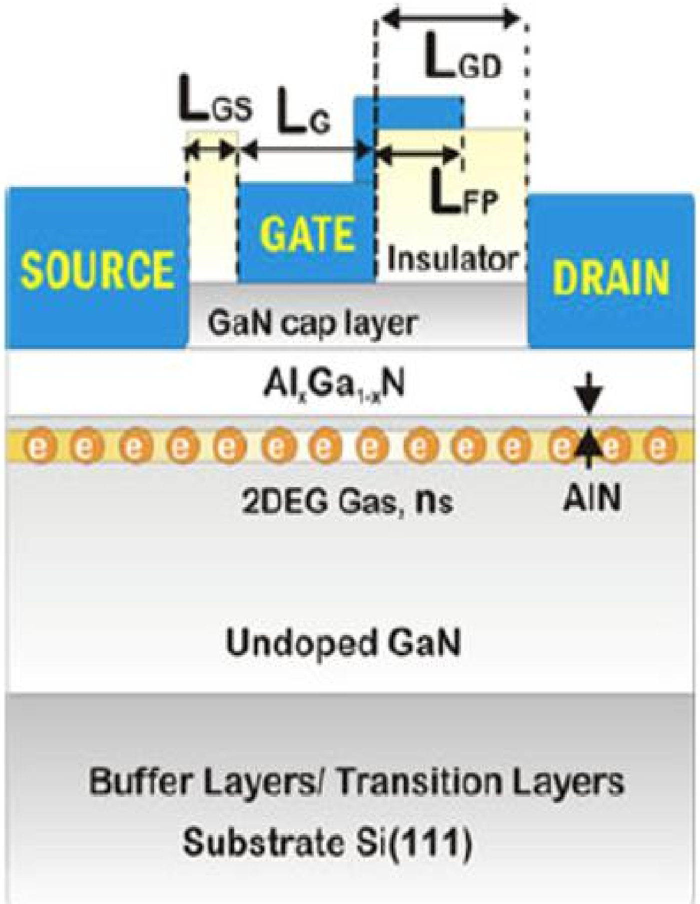
EPC2014 eGaN® FETs are supplied only in passivated die form with solder bumps

Applications

- High Speed DC-DC conversion
- Class D Audio
- Hard Switched and High Frequency Circuits


Electron trapping in AlGaN/GaN
and/or in passivation films
Source
Gate
Drain
Passivation
i-AlGaN
i-GaN
Damaging at
gate edge
Hot electron related
trap generation

Device Structures in GaN



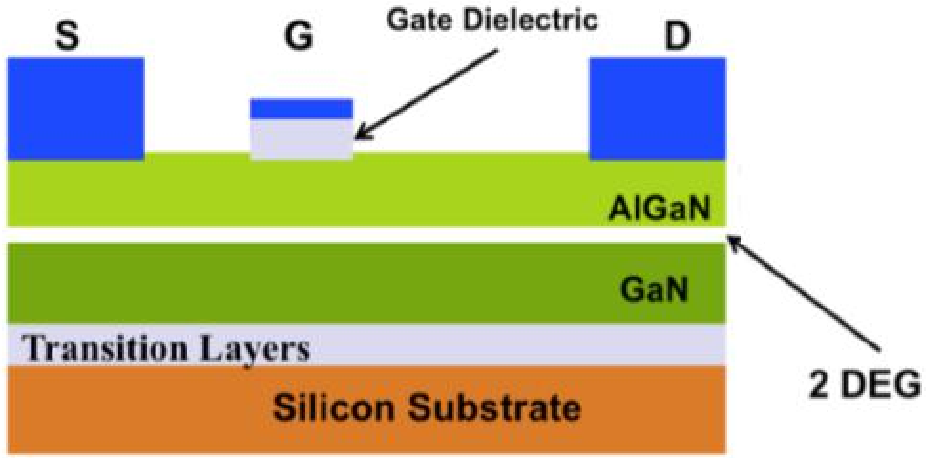
Bulk electron μ ≈ 1600 $cm^2/Vsec$
2DEG electron μ ≈ 2000 $cm^2/Vsec$
Bulk hole μ ≈ 175 $cm^2/Vsec$
Critical Field ≈ 3.5 MV/cm

E_{cr} is much better than Si.
2DEG μ is better than Si.

BUT – normally OFF devices
have lower performance.

- Heteroepitaxy on Si, SiC limits GaN to lateral devices, < 1000 V.
- Basic device is depletion mode (normally ON).
- No large diameter GaN wafers available.

Enhancement Mode GaN Devices



What's Needed?

- $V_T > 2$ volts
- $V_G > 10$ volts
- Cascode circuit with Si MOSFET + GaN HEMT can achieve this.

Eliminate 2DEG under gate:

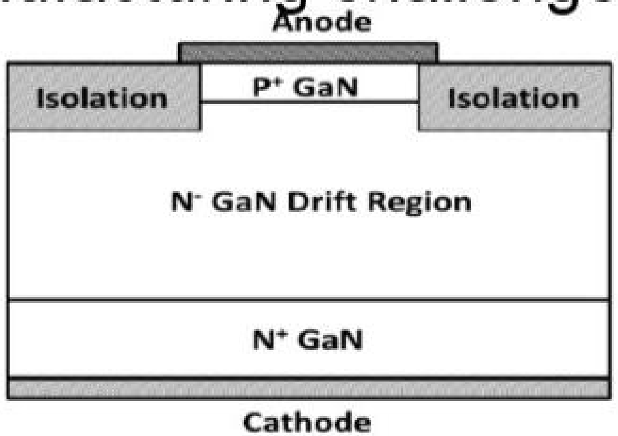
- Sub-critical barrier, e.g. recessed gate
- MOS-hybrid device
- Piezoelectric gate
- N-polar HEMT
- Lattice matched barrier (InAlN)

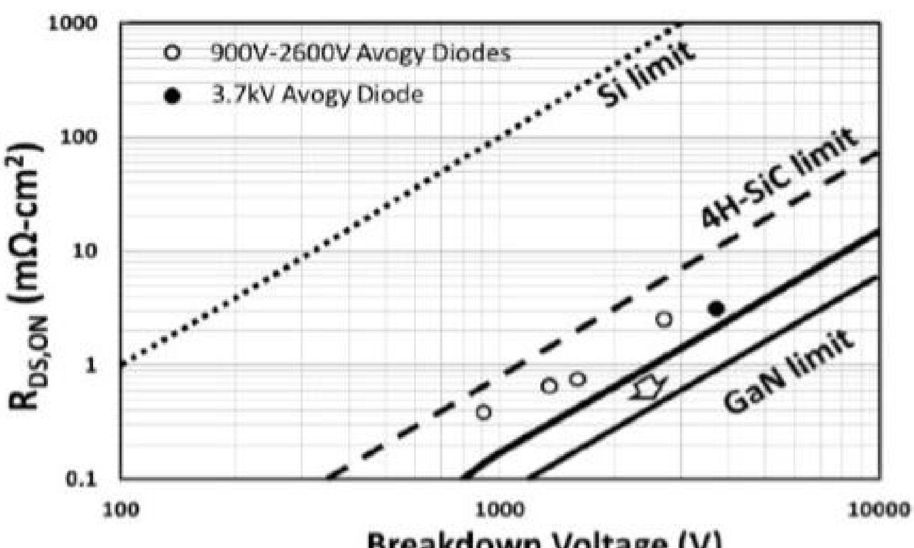
Negative charge between external gate electrode and 2DEG:

- PN junction (p GaN, p AlGaN under gate)
- Negative ions in insulator or barrier (e.g. F^-)
- Trapped electrons in gate insulator (floating gate or SiN-SiO_2)

Vertical GaN Devices
Homoepitaxy Examples

- The biggest challenge here is bulk GaN wafers. Only very small (2”) wafers currently available and the wafer manufacturing challenges are formidable.





(I. C. Kizilyalli et. al., Avogy, Inc. IEDM, 2013)

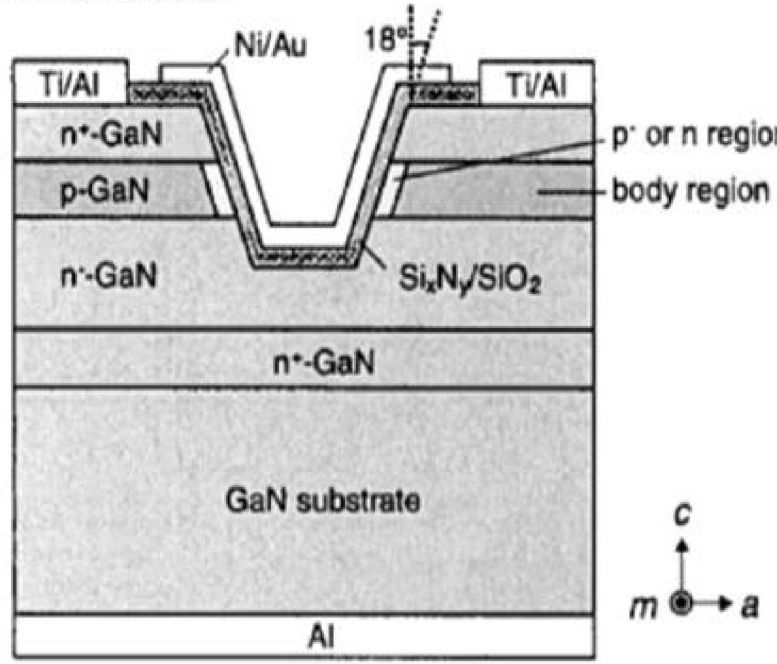


Fig. 2. Device structure of our trench gate MOSFET.

H. Otake et.al. APEX vol 1 (2008) p. 011105-1

What's Needed To Increase Market Penetration by GaN Devices?

- Much progress has been made in reducing crystal defects in GaN epi layers grown on Si. But the quality is not nearly as good as Si wafers. Si substrates are likely the best route to reduce lateral GaN HEMT manufacturing costs.

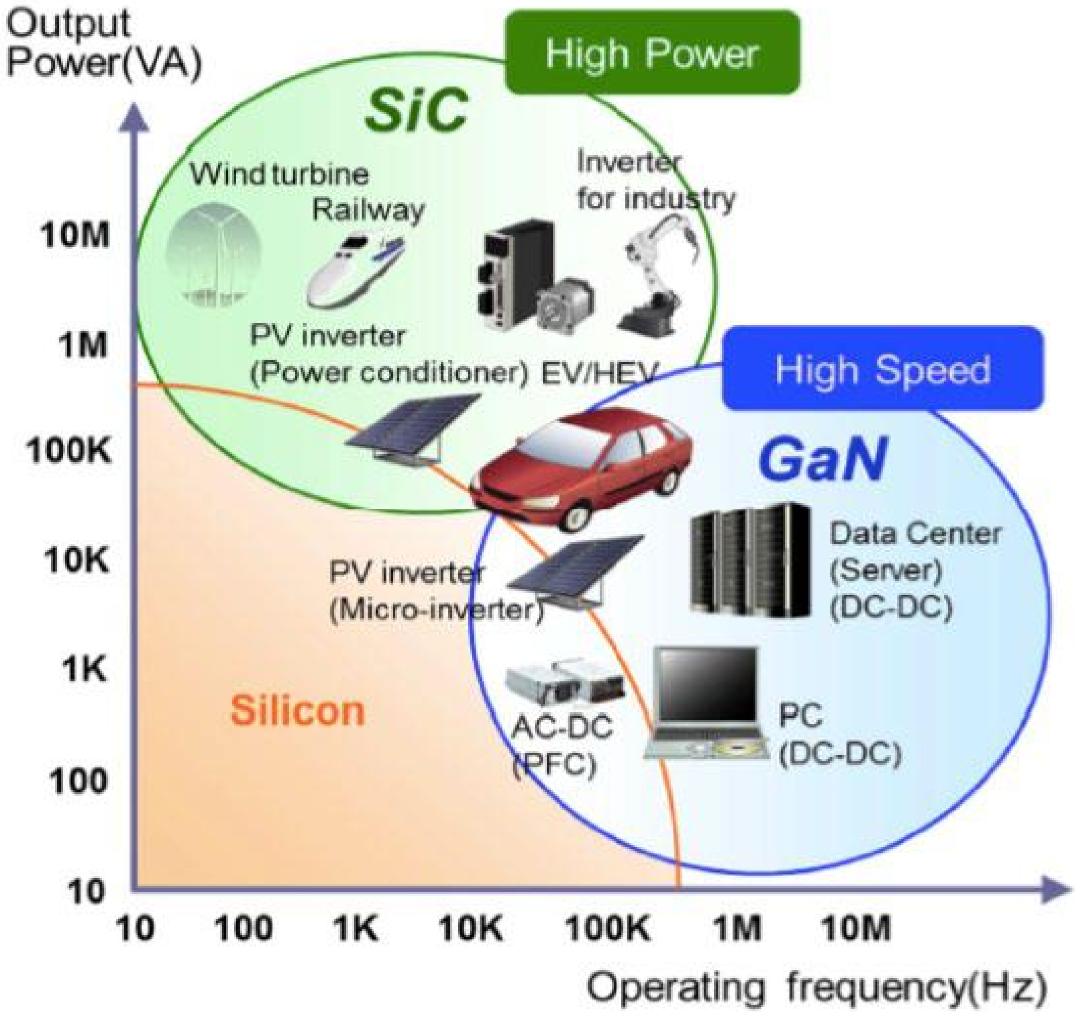
- Enhancement mode device structures need further development.

- Reliability, ON current collapse after high reverse bias, need further investigation.

- A breakthrough is needed in producing GaN bulk substrates.

So currently P/C is not > 2-3X silicon and GaN is largely addressing markets where Si cannot compete or which are not cost sensitive and these markets are not huge!

Current Market Opportunities for Gan and SiC



SiC for high power voltages (>1kV) with high current

GaN on Si for high frequency at mid-range voltages (<1kV)

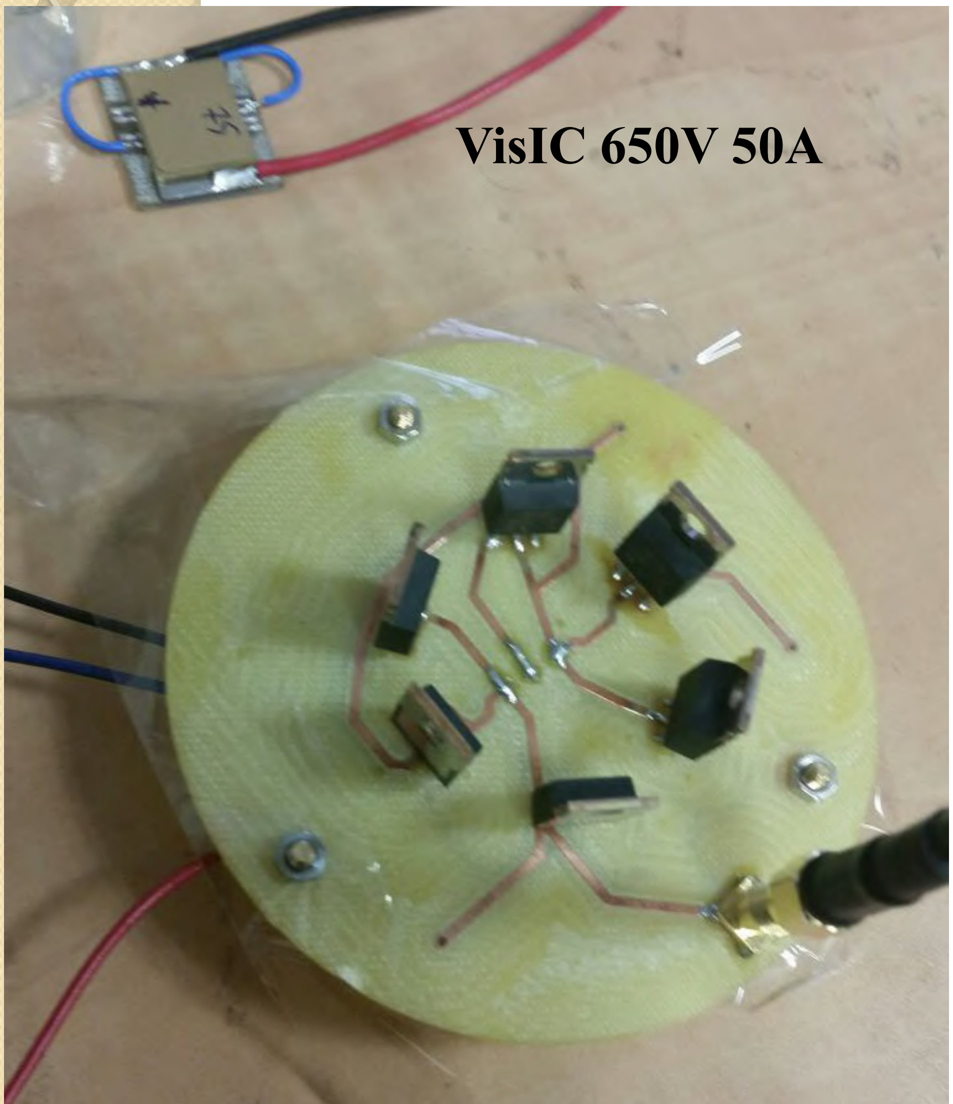
(Panasonic)

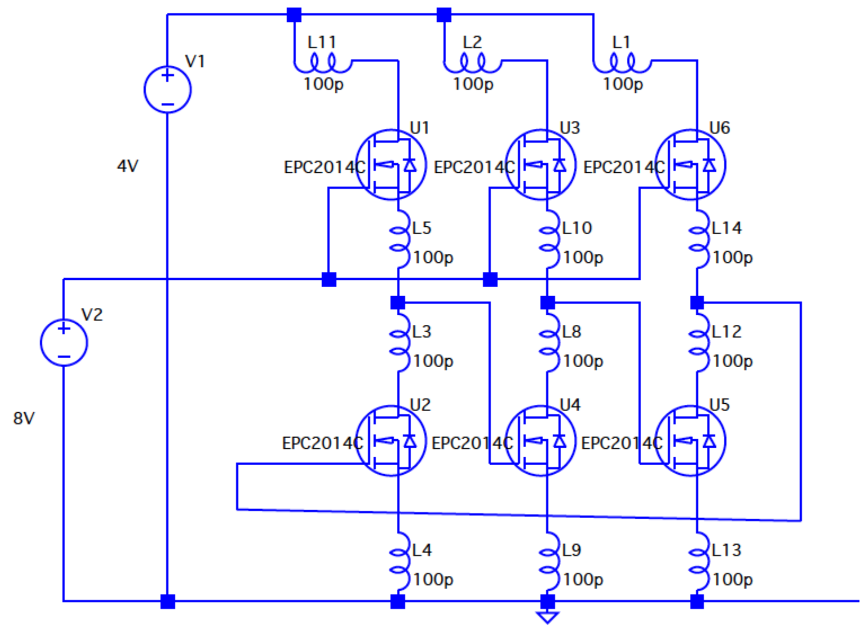
Given the current limitations of Gan and SiC in P/C, most applications are in regions where Si cannot compete.

The Situation Today

- GaN and SiC have very clear materials advantages over Si.
- In principle they allow power electronic components to be faster, smaller, more efficient and more reliable than Si parts.
- In principle they allow devices to operate at higher voltages, higher temperatures and higher frequencies than Si devices.
- Yet their market penetration is very small today. Some market projections (Lux) suggest Si will still have 87% of the power device market in 2024.
- What needs to happen to change this? Will it change?

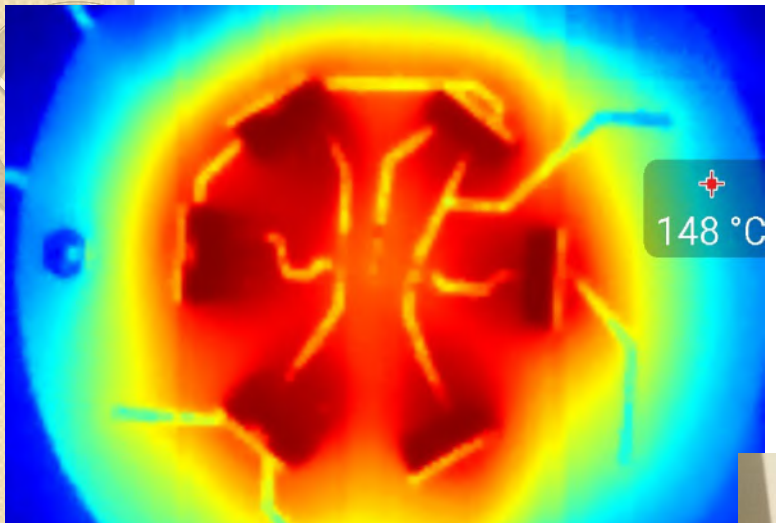
GaN Ring Oscillator Test Circuit



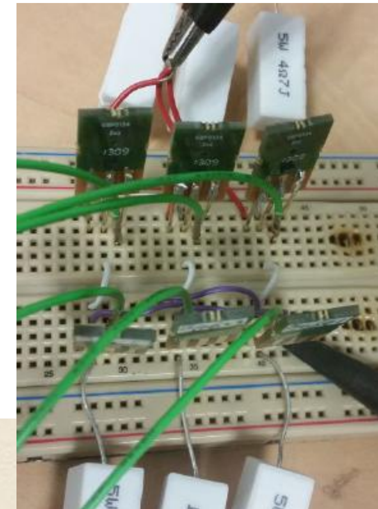


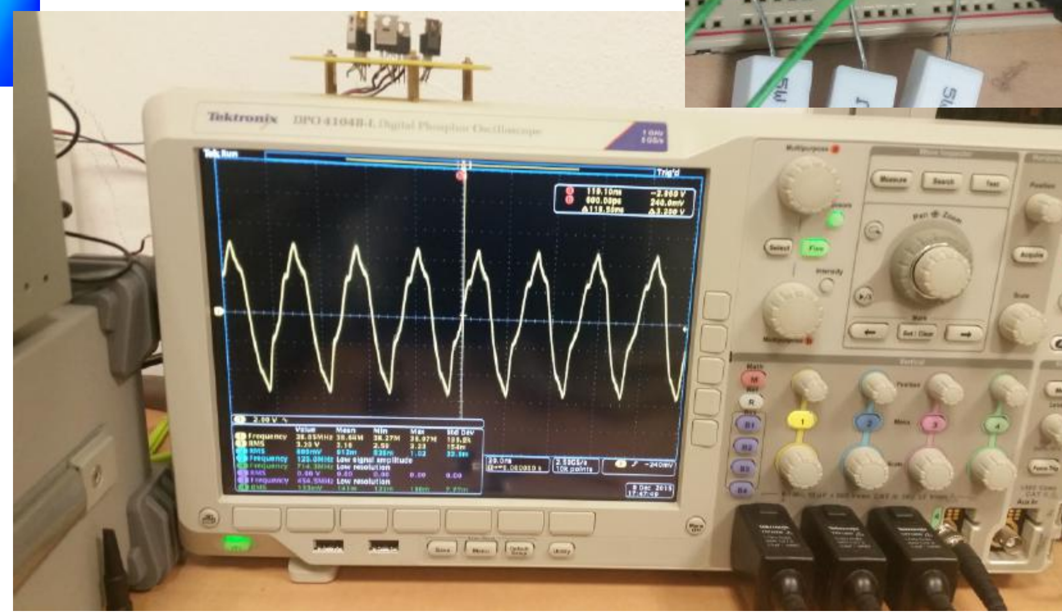
Patent applied for
5 May 2015
Serial No. 62/156,957.

GaN Ring Oscillator Test Circuit



GaN Ring Oscillator is in process with EPC and Texas Instruments





Thermal Picture shows that our temperature is evenly distributed. This is critical to test the average effect.

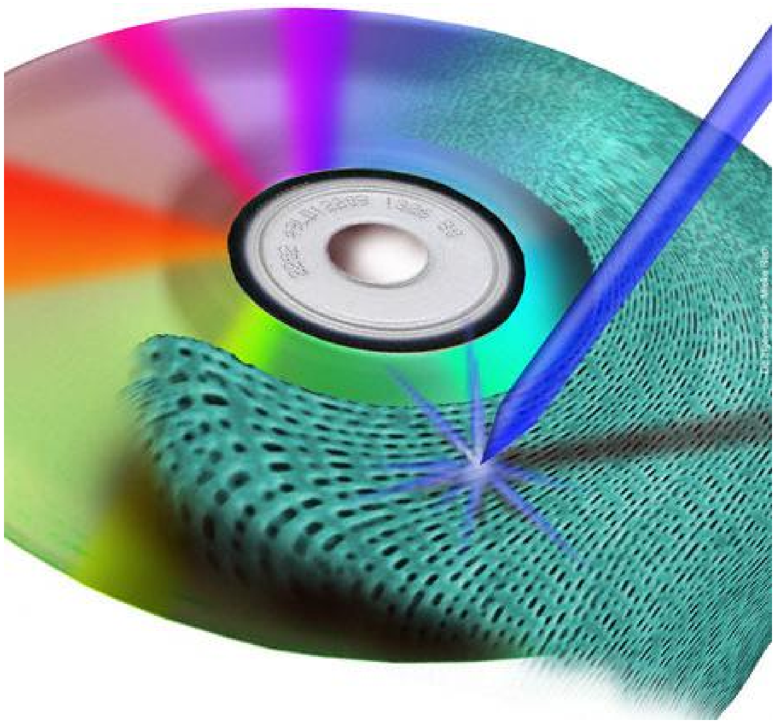
GaN Laser Diode

- Normally emits ultraviolet radiation
- Indium doping allows variation in band gap size
- Band gap energies range from 0.7eV – 3.4eV

http://www.lbl.gov/Science-Articles/Archive/assets/images/2002/Dec-17-2002/indium_LED.jpg

GaN Laser Diodes

- Applications in:
  - ‘Blu-Ray’ technology
  - Laser Printing



http://www.aeropause.com/archives/Blu-ray-cover_plat.jpg

GaN Solar Cells

- Indium doped (InGaN)
- Conversion of many wavelengths for energy
- Theoretical 40% maximum conversion rate.
  - Multiple layers attain higher efficiency.
  - Need many layers to attain 40%
- Lattice matching not an issue

GaN Solar Cells

Advantages:

- High heat capacity
- Resistant to strong radiation
- High efficiency

Difficulties:

- Too many crystal layers bring about system damaging stress
- Too expensive

Thanks !