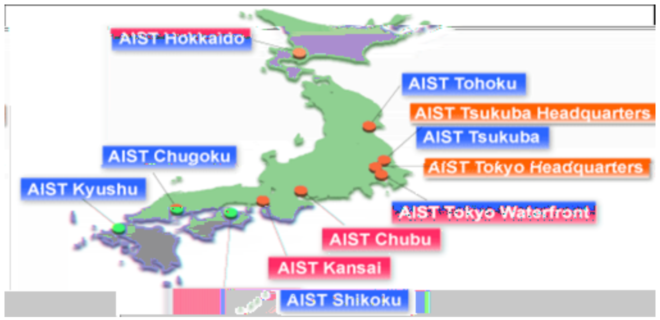
Beijing University Semimar

Present Status and Future Prospect of the Power Electronics Based on Widegap Semiconductors

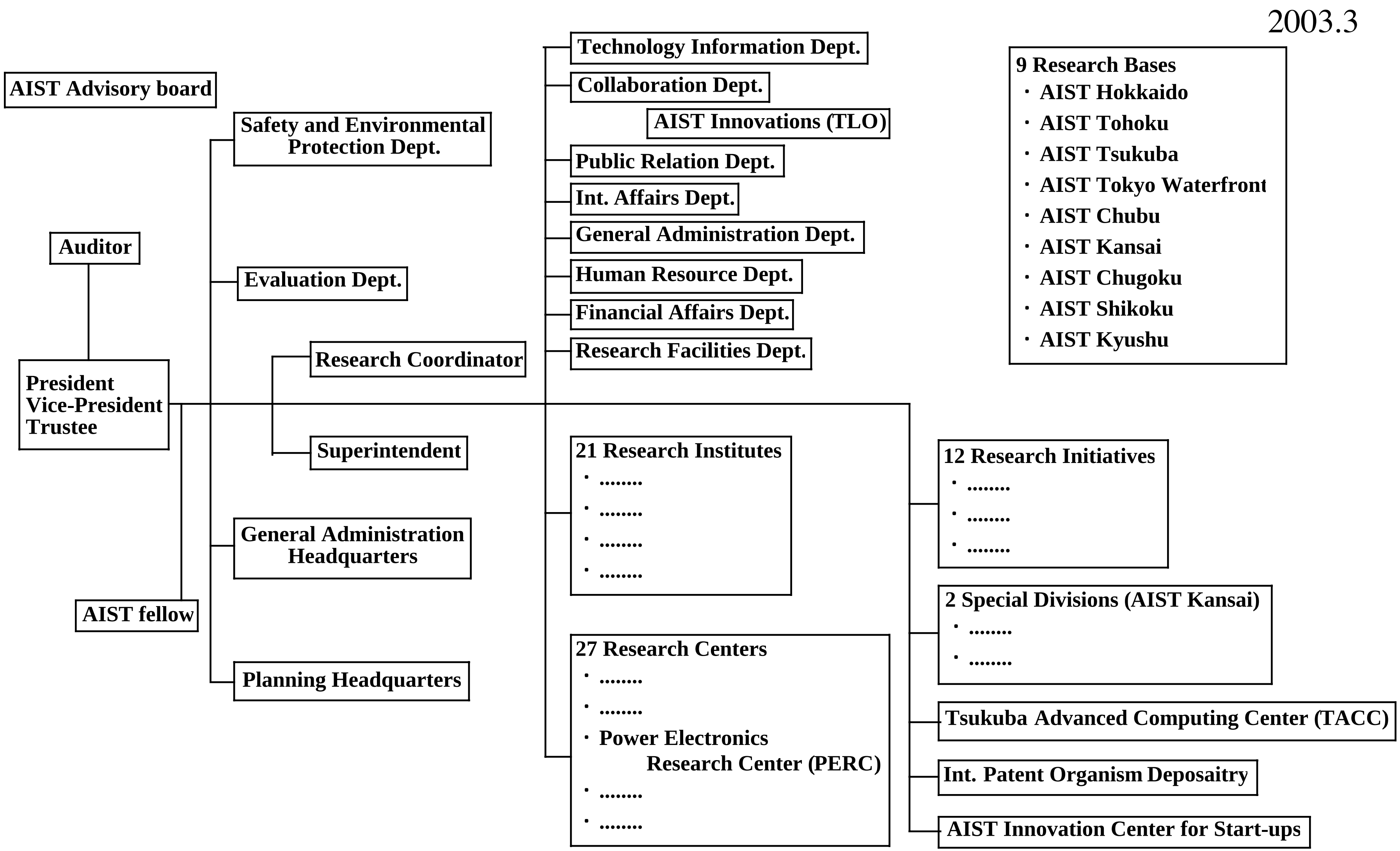
2007.11.22

National Institute of Advanced Industrial Science & Industry
Power Electronics Research Center

Hajime Okumura


AIST Hokkaido
AIST Tohoku
AIST Tsukuba Headquarters
AIST Tsukuba
AIST Chugoku
AIST Tokyo Headquarters
AIST Kyushu
AIST Tokyo Waterfront
AIST Chubu
AIST Kansai
AIST Shikoku

Organization of new AIST



Mission and Activity Area

- ## Mission

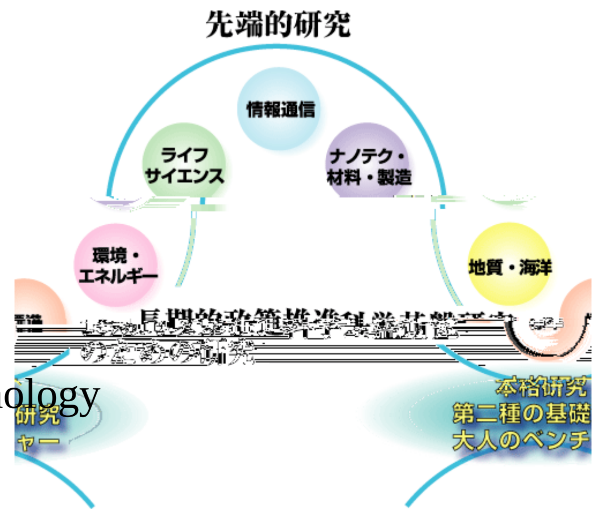
  (a) **Industrial infrastructure technology**, including measurement standards, geological surveys, and the development of base technologies necessary for the maintenance of the techno-infrastructure of Japan.

  (b) **Energy and environmental technology**, which because of long lead times and high risk require the government to search for solutions.

  (c) **Interdisciplinary and broad-spectrum research activities** to promote innovation and reinforce the international competitive strength of Japanese industry and encourage the creation of new industries.

- ## Activity (Research Fields)

  (1) Life Science and technology
  (2) Information Technology
  (3) Environment and Energy
  (4) Nanotechnology, Materials and Manufacturing
  (5) Geological Survey and Geoscience, Marine Science and Technology
  (6) Standards and Measurement Science and Technology



- Development of the **electronics based on widegap semiconductor materials and science**,
- Application of the related technology to actual **information and energy networks** in the human society, in order to contribute to the **innovation of life line and energy saving**

Contents

Widegap semiconductors

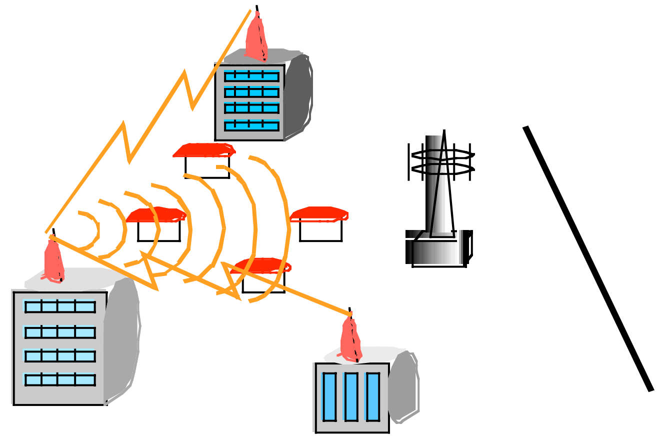
- SiC
- III-nitrides

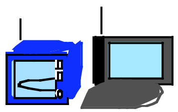
Electron devices (high-power)

- High-frequency device (analog appl.)
- Switching device (digital appl.)

1. Importance of wireless communication, power electronics in the 21th century
2. Requirements from system application to high-power electron device
3. Characteristics of widegap semiconductors
4. High-power operation by widegap semiconductor devices
5. Present R&D status of high-power electron devices
6. Problems and future prospect

   SiC devices or GaN devices ?





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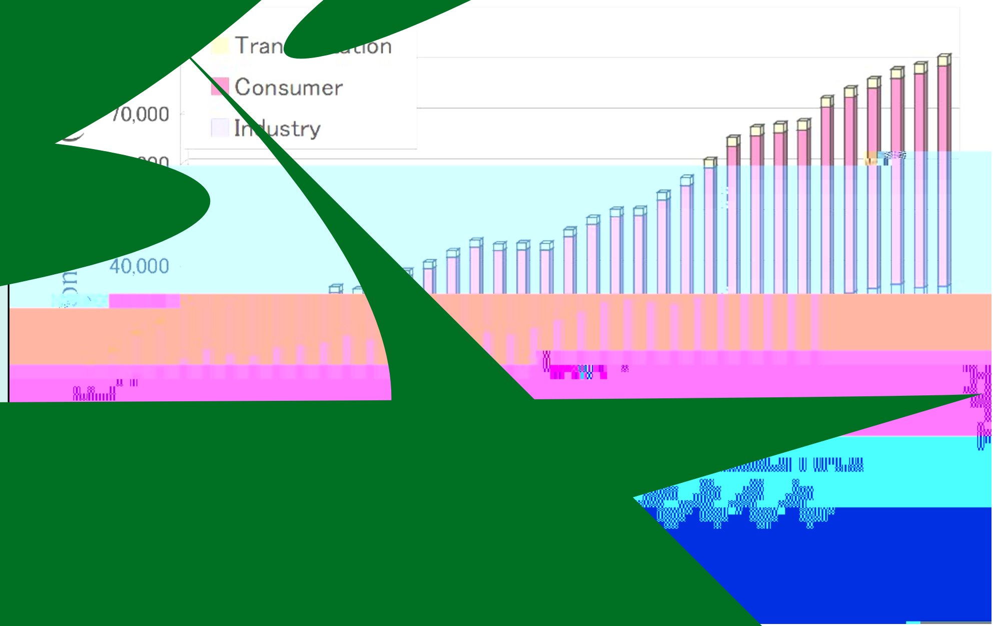
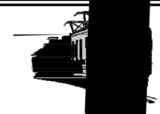
city C ption in various field



[出典]資源エネルギー庁(編):エネルギー20

Application Field of Power Ele[redacted]tronics



Energy Saving in Electric Power

→ **Urgent issue, considering Electricity Ratio**

Application of **Electronics** to the control of Electric Power :
(Energy Electronics, Power Electronics) **High Voltage, Large Current**

↓

Power Conversion
(AD/DA conversion

↓

Inverter circuit

↓

Power Device
(Transi[illegible]

Exan ple of Powe
in E ric Po wer Convert

s with small
w resistance

odules with small
s and higher operation
frequency

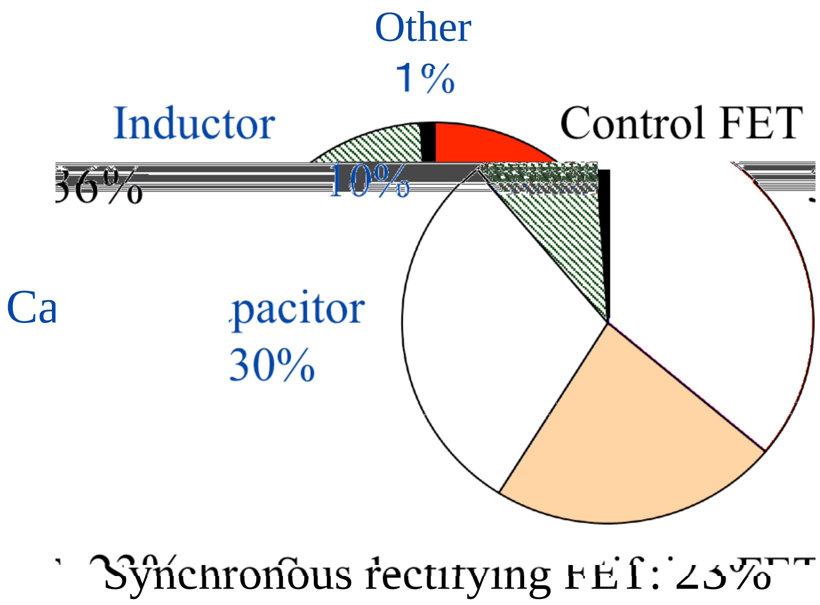
and small peripherals

on of
Pow onics

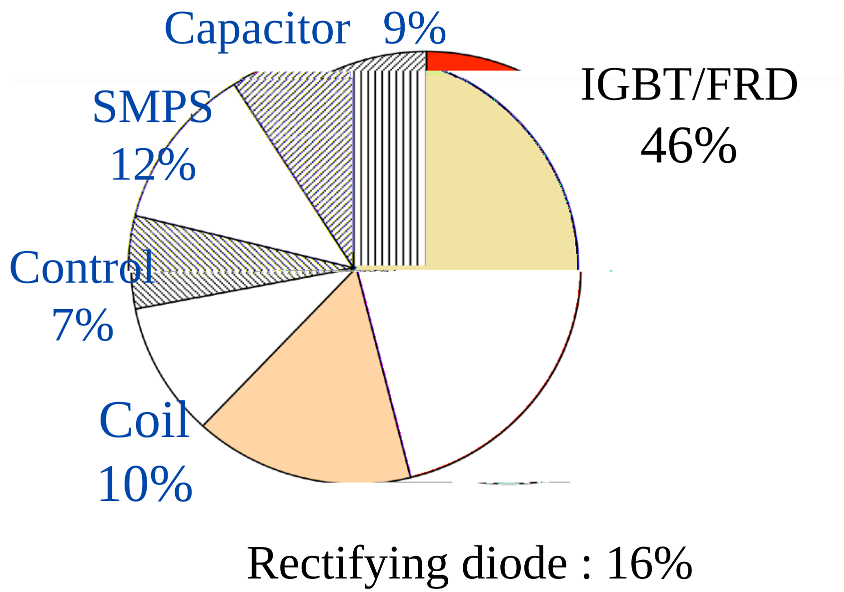
Key of Ene ving
echnol
in Electric Po

What is an ideal switc
on-state：zero resistance
off-state：resistance infinity

Analysis of Power Loss in Typical Electric Power Converters



(a): Switching Power Supply



(b): Motor Drive Inveter

Components of loss

Power devices : Passive elements ＝ 60% : 40%

Lidow, et.al, Proc. of IEEE, 89, 803 (2001)

Device Specification Requirements from Application Needs

High-frequency devices for wireless communication

1. High frequency:	Enlarged frequency domain, large-capacity high-speed communication, broad band
2. High output power :	long-distance transmission broad band, low distortion
3. High operation voltage:	high-efficiency, low-loss, small size

Switching devices for power electronics

1. High blocking voltage:	applicability, reliability
2. Low on-resistance:	reduction of conduction loss
3. High switching speed:	small size
4. Low electrostatic capacity:	reduction of switching loss, high-speed switching
5. High tolerance:	reliability, safety

What is Widegap Semiconductors ?

2					
3	Mg	Al	Si	P	S
4	Zn	Ga	Ge	As	Se
5	Cd	In	Sn	Sb	Te

C : Carbides
IV-IV group
polytypes
MOS structure
Indirect band structure

N : Nitrides
III-V group
Hetero sturucture
Alloys
Direct band structure

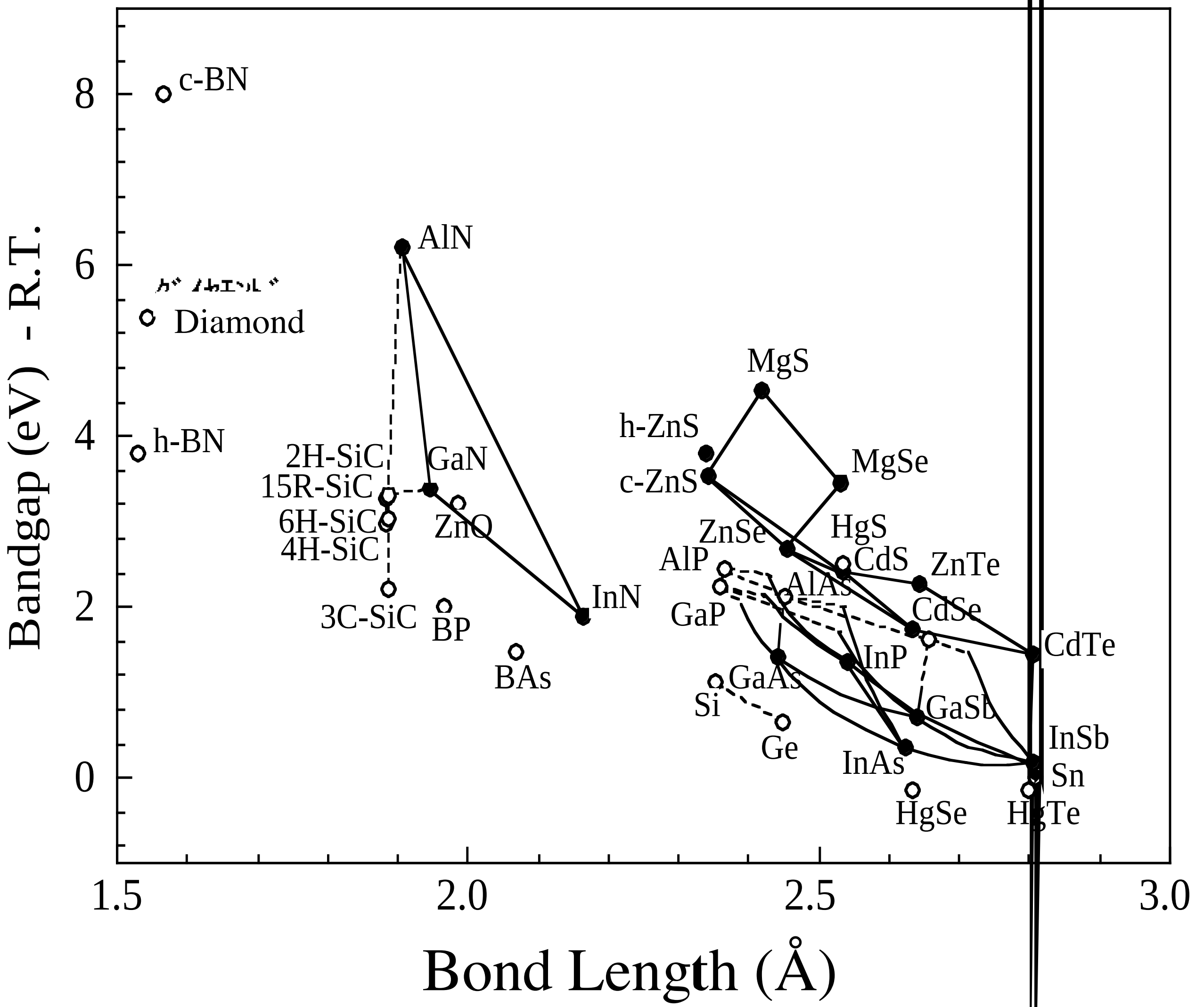
O : Oxides
II-VI group
Insulator to Superconductors

Light Element Semiconductors
- **Large binding energy**
- **High melting point**
- **Small lattice constant**

Large
- **Bandgap**
- **Thermal conductivity**
- **Breakdown voltage**
- **Saturation drift velocity**
- **thermal and chemical stability**

Hard Electronics
- **High temperature devices**
- **High power devices**
- **High frequency devices**
- **Short wavelength devices**

Lattice Constants and Bandgap



Physical Properties of Semiconductors

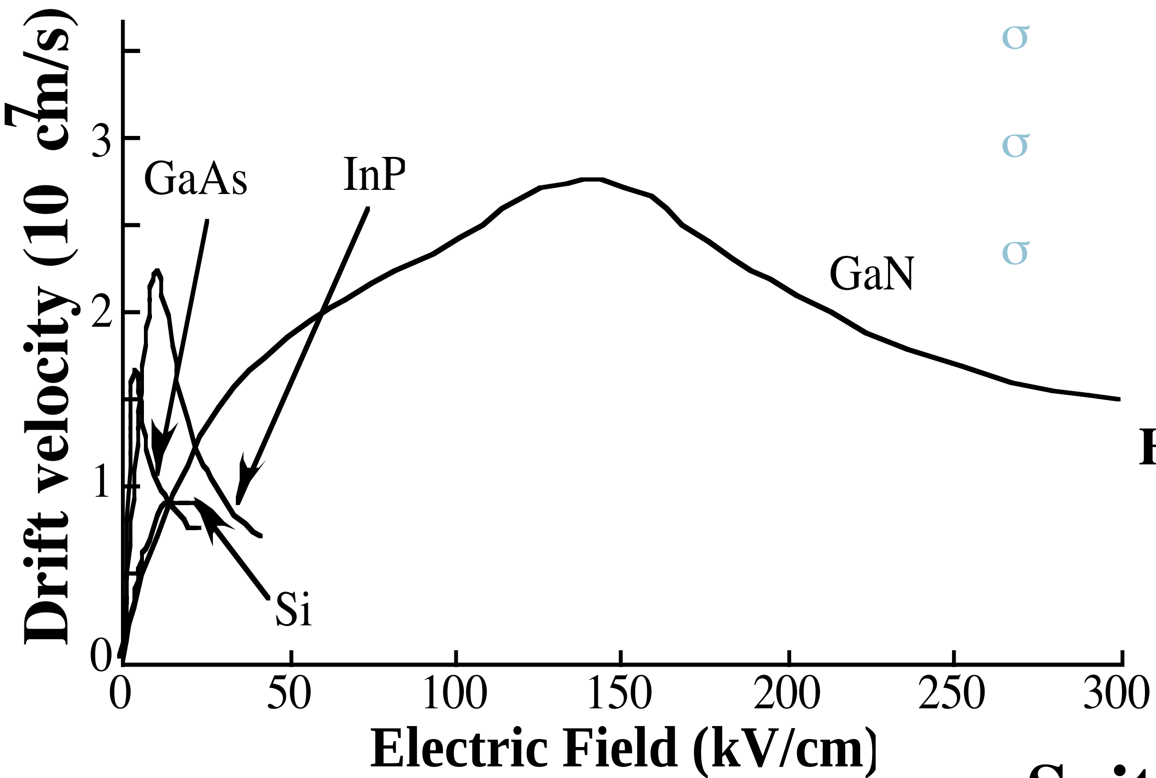
Material	E_g eV	ε	μ_ν cm^2/Vs	E_c $10^6V/cm$	ν_{sat} $10^7cm/s$	κ W/cmK	band type
Si	1.1	11.8	1350	0.3	1.0	1.5	I
GaAs	1.4	12.8	8500	0.4	2.0	0.5	D
c-GaN	3.27	9.9	1000	1	2.5	1.3*	D
h-GaN	3.39	9.0	900	3.3	2.5	1.3	D
3C-SiC	2.2	9.6	900	1.2	2.0	4.5	I
6H-SiC	3.0	9.7	370[a], 50[c]	2.4	2.0	4.5	I
4H-SiC	3.26	10	720[a], 650[c]	2.0	2.0	4.5	I
AlN	6.1	8.7	1100	11.7	1.8	2.5	D
Diamond	5.45	5.5	1900	5.6	2.7	20	I

a: along a-axis, c: along c-axis, *: estimate

Material	Johnson's FM	Keyes's FM	Shenai's FM(Q_{F1})	Shenai's FM(Q_{F2})	Baliga's FM	Baliga's HFM
	$(E_c \ _{sat}/\ )^2$	$(\ _{sat}/\ )^{1/2}$	$_A$	$_A E_c$	$\mu E_c{}^3$	$\mu E_c{}^2$
Si	1	1	1	1	1	1
GaAs	7.1	0.45	5.2	6.9	15.6	10.8
c-GaN	685	1.5	20	67	23	8.2
h-GaN	760	1.6	560	6220	650	77.8
3C-SiC	65	1.6	100	400	33.4	10.3

Saturation Drift Velocity & Breakdown Voltage vs. Electric Field

Characteristics of GaN



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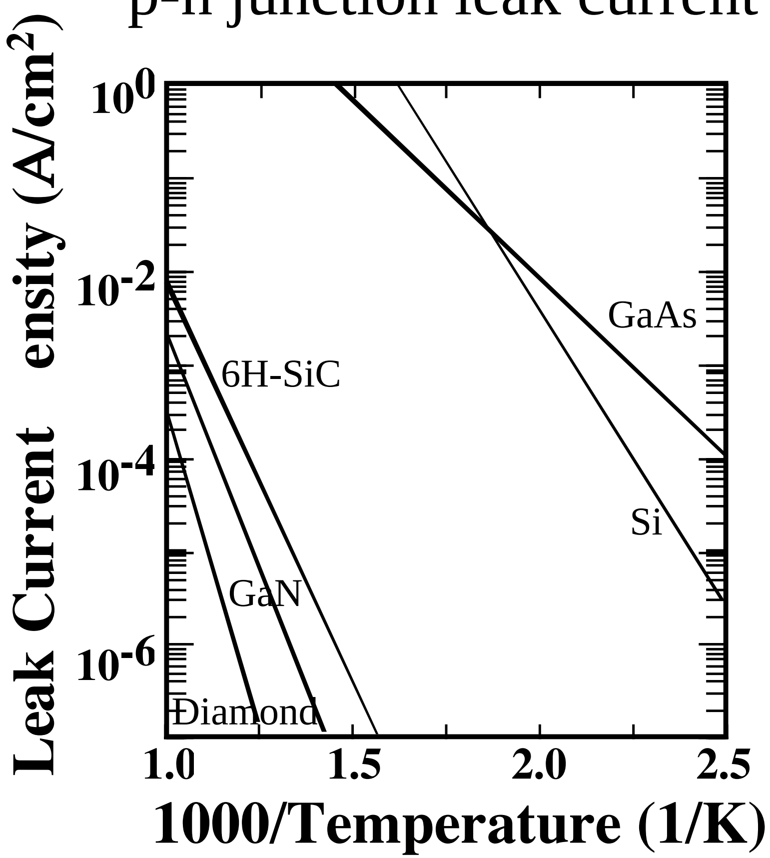
High Voltage operation is possible even after microintegratioin

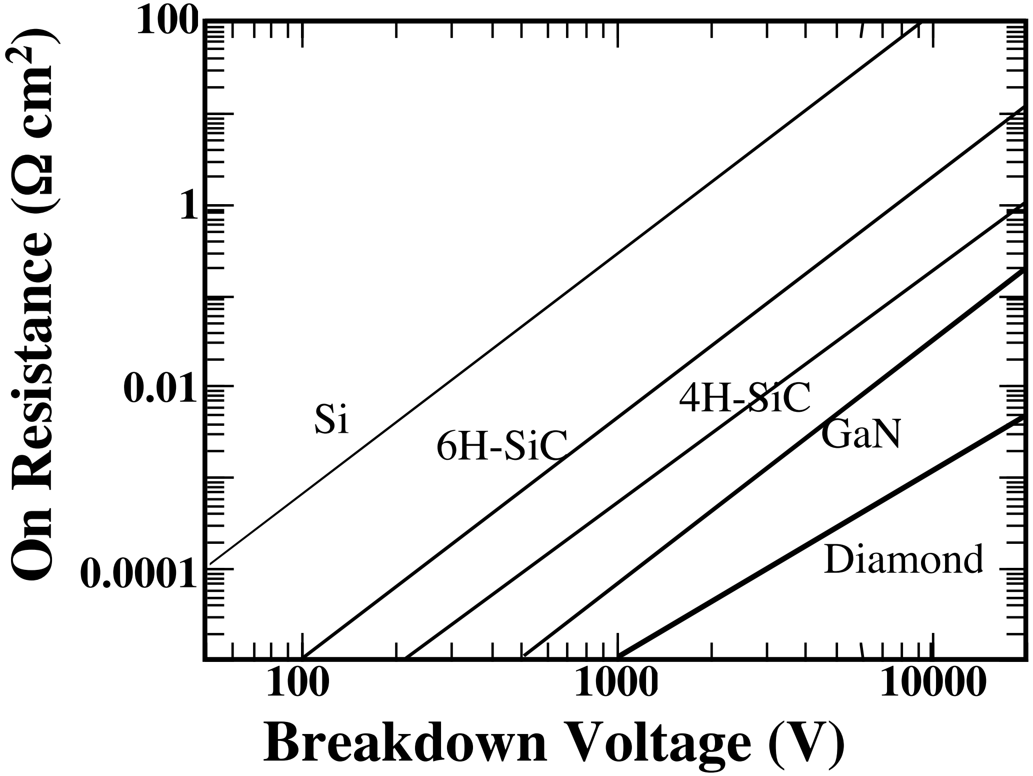
Suitable for high-power high-frequency operation

Properties of Wide Bandgap Semiconductor Devices

Temperature dependence of p-n junction leak current



On resistance and Breakdown Voltage

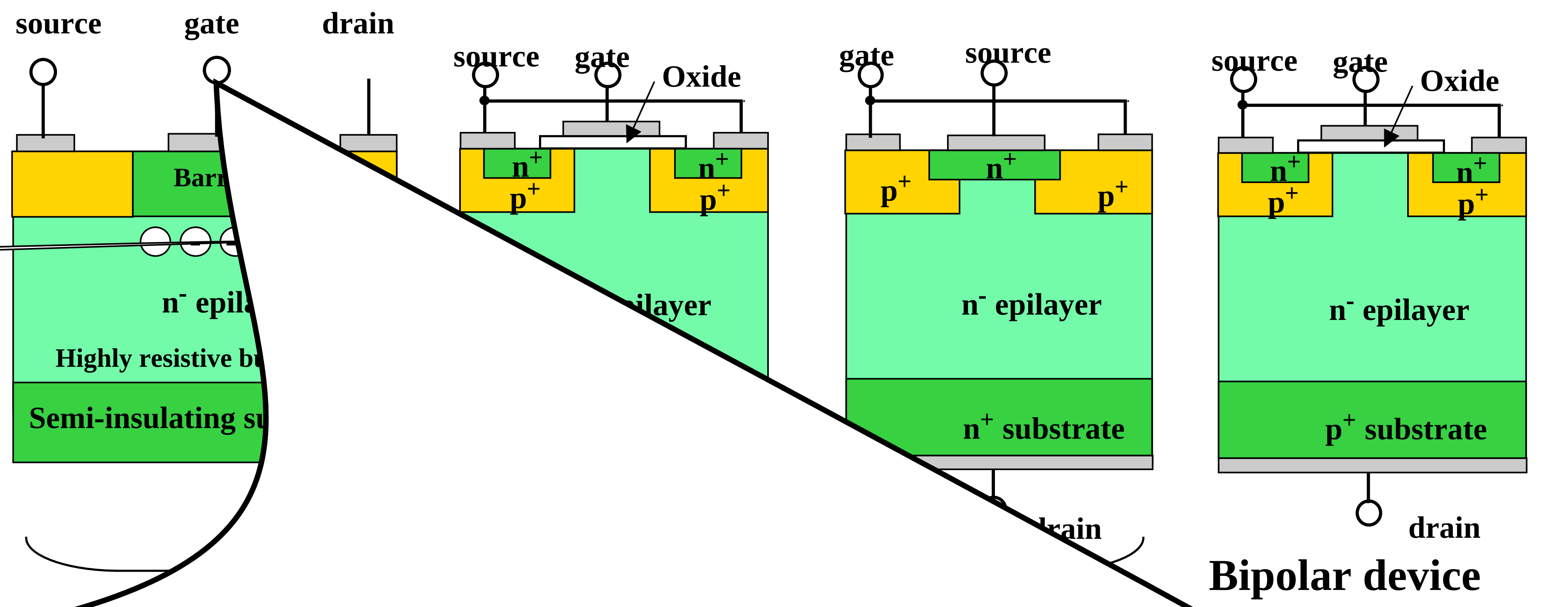


Structures of High-Power Electron Device

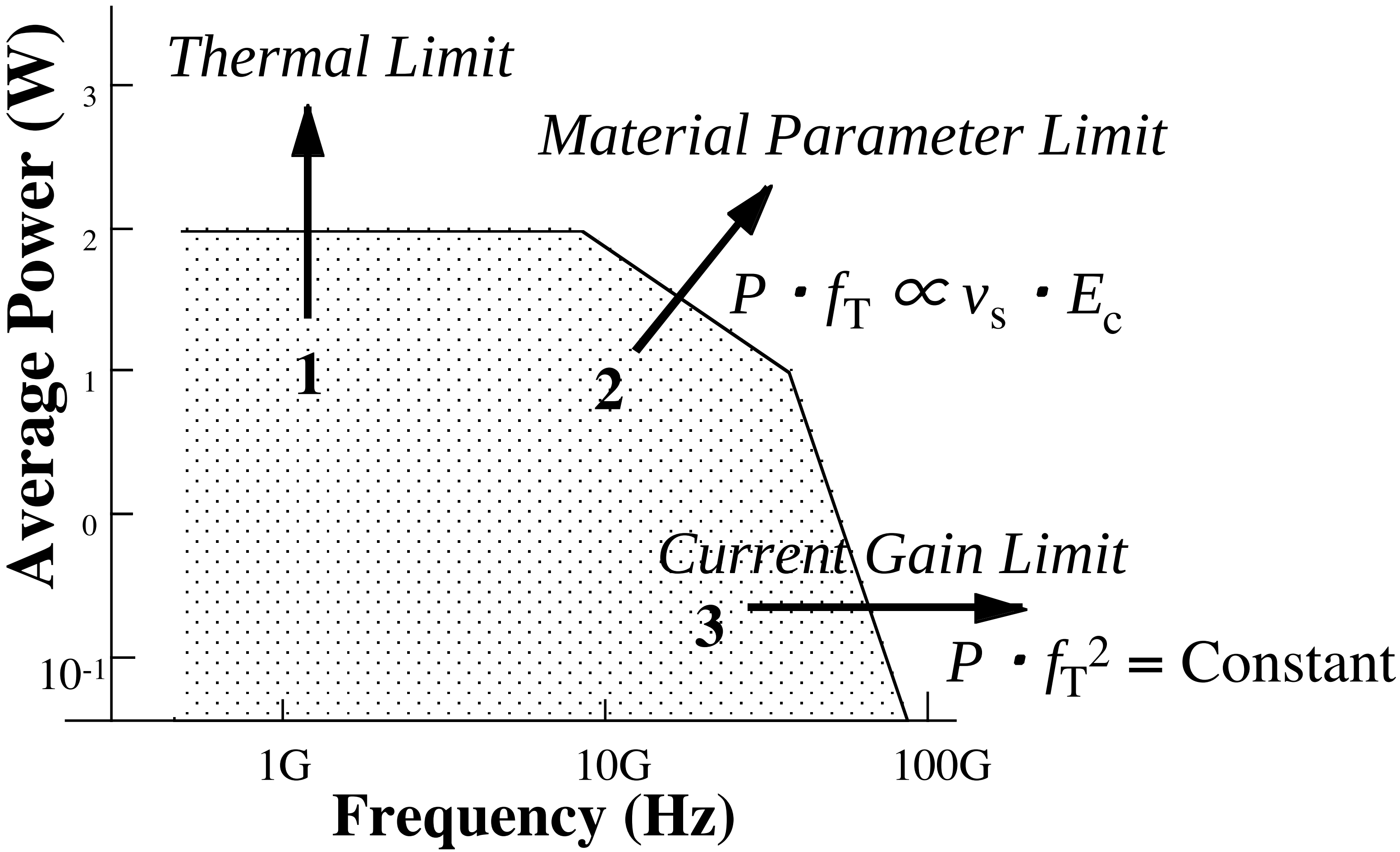
MOSFET
Metal Oxide Semiconductor Field Effect Transistor

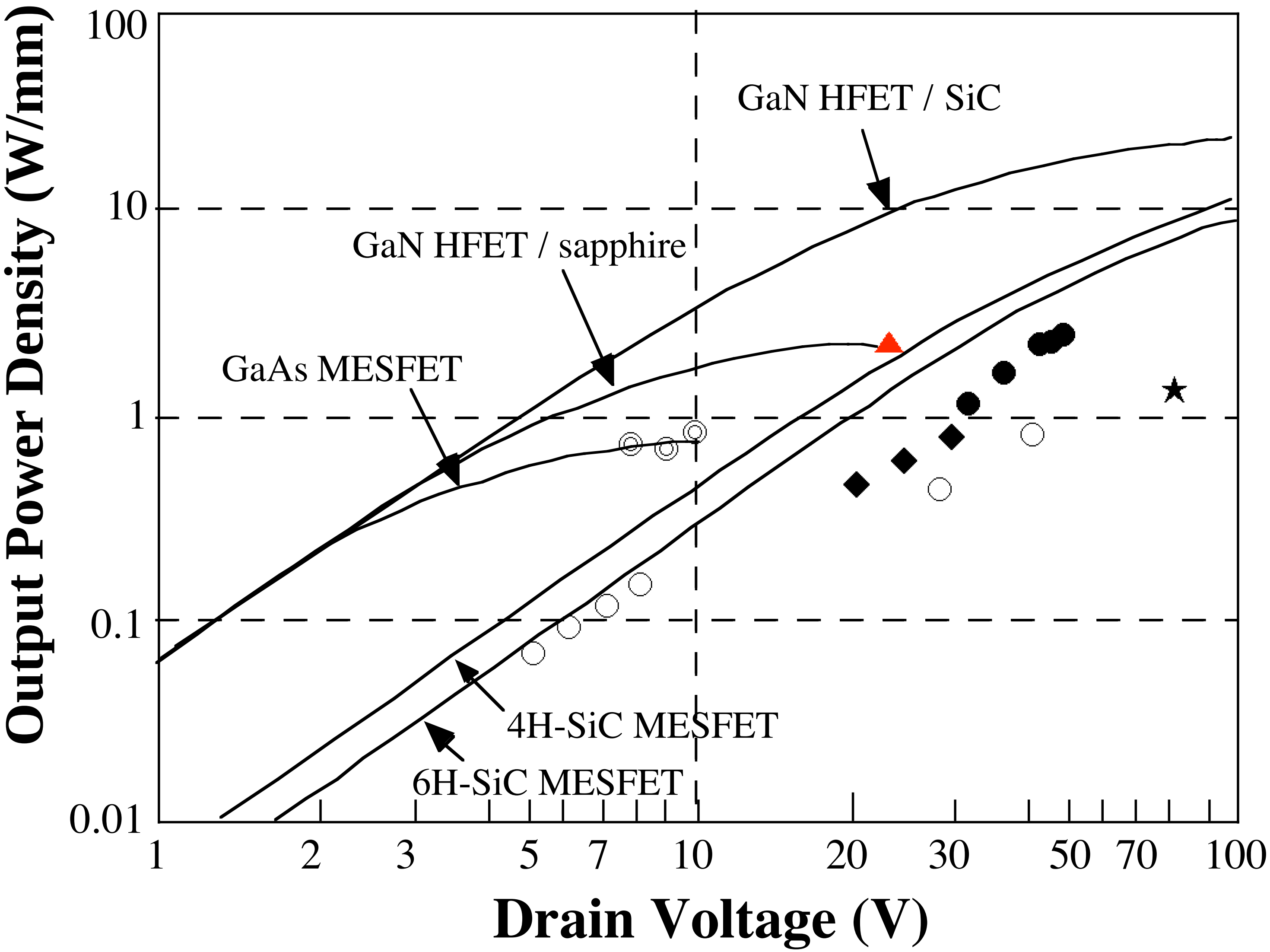
JFET
Junction field Effect Transistor

IGBT
Insulated Gate Bipolar Transistor



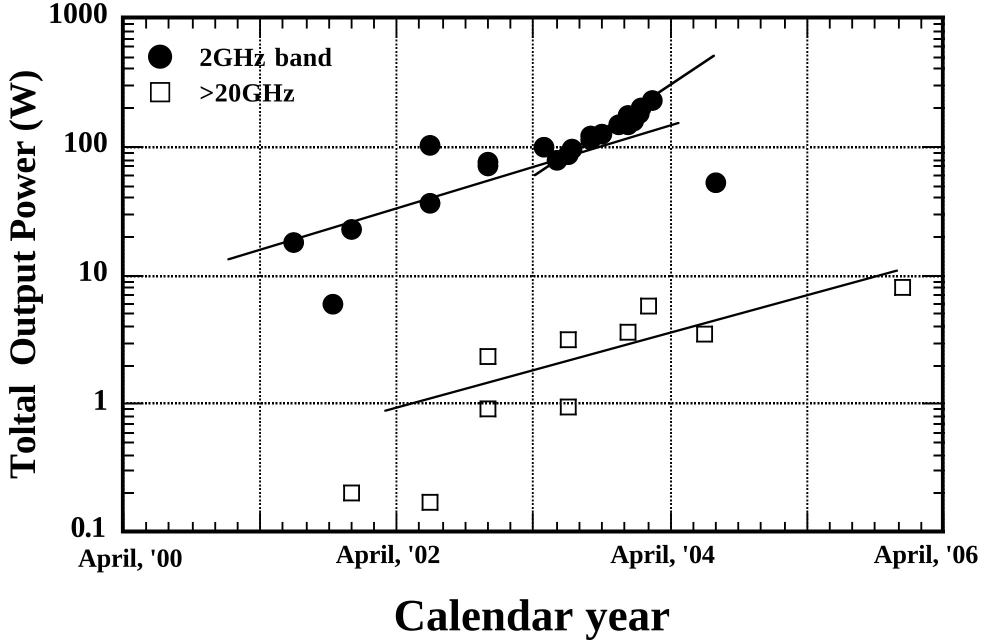
Operation limit of High-Frequency Devices



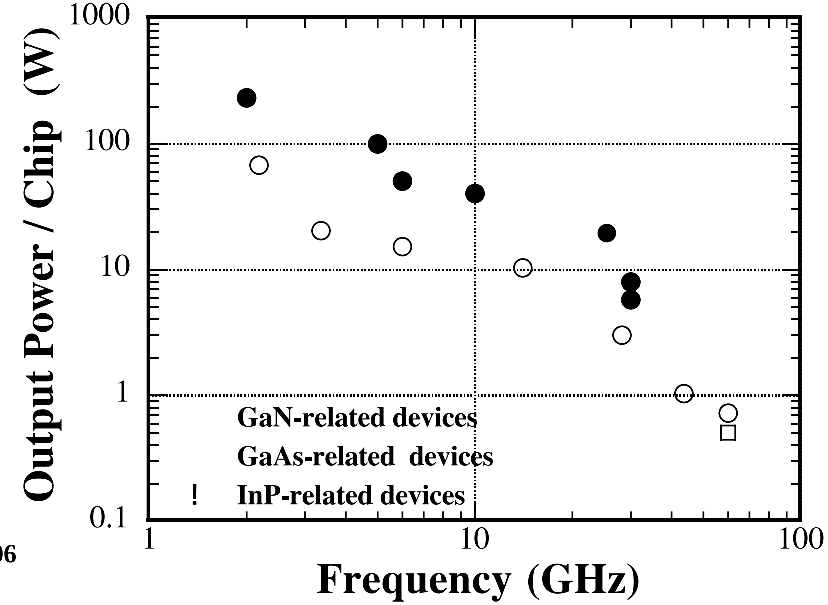

Output Power Density (W/mm)
100
10
1
0.1
0.01
GaN HFET / SiC
GaN HFET / sapphire
GaAs MESFET
4H-SiC MESFET
6H-SiC MESFET
1
2
3
5
7
10
20
30
50
70
100
Drain Voltage (V)

R&D Status of high-power HF devices

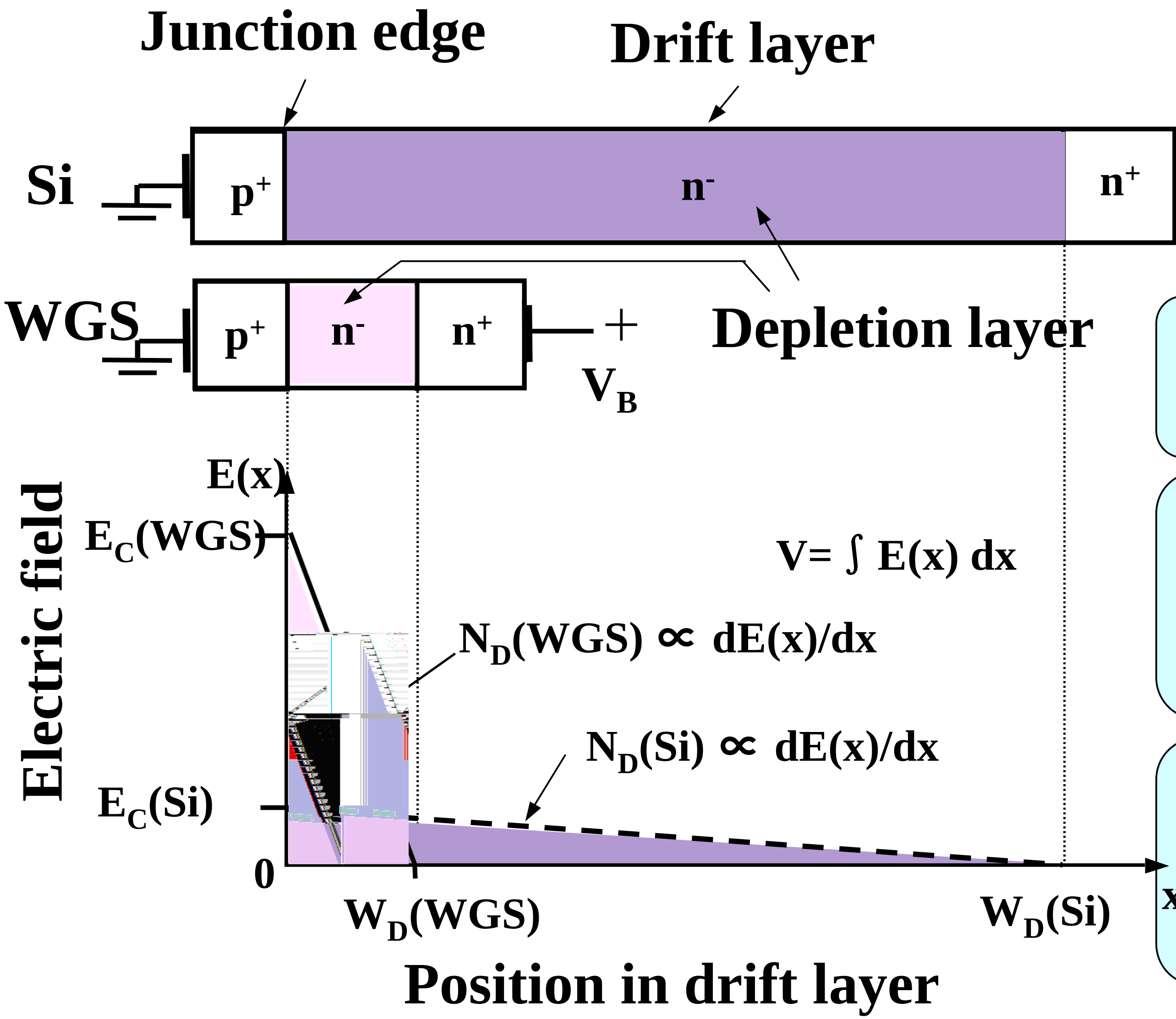
(a)



(b)



Comparison of Depletion Layer Expansion and Electric Field in a Switching Device



Blocking Voltage

$V_B = (E_C W_D) / 2$

On-Resistance

$R_{DS} = W_D / (q\,\mu_n N_D)$

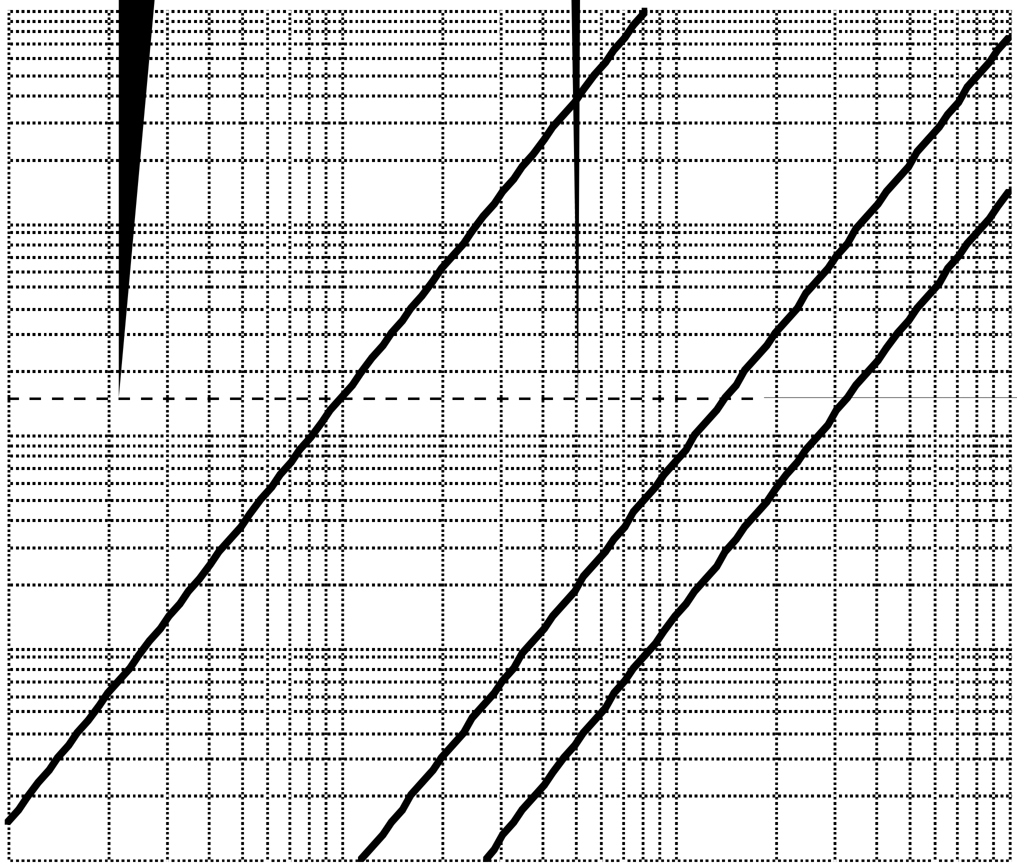
$= 4V_B^2 / (\epsilon\,\mu_n E_C^3)$

Carrier Density

$N_D = (\epsilon/q)\,(E_C/W_D)$

$= 2\,\epsilon\,E_C^2 / qV_B$

Performance Indices of Power Switching Devices



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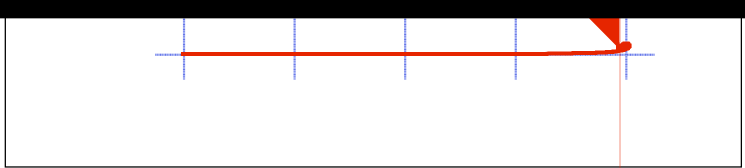
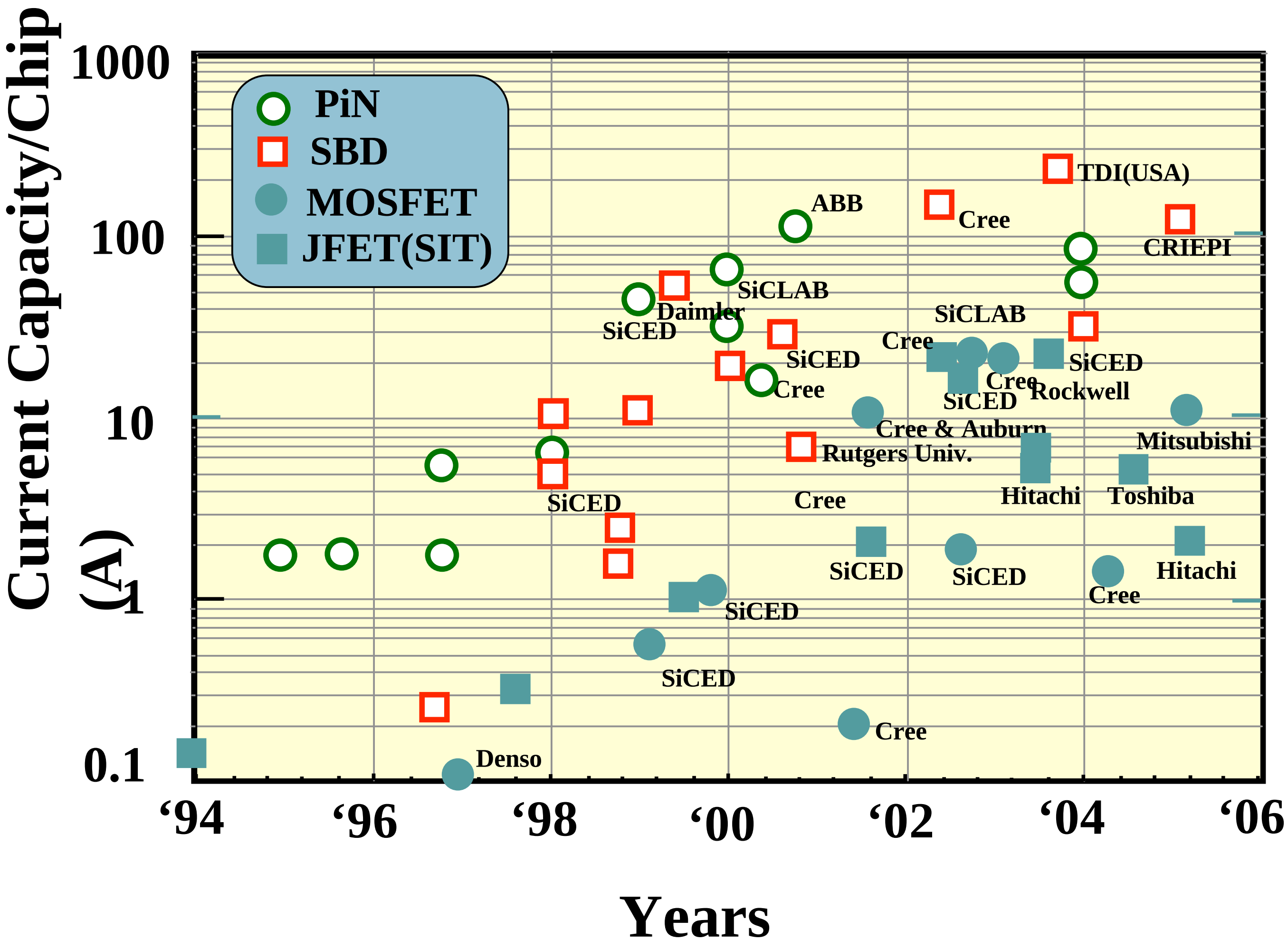


S. Yagi et al.: Solid-State Electron. **50** (2006) 1057.

R&D trend of Current Capacity on SiC Devices



Recent Results of Device/Inverter R&D (1)

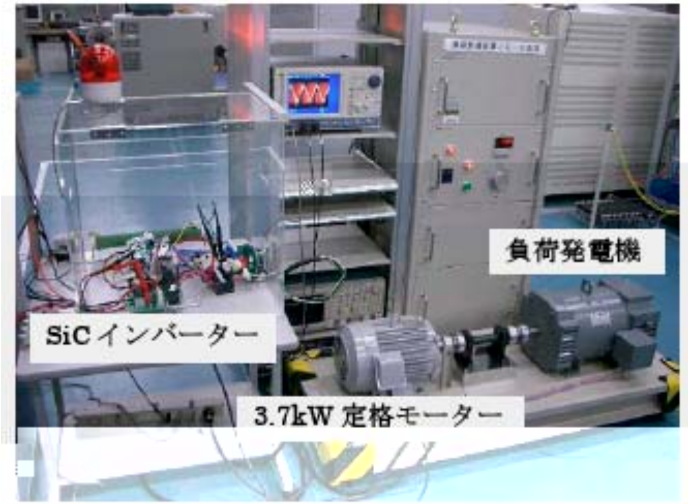
<u>Mitsubishi Electric</u> (2006.1.24)

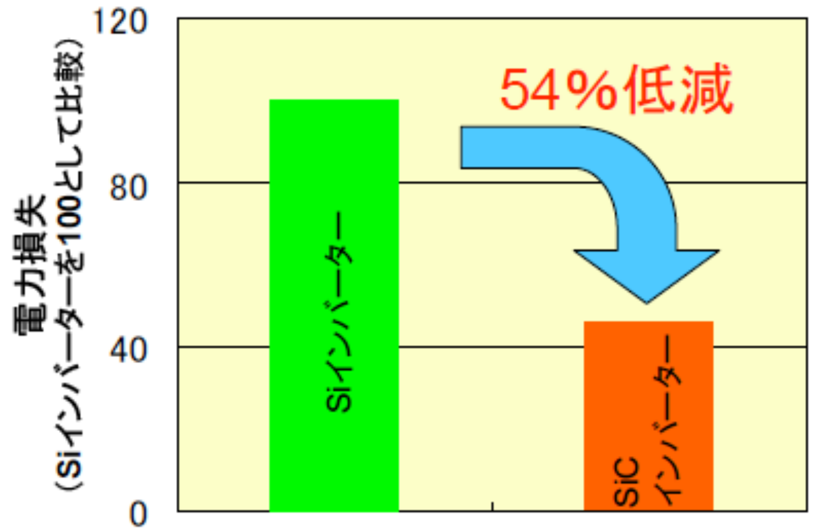
1. Module by 1200V, 10A MOSFETs (On-resistance :10mΩcm^2)
2. Inverter operation of a 3.7kW motor (SiC-MOSFET+SiC-SBD)
3. 54% reduction of a inveter loss (vs. Si-IGBT inverter)

表1. パワーモジュール化を行ったSiC-MOSFETとSiC-SBDの特性

半導体デバイス	耐圧	電流値	オン抵抗率※5	オン電圧※5
SiC-MOSFET	1200V	10A級	10mΩcm^2	—
SiC-SBD	1200V	10A級	—	1.2V

※5:オン抵抗率、オン電圧は電流密度 100A/cm^2における値





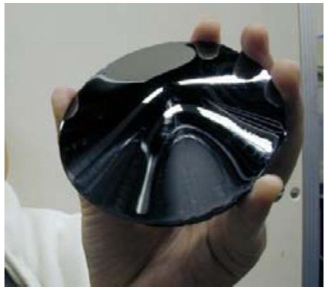
Recent Results of Device/Inverter R&D (2)

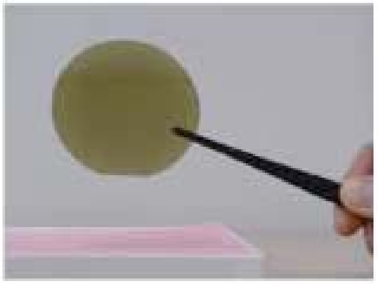
<u>Kansai Electric Power & Cree Inc.</u> (2006.1.25)

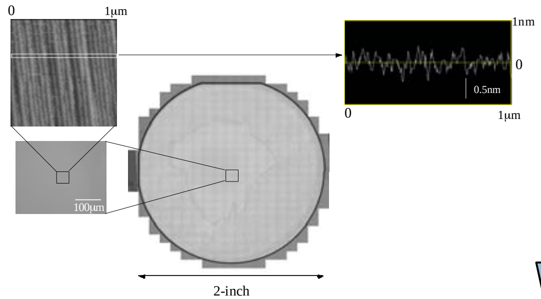
1. 4.5 kV, 100 A SiC Commutated Gate Turn-off Thyristor (SiCGT)
   $8x8mm^2$
2. 110kVA 3-phase inverter （SiC-MOSFET+SiC-PiN D）
   without snubber circuit, operation at 300˚C
3. Reduction of inverter loss by more than 50% (vs. Si-IGBT inverter)

From Crystal to Application System

SiC powder → Ingot (sublimation) → Bulk wafer (Slice, wrapping) → **Epitaxial wafer** (**Epitaxial growth**)





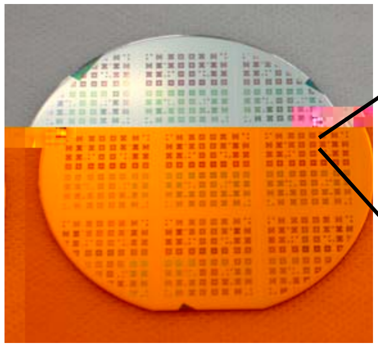


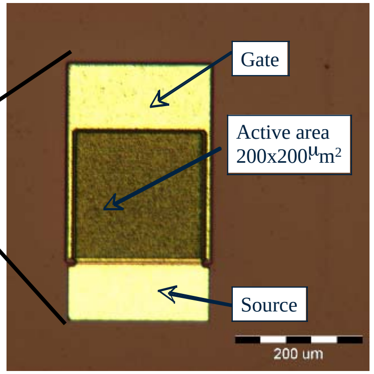
Ion Implantation
Dry etching
Metallization
RTA

Inverters ← Device modules (Circuit mounting) ← Device chips &MOSFET, SBD etc. ' (Dicing, Bonding, mounting)

! HP$%

" # ! HP$%





Problems in Widegap Semiconductor Device Technology

III-Nitrides | **SiC**

Defect Control

Device killer defects

- **Self-heating, Thermal mounting**
- **Channel mobility**
- **Gate Leakage (degradation of V_B, efficiency)**
- **Current Collapse (Insulator, surface/interface control)**
- **Normally-off operation**

Device structures

Module structures

- **Reliability (Oxide interface)**
- **Tolerance (Avalanche, Short-circuit capability)**
- **Wafer Quality**

- **Surface Morphology**
- **High Al content**
- **Purification of channel layer**
- **Highly resistive buffer layer**

Manufacturing Technology

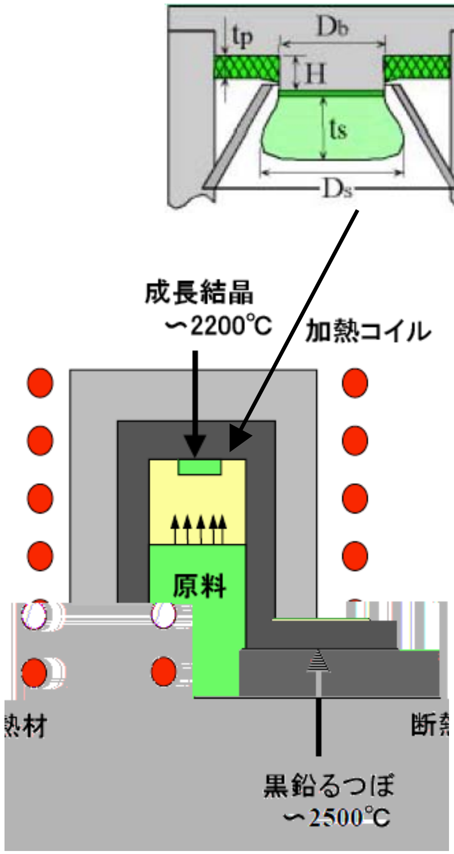
(Large size, multi-wafer)

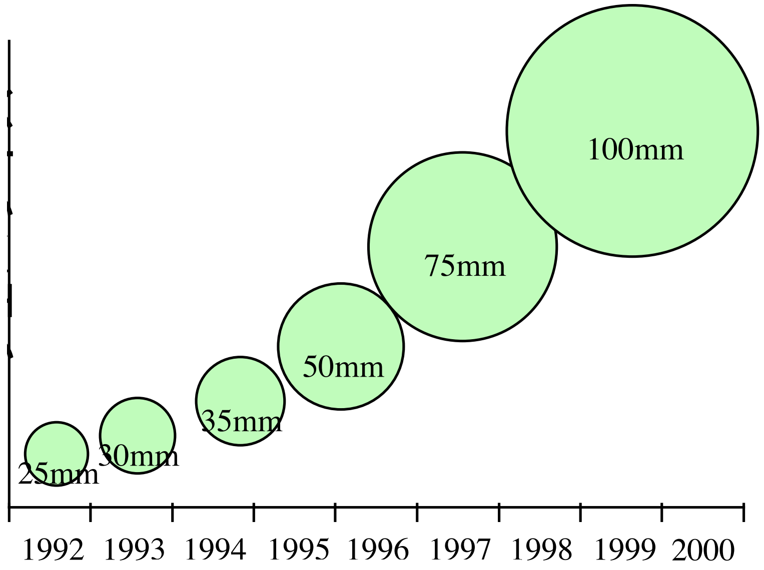
(Uniformity, reproducibility)

- **Reduction of off-angle**
- **Polarity control**
- **p-type control**
- **Uniformity in a wafer (thickness, doping, content)**
- **Dislocation, defects in epitaxial layers**
- **Bulk wafer**

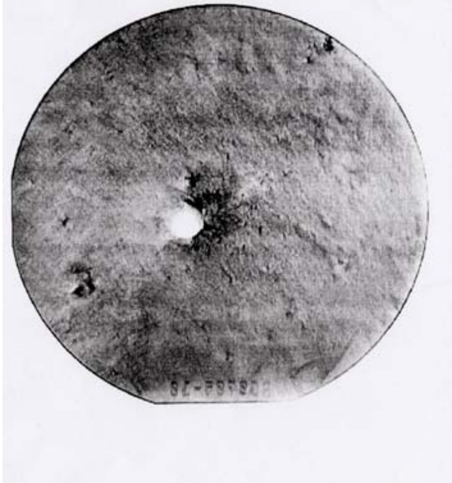
Enlargement of SiC Wafer Size and Defects

Sublimation Method

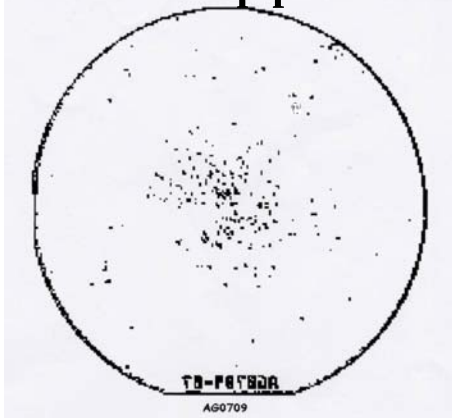




X-Ray Topography

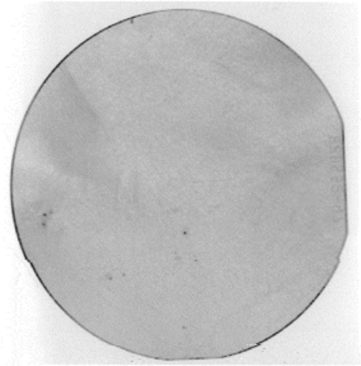


Micro-pipes

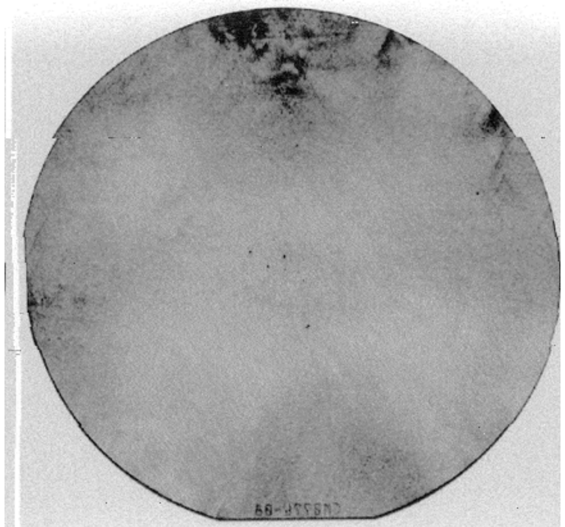


Comparison of SiC Single Crystal Wafer

C Corp. (2 inch)



MPD $< 15/cm^2$

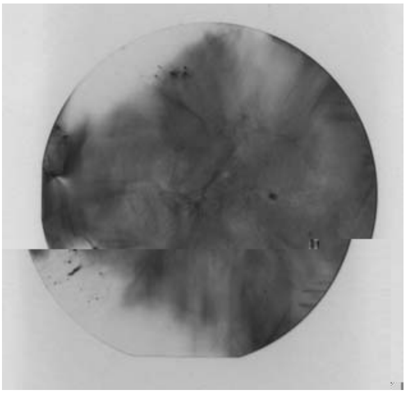


C Corp. (3 inch)

4 inch

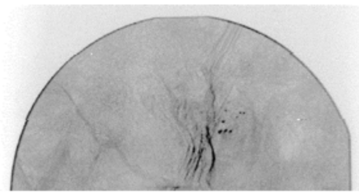
MPD $< 5/cm^2$

A Corp. (2 inch)



MPD $< 30/cm^2$

B Corp. (2 inch)

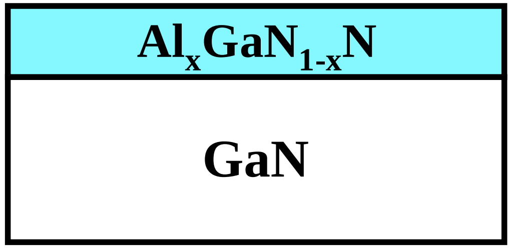


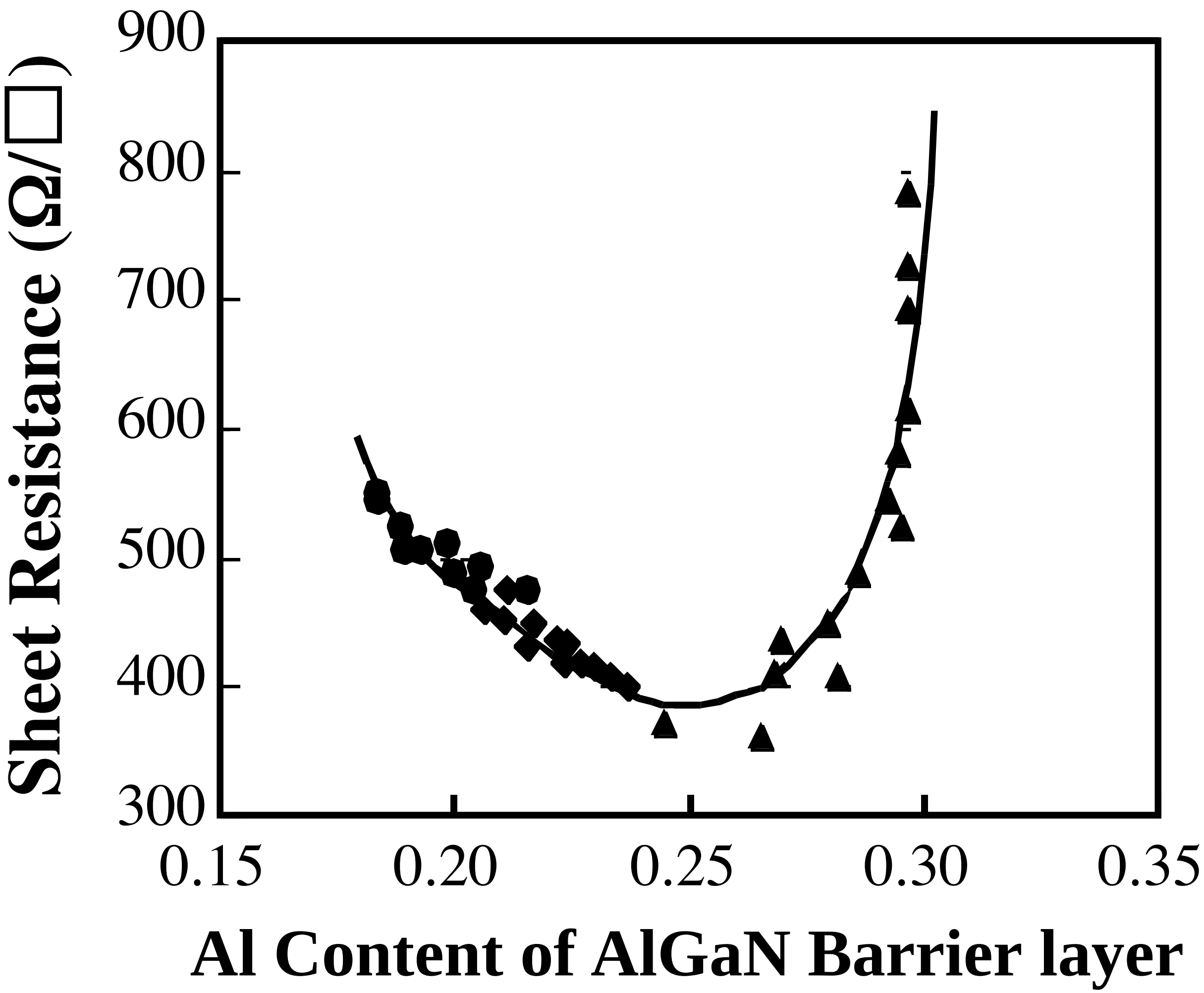
MPD $< 5/cm^2$

MP : Almost solved
Dislocation : Killer defects
determining device performance
Threading Dislocation (Screw, Edge)
Basal Plane Dislocation
Distortion of crystal planes
(Thermal distortion)

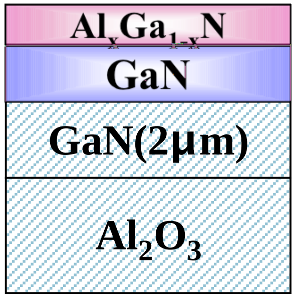
<u>EPD</u>

Al Content and Sheet Resistance of an AlGaN/GaN Heterostructure Wafer

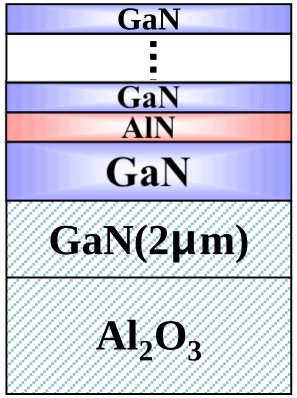




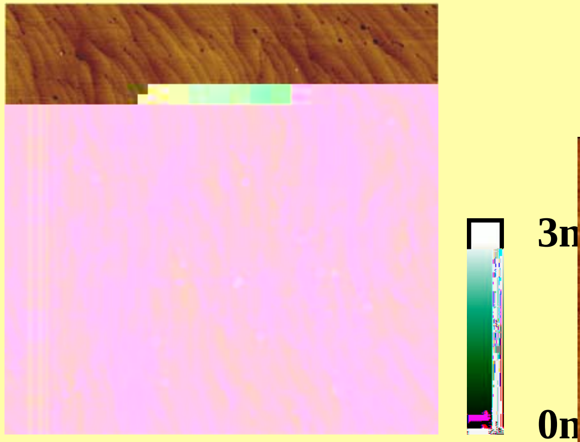
Surface morphology of high Al-content AlGaN epitaxial layer



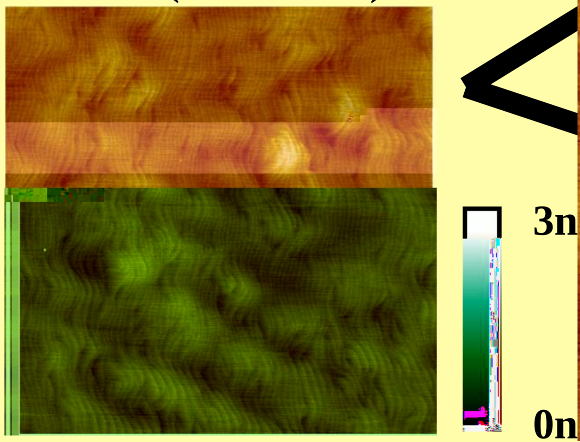
1. AlGaN/GaN
(0.2<x<0.6)



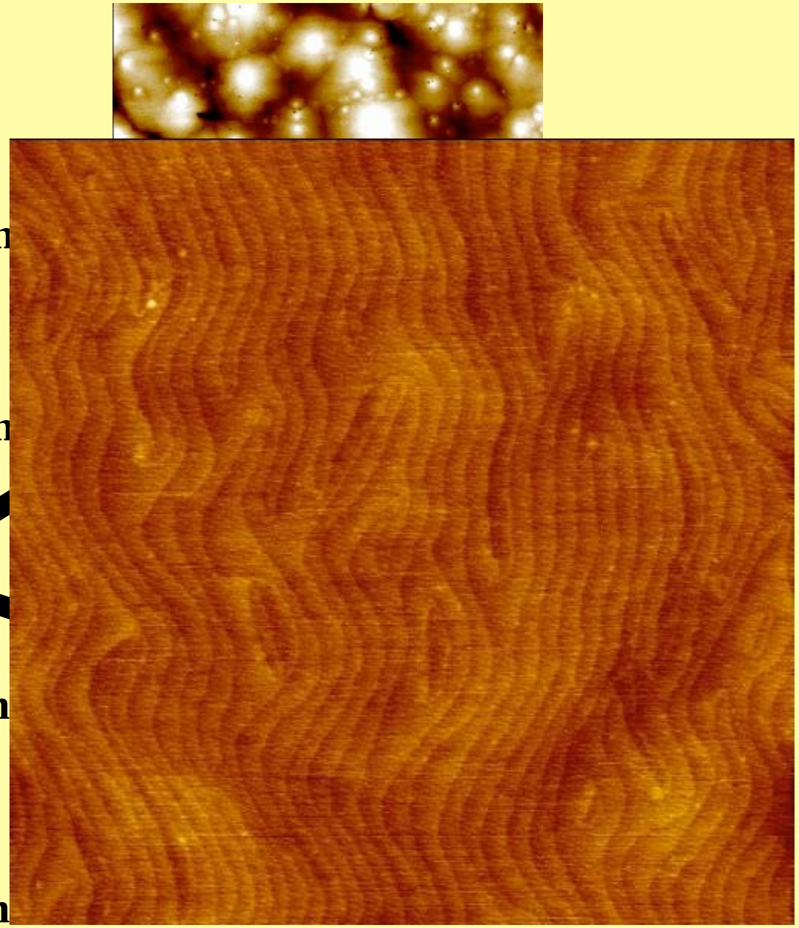
2. $(AlN/GaN)_n/GaN$



sub (RMS 0.2nm)

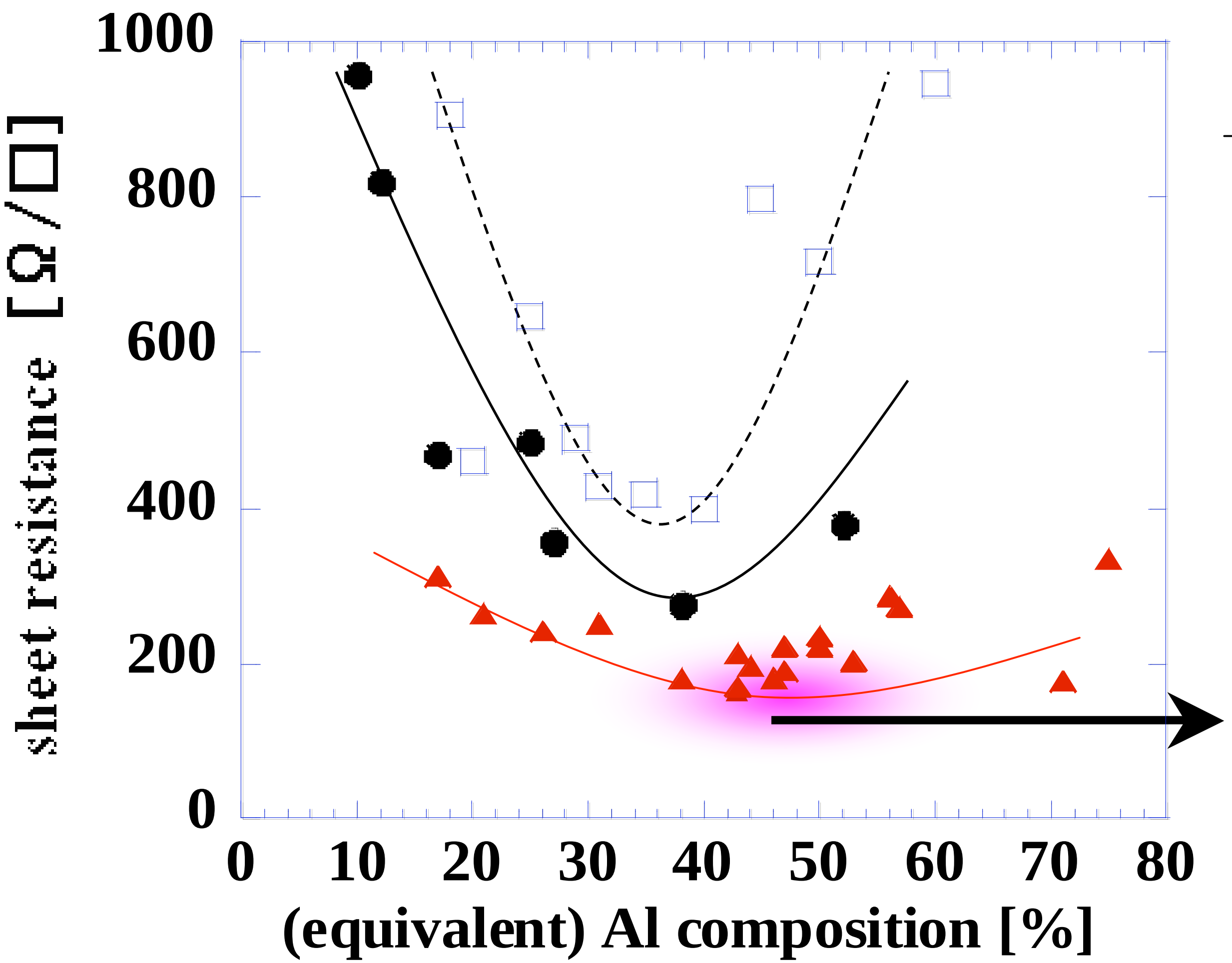


GaN epi-layer(RMS 0.3nm)



quasi-$Al_{0.5}Ga_{0.5}N$(RMS 0.2nm)

Al-content(equivalent) dependnce of Sheet resistance



Realization of
Lowest value
170Ω/□

Normally-off operation of GaN switching devices

Existing Gate drive circuit、
incompatibility of control power supply, gate signal
Care for Power supply circuit (Safety)

Confirmation of necessity ?

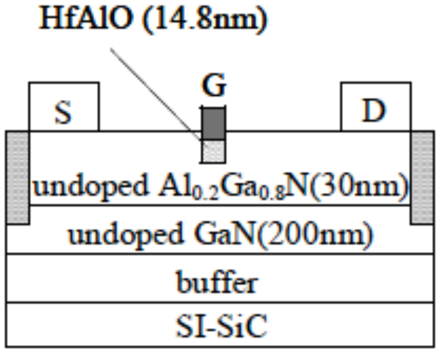
Trials by various approach

- Recess gate structure
- Introduction of fixed charge
- MOS structure
- Utilization of non-polar surface
- pn-junction gate
- GaN Cap layer
- Asymmetry AlGaN/GaN/AlGaN channel

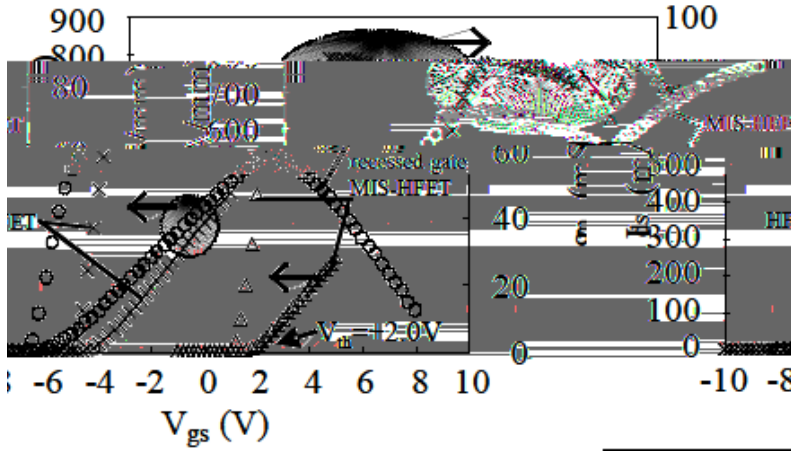
Examples of Normally-off operation

・recess gate with high-k insulator

H. Sazawa et al., IWN2006, Kyoto, Japan (2006.10)

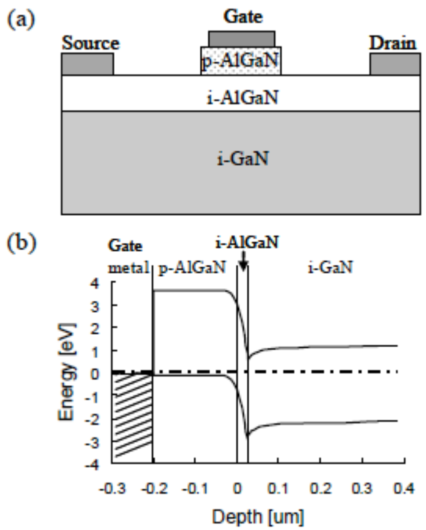


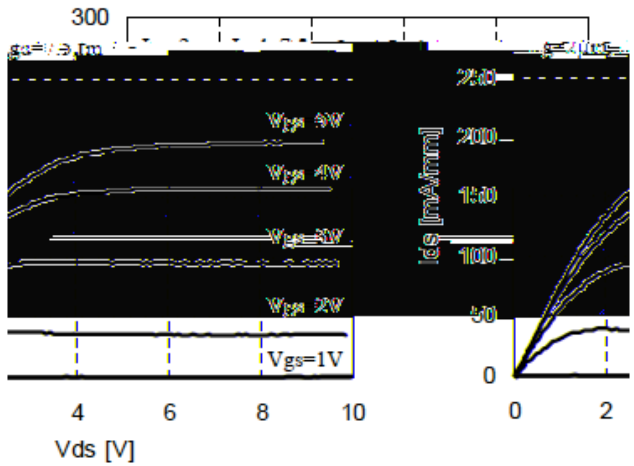
(c)



・pn-junction gate

Y. Uemoto et al., IEDM2006, San Francisco, USA (2006.12)





$R_{on} \cdot A$ = 2.6mΩcm², I_{dmax} = 200mA/mm

Important Technical Issue
for the Realization of WGS Inverters

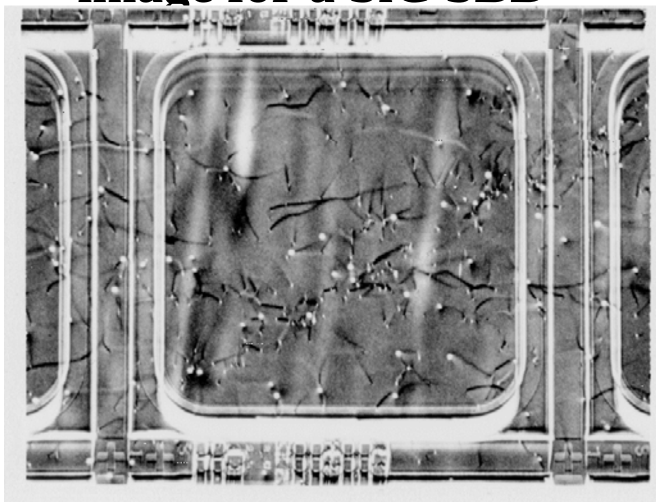
There remain many unknown factors in WGS Physics

- micropipe
- dislocation（SD, ED, BPD etc.）
- Grain boundary, oxide interface

- Channel mobility
- Blocking voltage, current leakage
- Reliability

(correlation between wafer characteristics and device performance)

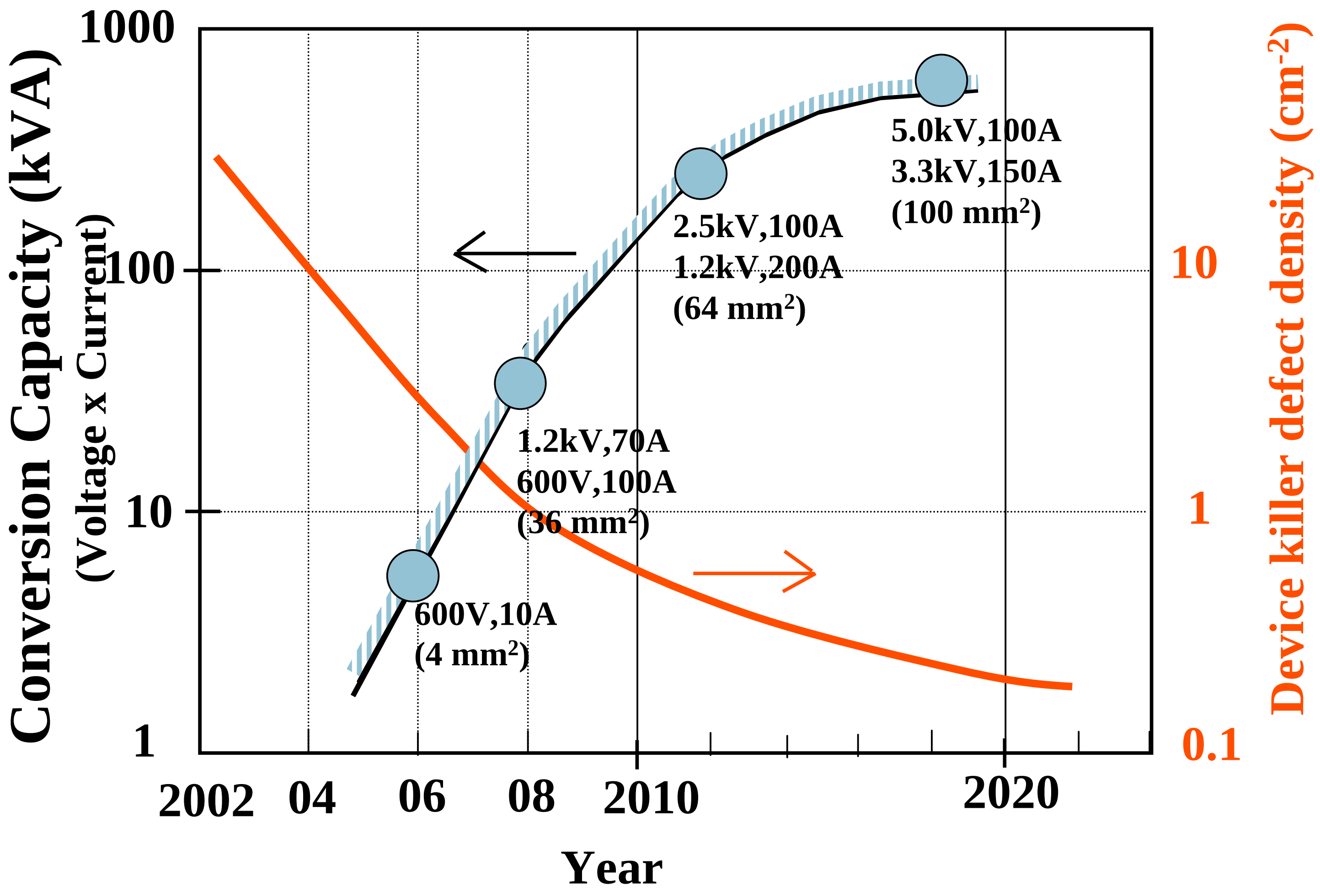
Reflection X-ray topograph image for a SiC SBD



threading screw：39 (3900 cm^{-2}),
threading edge：126 (12600 cm^{-2}),
basal plane：20 (200 cm^{-2})

Characterization Techniques/Tools

Required specification for voltage and current, relation with the density of device killer defects



Summary

- **High-power electron devices are key components** for wireless communication and power electronics, which are necessary for the sustainable development in the 21th century.
- **WGS are promising** for high-power application, due to their superior material characteristics.
- Owing to the recent R&D, high-power electron device **performance by WGS has been well demonstrated**, which much surpass those of conventional devices
- There **still remain technical issues to be solved**, for actual system application.