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

Establishment of New AIST
(Re-organization of Japanese National Institutes)

o **MITI**
(Ministry of International Trade and Industry)

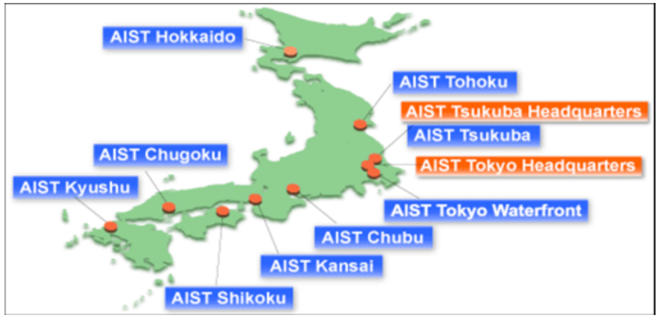
- AIST
  (Agency of Industrial Science and Technology)
  - …
  - …
  - **Electrotechnical laboratory(ETL)**
  - …
  - …

(15 Institutes)

o **METI**
(Ministry of Economy, Trade and Industry)

- **AIST** (3200 permanent staffs)
  (National institute of Advanced Industrial Science and Technology)
  - …
  - **Power Electronics Research Center (PERC)**
    Widegap Semiconductor Electronics
  - …

(56 Research Units)

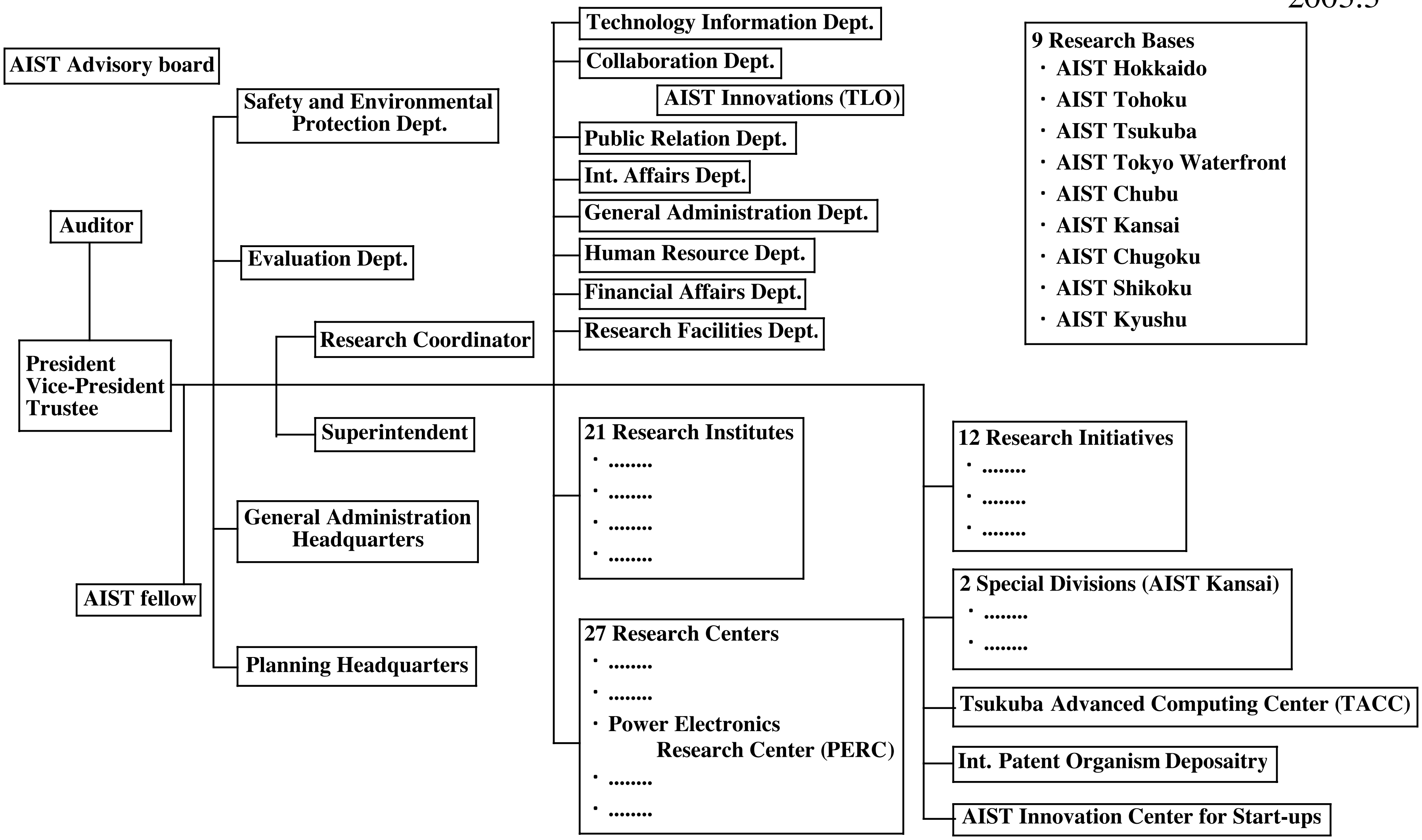


9 research bases and 2 headquarters

http://www.aist.go.jp

Organization of new AIST

2003.3



AIST Advisory board

Auditor

President
Vice-President
Trustee

AIST fellow

Safety and Environmental Protection Dept.

Evaluation Dept.

Research Coordinator

Superintendent

General Administration Headquarters

Planning Headquarters

Technology Information Dept.

Collaboration Dept.

AIST Innovations (TLO)

Public Relation Dept.

Int. Affairs Dept.

General Administration Dept.

Human Resource Dept.

Financial Affairs Dept.

Research Facilities Dept.

21 Research Institutes
- ....
- ....
- ....
- ....

27 Research Centers
- ....
- ....
- Power Electronics Research Center (PERC)
- ....
- ....

9 Research Bases
- AIST Hokkaido
- AIST Tohoku
- AIST Tsukuba
- AIST Tokyo Waterfront
- AIST Chubu
- AIST Kansai
- AIST Chugoku
- AIST Shikoku
- AIST Kyushu

12 Research Initiatives
- ....
- ....
- ....

2 Special Divisions (AIST Kansai)
- ....
- ....

Tsukuba Advanced Computing Center (TACC)

Int. Patent Organism Deposaitry

AIST Innovation Center for Start-ups

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

Research Scheme and Fund

- **Subsidy from METI,**
- **Entrustment from METI,**
- **Entrustment from other ministries,**
- **Subsidy or entrustment from public research funding organizations such as NEDO, JST**
- **Entrustment from or collaboration with private companies**

Trend of recent governmental fund

- **Industrialization,**
- **Collaboration of Univ., National Inst. and Private Sector**

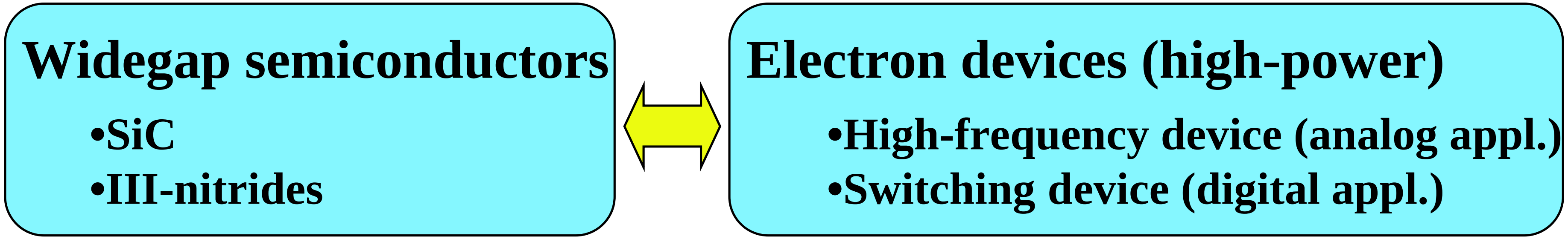
Mission of PERC

- 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**

Teams of PERC

1. Wafer & Characterization Team	SiC bulk & epitaxial growth, wafer characterization
2. SiC Power Device Team	SiC device technology
3. GaN Power Device Team	III-Nitride device technology
4. Power-Unit Super-Design Team	Design & simulation of power devices and modules
5. Super-Node Network Team	Networking technology using low-loss power devices
6. Advanced power electronics promotion team	Industrialization of power device technology

Contents



Widegap semiconductors

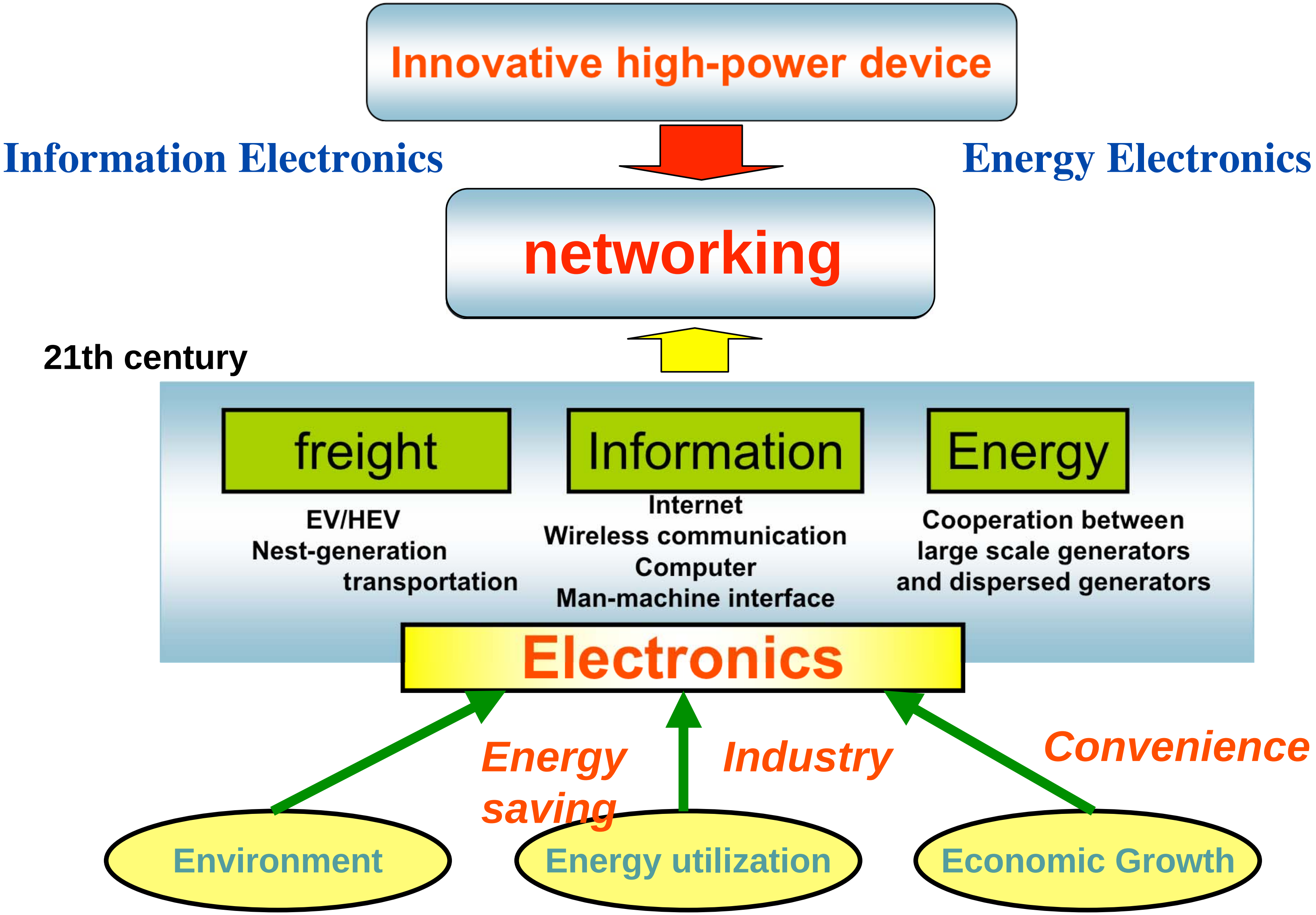
- SiC
- III-nitrides

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 ?）**

Infrastructure of the 21th century



Innovative high-power device

Information Electronics

Energy Electronics

networking

21th century

freight

EV/HEV
Nest-generation
transportation

Information

Internet
Wireless communication
Computer
Man-machine interface

Energy

Cooperation between
large scale generators
and dispersed generators

Electronics

Energy saving

Industry

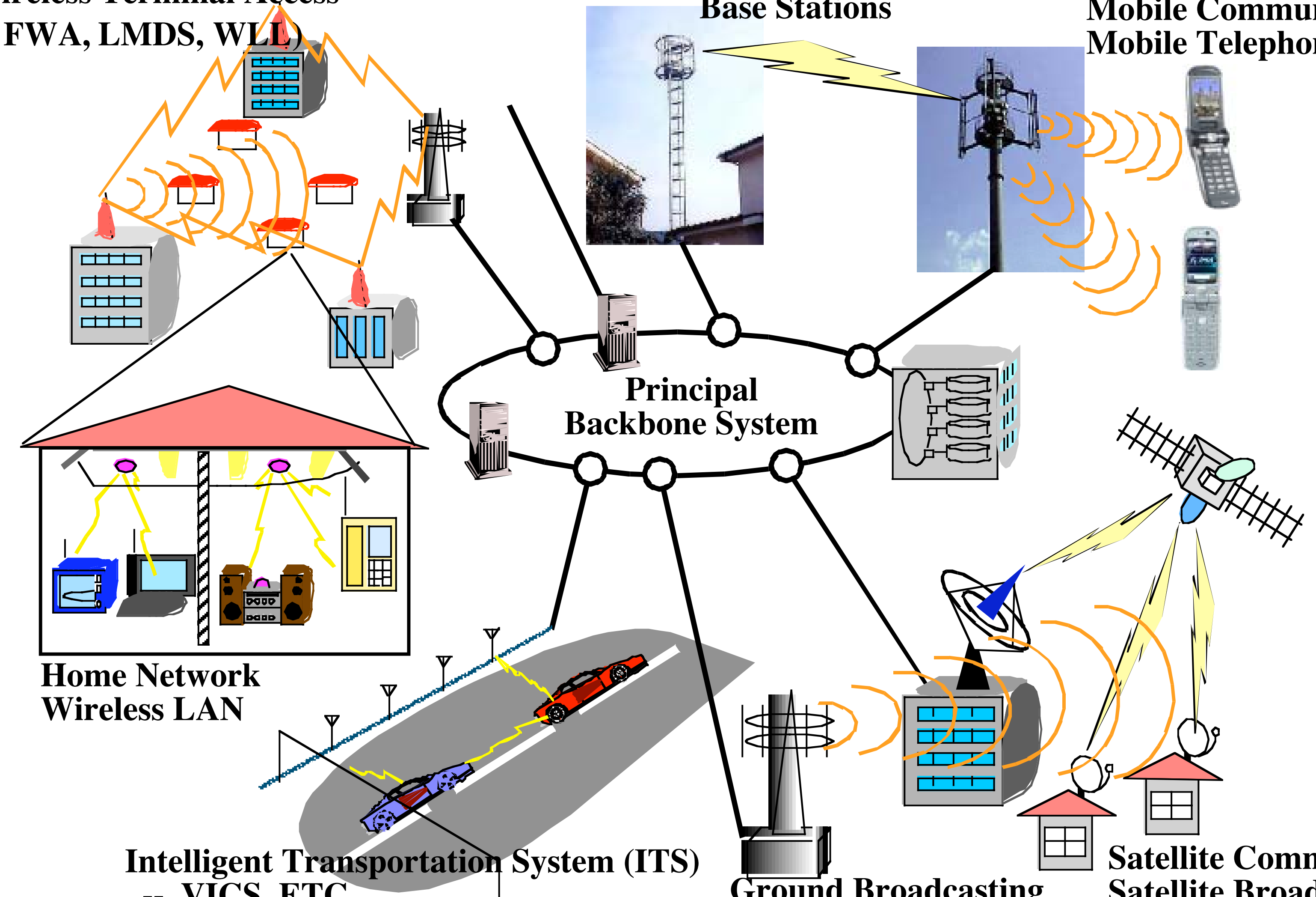
Convenience

Environment

Energy utilization

Economic Growth

Various applications of wireless communication



Fixed Wireless Communication
Wireless Terminal Access
（FWA, LMDS, WLL）

Communication between
Base Stations

Mobile Communication
Mobile Telephone System

Principal
Backbone System

Home Network
Wireless LAN

Intelligent Transportation System (ITS)
-- VICS, ETC

Ground Broadcasting

Satellite Communication
Satellite Broadcasting

Trend of Power FET Specification for Mobile Telephone Base Station

■ **<u>1st gen.</u>** (Analog cellular)

- **Saturated** region is enough

■ **<u>2nd gen.</u>** (Digital cellular)

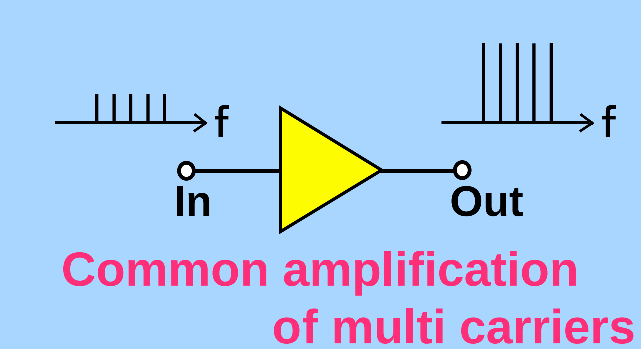
- **Quasi-Linear** region
- multi-carrier common amp.

→ **～200W/sector**

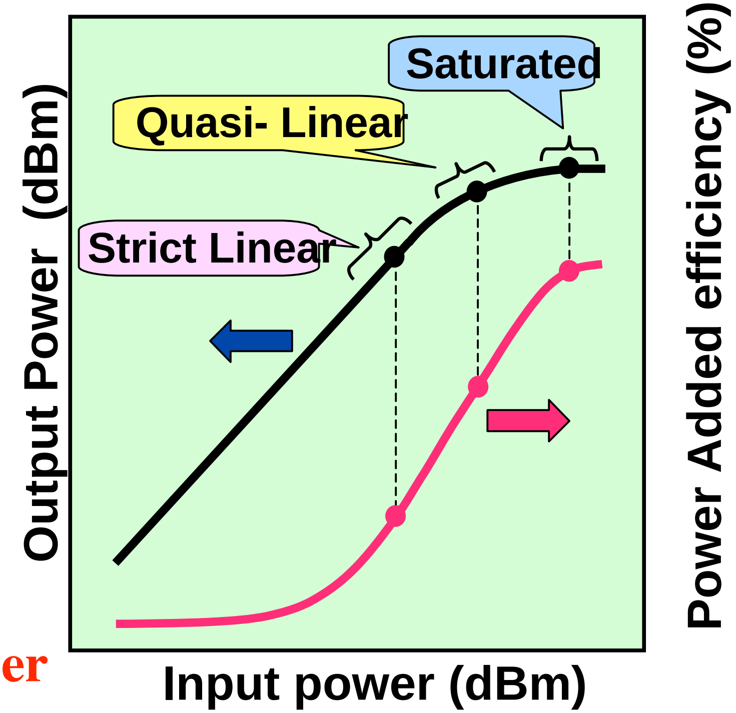
■ **<u>3rd gen.</u>** (Total Digital Service)

- **Strict Linear** region
- **W-CDMA（IMT-2000）**

→ **500W～1kW/sector**



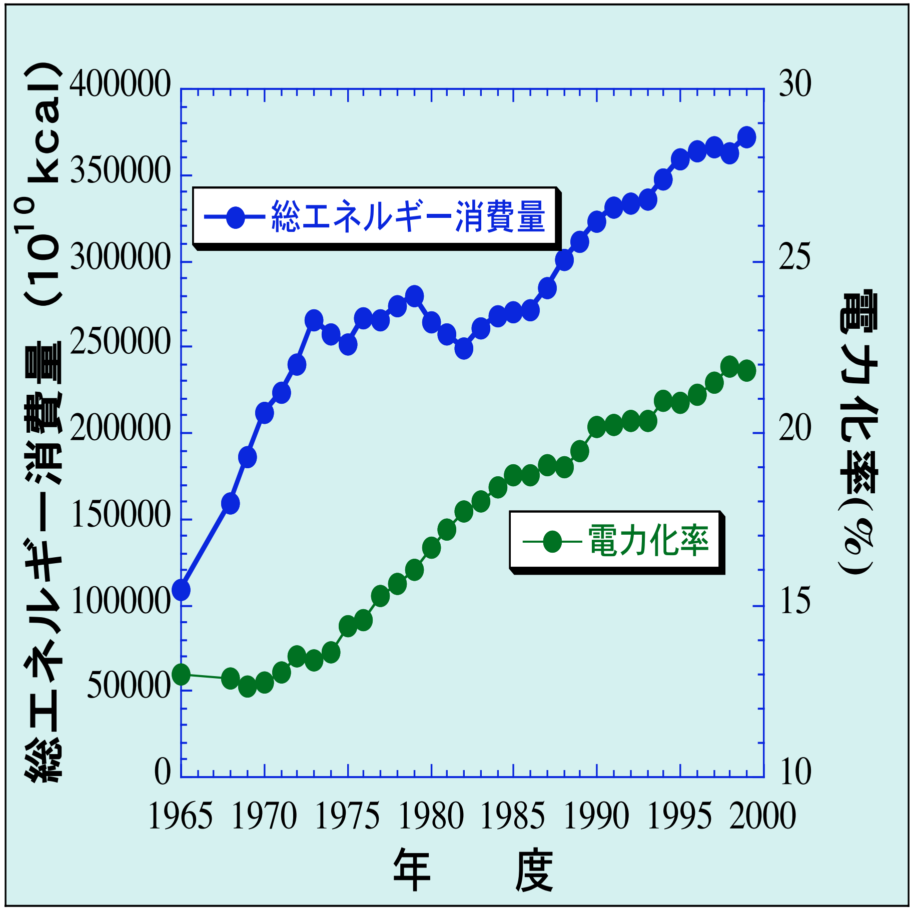
Common amplification of multi carriers



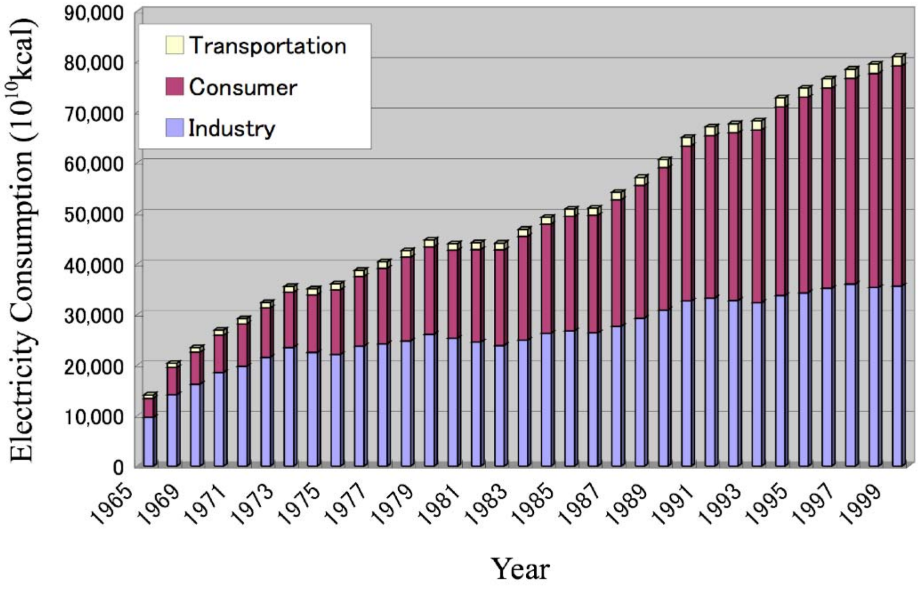
Keeping Transmission distance
Enlarging band width (Channel number)
Keeping Linearity

Higher Power

Energy Consumption and Electricity Ratio



Electricity Consumption in various field

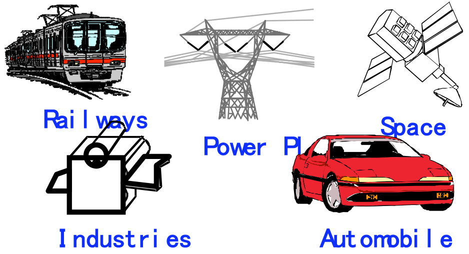


[出所]『総合エネルギ統計」
[出典]資源エネルギー庁(編):エネルギー2002、(株)エネルギーフォーラム
(2001年12月10日)p.261

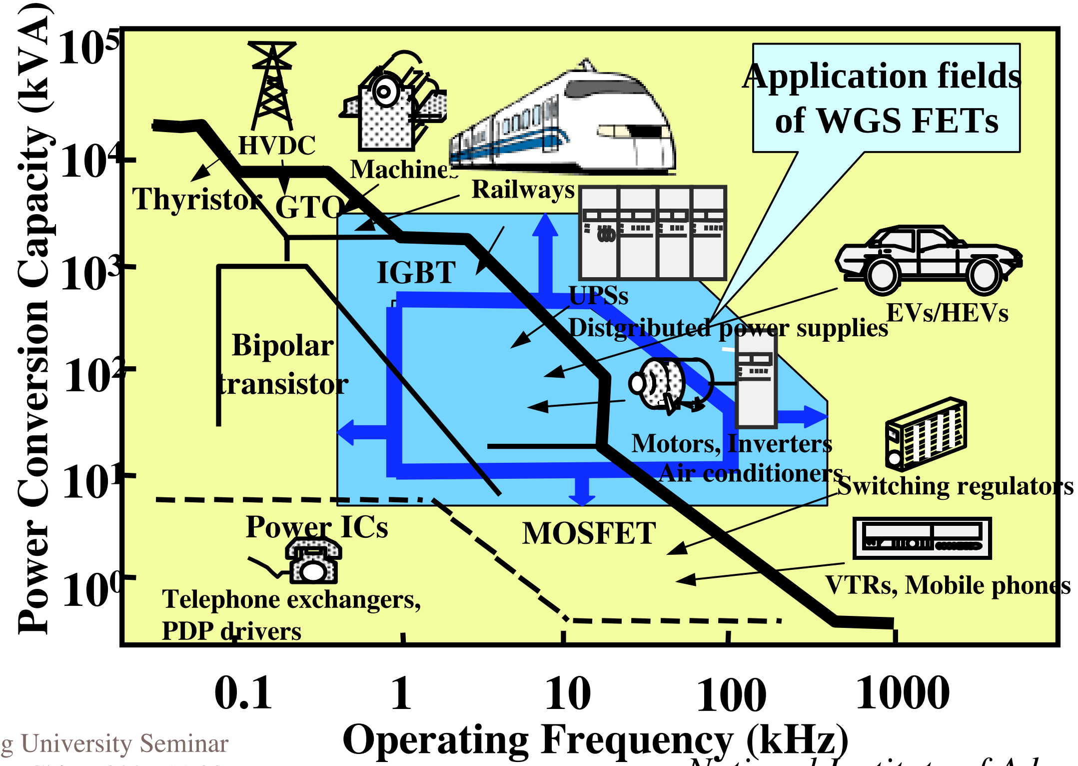
Application Field of Power Electronics

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**



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Power Conversion
(AD/DA conversion

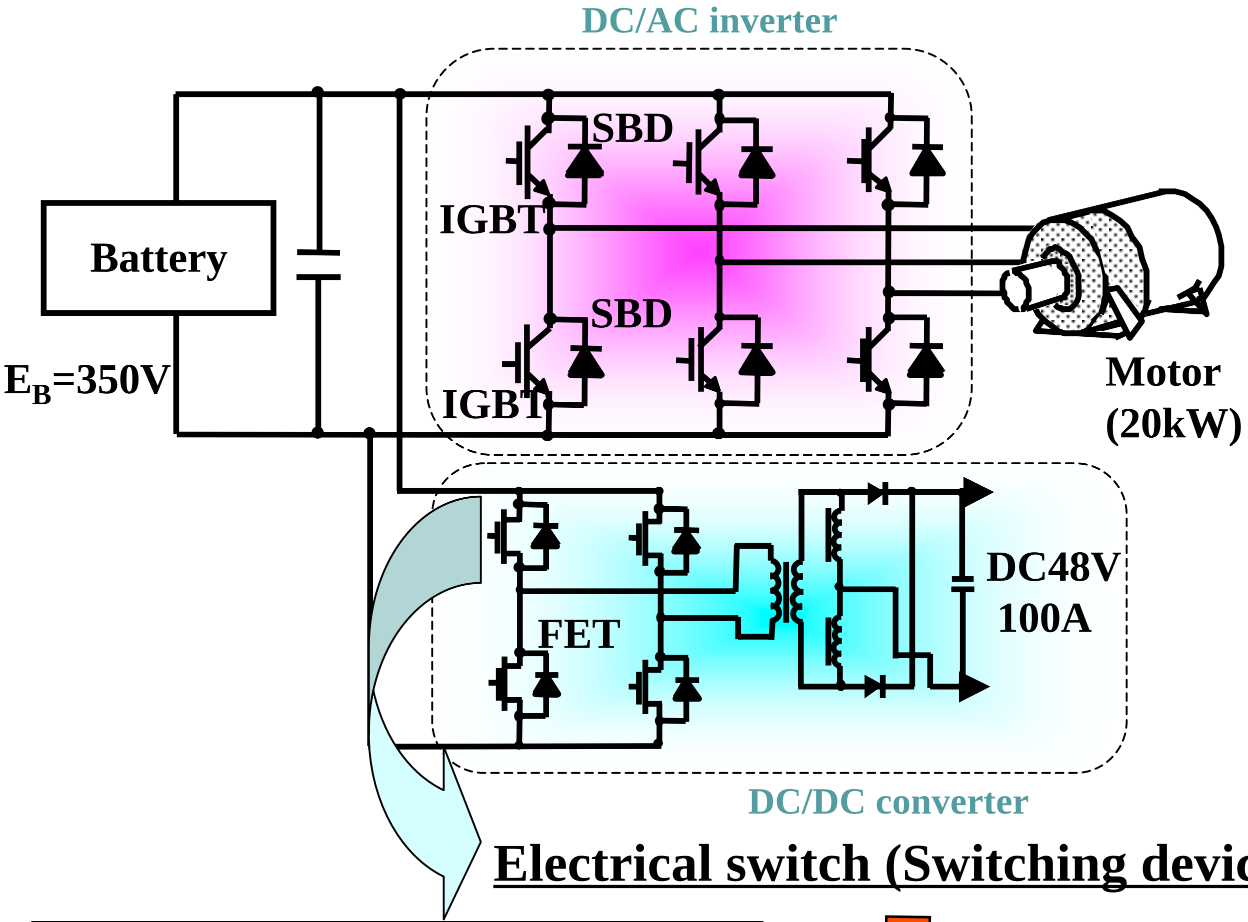
↓

Inverter circuit

↓

Power Device
(Transistor)

Example of Power device usage in Electric Power Converter



<u>Electrical switch (Switching device)</u>

Device chips with small size and low resistance

Device modules with small size and higher operation frequency

Simple and small peripherals

Innovation of
Power Electronics

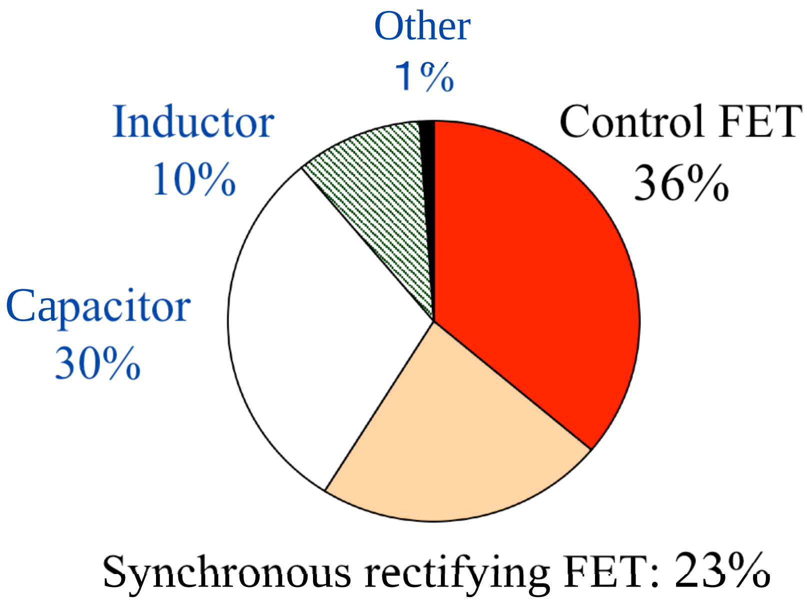
Key of Energy saving technology in Electric Power

What is an ideal switch ?

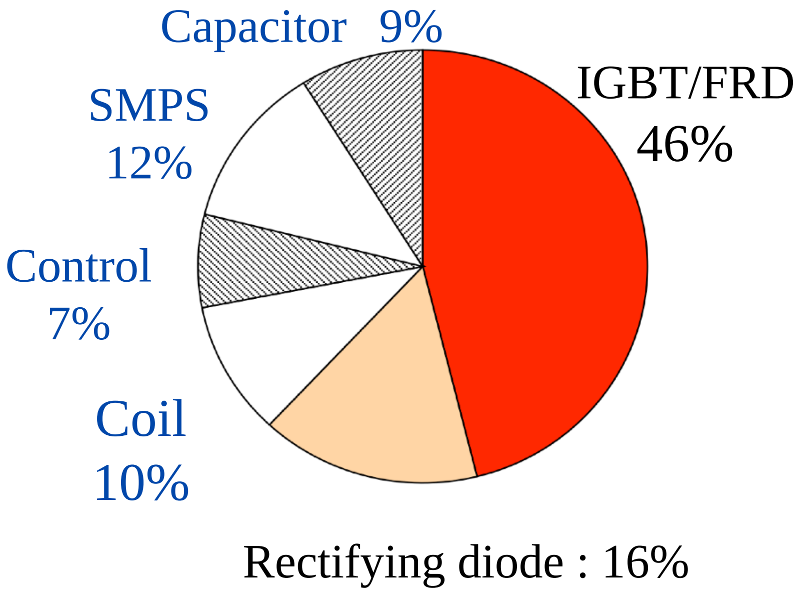
on-state：zero resistance
off-state：resistance infinity

Blocking voltage and conduction loss (on resistance) show a trade-off relation

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

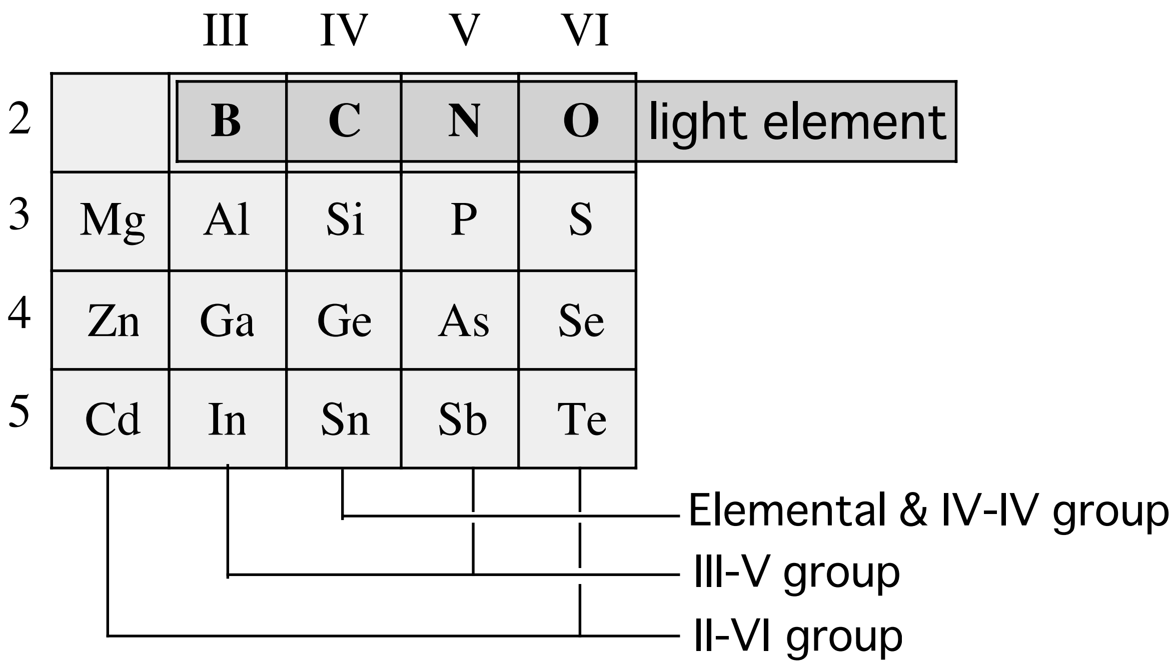
High-frequency devices for wireless communication

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 ?



		III	IV	V	VI
2		B	C	N	O
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

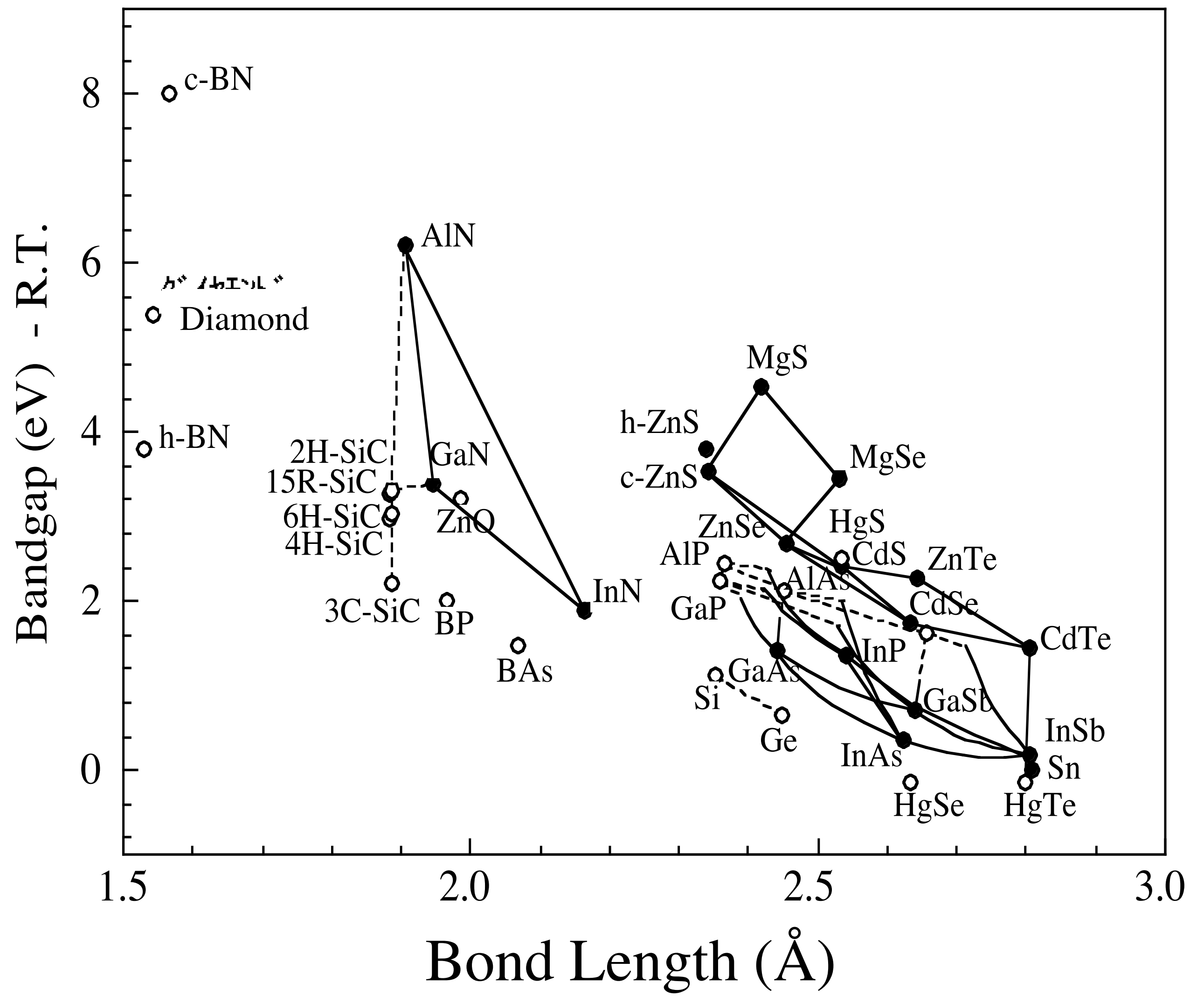
II-VI group
Insulator to Superconductors

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



Beijing University Seminar
Beijing, China, 2007.11.22

Physical Properties of Semiconductors

Material	E_g eV	ε	μ_ν cm^2/Vs	E_c $10^6 V/cm$	ν_{sat} $10^7 cm/s$	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

Figures of Merits of Several Semiconductors and their Hetrostuructures

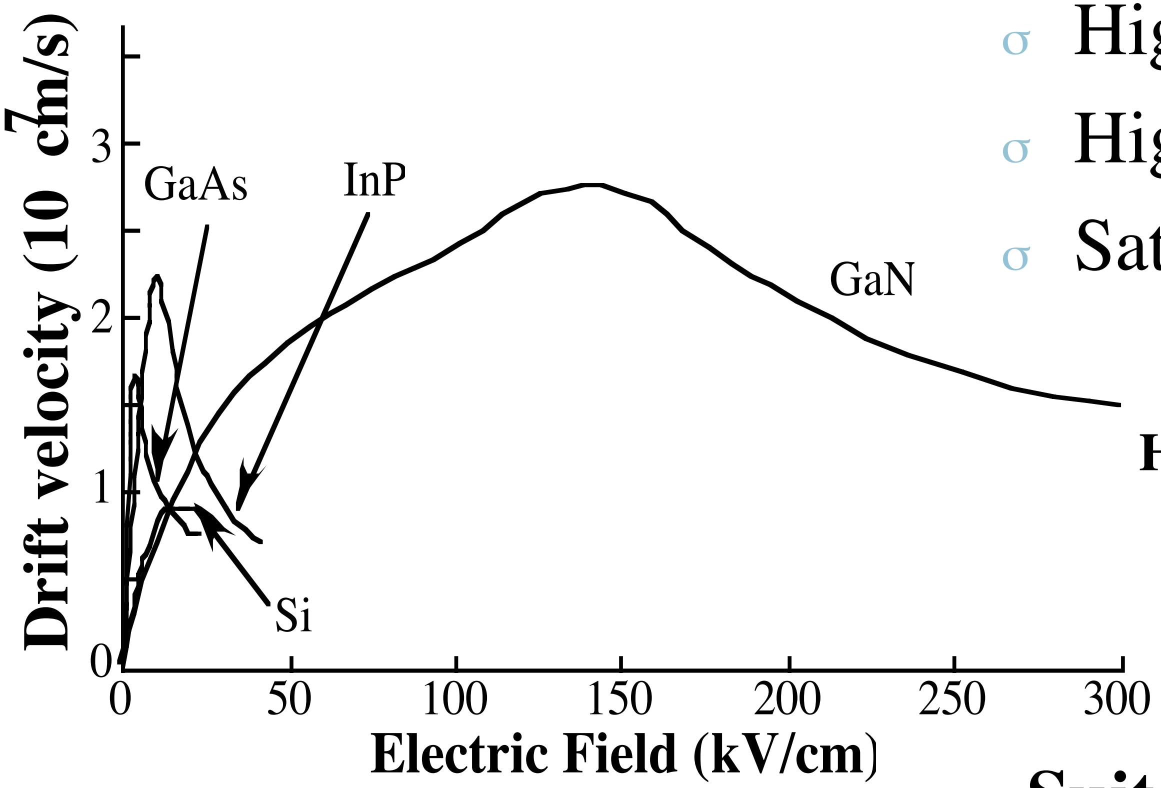
Material	Johnson's FM $(E_c v_{sat}/\pi)^2$	Keyes's FM $\kappa (v_{sat}/\varepsilon)^{1/2}$	Shenai's FM(Q_{F1}) $\kappa\sigma_A$	Shenai's FM(Q_{F2}) $\kappa\sigma_A E_c$	Baliga's FM $\varepsilon\mu E_c{}^3$	Baliga's HFM $\mu E_c{}^2$
Si	1	1	1	1	1	1
GaAs	7.1	0.45	5.2	6.9	15.6	10.8
c-GaN	685	1.5	20	67	23	8.2
h-GaN	760	1.6	560	6220	650	77.8
3C-SiC	65	1.6	100	400	33.4	10.3
6H-SiC	260	4.68	330	2670	110	16.9
4H-SiC	180	4.61	390	2580	130	22.9
AlN	5120	21	52890	2059000	31700	1100
Diamond	2540	32.1	54860	1024000	4110	470

σA=Shenai's FM(QF3)=_εμEc3 T.P. Cho, Materials Science Forum, Vols. 338-342 (2000) 1155.

	SH-HEMT on GaAs	DH-HEMT on GaAs	P-HEMT on InP	GaN-HEMT on sapphire
μ (cm^2/Vs)	5000 ～ 6500	5000 ～ 6500	9500 ～ 12000	800 ～ 1700
n_s ($10^{12}/cm^3$)	1.5 ～ 2.5	2.0 ～ 3.0	3.0 ～ 4.0	15 ～ 20
$n_s \mu$ (10^{15}/Vs)	7 ～ 16	10 ～ 20	30 ～ 50	12 ～ 34
R_{ch} (Ω/sq)	400 ～ 600	300 ～ 500	150 ～ 250	200 ～ 520

By H. Kawai

Saturation Drift Velocity & Breakdown Voltage vs. Electric Field



Characteristics of GaN

- High Breakdown Voltage
- High Drift Velocity
- Saturation at High Field

⇓

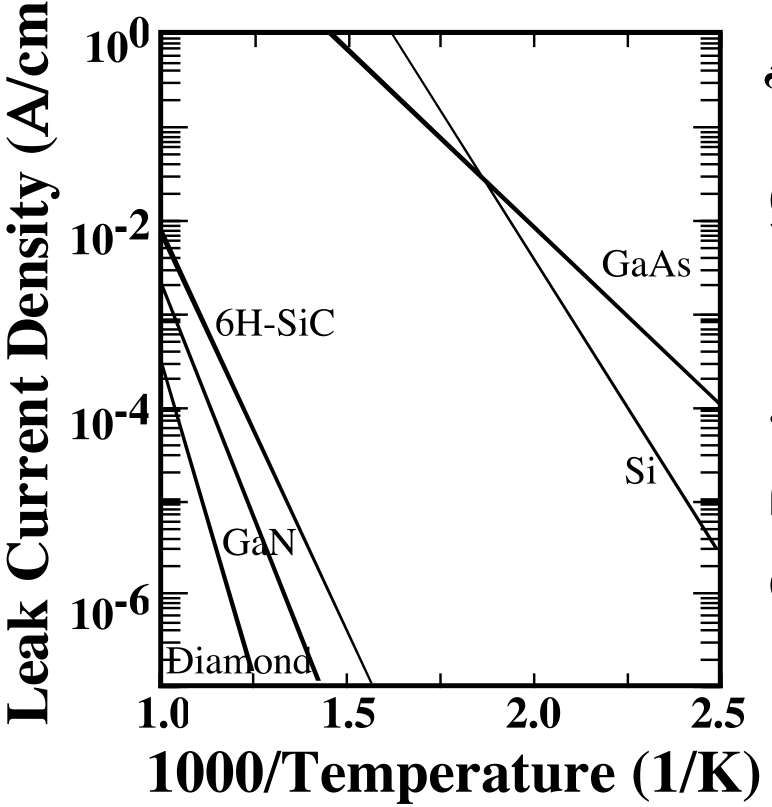
High Voltage operation is possible even after microintegratioin

⇓

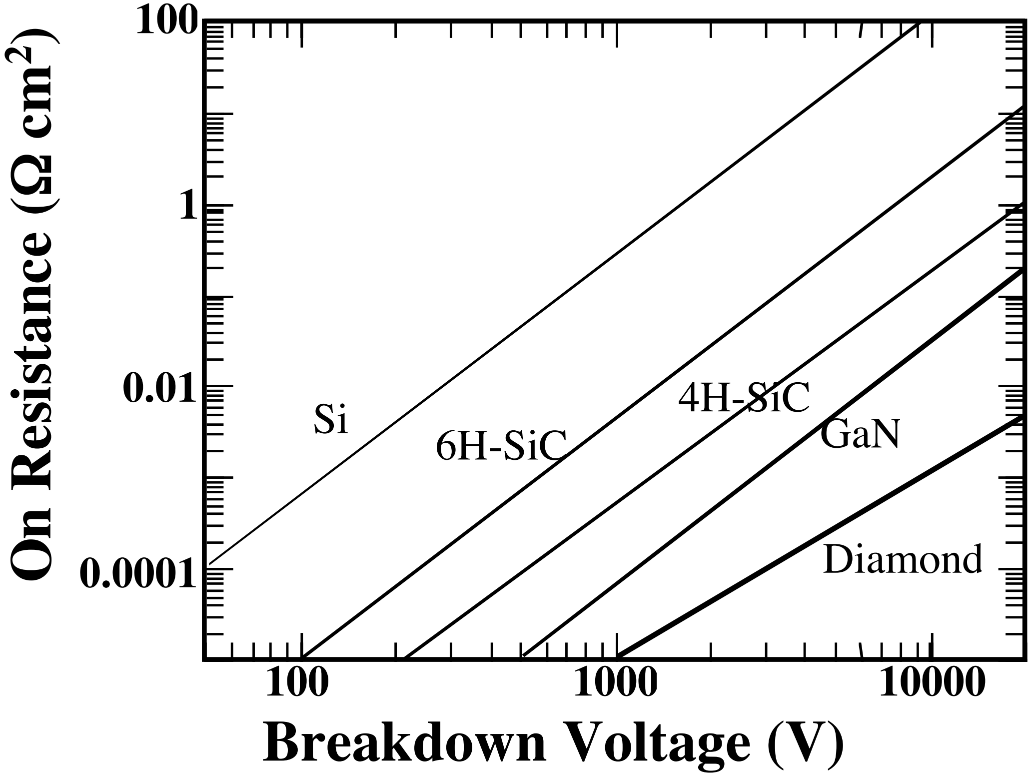
Suitable for high-power high-frequency operation

Properties of Wide Bandgap Semiconductor Devices

Temperature dependence of p-n junction leak current

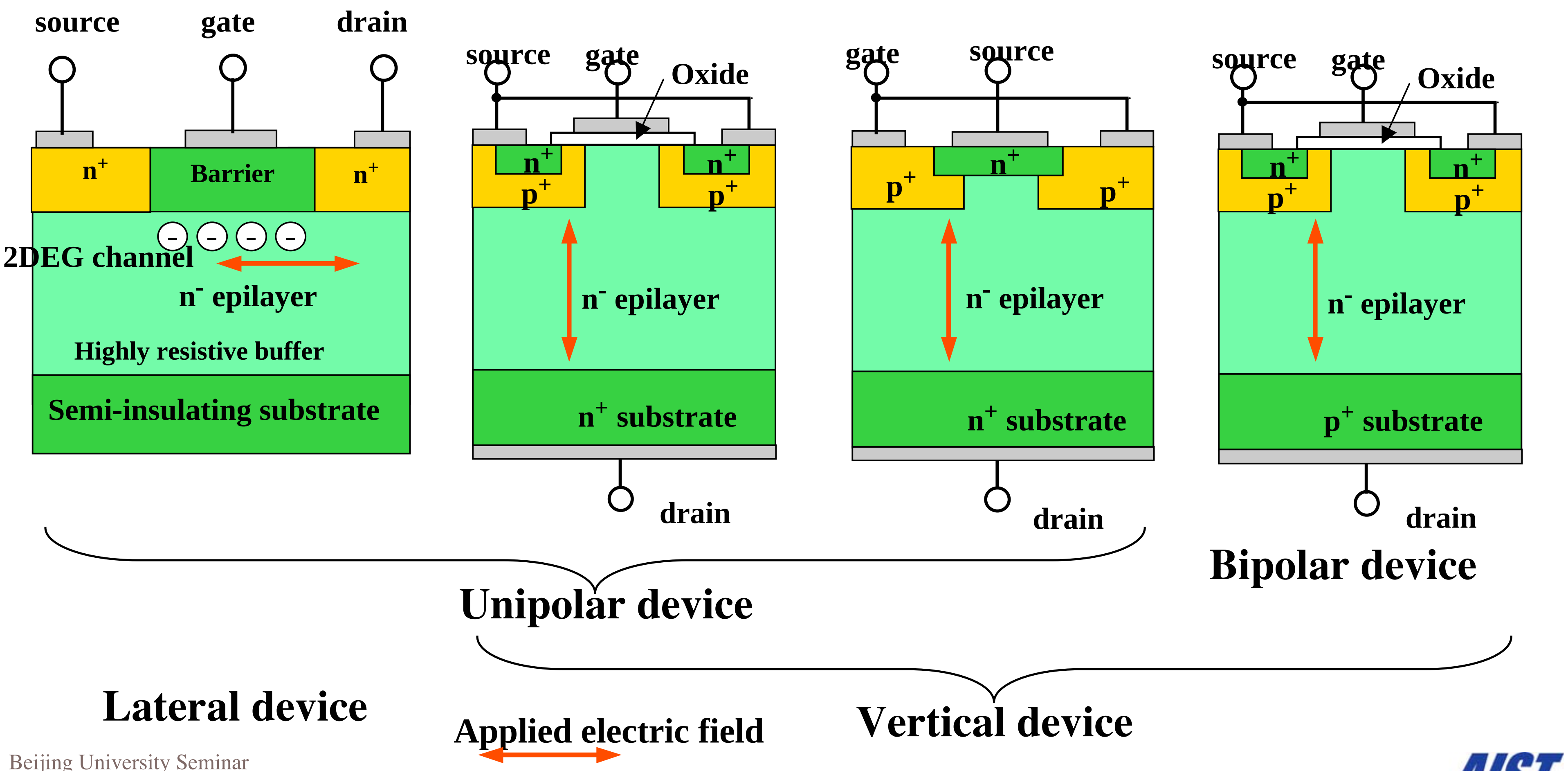


On resistance and Breakdown Voltage

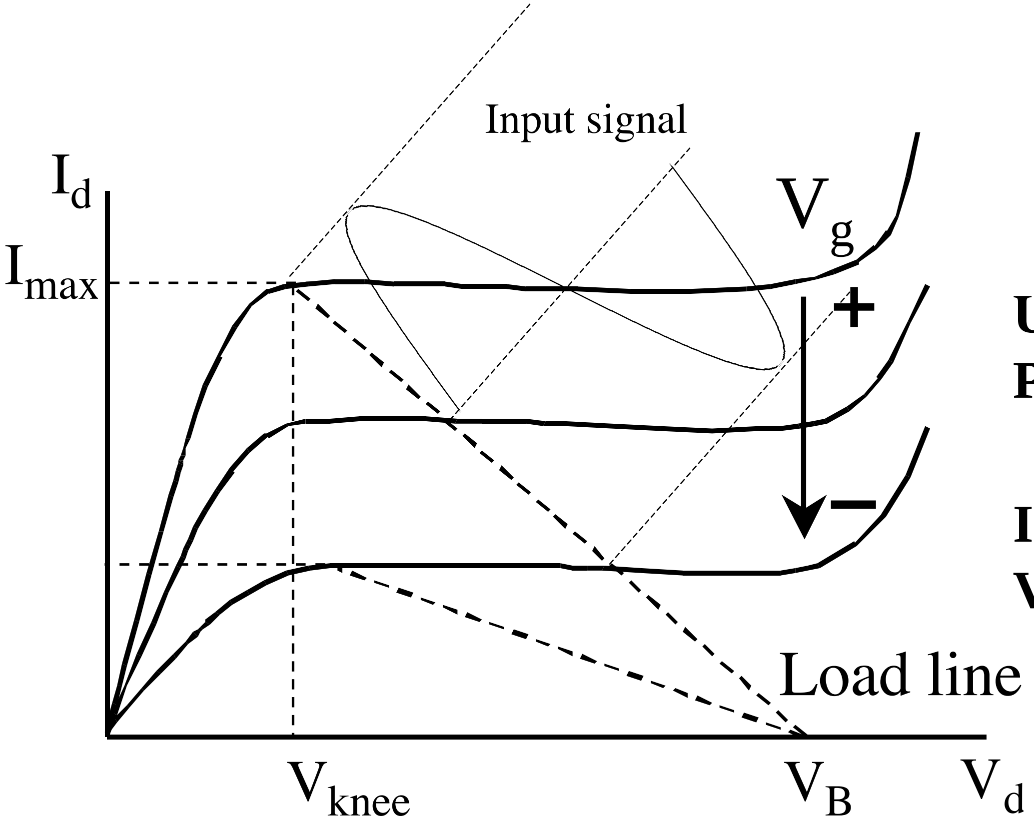


Structures of High-Power Electron Device

HFET	MOSFET	JFET	IGBT
Heterojunction Field Effect Transistor	Metal Oxide Semiconductor Field Effect Transistor	Junction field Effect Transistor	Insulated Gate Bipolar Transistor



High-power operation of HF device



Under Class A amplification,

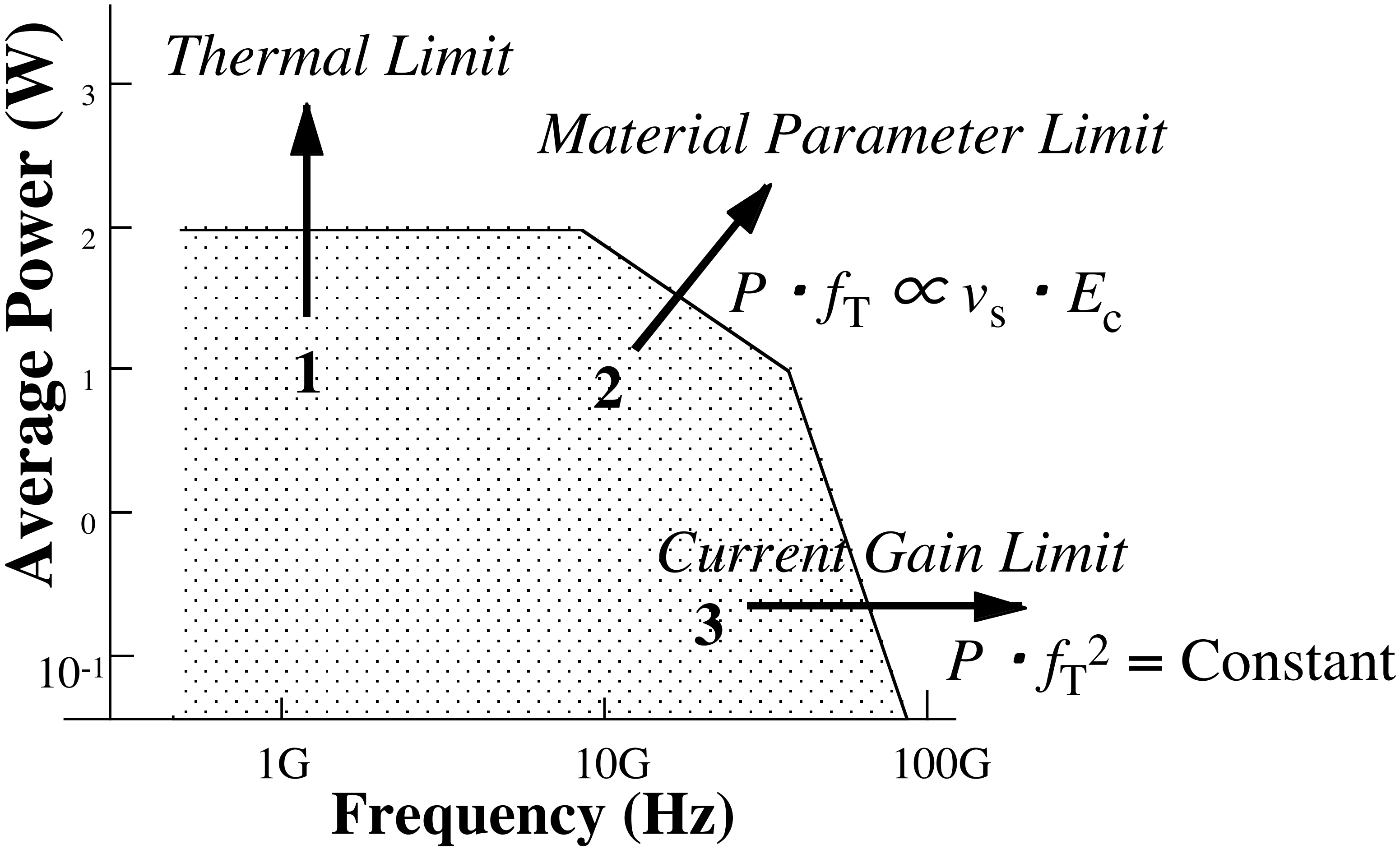
$$P_{out} = (1/8) \cdot (V_B - V_{knee}) \cdot I_{max}$$

$$I_{max} \sim n_s \cdot \mu$$

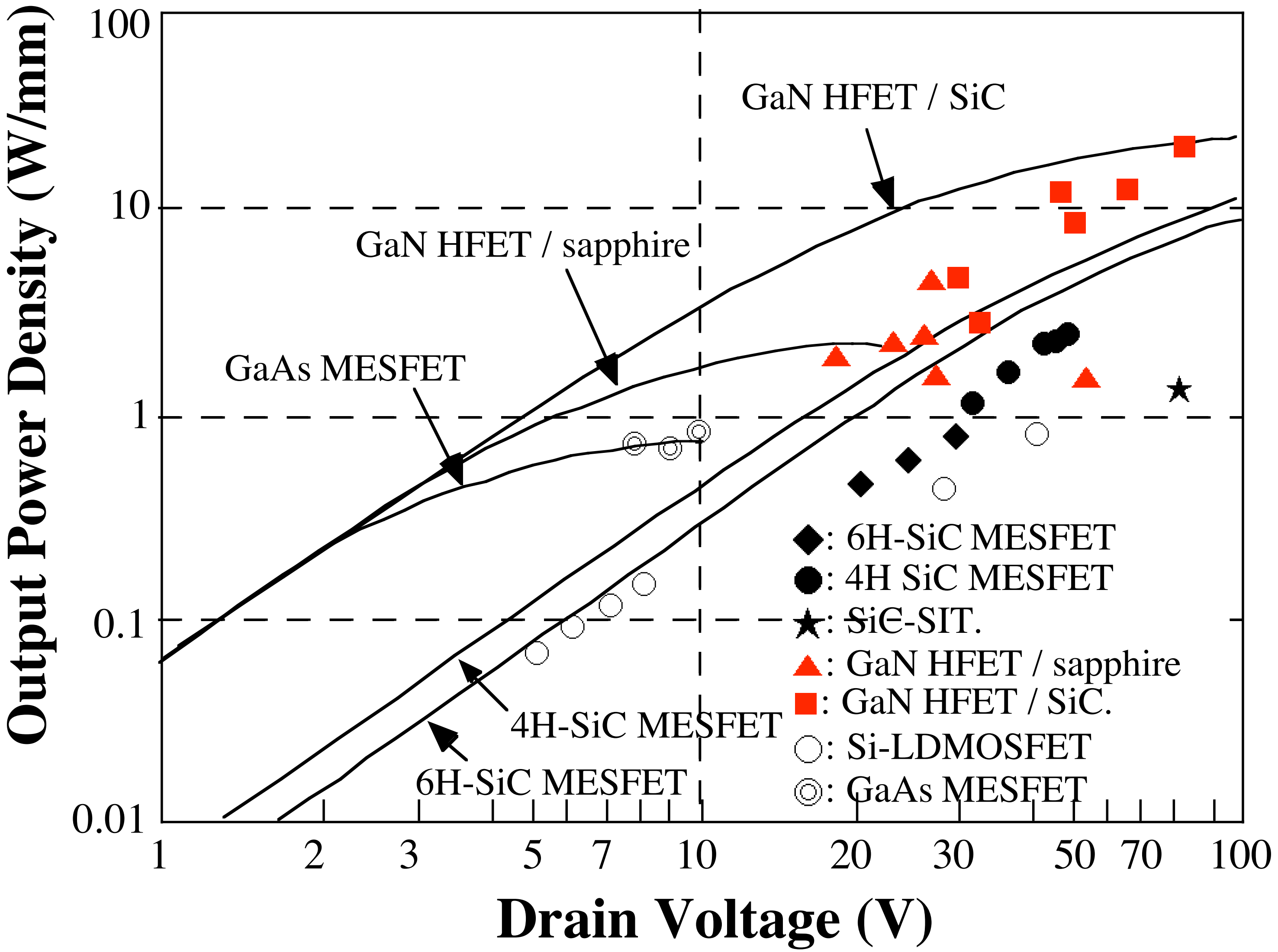
$$V_B \sim E_C$$

Under I_{max}=1A/mm, V_B=80V (V_{sd}=40V), and W_g=20mm, P_{out}=10W/mm and P_{total}=200W are obtained.

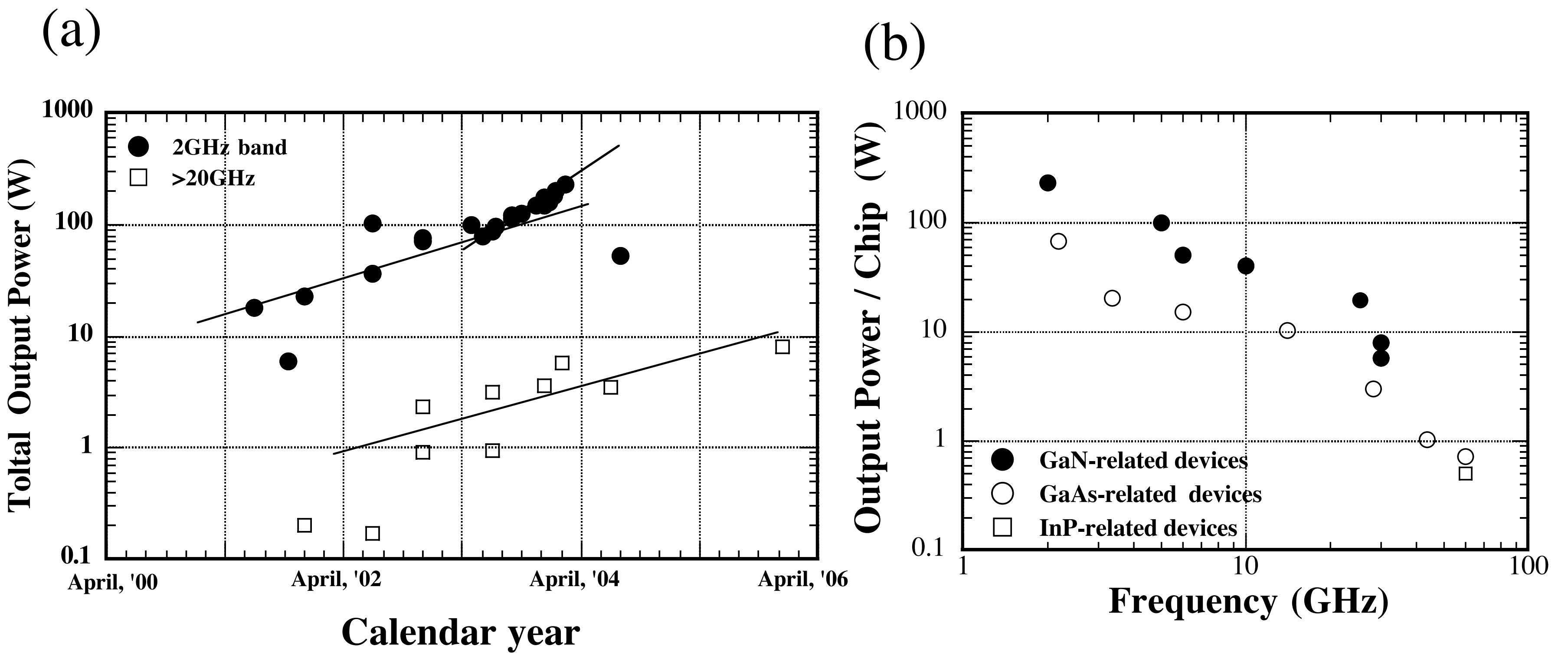
Operation limit of High-Frequency Devices



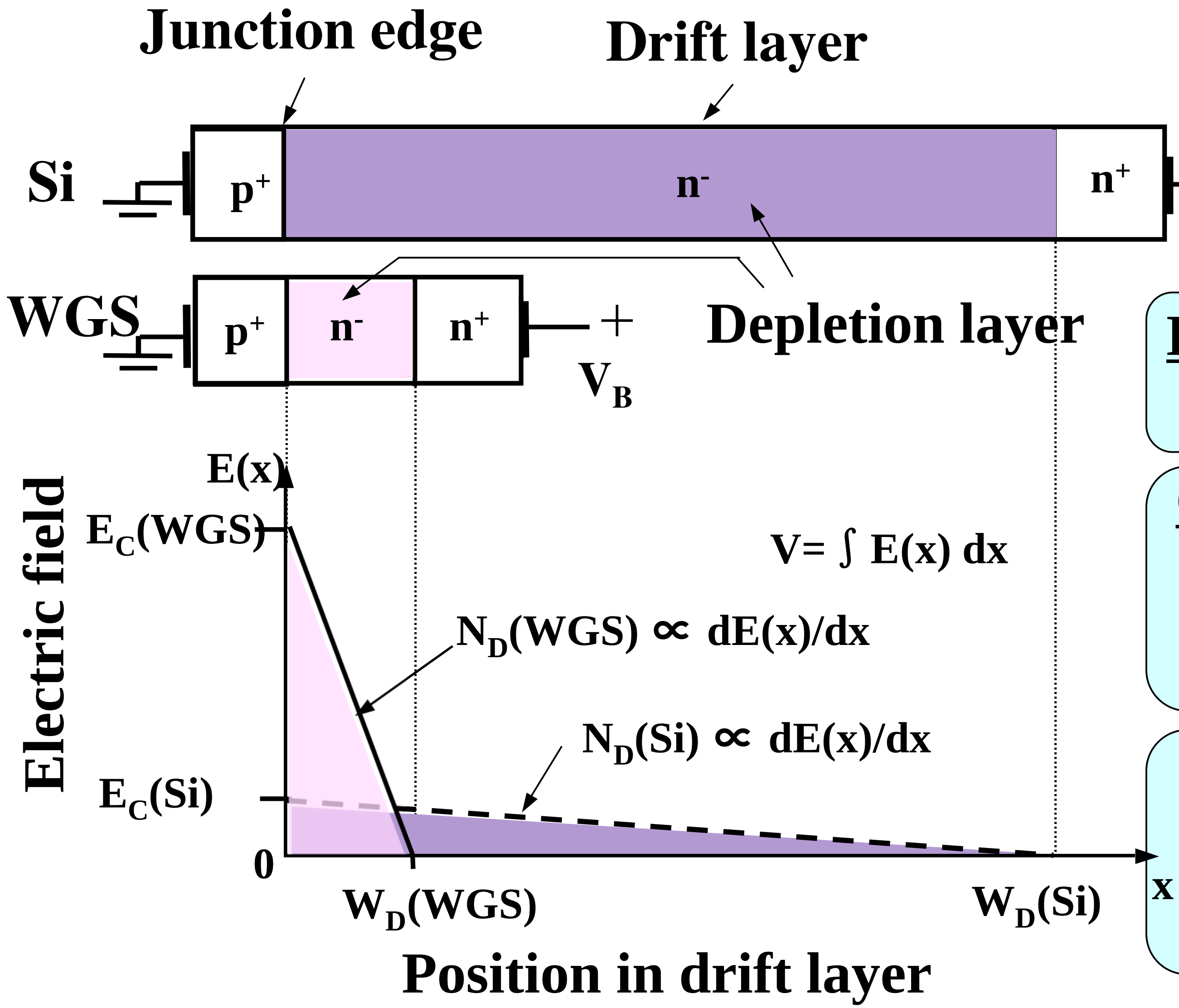
Operation Voltage and Power Density of High-Power HF devices



R&D Status of high-power HF devices



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



Blocking Voltage

$$V_B = (E_C W_D) / 2$$

On-Resistance

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

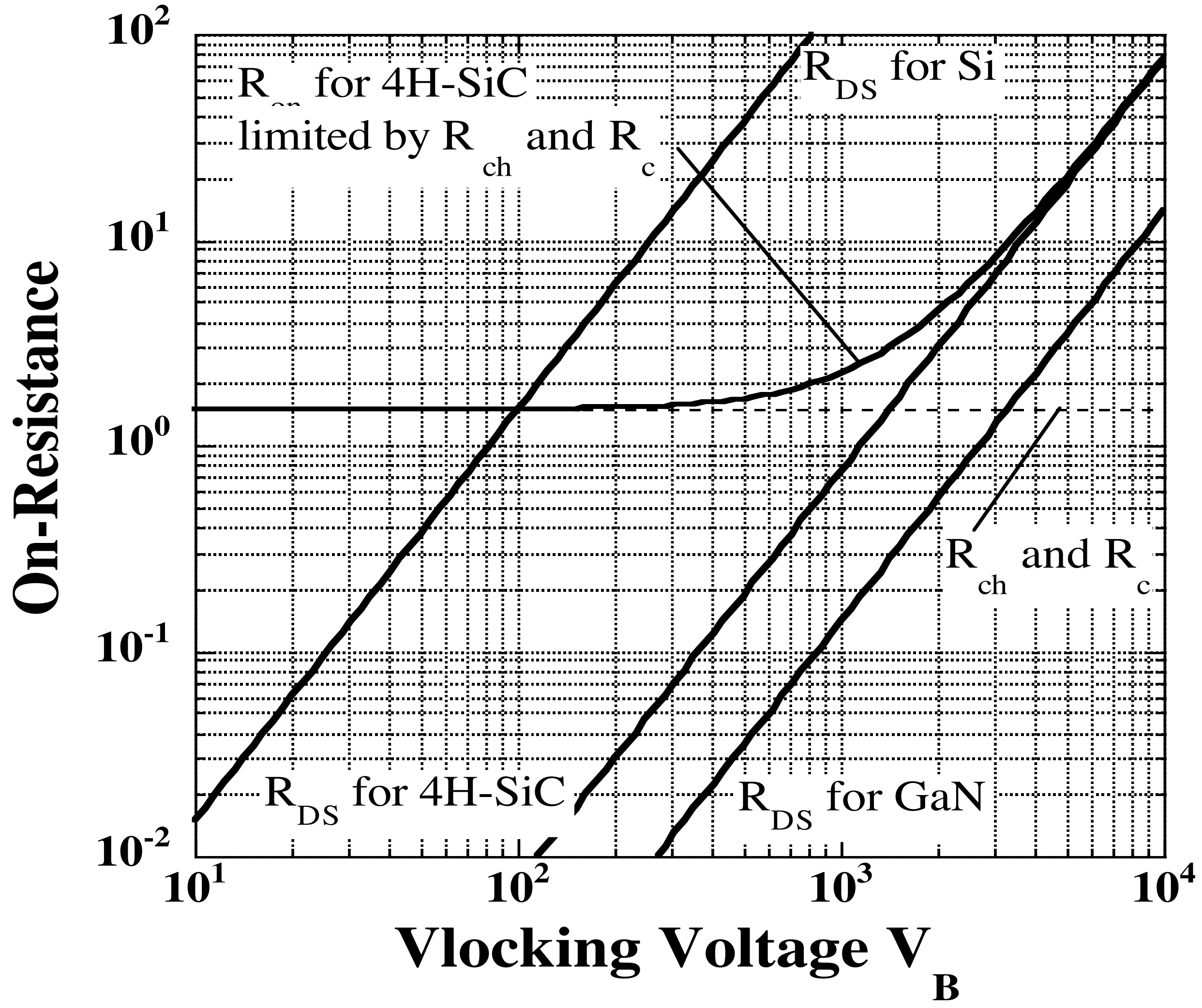
$$= 4 V_B^2 / (\epsilon\,\mu_n E_C^3)$$

Carrier Density

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

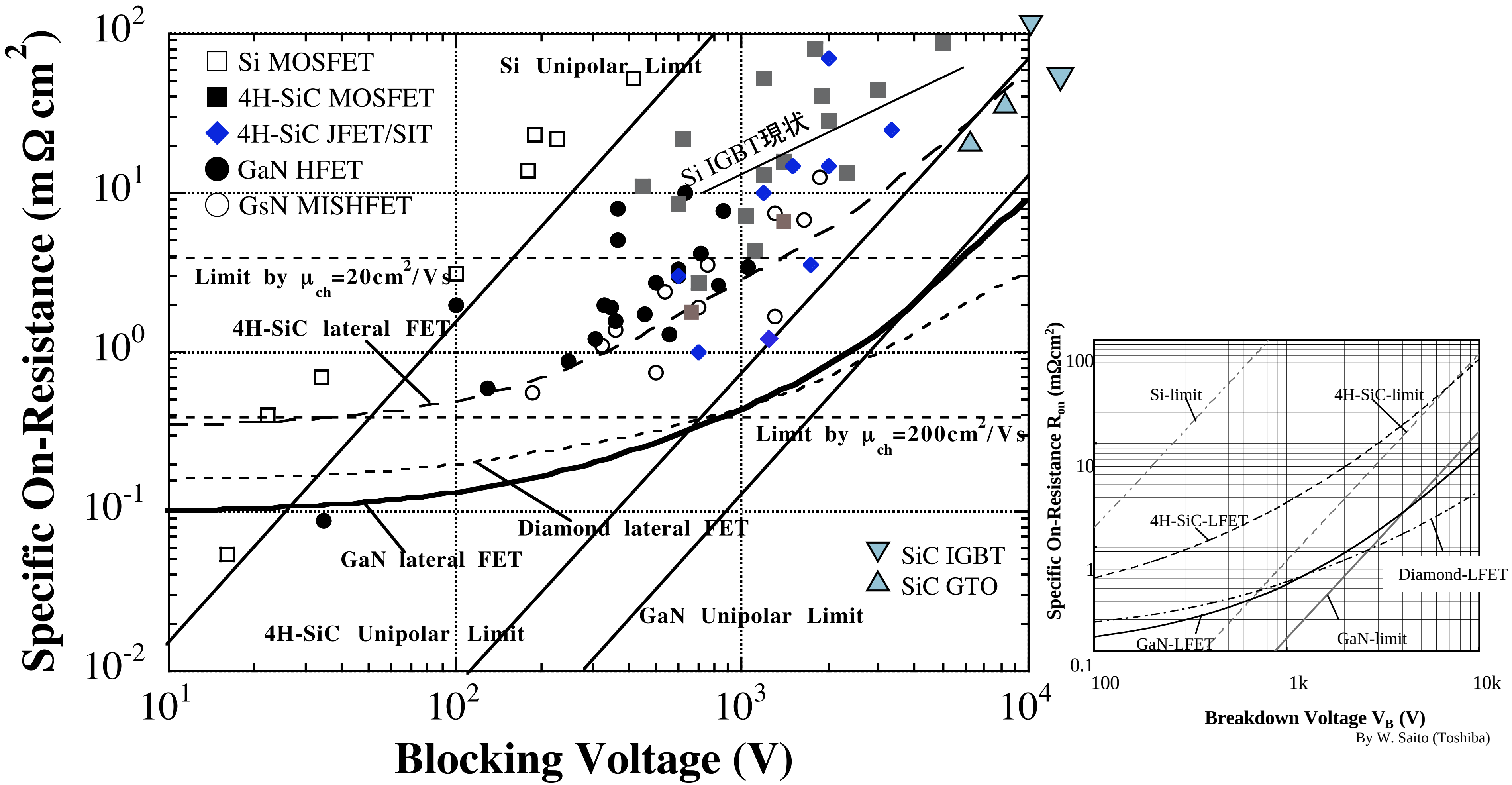
$$= 2\,\epsilon\,E_C^2 / q V_B$$

Performance Indices of Power Switching Devices



R&D Status of Low-Loss Swtching Devices

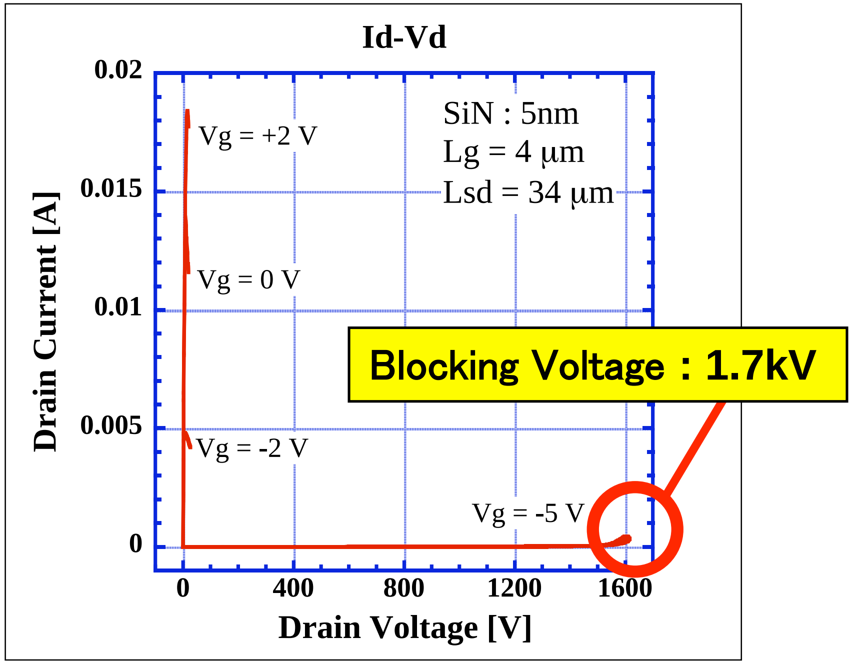
--- Fabrication Trials and Simulation ---



By W. Saito (Toshiba)

Blocking Voltage and On-Resistance of GaN HFET

High blocking voltage HFET

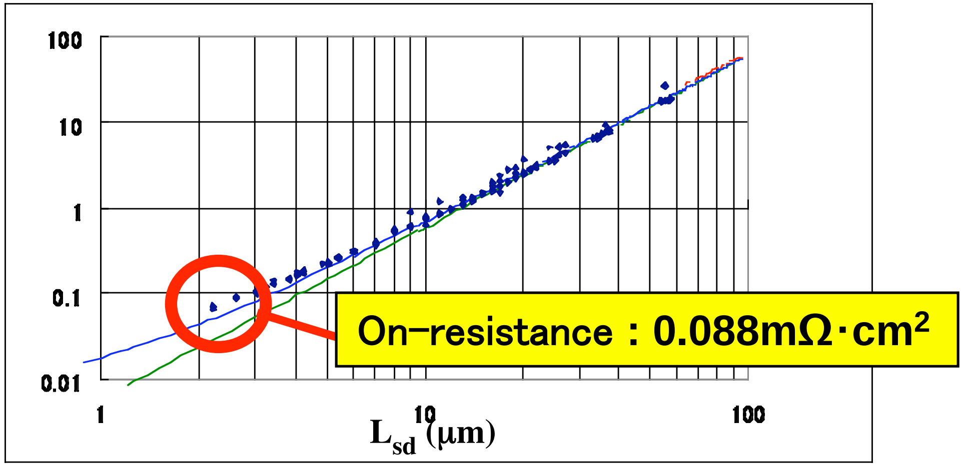


Blocking Voltage : 1.7kV

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

Low on-resistance HFET

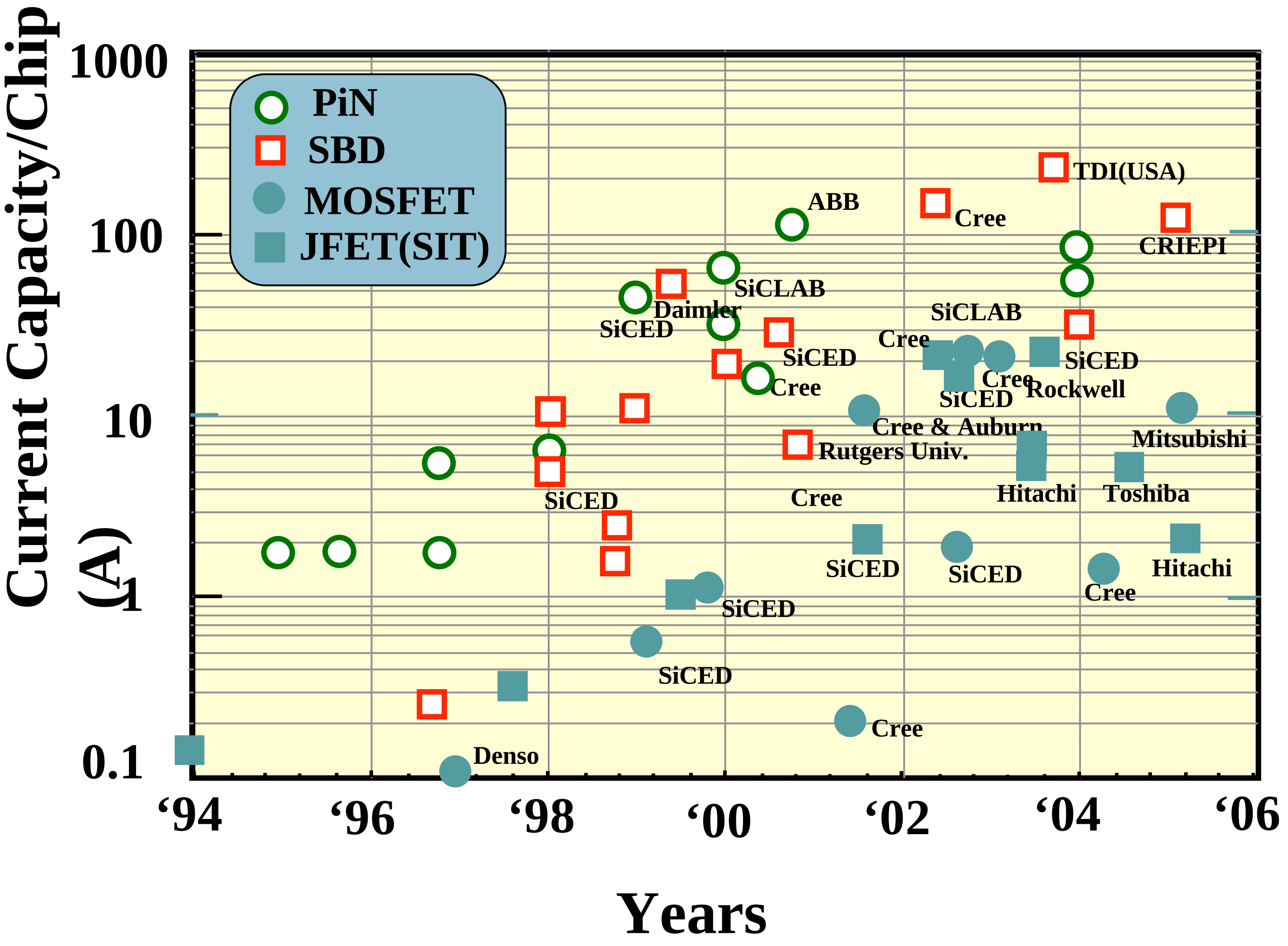
Source-Drain distance dependence of on-resistance



On-resistance : 0.088mΩ·cm^2

M. Inada et al. : *Proc. Int. Symp. Power Semicond. Devices & ICs, Naples, 2006,* p.121.

R&D trend of Current Capacity on SiC Devices



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

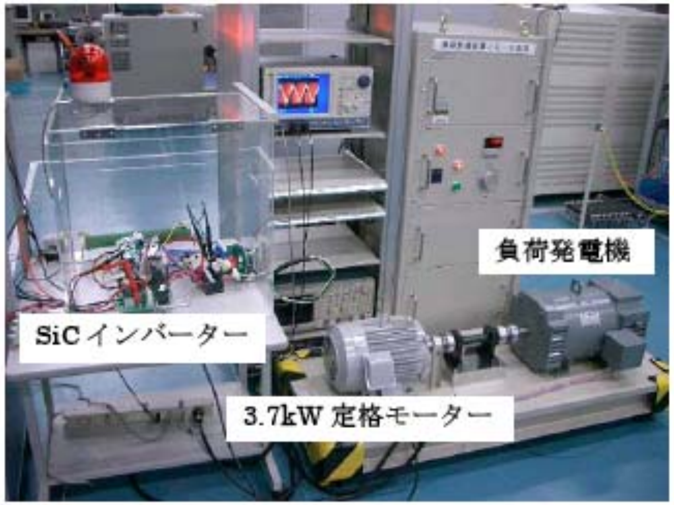
<u>Mitsubishi Electric</u> (2006.1.24)

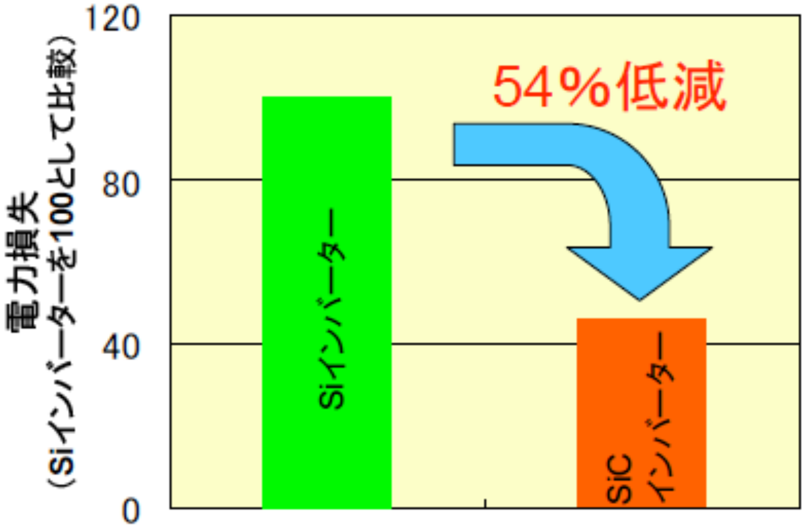
1. Module by 1200V, 10A MOSFETs (On-resistance :10mΩcm^2）
2. Inverter operation of a 3.7kW motor (SiC-MOSFET+SiC-SBD）
3. 54% reduction of a inveter loss (vs. Si-IGBT inverter)

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





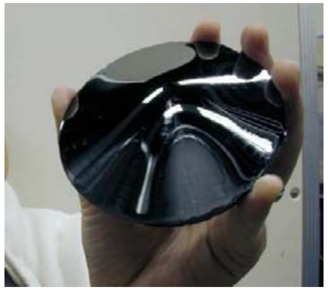
Recent Results of Device/Inverter R&D (2)

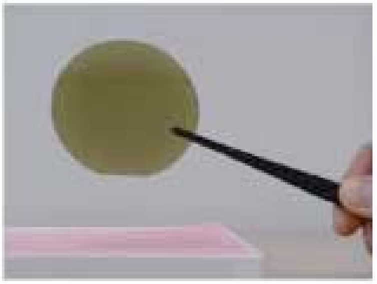
Kansai Electric Power & Cree Inc. (2006.1.25)

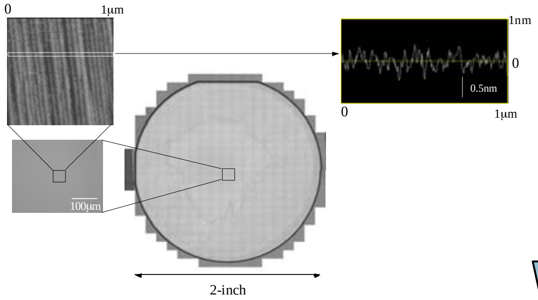
1. 4.5 kV, 100 A SiC Commutated Gate Turn-off Thyristor (SiCGT)
   8x8mm^2
2. 110kVA 3-phase inverter （SiC-MOSFET+SiC-PiN D）
   without snubber circuit, operation at 300°C
3. Reduction of inverter loss by more than 50% (vs. Si-IGBT inverter)

From Crystal to Application System

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





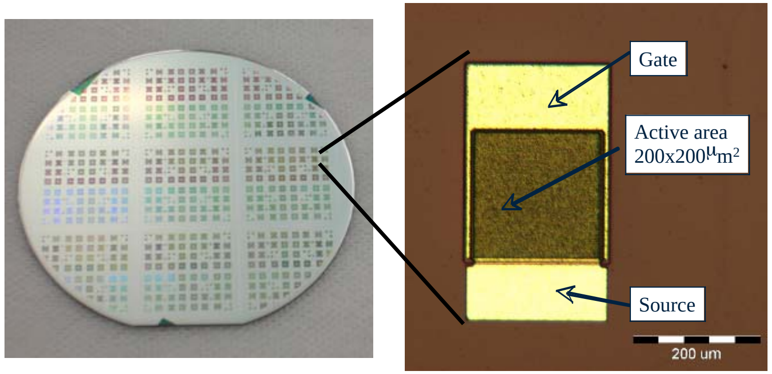


Ion Implantation
Dry etching
Metallization
RTA

↓

Device chips
（MOSFET, SBD etc.）

← Dicing
Bonding
mounting



Device modules

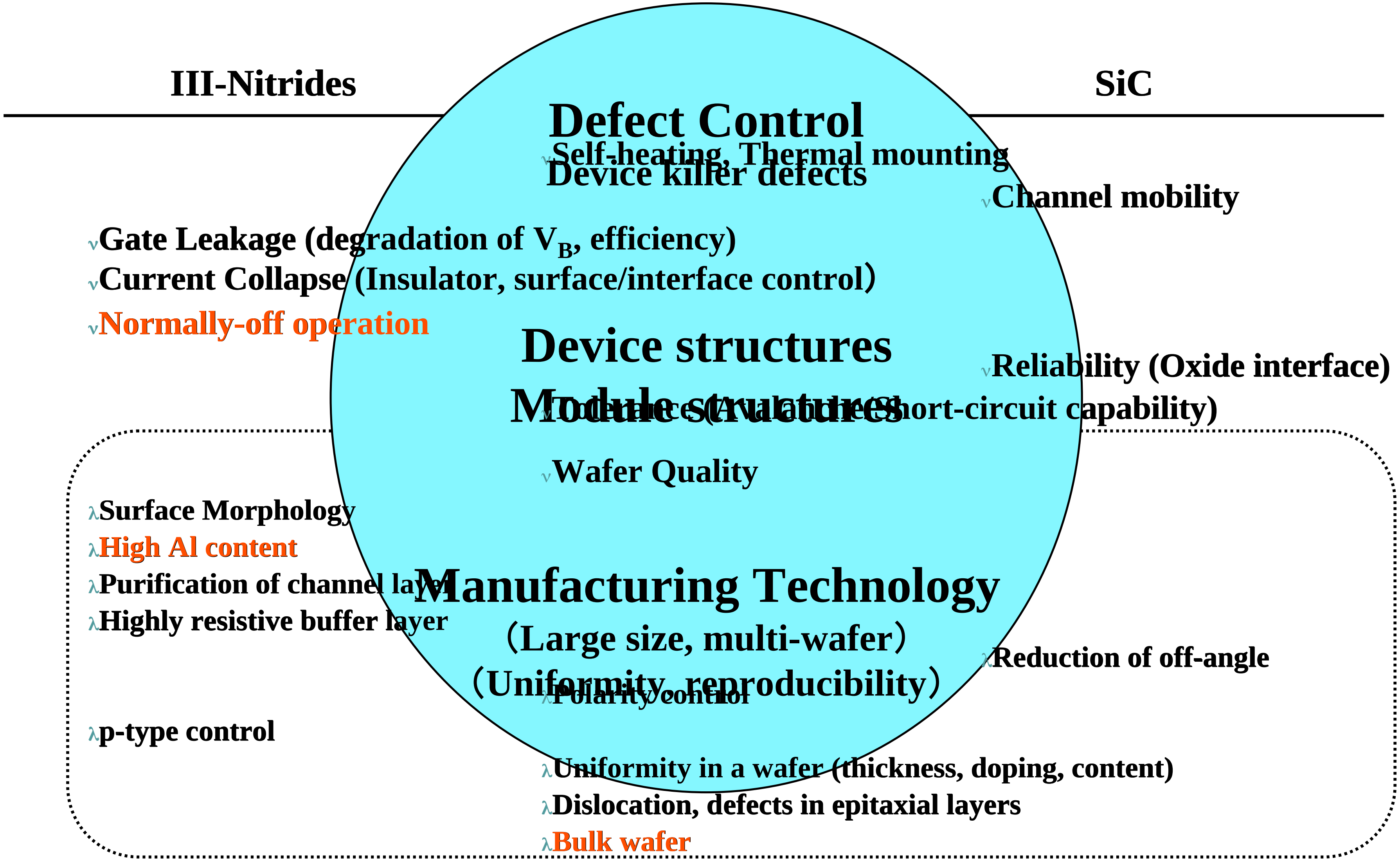
三菱電機 HPより

← Circuit mounting

Inverters

安川電機 HPより

Problems in Widegap Semiconductor Device Technology



III-Nitrides

SiC

Defect Control

Device killer defects

Device structures

Module structures

Manufacturing Technology

（Large size, multi-wafer）

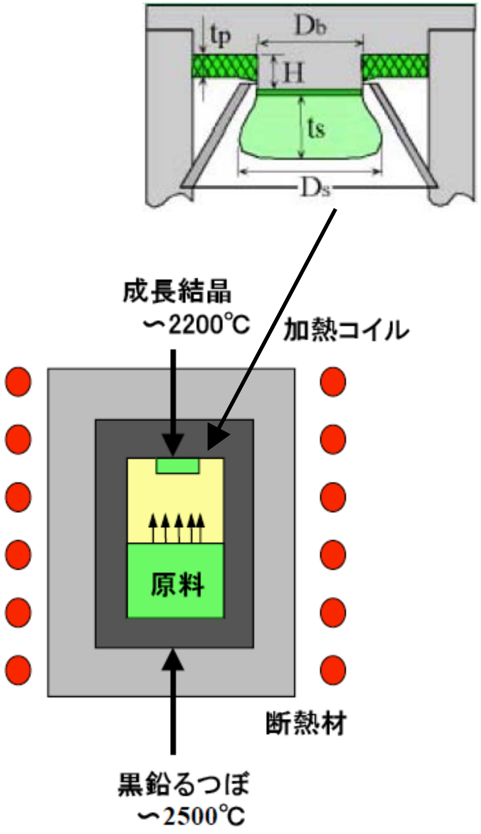
（Uniformity, reproducibility）

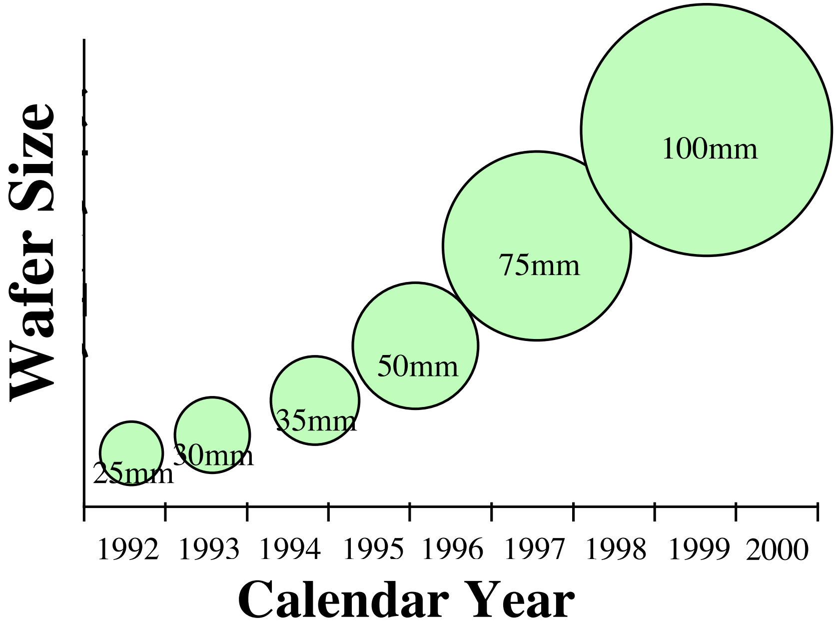
- **Self-heating, Thermal mounting**
- **Channel mobility**
- **Gate Leakage (degradation of V_B, efficiency)**
- **Current Collapse (Insulator, surface/interface control）**
- **Normally-off operation**
- **Reliability (Oxide interface)**
- **Tolerance (Avalanche, Short-circuit capability)**
- **Wafer Quality**

- **Surface Morphology**
- **High Al content**
- **Purification of channel layer**
- **Highly resistive buffer layer**
- **Reduction of off-angle**
- **Polarity control**
- **p-type control**
- **Uniformity in a wafer (thickness, doping, content)**
- **Dislocation, defects in epitaxial layers**
- **Bulk wafer**

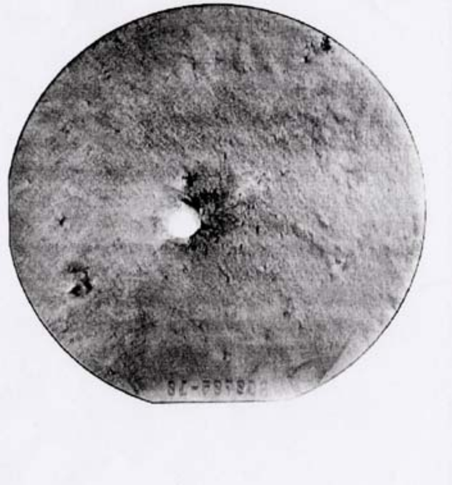
Enlargement of SiC Wafer Size and Defects

Sublimation Method

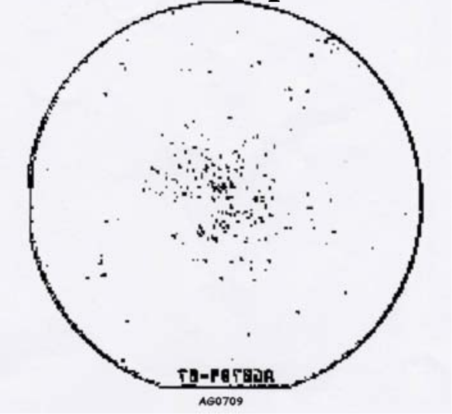




X-Ray Topography

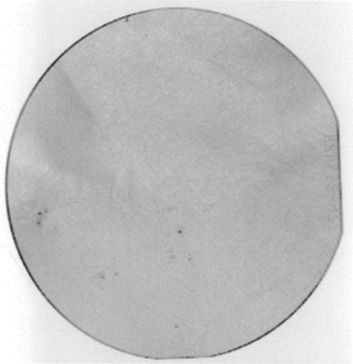


Micro-pipes

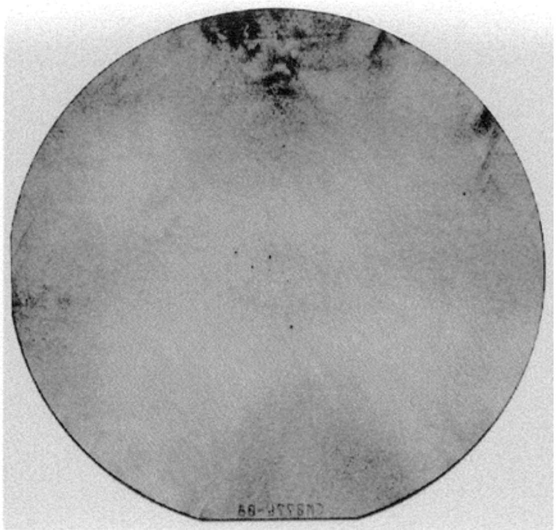


Comparison of SiC Single Crystal Wafer

C Corp. (2 inch)



MPD＜15/cm^2

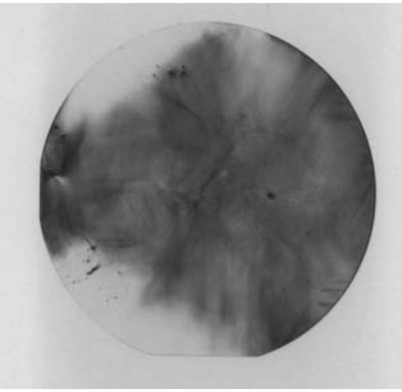


C Corp. (3 inch)

→ **4 inch**

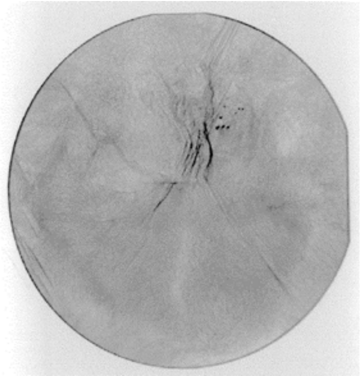
MPD＜5/cm^2

A Corp. (2 inch)



MPD＜30/cm^2

B Corp. (2 inch)



MPD＜5/cm^2

MP：Almost solved

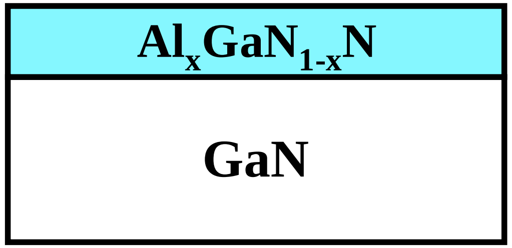
Dislocation：Killer defects determining device performance

- **Threading Dislocation (Screw, Edge)**
- **Basal Plane Dislocation**

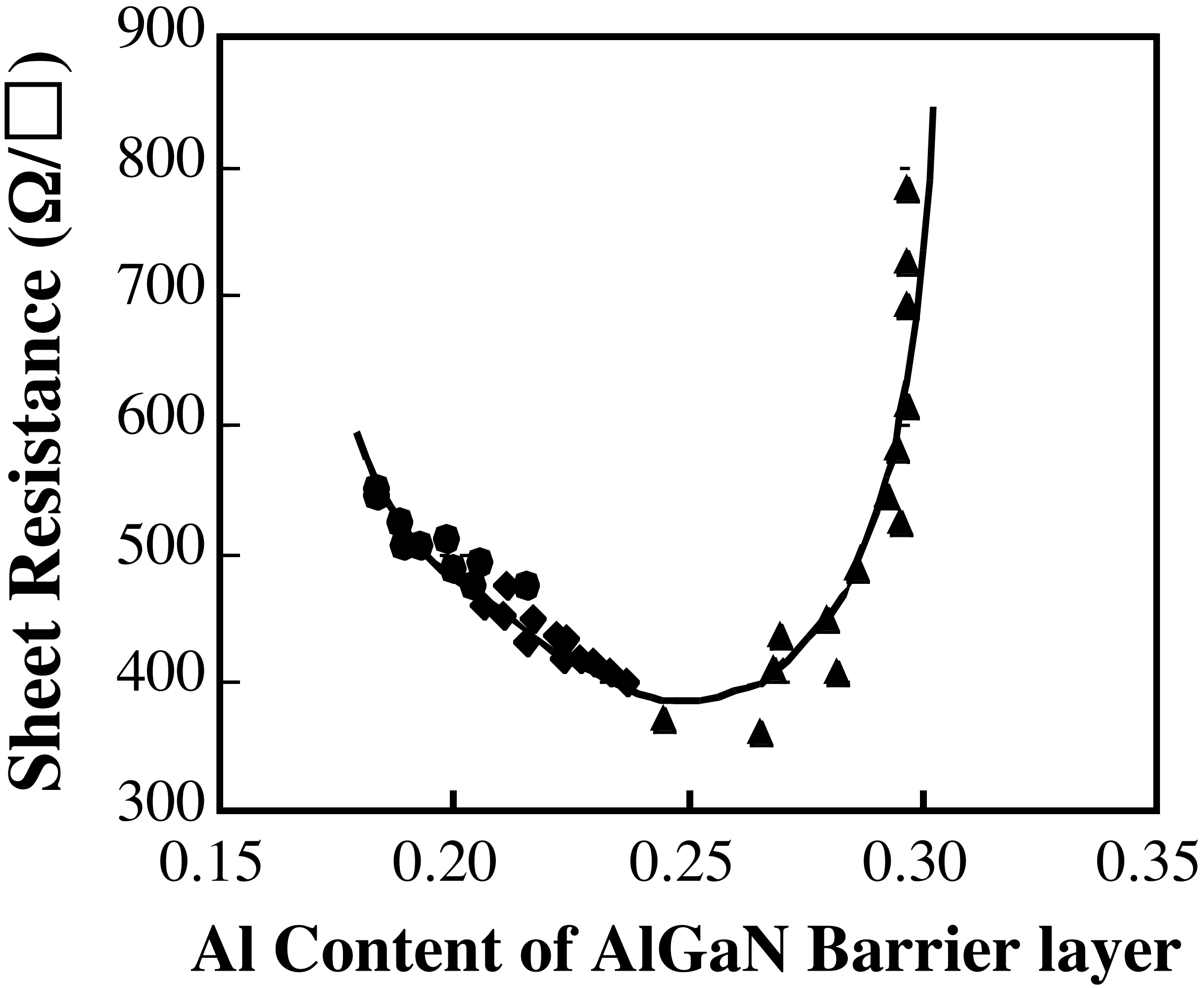
Distortion of crystal planes (Thermal distortion)

EPD

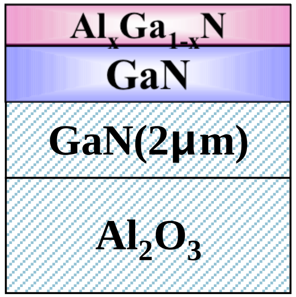
Al Content and Sheet Resistance of an AlGaN/GaN Heterostructure Wafer


$Al_xGaN_{1-x}N$

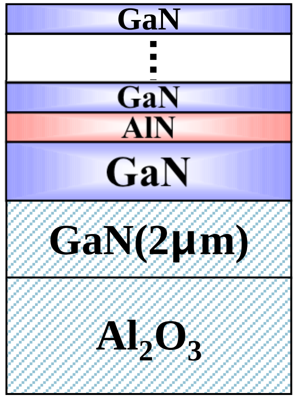
GaN



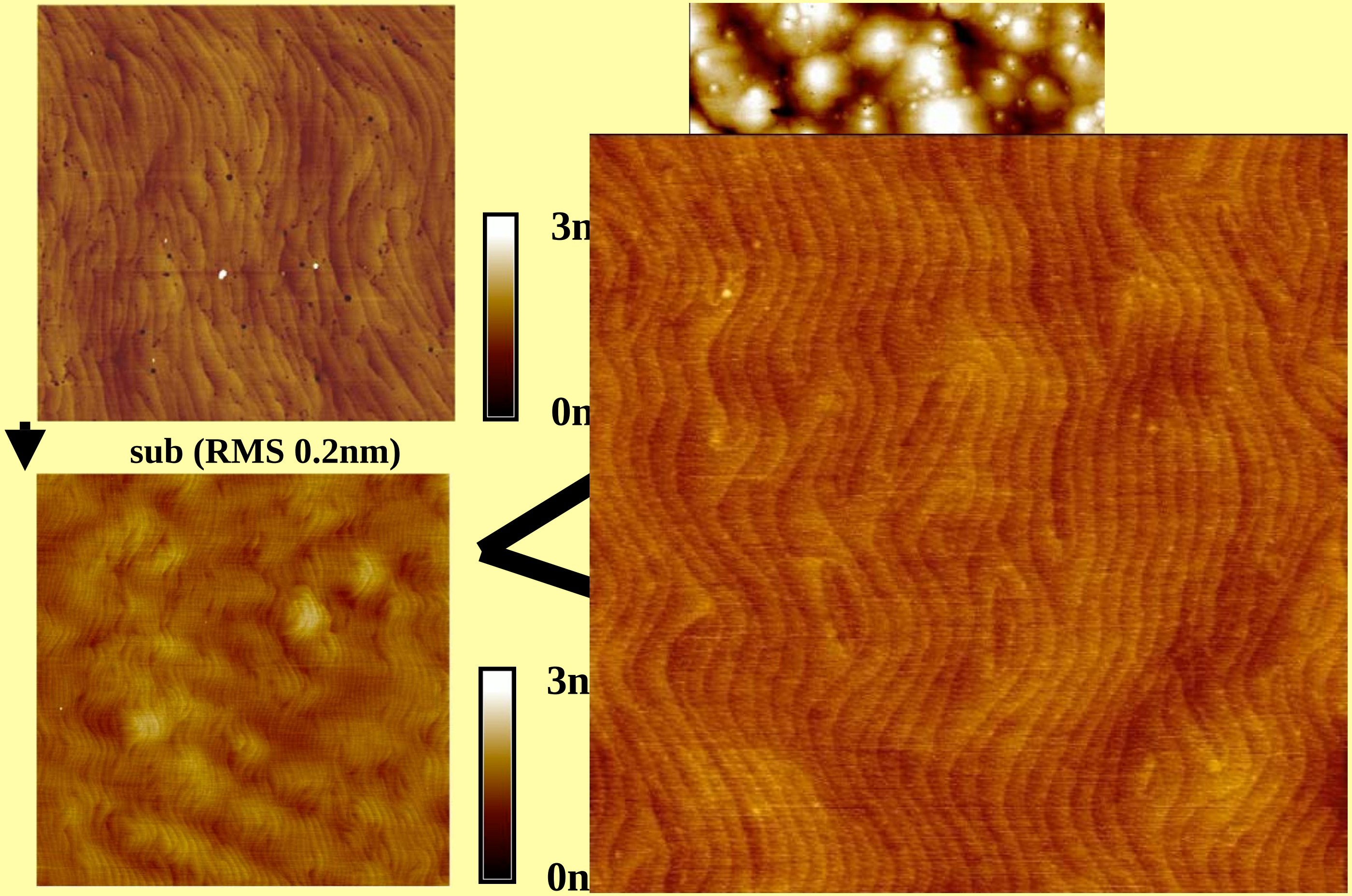
Surface morphology of high Al-content AlGaN epitaxial layer



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



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

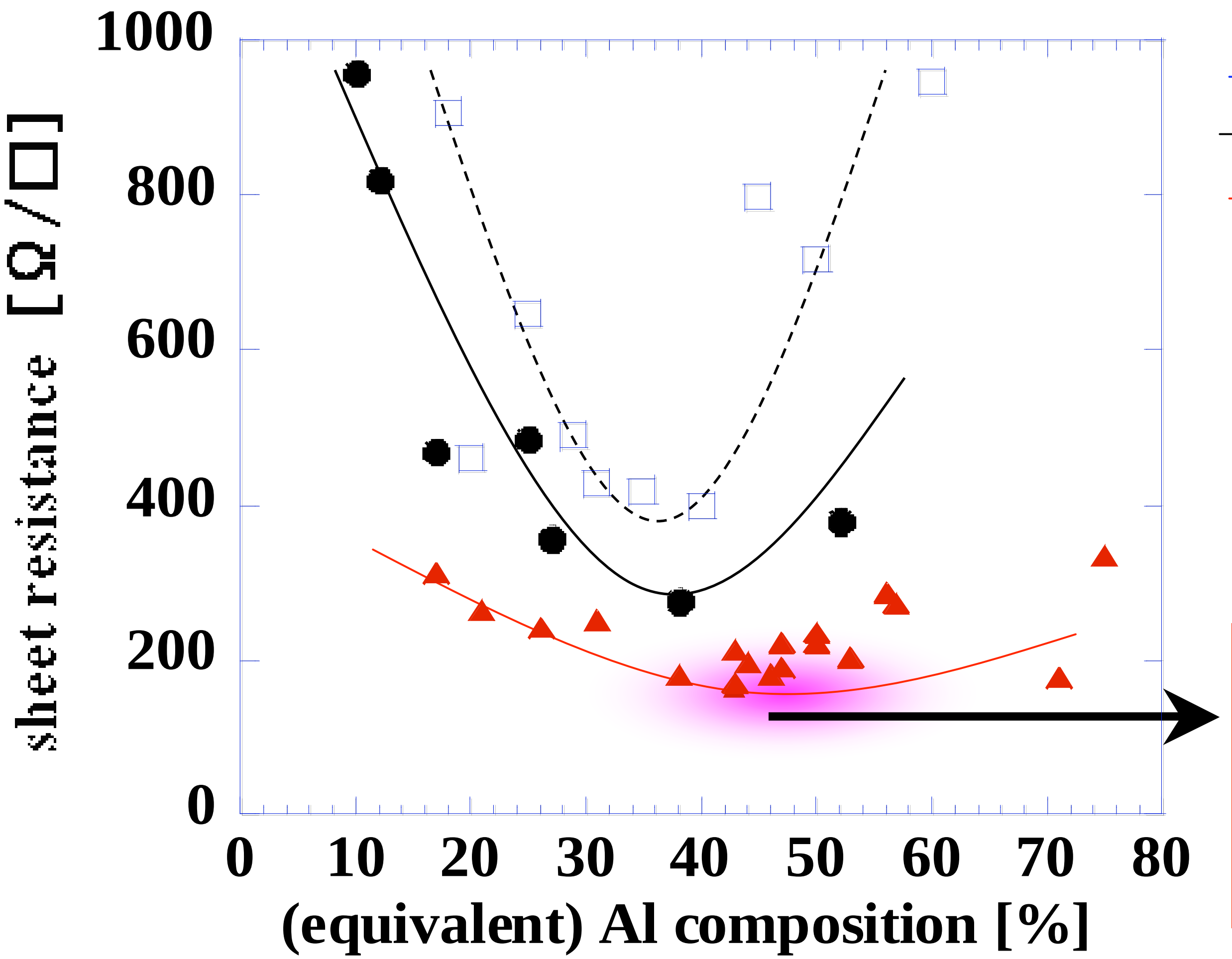


sub (RMS 0.2nm)

GaN epi-layer(RMS 0.3nm)

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

Al-content(equivalent) dependnce of Sheet resistance



- □ AlGaN alloy
- ● AlGaN alloy (ref.)
- ▲ quasi AlGaN

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 ?

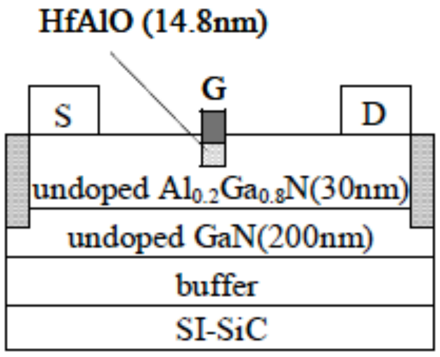
Trials by various approach

- 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

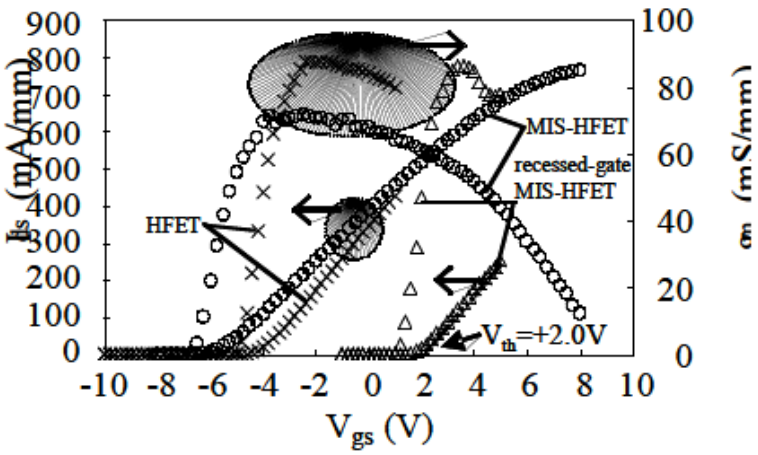
Examples of Normally-off operation

- recess gate with high-k insulator

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

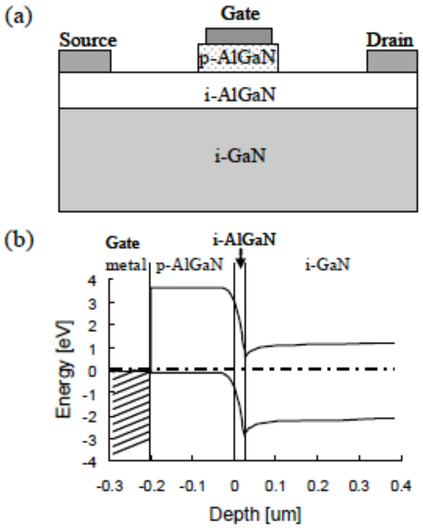


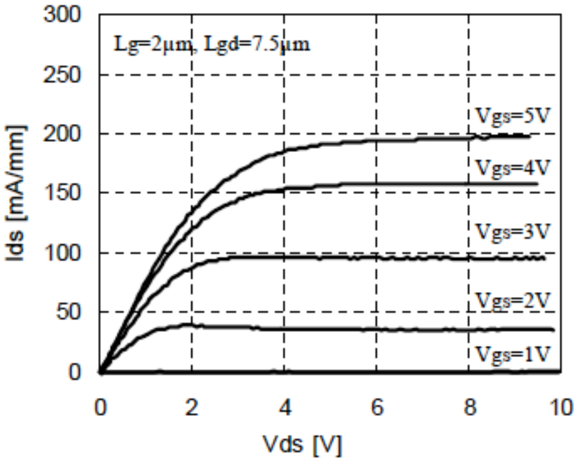
(c)



- pn-junction gate

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



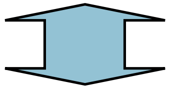


$R_{on}\cdot A$ = 2.6mΩcm^2, I_{dmax} = 200mA/mm

Important Technical Issue for the Realization of WGS Inverters

There remain many unknown factors in WGS Physics

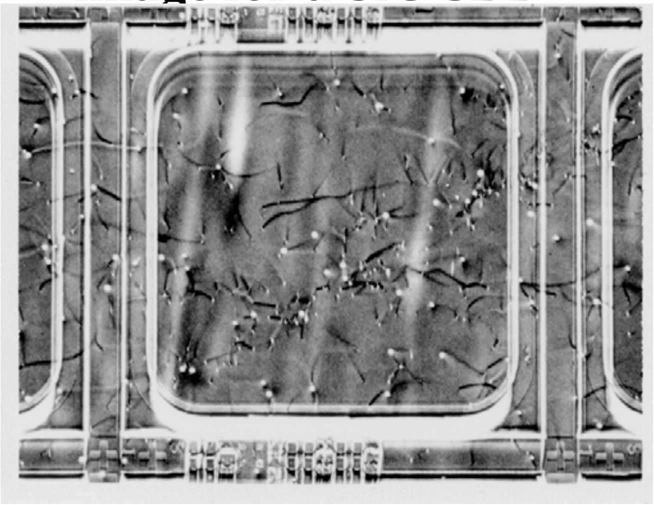
- micropipe
- dislocation（SD, ED, BPD etc.）
- Grain boundary, oxide interface



- Channel mobility
- Blocking voltage, current leakage
- Reliability

(correlation between wafer characteristics and device performance)

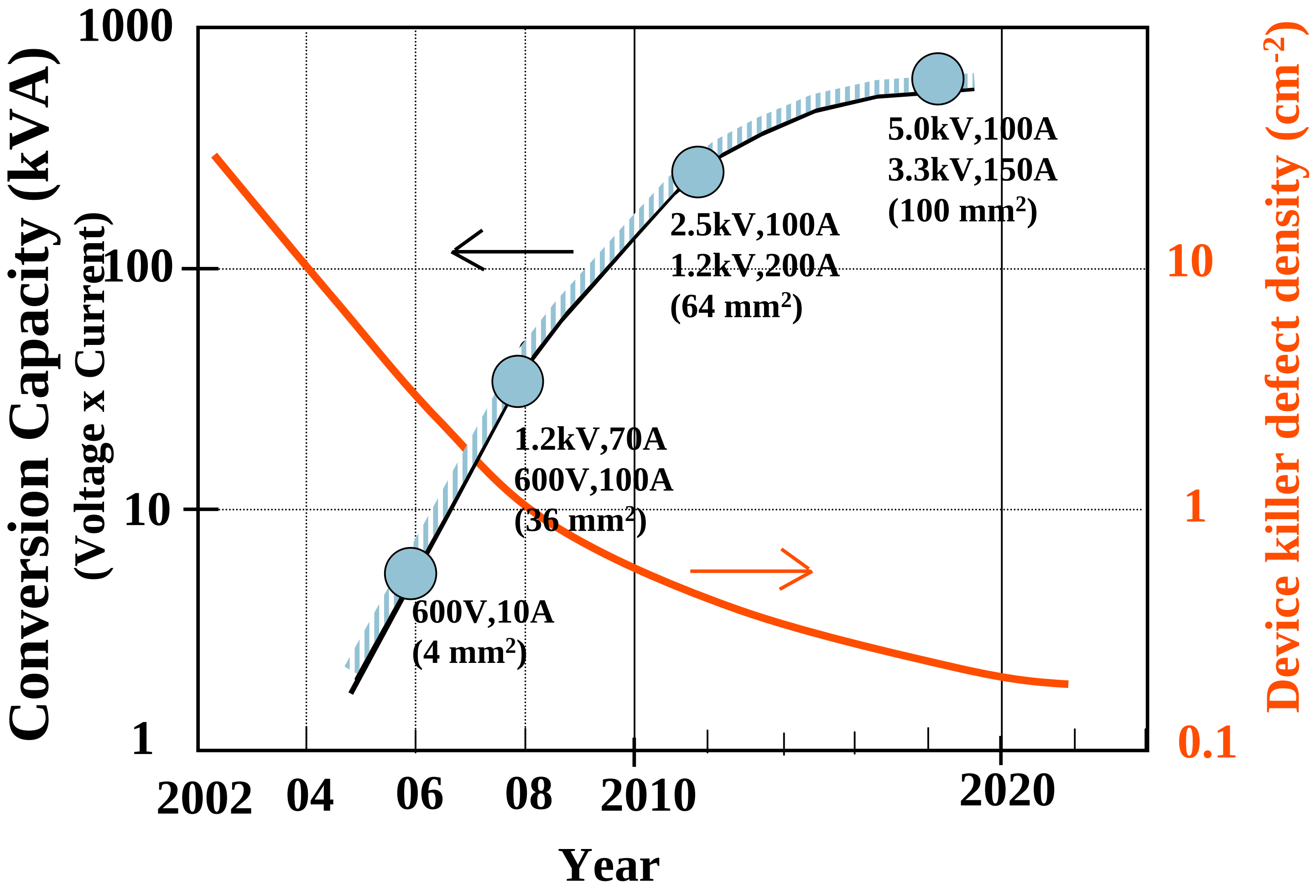
Reflection X-ray topograph image for a SiC SBD



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.