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Characterization and control of GaN-based MOS structures

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Outline

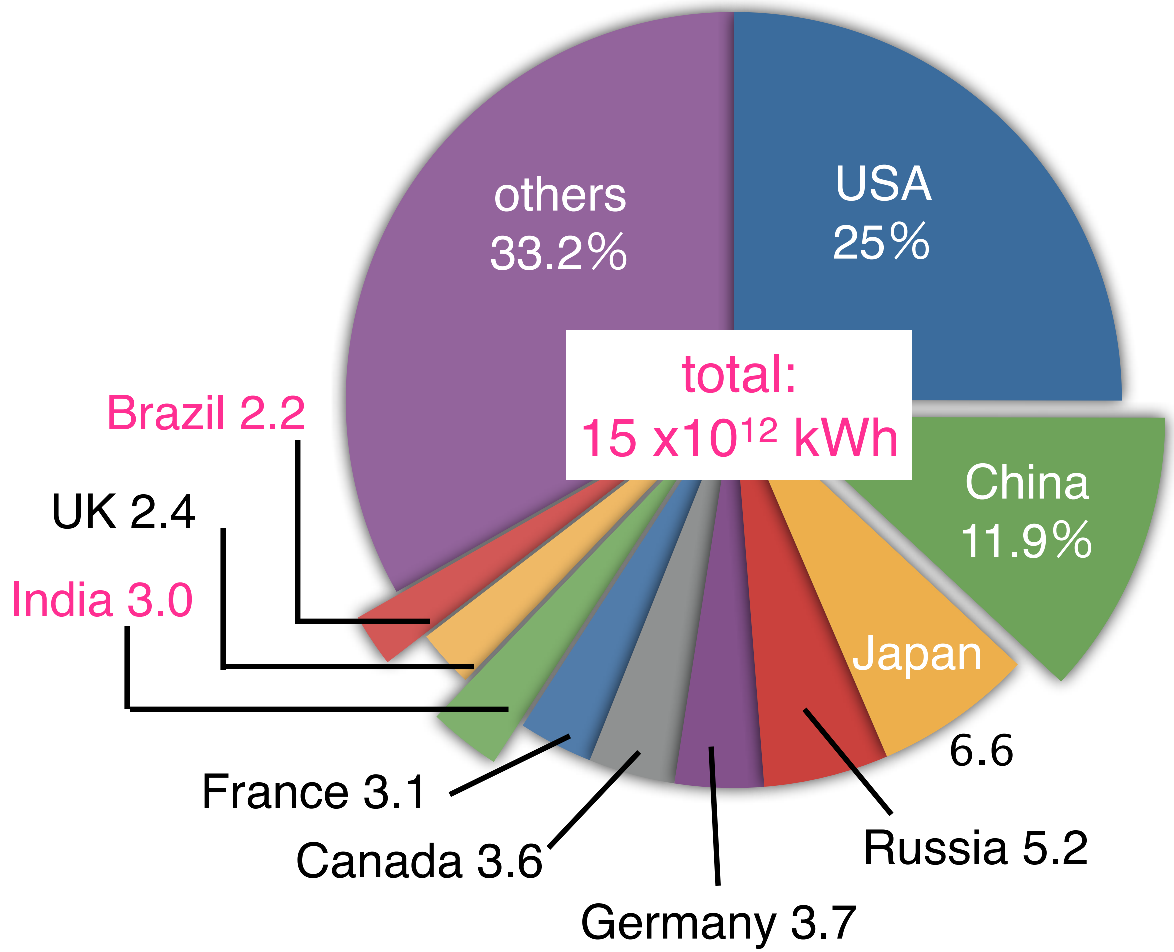
1) Advantage of GaN transistors for power inverter application

2) Electrical properties of Al_2O_3-based GaN MOS interfaces

3) Characterization of Al_2O_3/AlGaN/GaN structures

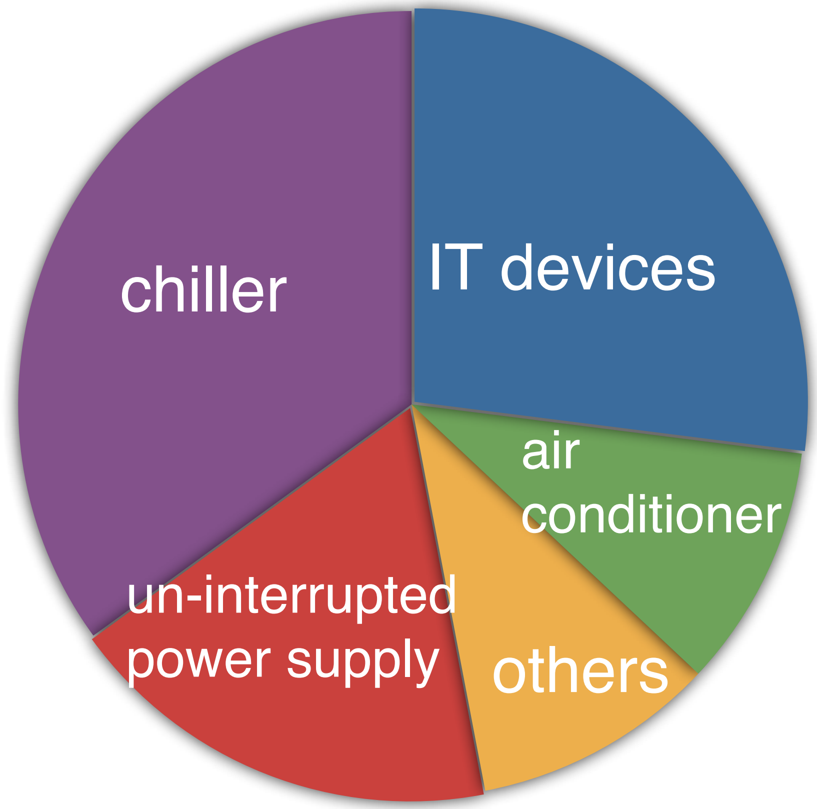
Electric power consumption

power consumption in the world



Electricity saving is very important.

Power for Data Center in Japan



At present
about 5% of total consumption

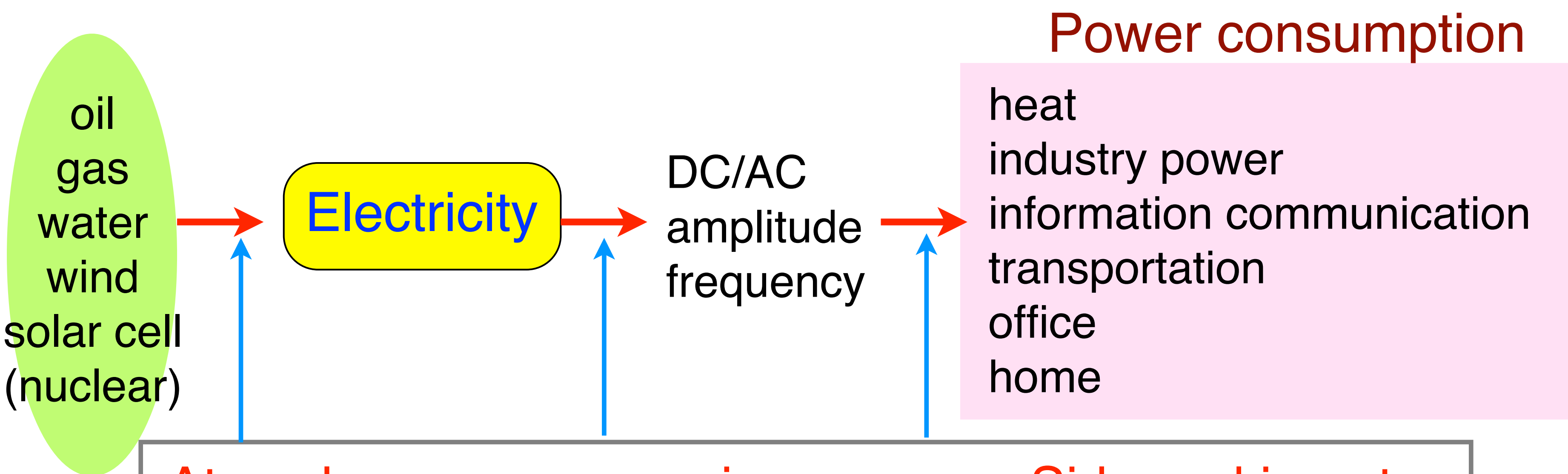
↓

over 50% in 2030

Importance of power inverters for energy saving

Primary energies

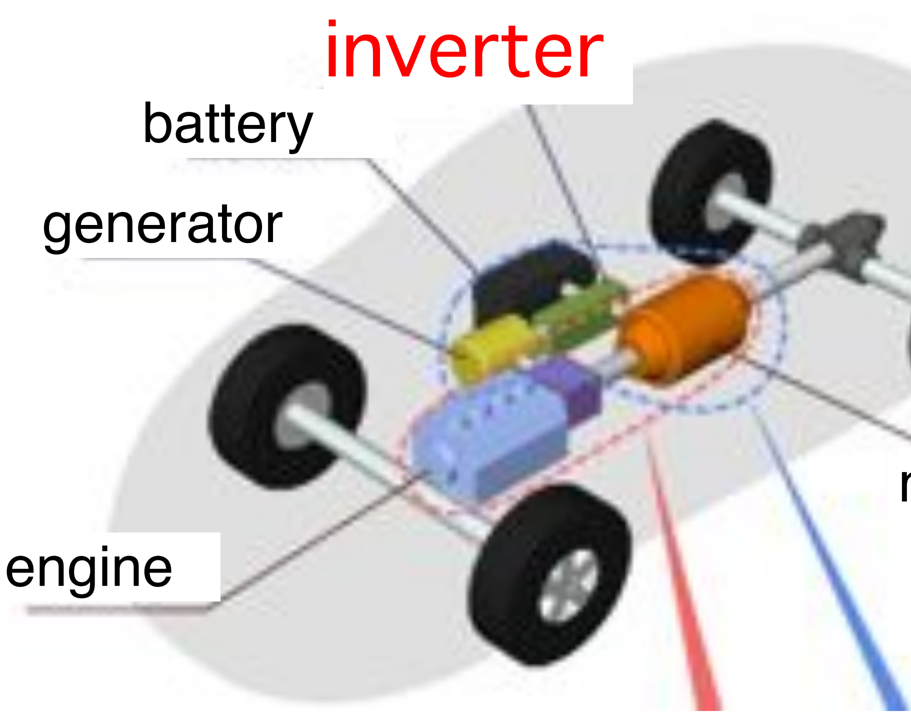
Most of them are once converted to electricity, because the electricity is very handy for energy transportation and distribution in various forms of DC/AC, amplitude and frequency.

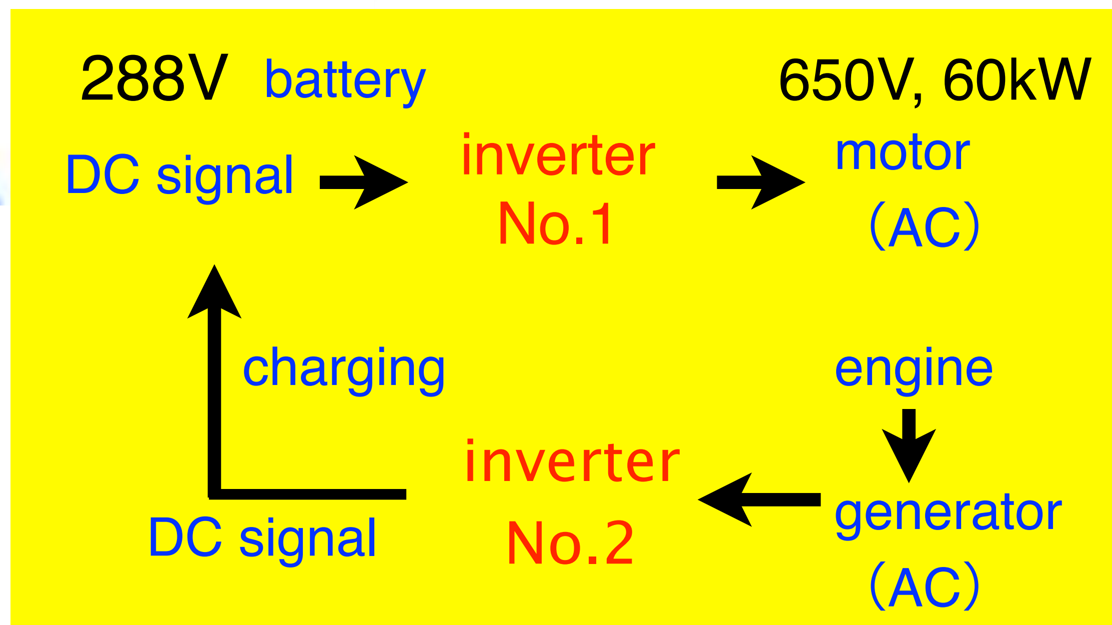


At each power conversion process, Si-based inverter devices (IGBTs) play important roles at present.

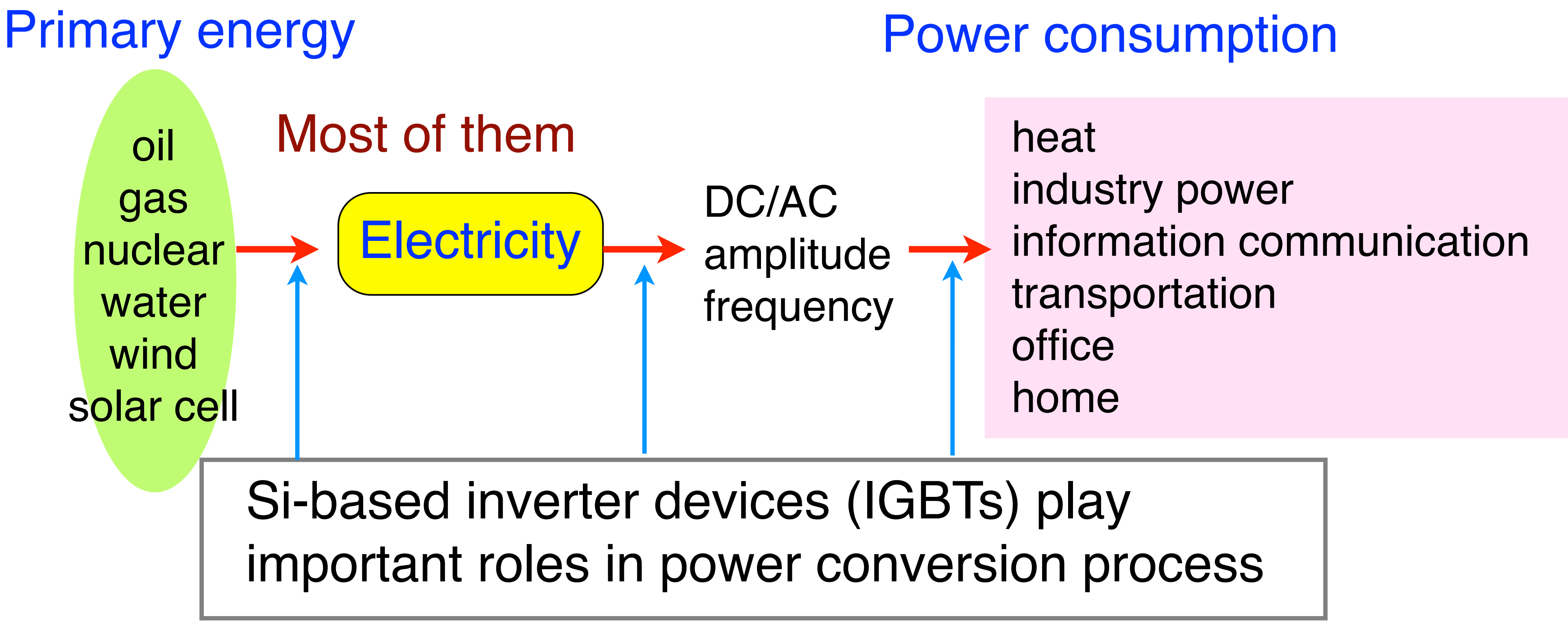
Example: Inverter system for hybrid cars

Hybrid car





Importance of power inverters for energy saving

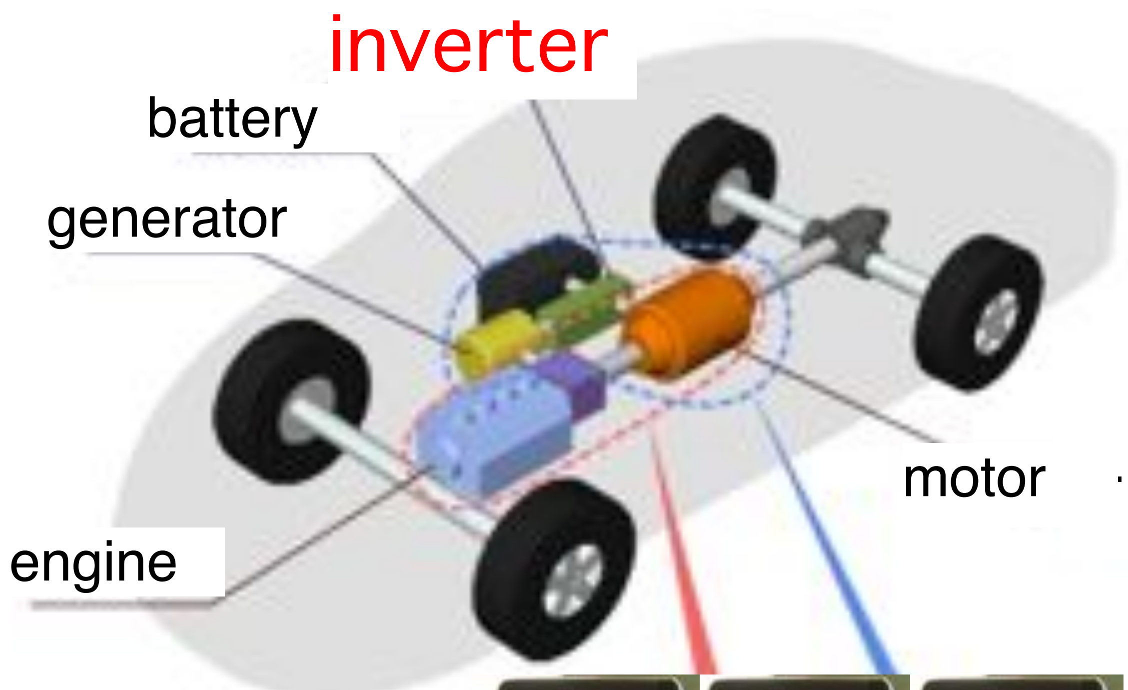


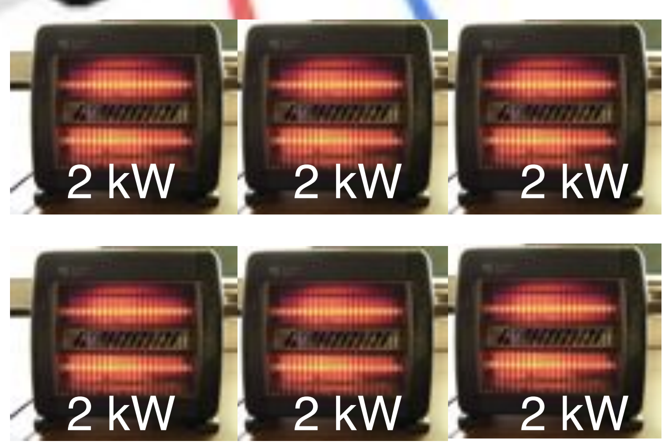
Efficiency of present inverter : 80~ 90%
10~20% loss still remains !!
mainly due to material limit of Si

For next-generation energy saving society, we need an ultra-low loss inverter system.

Power loss of inverter system in Hybrid car

Hybrid car





Inverter efficiency: 80~ 90%

10~20% loss

Example:

Prius uses 60-kW motor.

60 kW x 0.2= 12 kW (heat)

↓

corresponding to
6 electric heaters

Basic material properties of Si, GaAs and GaN

GaN group Hokkaido University

	E_G (RT)	Electron mobility (cm^2/Vs)	Saturation velocity (cm/s)	Electron density (cm^{-2})	Breakdown field (V/cm)
Si	1.11 eV	1500	1.0×10^7	1×10^{13} (MOS)	0.3×10^6
GaAs	1.43 eV	8000	2.0×10^7	2×10^{12} (HEMT)	0.4×10^6
GaN	3.4 eV	2000	2.7×10^7	2×10^{13} (HEMT)	3.0×10^6
(AlN)	(6.2 eV))				

↓ high-temperature operation

↓ high-frequency operation

↓ high-current operation

↓ high-voltage operation

Figure of merit for power-switching transistor

Hokkaido University GaN group

On-state resistance R_{on} of transistor

$$R_{on} = \frac{V_B{}^2}{\varepsilon \mu E_{\max}^{3}}$$

denominator term

Baliga figure of merit (BFM)

high E_{max}

↓

extremely low R_{on}

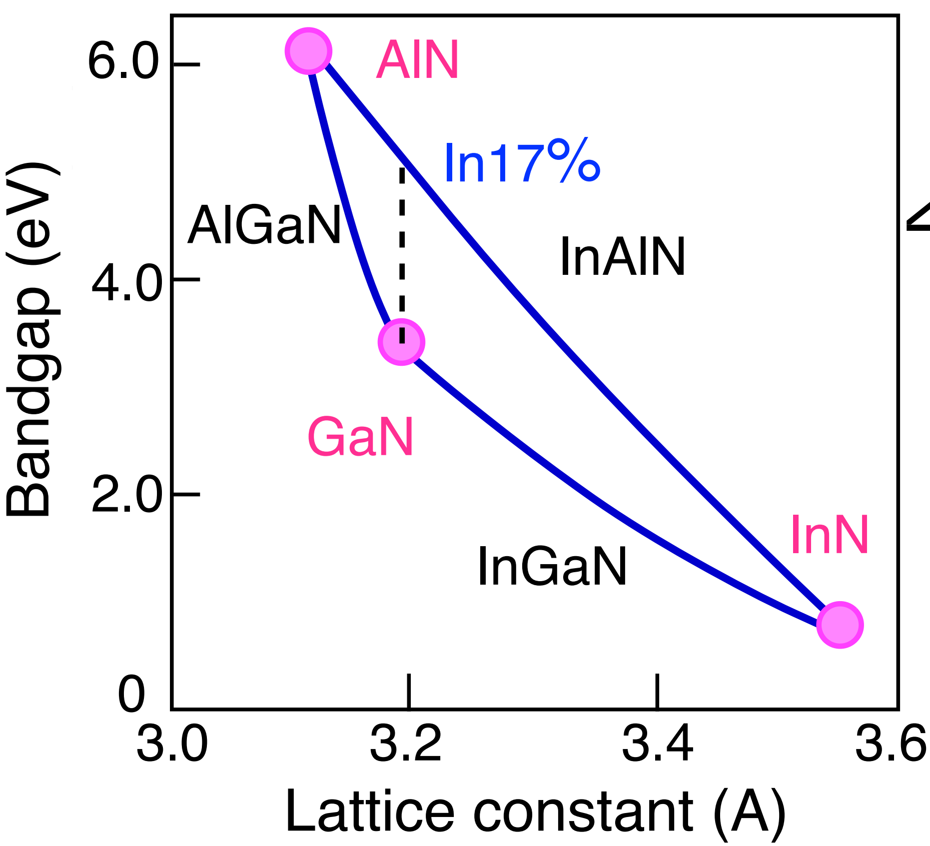
↓

Material	Breakdown field (MV/cm)	Baliga FM
Si	0.3	1
GaAs	0.4	15
4H-SiC	3.0	400
GaN	3.0	400

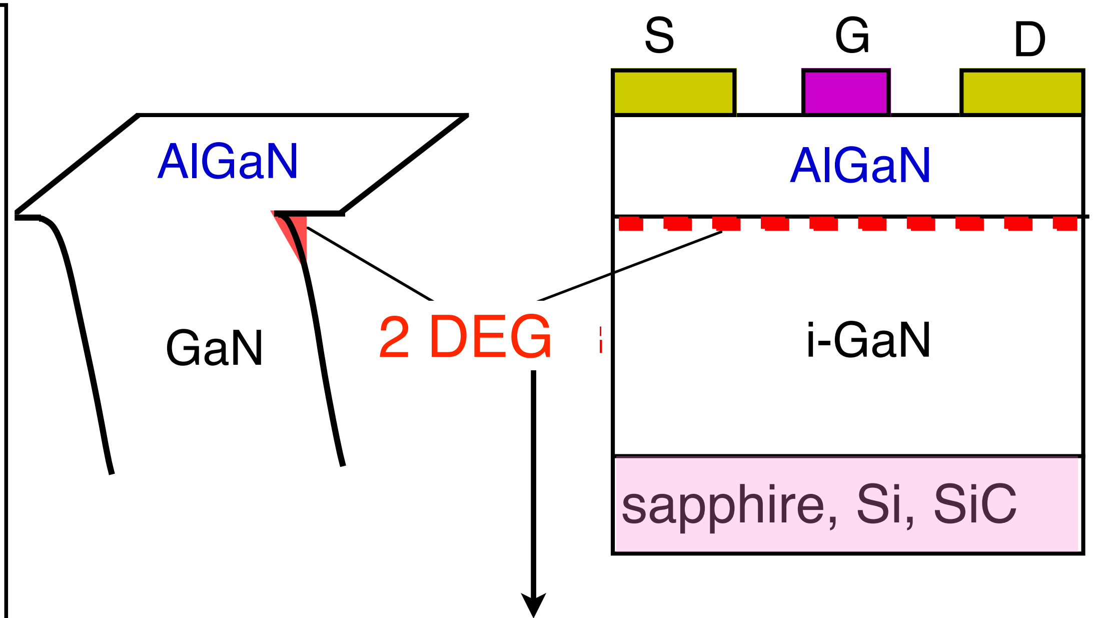
GaN transistor is attractive for ultra-low loss inverter

Advantage of GaN transistors
Use of various kinds of heterostructures

E_G: 1 ~ 6 eV



AlGaN/GaN heterostructure
is generally used for transistor

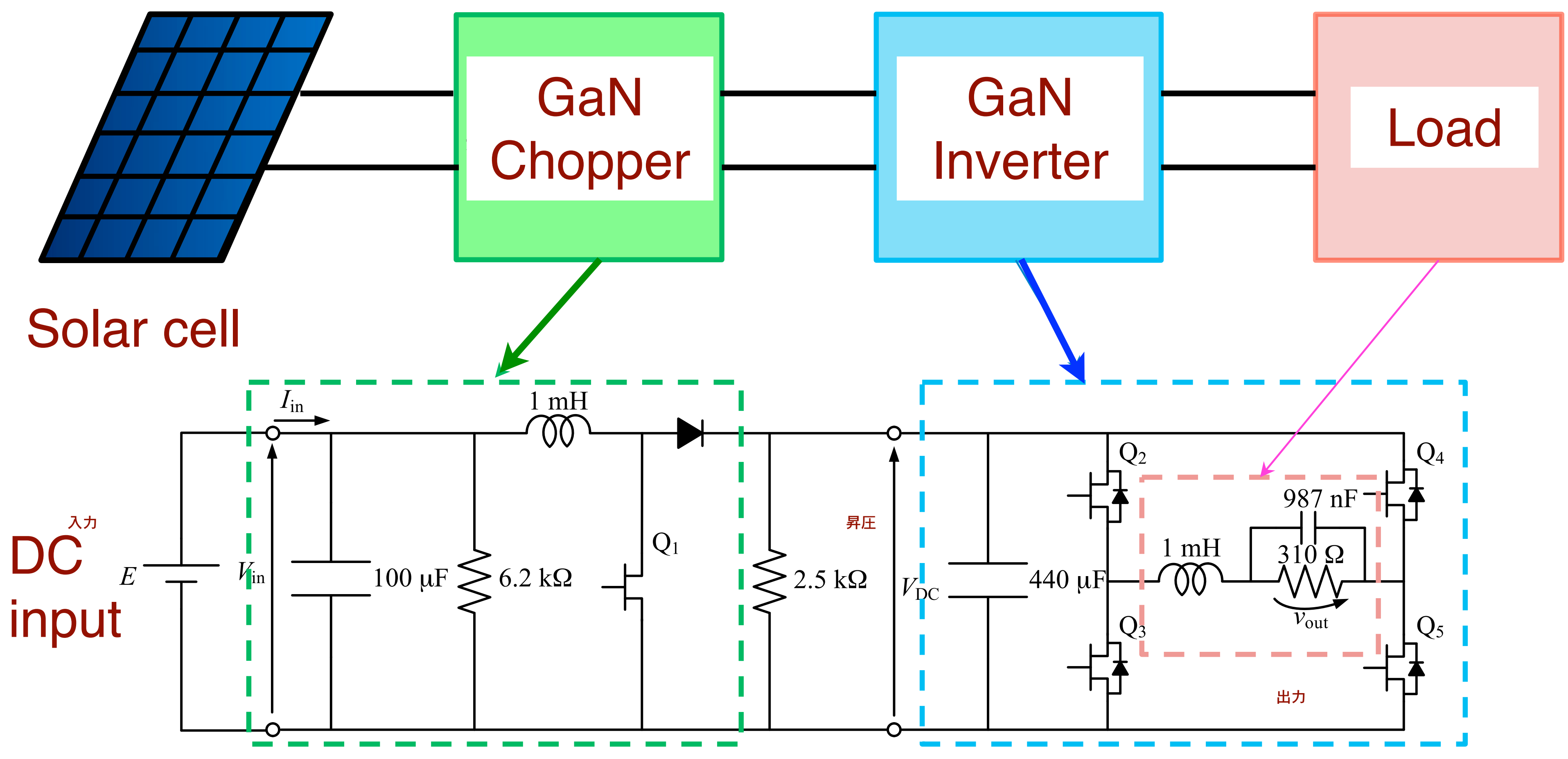


N_S ~ 1 x 10^{13} cm^{-2}
μ ~ 1500 cm^2 /Vs

GaN family has a variety of heterostructures
which cover bandgap range from 0.7 to 6.0 eV.

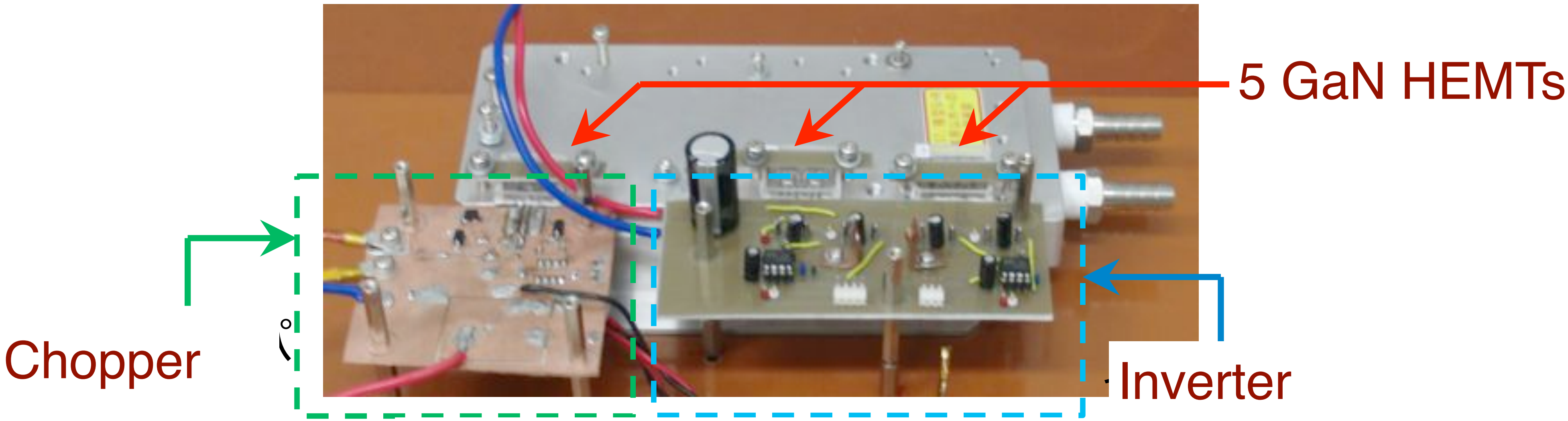
GaN Inverter system for solar cell power conditioner

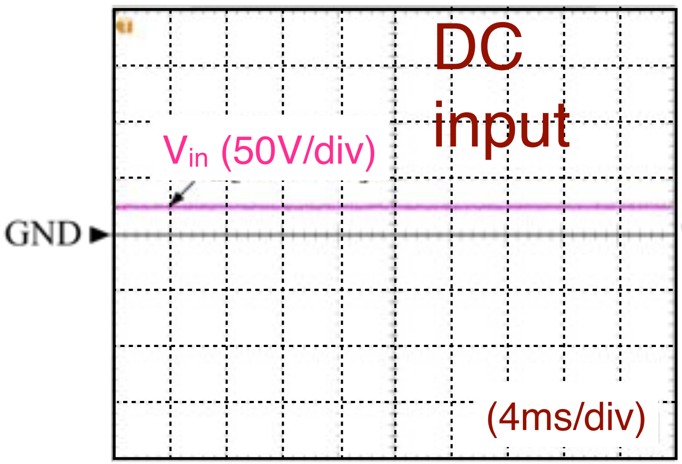
Joint research between Hokkaido Univ., Toyota Central R/D Labs. and Yamaguchi Univ.

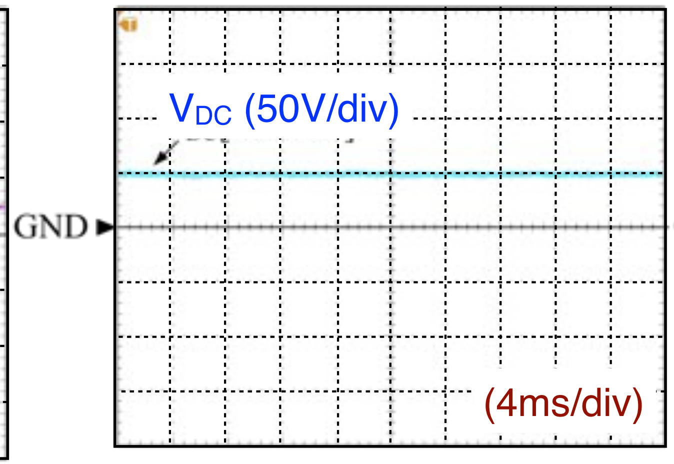


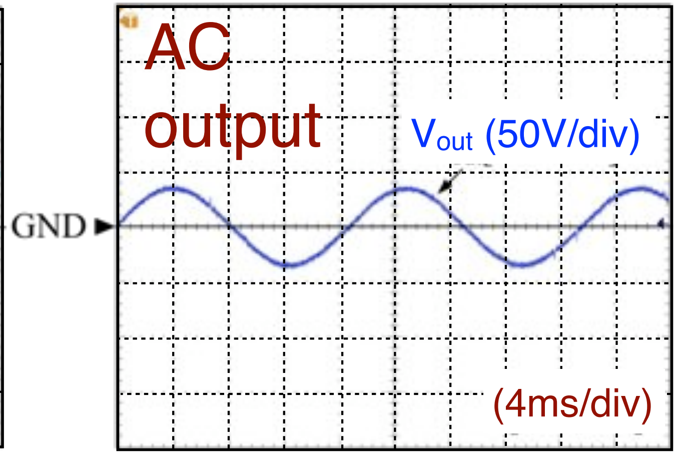
GaN Inverter for solar cell power conditioner

Fabricated GaN inverter system









DC input is successfully converted to beautiful AC signal, because we can use a high-switching frequency of 500 kHz.

Research issues for GaN inverter

There remain issues to be solved for GaN transistors

1) Substrate

2) Characterization and control of deep levels

3) MIS (MOS) gate technology

4) Control of threshold voltage

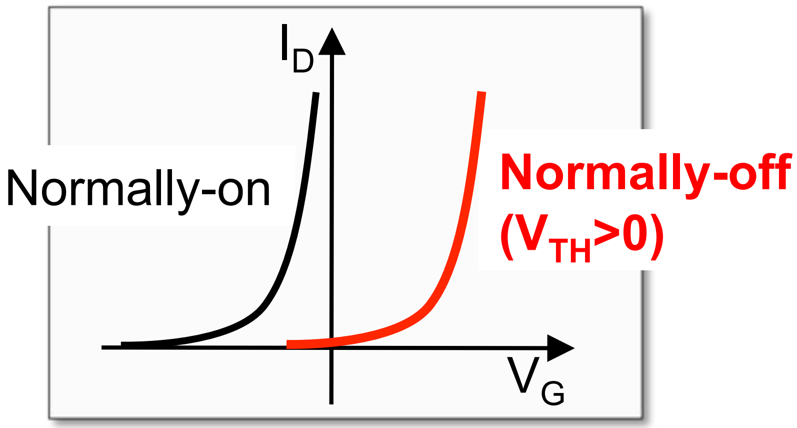
5) Reliability and stability

6) Design, fabrication and characterization of optimum device structure for GaN HEMT

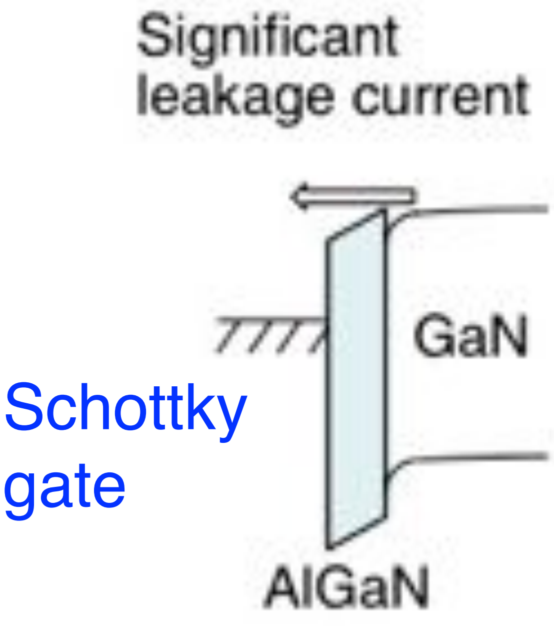
Effects of process condition on electrical properties of Al_2O_3/n-GaN prepared by atomic layer deposition (ALD)

Importance of MOS (MIS) gate structure

Normally-off operation is required for failure safe of inverter.

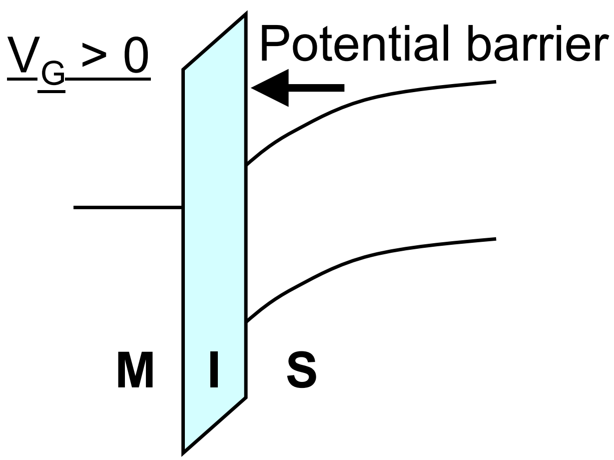


Forward bias operation



0)

Insulated-gate structure

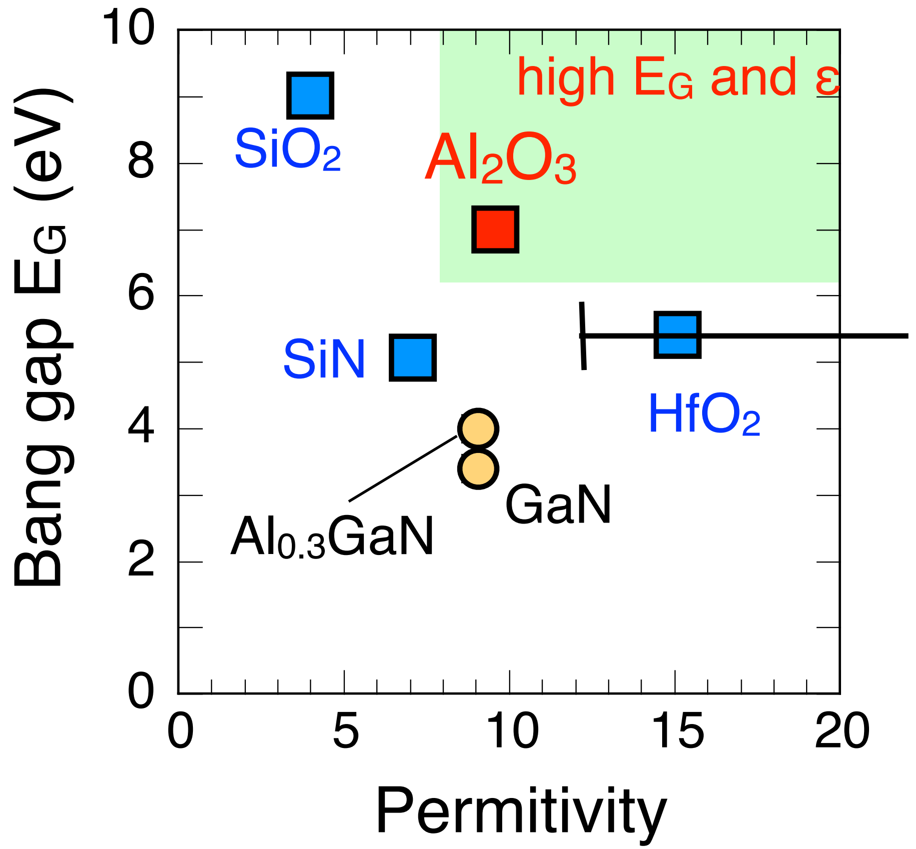


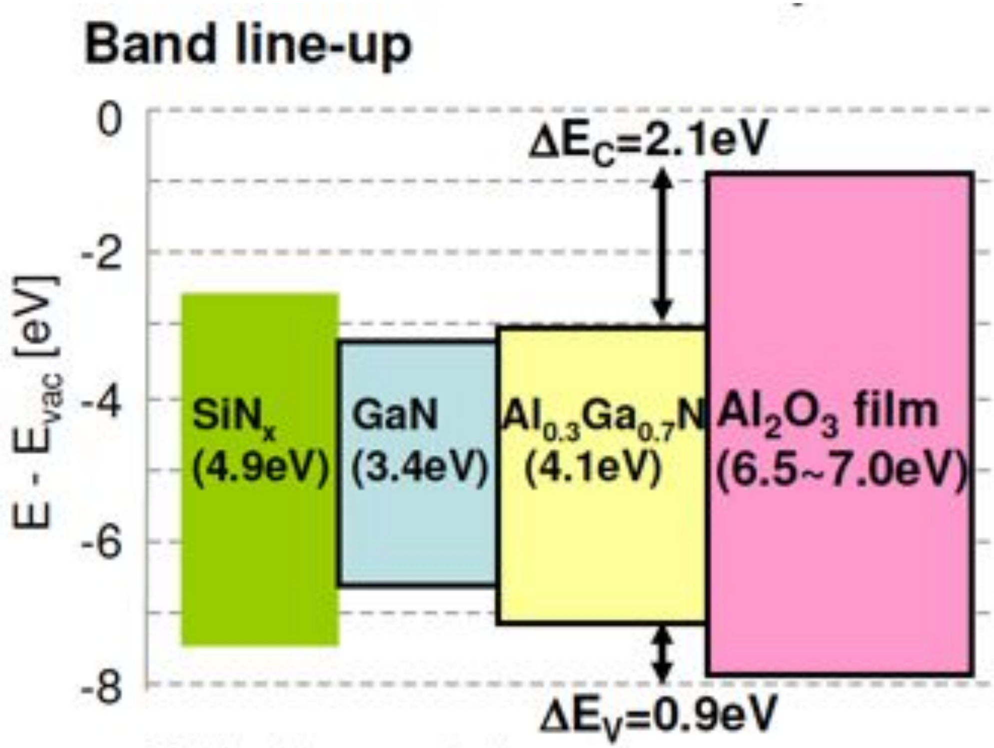
Suppression of gate leakage current
Enhancement of dynamic range of input signal

Indispensable for the improvement of operational performance and stability in the power-switching transistors

Why Al_2O_3 ?

It is not so easy to choose a suitable dielectric for GaN-based transistors due to their wide-gap nature.





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J. Vac. Sci. Technol. B, **21(4)**, (2003), 1828

SiN is good insulator for Si or GaAs. But its bandgap is not enough to produce high potential barrier for GaN or AlGaN

Our choice is Al_2O_3

E_G ~ 7 eV
ε: 9 ~ 10

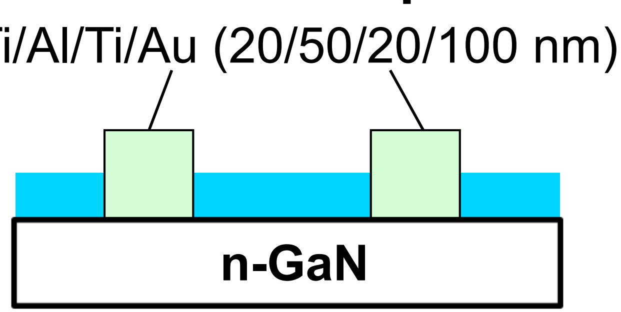
Fabrication of MIS structure : “deposition-first” process

1. Pretreatment(30%-HF、5min.)

2. ALD deposition of Al_2O_3
(at 250°C)

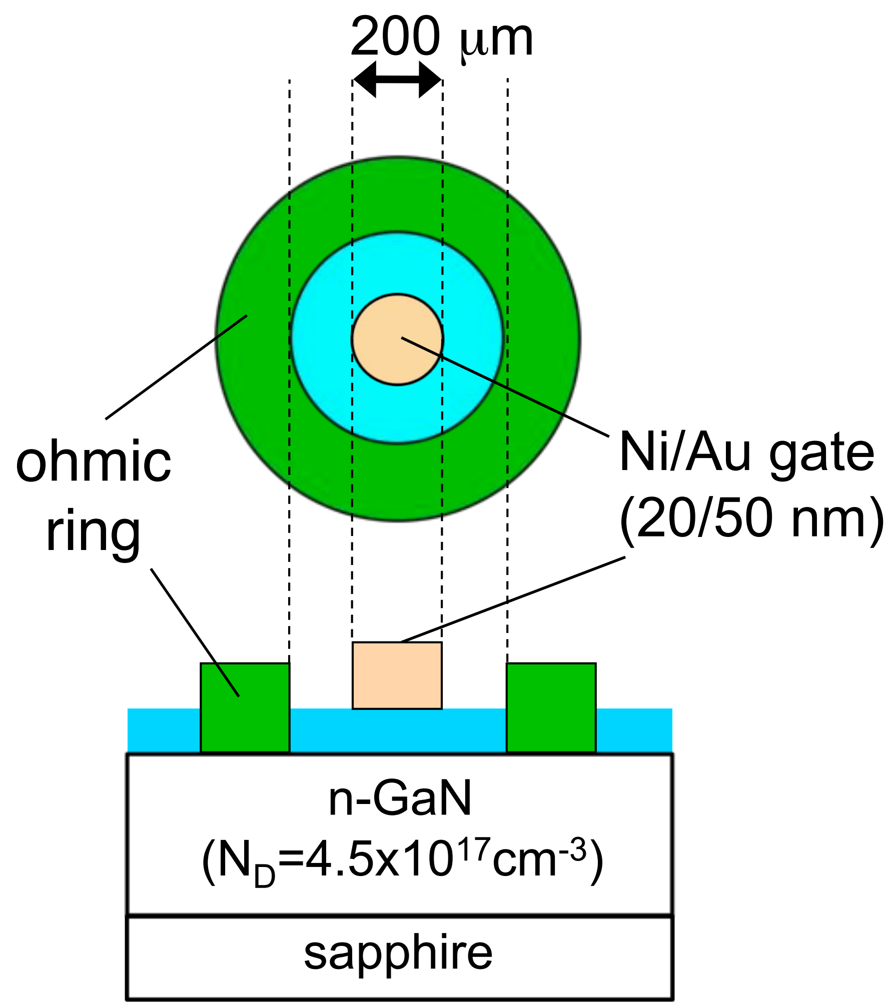
3. Post-deposition-annealing
(400°C, 15mi, N_2 ambient)

4. Ohmic electrode evaporation

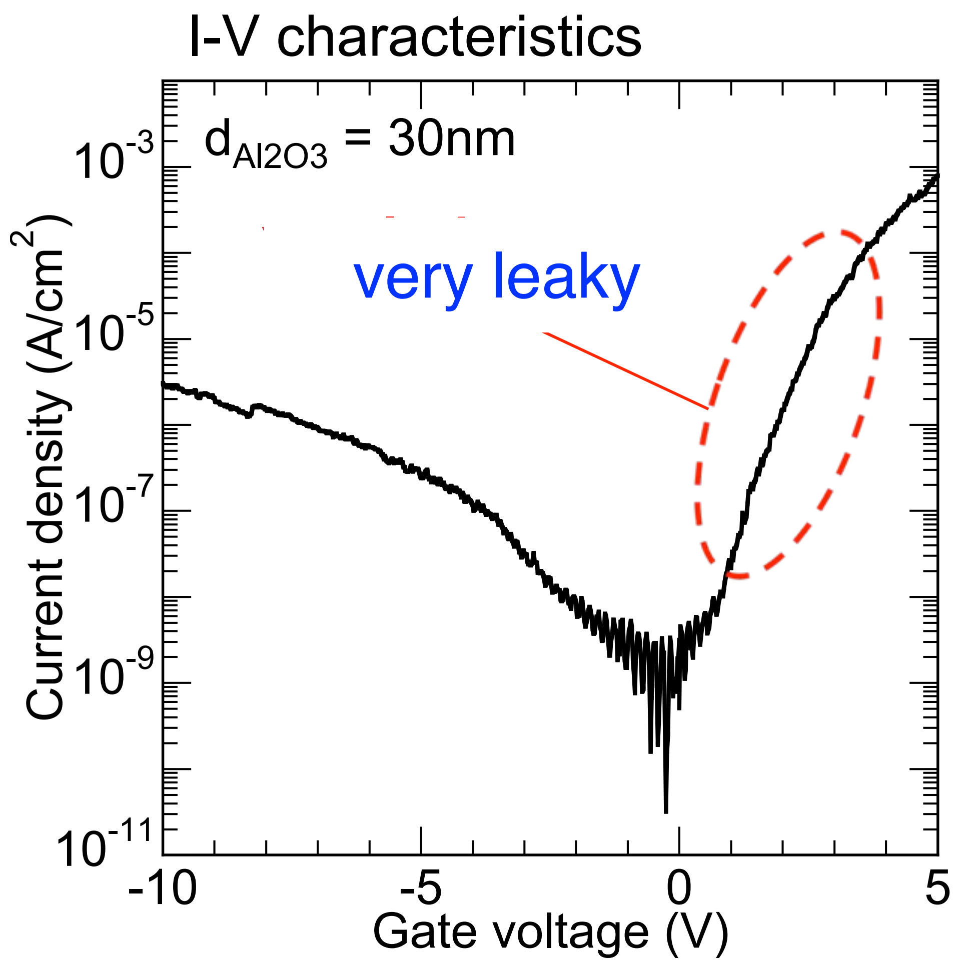


5. Ohmic-annealing
(800°C, 1min, N_2 ambient)

6. Gate electrode evaporation

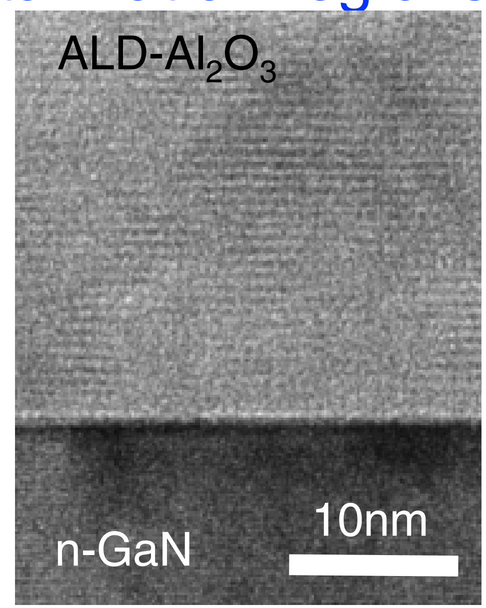


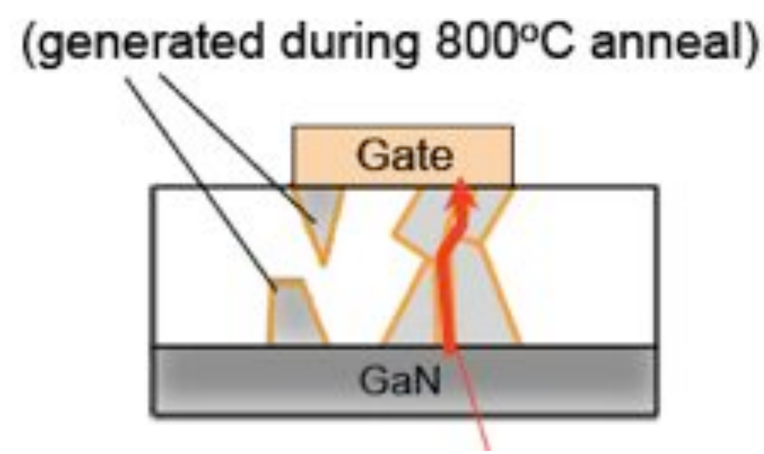
I-V curve and TEM observation



high leakage currents
at both bias directions

large numbers of nano-
crystallization regions





grain boundaries act as leakage paths

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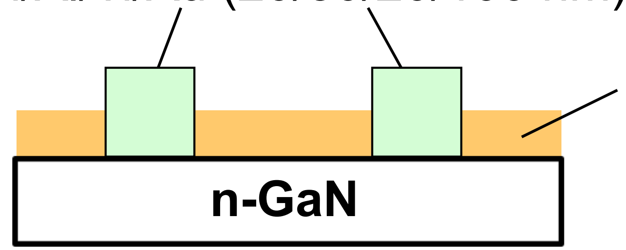
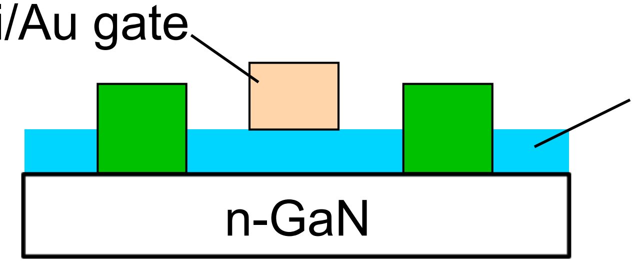
“Ohmic first + surface protection” process

1. Deposition of SiN protection layer at the GaN surface
2. Ohmic electrode evaporation

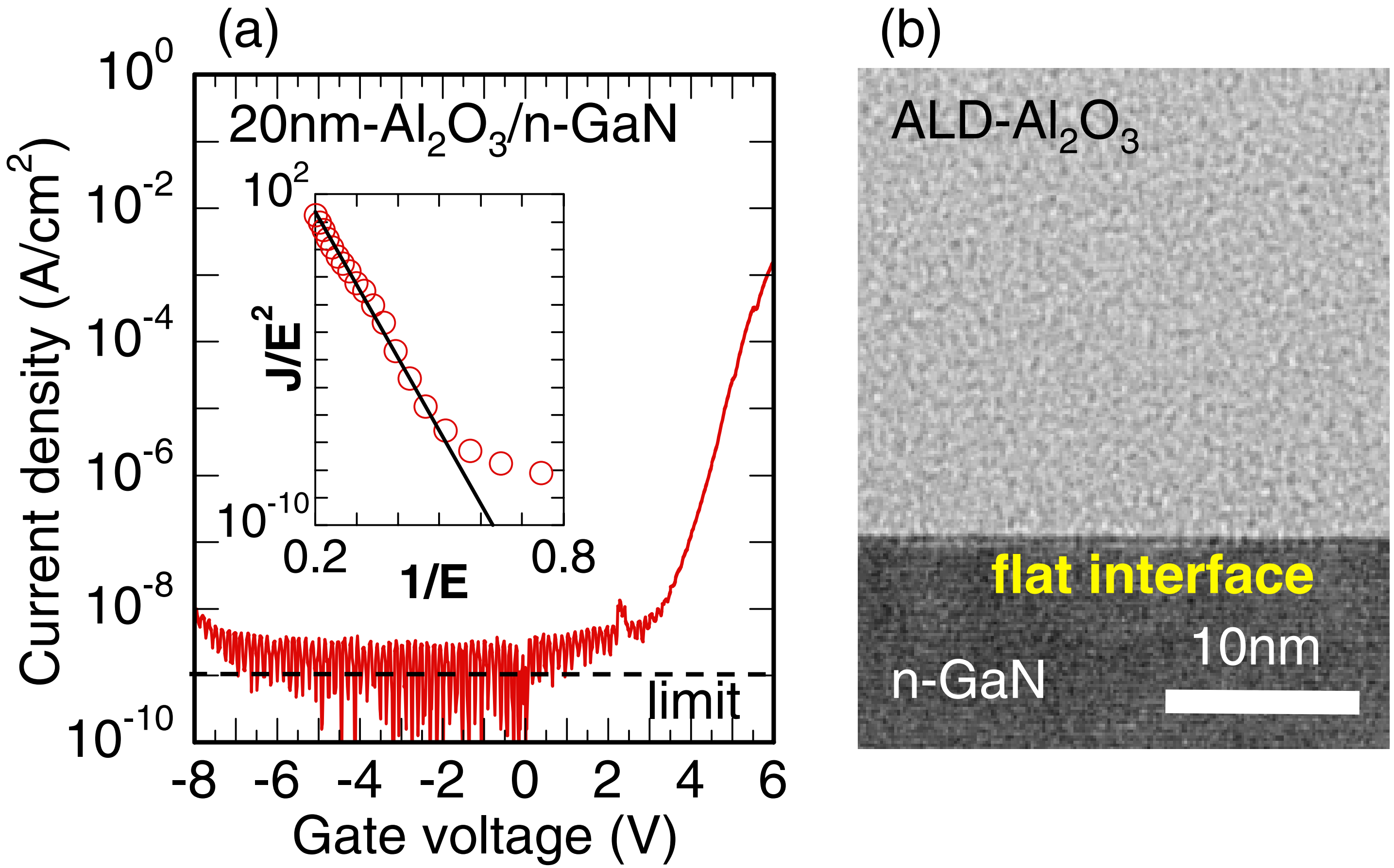


3. Ohmic-annealing（800°C, 1 min, N_2 ambient）
4. Removal of surface protection layer with Buffered HF

5. Formation of the gate insulator and electrode



TEM image and I-V curves



An amorphous phase was kept in the atomic bonds of Al_2O_3.

The “ohmic-first” process suppressed the leakage current effectively.

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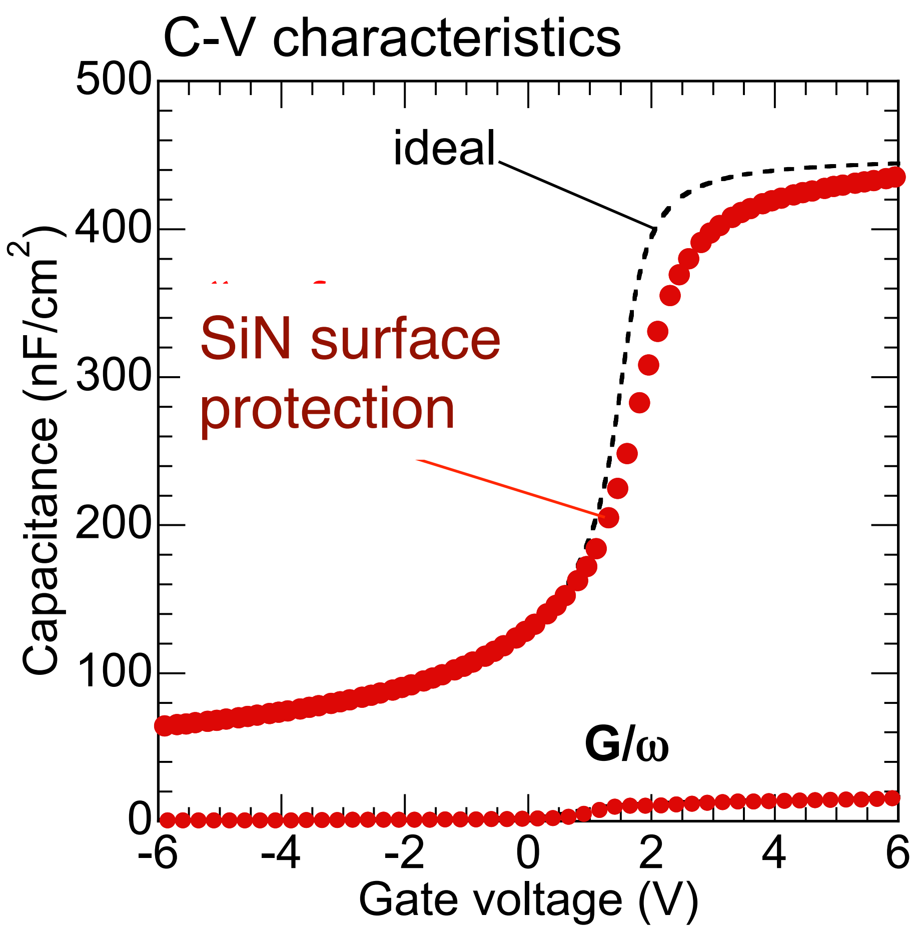
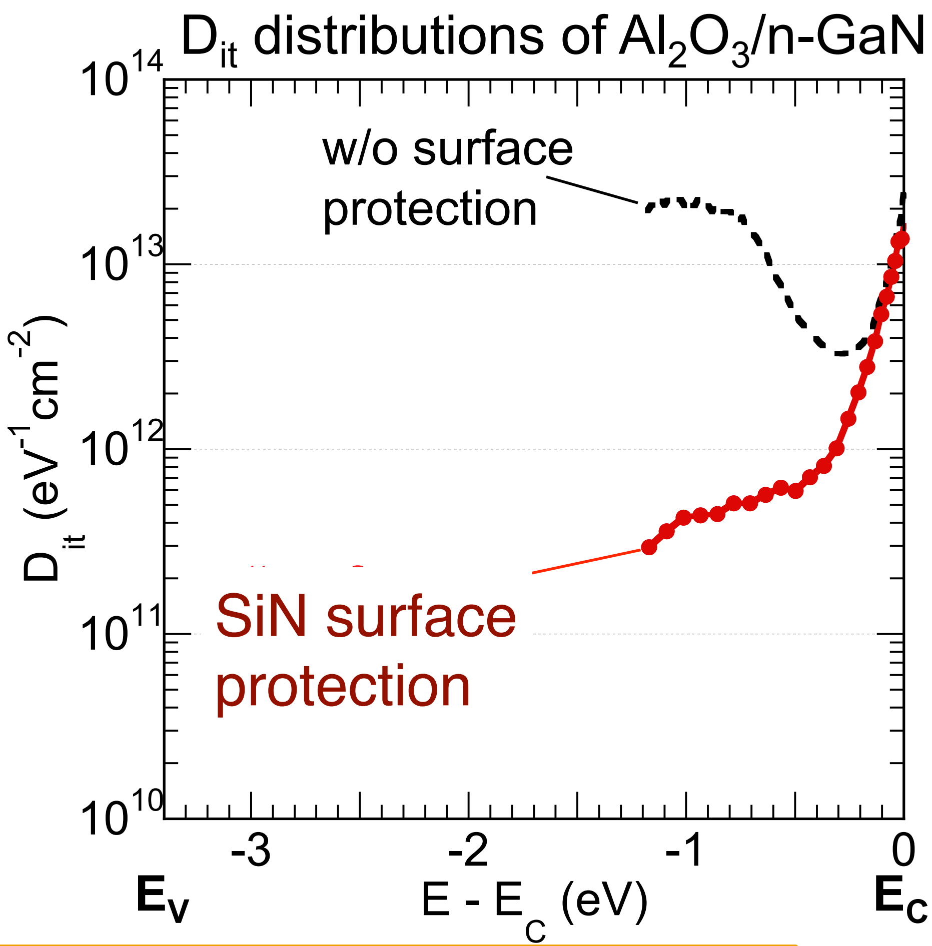
C-V characteristics of Al_2O_3/n-GaN strcuture prepared by “Ohmic first + surface protection” process





The surface protection layer could suppress N desorption and related chemical disorder at the GaN surface.

→ Reduction of interface states

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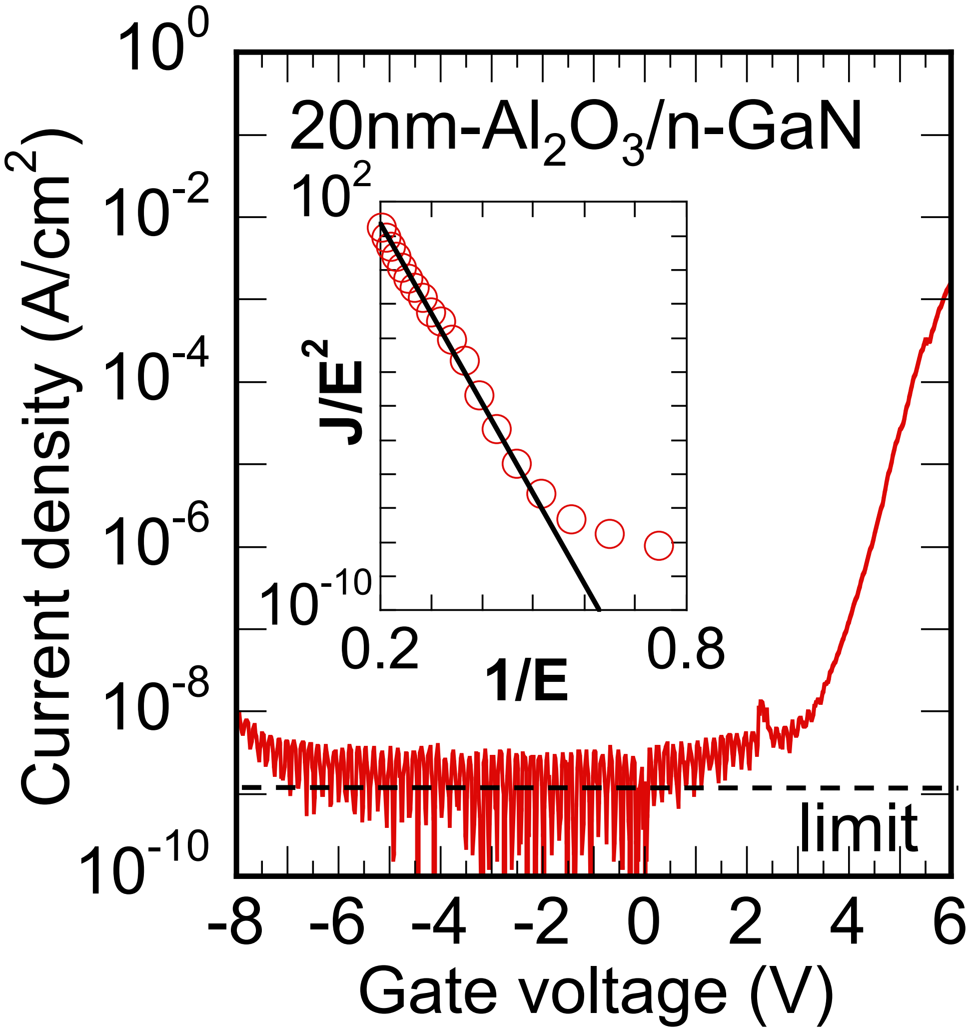
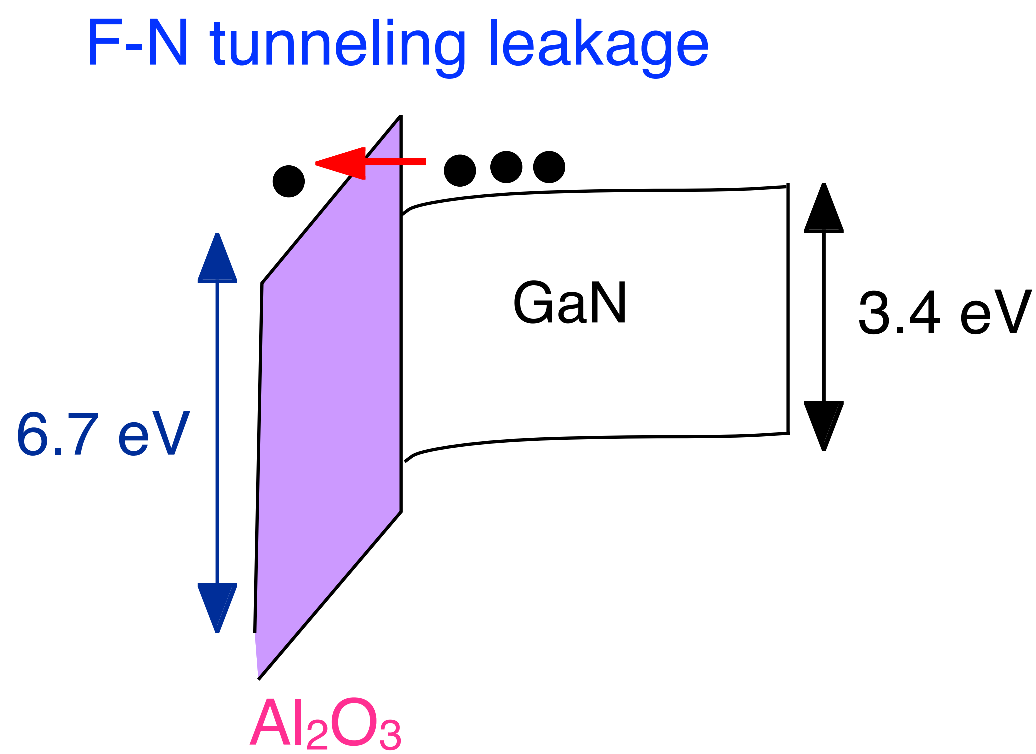
F-N leakage current at forward bias

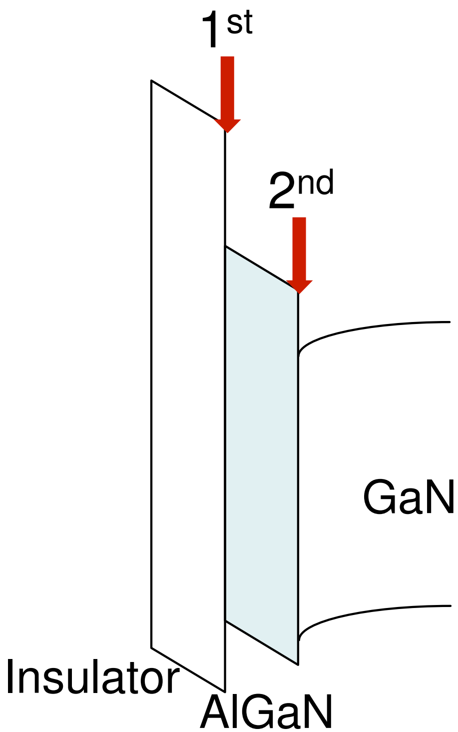


Fowler–Nordheim mechanism



Difficulty in C-V characterization of HEMT MOS structures

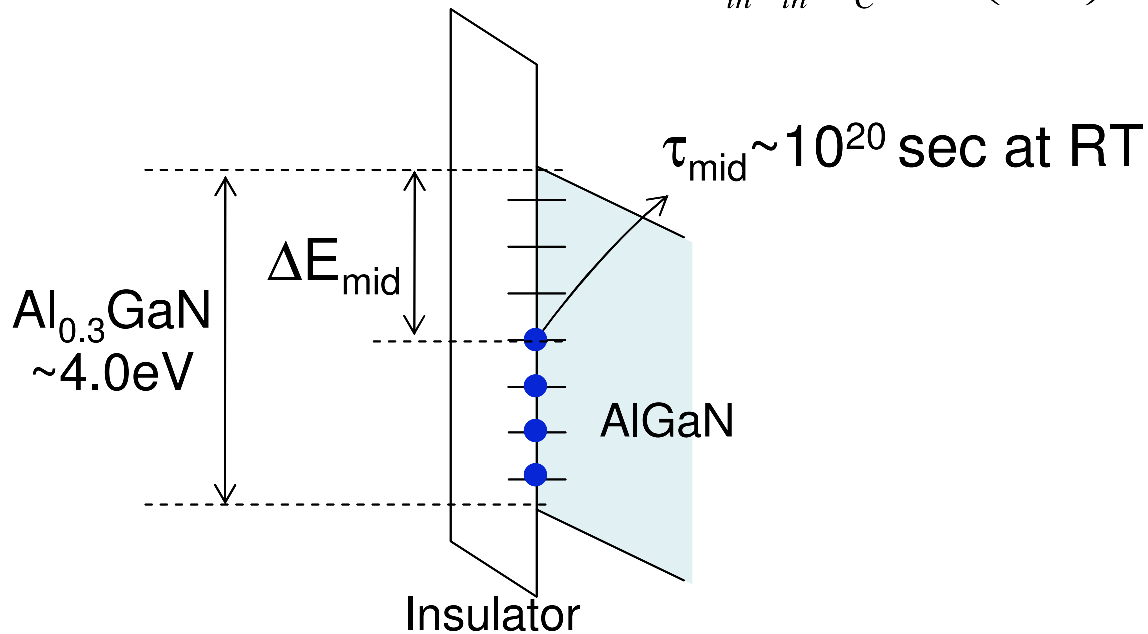
- Two interfaces:



makes the potential control complicated

- Shockley-Read-Hall statistic

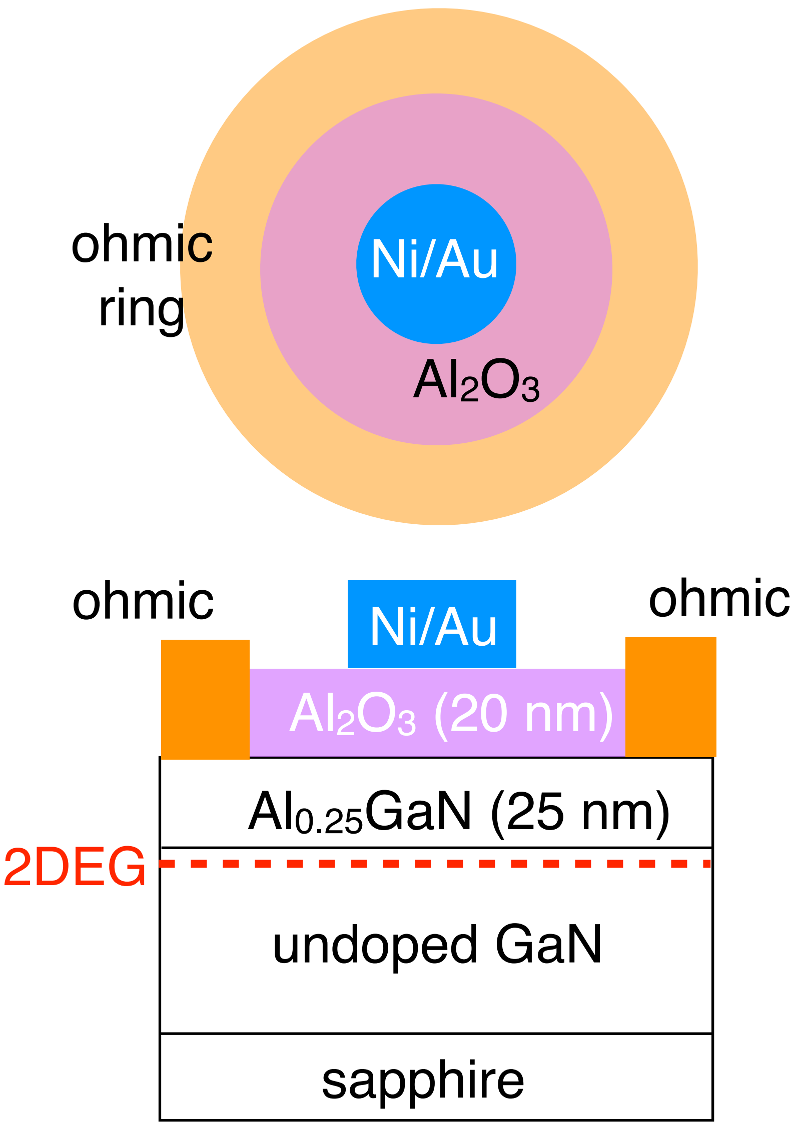
Emission time constant $\tau = \frac{1}{\sigma_{th} v_{th} N_C} \exp\left(\frac{\Delta E}{kT}\right)$

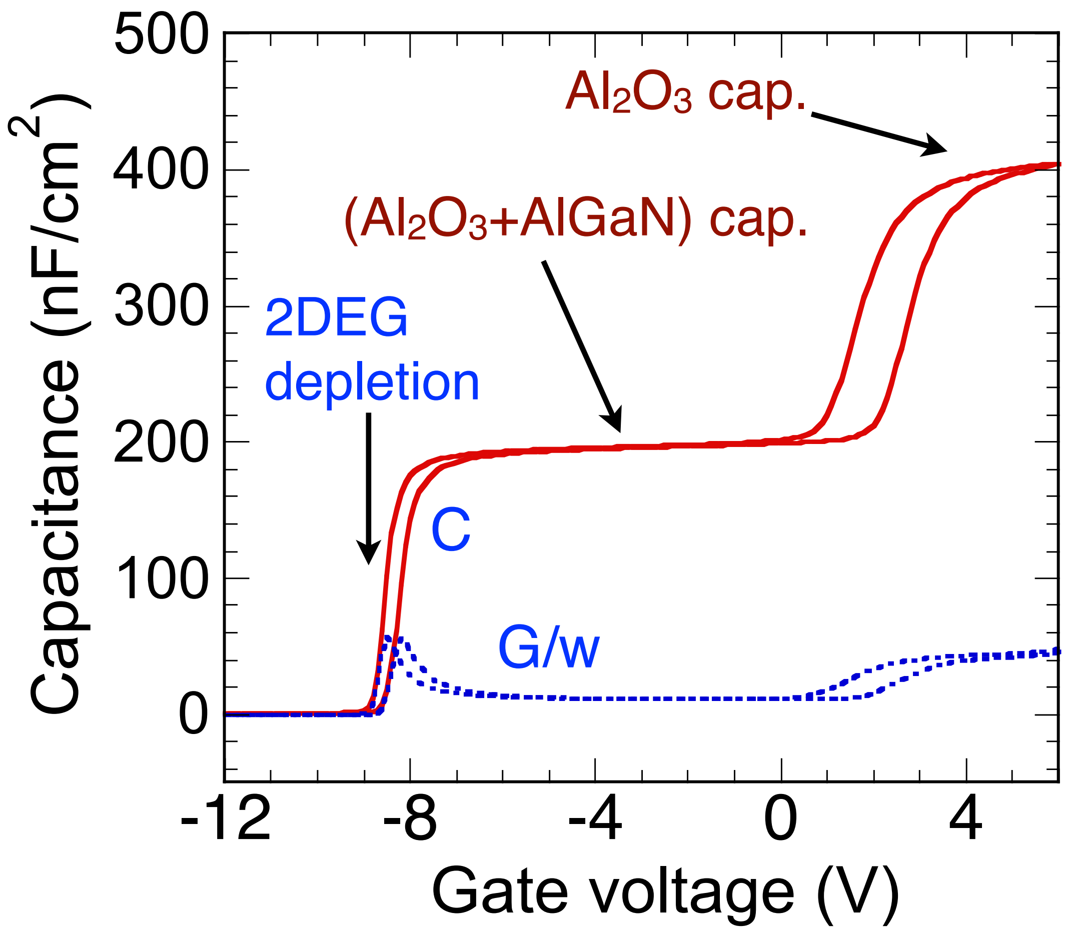


Large bandgap of AlGaN causes extremely long time for electron emission from the interface states near midgap or at deeper energies.

Then, we cannot change a charge condition of such deeper states by a bias sweeping in a standard capacitance-voltage measurement.

Typical C-V characteristics of Al_2O_3/AlGaN/GaN structure





characteristic feature:
two-step capacitance change

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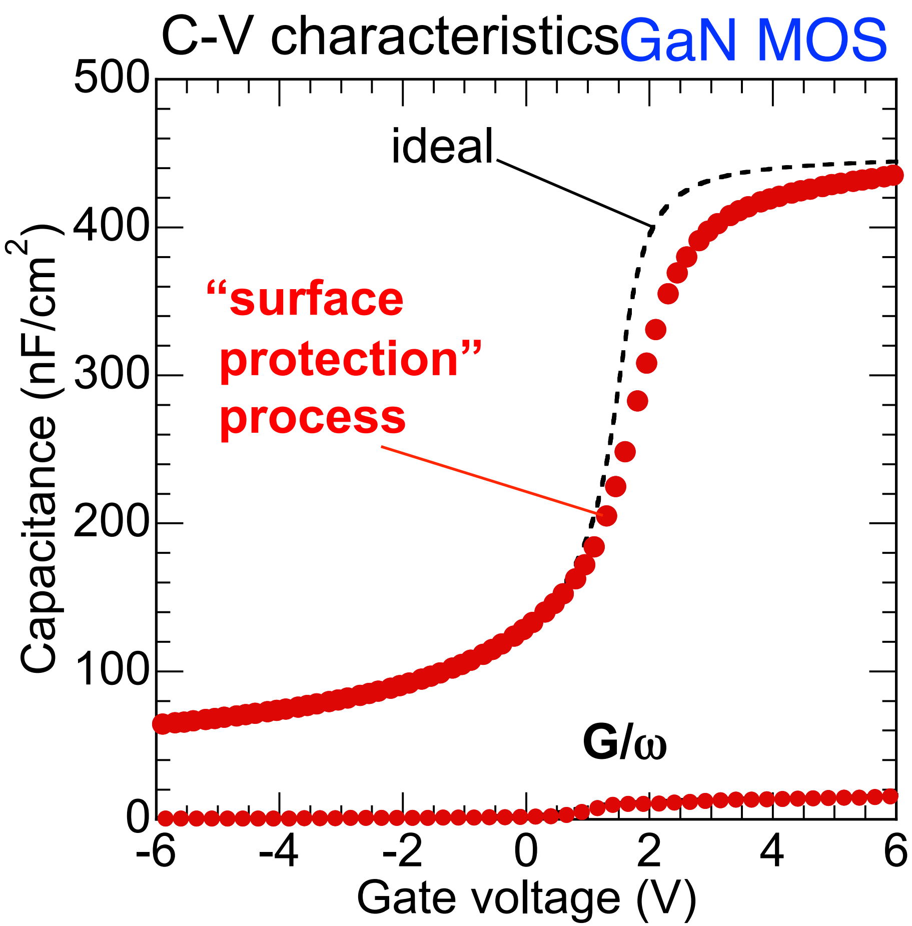
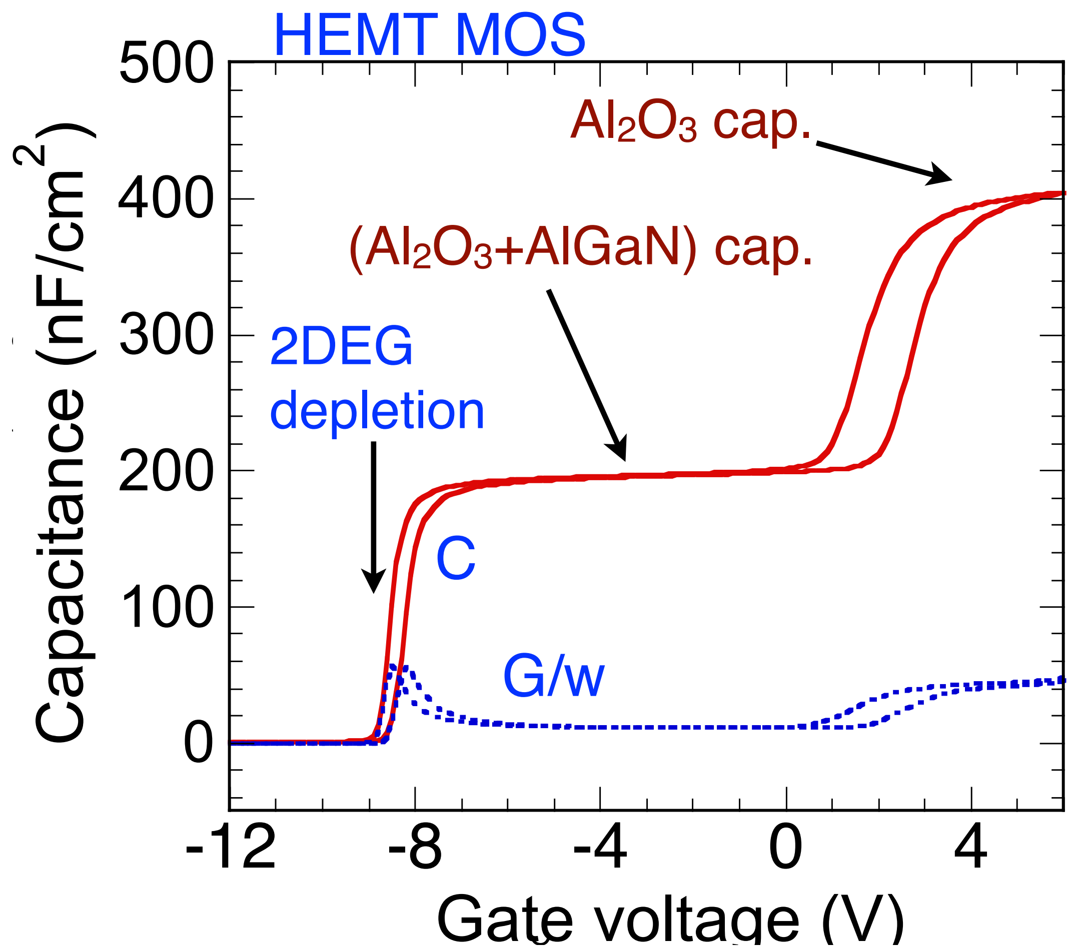
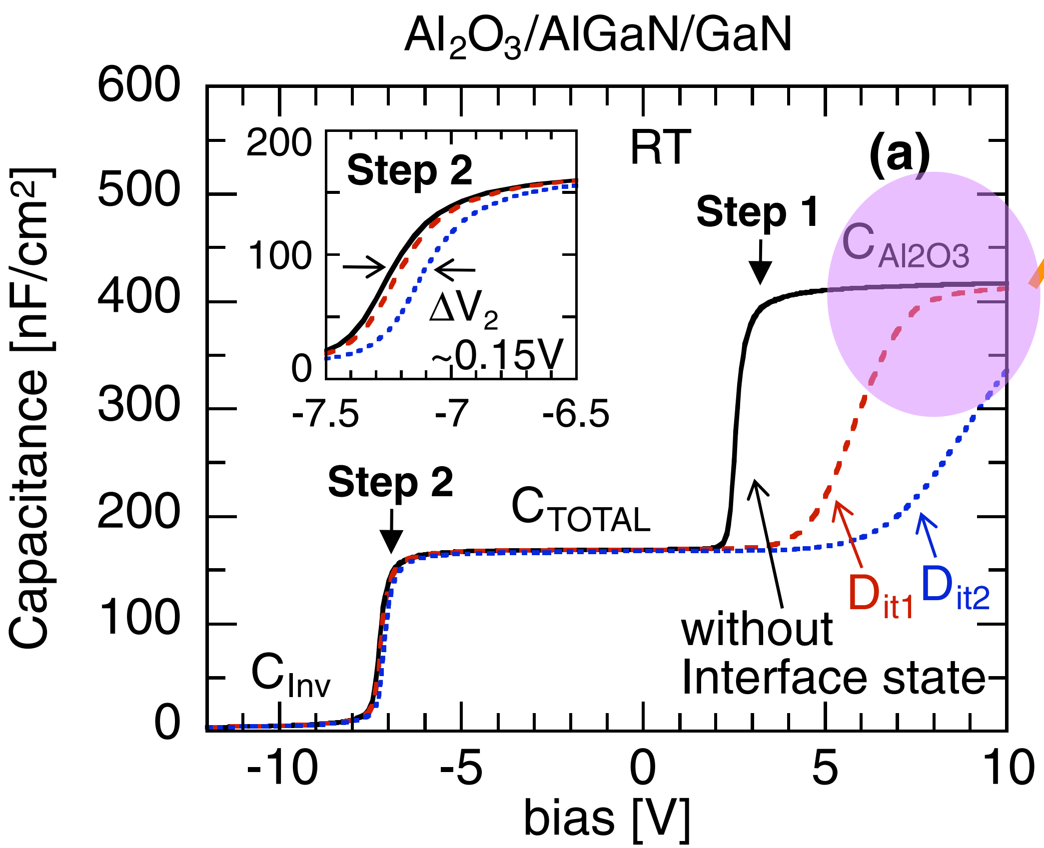
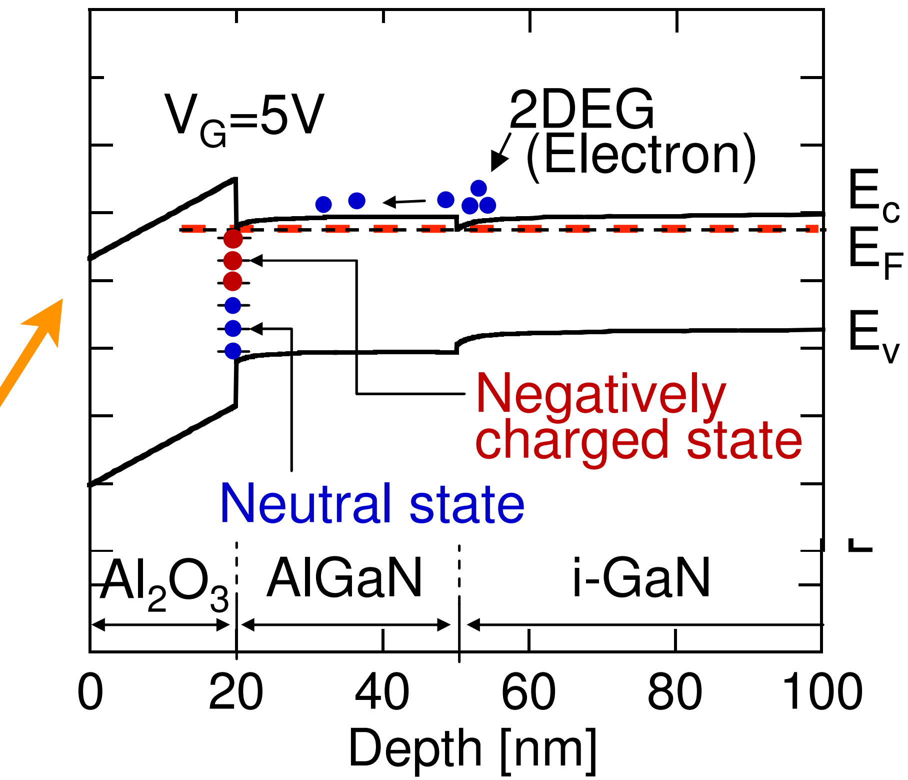
Typical C-V characteristics of Al_2O_3/AlGaN/GaN structure





Calculation of C-V curves and band diagrams



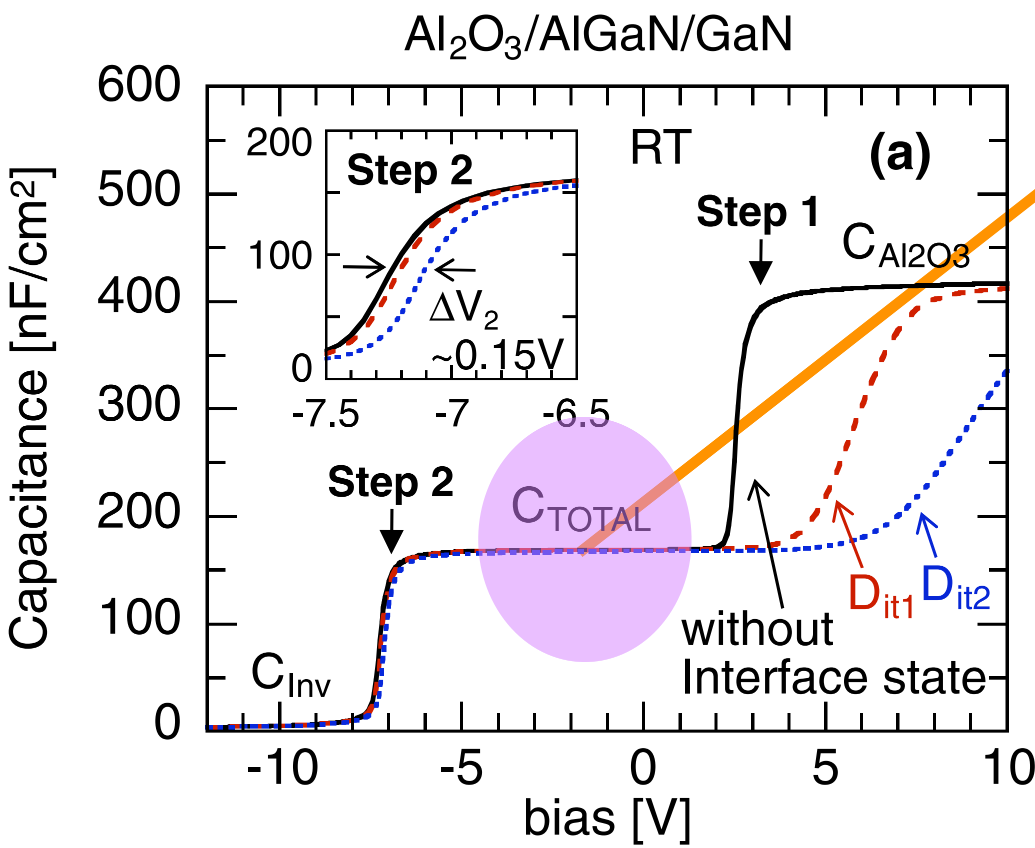


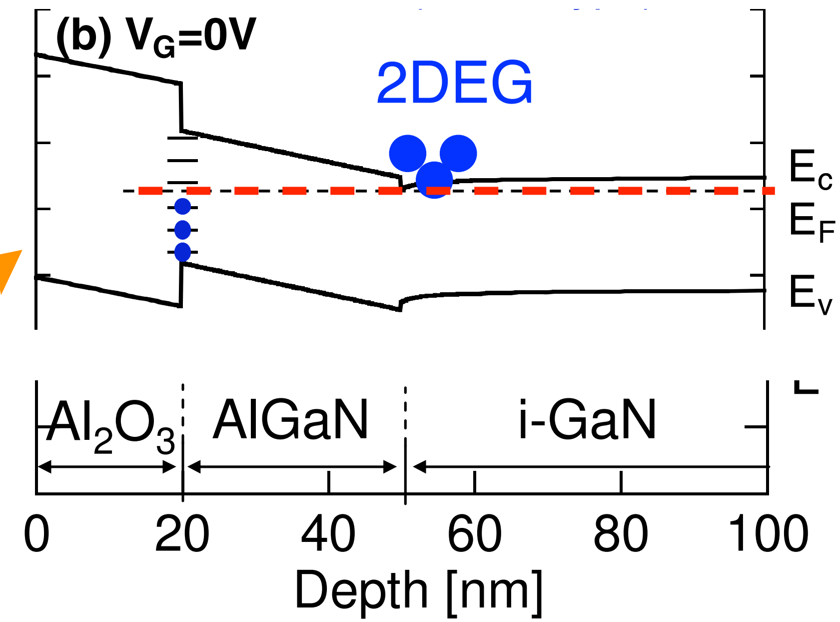
Electron accumulation at the Al_2O_3/AlGaN interface

↓

corresponding to C determined by the Al_2O_3 thickness and permitivity

Calculation of C-V curves and band diagrams



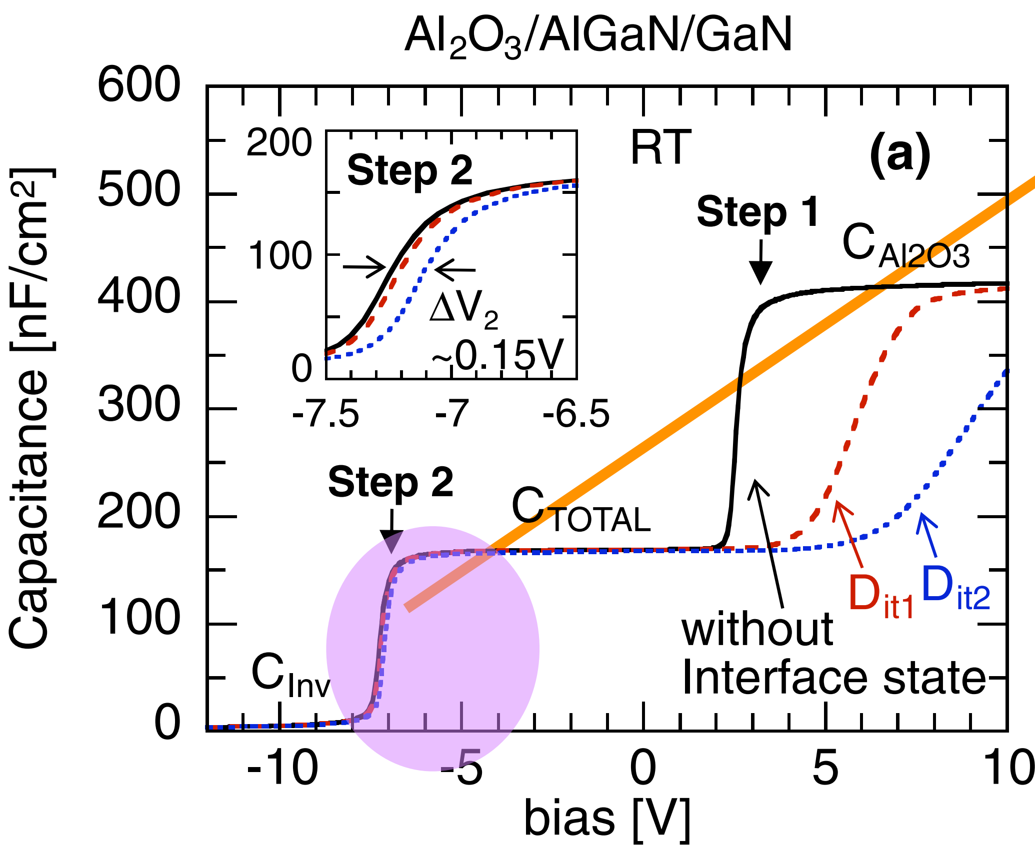


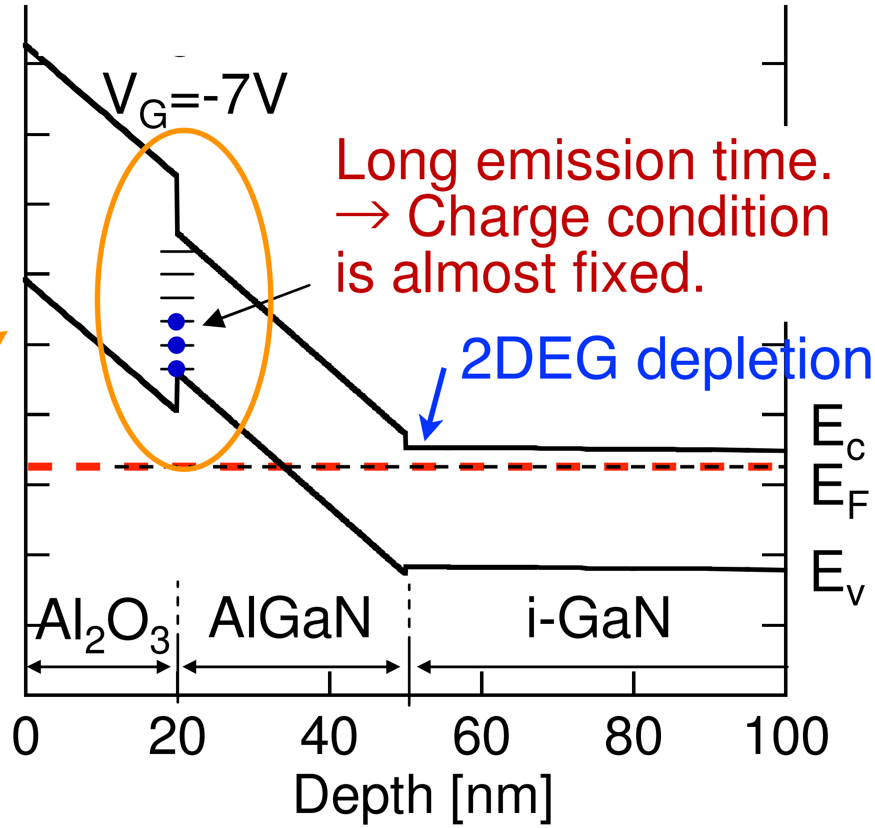
Electron accumulation
at the AlGaN/GaN interface

↓

corresponding to C determined
by the Al_2O_3 and AlGaN layer

Calculation of C-V curves and band diagrams





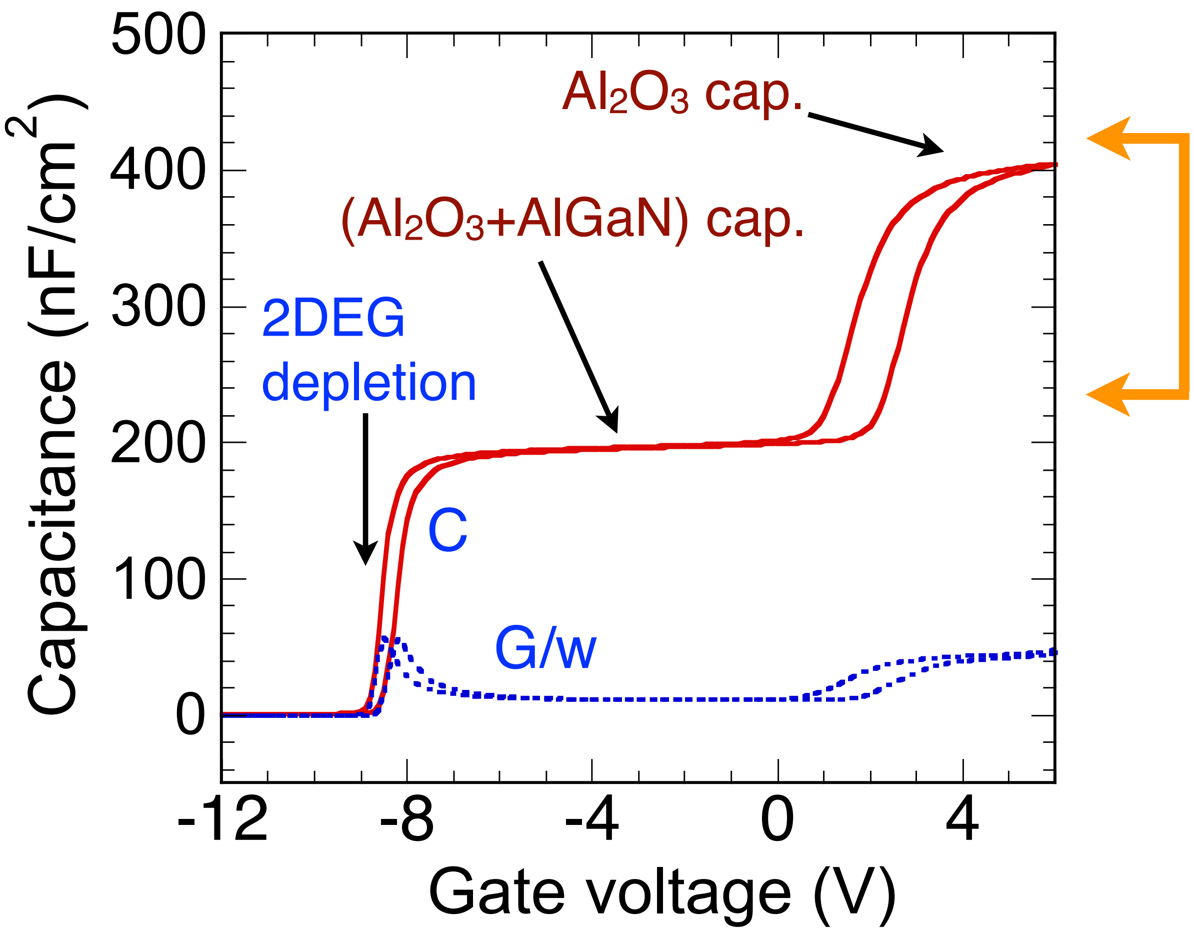
Long emission time.
→ Charge condition is almost fixed.

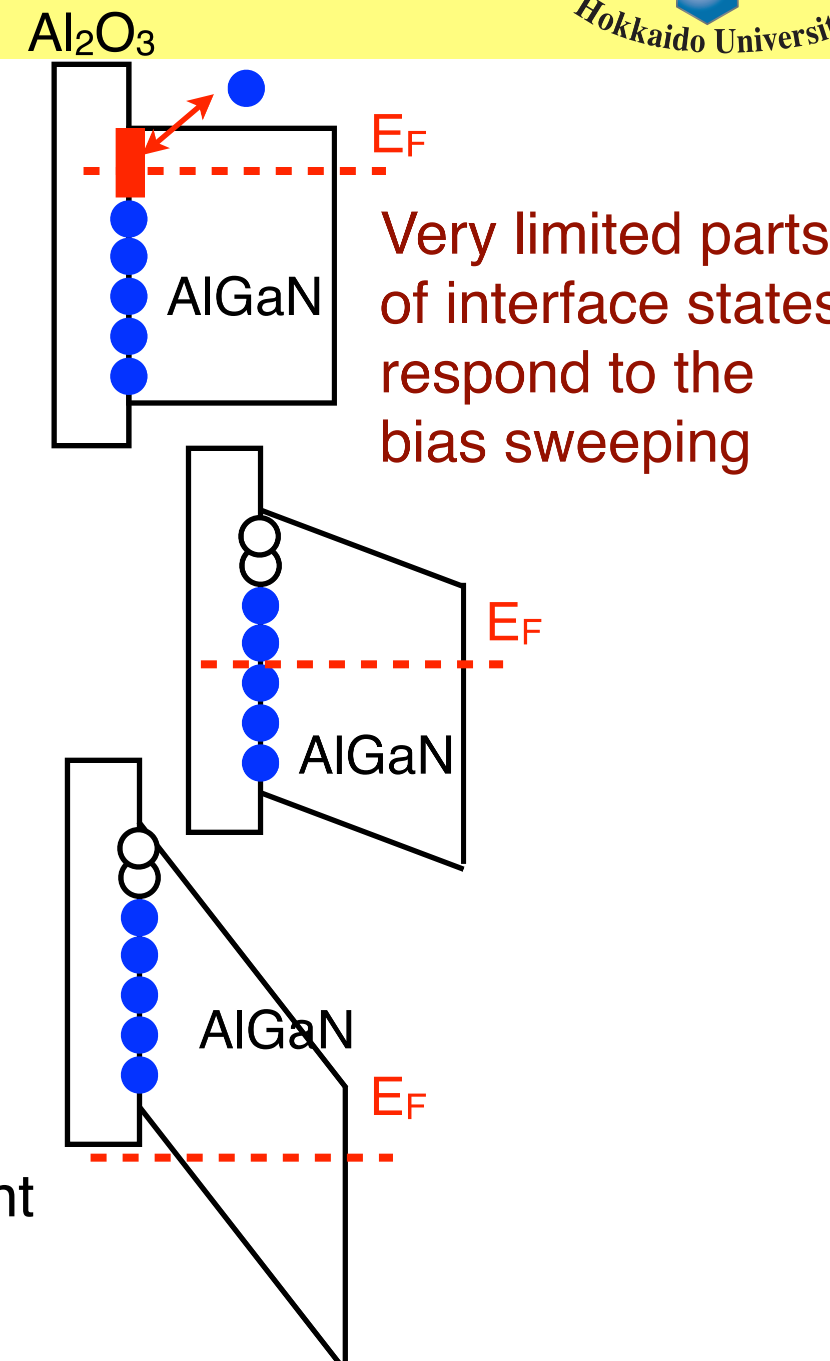
E_F is located far from the E_V top
Extremely long time for emission

↓

Interface states act as "fixed charge"

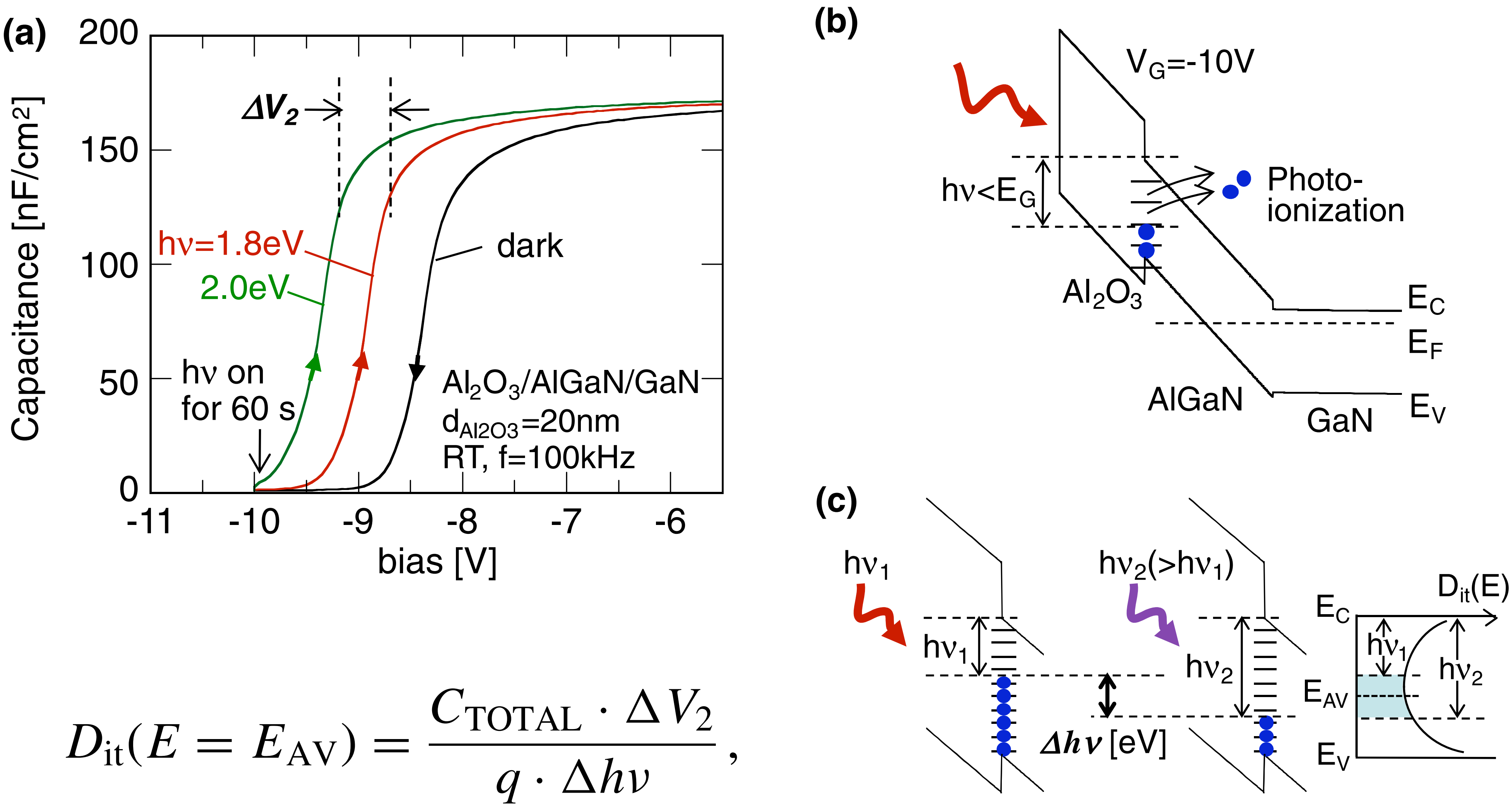
"Sleeping states" at Al_2O_3/AlGaN interface





Almost all of interface states are in "sleeping" condition during C-V measurement at room temperature.

Photo-assisted CV analysis



$$D_{\mathrm{it}}(E = E_{\mathrm{AV}}) = \frac{C_{\mathrm{TOTAL}} \cdot \Delta V_2}{q \cdot \Delta h\nu},$$

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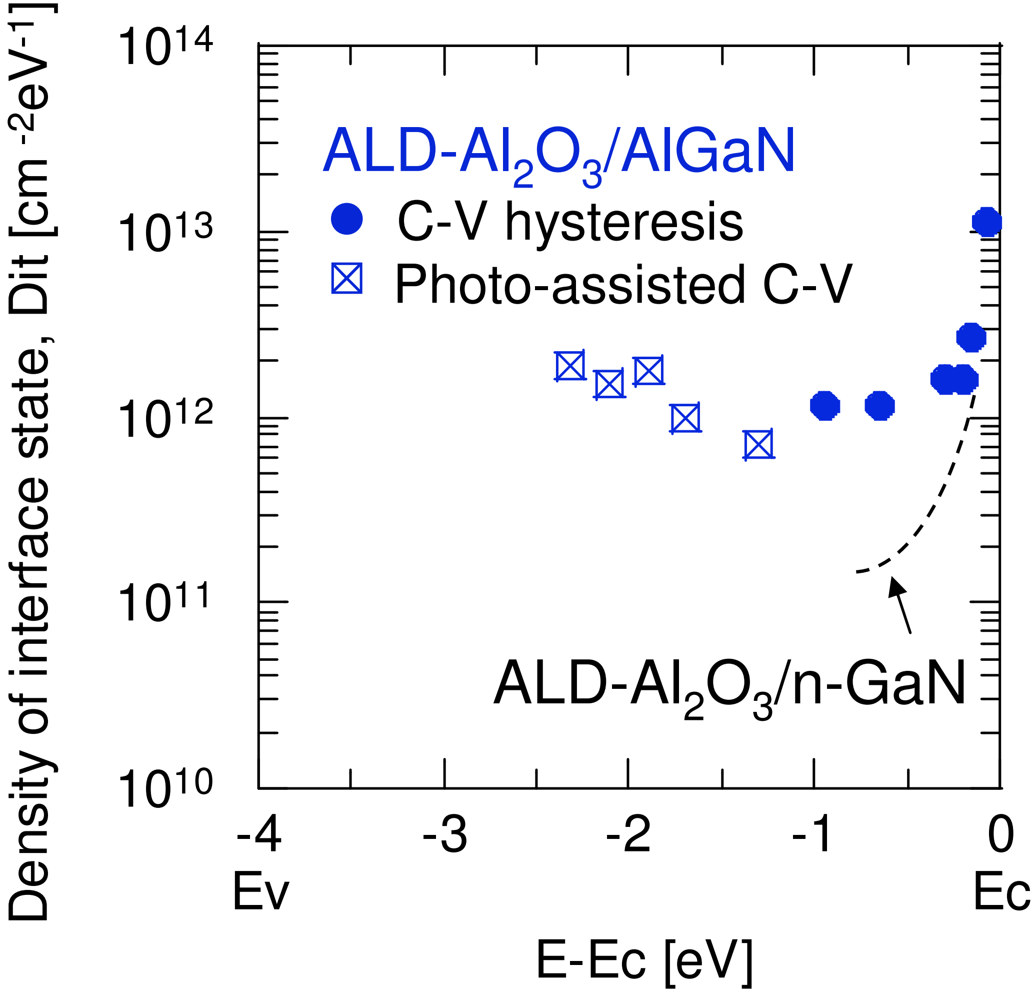
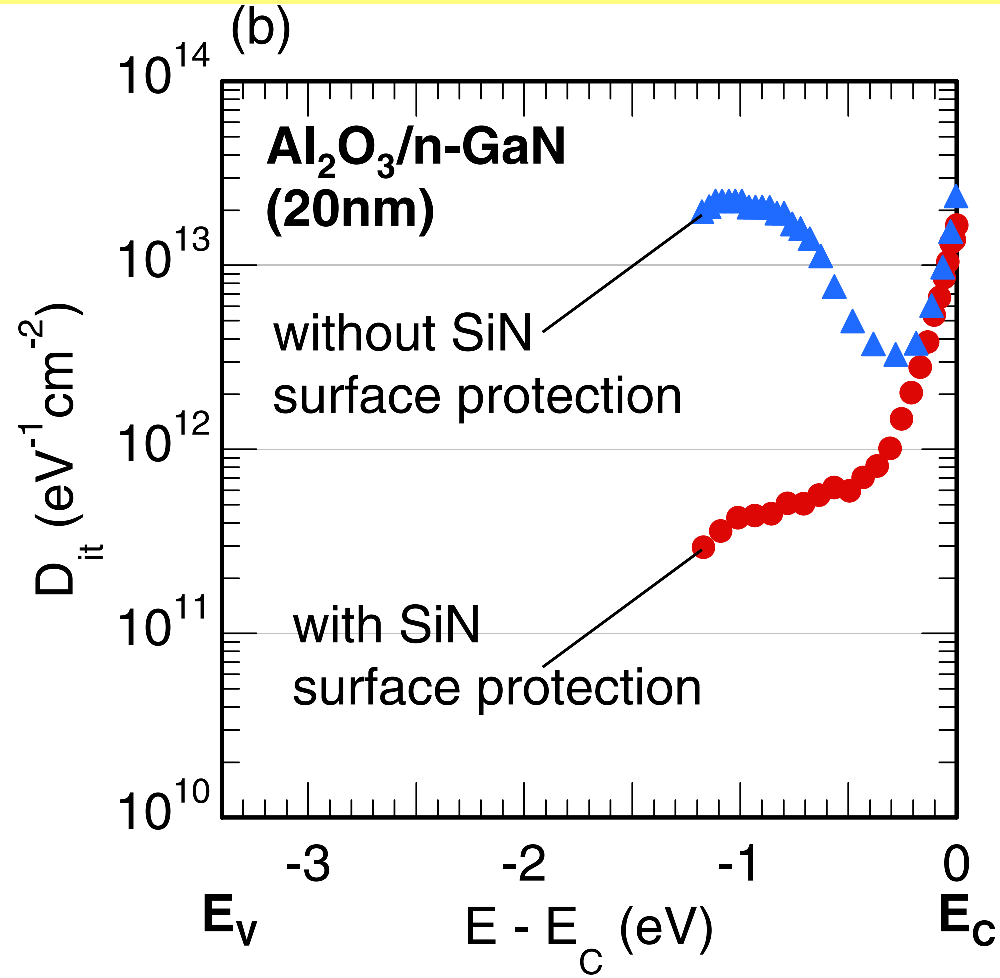
State density distributions at Al_2O_3/AlGaN interface



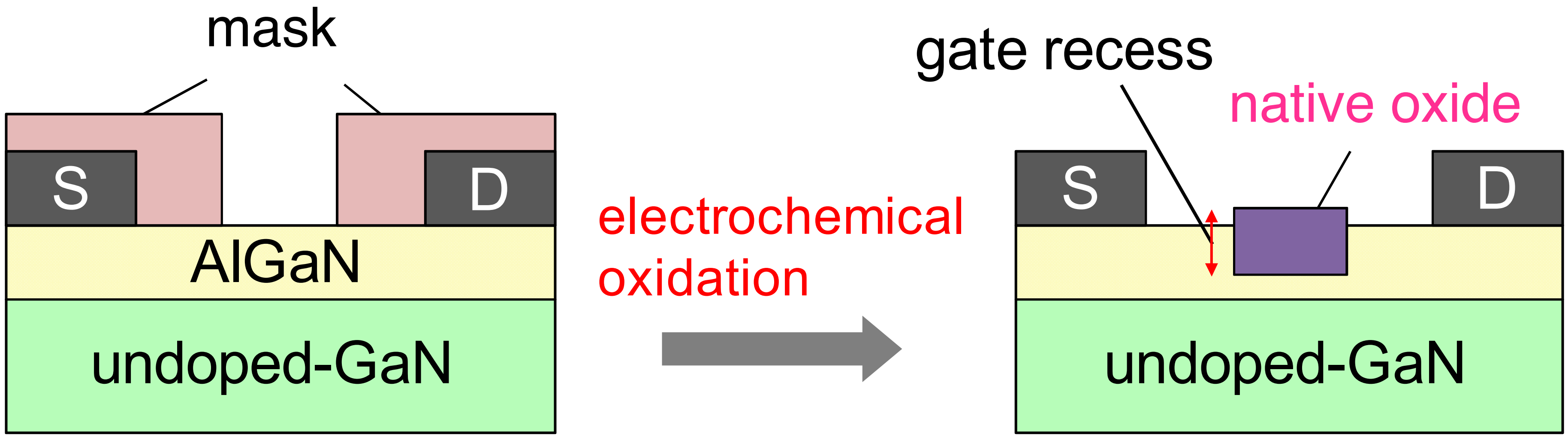


First report for the Al_2O_3/AlGaN interface using the HEMT-MOS structure

About one order magnitude higher than D_{it} of GaN MOS

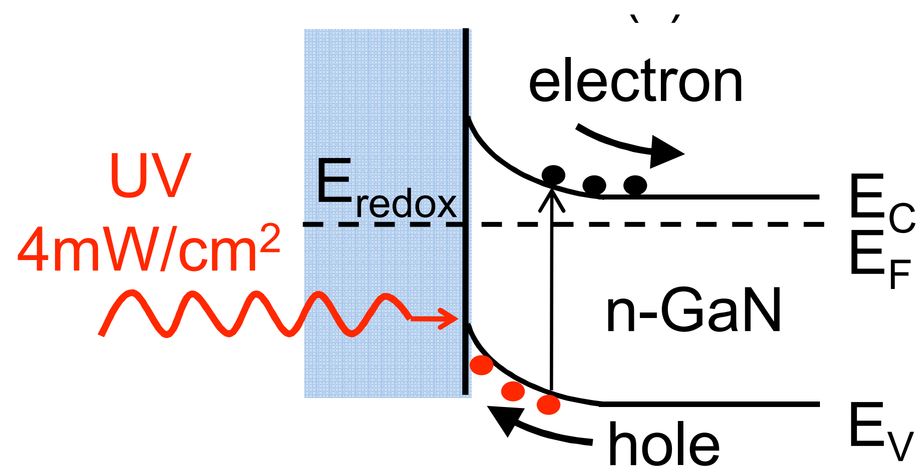
Recessed oxide gate for V_{th} control of AlGaN/GaN HEMT by electrochemical process

Formation of recess+oxide structure by electrochemical process

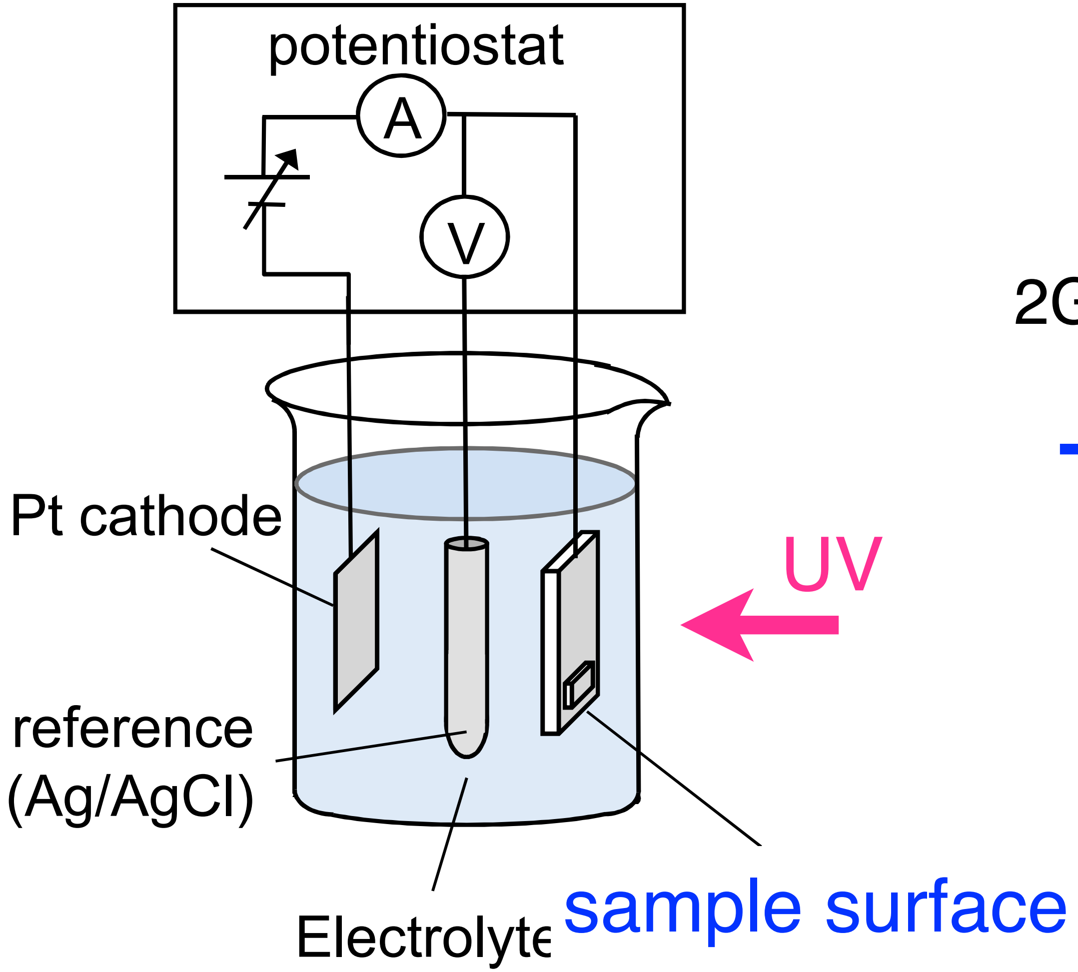


$$2GaN + 6h^{+} + 6OH^{-}$$

$$\rightarrow Ga_2O_3 + 3H_2O + N_2\uparrow$$



Electrochemical cell

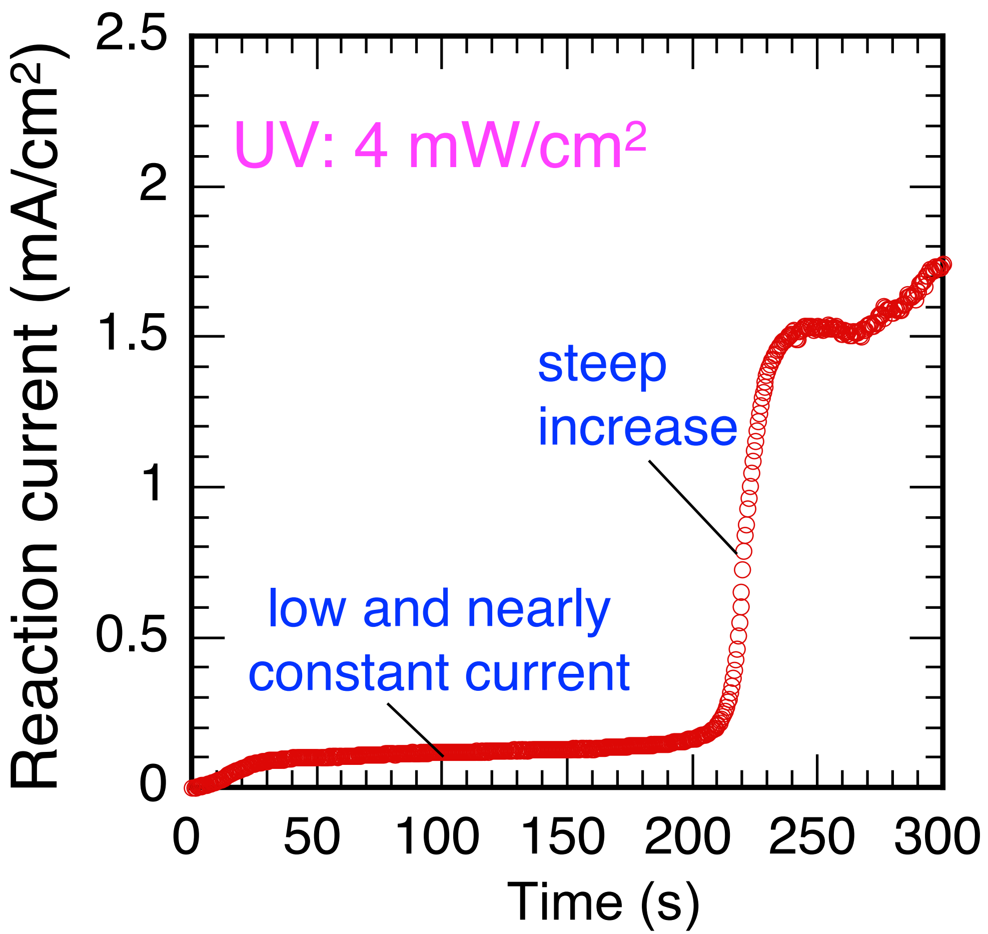


$$2GaN + 6h^{+} + 6OH^{-}$$

$$\rightarrow Ga_2O_3 + 3H_2O + N_2\uparrow$$

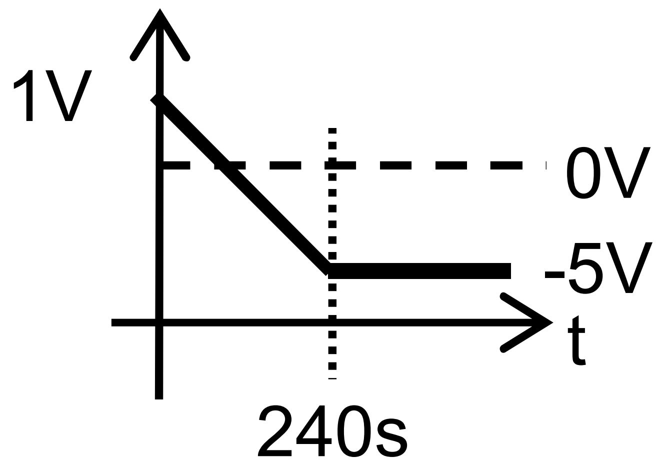
propylene glycol : 3%,tartaric acid (pH=7)=2:1

Reaction current correlated with heterostructure potential



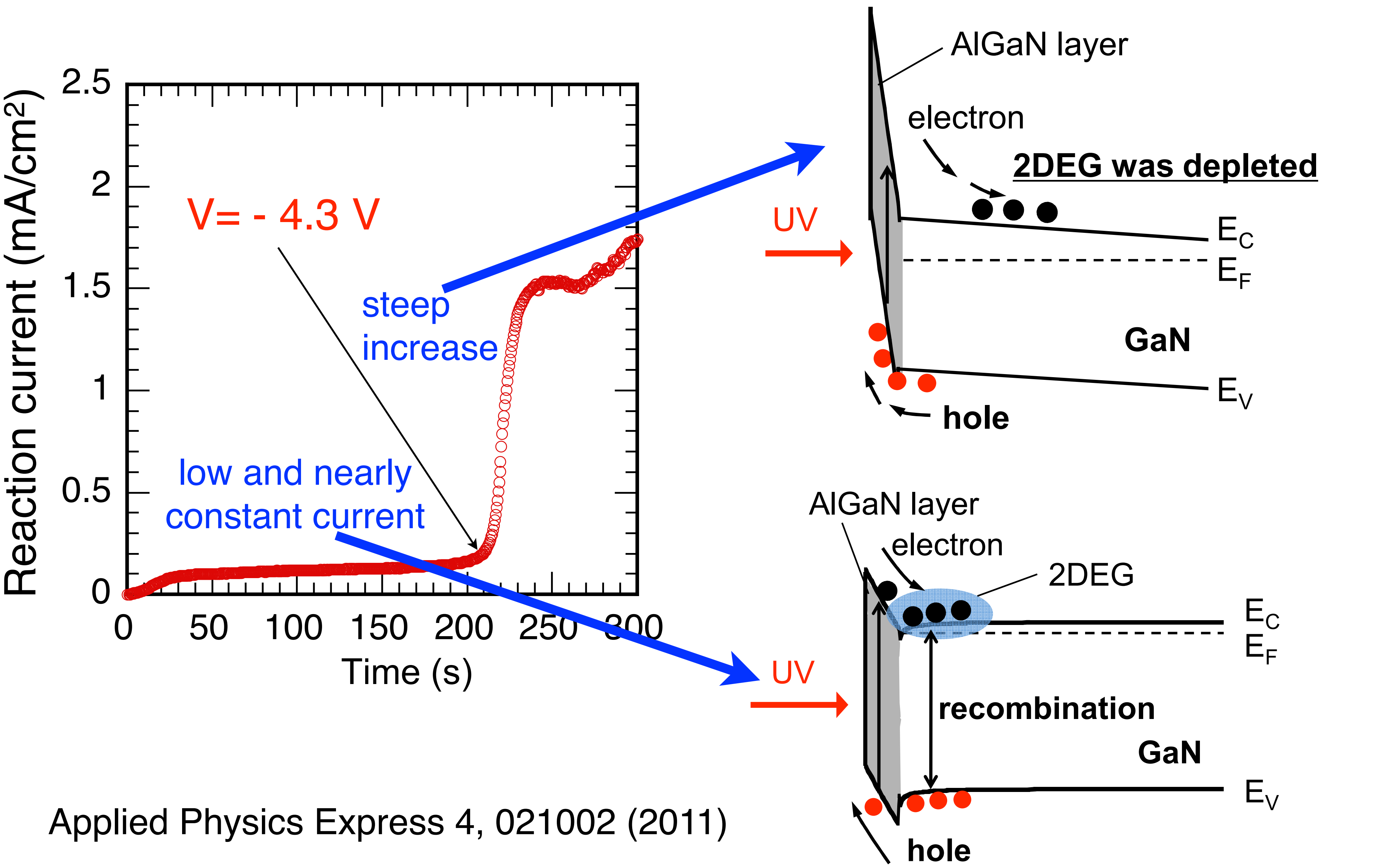
Bias form

ramp: 25 mV/s
constant: -5 V



Characteristic reaction current
reflecting heterostructure potential distribution

Reaction current correlated with heterostructure potential



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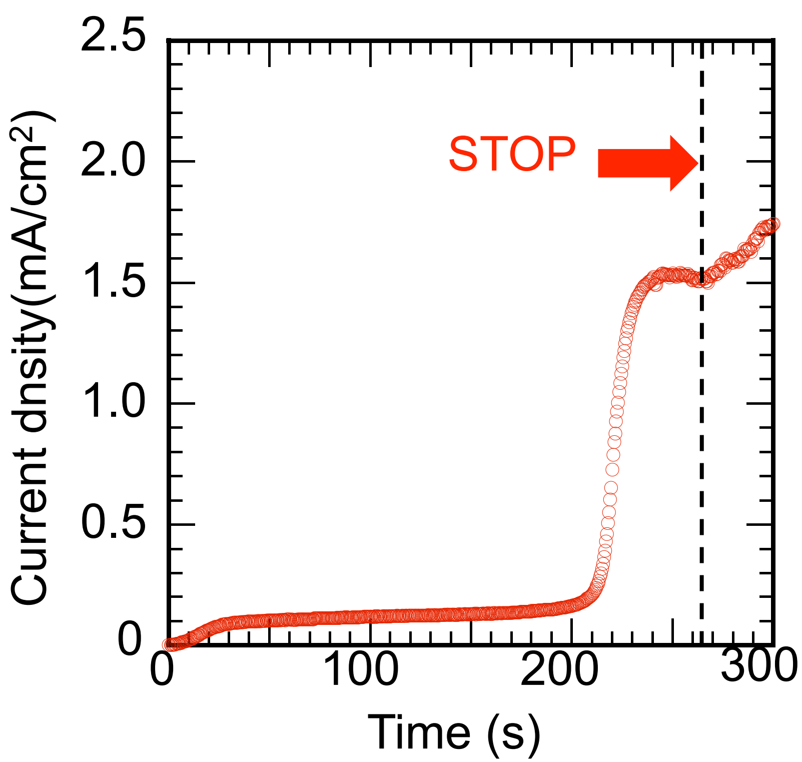
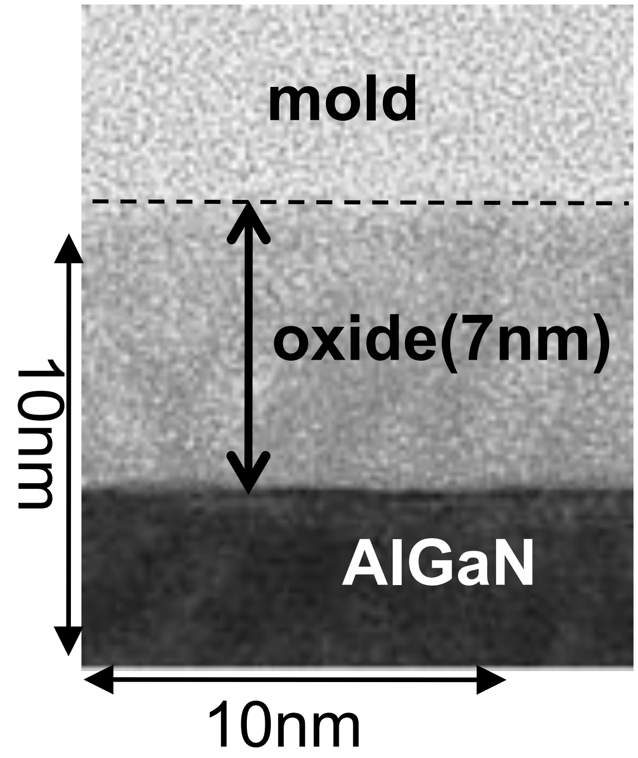
Investigation of oxide/AlGaN interface by TEM

➢**Cross-section TEM observation**





- ◆ Oxide/AlGaN interface was relatively flat.
- ◆ Thickness of oxide was uniform.

➡ **Uniform recessed oxide**

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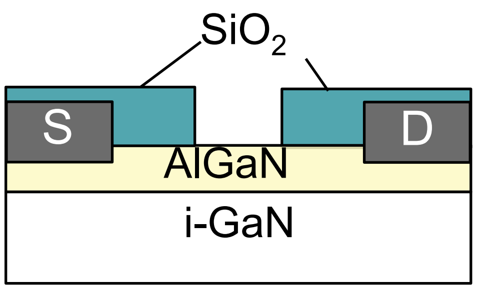
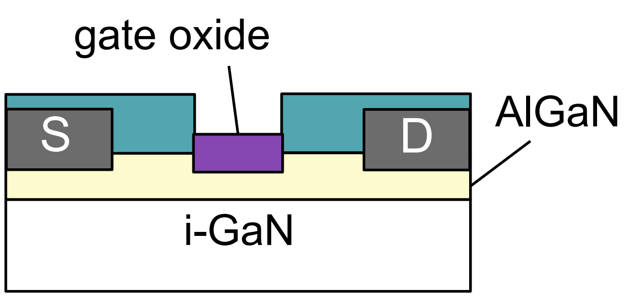
Fabrication of the recessed oxide gate HEMT

➢ **Process flow**

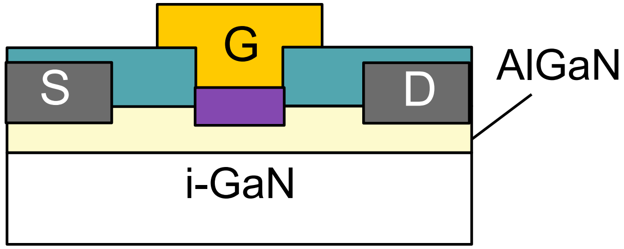
1. **Photolithography and wet etching**



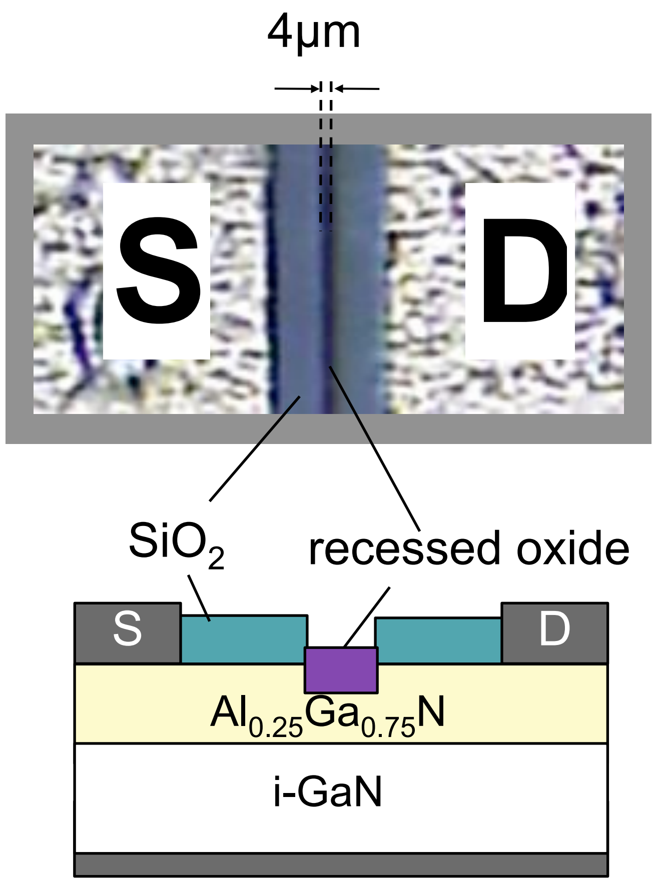
2. **Oxidation**



3. **Formation of gate electrode**



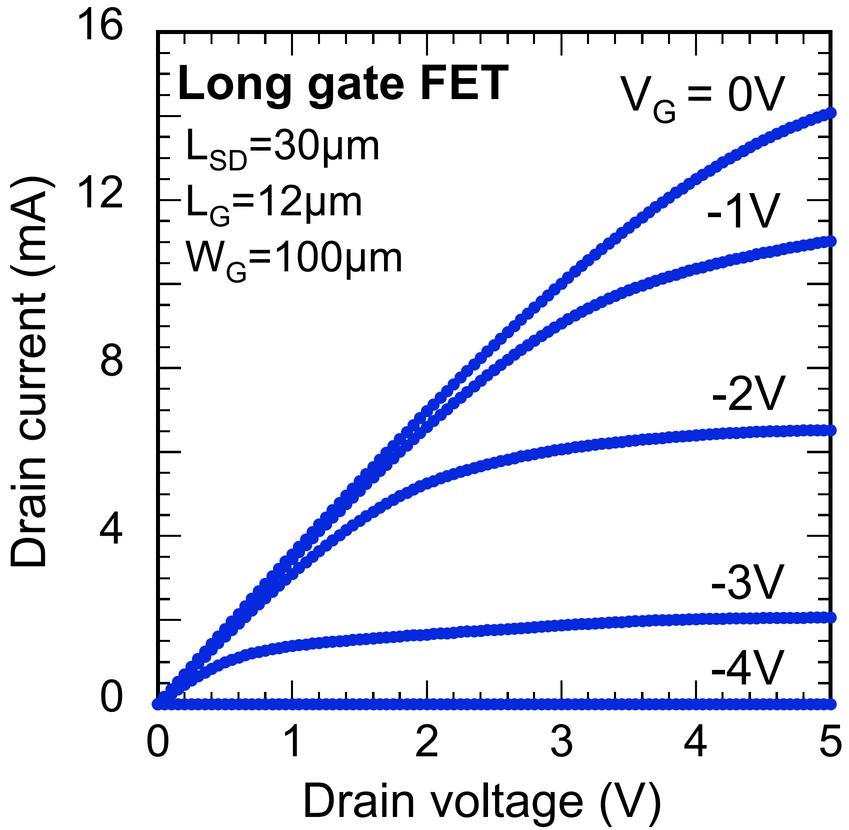
➢ **A plan-view optical microscope image and cross-sectional illustration of recessed oxide gate HEMT**



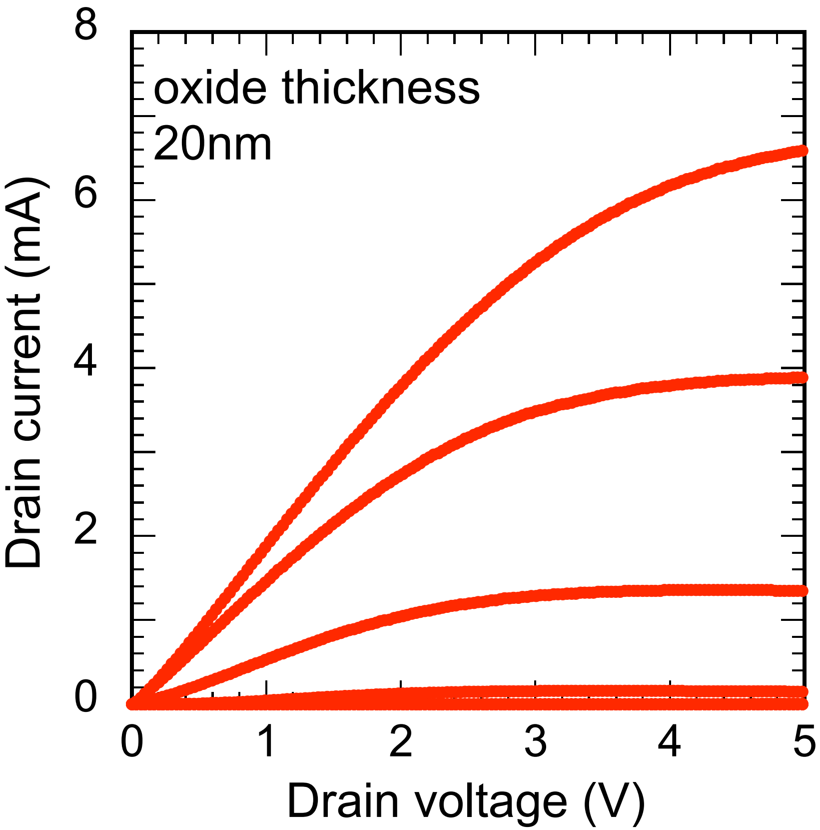
Selective formation of recessed oxide between source and drain electrode was achieved.

Drain I-V characteristics of recessed oxide gate HEMT

➢**Schottky gate HEMT(reference)**



➢**Recessed oxide gate HEMT**



A normally-off device operation was observed.

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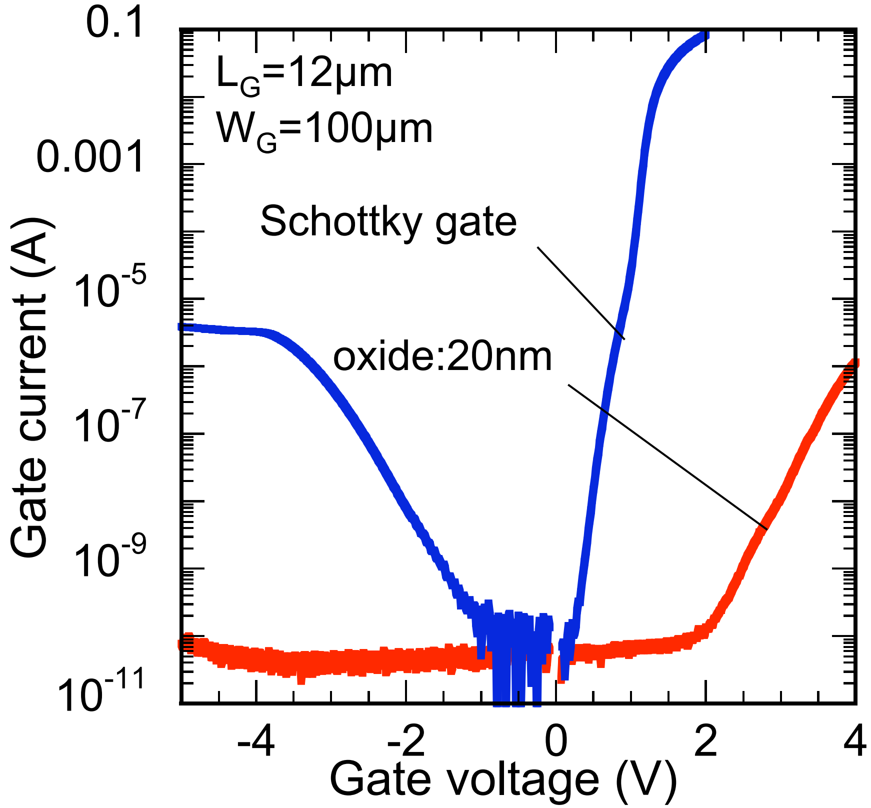
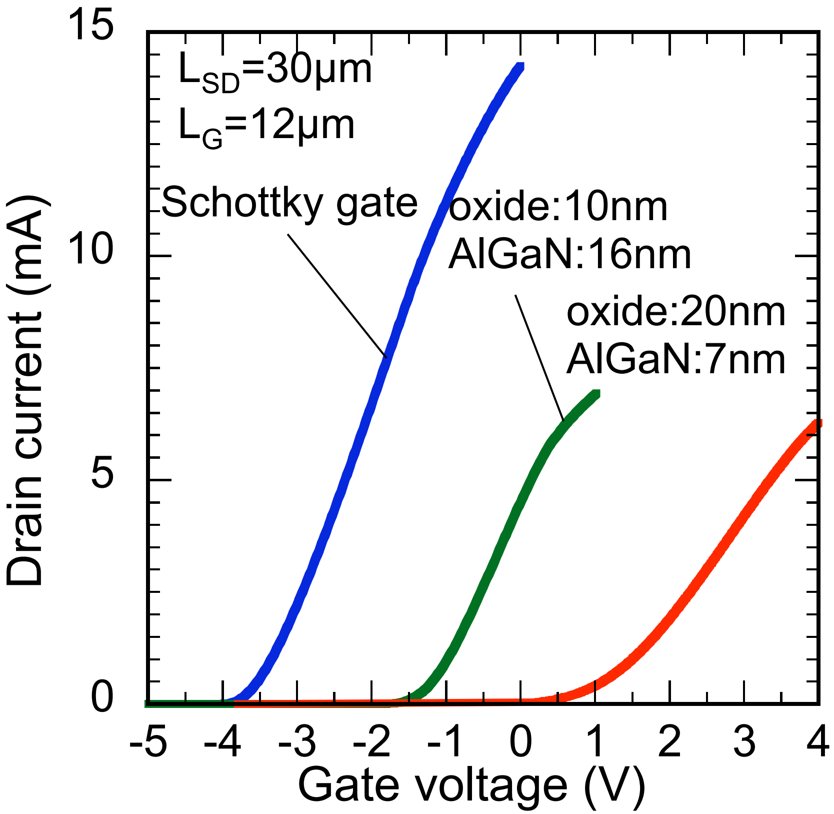
Gate current and transfer characteristics

- Gate current characteristics



- Transfer characteristics of recessed oxide gate HEMT



- ◆ As the thickness of oxide increased, the threshold voltages of HEMTs were shifted towards the positive voltage direction.
- ◆ The slope of transfer curves of the recessed oxide gate HEMTs were almost the same as that of the Schottky gate HEMT.

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Summary

1) Advantage of GaN transistors for power inverter application

2) Al_2O_3/GaN structures by ALD

- Micro-crystallization in Al_2O_3 layer at high-temperature processes
- "Ohmic first + surface protection" process is effective for low leakage current and low D_{it}.

3) C-V analysis of Al_2O_3/AlGaN/GaN structures

- Almost all of states at Al_2O_3/AlGaN interface are in "sleeping" condition during C-V measurement at RT.
- Using the photo-assisted C-V method, the state density distribution at the Al_2O_3/AlGaN interface was determined for the first time

4) We have applied the electrochemical oxidation process to formation of recessed oxide structure in AlGaN/GaN HEMTs. A normally-off device operation was observed in the recessed oxide gate HEMT.