# Current controllability and stability of multi-mesa-channel AlGaN/GaN HEMTs

Tamotsu Hashizume and Kota Ohi

*Research Center for Integrated Quantum Electronics (RCIQE)*
*Hokkaido University*

*JST-CREST*

# Research issues for GaN inverter

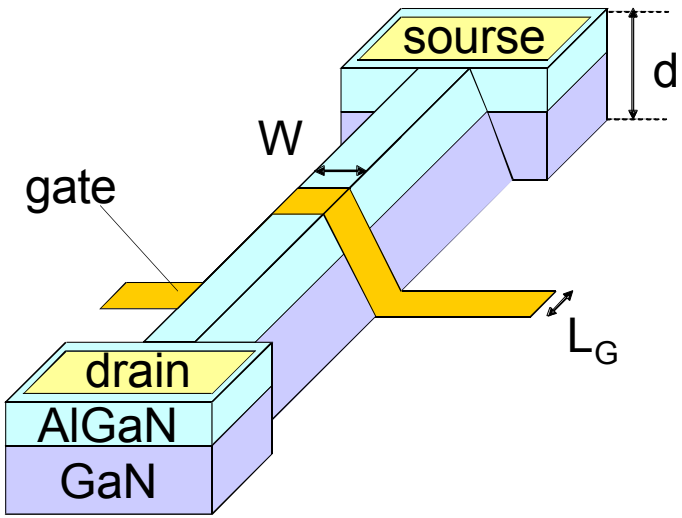


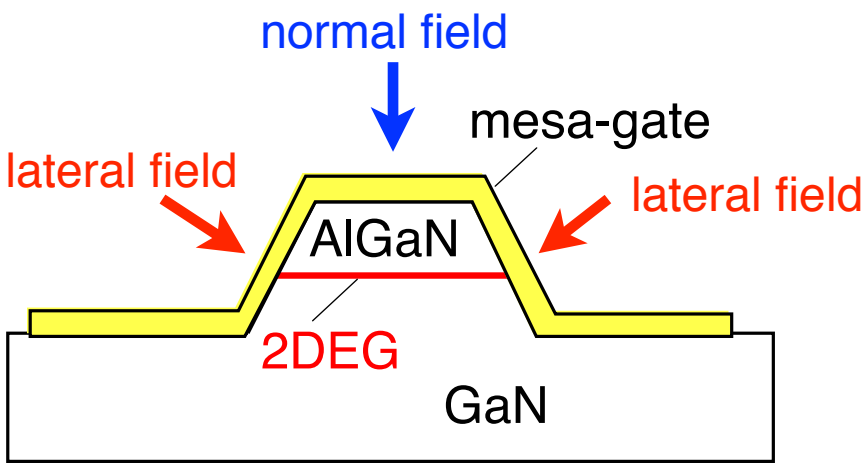
There are many issues to be solved in GaN transistors

1) Surface control
2) Characterization and control of deep levels
3) IS interface and MIS (MOS) gate structures
4) Reliability characterization
5) Design, fabrication and characterization of optimum device structure for GaN HEMT

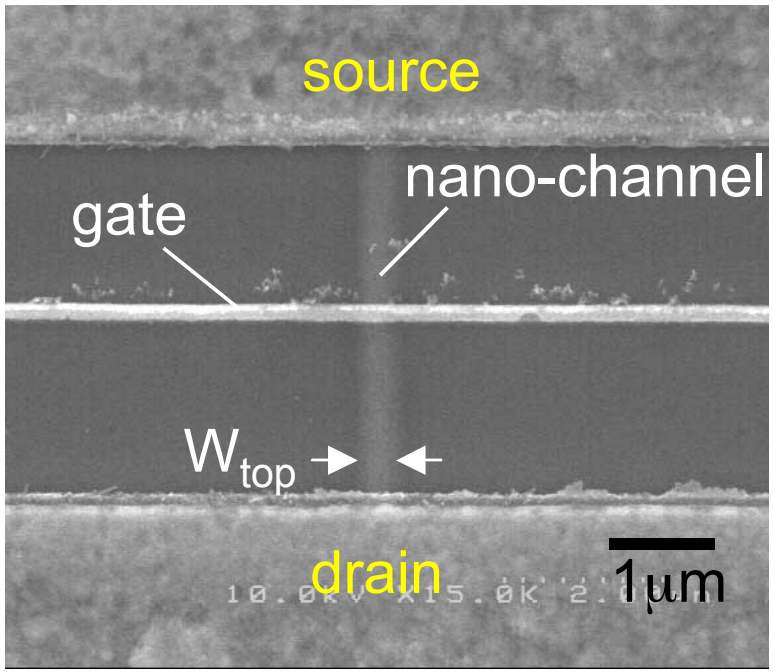
# Mesa-gate AlGaN/GaN HEMT with a single channel

To improve gate controllability and field uniformity in channel, the mesa-gate structures have been investigated.




SEM image



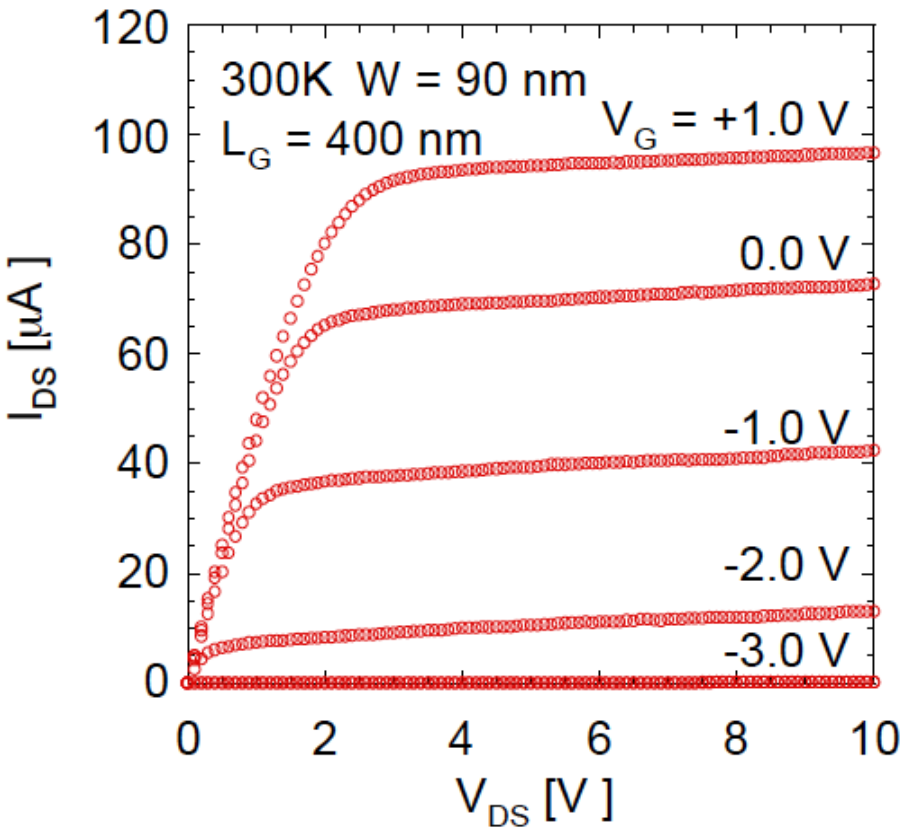

- ECR-assisted dry etching
- etching depth: 50 nm

Tamura, Hashizume, Appl. Phys. Express, 2008

# Mesa-gate AlGaN/ GaN HEMT with a single channel

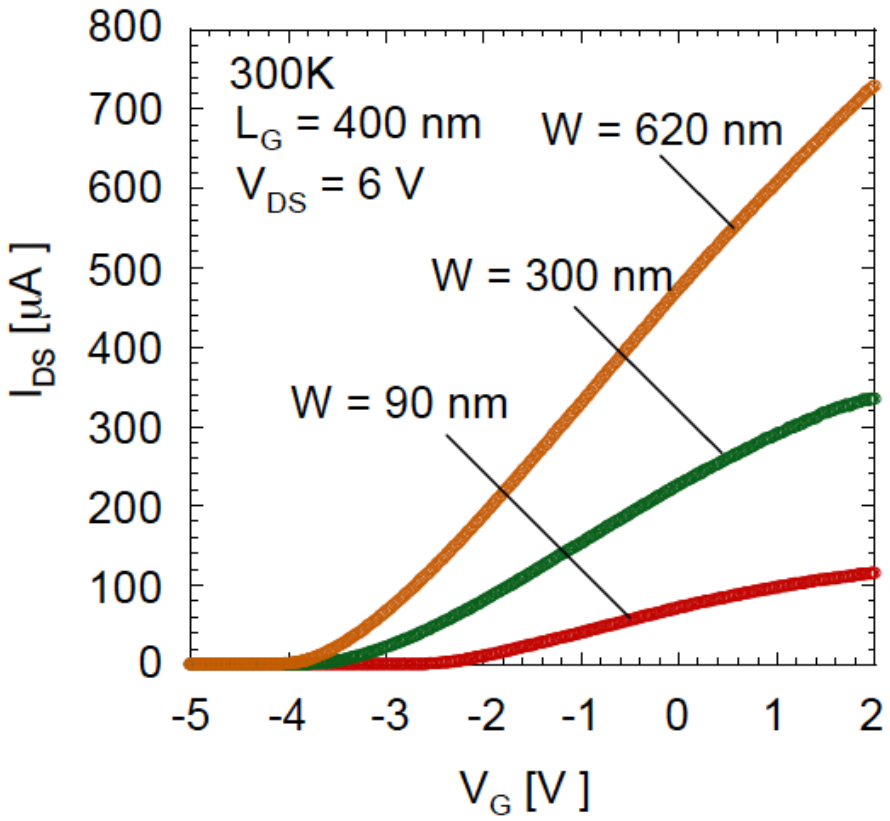
GaN group
Hokkaido University

## drain I-V




good gate control

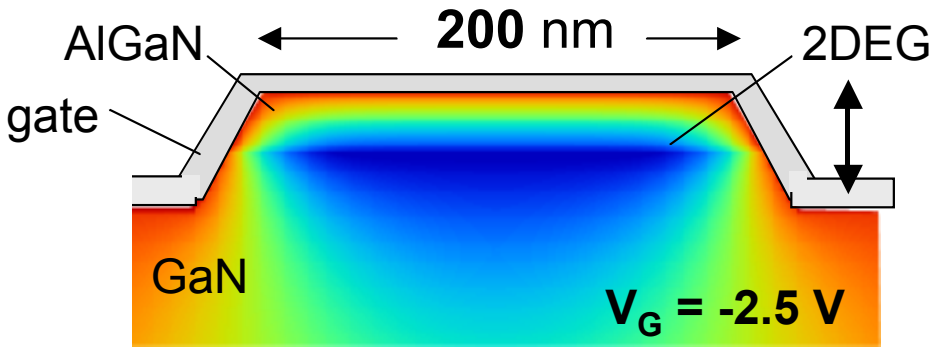
## transfer




systematic $V_{TH}$ shift

# Potential distribution -calculation-

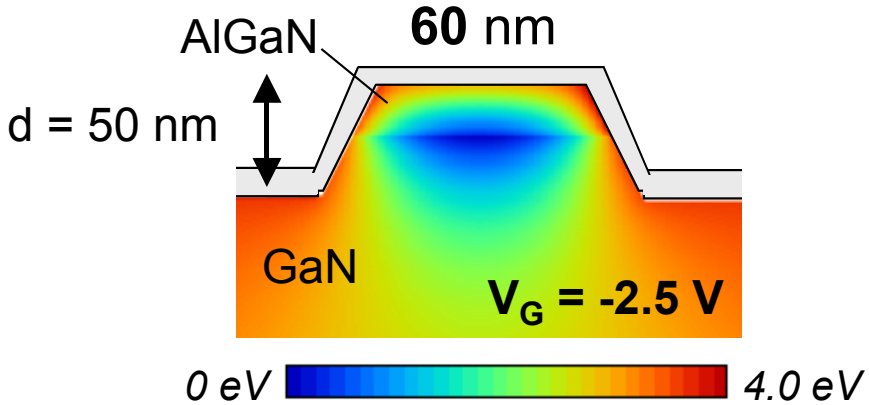
$W_{channel} > 100$ nm




side-gate effect is weak,
due to high 2DEG density

gate control is similar to
a planar structure

$W_{channel} < 100$ nm




the potential modulation from the side gate and through the undoped GaN layer becomes remarkable

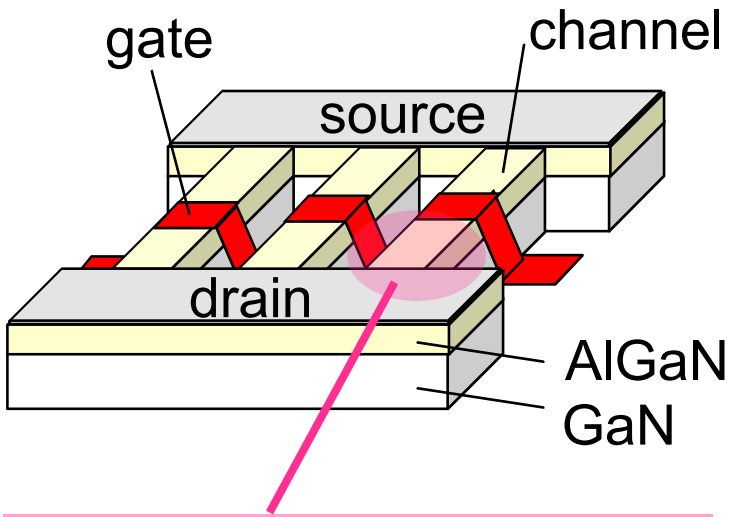
surrounding gate effect

# Multi-mesa-channel AlGaN/GaN HEMT

Surrounding-field effect in the mesa-gate with $W_{channel}$ less than 100 nm

→ Multi-channel AlGaN/GaN HEMTs

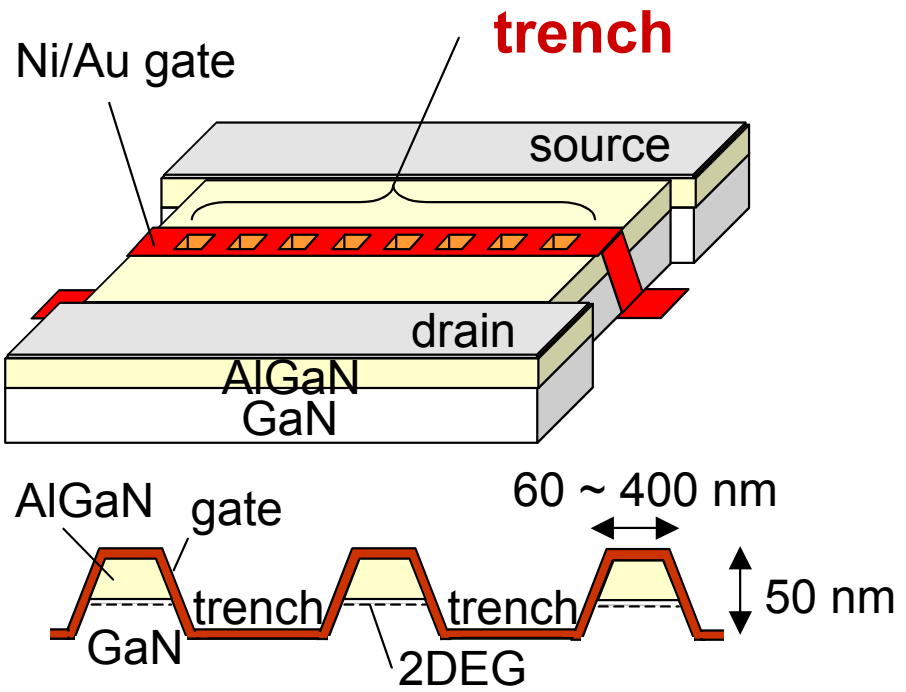
parallel channels →



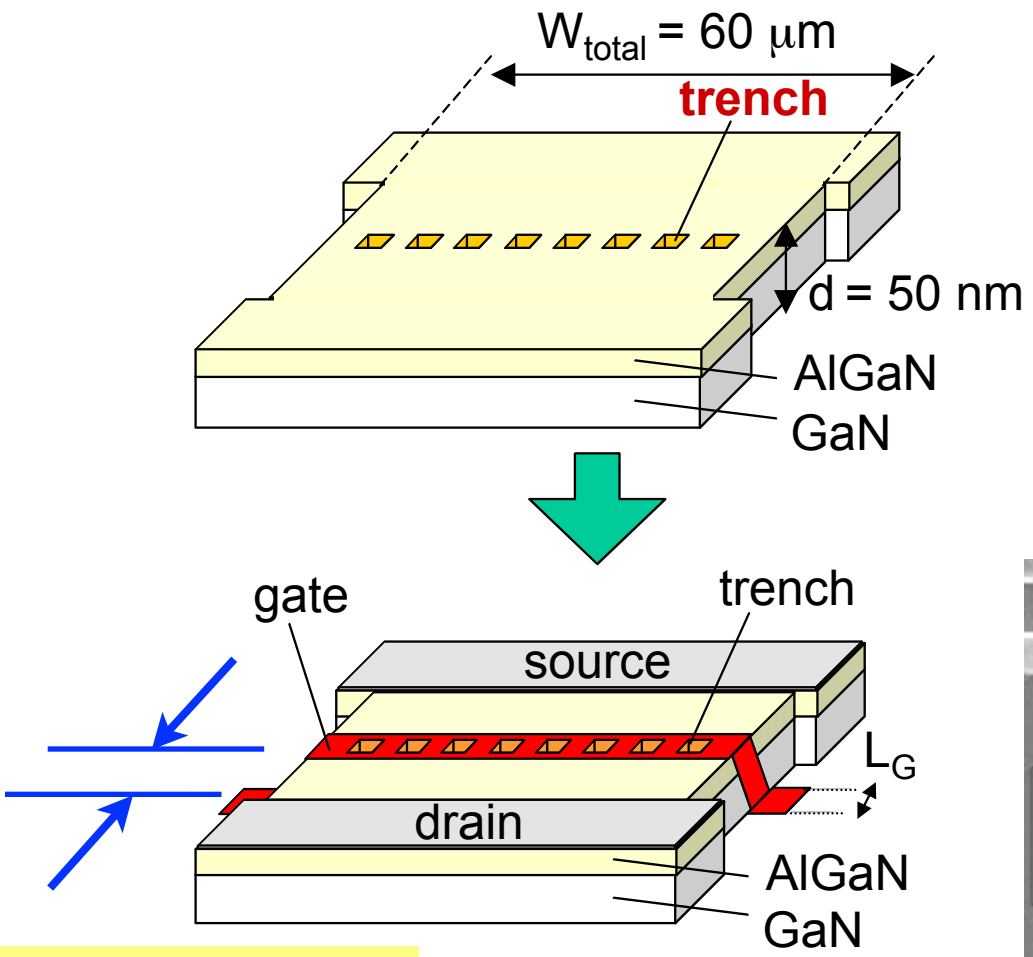

a problem is
large access resistance

Multi-mesa channel

periodic trench just under gate



# Fabrication process and SEM observation



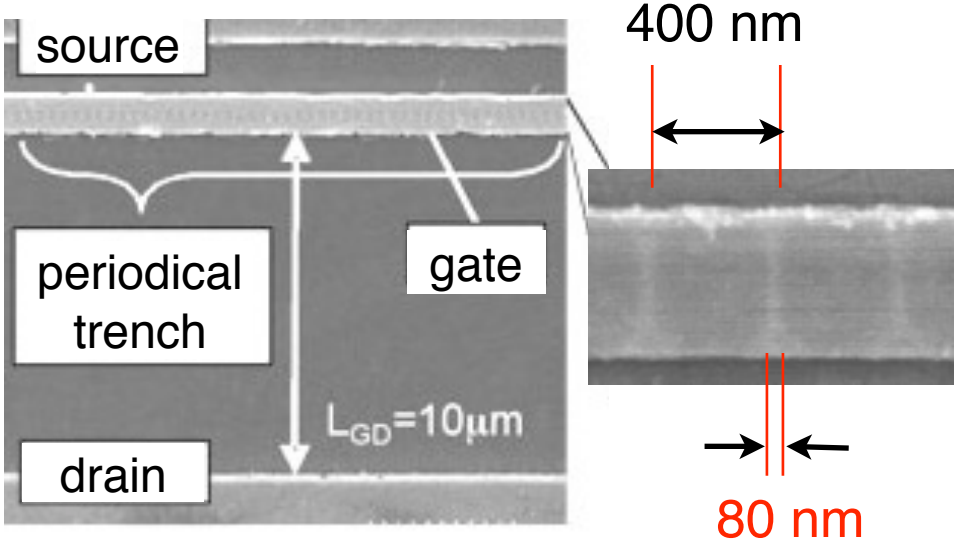

$L_{GD}$= 10 μm (power switching application)

ECR-plasma assisted RIBE

$CH_4/H_2/Ar/N_2$ = 5/15/3/3 sccm

microwave power: 250 W

etching rate: 10 nm/min.@RT

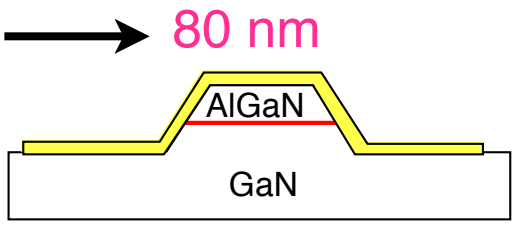



Jpn. J. Appl. Phys. 48, 081002 (2009)

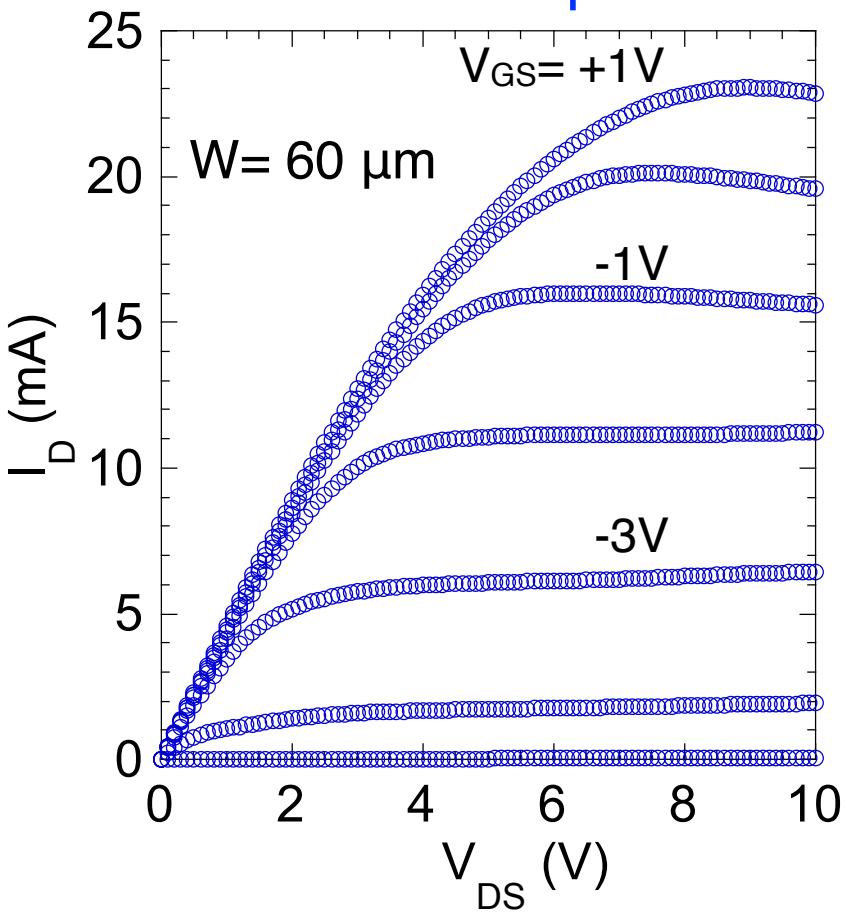
# Comparison of I-V characteristics between conventional and MMC HEMTs

$L_G$= 0.5 μm

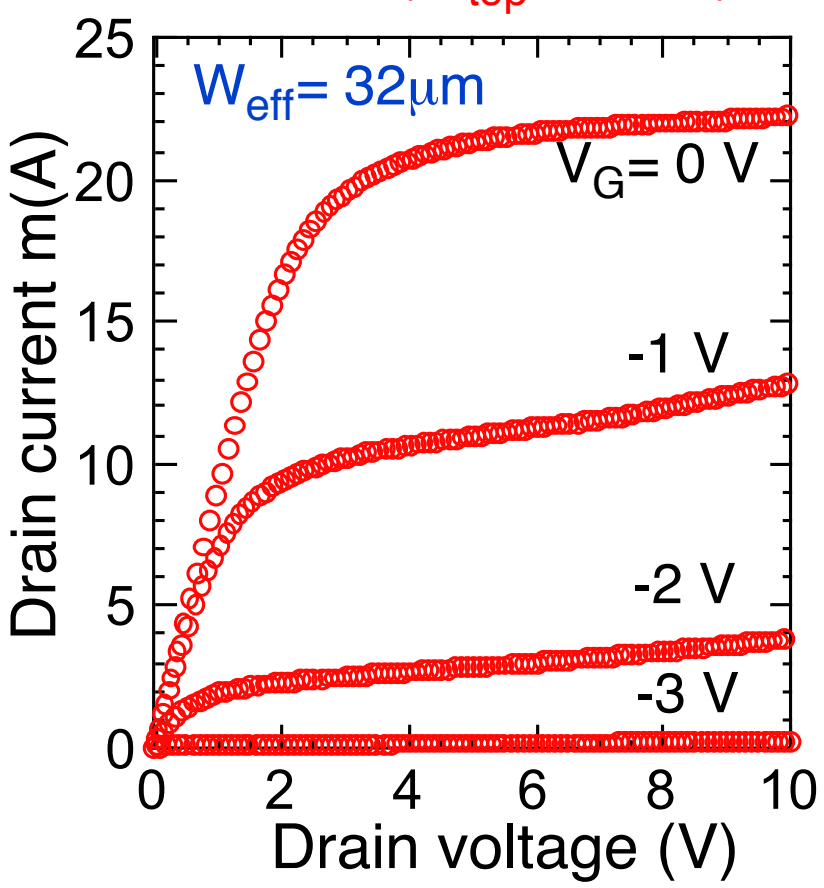
G/D spacing: 10 μm



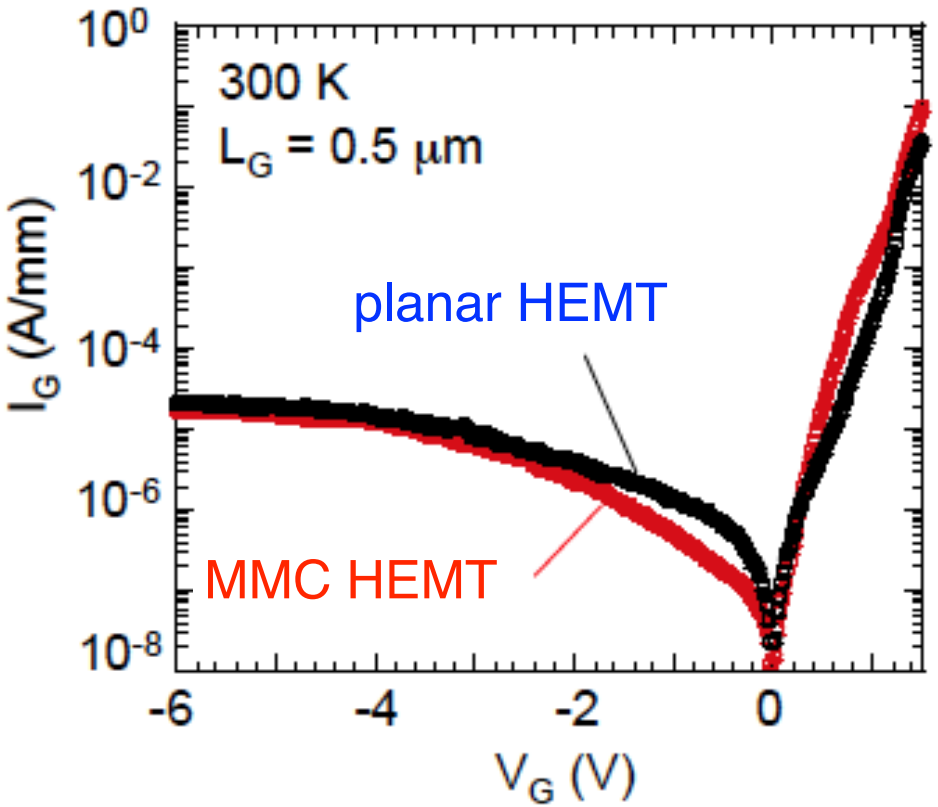

conventional planar



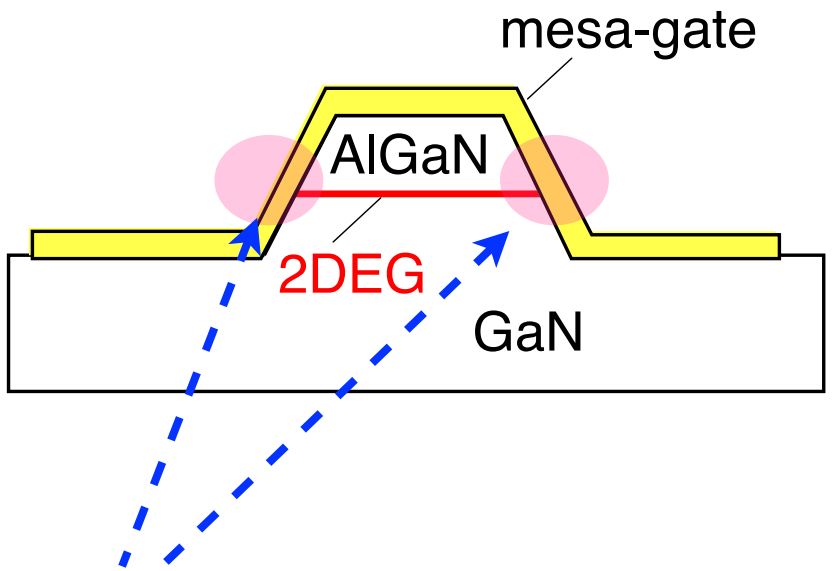

MMC ($W_{top}$= 80nm)



# Gate leakage characteristics

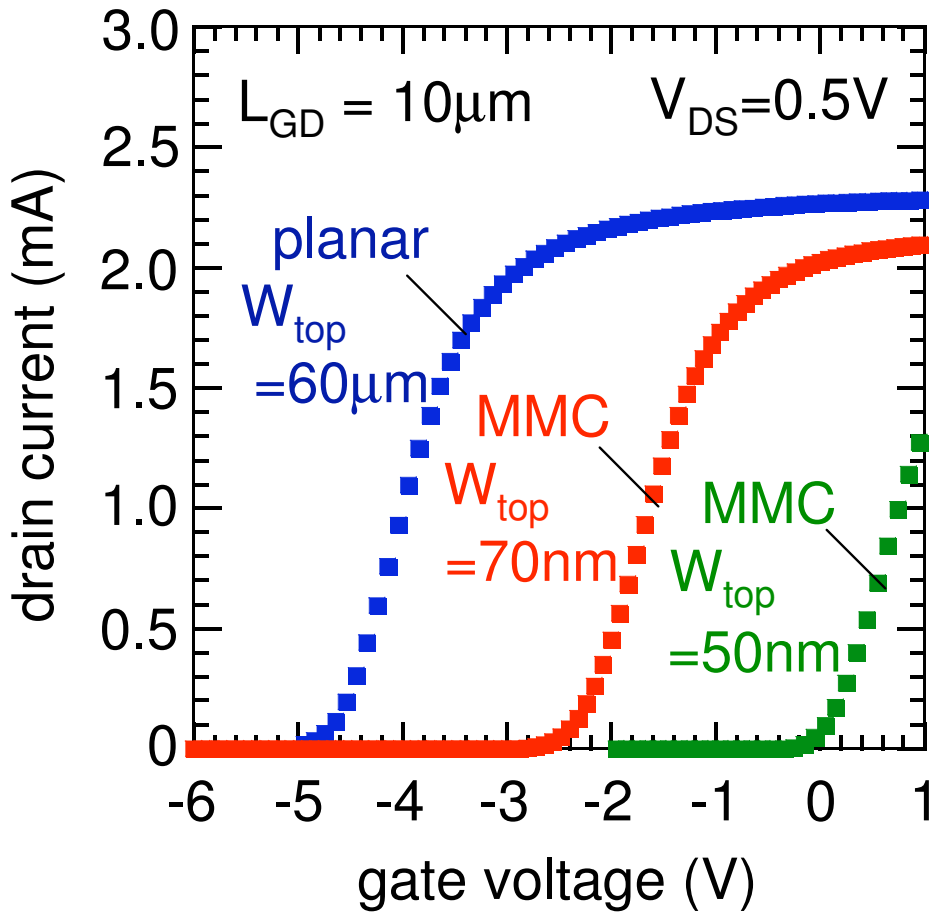



No significant difference of gate leakage currents between two HEMTs




The leakage through the mesa region is negligible in the MMC HEMT

# Transfer characteristics in linear region ($V_{DS}$=0.5 V)




**As $W_{top}$ decreases, a systematic shift in threshold voltage is observed.**

→ MMC structure is attractive for the control of threshold voltage.

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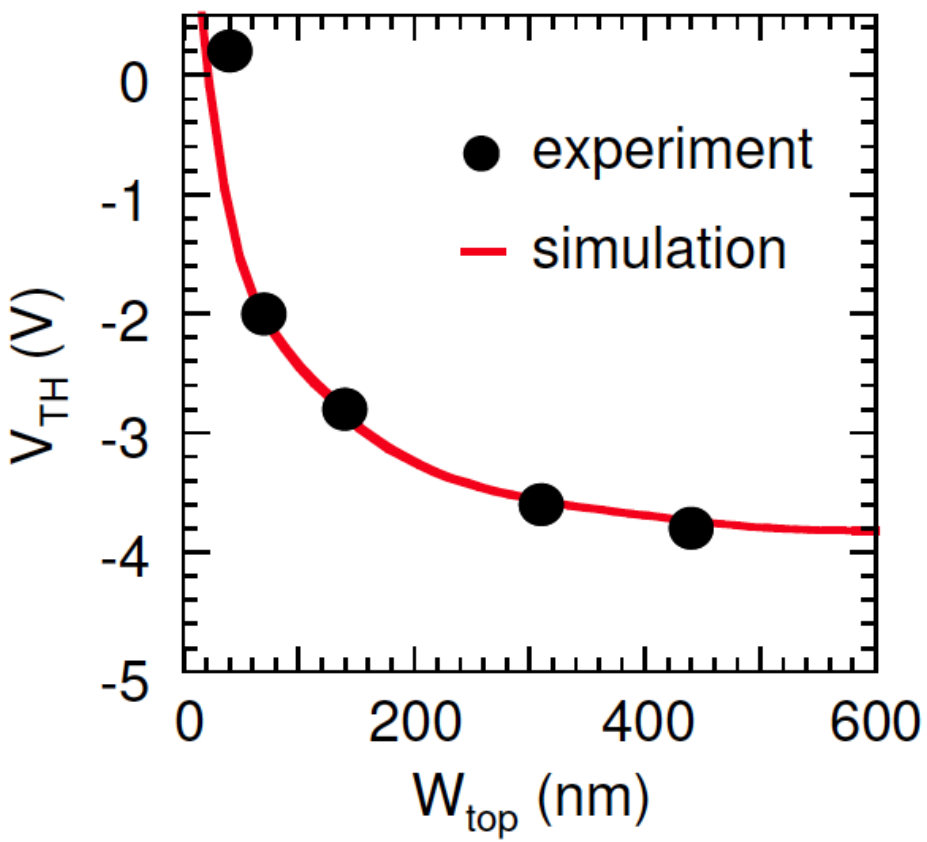
# $V_{TH}$ control in MMC HEMT

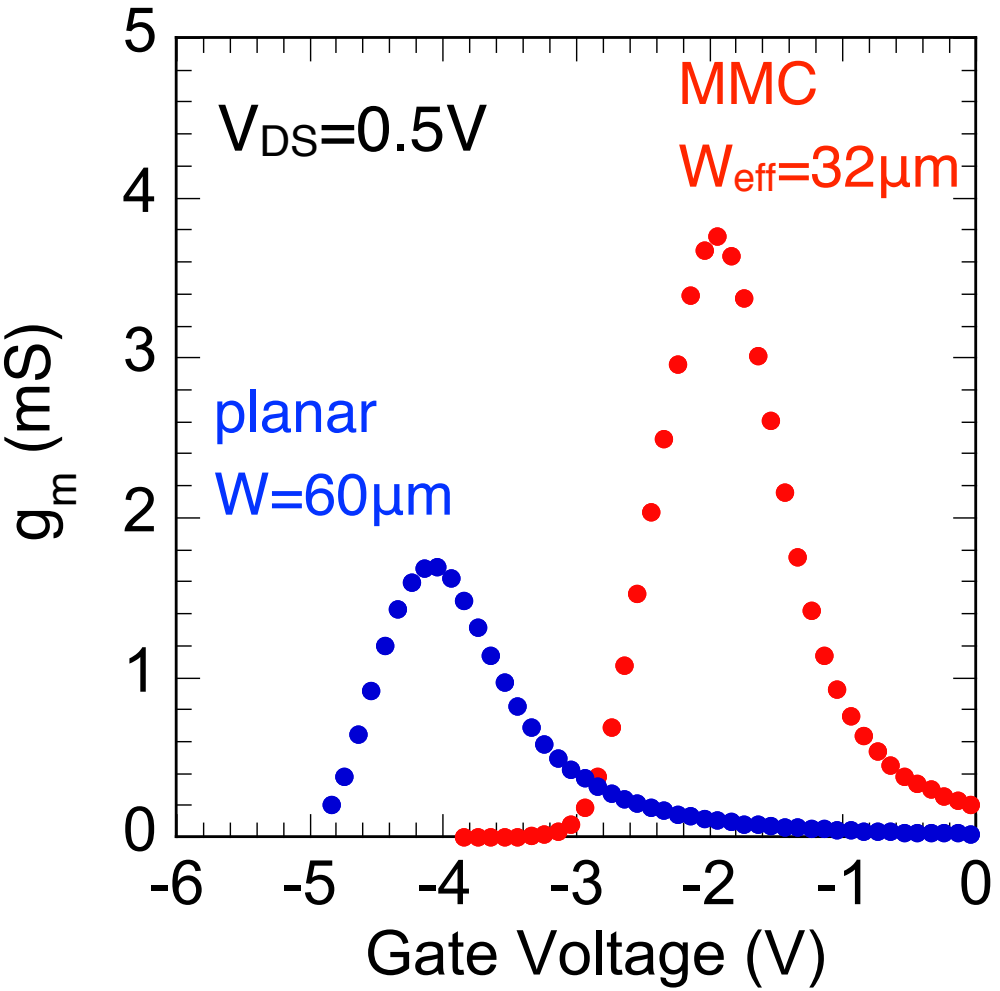
- $W_{top}$ dependence of $V_{TH}$




Excellent agreement between the experimental and calculated $V_{TH}$ values

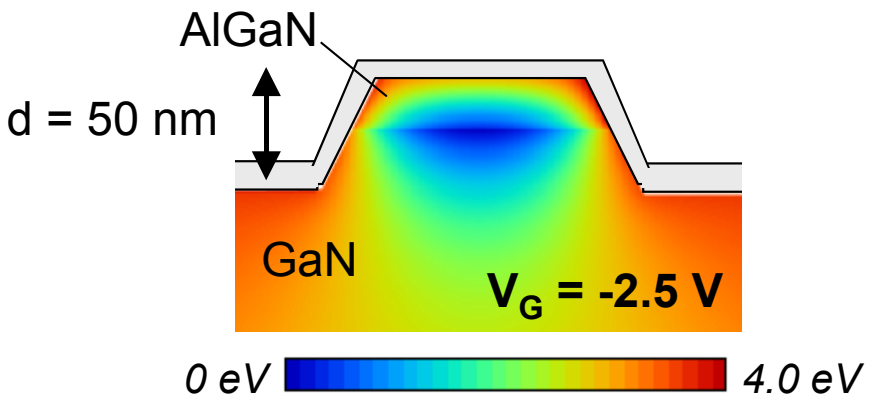
Surrounding-field effect is remarkable when $W_{top}$ of the mesa channel less than 100 nm

# Increase of $g_m$ in MMC HEMT

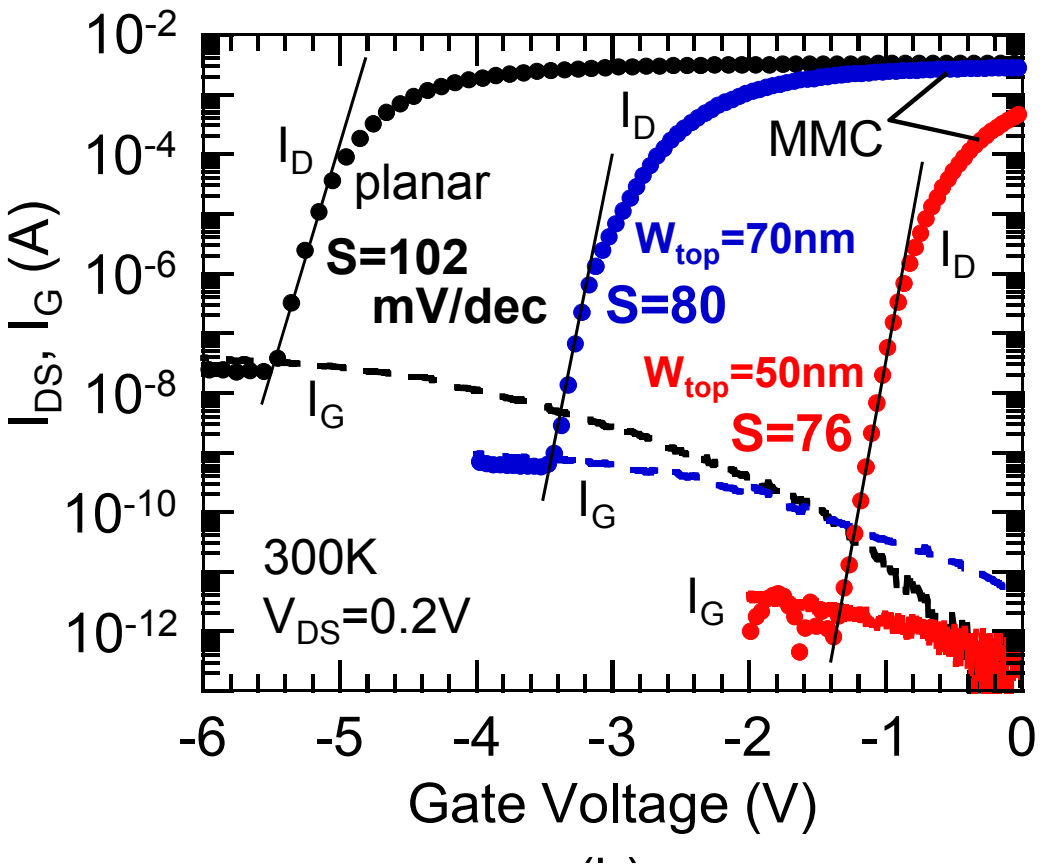


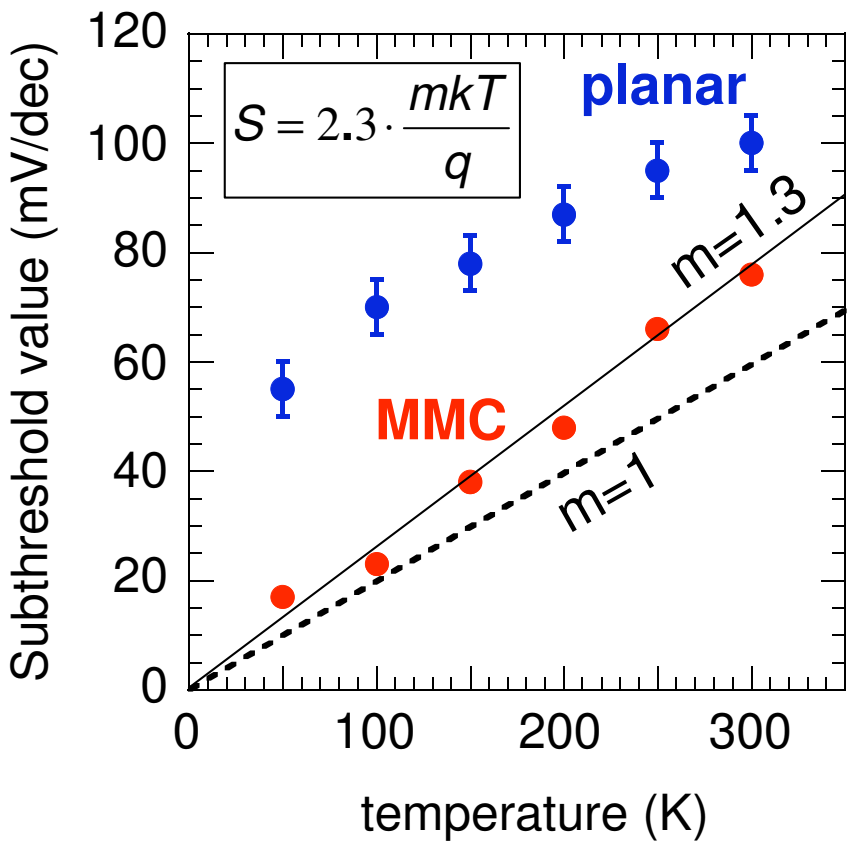

Pronounced $g_m$ increase

probably due to surrounding-field effect



# Sub-threshold characteristics




- small sub-threshold slope
- high on/off ratio **( $10^8$)**

Temperature dependence of S slope is close to theory

↓ ↓

**Excellent gate controllability**

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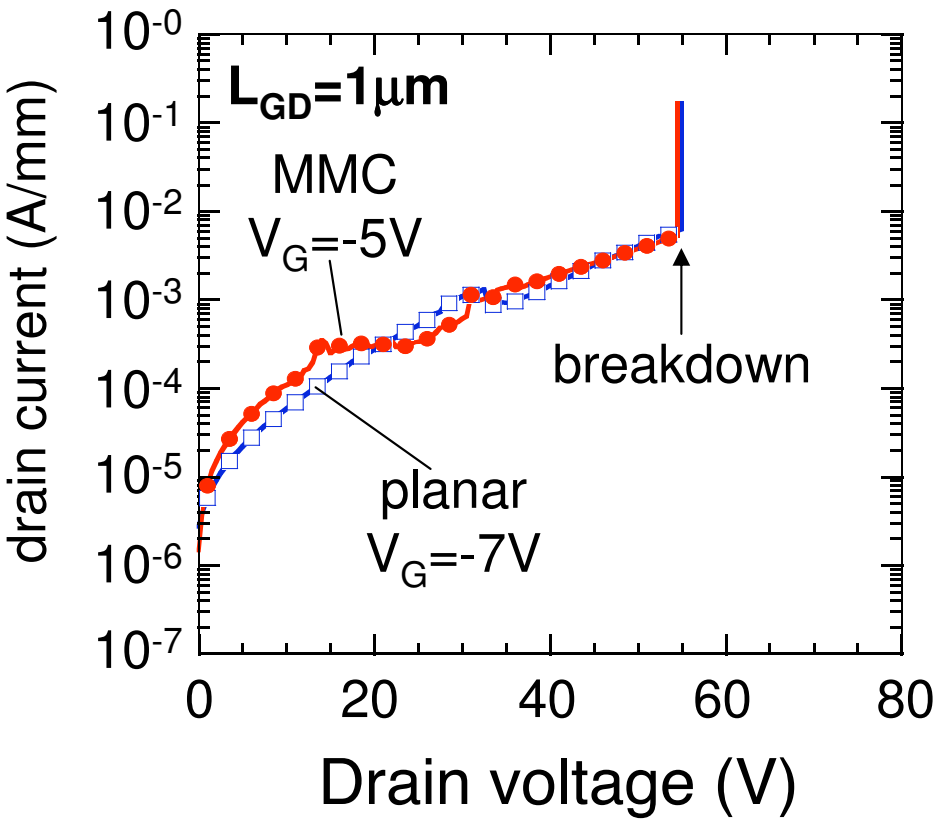
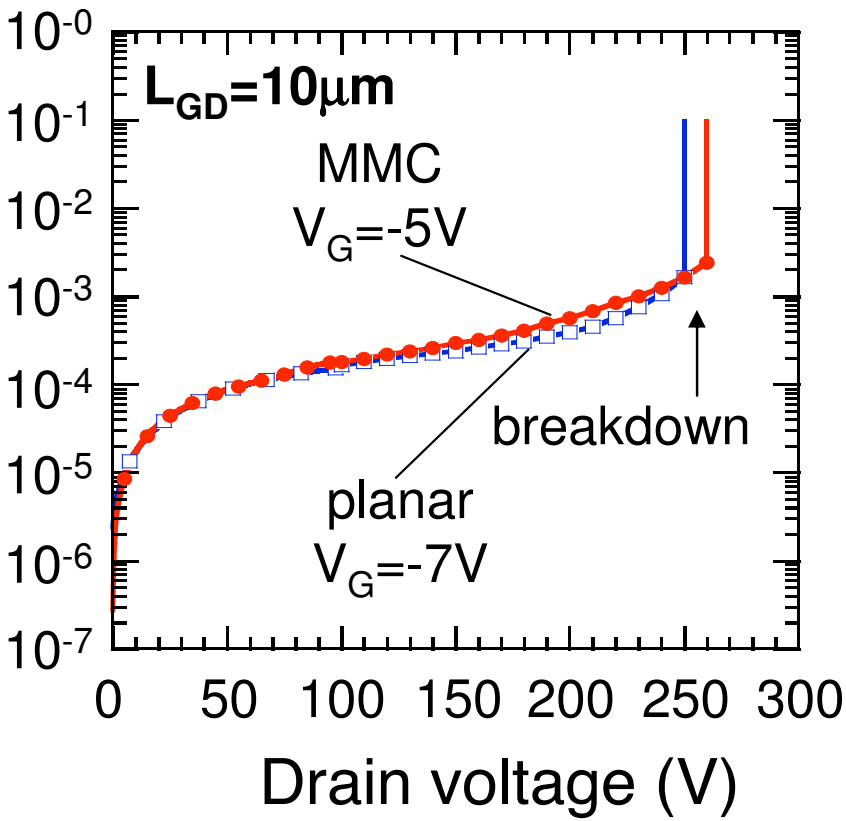
# Breakdown characteristics of planar and MMC HEMTs



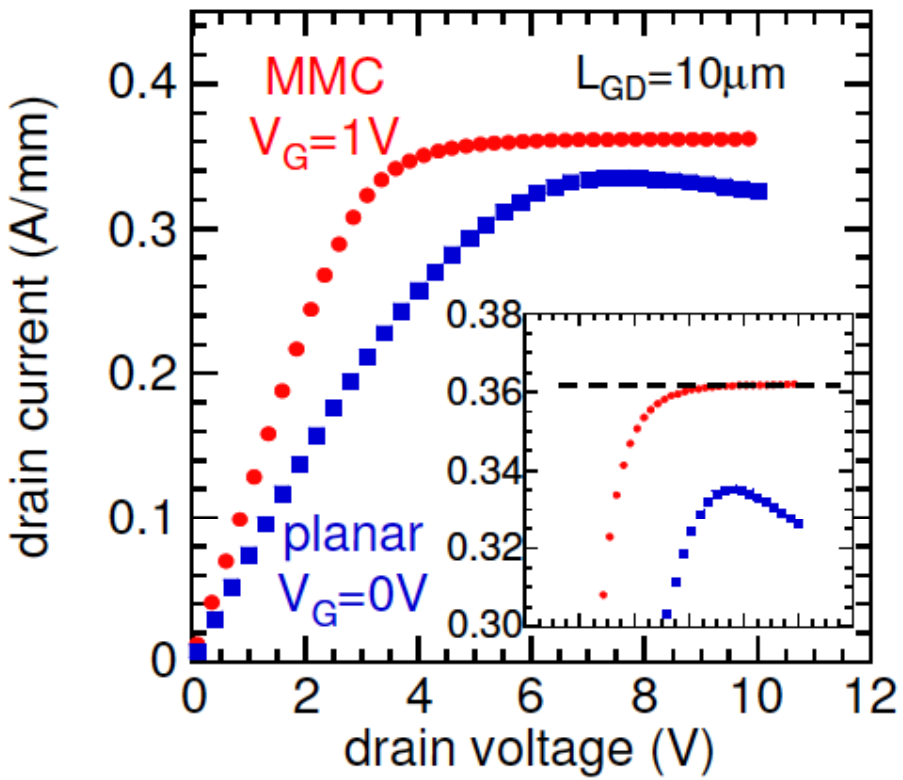

Both devices showed similar breakdown behavior under off-state operation

No significant degradation in the breakdown characteristics of MMC HEMT.

# Current stability of MMC HEMT-thermal effect-

GaN group
Hokkaido University

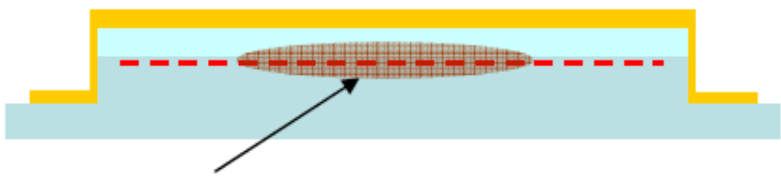
- $I_{DS}$-$V_{DS}$ characteristics




planar ~ **the saturation drain current gradually decreased with increasing drain voltage.**

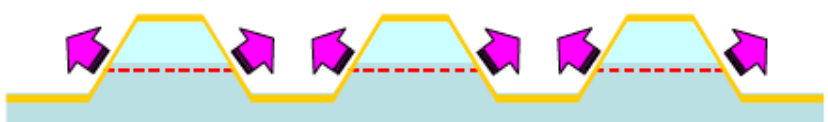
MMC ~ **constant saturation drain current**

- **planar HEMT**



thermal effect in the channel
→ decrease of drain current

- **MMC HEMT**



**Effective radiation of heat**
from both mesa sides of each channel is remarkable.

→ **Good current stability**

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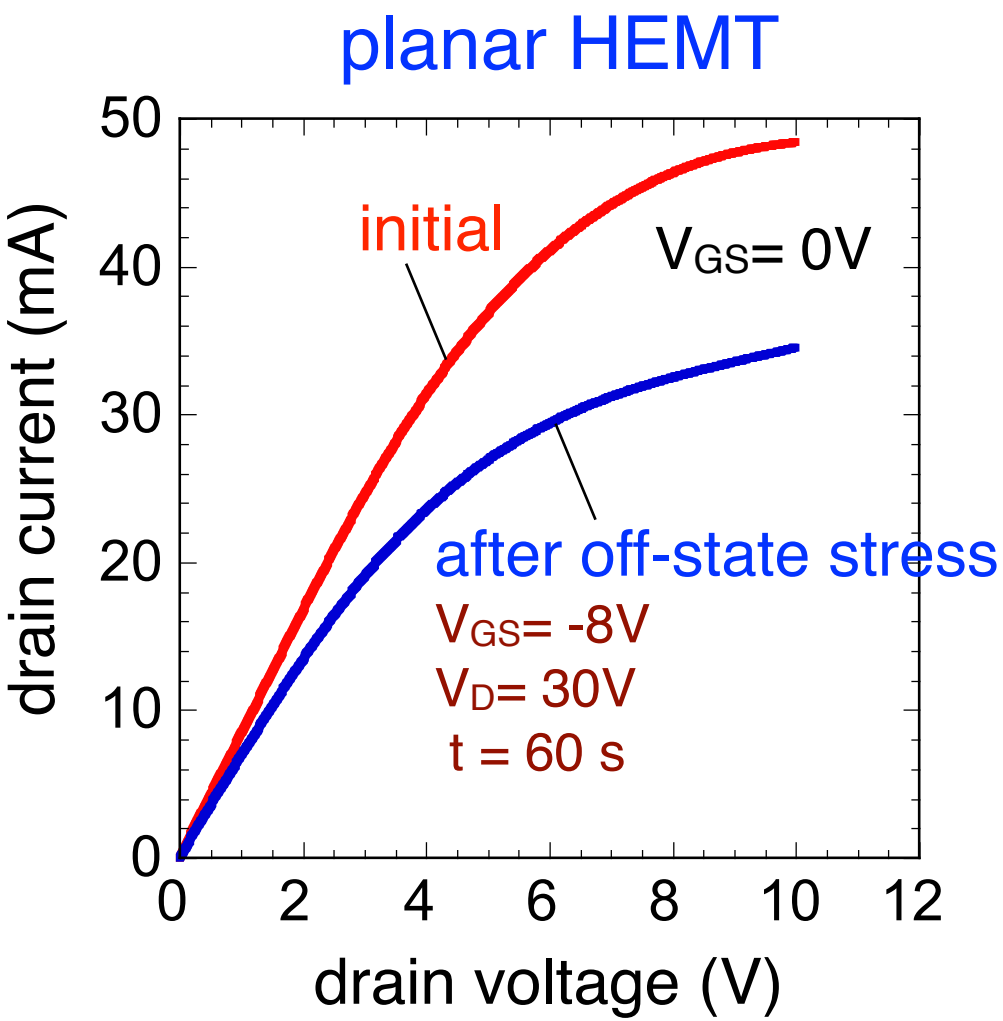
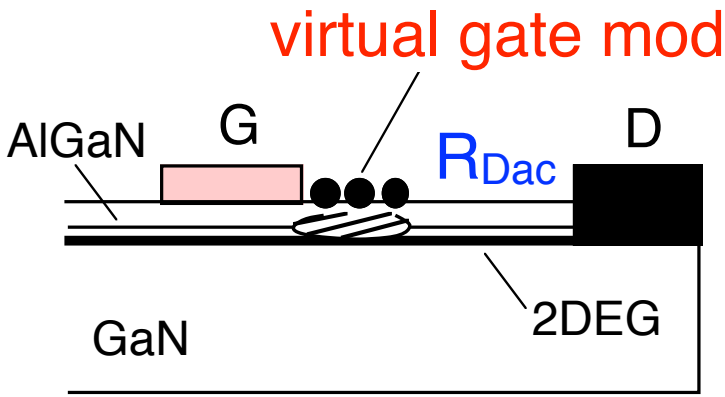
# Current decrease after off-state stress in planar HEMT



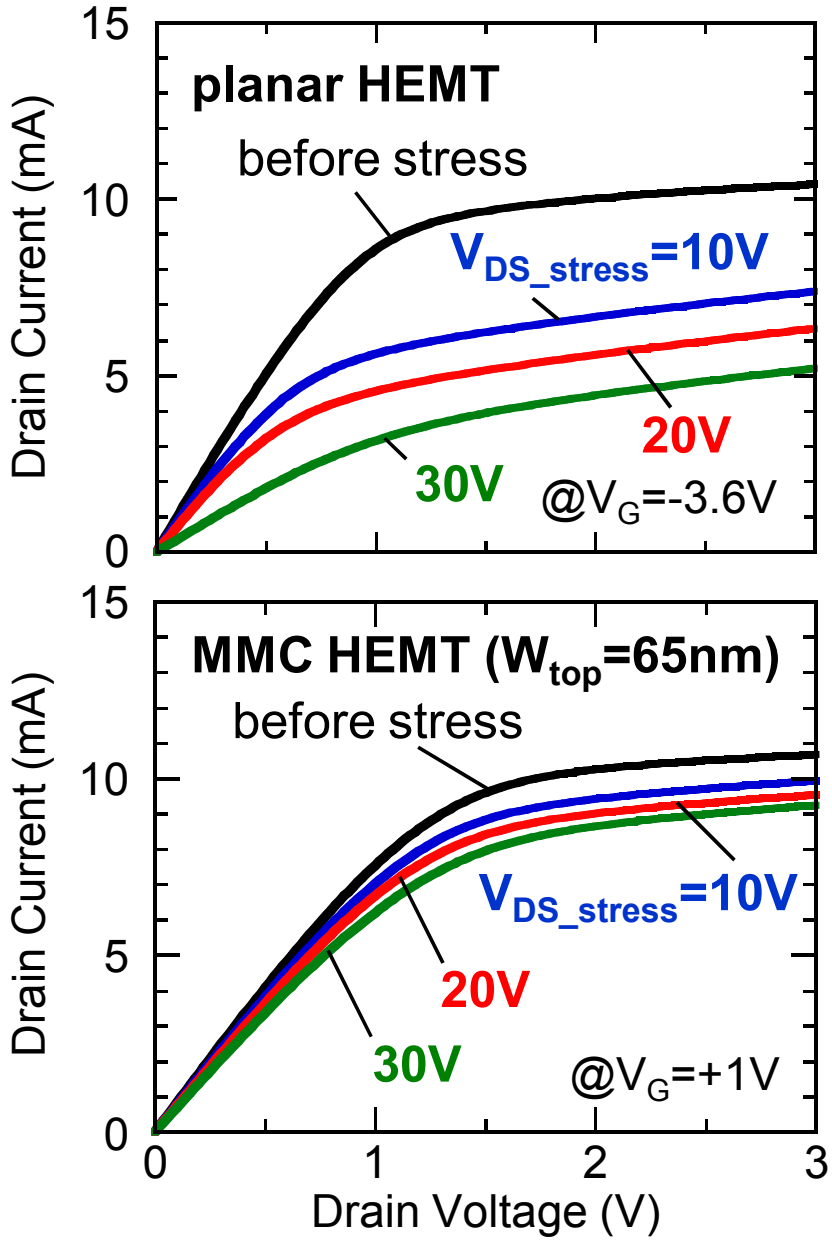

during the stress
electrons are injected to
the surface states

negatively charged states
reduce the 2DEG density

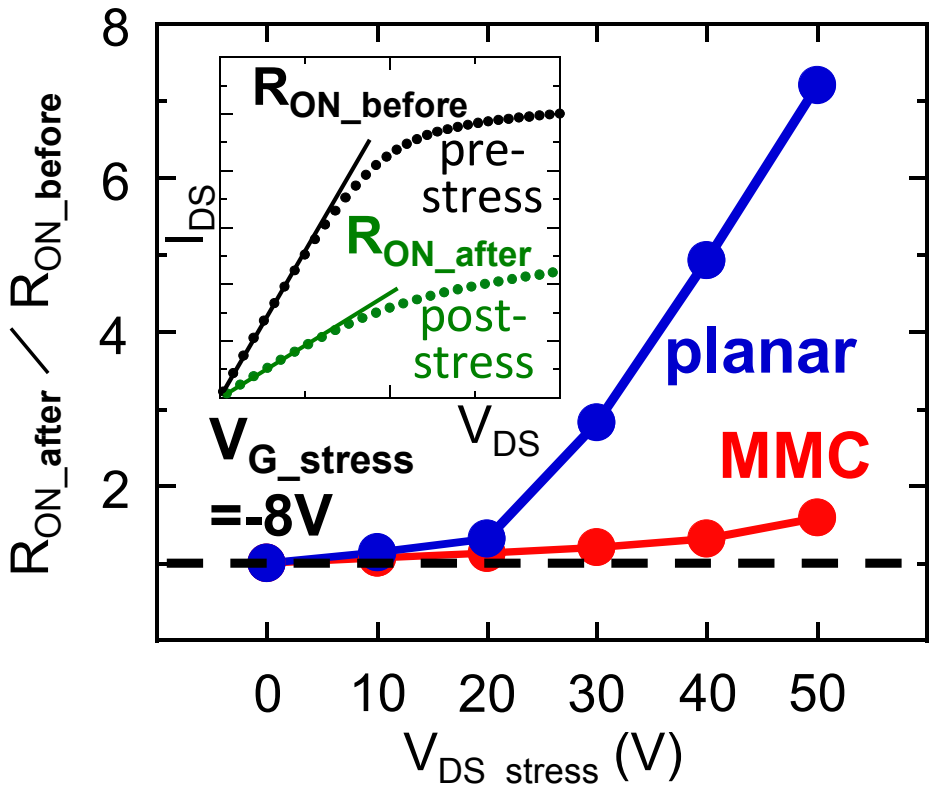
↓

increase of drain access
resistance $R_{Daccess}$

# Current stability of MMC HEMT against off-stress



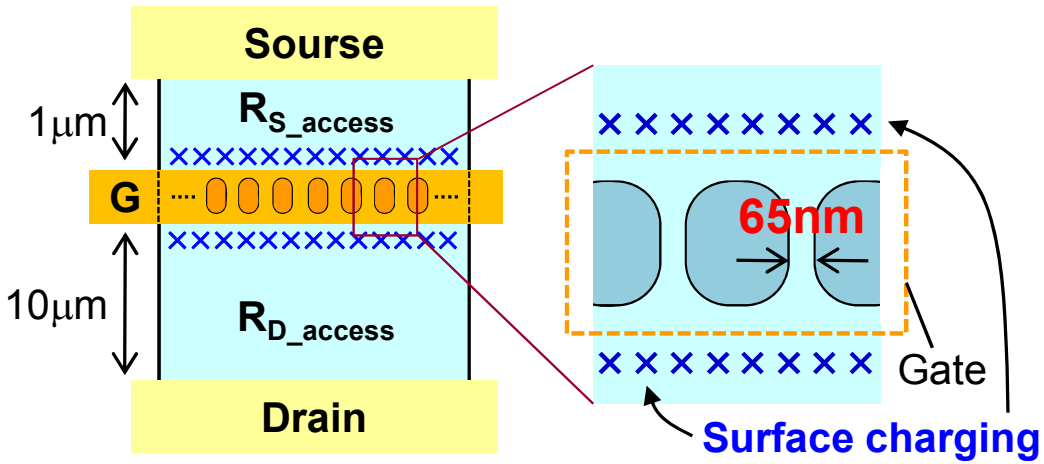

$R_{ON}$ ration before and after off-state stress




Phys. Status Solidi (c), in press (2012)

# Advantage of high-impedance channel in MMC HEMT

| | Before stress ($R_0$) | After stress ($R_0 + R_{stress}$) |
|---|---|---|
| $R_{S\_access}$ | 4 ~ 5 Ω | 60 ~ 70 Ω |
| $R_{D\_access}$ | 40 ~ 50 Ω | 140 ~ 180 Ω |




$V_G$ : 0 ~ +1V

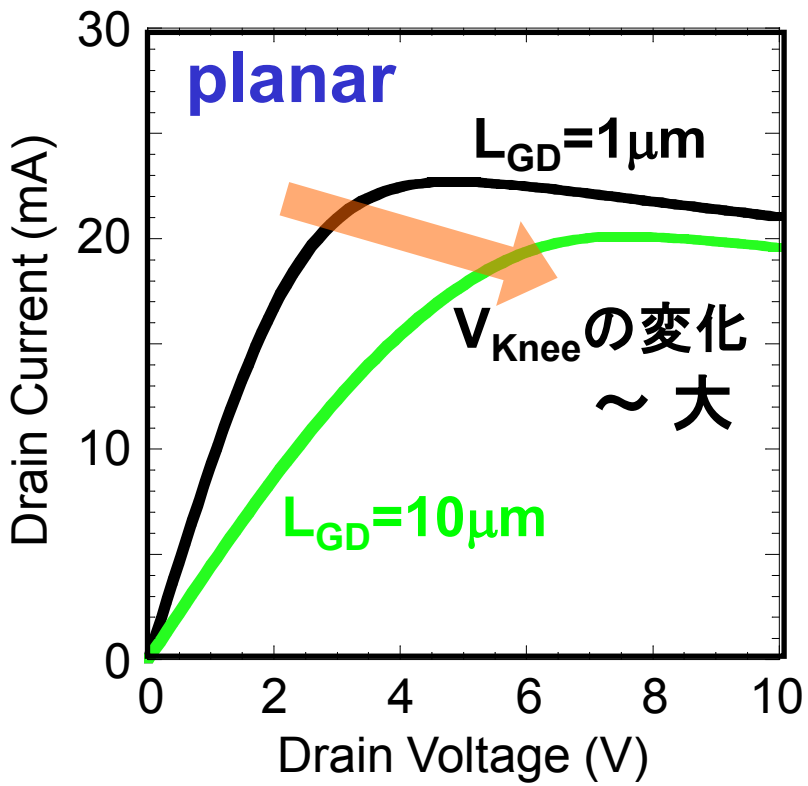
$R_{channel}$ : 4 ~ 6kΩ

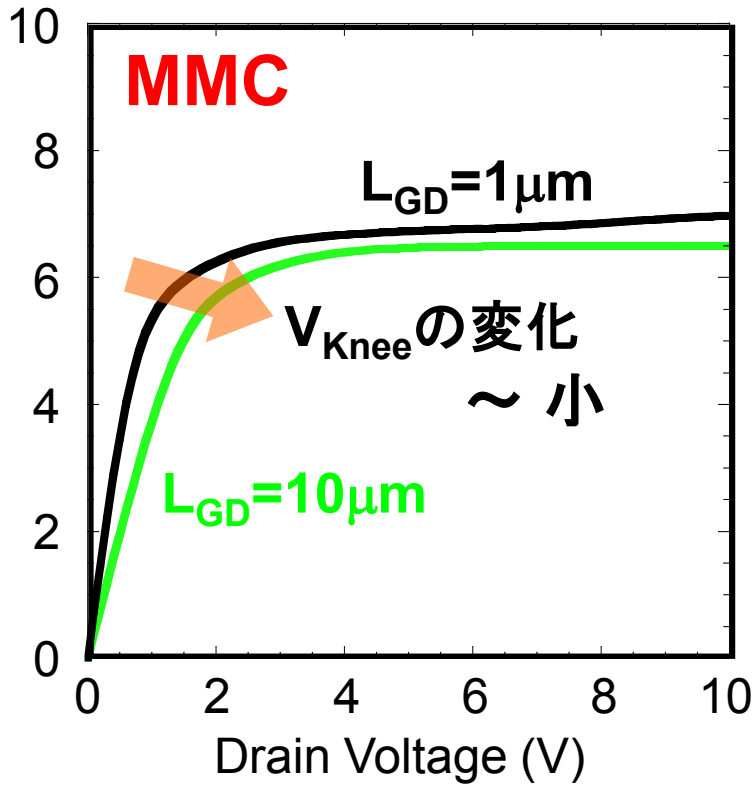
**MMC HEMT**

$R_{channel} \gg R_{D\_stress}$

Operation of the MMC HEMT is rather insensitive to change in access resistance, leading to resistance to off-stress-induced current collapse.

# Advantage of high-impedance channel in MMC HEMT



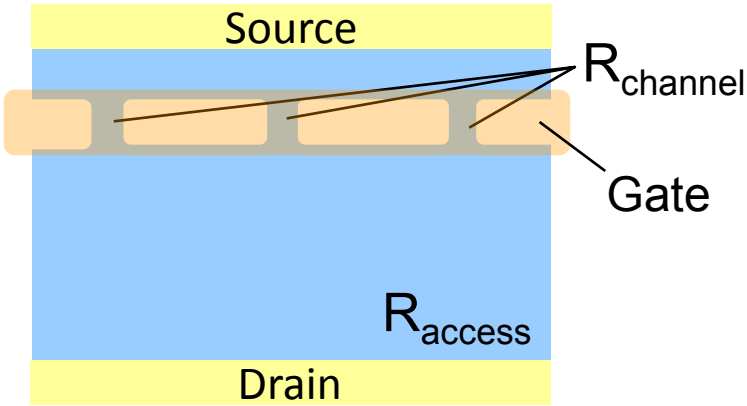

$R_{ON}$ is strongly dependent on $L_{GD}$ (drain access resistance)

High-impedance channel brought weak dependency

# Summary

To improve current controllability, MMCs with channel widths less than 100 nm were fabricated in an AlGaN/GaN HEMT, by forming a periodic trench structure under a gate electrode.

- Control of threshold voltage
- High current drivability
- Good subthreshold characteristics
- Good current stability




**Unique and promising characteristics for inverter application**

- **surrounding field effect and high-impedance channel**

Very recently, similar device structures were applied to AlGaN/GaN HEMTs [EDL, 33, 360(2012), EDL, 33, 354(2012)].