Ultra-Wide Bandgap AlGaN Channel MISFET with Graded Heterostructure Ohmic Contacts

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Acknowledgment:
ONR (Dr. Paul Maki), NSF (ECCS-1408416), Raytheon IDS Microelectronics

Outline

- Motivation
- Heterostructure graded ohmic contacts
  - Experimental results
- MISFET device operation

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- **Motivation**
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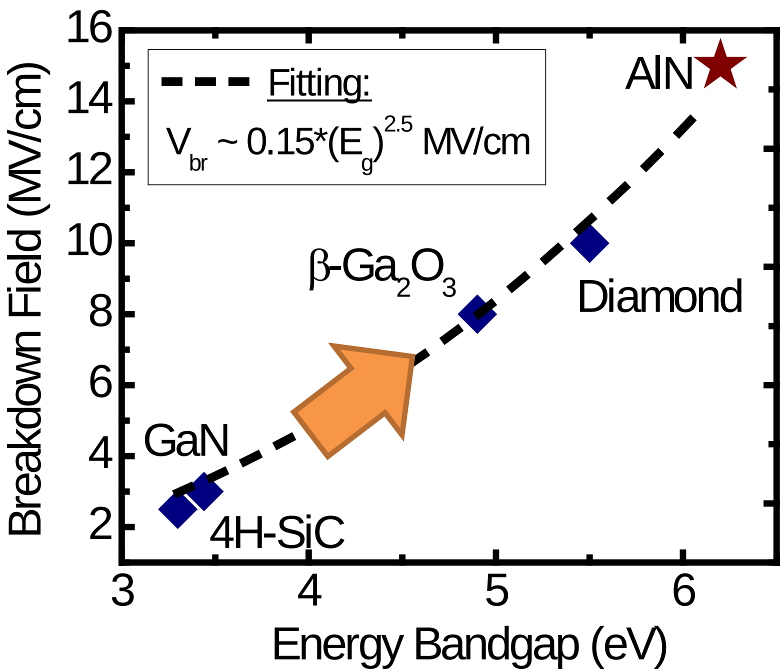
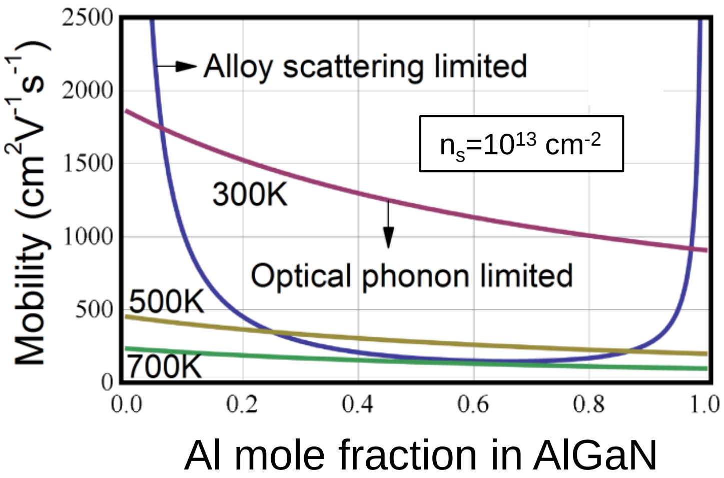
Ultra-wide bandgap material systems

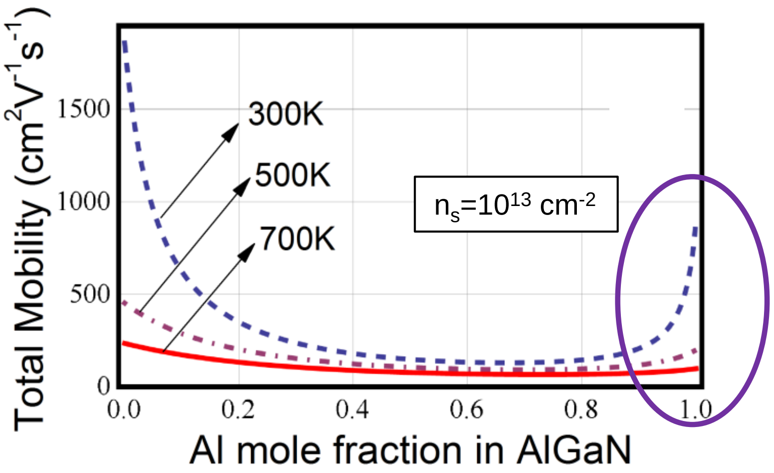


- GaN – wide bandgap (3.4 eV)
- Ultrawide bandgap (UWBG) material systems with bandgap exceeding 4 eV
- AlN with extremely high (theoretical) breakdown field ~ 5X of GaN
- Results in high composition AlGaN with superior device figures of merits – next-generation rf amplifiers? Power switches?

Hudgins et al. *IEEE TED* 18.3 (2003)

Switching figure of merit





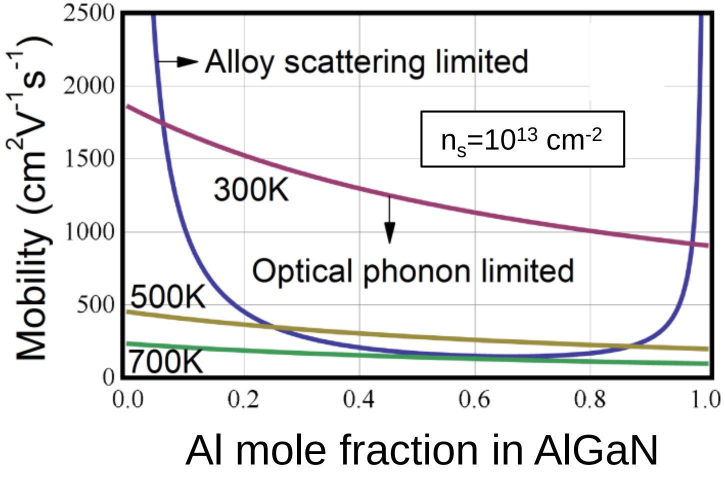
2DEG mobility:

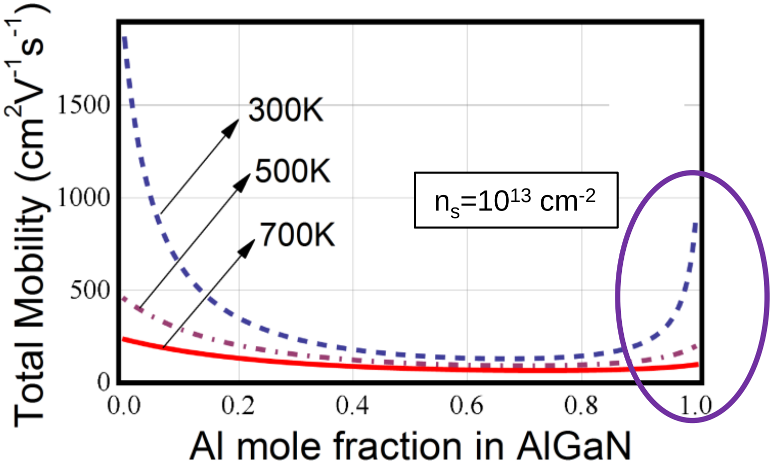
- Limited by Alloy Scattering + Optical Phonon Scattering

$$\frac{1}{\mu_{total}} = \frac{1}{\mu_{phonon}} + \frac{1}{\mu_{alloy}}$$

Bajaj et al., APL 105.26 (2014)

Switching figure of merit





2DEG mobility:

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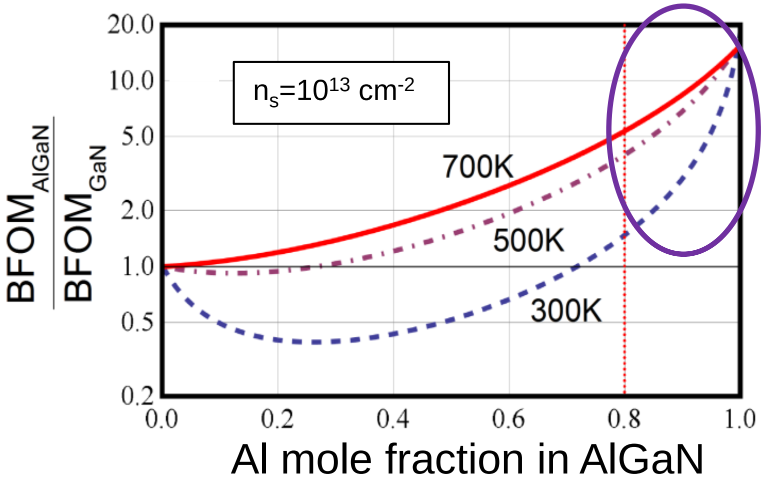
Baliga figure of merit ($\varepsilon\mu E_C^3$):

- Superior for larger Al compositions in channel than GaN



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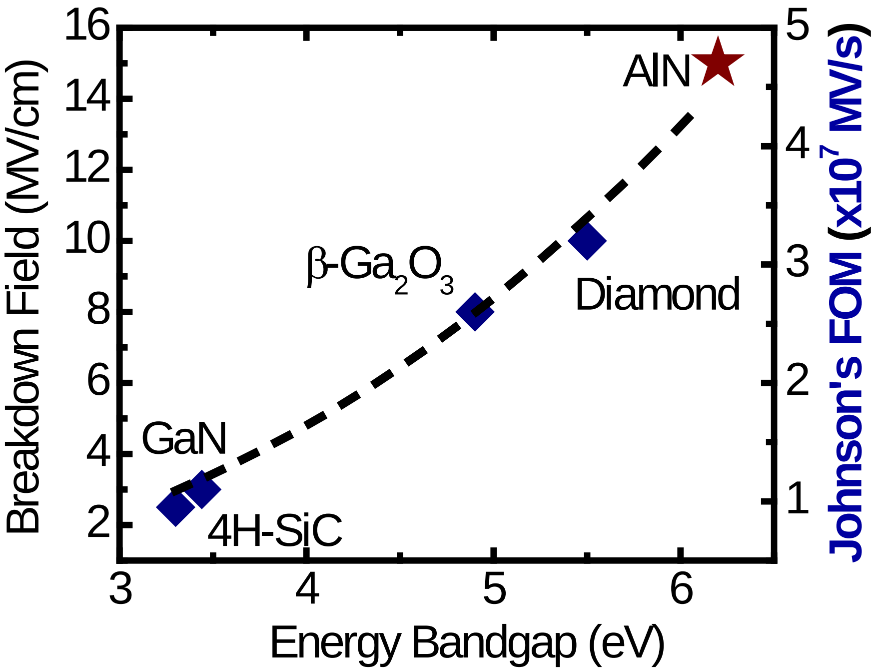
AlGaN for rf electronics

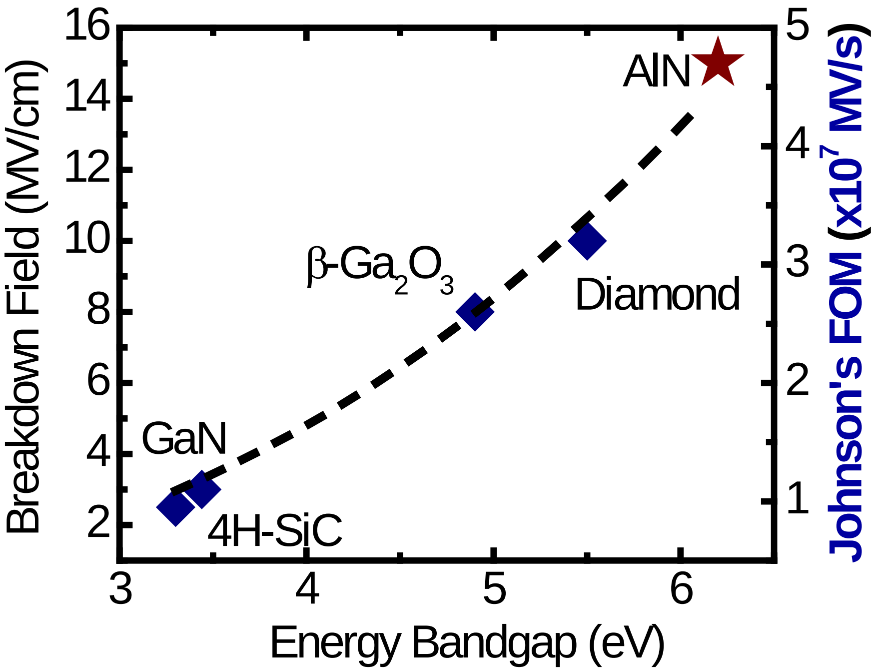


- AlGaN channels with predicted electron velocities comparable to GaN – superior Johnson’s figure of merit (theoretical)

Farahmand *et al*. *IEEE TED* 48.3 (2001)

Anwar *et al*. *IEEE TED* 48.3 (2001)

AlGaN for rf electronics / optoelectronics



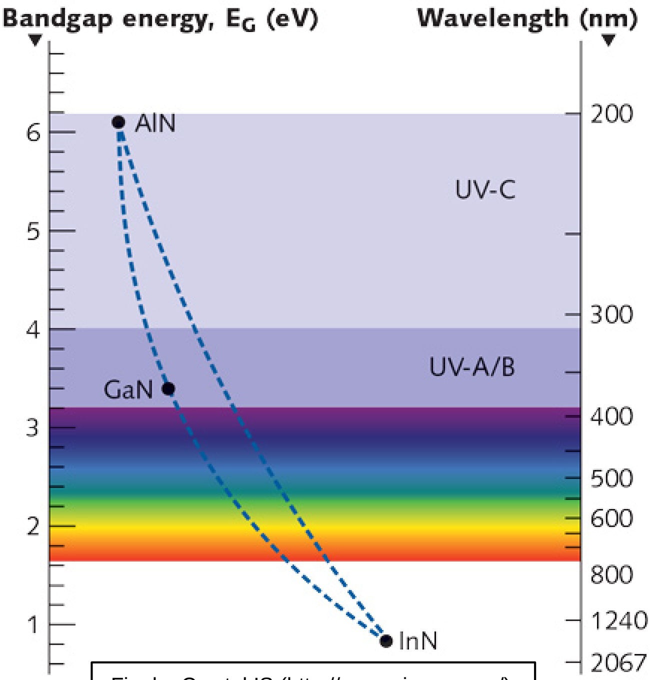


Fig. by Crystal IS (http://www.cisuvc.com/)

- AlGaN channels with predicted electron velocities comparable to GaN – superior Johnson’s figure of merit (theoretical)
- Also enables deep-UV emitters and detectors

Farahmand *et al*. *IEEE TED* 48.3 (2001)

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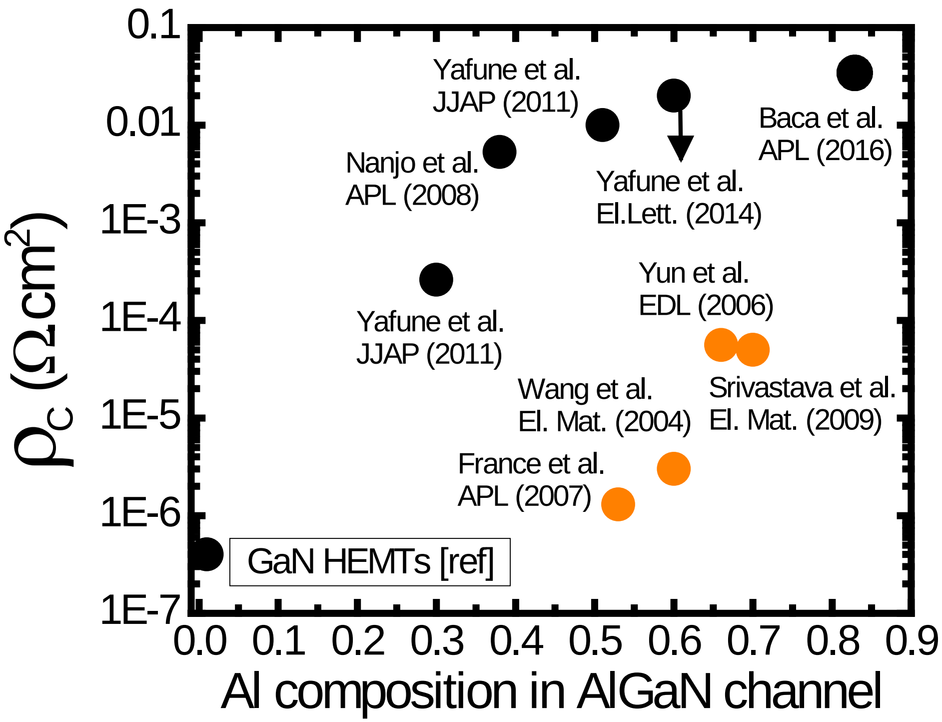
Key Challenges

Material Challenges: Defects, Mobility

Device Challenges: High contact resistances to AlGaN Channels



Li et al., *IEEE EDL* 20.7 (1999)

Yue et al., *IEEE EDL* 33.7 (2012)

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- **Heterostructure graded ohmic contacts**
    - Experimental results
- MISFET device operation

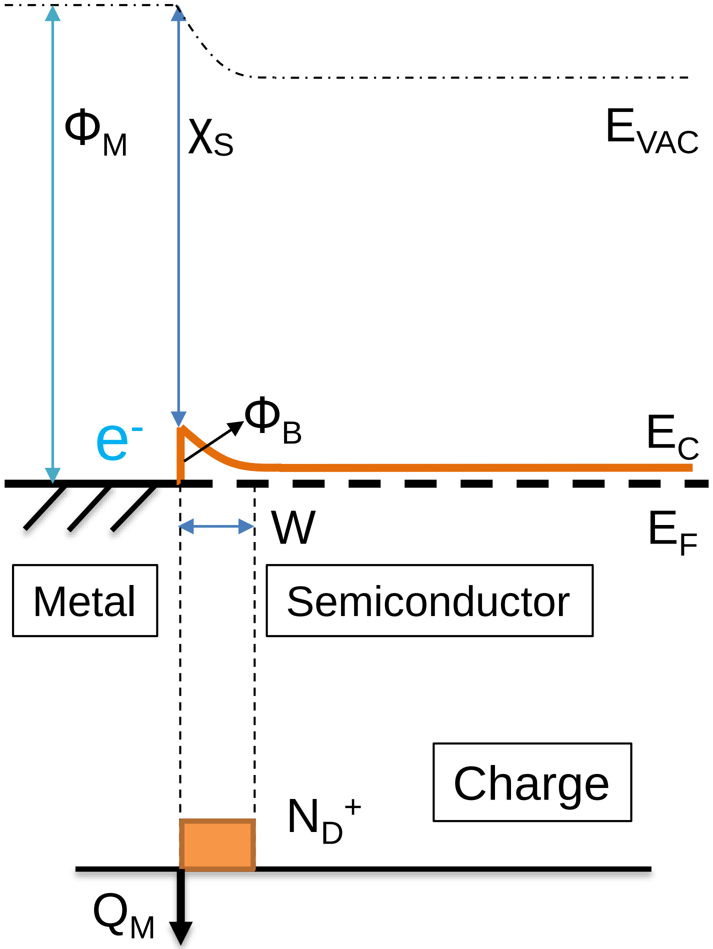
Ohmic Contact Formation

Requirements:

1. High channel electron affinity / matching metal work function
2. High doping density

- Result in small tunneling barrier and width for electrons – high tunneling probability

$$T = e^{\frac{-4\sqrt{2m^*}\,\phi_B^{1/2}\,W}{3e\hbar}}$$



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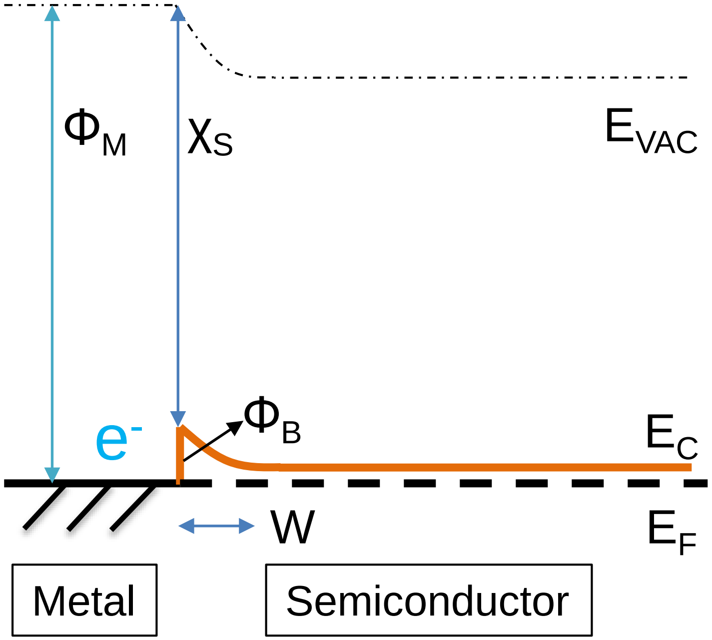

Conventional n-GaN channel:

- Relatively high electron affinity (4.1 eV)
- Metals with similar work function result in small tunneling barrier – R_C below 10^{-6} $\Omega.cm^2$

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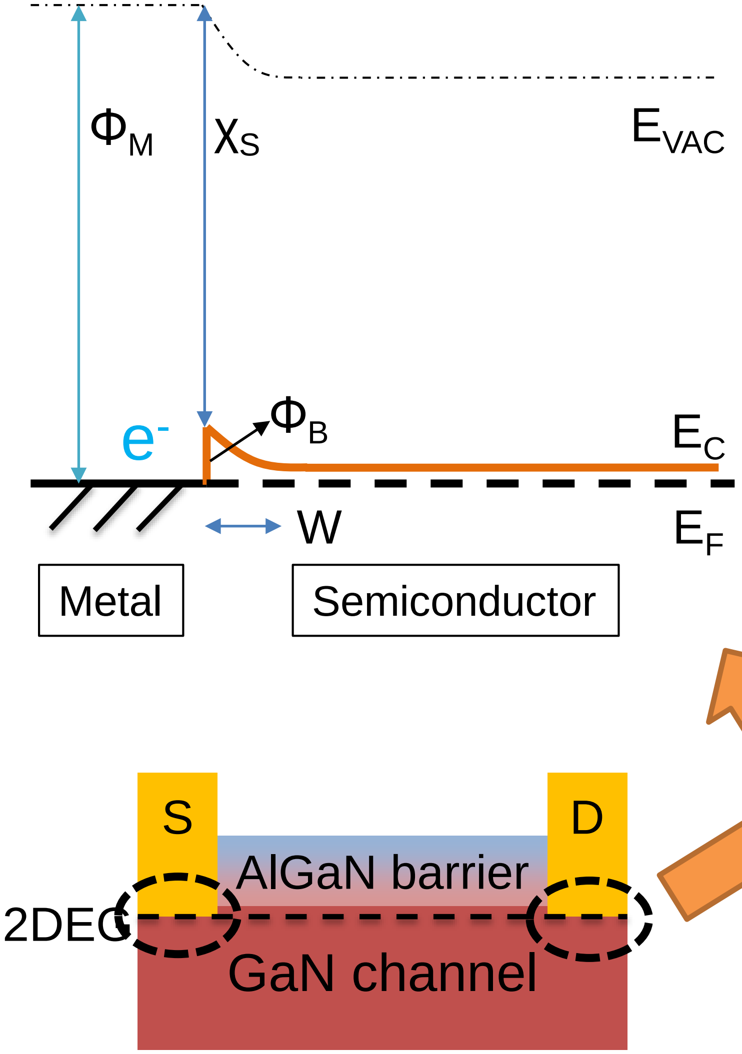


Conventional n-GaN channel:

- Relatively high electron affinity (4.1 eV)
- Metals with similar work function result in small tunneling barrier – R_C below 10^{-6} Ω.cm^2

- GaN HEMTs – alloyed / regrown contacts give low R_C to 2DEG

Li et al., *IEEE EDL* 20.7 (1999)

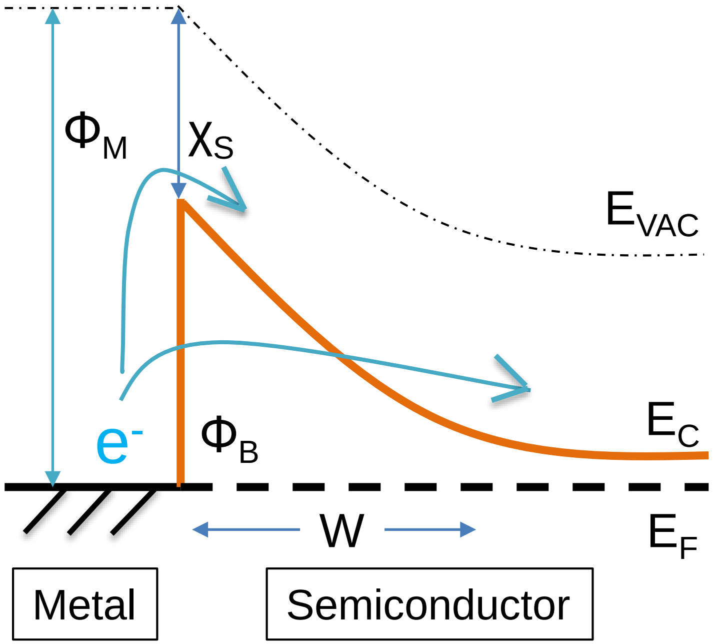
Yue et al., *IEEE EDL* 33.7 (2012)

Ohmic Contacts to UWBG AlGaN

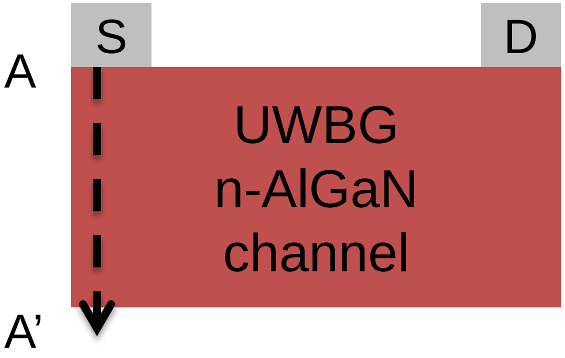
Challenges:

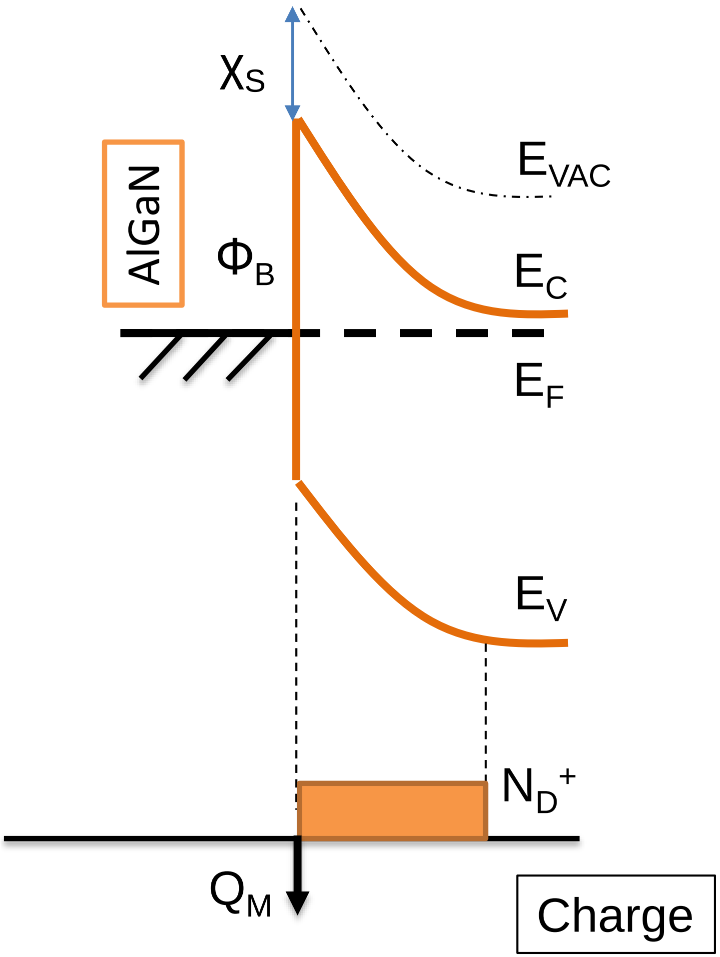
1. Low electron affinity of AlN (0.6 eV) – high Schottky barrier
2. Low doping efficiency

- Result in low tunneling probability, high R_C



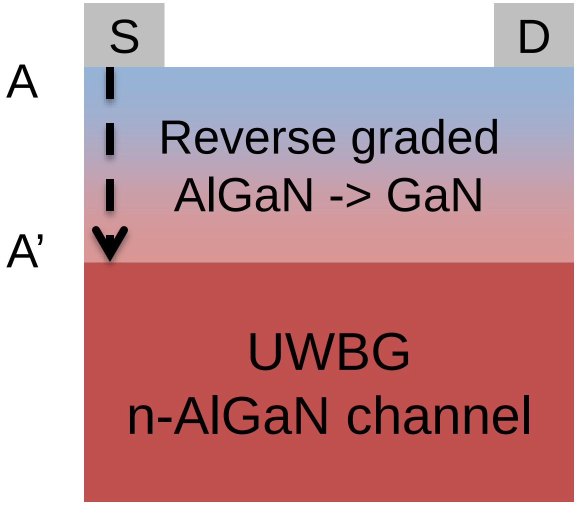
Heterostructure-engineered ohmic contacts

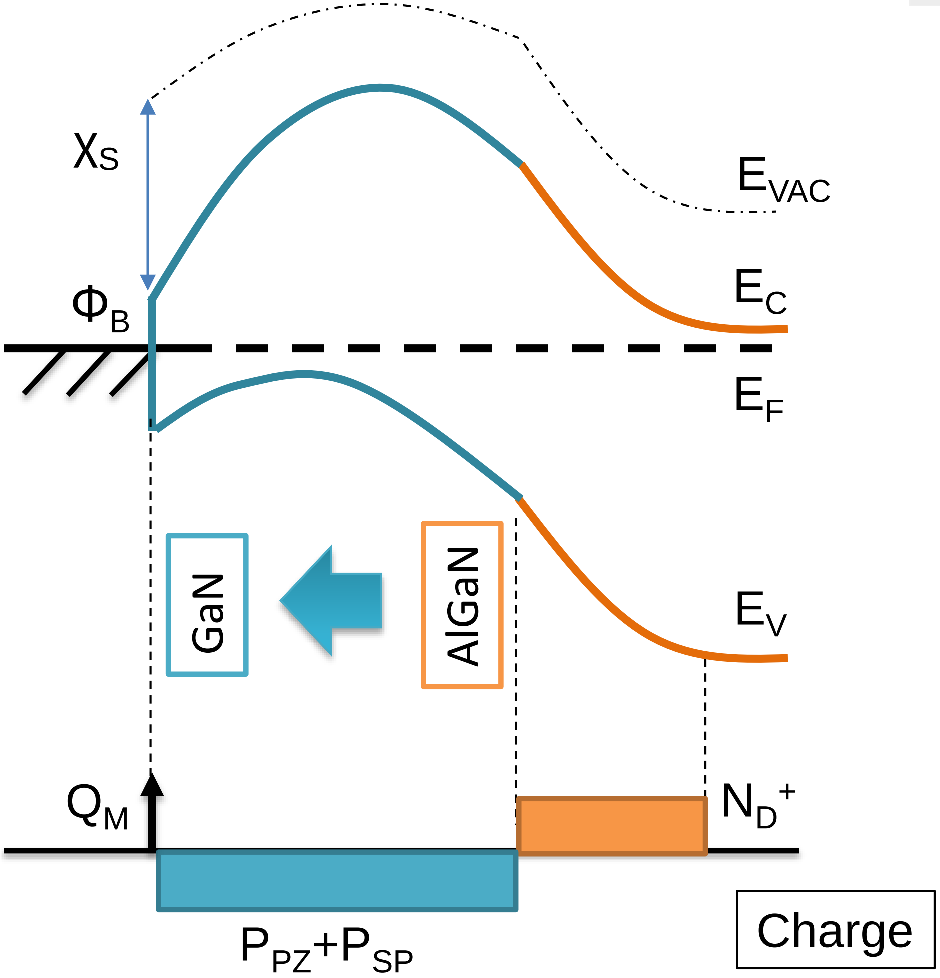




- Conventional ohmic contact to n-type UWBG AlGaN channel – large Schottky barrier

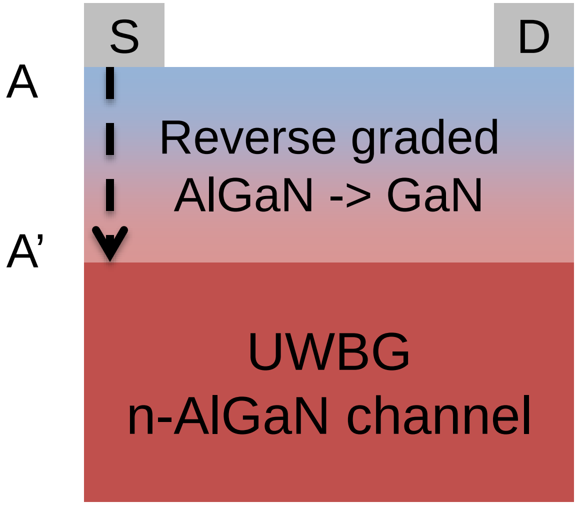
Heterostructure-engineered ohmic contacts

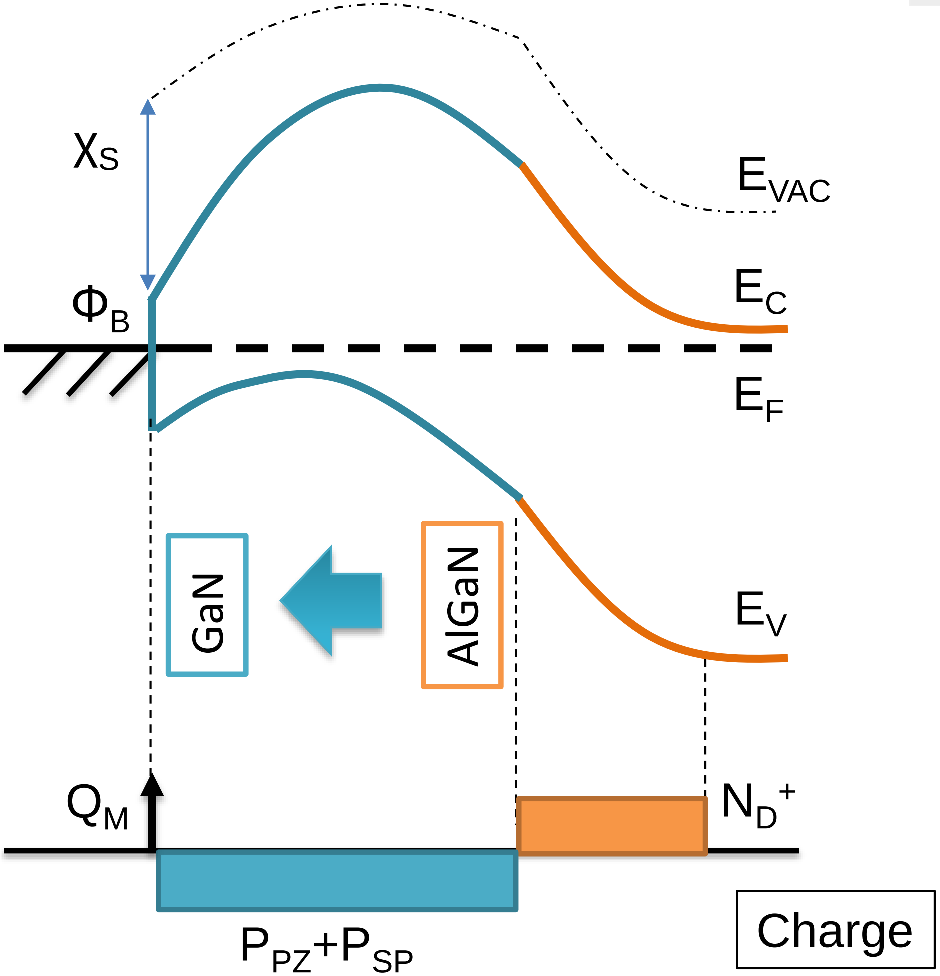




- Contact layer with reverse composition-grading from wider bandgap AlGaN to lower bandgap GaN – **lower Schottky barrier**

Heterostructure-engineered ohmic contacts





- Negative polarization charge (spontaneous + piezoelectric) raises E_C (0001 direction) – large barrier for electrons!

Jena et al., *APL* 81.23 (2002)	Rajan et al., *APL* 84.9 (2004)

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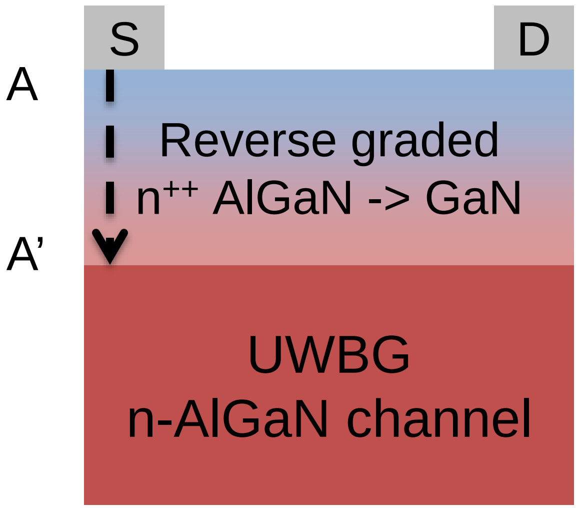
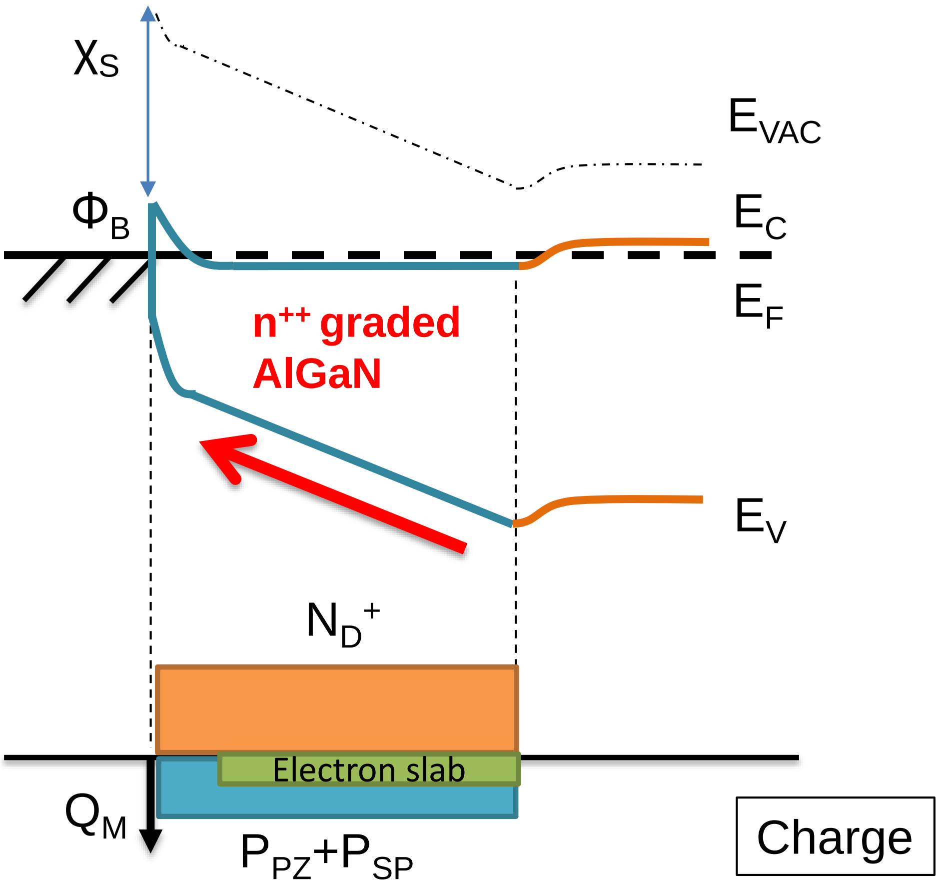
Heterostructure-engineered ohmic contacts





- High donor concentration **compensates** negative polarization charge – flat E_C profile, low R_{SH}

Jena et al., *APL* 81.23 (2002) Rajan et al., *APL* 84.9 (2004)

Park et al., *IEEE EDL* 36.3 (2015)

- Contact layer with reverse composition-grading from wider bandgap AlGaN to lower bandgap GaN – **lower Schottky barrier**

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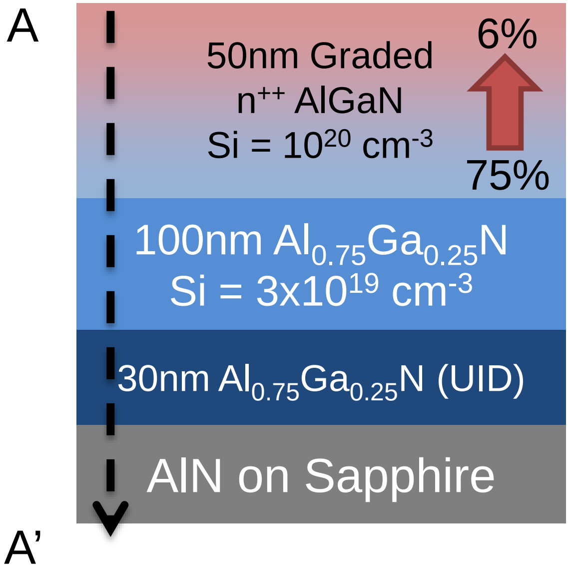
    - **Experimental results**
- MISFET device operation

Experiment – n-type $Al_{0.75}Ga_{0.25}N$ Channel


A

50nm Graded n^{++} AlGaN $Si = 10^{20}$ cm^{-3}

6%

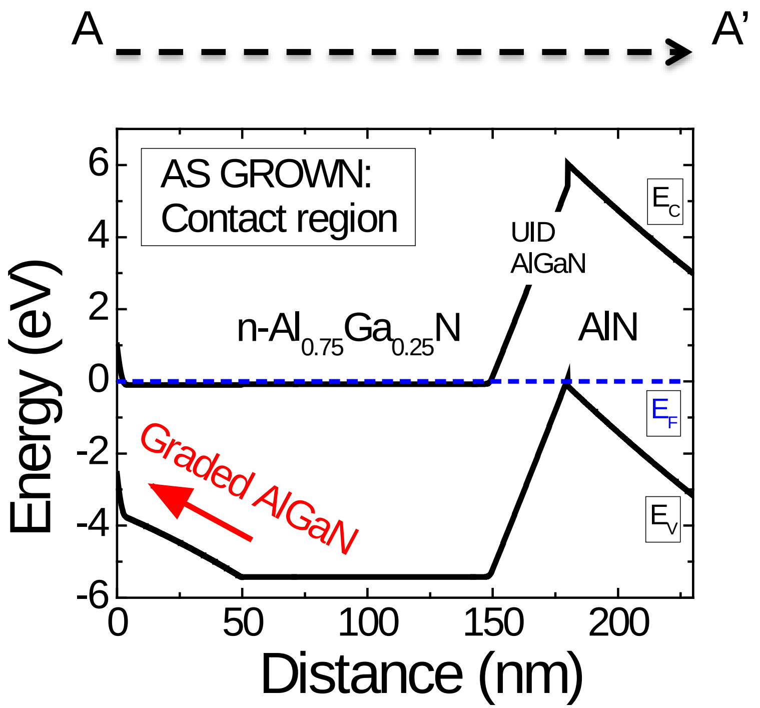
75%

100nm $Al_{0.75}Ga_{0.25}N$ $Si = 3x10^{19}$ cm^{-3}

30nm $Al_{0.75}Ga_{0.25}N$ (UID)

AlN on Sapphire

A’



- 100 nm 75% n-AlGaN channel with $E_G = 5.35$ eV (MBE growth on AlN/Sapphire template)
- Si donor concentration = $3x10^{19}$ cm^{-3}
- 50 nm n^{++} reverse polarization-graded contact layer

- Conduction band profile under ohmic region (as-grown)

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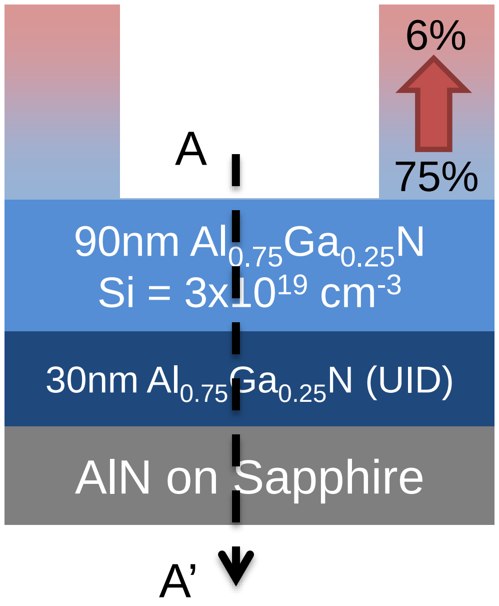

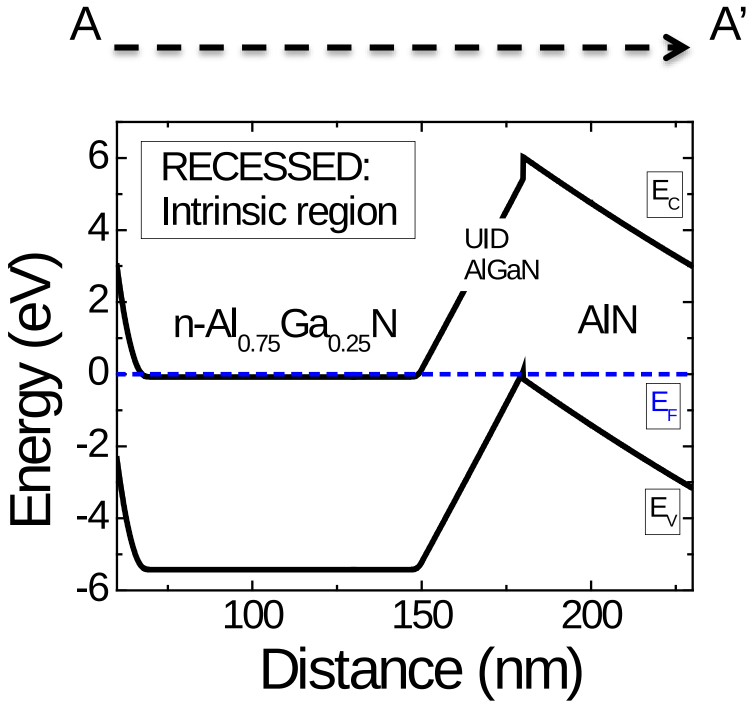

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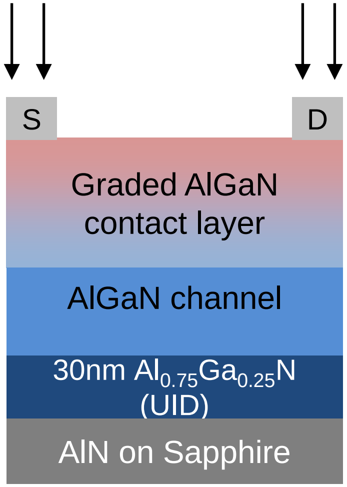
- Conduction band profile under gate region (recessed)

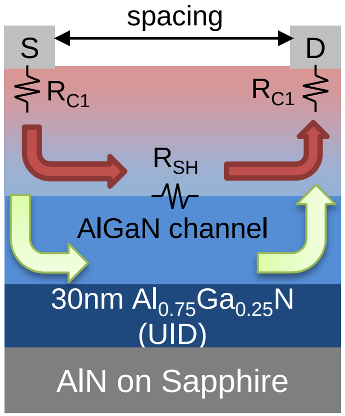
Non-Alloyed Ohmics Contacts

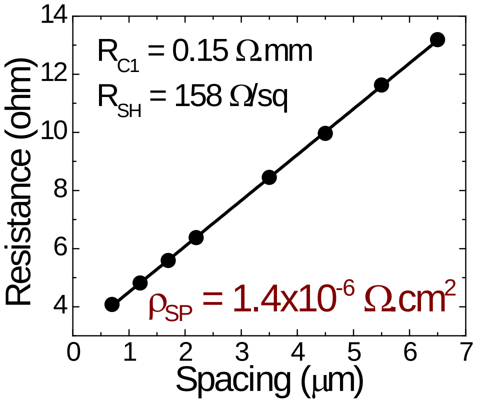


Non-alloyed ohmic contacts – Ti/Al/Ni/Au = 20/120/30/50 nm

IWN2016 Sanyam Bajaj: bajaj.10@osu.edu Prof. Siddharth Rajan: rajan.21@osu.edu

Contact Resistance using TLM





As-grown structure:

- R_{C1} (Metal-semiconductor interface resistance) = 0.15 Ω.mm
- $\rho_{SP} = 1.4\text{x}10^{-6}\ \Omega.\text{cm}^2$

Recessed structure:

- Net R_C to 75% AlGaN channel = 0.32 Ω.mm
- $\rho_{SP} = 1.9\text{x}10^{-6}\ \Omega.\text{cm}^2$

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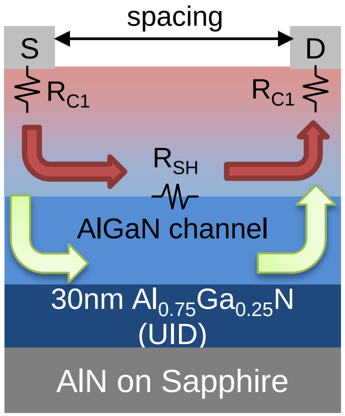

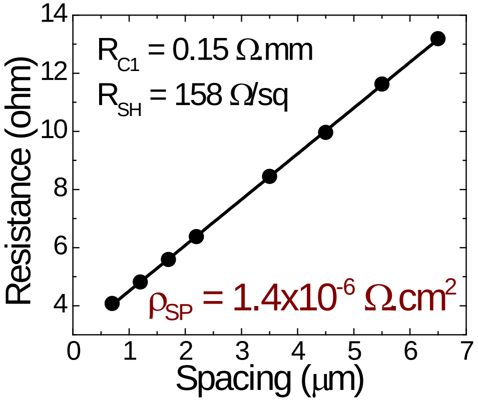

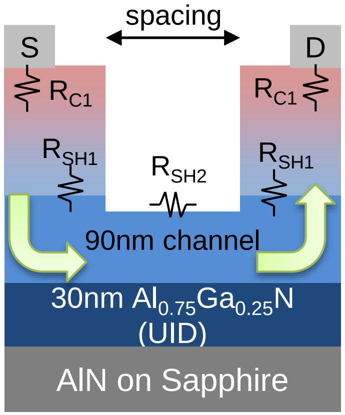

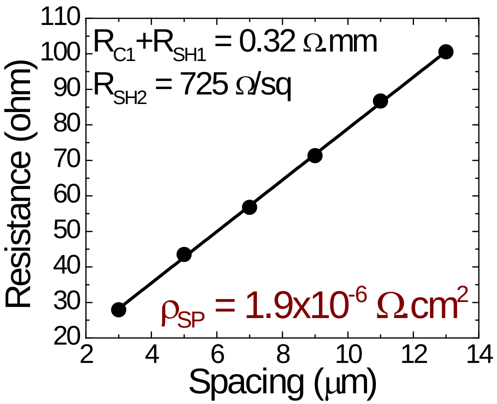

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Cl_2-based ICP-RIE etch to test contact to AlGaN channel

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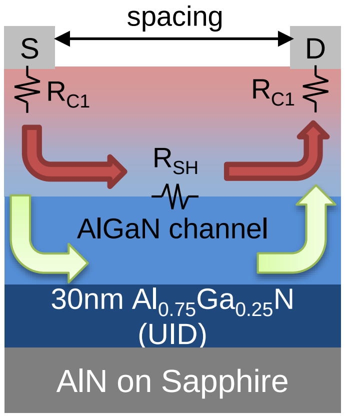

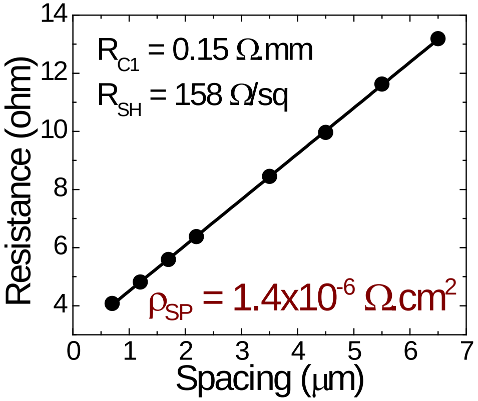

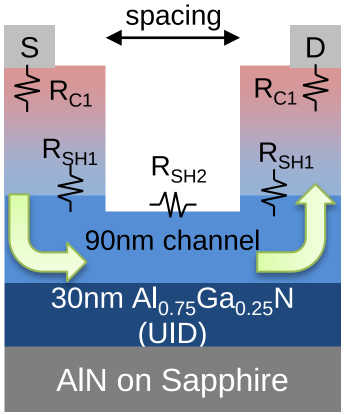

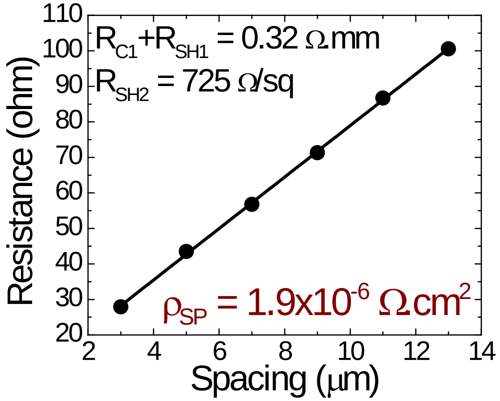

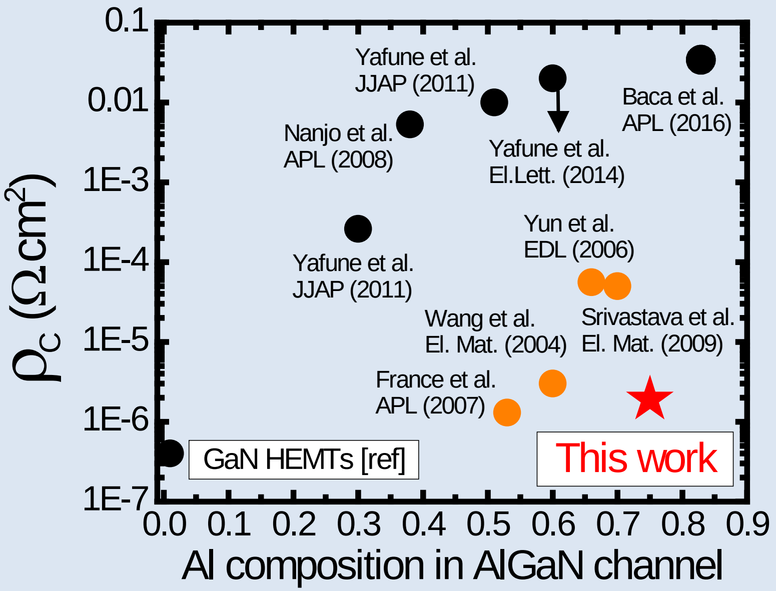

- $\rho_{SP} = 1.9\times10^{-6}\ \Omega.cm^2$

Low ρ_{SP} to UWBG AlGaN ~ 5.3 eV (Non-alloyed)

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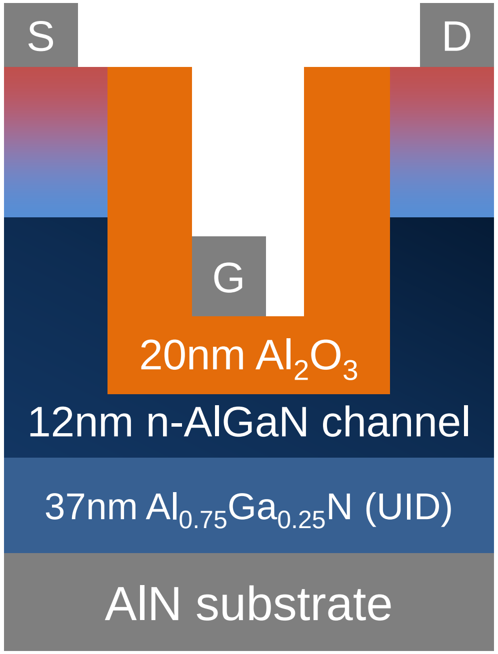
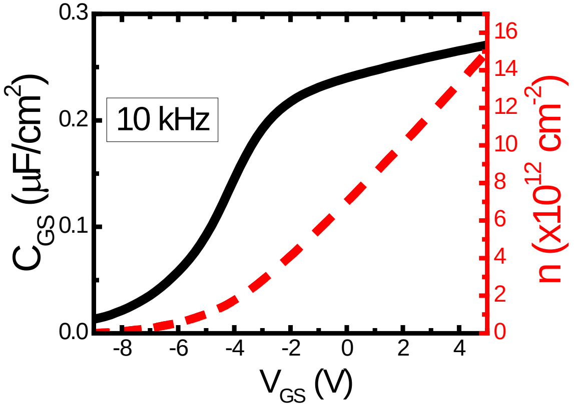
$Al_{0.75}Ga_{0.25}N$ Channel MIS-FET

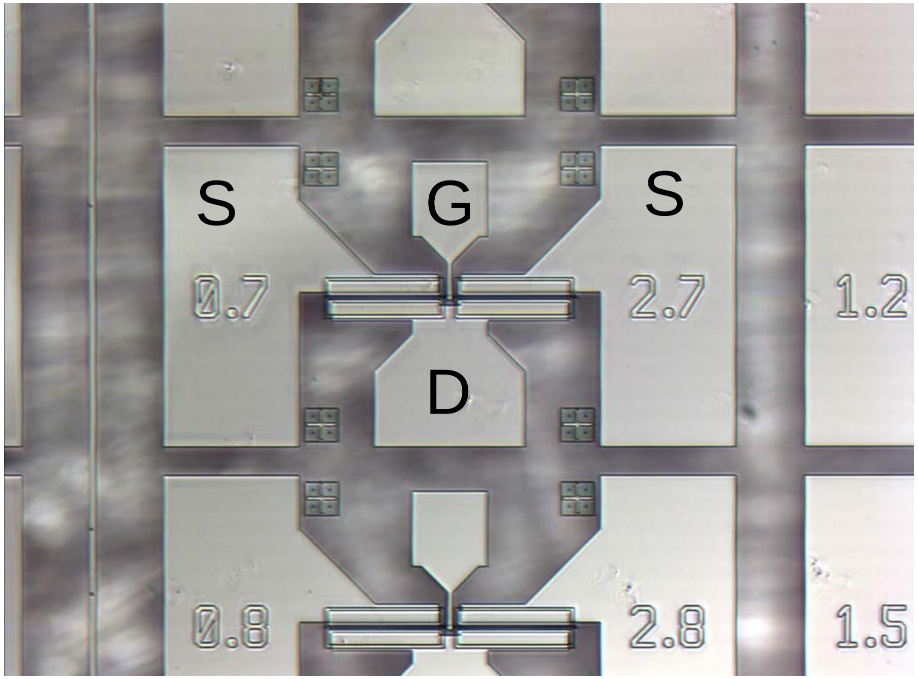




- Recessed structure with 12 nm n-$Al_{0.75}Ga_{0.25}N$ channel

- 20 nm ALD Al_2O_3 followed by 700°C PDA (30s)

- C-V profile resulted in pinch-off voltage = - 6 V ; accumulation region with MESFET-like behavior ; charge = $1.5x10^{13}$ cm^{-2}



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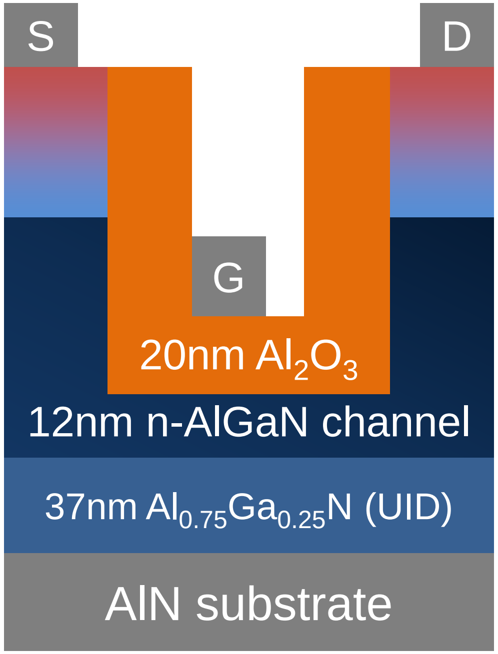

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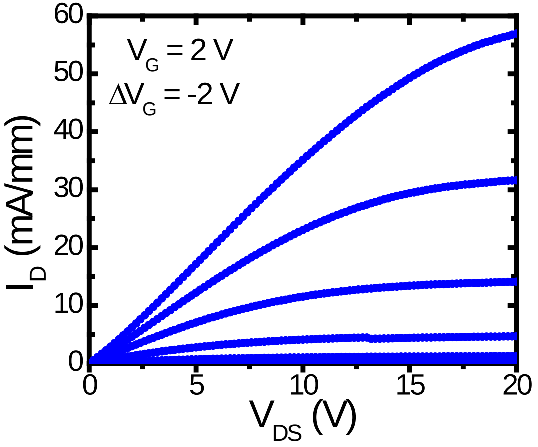
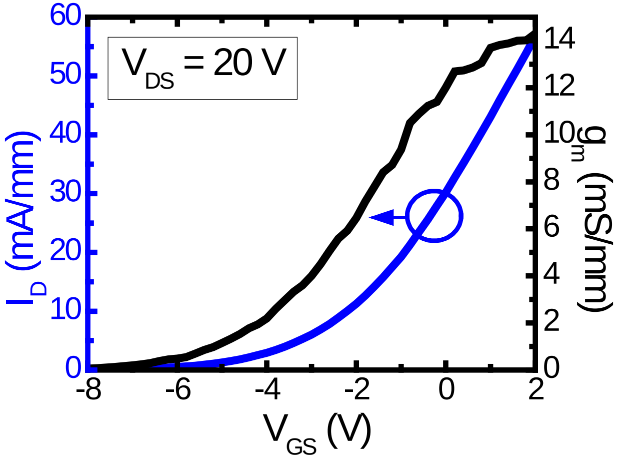
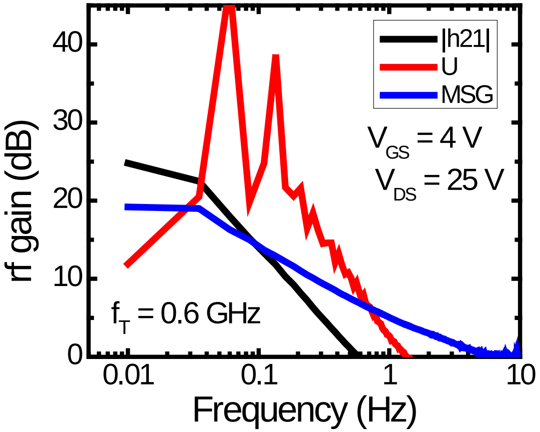
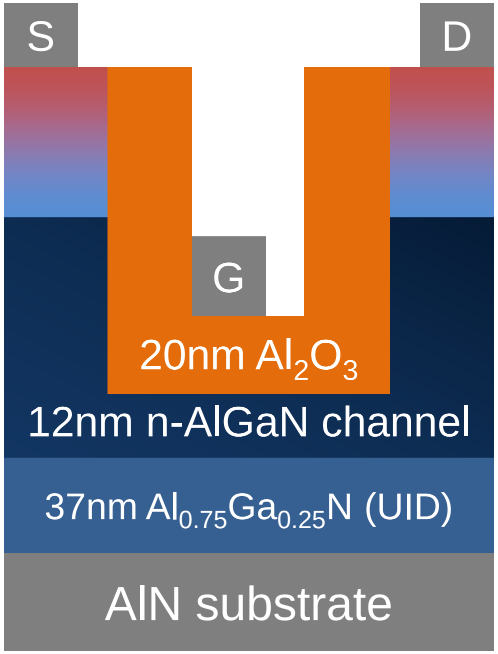






- I_{DS_MAX} ~ 60 mA/mm ; g_{m_MAX} = 14 mS/mm
- f_{T_PEAK} of 0.6 GHz ; f_{MAX_PEAK} of 1.4 GHz
- Limited by low channel mobility of 16 cm^2/Vs
- Defect related compensation

$Al_{0.75}Ga_{0.25}N$ Channel MIS-FET



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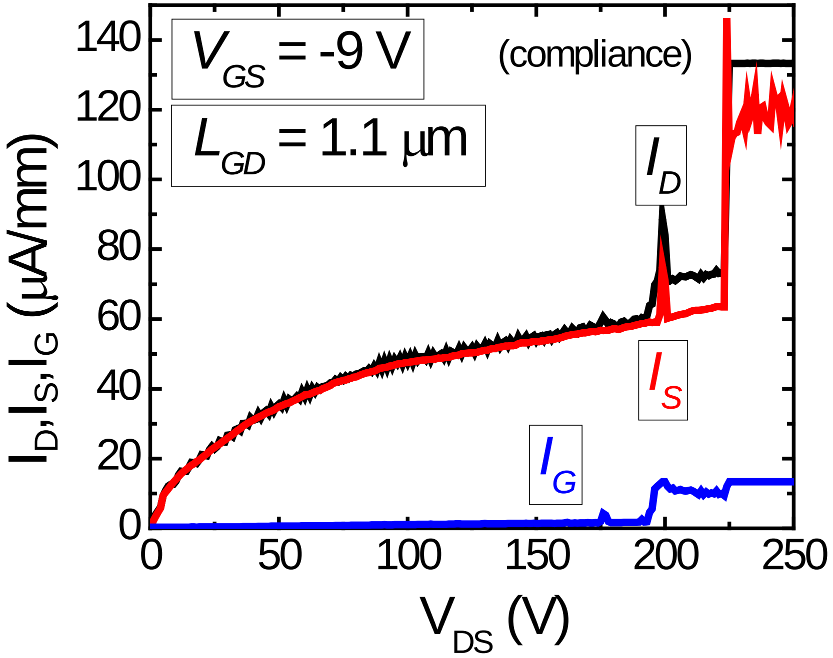

- V_{br} = 224 V @ V_{GS} = -9 V for L_{GD} = 1.1 μm in Fluorinert
- no field plates
- Average field > 2 MV/cm – higher than GaN FETs

SUMMARY

- Heterostructure graded ohmic contacts to UWBG AlGaN – compositional grading + high doping
- Achieved low specific contact resistance to $Al_{0.75}Ga_{0.25}N$ channels (NON-ALLOYED)
- Demonstrated the 1st UWBG $Al_{0.75}Ga_{0.25}N$ channel MISFET with low-resistance ohmics (MBE)
- This work removes one of the principle challenges for UWBG AlGaN devices; applications in large range of electronic and photonic devices