Ultra-Wide Bandgap AlGaN Channel MISFET with Heterostructure Engineered Ohmics

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

Outline

- Motivation
- Heterostructure engineered ohmics
- MISFET device operation

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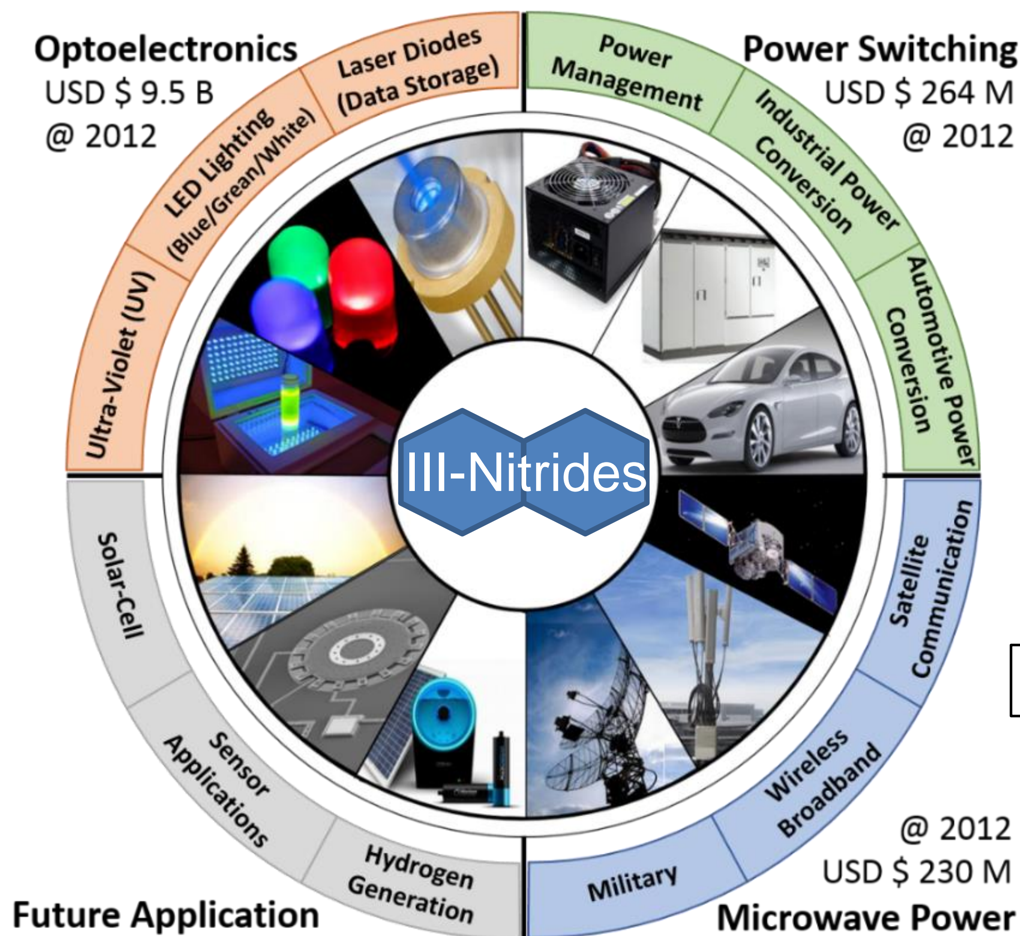
Applications – III-Nitrides



Dissertation, Pil Sung Park, OSU (2013)

High composition AlGaN with large bandgap / breakdown field:

- Next-generation High Power RF amplification / Switching
- Optoelectronics / Deep-UV emitters

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UWBG Material Systems

Properties	4H-SiC	GaN	Ga_2O_3	C	AlN
Bandgap (eV)	3.3	3.4	4.9	5.5	6.2
Breakdown Field (MV/cm)	2.5	3.3	8	10	12-16 [1]
Saturation velocity, v_{sat} (cm/s)	$2x10^7$	$2x10^7$	--	$\sim 2x10^7$	$\sim 2.2x10^7$ [2]
JFOM = $E_c v_{sat}/2\pi$ ($x10^7$ MV/s)	0.8	1.1	2.5	3.2	3.8 - 5
Relative dielectric constant (ε)	9.7	9	10	5.5	8.5
Electron mobility (cm^2/Vs)	1000	2000	300	2000	800 [3]
$BFOM/BFOM_{Si}$ ($\varepsilon \mu E_C^3$)	340	1450	3500	24660	> 26350
Polarization		YES			YES

[1]Hudgins et al. *IEEE Trans. on* 18.3 (2003)

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UWBG AlGaN:

- Extremely high (theoretical) critical breakdown field > 12 MV/cm

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UWBG AlGaN:

- Extremely high (theoretical) critical breakdown field > 12 MV/cm
- High saturation velocity predicted (Monte Carlo calculations) – more research needed to confirm experimentally
- Superior Johnson's FOM and Baliga's FOM – ideal for high power / high temperature / high frequency applications

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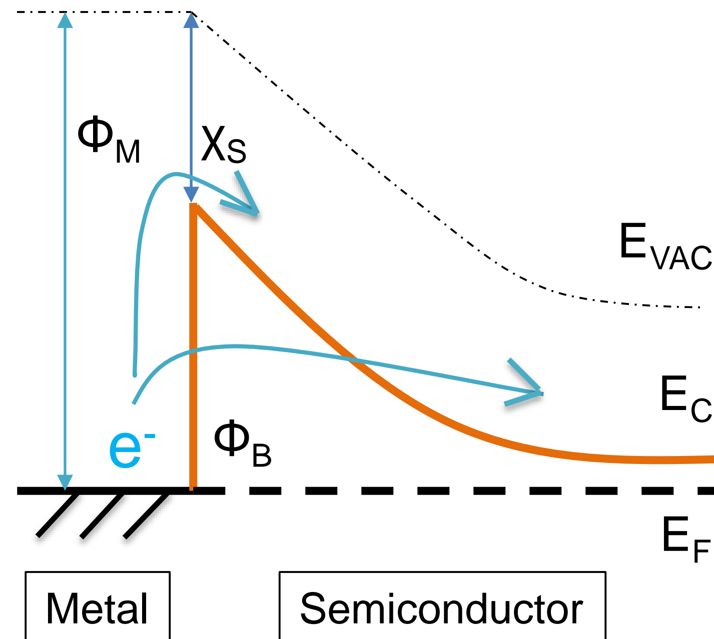
Challenge: Ohmic Contact Formation

WBG semiconductors –
1. Low electron affinity
2. Low dopant ionization

- Result in large tunneling barrier and width for electrons – low tunneling probability, high R_C

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



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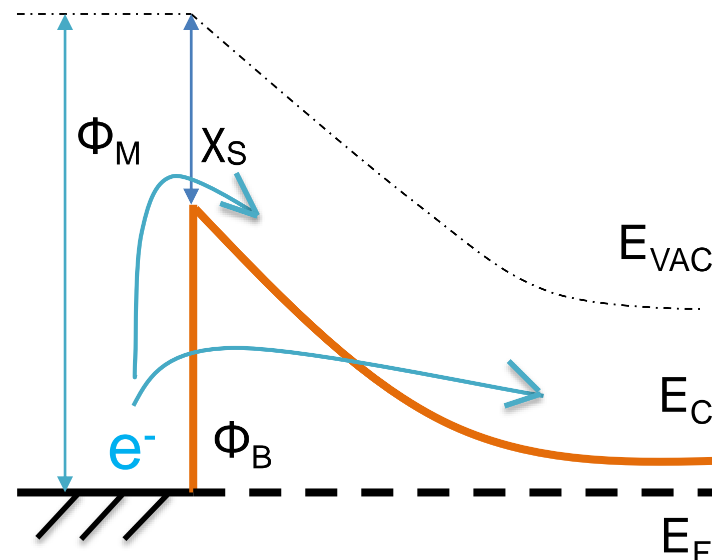
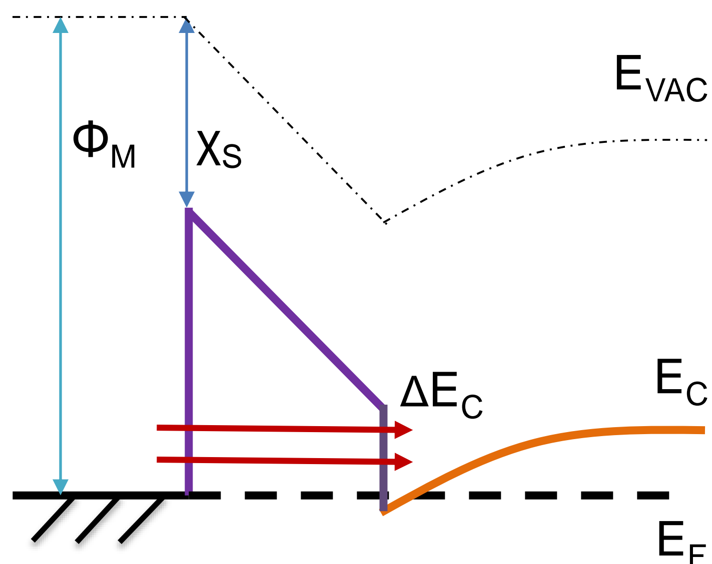


AlGaN channel HEMT structure: challenging to achieve alloyed ohmics

- Electron affinity of AlGaN lower than GaN
- Difficulty in spiking metal through high Al composition in barrier layer



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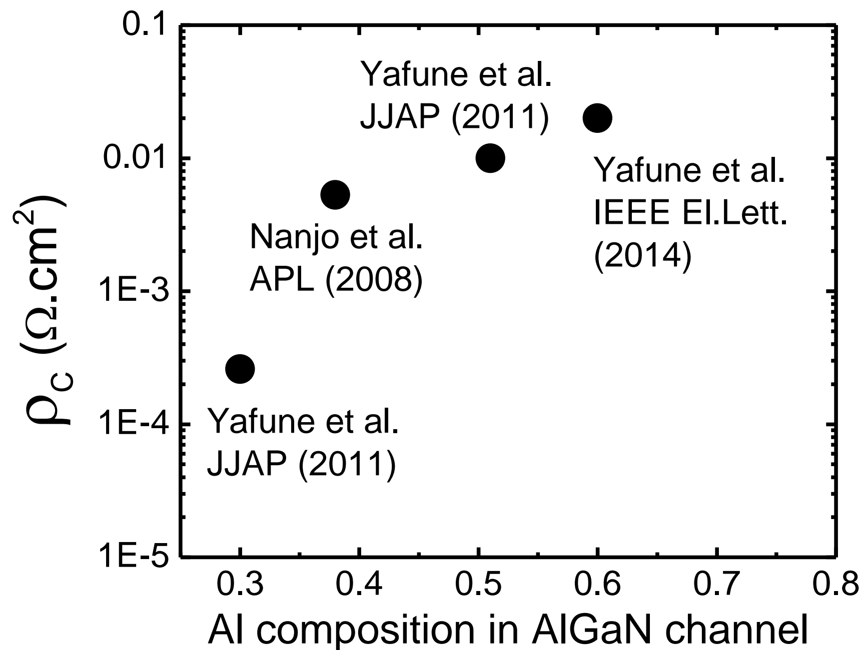
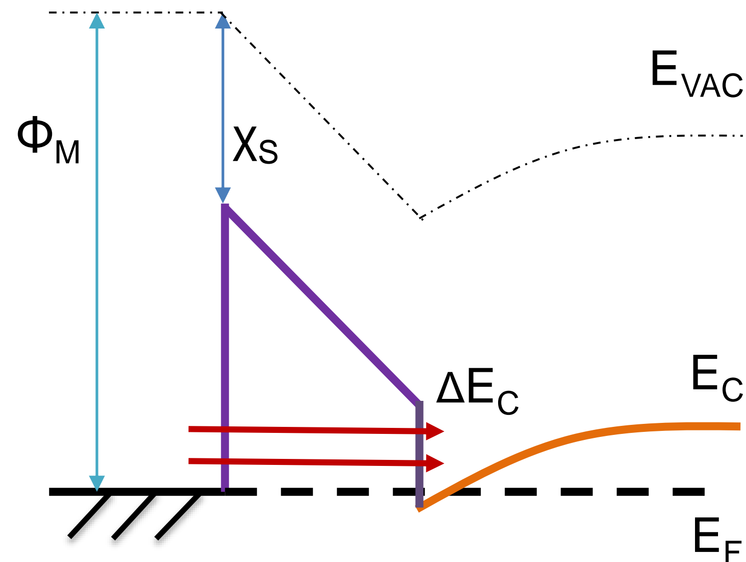
Previous work in Literature





Previous work on AlGaN channel HEMTs:

1) Zr/Al/Mo/Au metal-based alloyed ohmic contacts up to 60% AlGaN channel [Yafune et al., 2014]

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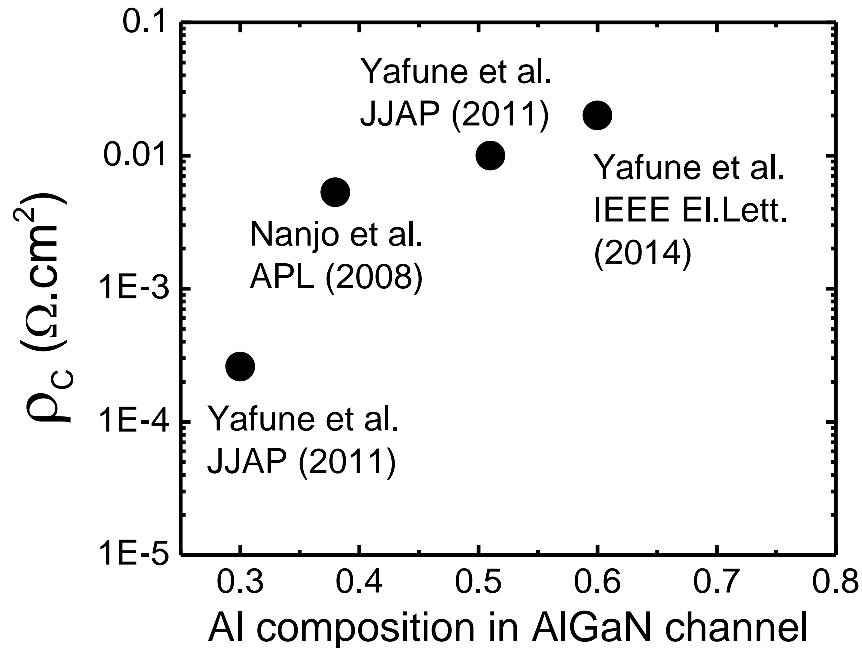

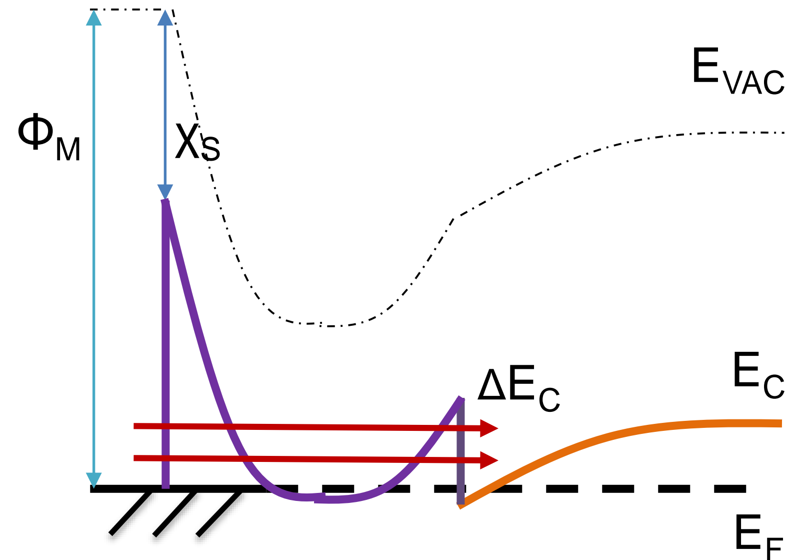

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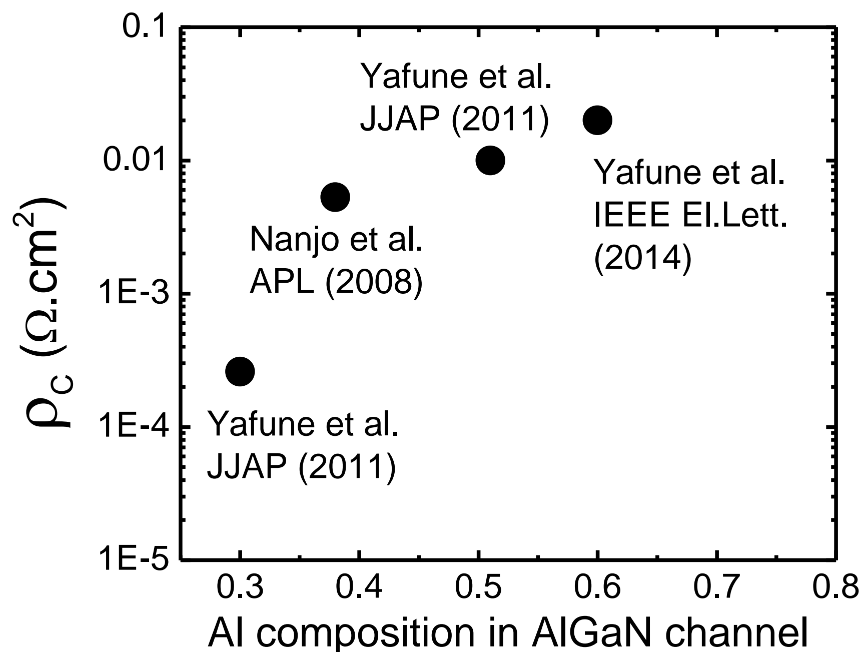

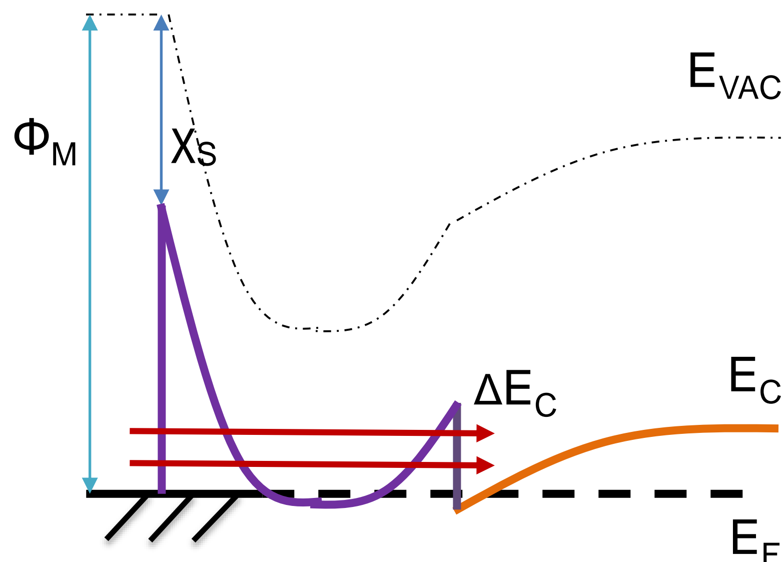

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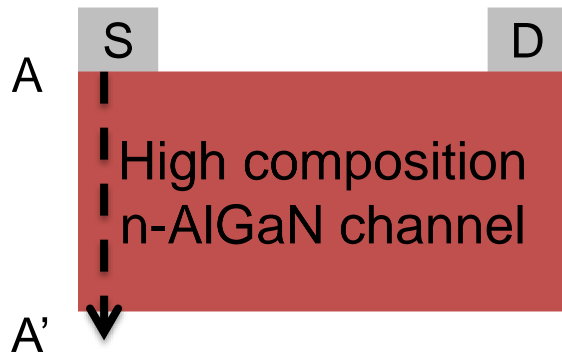
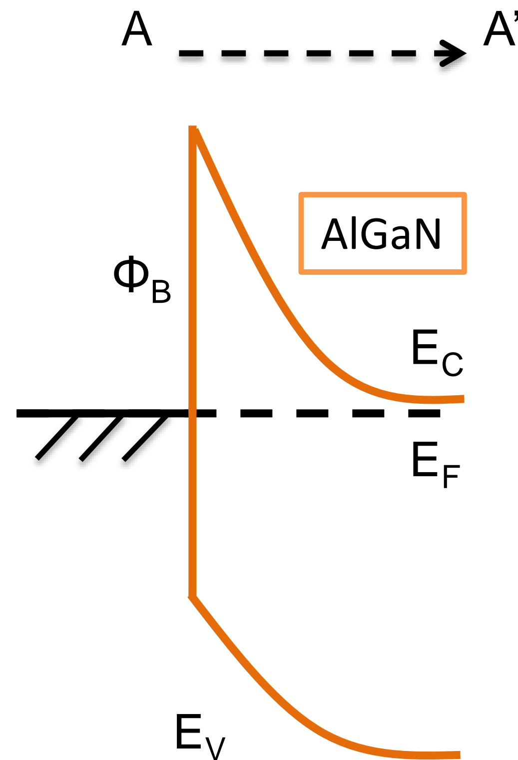
- Contact resistance increased with higher Al composition in channel and barrier layers

Heterostructure-Engineered Ohmics





- Conduction band profile under the contacts – n-type doped wide bandgap AlGaN with large Schottky barrier height

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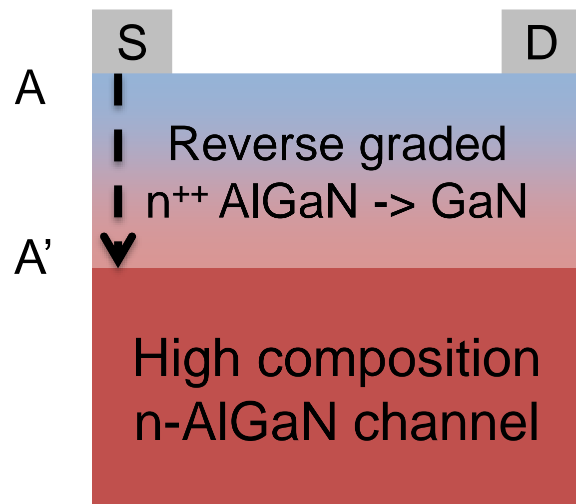
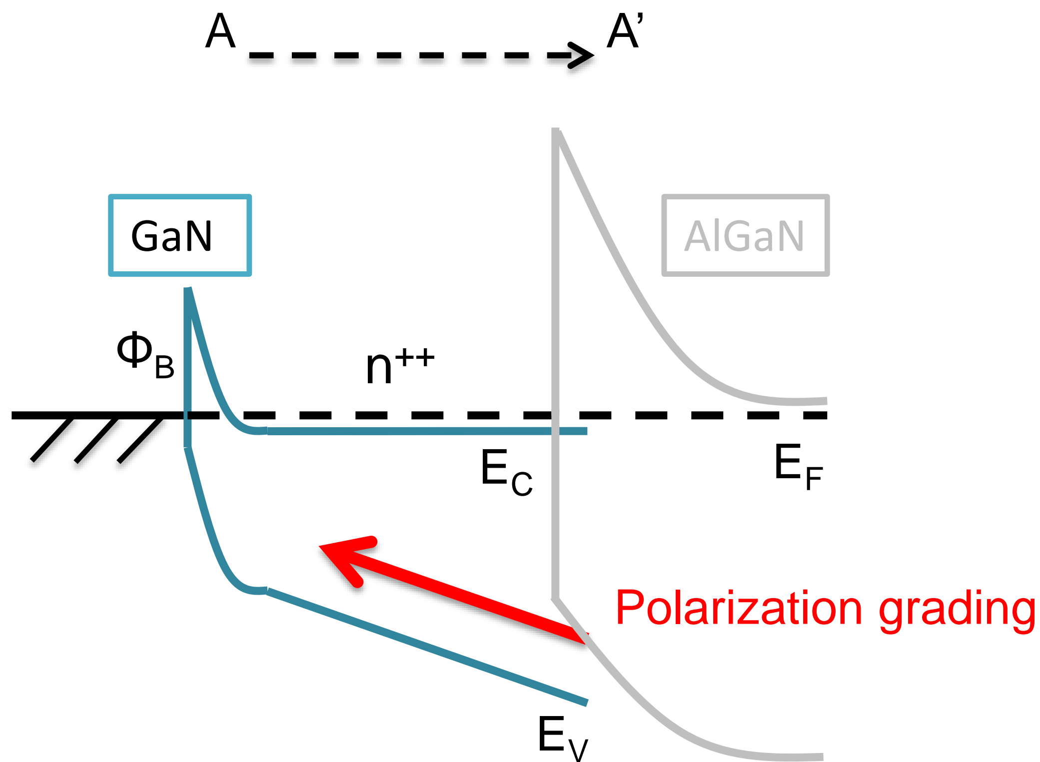
Heterostructure-Engineered Ohmics





- Contact layer with reverse polarization-grading to GaN
- High doping concentration to compensate negative polarization charges (reduce sheet resistance of contact layers)

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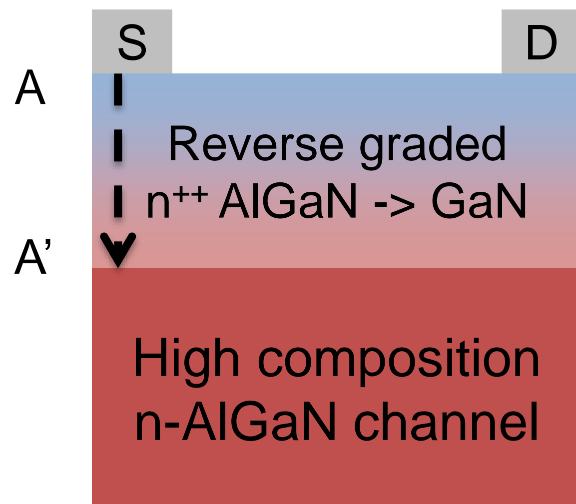
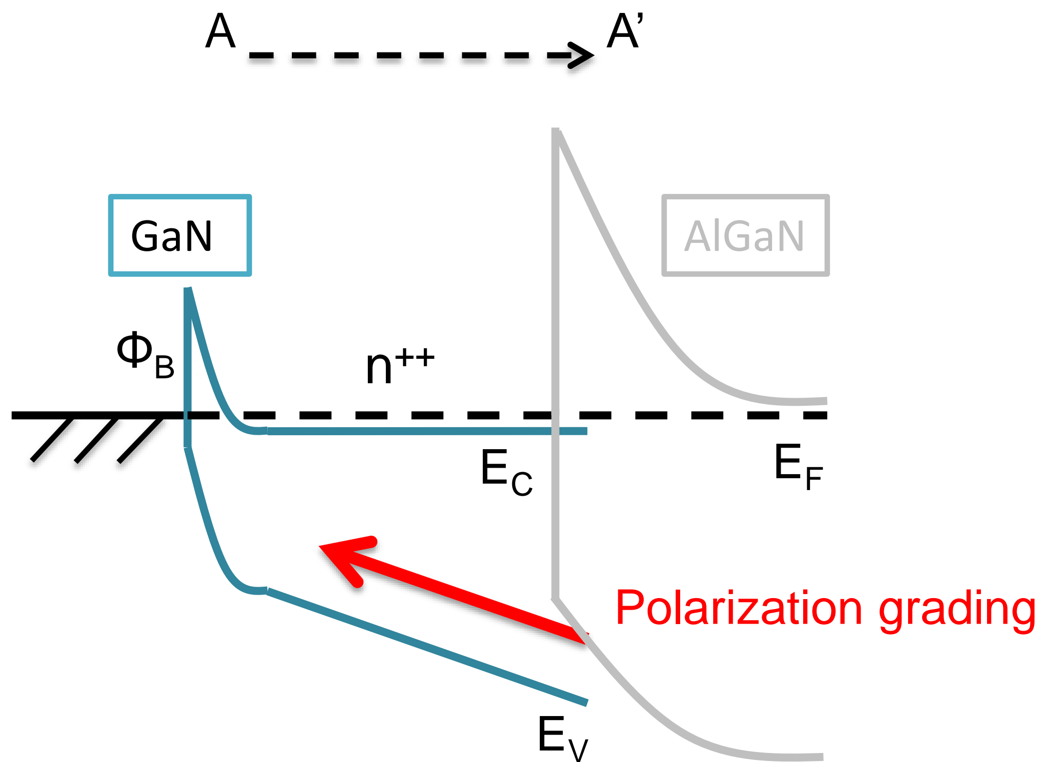
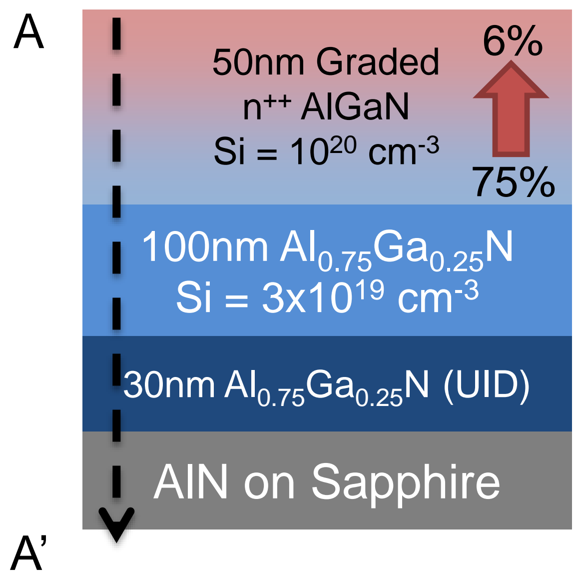
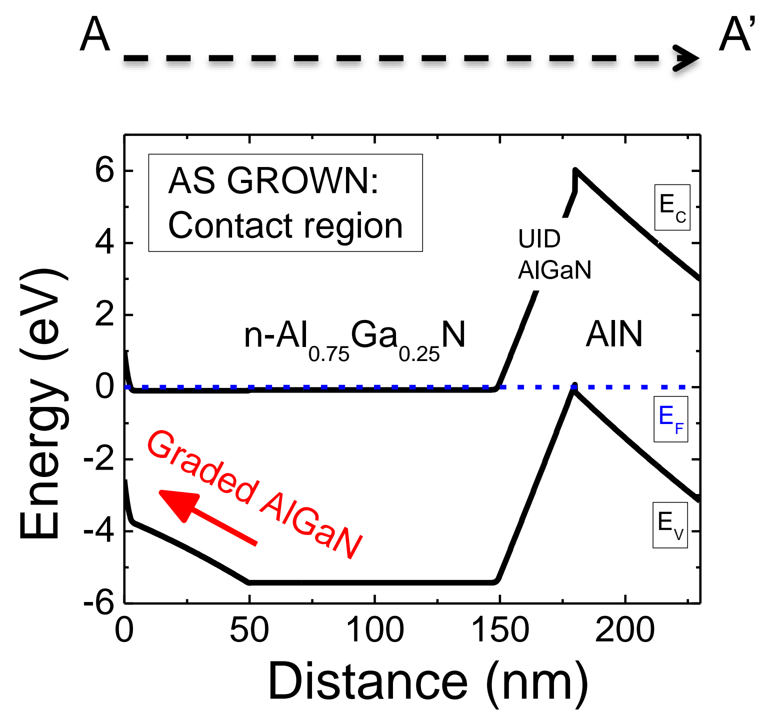




- Contact layer with reverse polarization-grading to GaN
- High doping concentration to compensate negative polarization charges (reduce sheet resistance of contact layers)
- This approach does not require regrowth (challenging for high composition AlGaN due to surface oxidation / GaN decomposition)

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





- 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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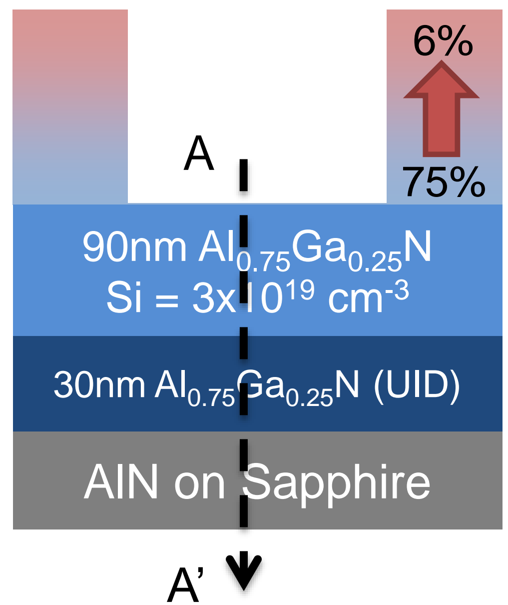

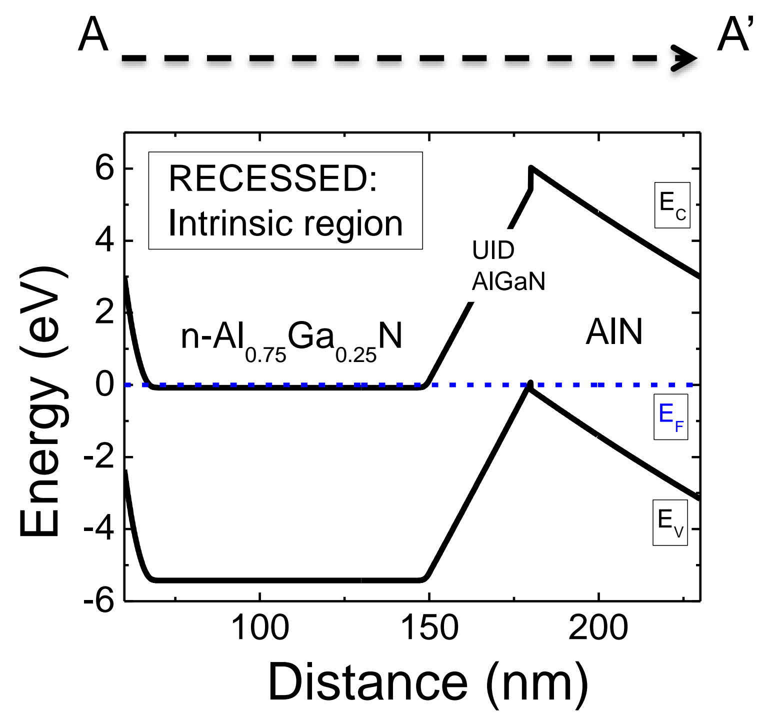

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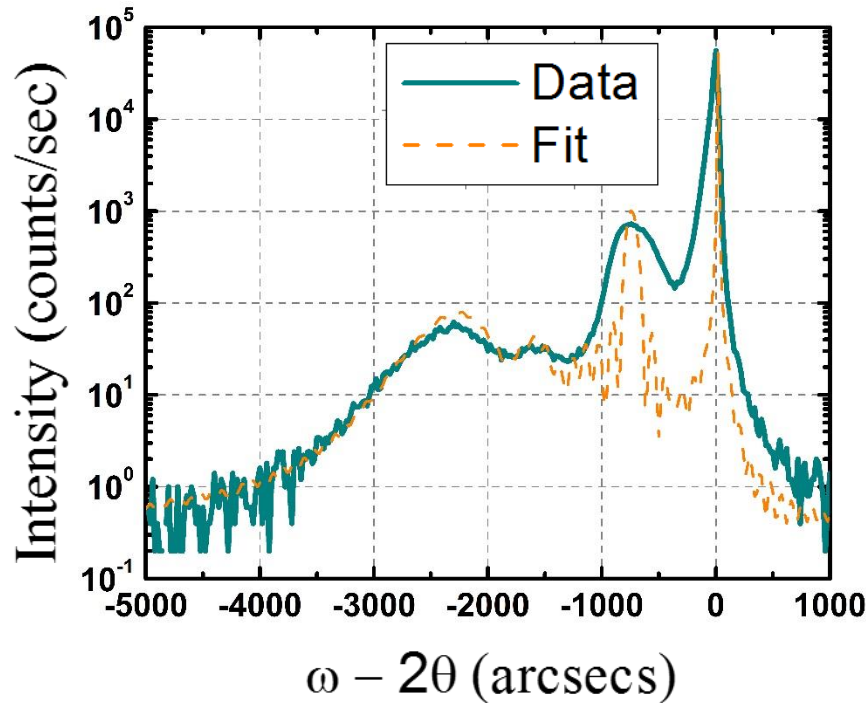
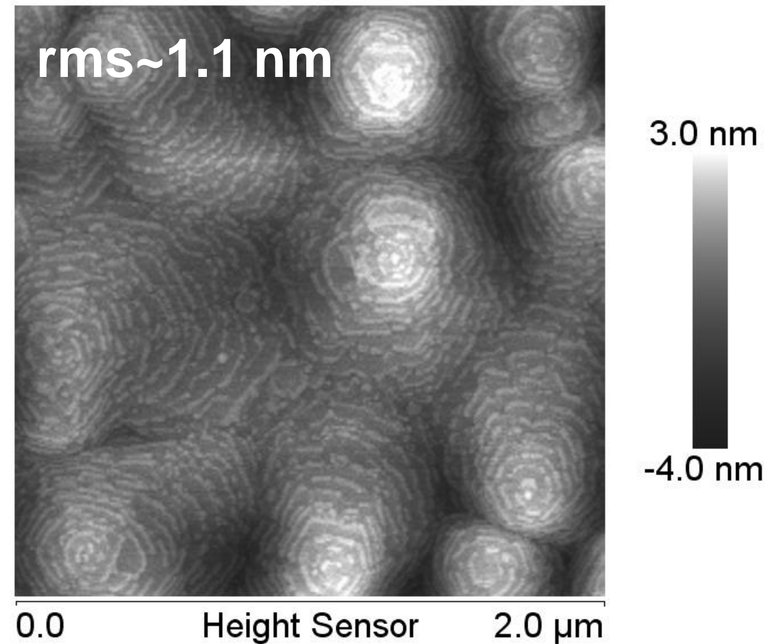
- Conduction band profile under gate region (recessed)

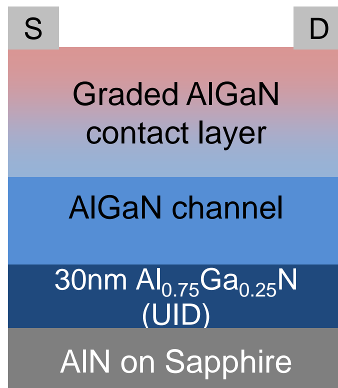
XRD and AFM





- X-ray diffraction scan to confirm AlGaN channel / graded contact layer
- Atomic-Force Microscopy to confirm smooth surface morphology (as-grown surface)

Contact Resistance using TLM



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

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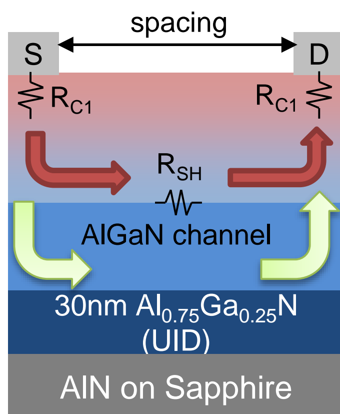

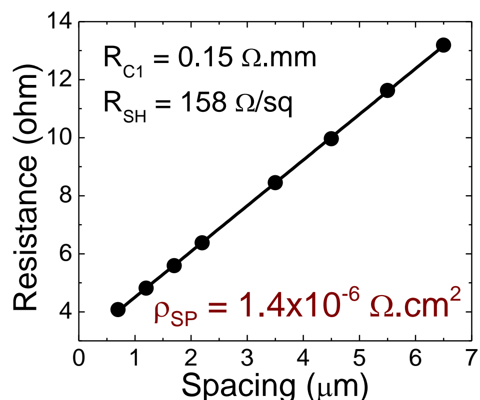

As-grown structure:

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

Recessed structure:

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

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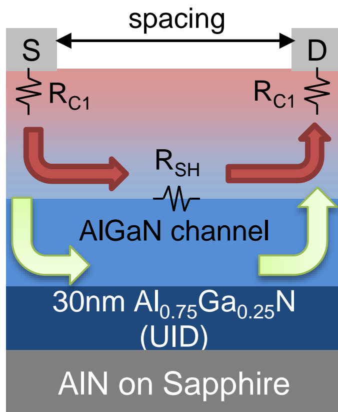

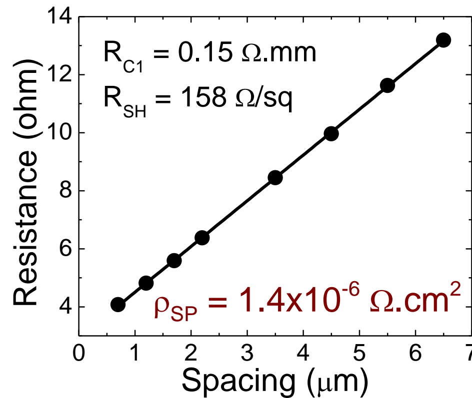

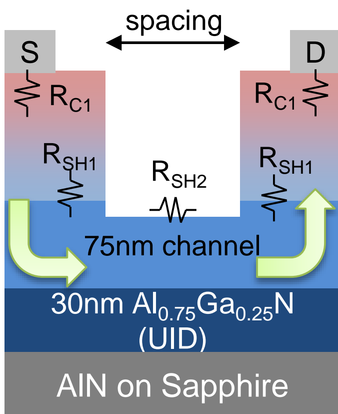

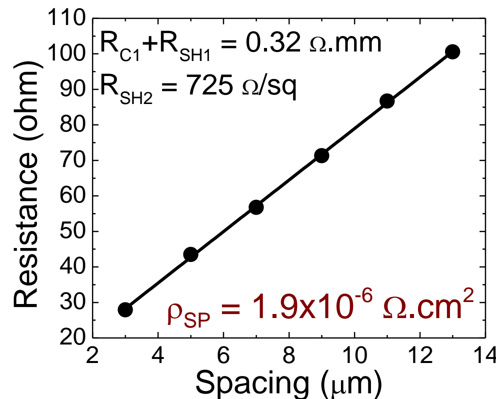

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Cl_2-based ICP-RIE etch to test contact to AlGaN channel

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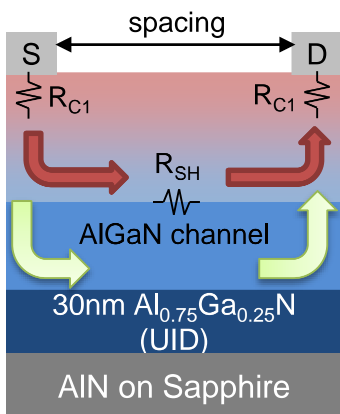

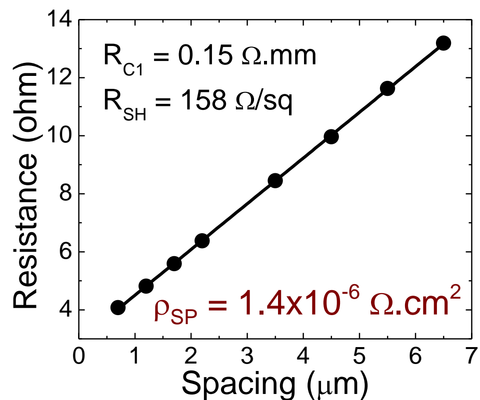

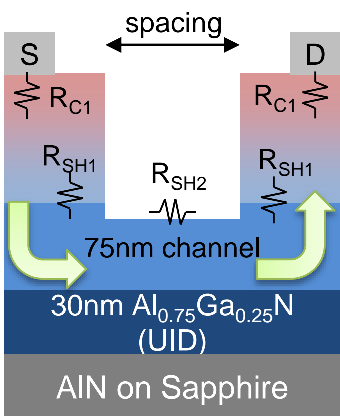

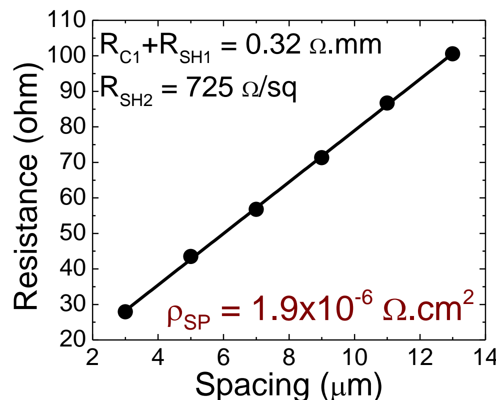

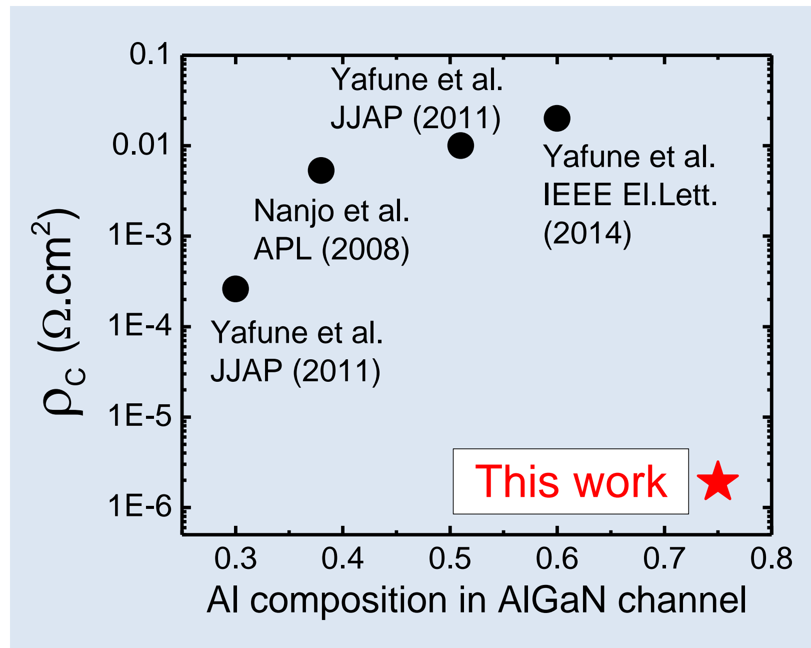

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Record-low ρ_{SP} to Wide bandgap AlGaN > 5 eV (Non-alloyed)

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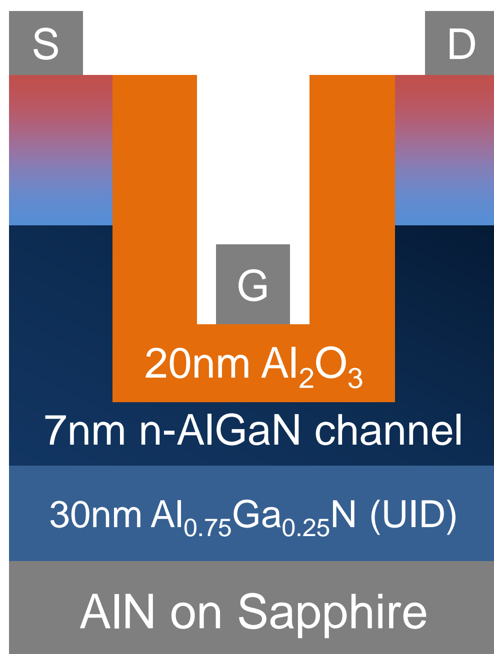
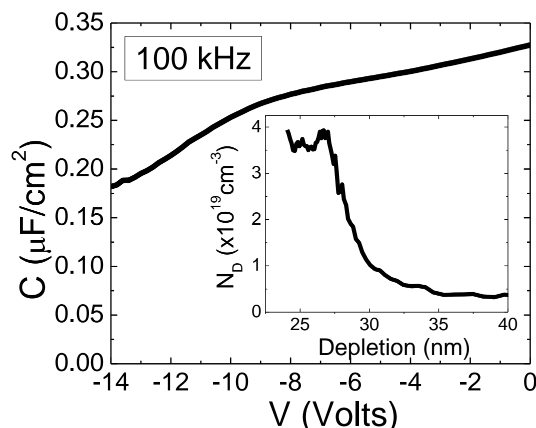
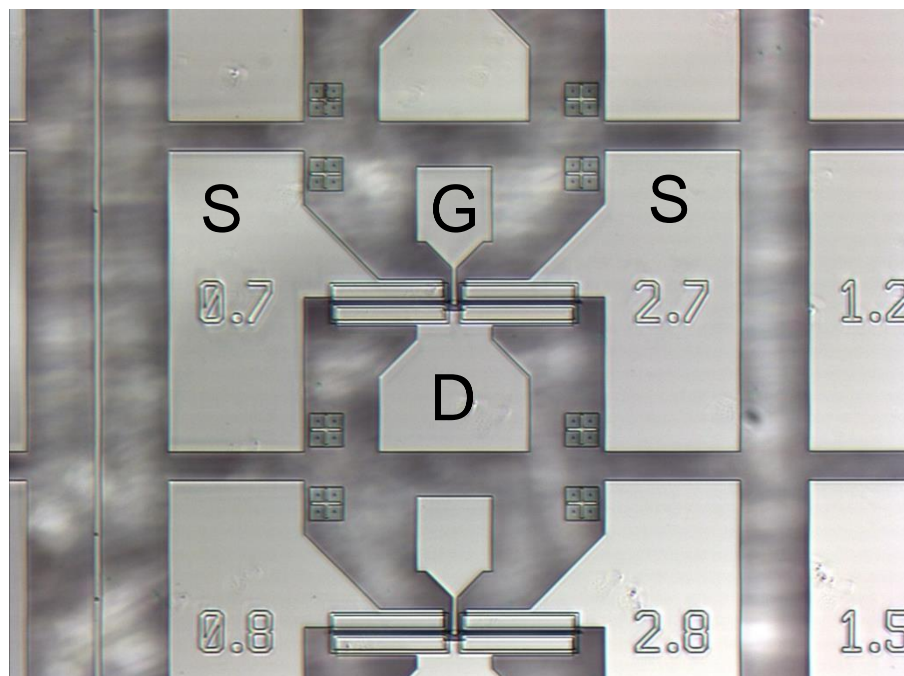




- Recessed structure with 7 nm n-$Al_{0.75}Ga_{0.25}N$ channel

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

- C-V / doping profile confirmed donor concentration and channel thickness – some depletion at 0 bias



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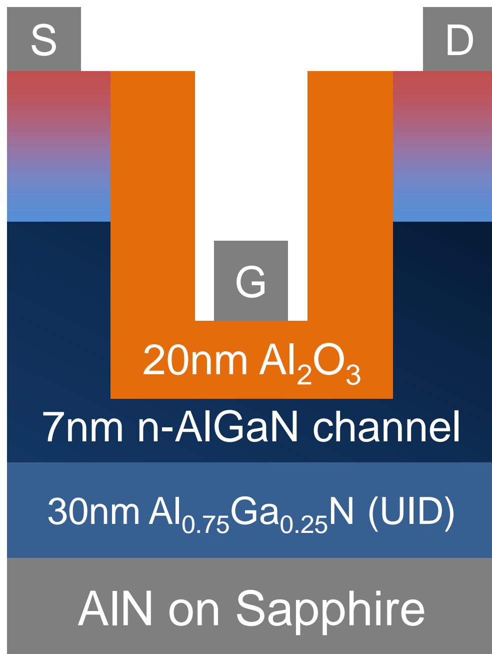

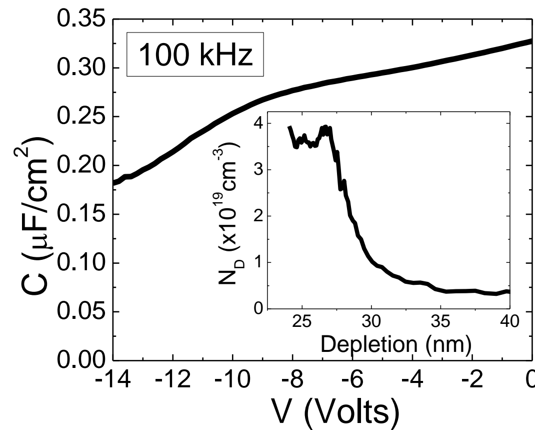

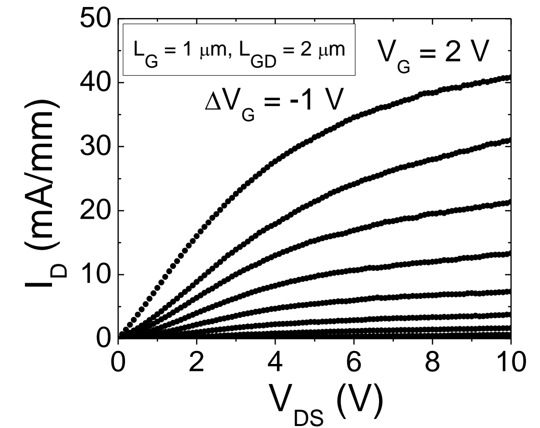

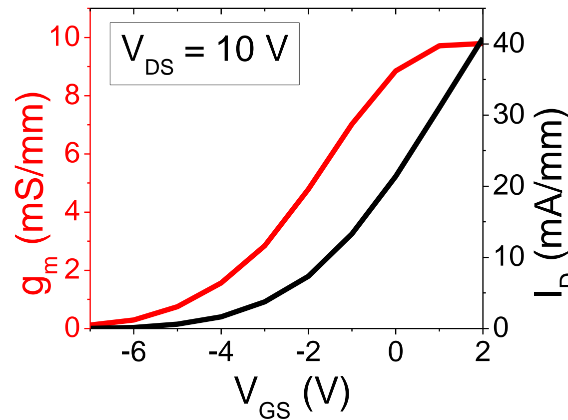

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- I_{DS_MAX} > 40 mA/mm ; g_{m_MAX} = 10 mS/mm (limited by low channel mobility of 15 cm^2/Vs)
- High Si doping needed to overcome defect related compensation – expect higher mobility with lower dopant concentration

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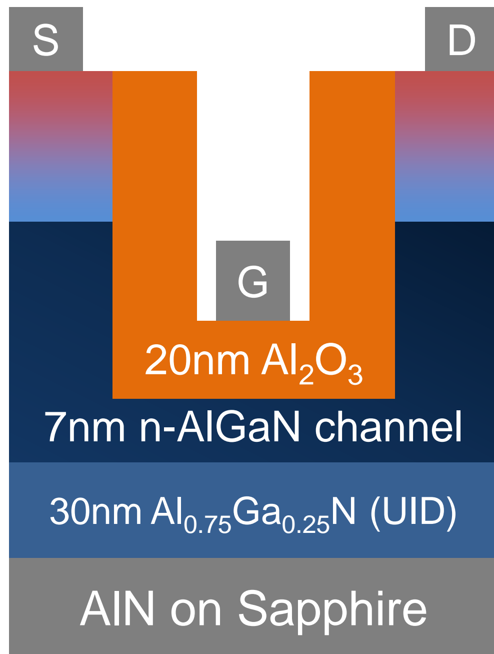

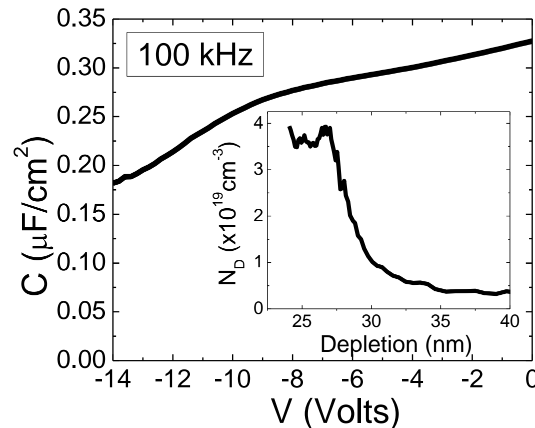

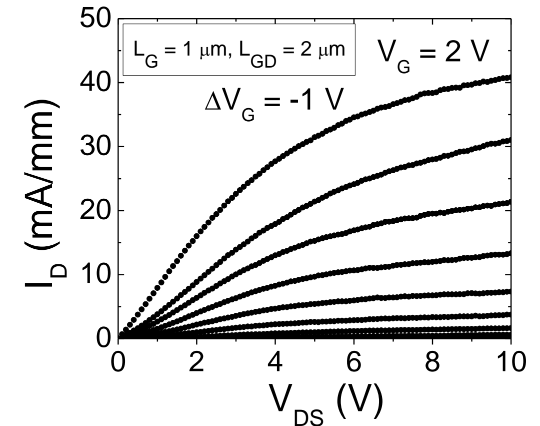

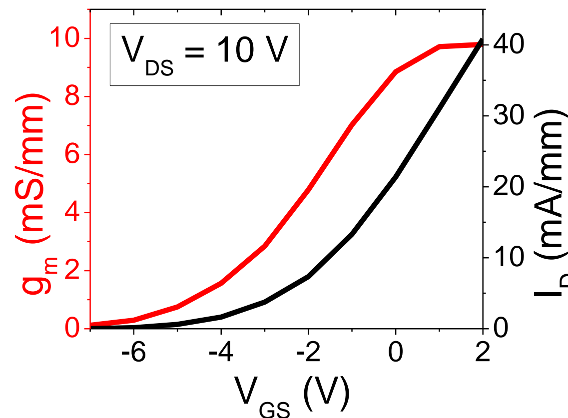

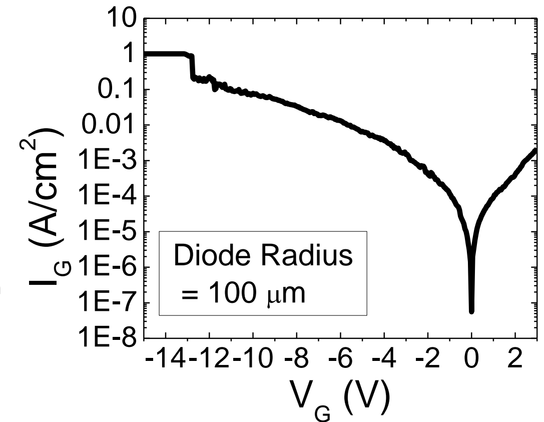

- Recessed structure with 7 nm n-$Al_{0.75}Ga_{0.25}N$ channel
- 20 nm ALD Al_2O_3 followed by 700°C PDA (30s)
- C-V / doping profile confirmed donor concentration and channel thickness – some depletion at 0 bias

- I_{DS_MAX} > 40 mA/mm ; g_{m_MAX} = 10 mS/mm (limited by low channel mobility of 15 cm^2/Vs)
- High Si doping needed to overcome defect related compensation – expect higher mobility with lower dopant concentration
- Low 2-terminal diode breakdown due to high net charge in the channel (~ 5×10^{13} cm^{-2})

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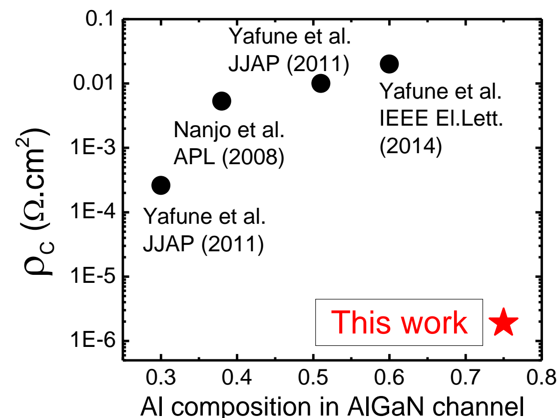
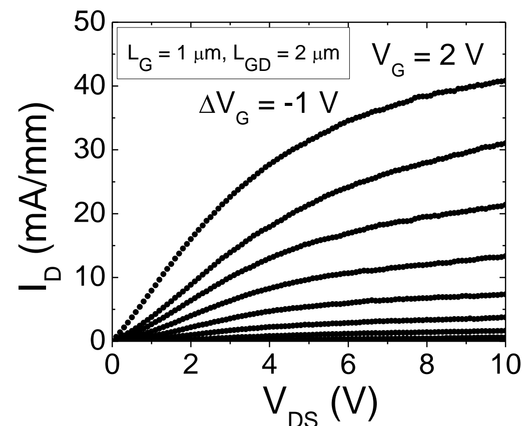
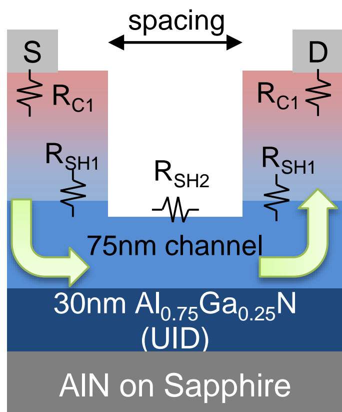
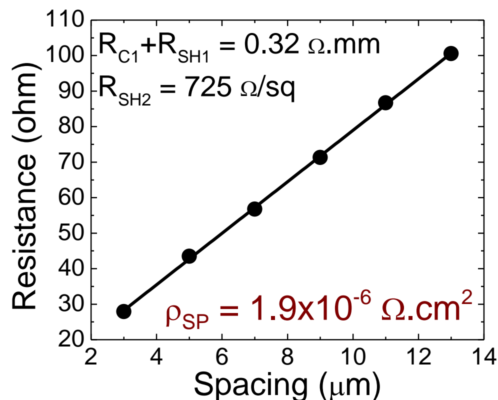
SUMMARY

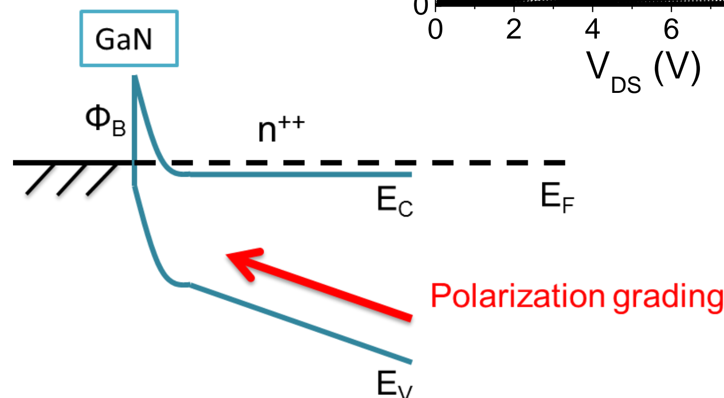
- Achieved record-low specific contact resistance to UWBG $Al_{0.75}Ga_{0.25}N$ channel (NON-ALLOYED)
- Heterostructure engineered ohmics to UWBG AlGaN – polarization-graded + doped contact layers
- Demonstrated the 1st UWBG $Al_{0.75}Ga_{0.25}N$ channel MISFET with low-resistance ohmics (MBE)
- This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











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