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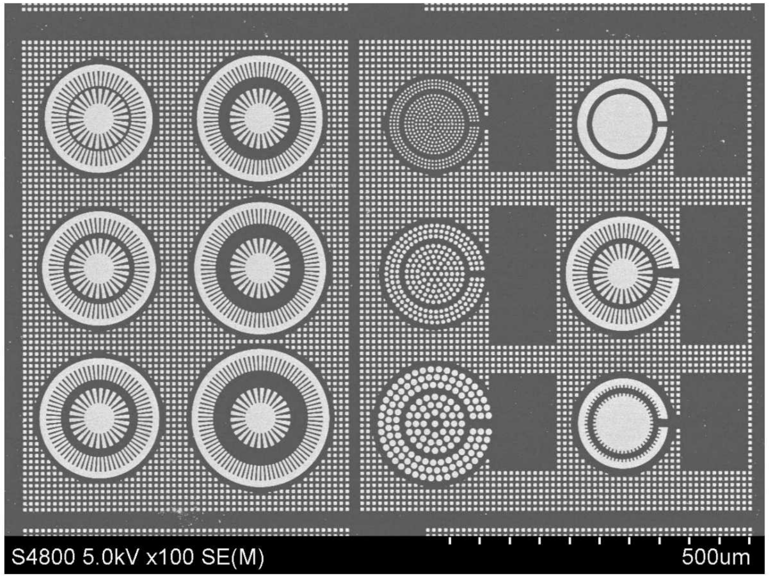
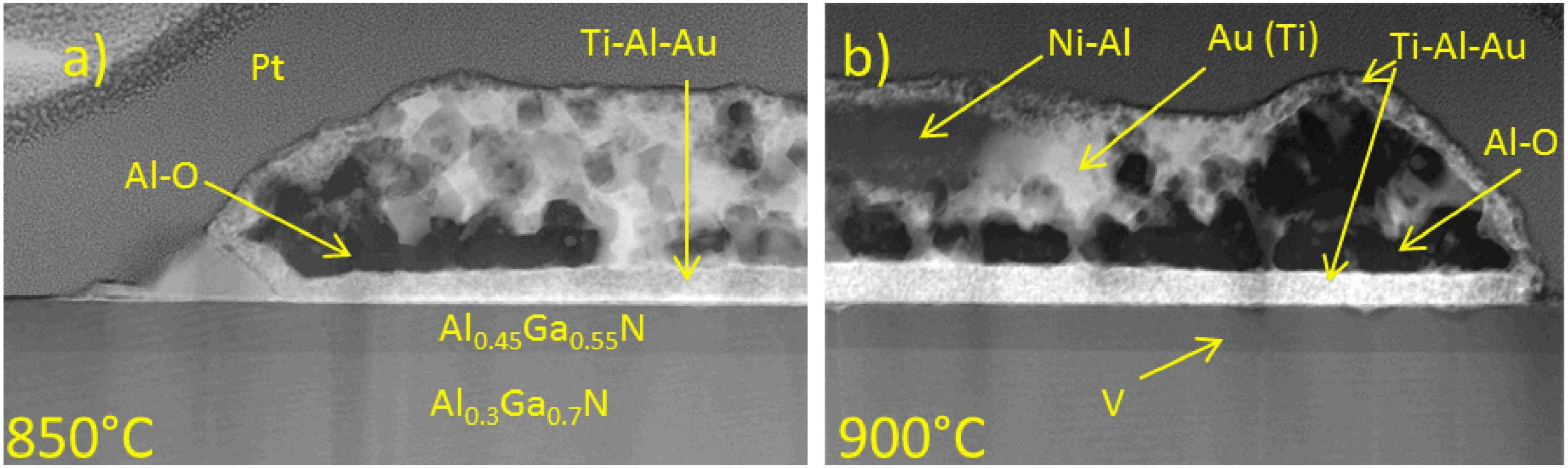
Current Enhancement for Ultra-Wide Bandgap AlGaN High Electron Mobility Transistors by Regrowth Contact Design

E.A. Douglas, B. Klein, S. Reza, A.A. Allerman, R.J. Kaplar, A.M. Armstrong, & A.G. Baca

Outline

1. Motivation
2. Challenges for Ultra-Wide Bandgap Contacts
3. Fabrication Method
4. Regrowth and Electrical Characterization

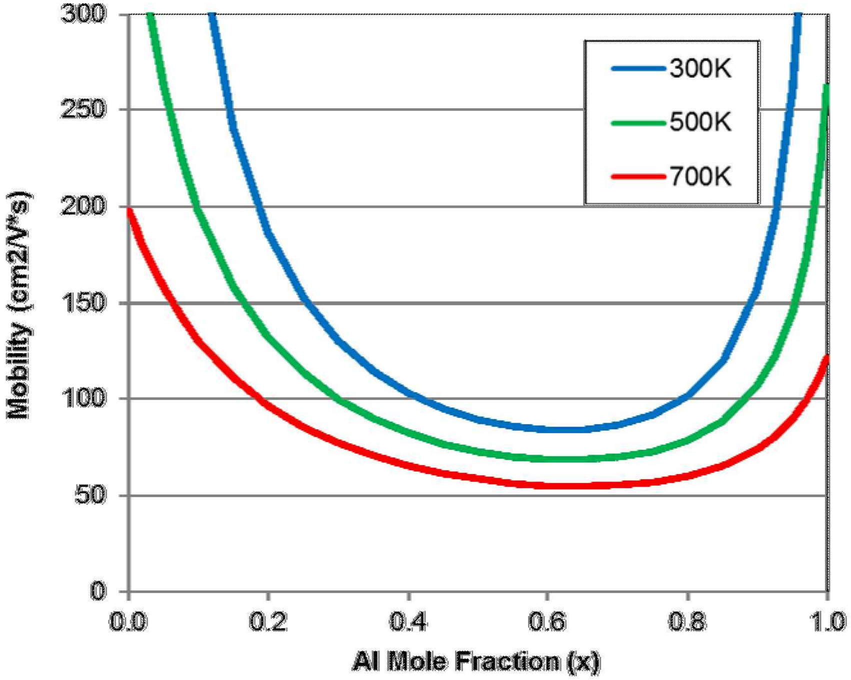


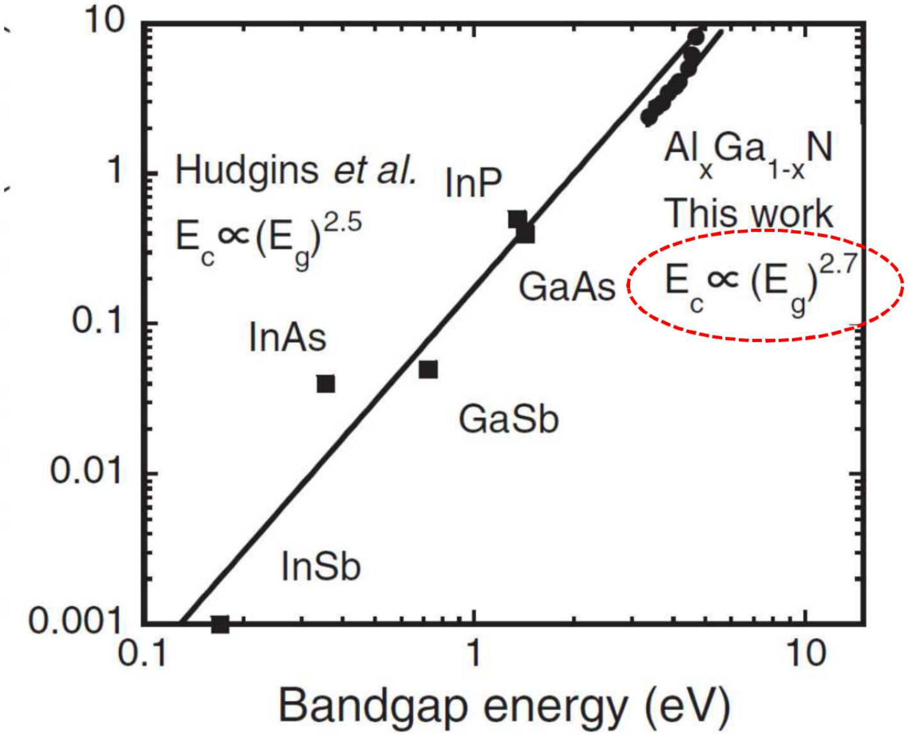


Why High Al Content?

Electrical power density scales *dramatically* with band gap

Band gap energy (E_g) is a critical material property for power electronics





Nishikawa, *et al.*, JJAP 46, 2316 (2007).

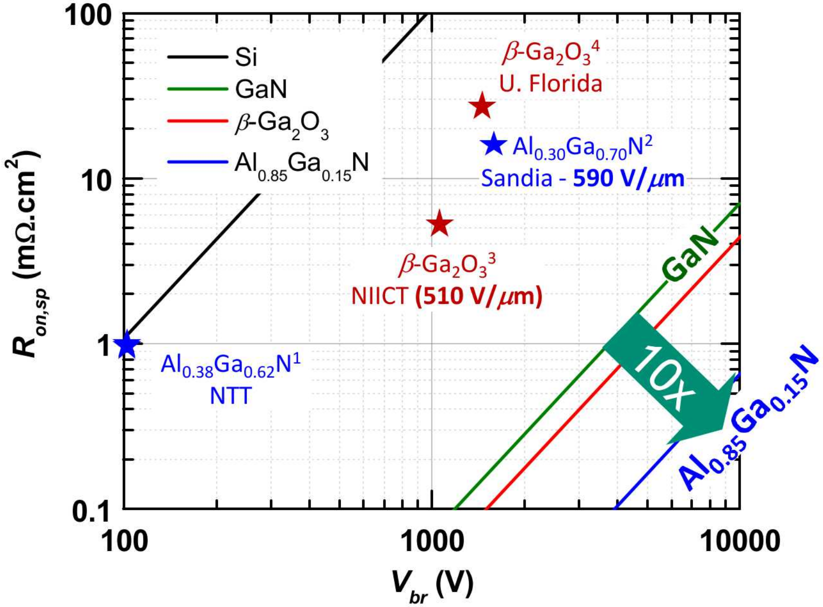
$$R_{on,sp} = \frac{v_{br}}{q\mu n_s E_{crit}^2}$$

$$Power\ density \sim 1/R_{on,sp} \sim \mu E_g^{5.4}$$

Electrical power density of AlN > 7x GaN

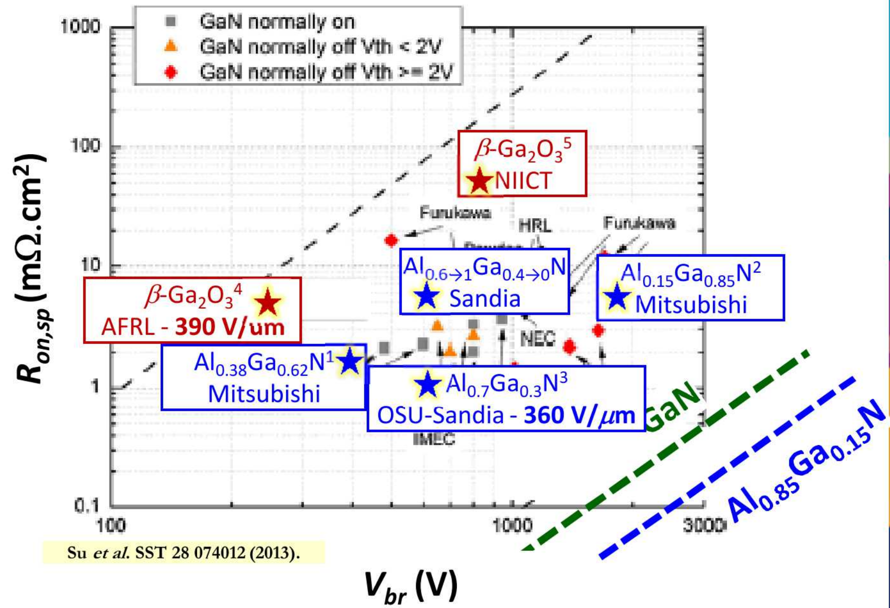
Figure of Merit

$$\text{Unipolar FOM} = \frac{\epsilon \mu E_{crit}^3}{4} \propto E_g^8$$



1. Nishikawa *et al*. JJAP 46 2319 (2007).
2. Allerman *et al*. Electronics Lett. 52 1319 (2016).
3. Konishi *et al*. APL 110 103506 (2017).
4. Yang et al., IEEE EDL 38 906 (2017).

$$\text{Lateral FOM} = q\mu n s E_{crit}^2 \propto E_g^5$$



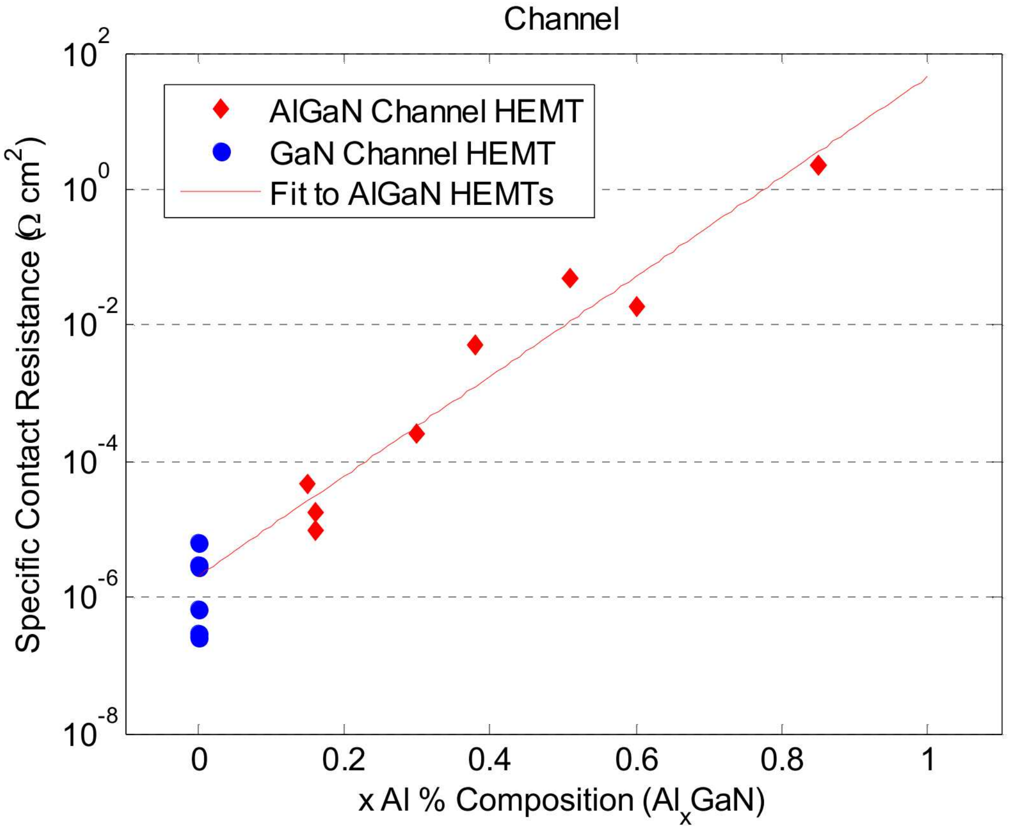
1. Nanjo et al. Appl. Phys. Lett. 92 263502 (2008).
2. Nanjo et al. IEEE Trans. Electron Dev. 60 1046 (2013).
3. Bajaj *et al*. IEEE EDL 39 256 (2018).
4. Green et al. IEEE EDL 37 902 (2016).
5. Wong et al. IEEE EDL 37 212 (2016).

➢ AlGaN material advantages do translate to device improvements

Realistic for AlGaN to achieve 3-10x better power density *vs*. GaN…but better enough?

Challenges

- Reported specific contact resistance increases exponentially with increasing Al fraction in the channel.
- Increased mobility pushes desire to increase Al fraction, but platform for Ohmic contacts becomes challenging
- Can we use similar techniques developed for GaN-channel HEMTs to enable AlGaN-channel devices?



Klein, B. A., (2017). ECS Journal of Solid State Science and Technology **6**(11): S3067-S3071.

AlGaN/GaN HEMT Ohmic Contacts

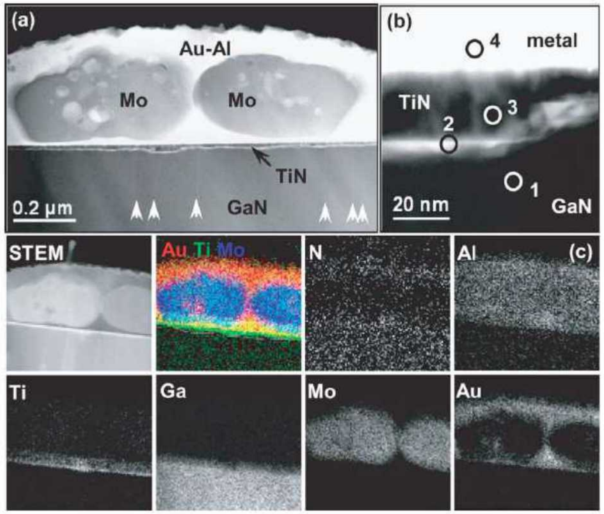


FIG. 2. (Color online) Z-contrast image of the Ti/Al/Mo/Au metallization on *n*-GaN after annealing. (a) Low magnification Z-contrast image, (b) magnified image of the interfacial region, and (c) EDS element mappings for N, Al, Ti, Ga, Mo, and Au. The overlay images of Ti, Mo, and Au mapping show that these three elements do not mix with each other.

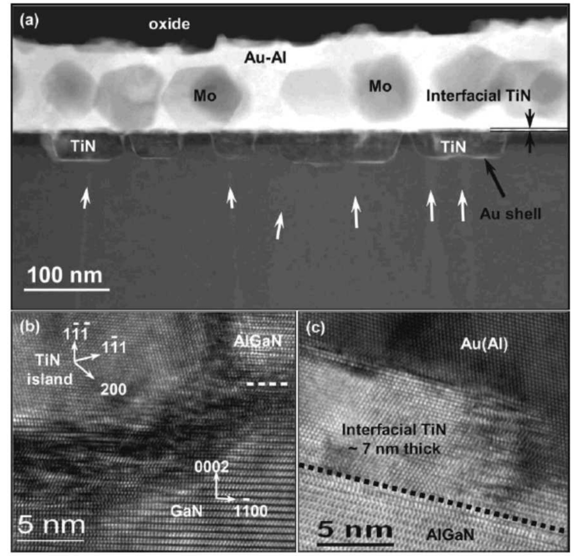
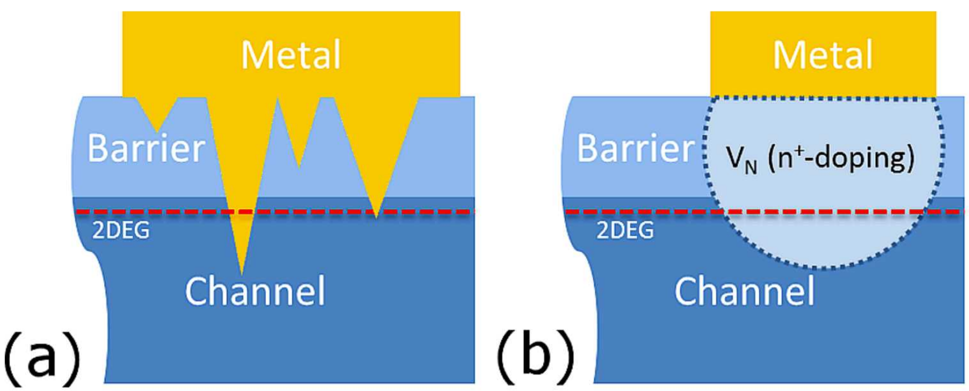


FIG. 5. (a) Z-contrast image of the contacts on AlGaN/GaN after annealing. The threading dislocations are labeled by white arrows. Two types of TiN, discrete TiN islands formed along dislocations and interfacial patchy TiN layer, are observed. (b) HRTEM image showing portions of the TiN island, GaN, and AlGaN. (c) HRTEM image of one interfacial TiN grain.

Wang et al., J. Appl. Phys. **101**, 013702 (2007).

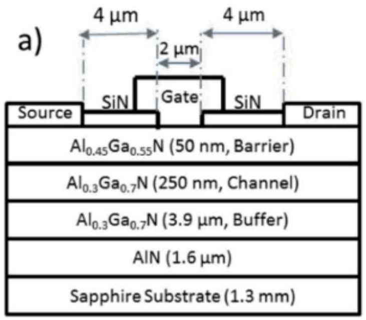


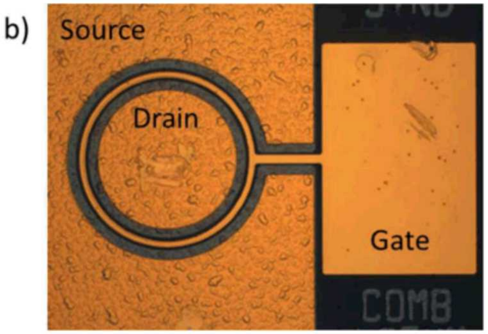
Ohmic formation for GaN channel HEMTs are likely due to either metal spike formation or nitrogen vacancy formation (resulting in effective n^+- doping). Many groups have observed and reported significant metal reaction and spike formation.

Previous Research (45/30)

Table I. Reported contact resistances as a function of AlGaN barrier and channel composition.

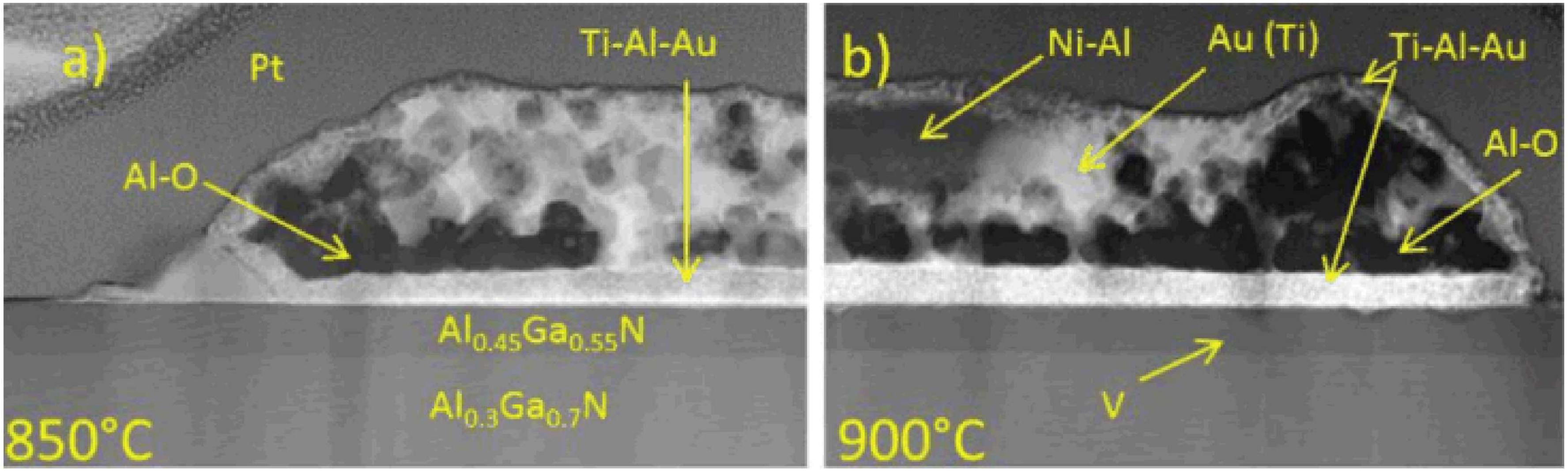
Reference	Ohmic metal	$x_{Barrier}$ ($Al_yGa_{1-y}N$)	$x_{Channel}$ ($Al_xGa_{1-x}N$)	ρ_c (Ω cm^2)	HEMT device results?
Nanjo 2008[6]	Ti/Al + Si implant	0.18	0	6.9×10^{-7}	Yes
Bright 2001[21]	Ti/Al/Ni/Au	0.24	0	2.8×10^{-6}	No
Nanjo 2013[5]	Ti/Al + Si implant	0.25	0	2.8×10^{-6}	Yes
Vanko 2008[13]	Nb/Ti/Al/Ni/Au	0.25	0	3.0×10^{-6}	No
Lee 2011[15]	Ti/Al/W	0.26	0	6.5×10^{-6}	Yes
Basu 2006[26]	Mo/Al/Mo/Au	0.3	0	2.63×10^{-7}	No
Wang 2005[17]	Ti/Al/Mo/Au	0.3	0	2.9×10^{-7}	No
Nanjo 2013[5]	Ti/Al + Si implant	0.4	0.15	4.5×10^{-5}	Yes
Nanjo 2009[16]	Ti/Al	0.39	0.16	9.68×10^{-6}	Yes
Nanjo 2008[6]	Ti/Al + Si implant	0.39	0.16	1.79×10^{-5}	Yes
Yafune 2011[14]	Zr/Al/Mo/Au	0.55	0.3	2.6×10^{-4}	Yes
This Work	Ti/Al/Ni/Au	0.45	0.3	2.5×10^{-5}	Yes
Nanjo 2008[6]	Ti/Al + Si implant	0.53	0.38	5.28×10^{-3}	Yes
Tokuda 2010[8]	Zr/Al/Mo/Au	0.86	0.51	4.8×10^{-2}	Yes
Yafune 2014[4]	Zr/Al/Mo/Au	1	0.6	1.9×10^{-2}	Yes
Baca 2016[3]	Ti/Al/Ni/Au	1	0.85	2.2×10^{0}	Yes
France 2007[12]	V/Al/V/Au	0	—	2.2×10^{-6}	No
France 2007[12]	V/Al/V/Au	0.24	—	3.2×10^{-6}	No
France 2007[12]	V/Al/V/Au	0.4	—	2.4×10^{-6}	No
Mori 2016[11]	V/Al/Ni/Au	0.62	—	1.1×10^{-6}	No





Early work on Ohmics for GaN channel HEMTs relied heavily on planar contacts, with various metals and even implant. Same is true for AlGaN channel HEMTs.

Previous Research (45/30)



Ohmic metal reaction within stack still observed, but reaction with underlying AlGaN not observed as significantly as reported for lower Al-content barriers.

Previous Research (85/70)

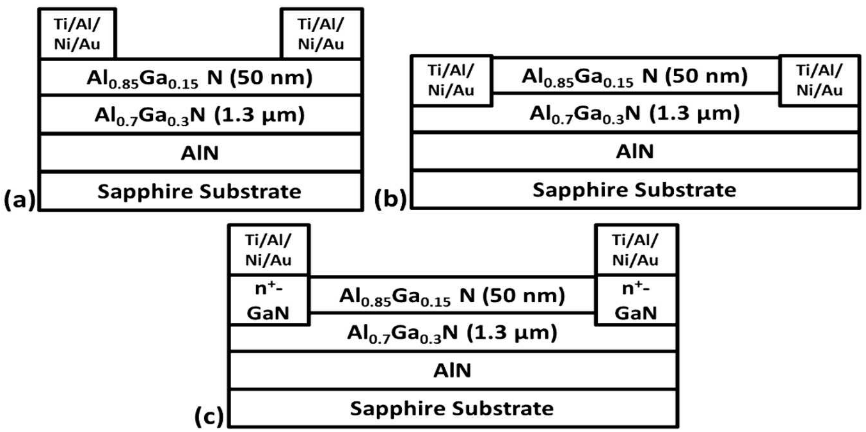
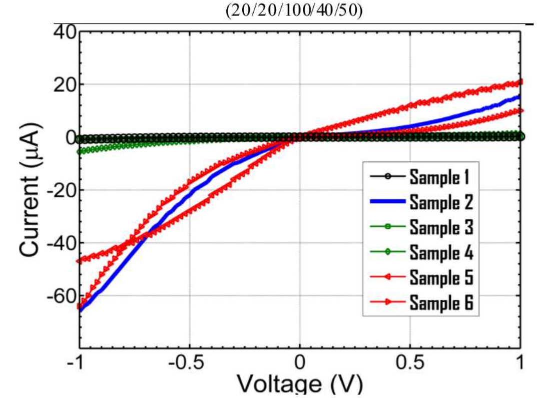
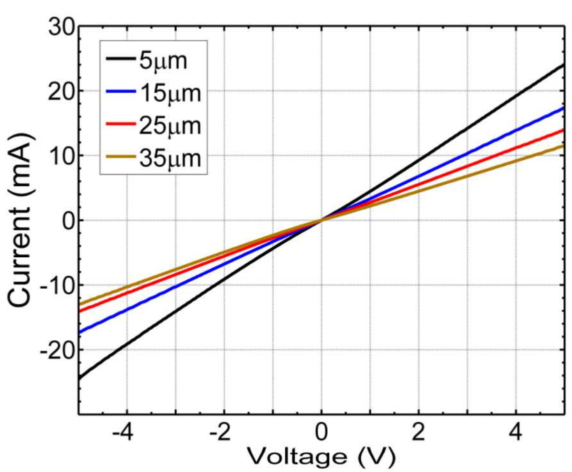


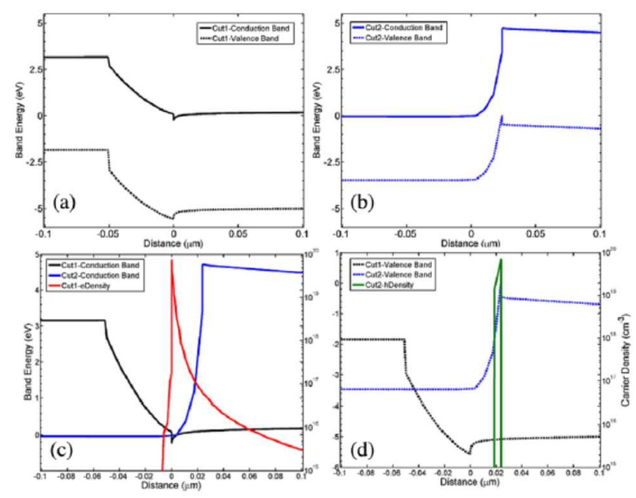
Figure 1 Schematic cross-section of the three TLM structures investigated: (a) planar structure, (b) recessed structure, and (c) n^{+}-GaN regrowth.

PLANAR

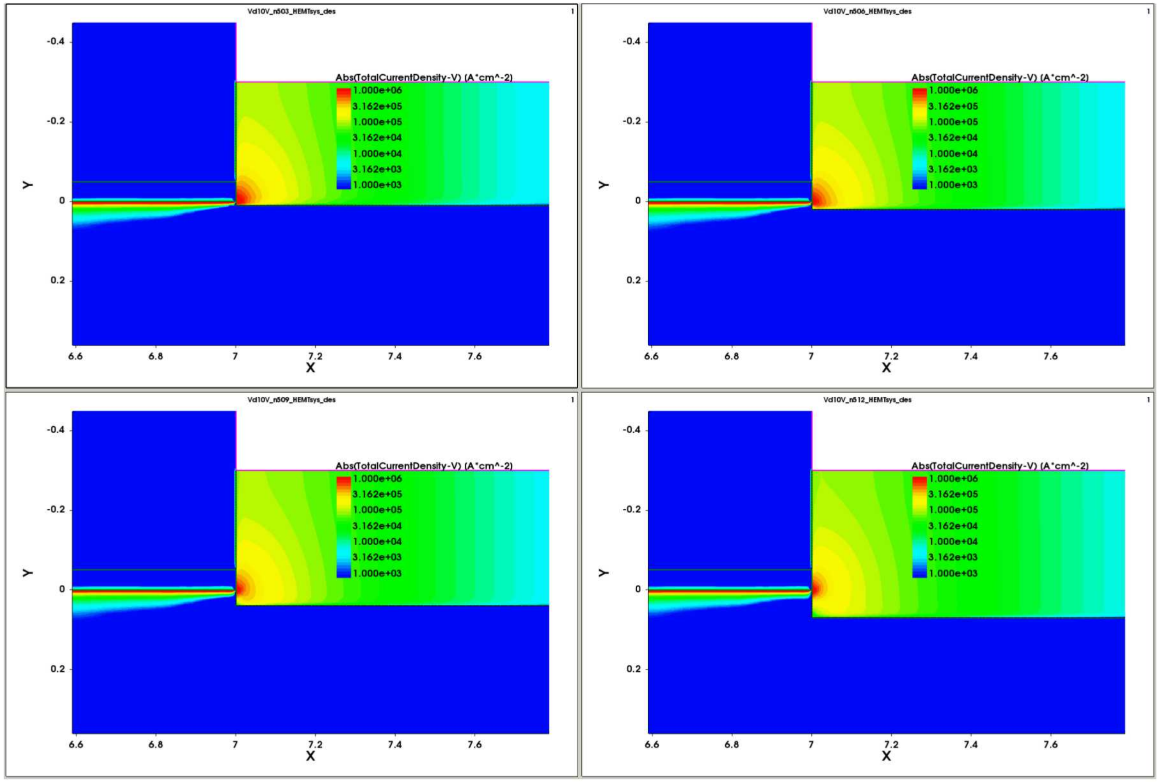
Sample	Metal (nm)	Anneal (°C)
1	Ti/Al/Ni/Au (25/100/15/50)	850
2	Zr/Al/Mo/Au (15/120/35/50)	950
3	V/Al/V/Au (15/80/20/100)	900
4	V/Al/V/Au (15/80/20/100)	950
5	Nb/Ti/Al/Mo/Au (20/20/100/40/50)	900
6	Nb/Ti/Al/Mo/Au (20/20/100/40/50)	950







GaN Regrowth Simulation



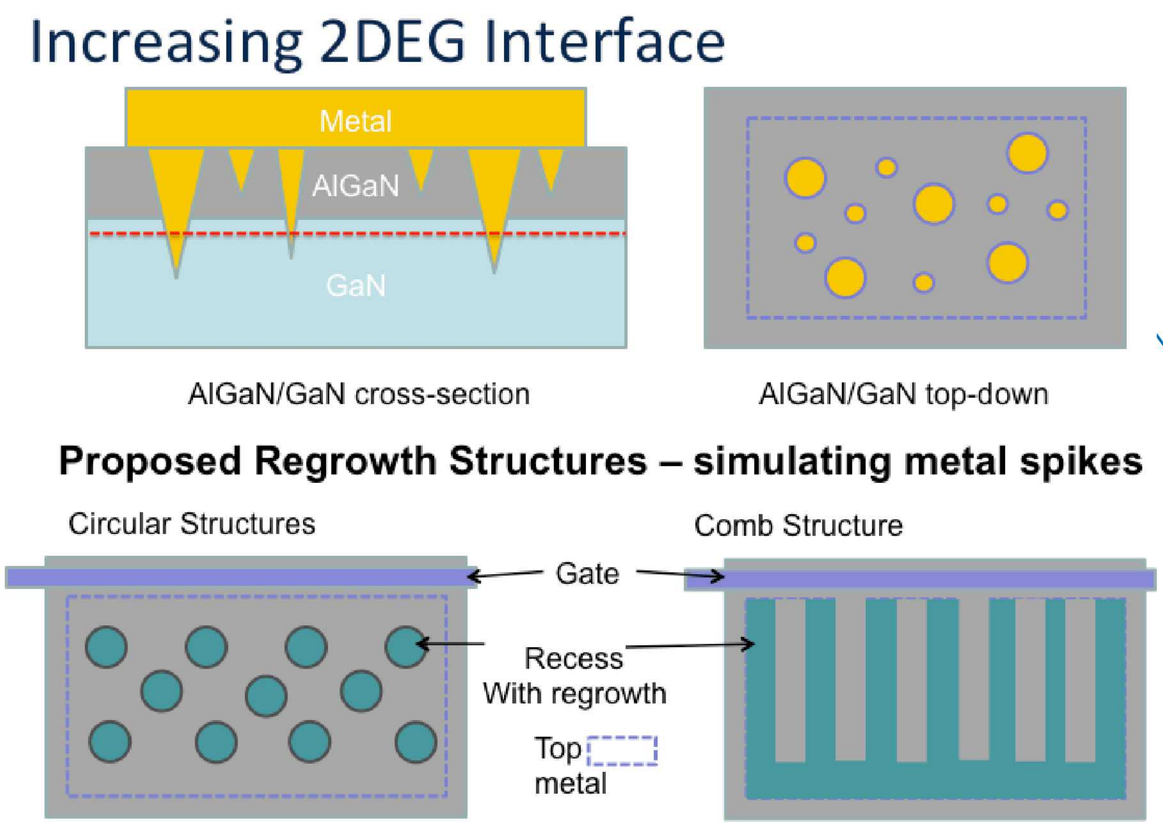
TCAD simulation studying effect of recess depth of dry-etch/regrowth.

Current crowding occurs at interface between 2DEG and GaN regrowth.

Previous work on n^+-GaN regrowth still resulted in lower current density than predicted by theory.

Could current crowding limit electron density in 2DEG?
Is it possible to increase current conduction into 2DEG?

Engineering Regrowth



In GaN channel, spike formation is random and uncontrolled.

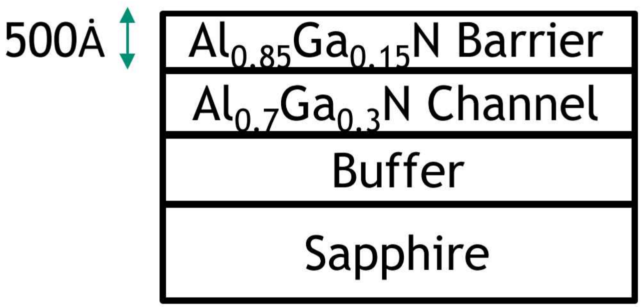
For recess + regrowth, assuming current crowding is limiting factor, then blue dashed line sets boundary condition.

Can we increase 2DEG interface through engineering?

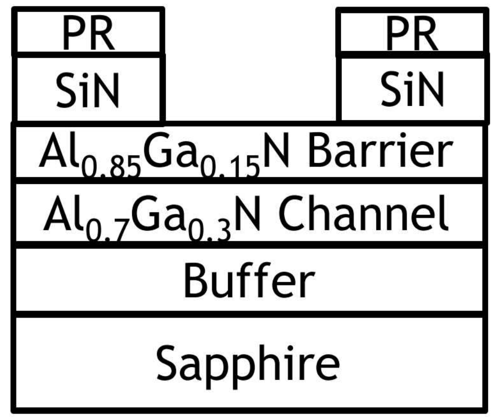
Regrowth patterns were investigated in order to optimize interaction length of interface between regrowth material and the 2DEG.

Fabrication Method

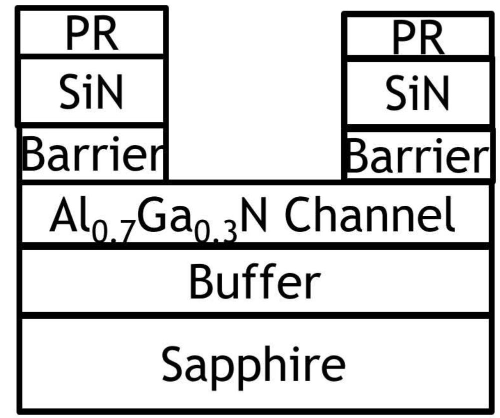
Starting Material



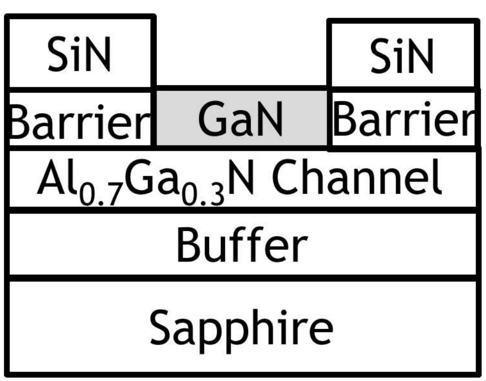
1. Pattern and etch selective hard-mask



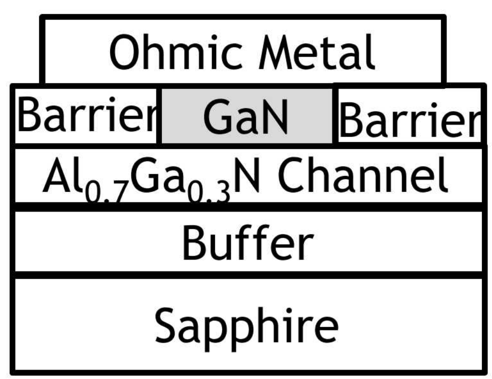
2. Recess barrier by dry-etch (600Å)



3. Selective GaN regrowth



4. Strip hard-mask, Metal dep and anneal



Ti: 250Å
Al: 1000Å
Ni: 150Å
Au: 500Å

Anneal: 850 °C
30 sec in N_2

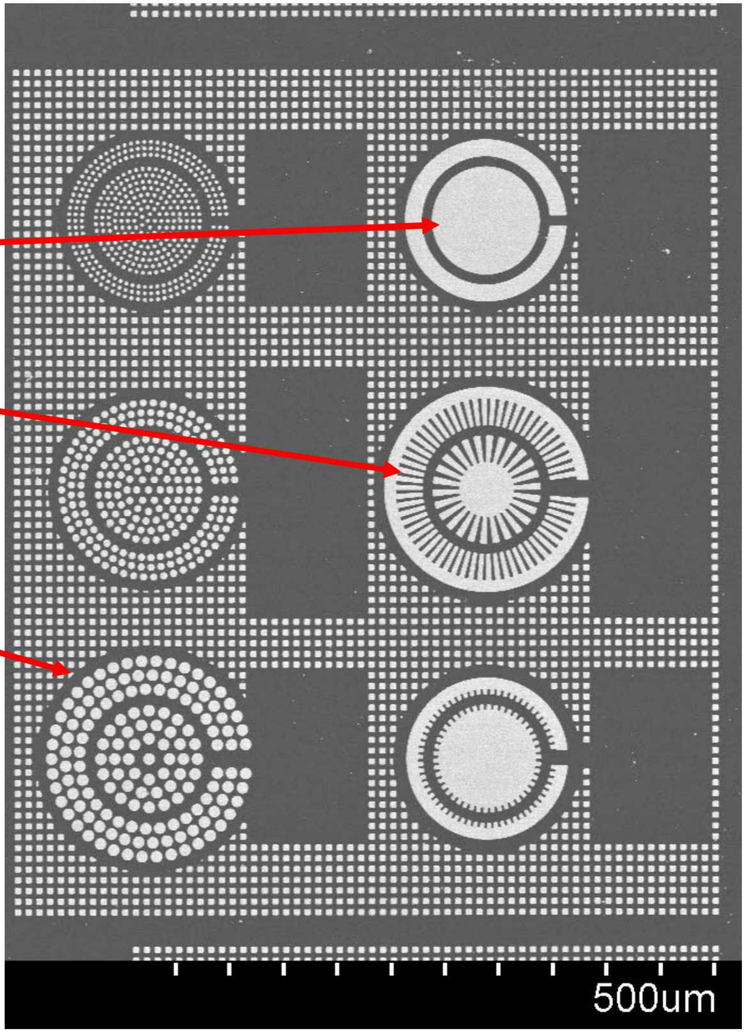
Fabrication Method (2)

3 designs for investigating 2DEG contact length enhancement for circular TLMs and transistors:

Standard (full removal of barrier)

Comb-like (varying length of fingers)

Holes (varying radius)

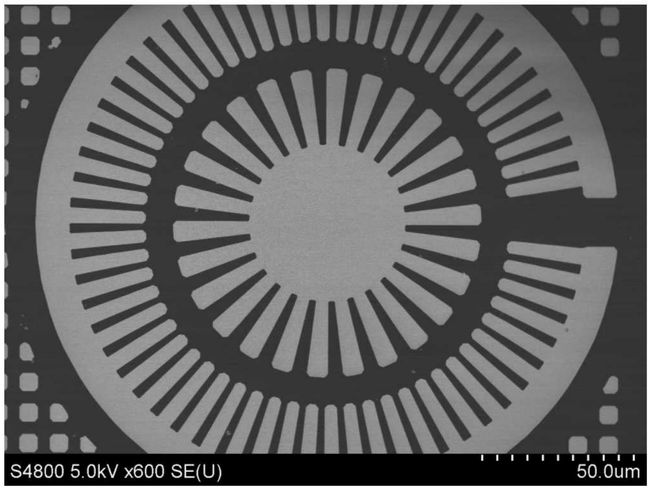


2DEG Perimeter	um
Standard CTLM	314
Comb Length 5um	768
Comb Length 25um	1536
Hole Radius 1.5um	2139
Hole Radius 3um	1866
Hole Radius 5um	1508

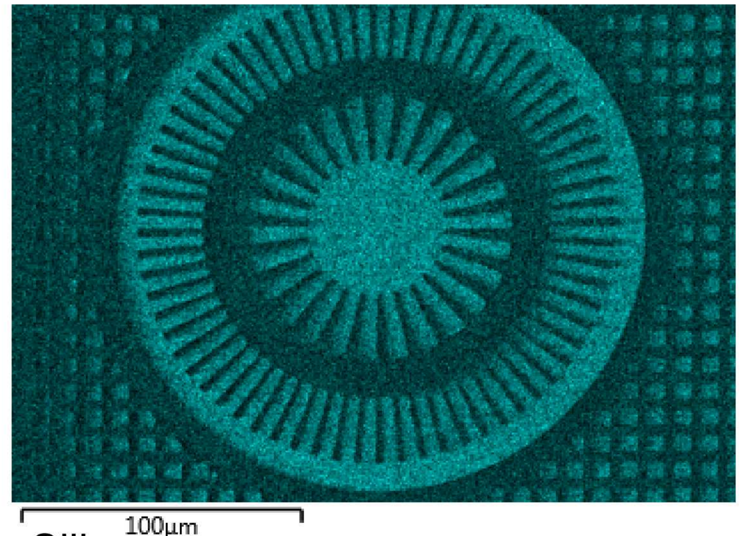
Regrowth Characterization

EDS post-regrowth, prior to removal of SiN hardmask

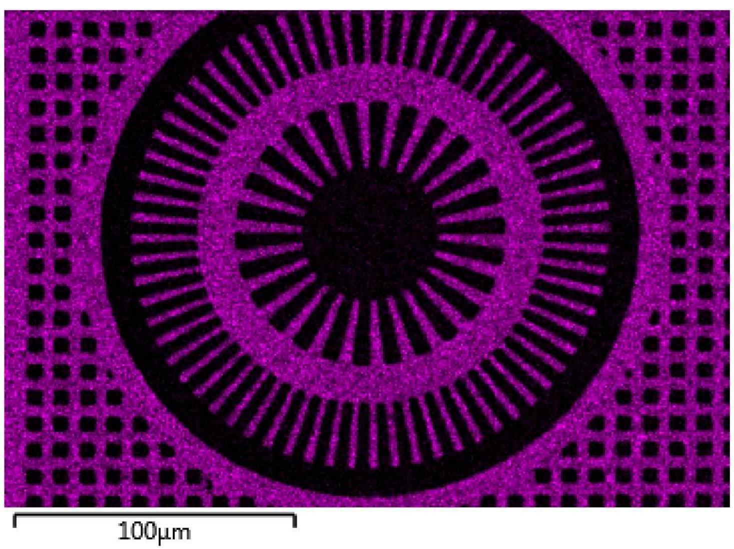
Representative SEM



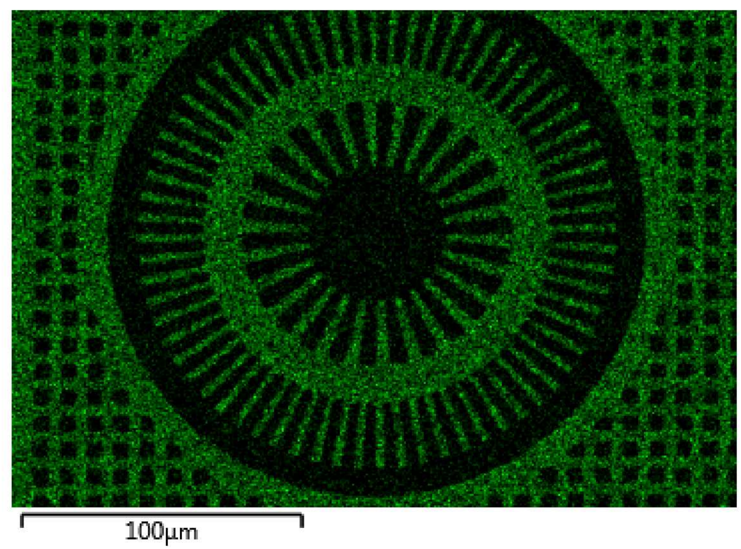
Ga



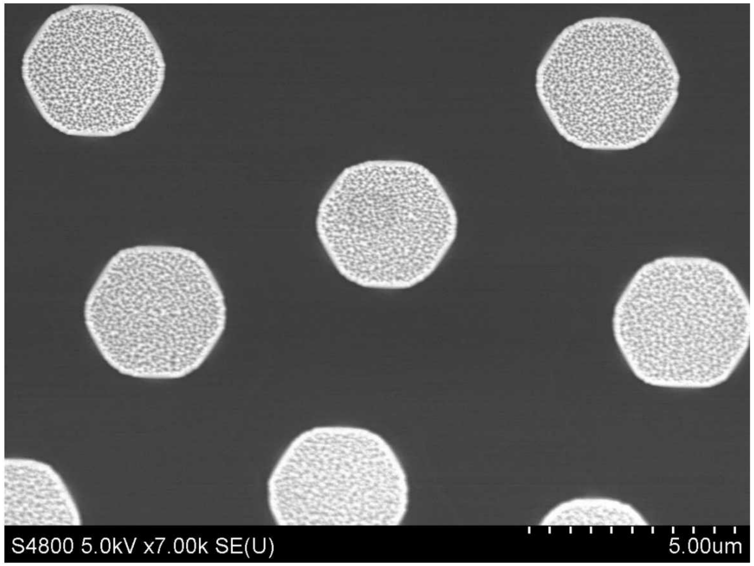
Al

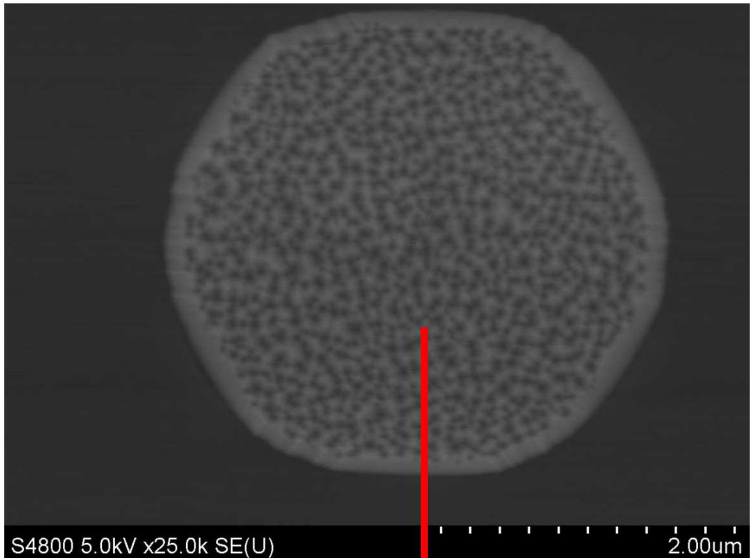


Silicon



Regrowth Characterization (2)

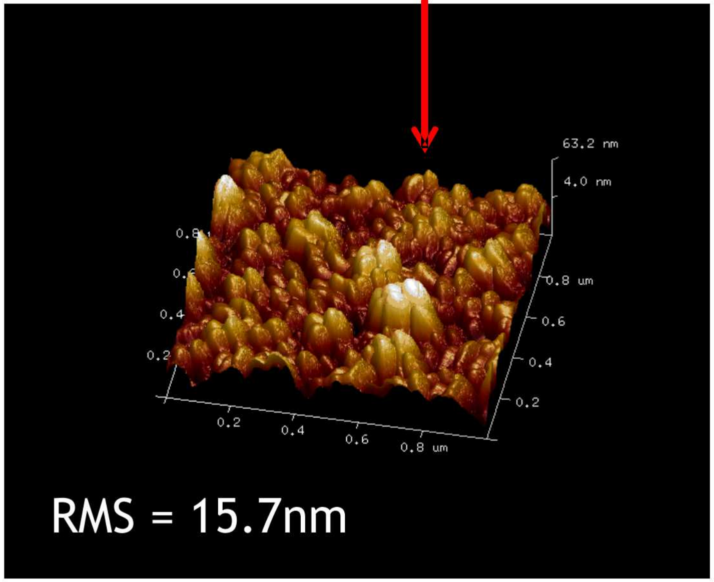




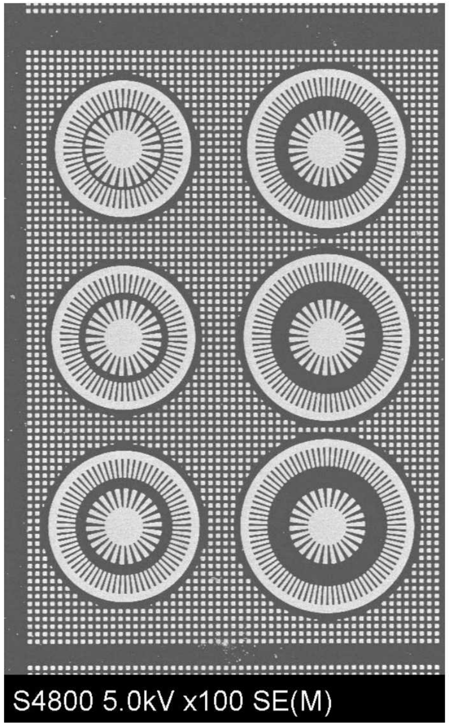
As-grown epi: RMS < 1nm

Etched surface: RMS < 1.5nm

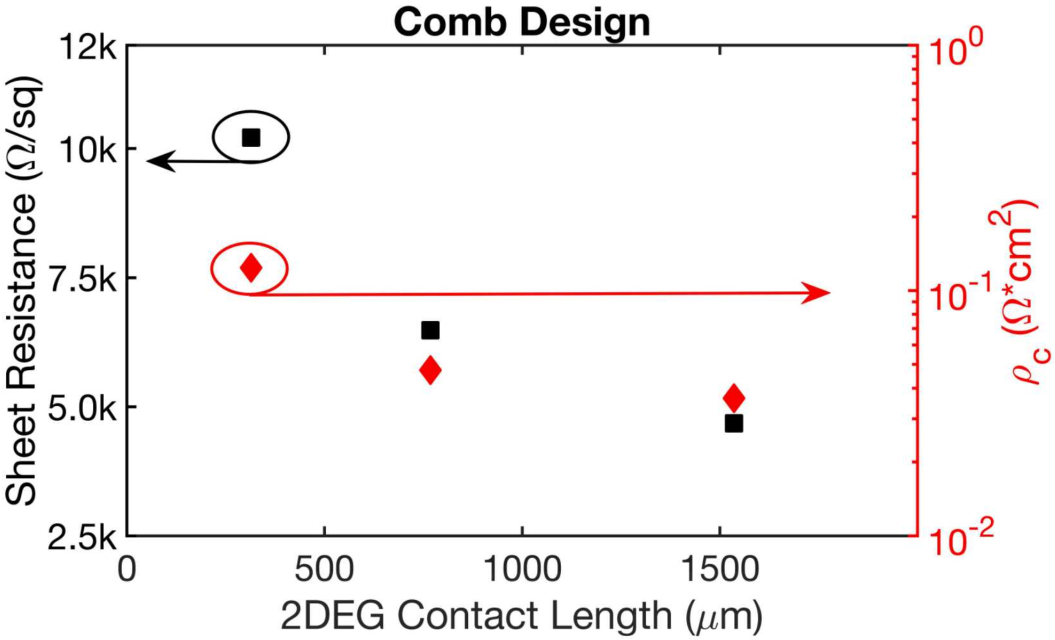
Regrowth surface: RMS < 16nm



Electrical Characterization (Comb)

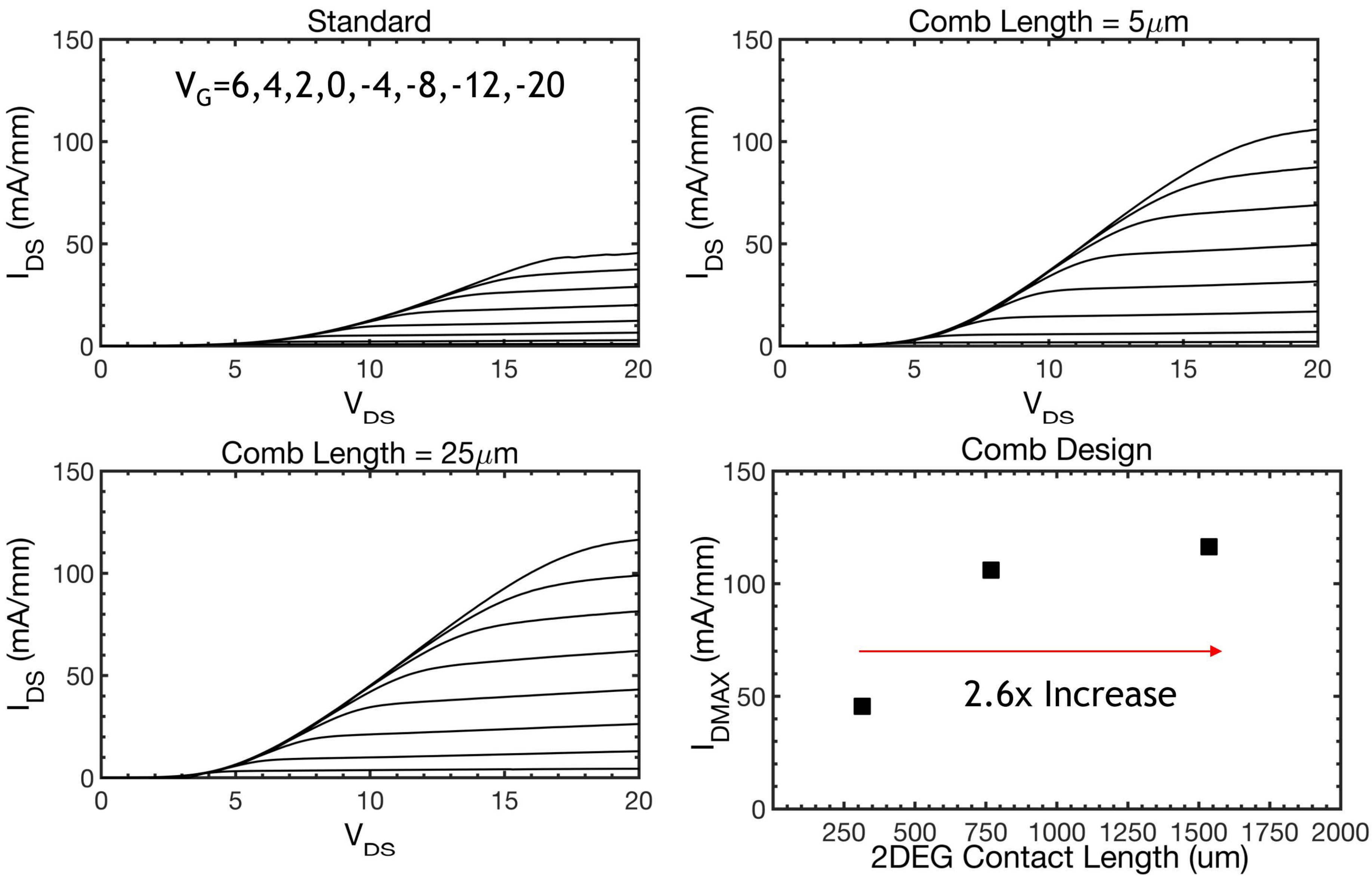


Circular TLM Structure to evaluate contact resistance
Gap varying from 5um to 30um, 5um increments
Finger length 5um or 25um
Inner diameter held constant

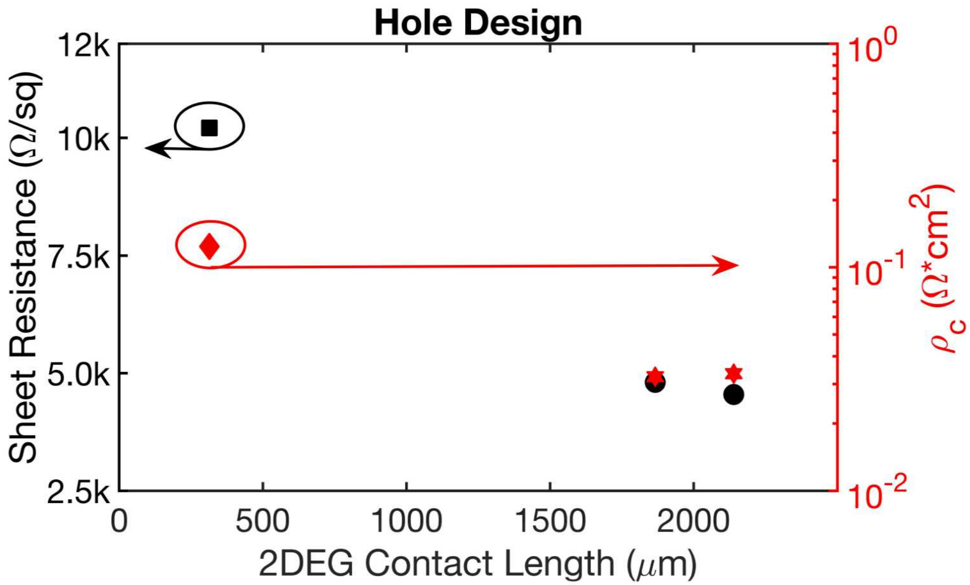


- Calculated R_{SH} reduced by half.
- Sheet resistance measured by contactless Lehighton of as-grown 85/70 structure: ~1700 Ohm/sq
- Specific contact resistance reduced by almost an order of magnitude

Electrical Characterization (Comb)

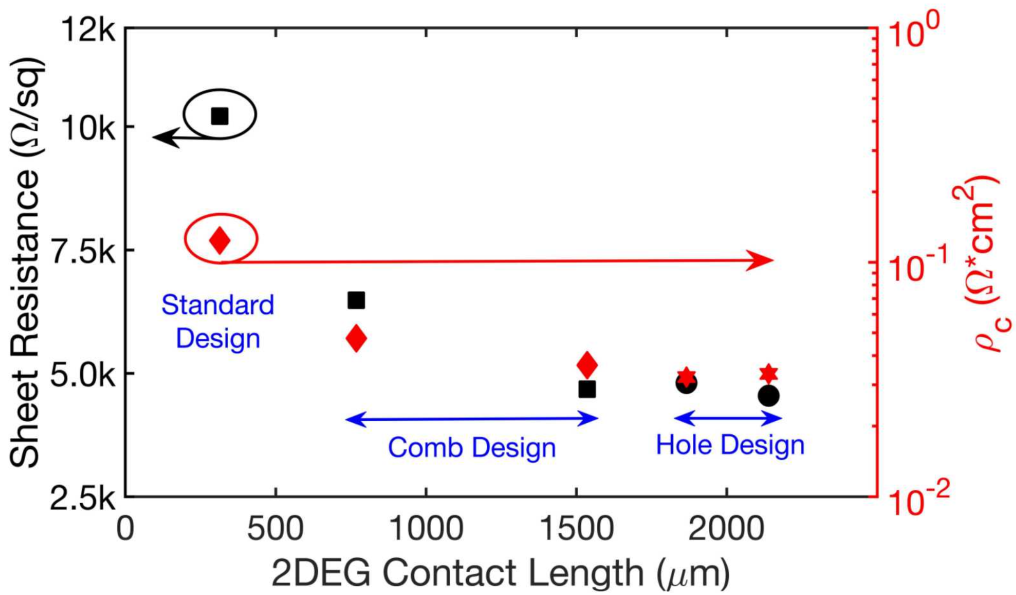


Electrical Characterization (Hole)



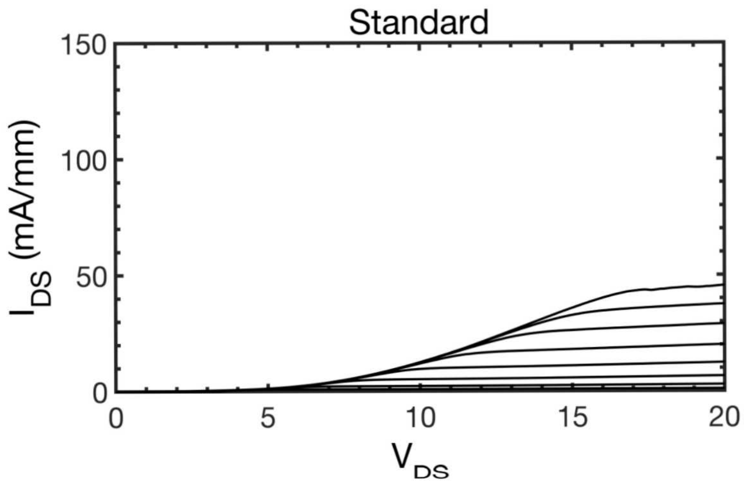
Sheet resistance decreased from >10kΩ to ~4.5kΩ.

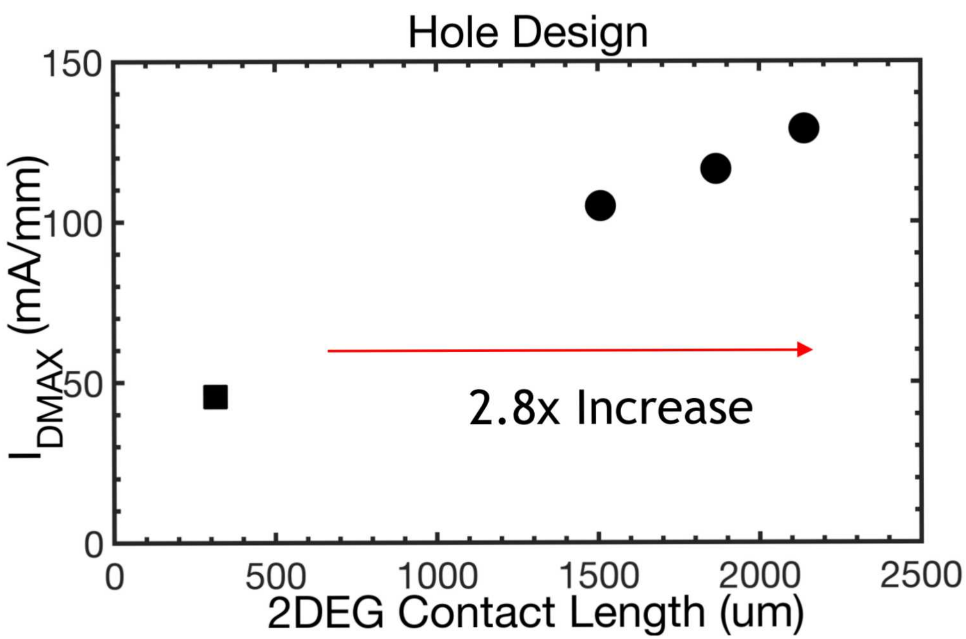
Specific contact resistance decreased from 1.2×10^{-1} to 3.2×10^{-2}

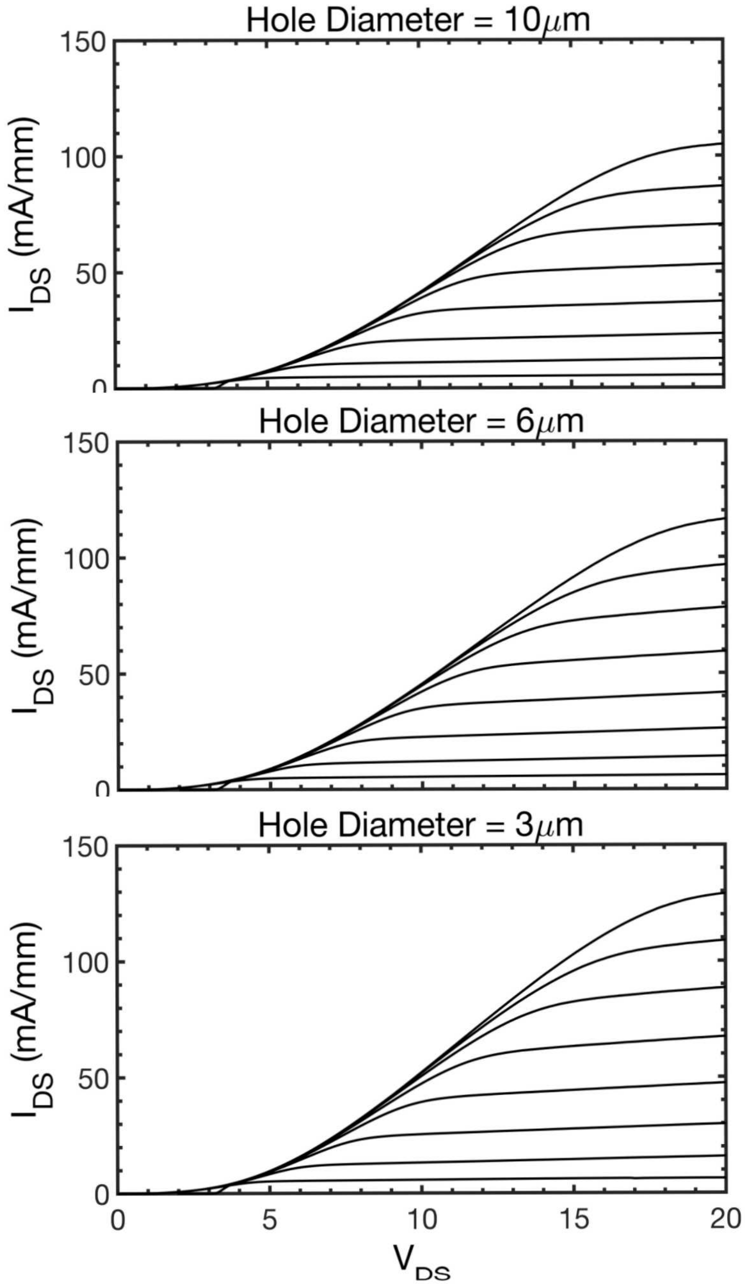


Increasing 2DEG contact length results in marked improvement in contacts

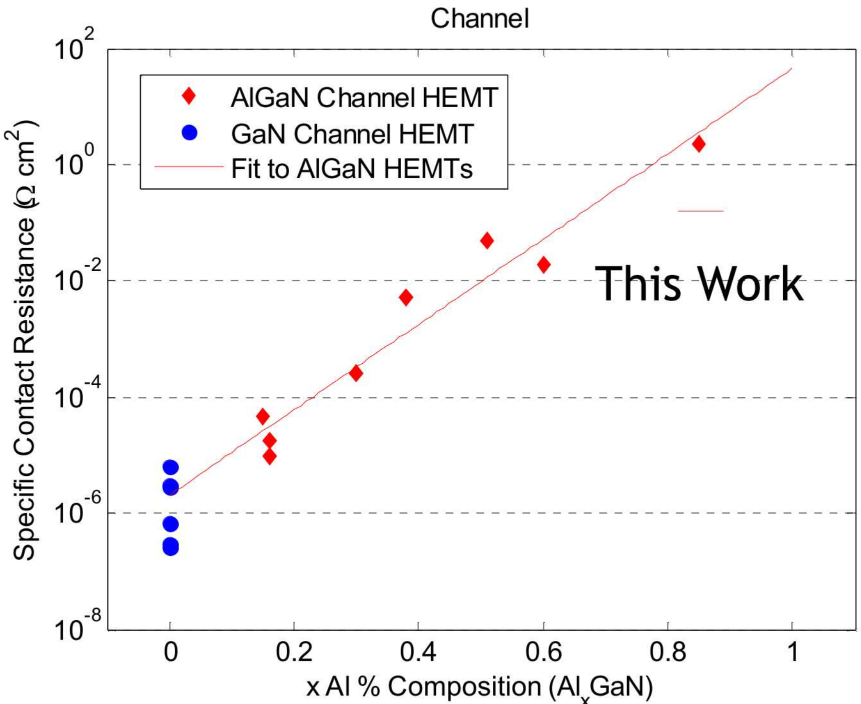
Electrical Characterization (Hole)







Conclusion



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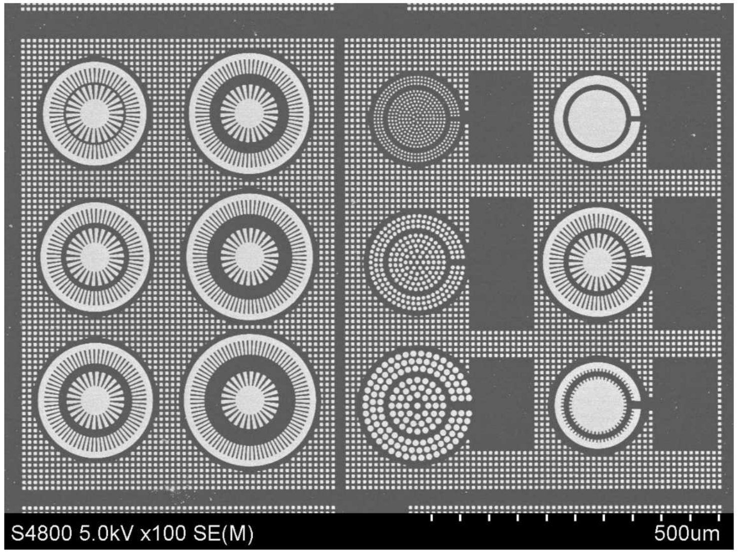
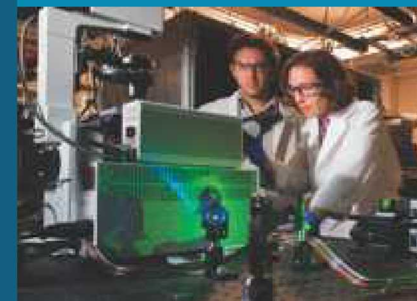


- 2DEG contact length varied from 300μm to 2.1mm
- Sheet resistance decreased from >10kΩ to ~4.5kΩ.
- Specific contact resistance decreased from $1.2\text{x}10^{-1}$ to $3.2\text{x}10^{-2}$ $\Omega\text{*cm}^2$
- 2.8X increase in maximum drain current at V_{GS} = 8V

Current Enhancement for Ultra-Wide Bandgap AlGaN High Electron Mobility Transistors by Regrowth Contact Design



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