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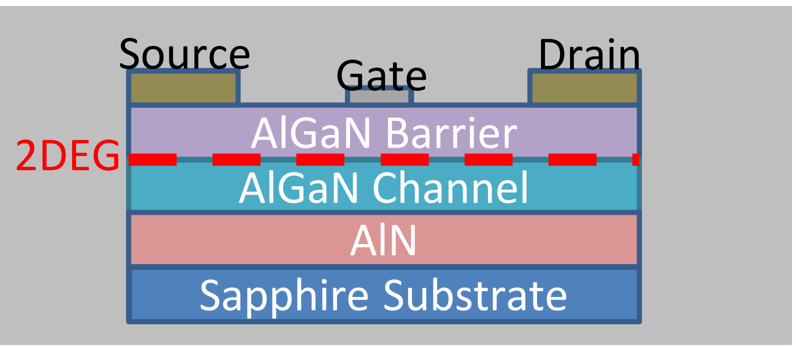

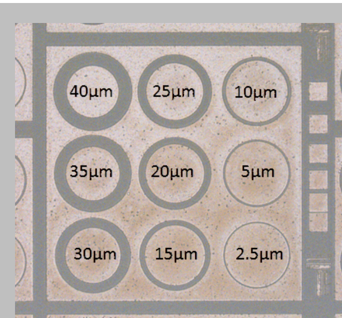

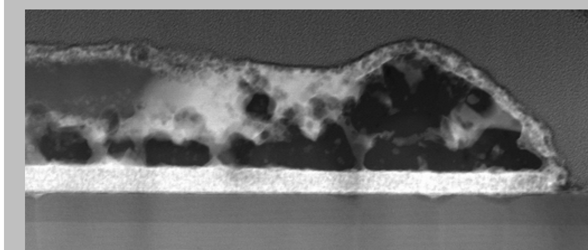

Low-resistance Ohmic contacts to $Al_{0.45}Ga_{0.55}N$/ $Al_{0.3}Ga_{0.7}N$ HEMTs

B. Klein, A.G. Baca, A.M. Armstrong, A.A. Allerman, E.A. Douglas, C.A. Sanchez, P. Kotula, M. Miller, S. Reza

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Outline

Introduction and Background

Ohmic metal evaluation
- Five metal stacks
- Rapid thermal anneal process
- TEM analysis of Ti/Al/Ni/Au

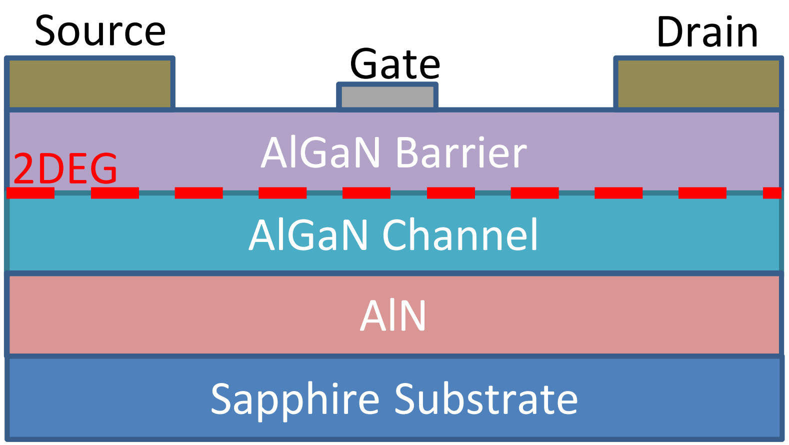
HEMT device
- Fabrication
- Characterization results

Conclusions

Introduction

Project Goal

- Develop Ohmic contacts $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ High Electron Mobility Transistors (HEMTs)



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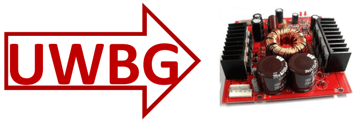
Motivation

- Next-generation power switches
- RF devices
- Optoelectronic applications
- **Higher Al compositions have potentially superior electrical and thermal properties**, but making Ohmic contacts is challenging



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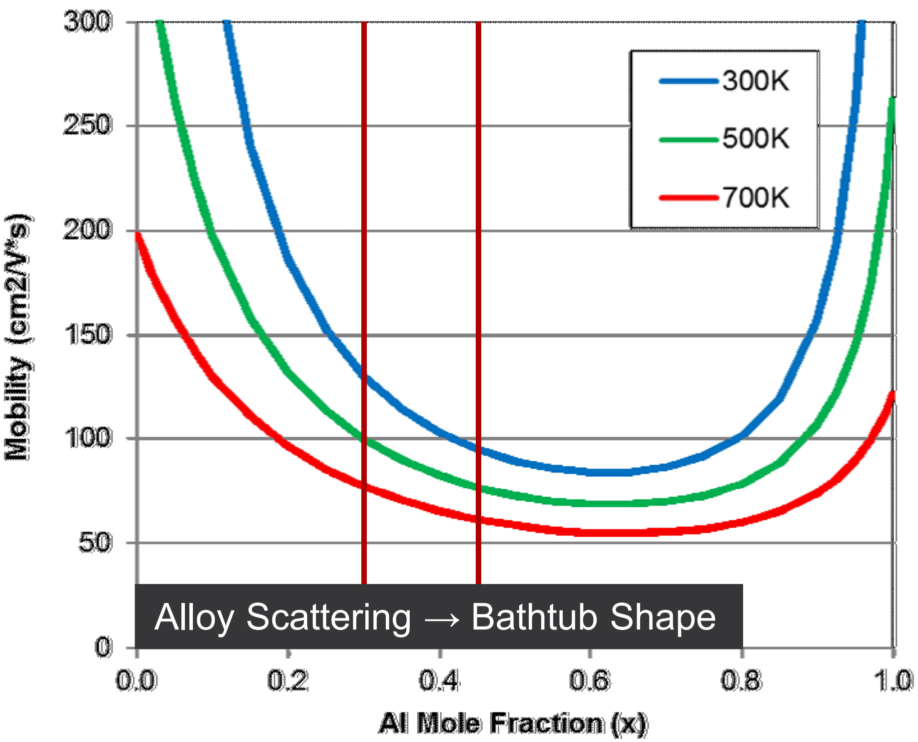

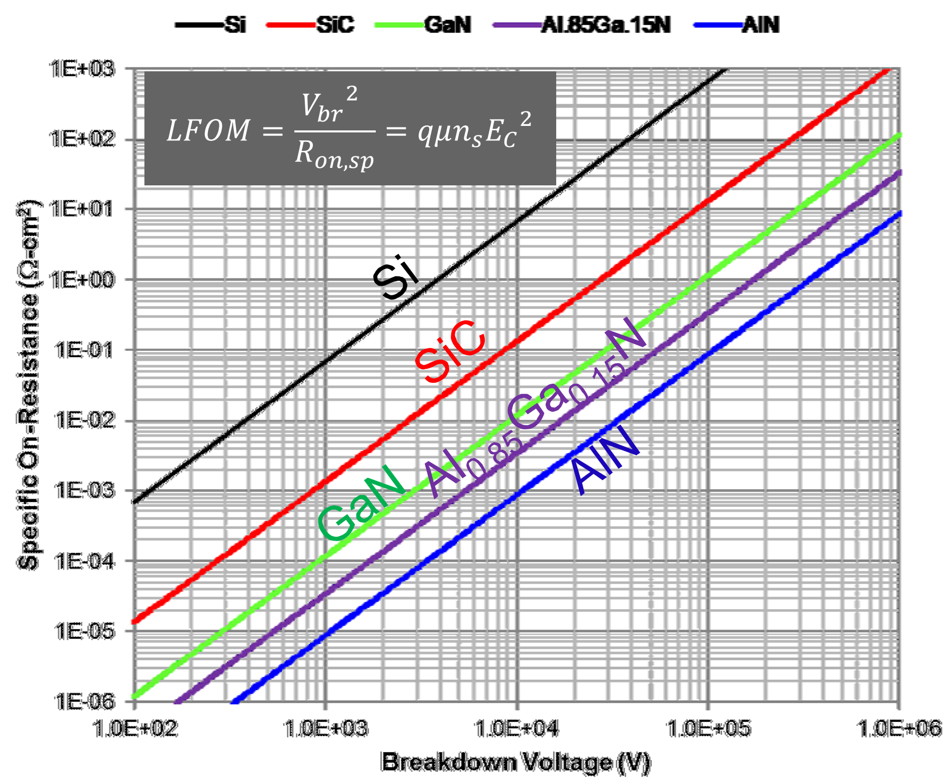

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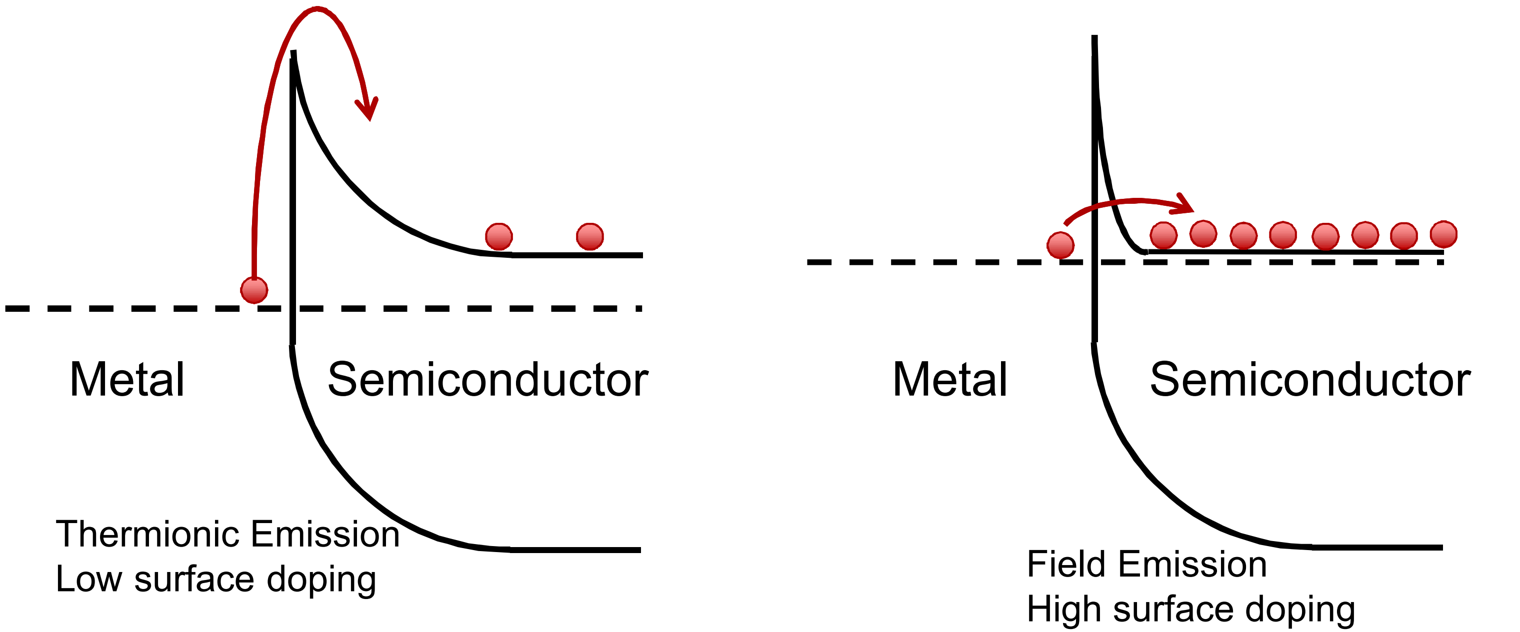
- Higher Al compositions have potentially superior electrical and thermal properties, but making Ohmic contacts is challenging

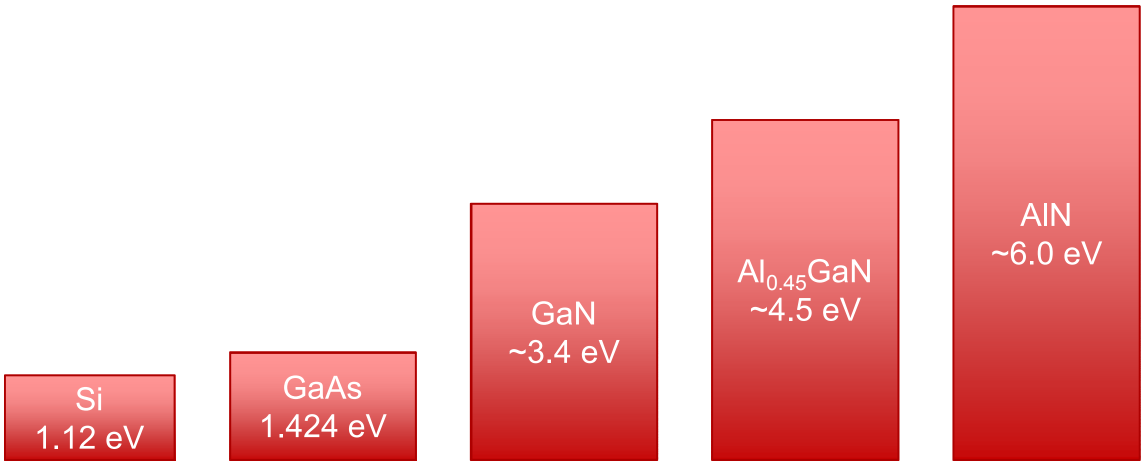
Approach

- Intermediate aluminum fraction
- Low mobility, but good platform for Ohmic contact development
- Evaluate five Ohmic contact stacks; planar configuration
- Build HEMT

HEMT Contact Resistance Overview

Why is making an Ohmic contact to AlGaN challenging?





Schroder, D. K. (2006). Semiconductor Material and Device Characterization.

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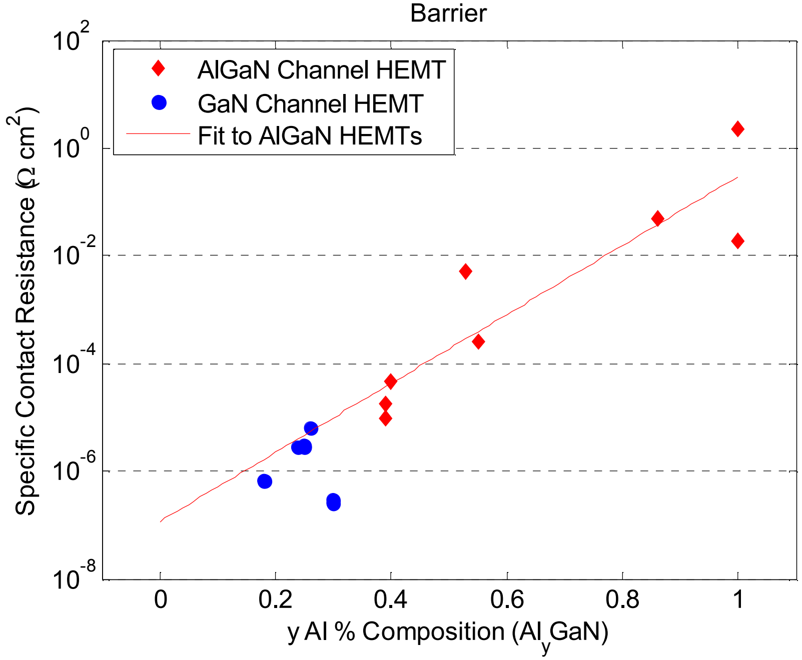

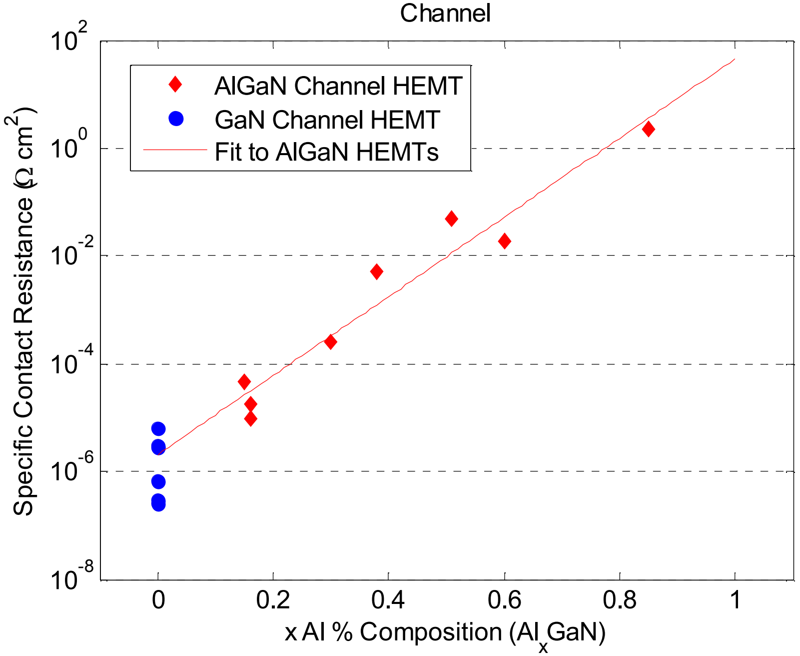

Klein, B. A., (2017). ECS Journal of Solid State Science and Technology **6**(11): S3067-S3071.

Reported specific contact resistances of AlGaN-channel HEMTs rise exponentially with increasing Al fraction.

[1] Nanjo, T., (2008). Applied Physics Letters **92**(263502).
[2] Bright, A. N., (2001). Journal of Applied Physics **89**(6): 3143-3150.
[3] Nanjo, T., (2013). IEEE Transactions on Electron Devices **60**(3): 1046-1053.
[4] Vanko, G., (2008). Vacuum **82**: 193-196.
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[6] Basu, A., (2006). Journal Vacuum Science and Technology B **24**(2).
[7] Wang, L., (2005). Applied Physics Letters **87**(141915).
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[9] Yafune, N., (2011). Japanese Journal of Applied Physics **50**(100202).
[10] Tokuda, H., (2010). Applied Physics Express **3**(121003).
[11] Yafune, N., (2014). Electronics Letters **50**(3): 211-212.
[12] Baca, A. G., (2016). Applied Physics Letters **109**(033509).
[13] Douglas, E. A., (2017). Physica Status Solidi A **214**(8).
[14] France, R., (2007). Applied Physics Letters **90**(062115).
[15] Mori, K., (2016). Japanese Journal of Applied Physics **55**(05FL03).
[16] Tokuda, H., (2012). Applied Physics Letters **101**(262104).

HEMT Contact Resistance Overview

Techniques/Approaches

Various metal stacks

- Ti/Al[1,3,8]
- Ti/Al/Ni/Au[2,12]
- Ti/Al/Mo/Au[7]
- Ti/Al/W[5]
- V/Al/Ni/Au[15]
- Mo/Al/Mo/Au[6]
- Nb/Ti/Al/Ni/Au[4]
- Zr/Al/Mo/Au[9,10,11]
- V/Al/V/Au[14]

Treatments

- Si implant in Ohmic regions[1,3]
- Selective area regrowth[12]
- Recessed etching[13]

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Proposed AlGaN HEMT Ohmic Contact Mechanisms[16]

- Metal spiking through the barrier
- Ti-N forms → lowers barrier height
- Ti reacts with N → forms N-vacancies or Ti-N complex that is highly conductive
- Other possibilities

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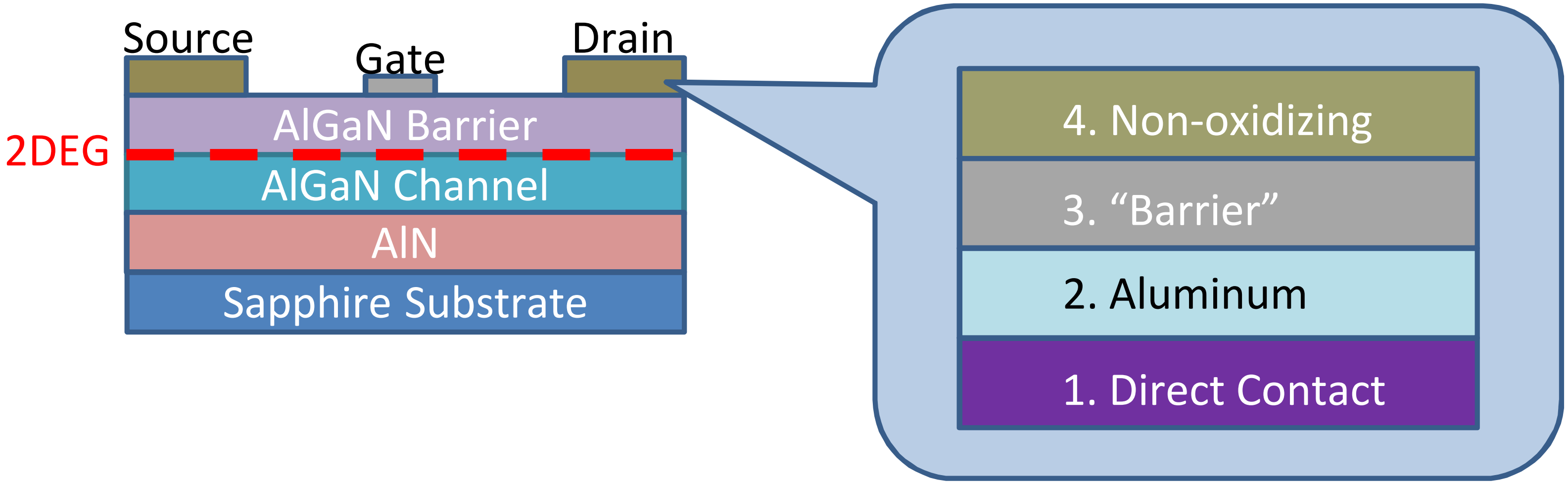
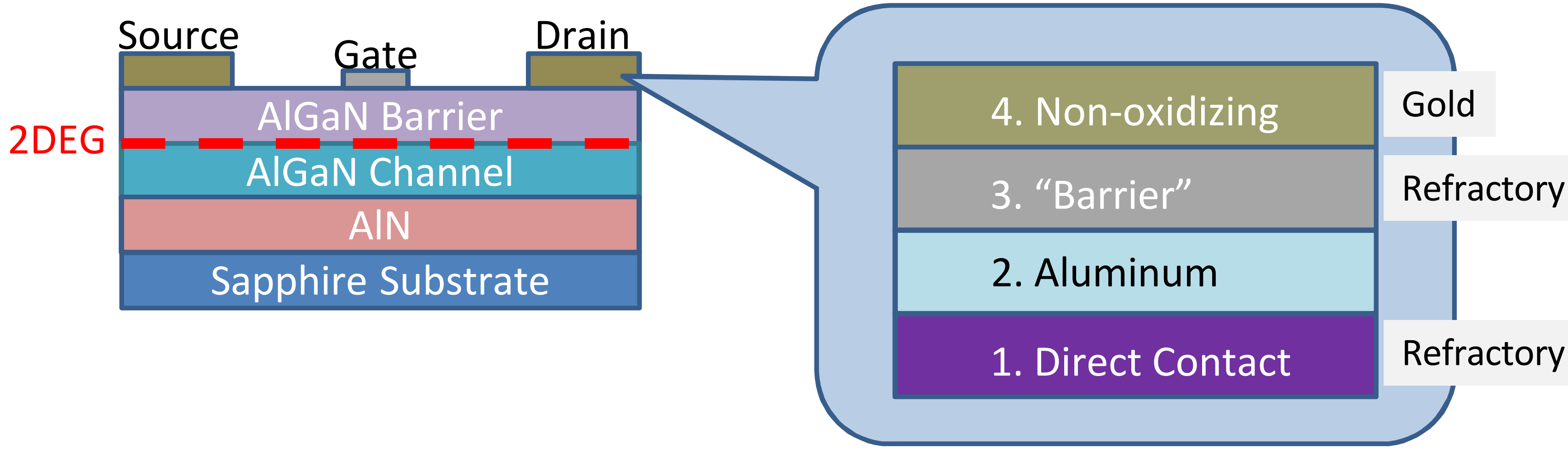
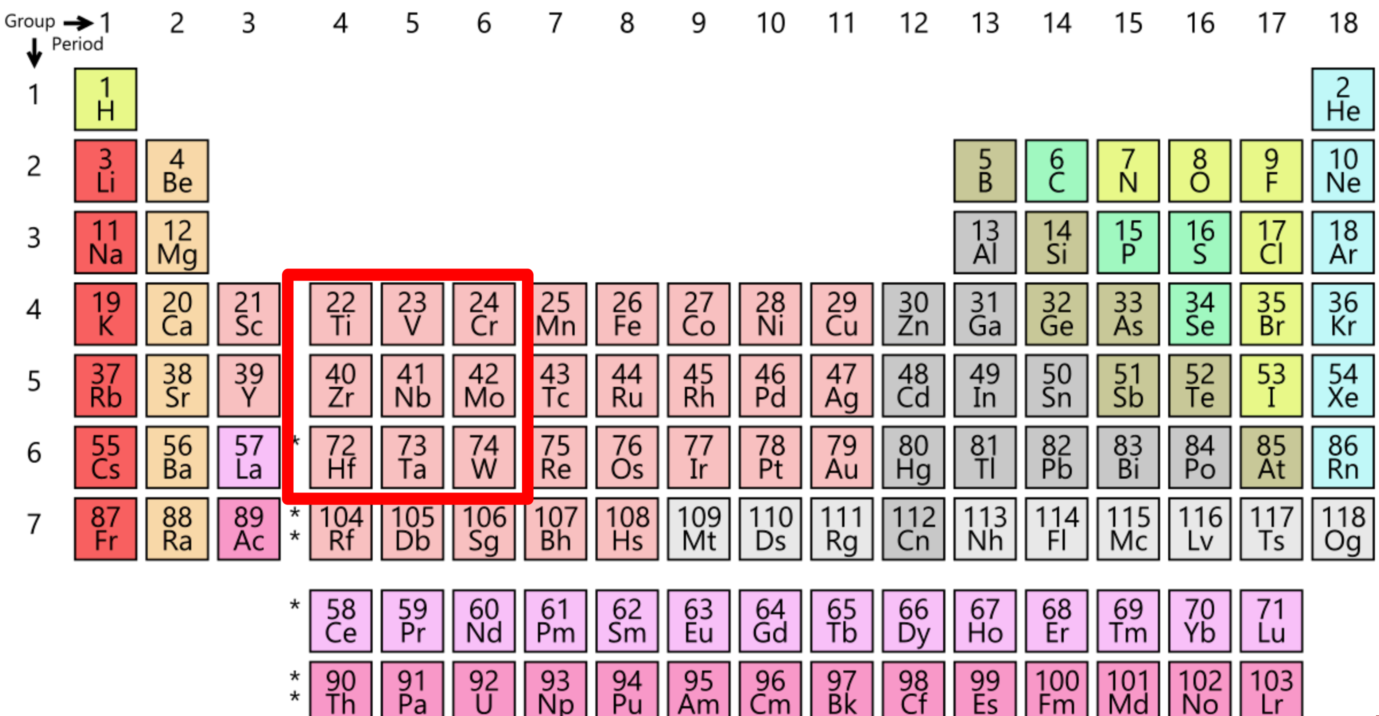
Ohmic contact metal stack evaluation

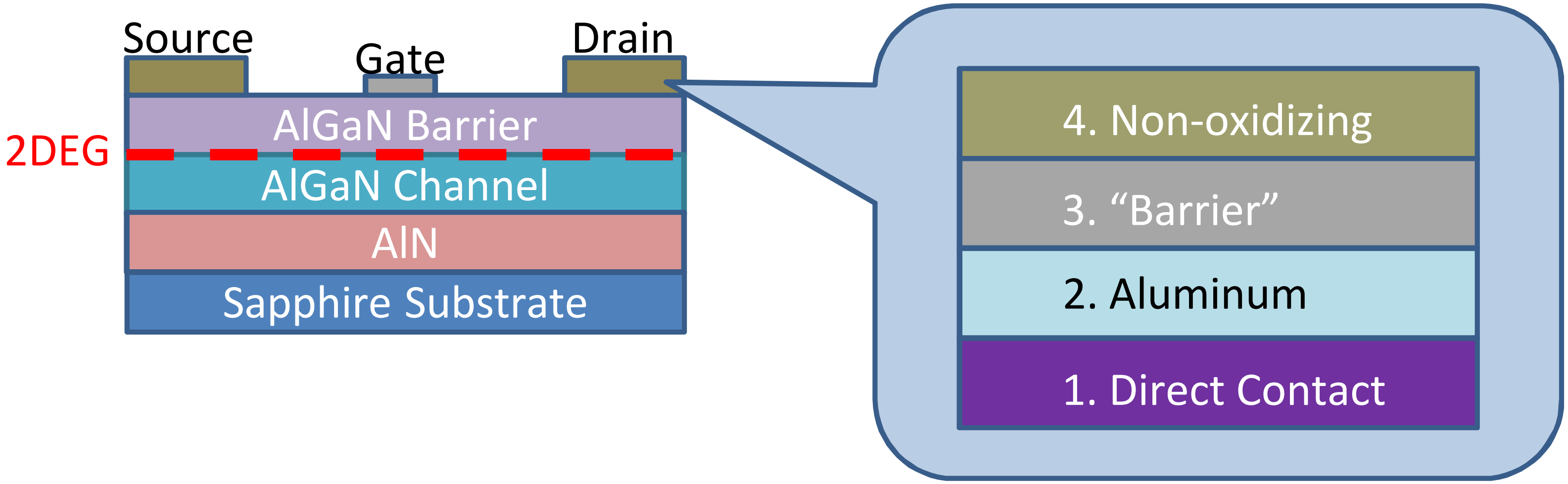


Ohmic contact metal stack evaluation





Ohmic contact metal stack evaluation



The five stacks we tried:

Metallization Stacks

Stack A	Stack B	Stack C	Stack D	Stack E
500 Å Au	500 Å Au	500 Å Au	500 Å Au	1000 Å Au
150 Å Ni	350 Å Mo	350 Å Mo	400 Å Mo	200 Å V
1000 Å Al	600 Å Al	1200 Å Al	1000 Å Al	800 Å Al
250 Å Ti	150 Å Ti	150 Å Zr	200 Å Ti	150 Å V
			200 Å Nb	

Circular Transmission Line Method

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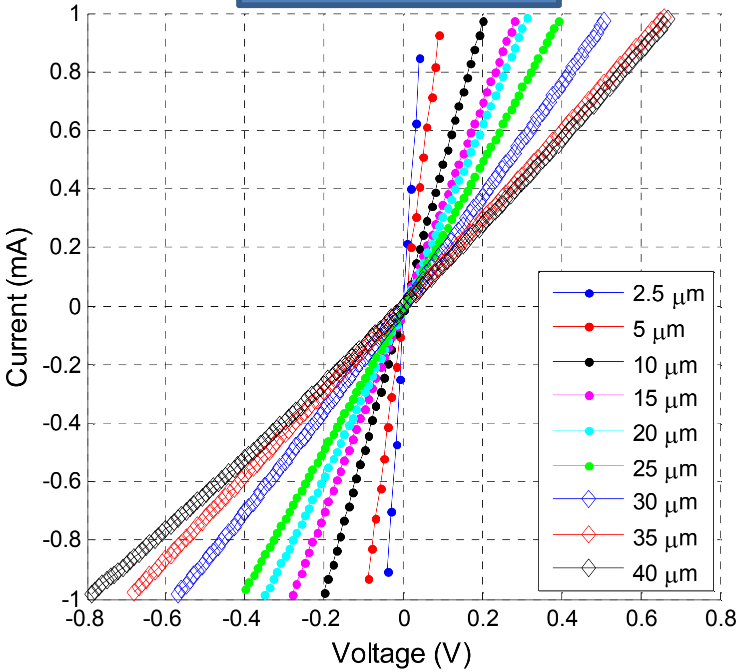
Good



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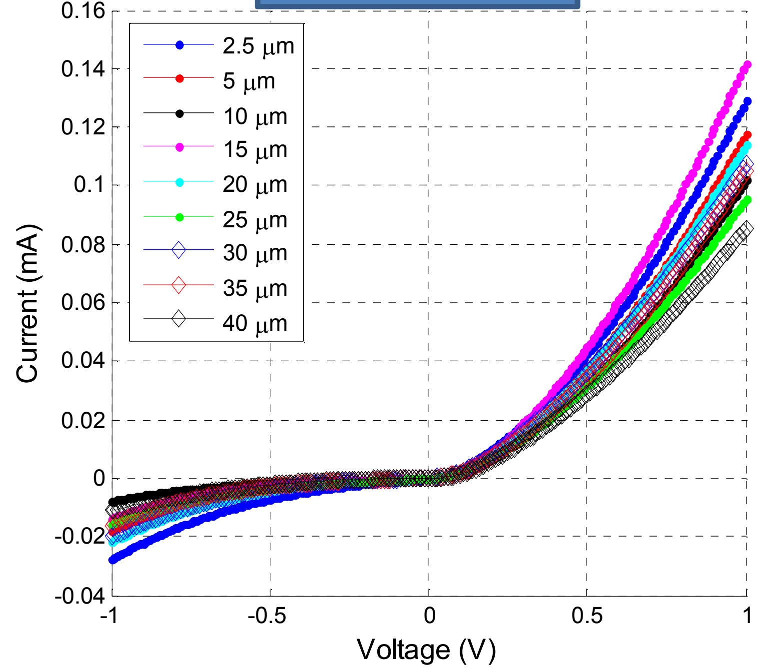

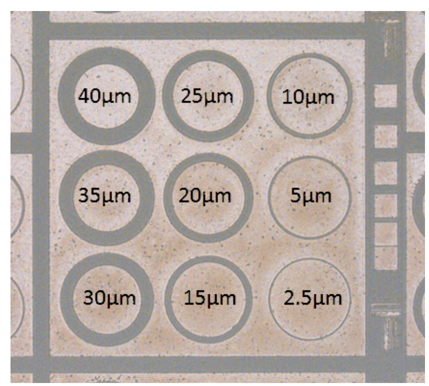

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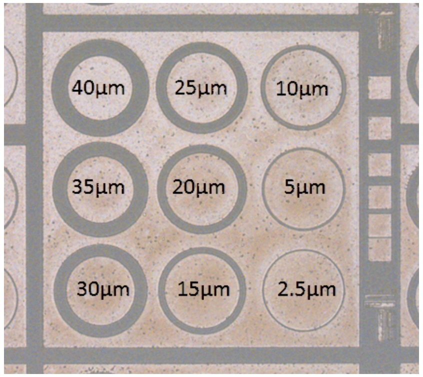
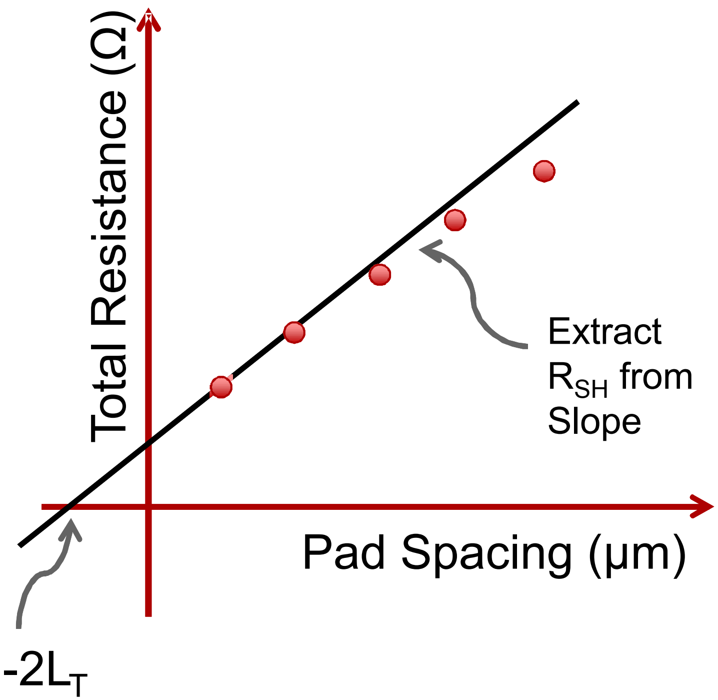




Characteristic Equation for Measured Resistance:

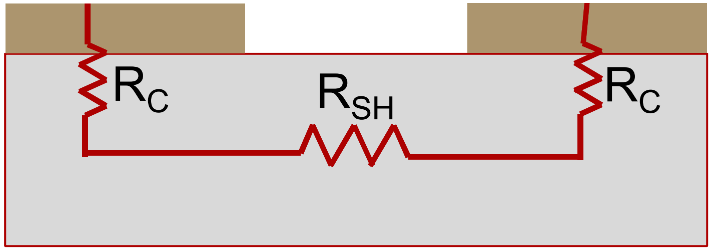
$$R_T = \frac{R_{SH}C}{2\pi L}(d + 2L_T)$$

Slope of RT dependent on Sheet Resistance:

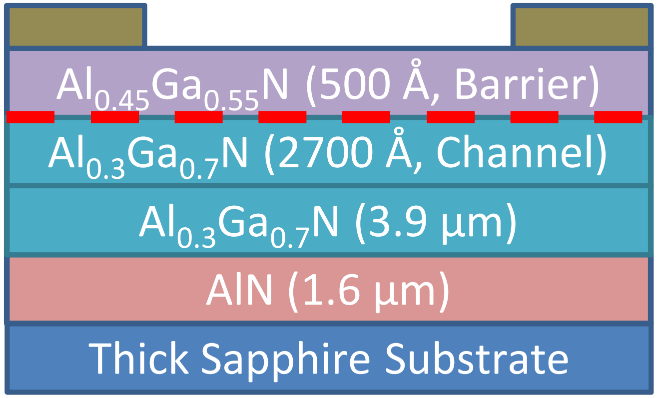
$$R_{SH} = (slope)2\pi L$$

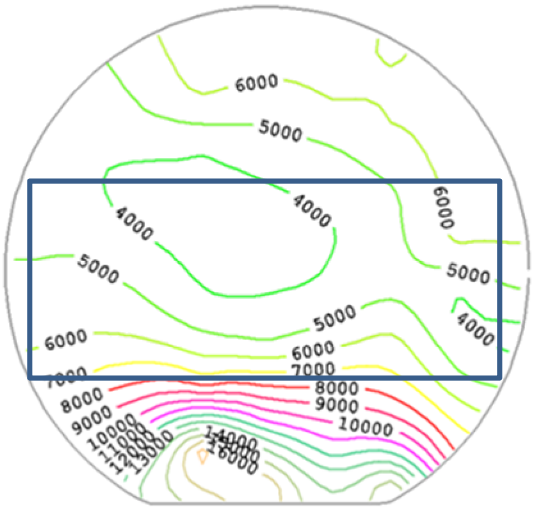
Specific contact resistance (Ω cm²):

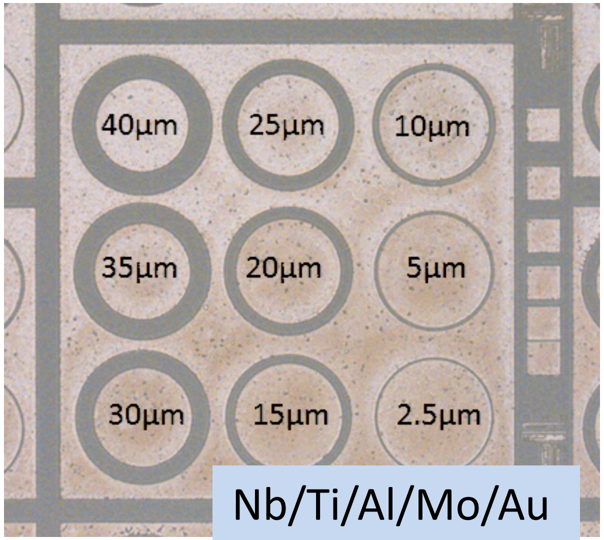
$$\rho = L^2{}_T\, R_{SH}$$

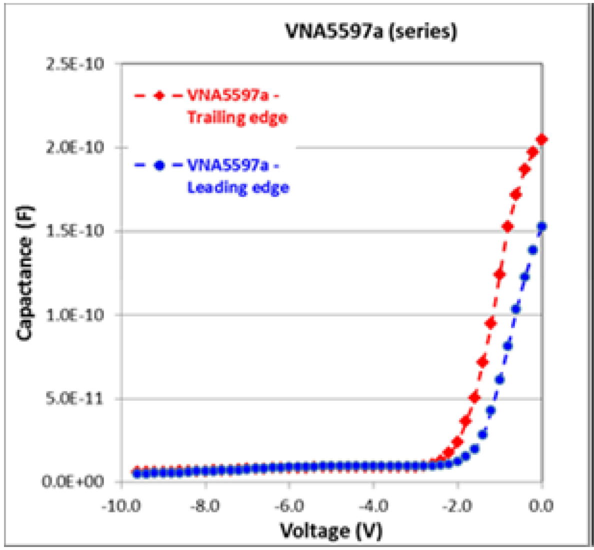


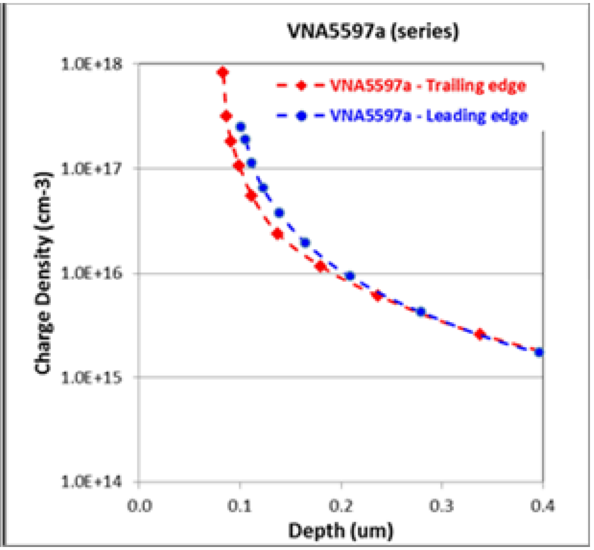
CTLM Test Samples





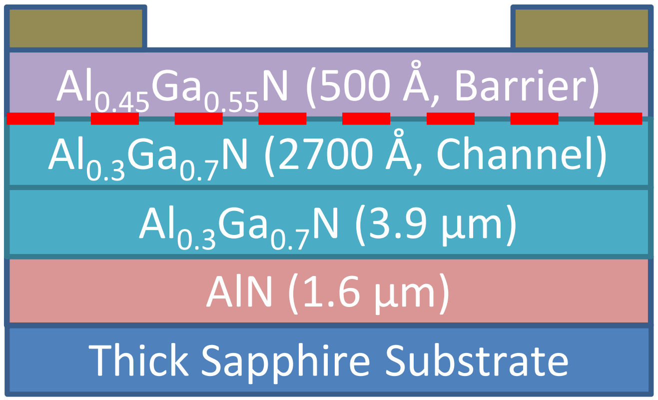


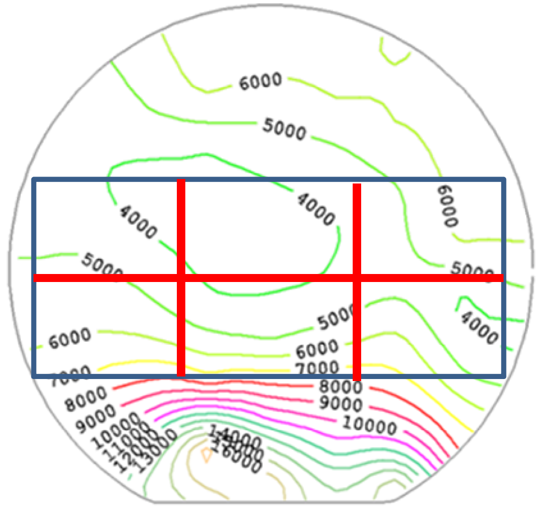


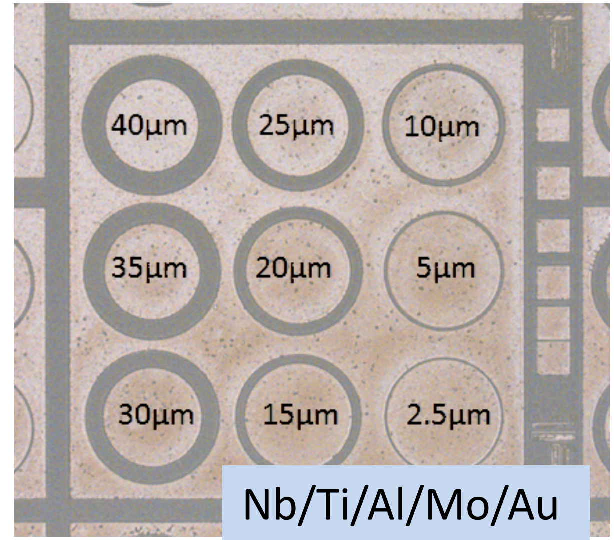


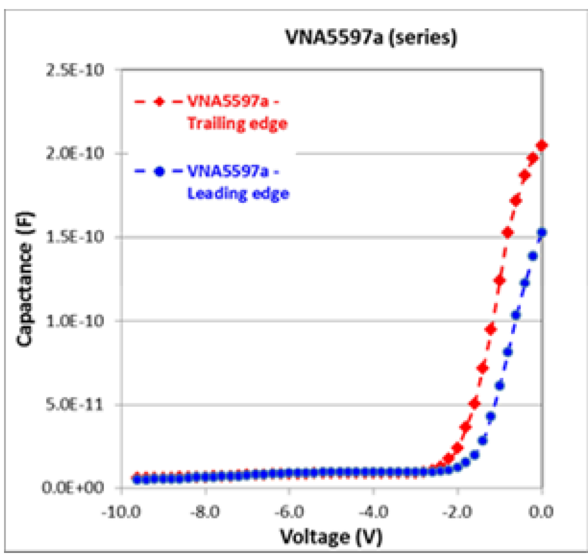
- Standard photolithography
- Metal deposition and liftoff
- Singulate
- Rapid thermal anneal (30 s, Nitrogen ambient)
  - 850°C
  - 900°C
  - 950°C
- Current-Voltage measurements
- Extract sheet and specific contact resistance

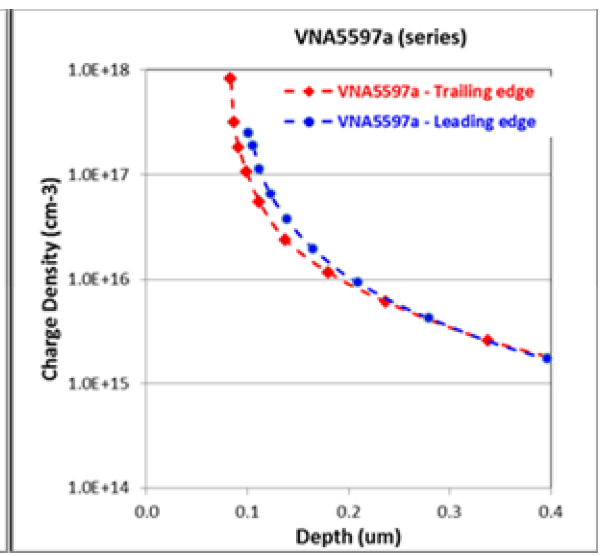
CTLM Test Samples











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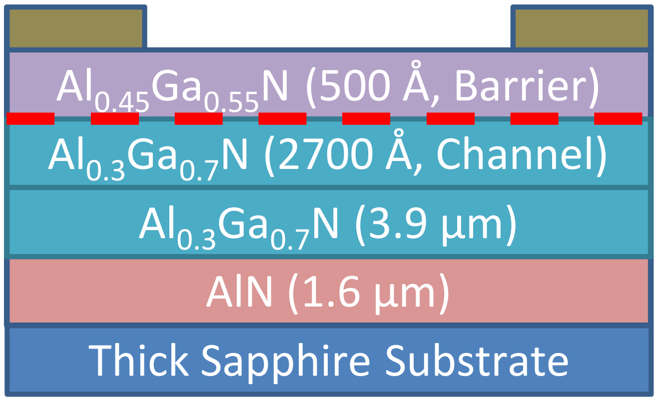

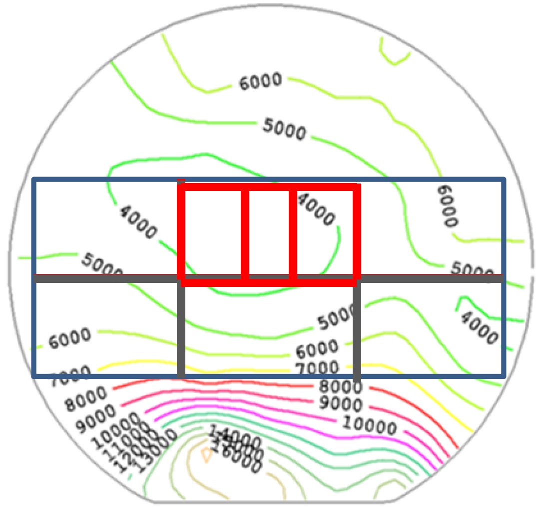

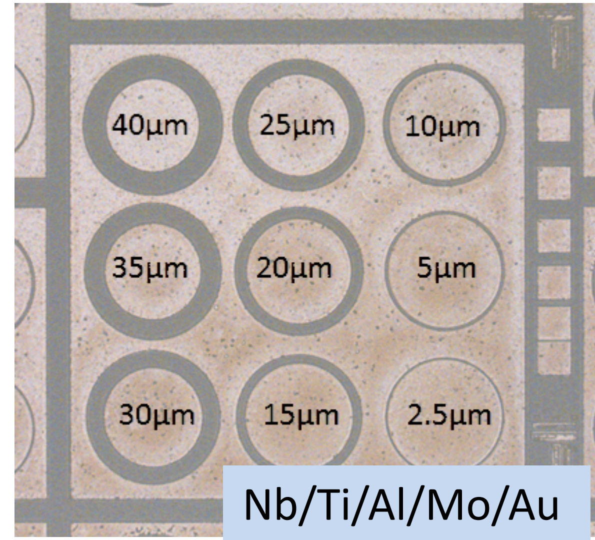

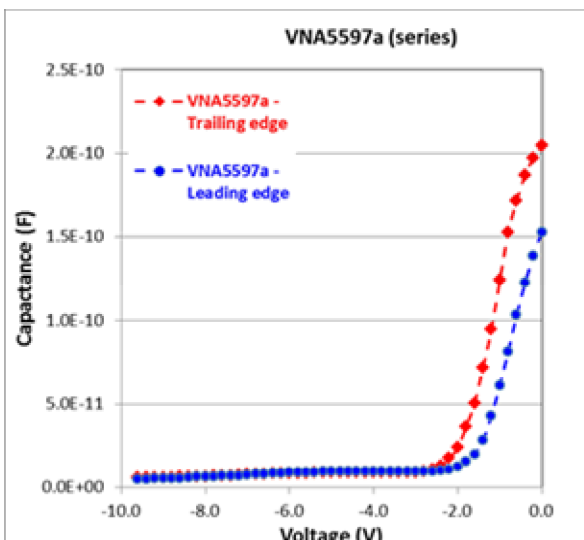

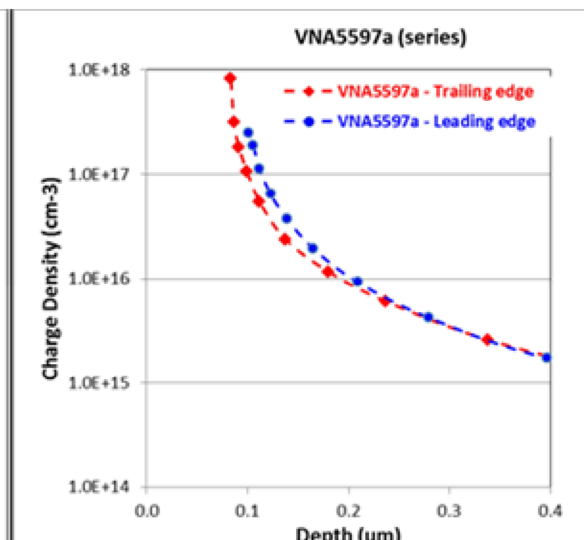

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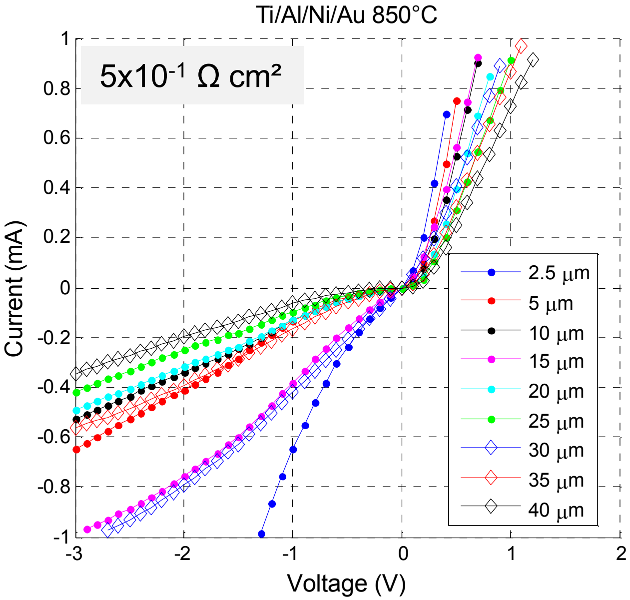
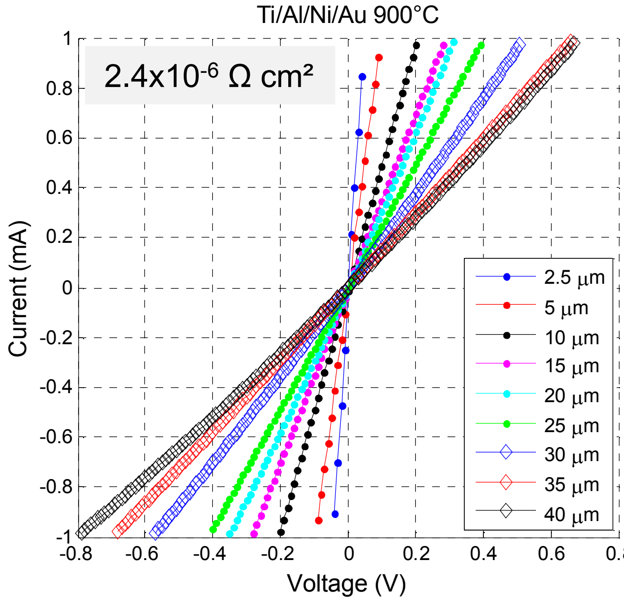
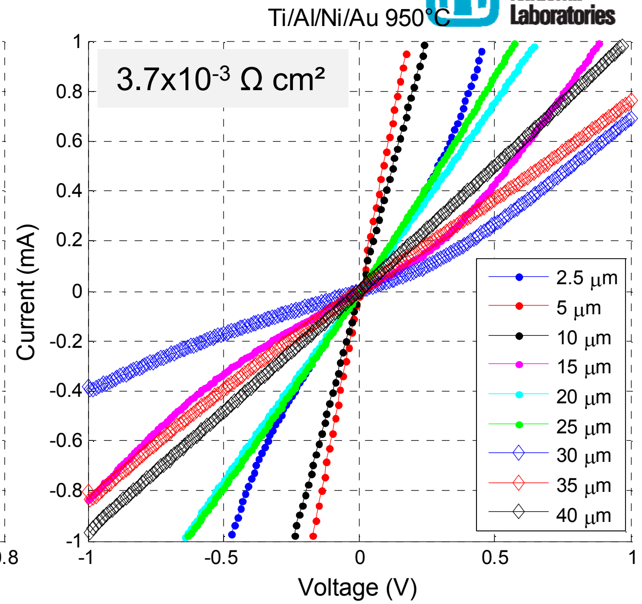
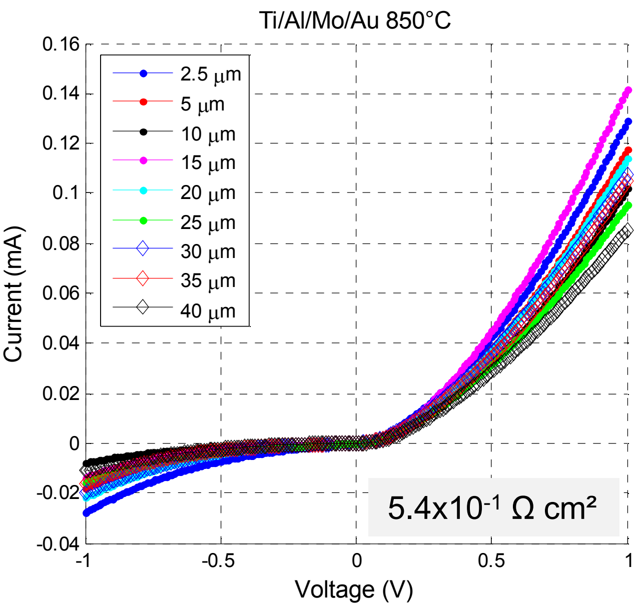
Ti/Al/Ni/Au 850°C 900°C 950°C

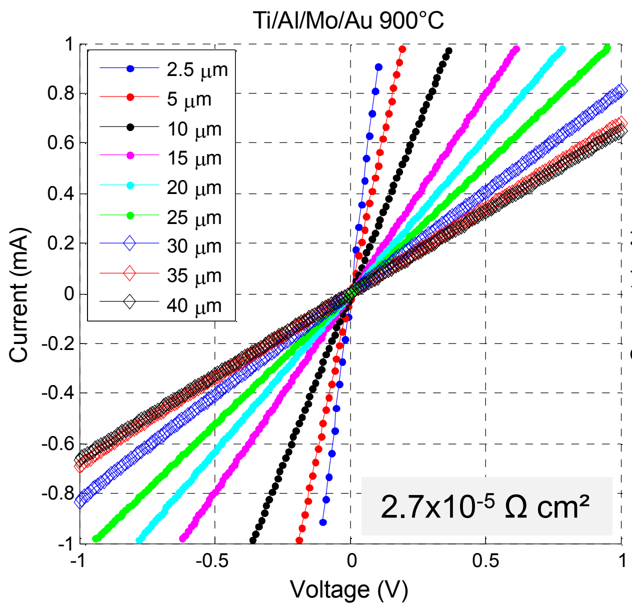


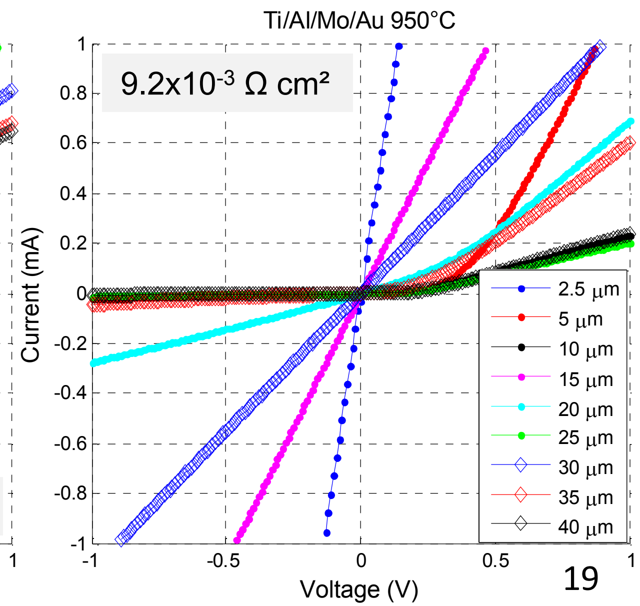




Ti/Al/Mo/Au







850°C 900°C 950°C

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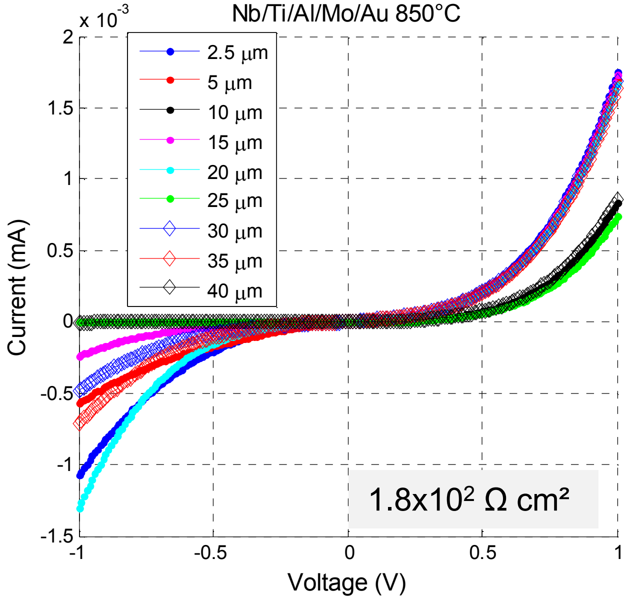
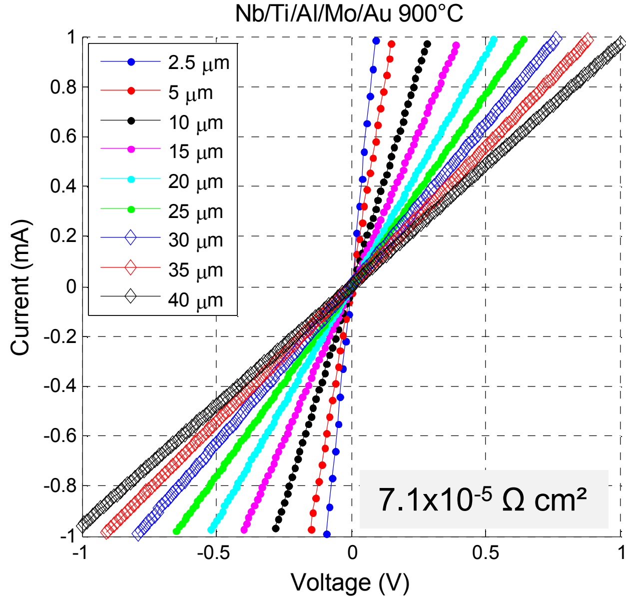
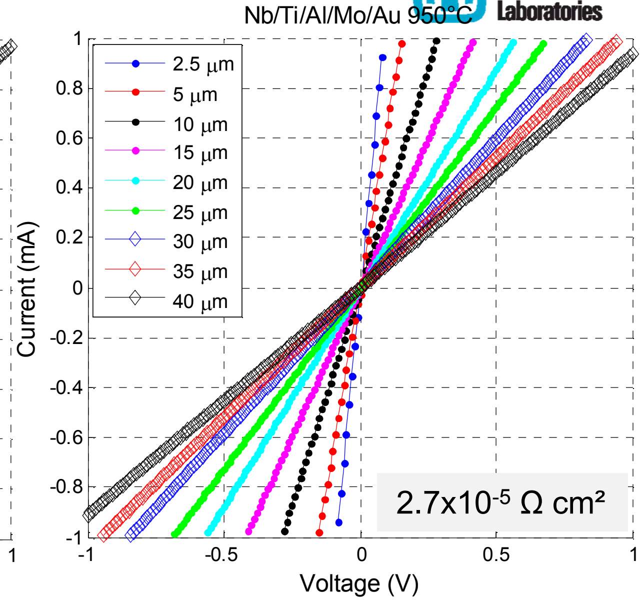
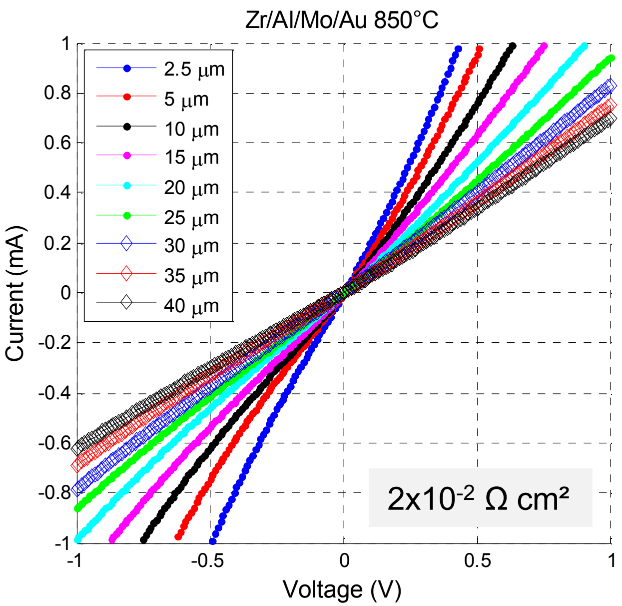
Nb/Ti/Al/Mo/Au

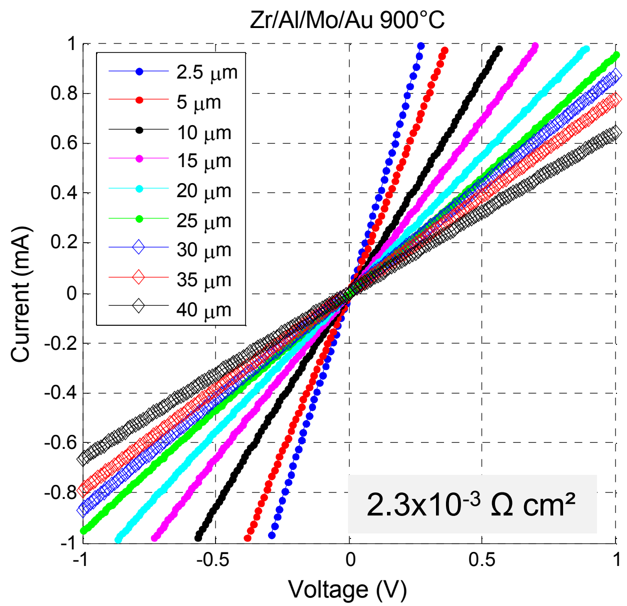


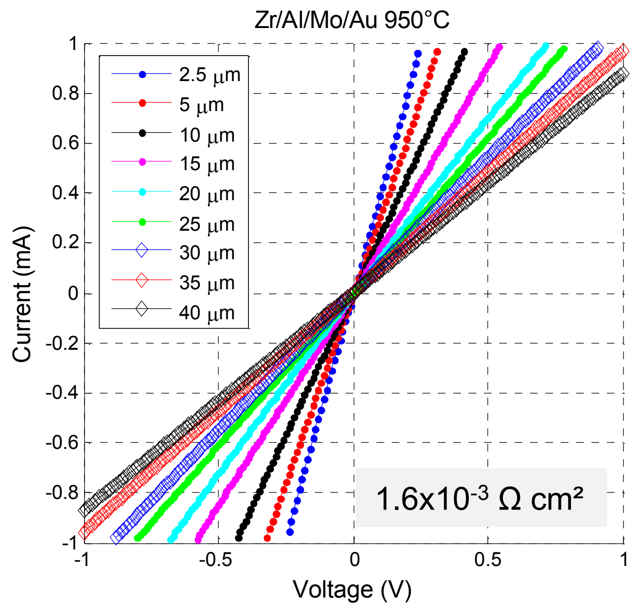




Zr/Al/Mo/Au

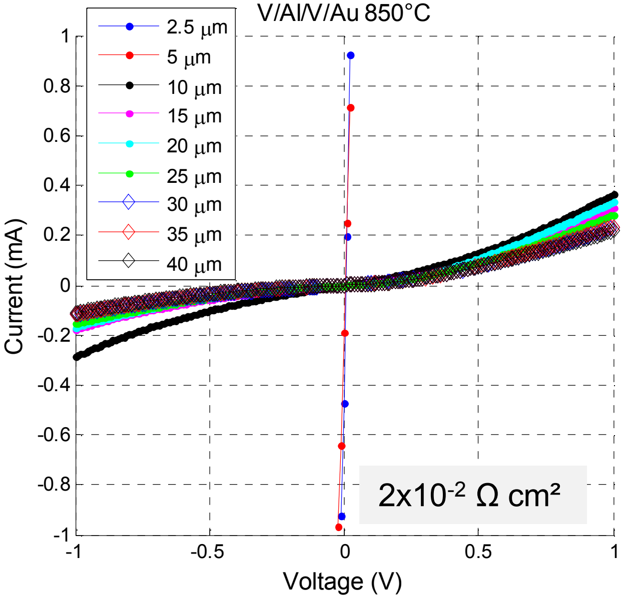




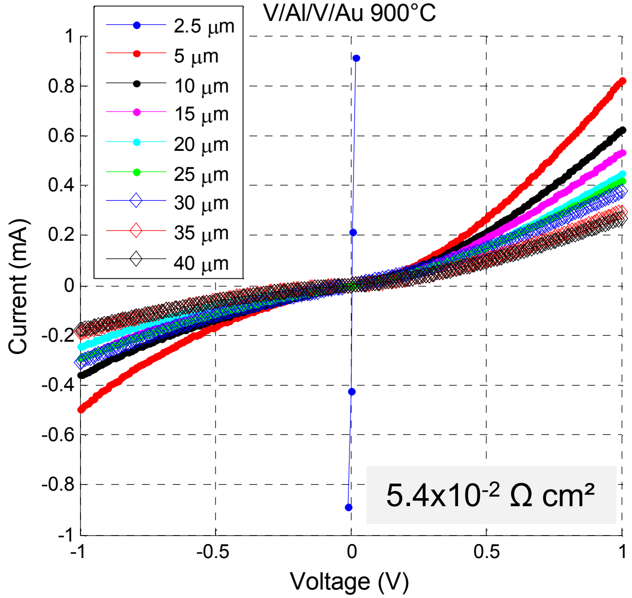


V/Al/V/Au

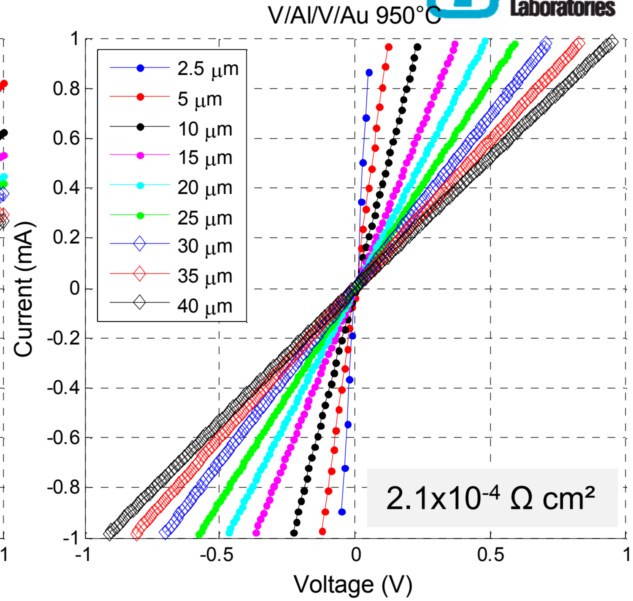
850°C



900°C



950°C



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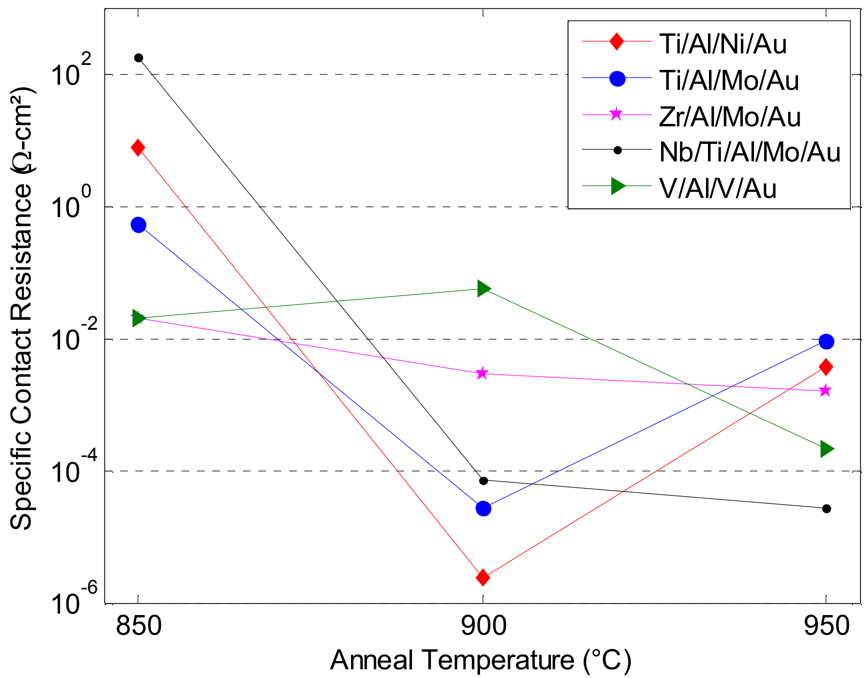
Specific Contact Resistance Comparison

Summary of metal stack and RTA results

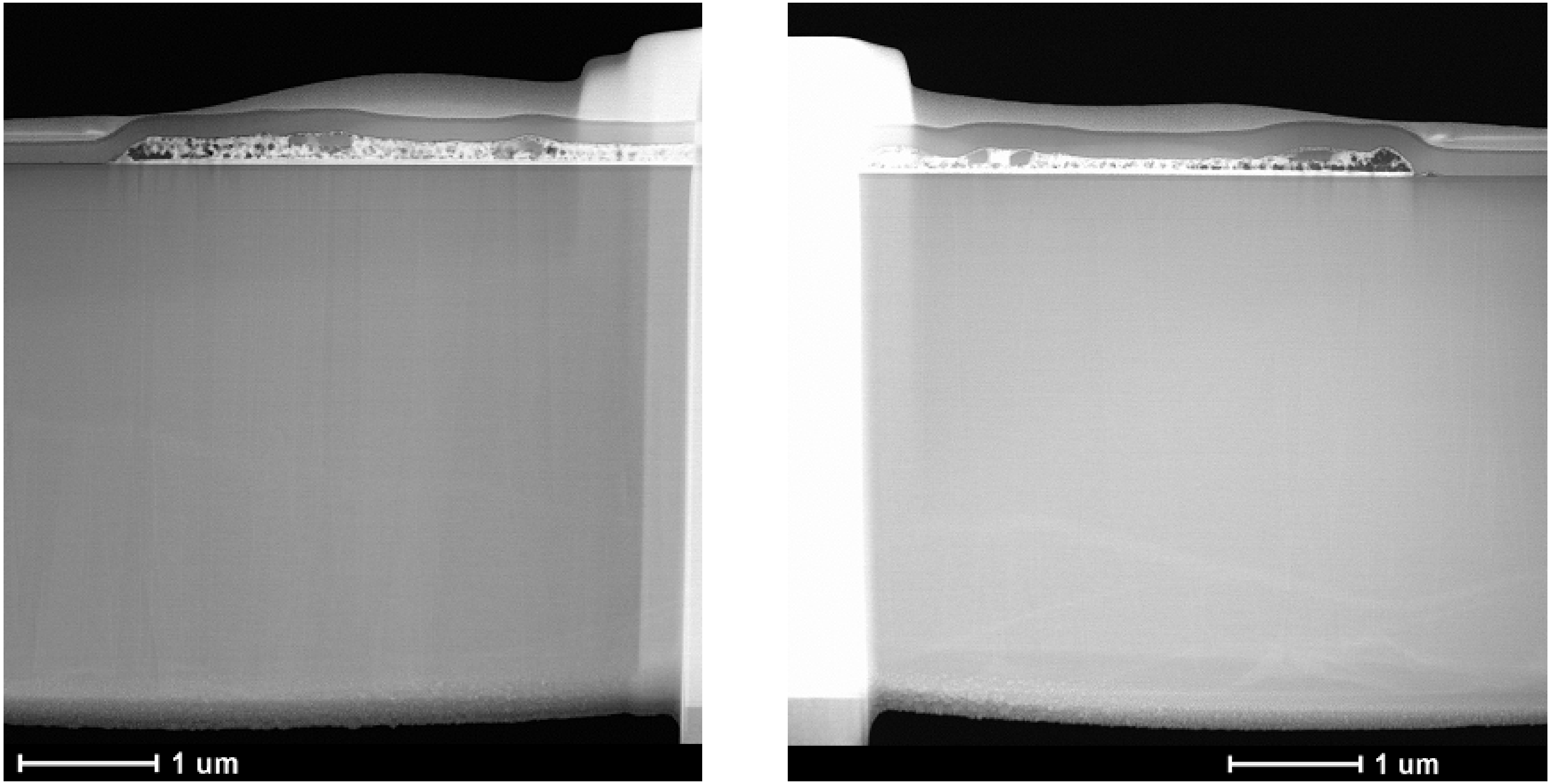


- Ti/Al/Ni/Au produced lowest specific contact resistances (3×10^{-6} Ω cm²)
- All three Ti-based metals had good performance at 900°C
- Zr/Al/Mo/Au was consistently linear at all annealing temperatures studied
- <u>What is happening between 850 and 900°C? → TEM</u>

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

TEM: Ti/Al/Ni/Au

850°C Anneal 900°C Anneal

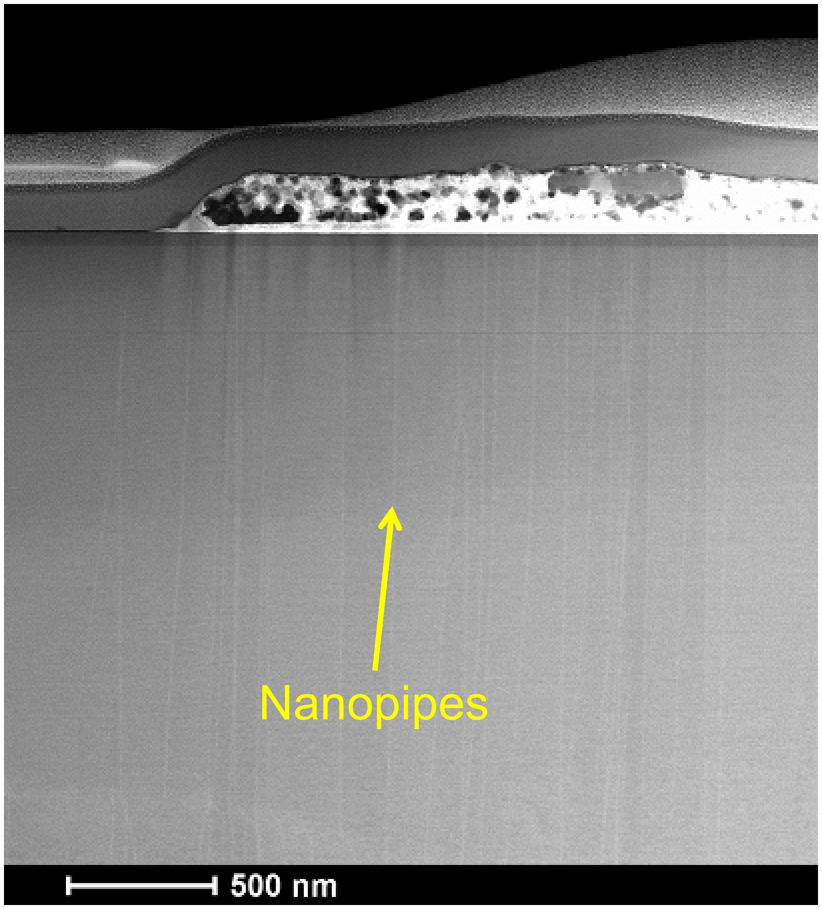


View of available imaging area

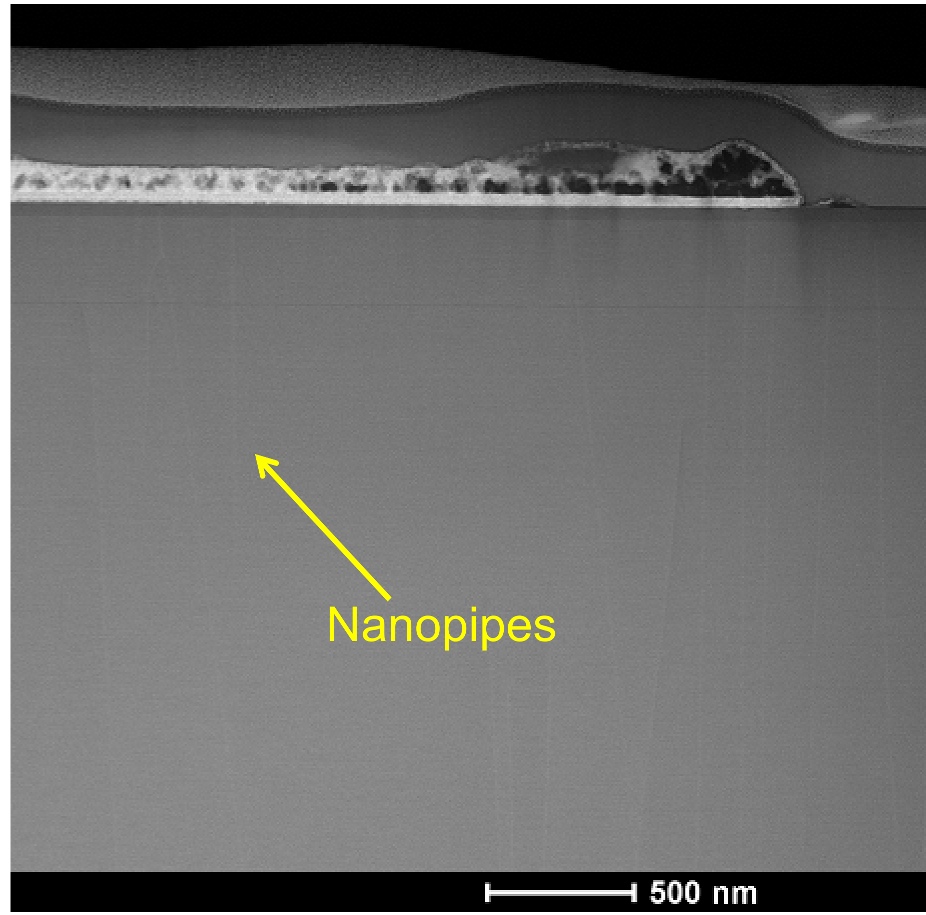
HAADF STEM, Z-Contrast

TEM: Ti/Al/Ni/Au

850°C Anneal



900°C Anneal

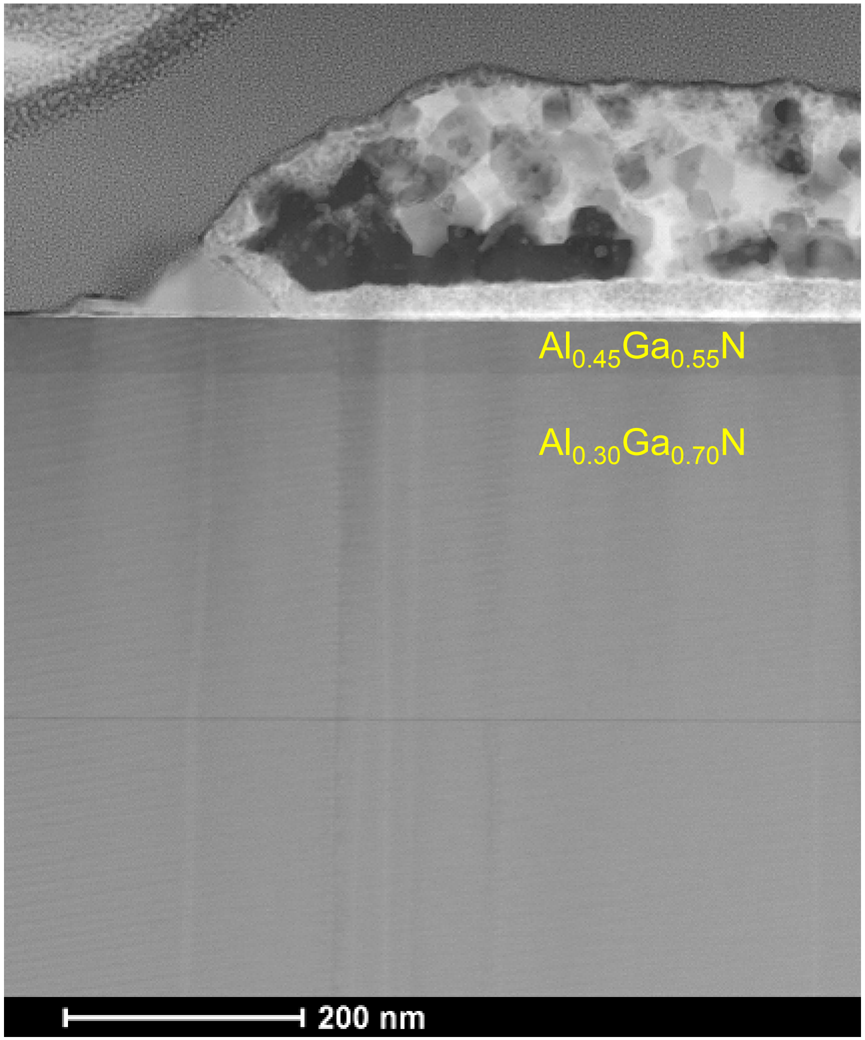


Vertical threading dislocations visible on both samples

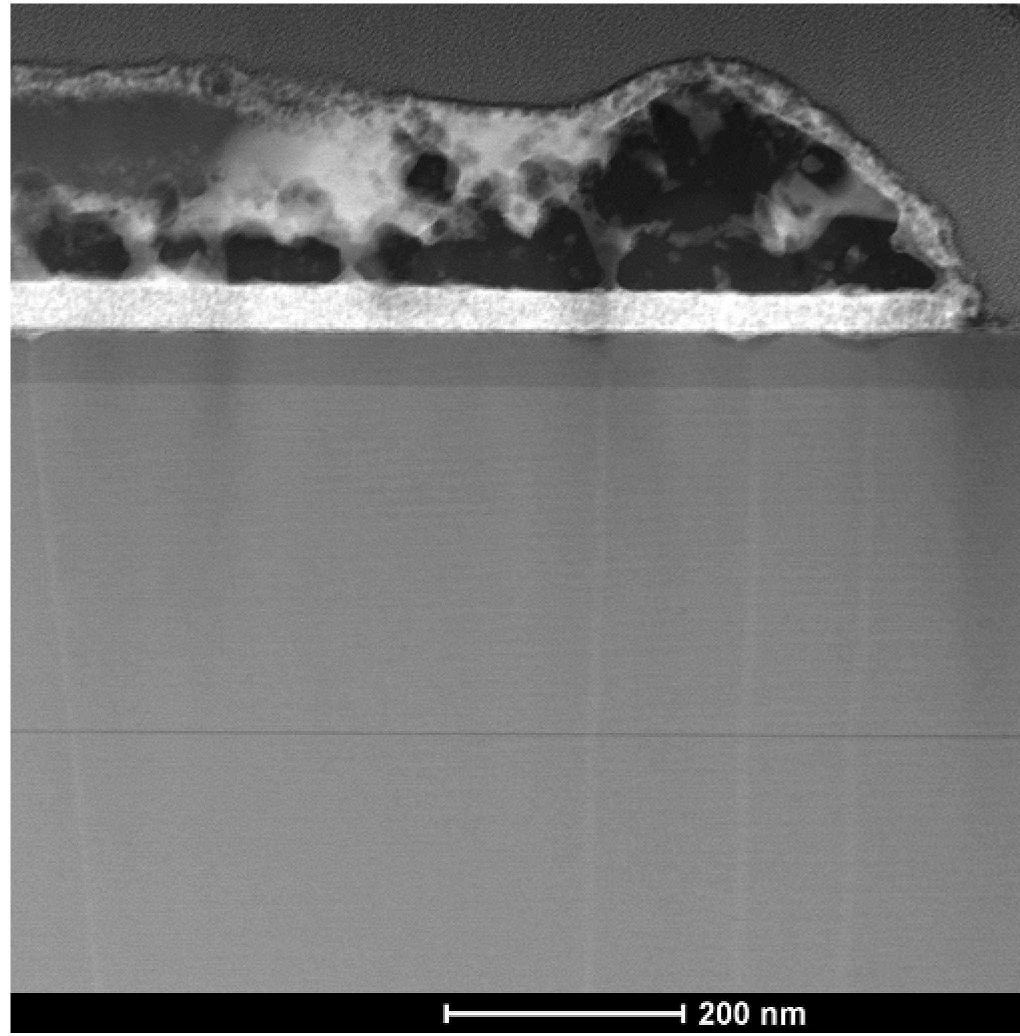
HAADF STEM, Z-Contrast

TEM: Ti/Al/Ni/Au

850°C Anneal

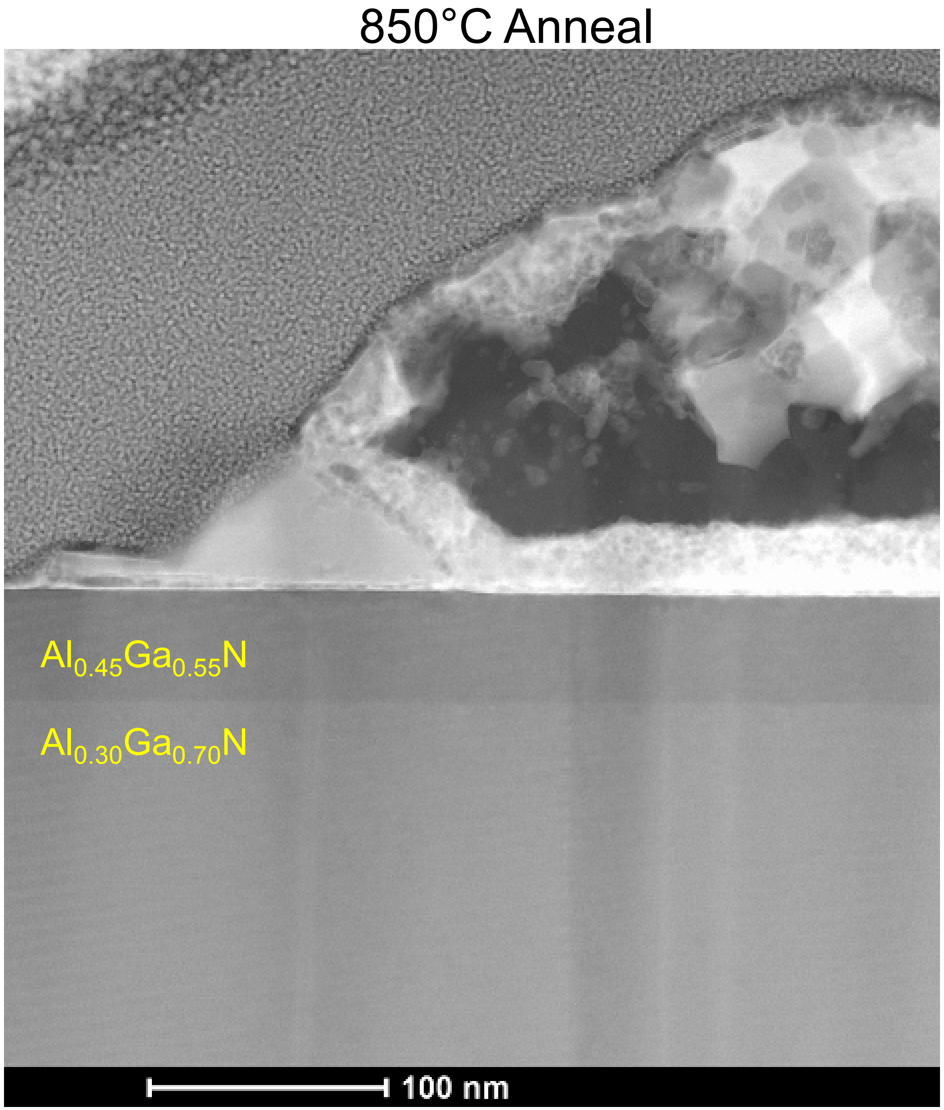


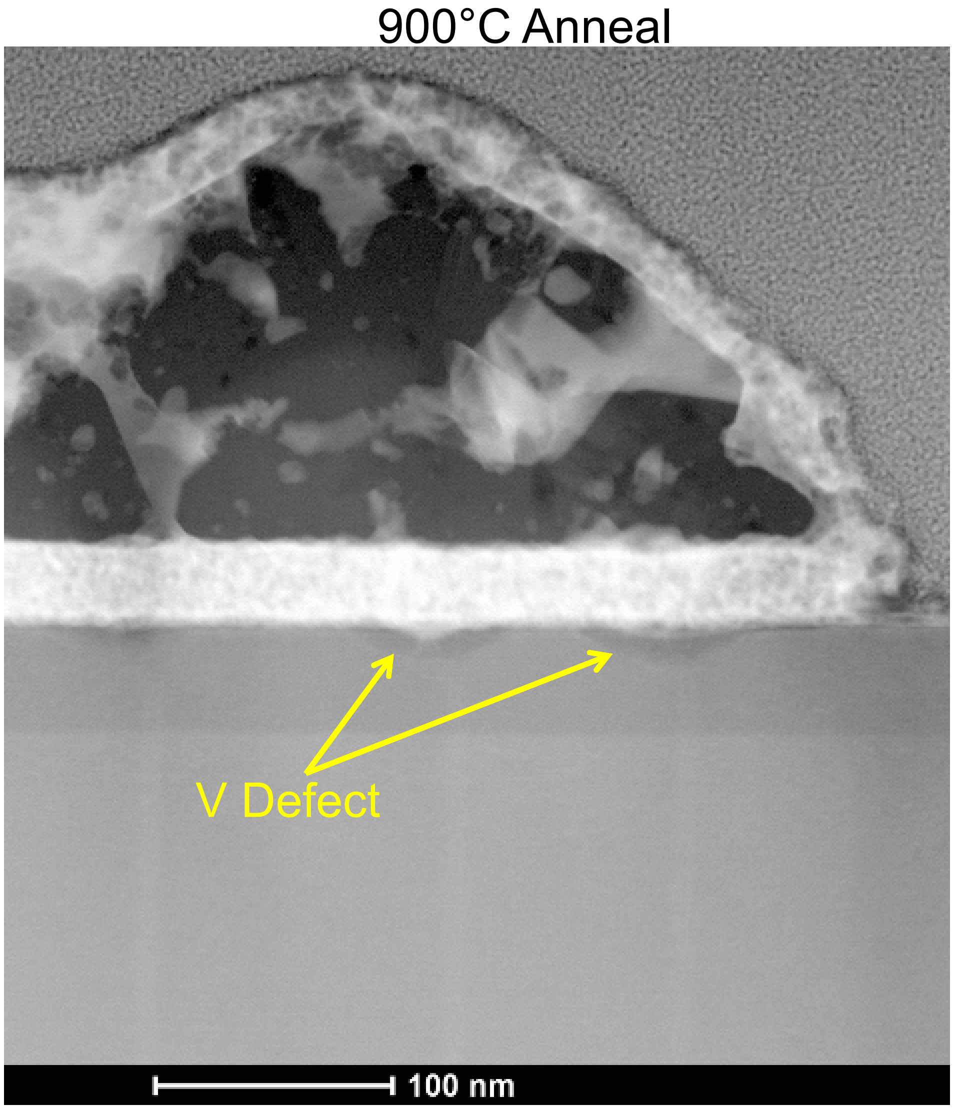
900°C Anneal



HAADF STEM, Z-Contrast

TEM: Ti/Al/Ni/Au



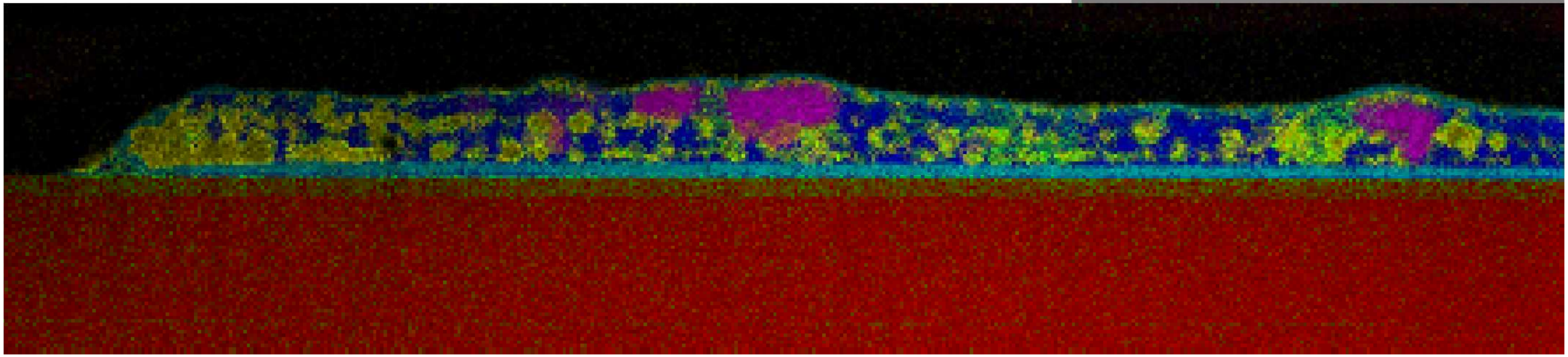


HAADF STEM, Z-Contrast

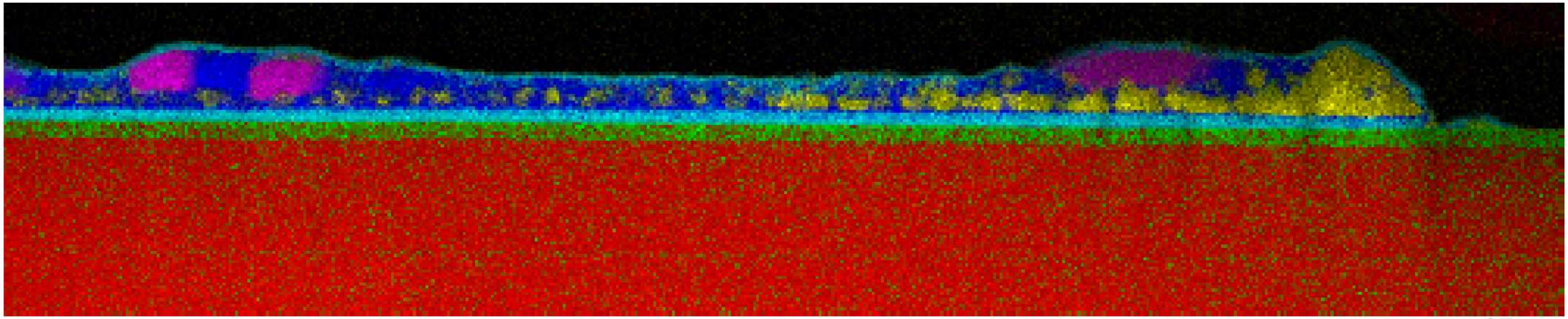
EDS Overlay

Red = Al-Ga-N (low Al)
Green = Al-Ga-N (high Al)
Cyan = Ti-Au-Al
Blue = Au (Ti)
Magenta = Ni-Al
Yellow = Al-O

850°C Ti/Al/Ni/Au Anneal



900°C Ti/Al/Ni/Au Anneal

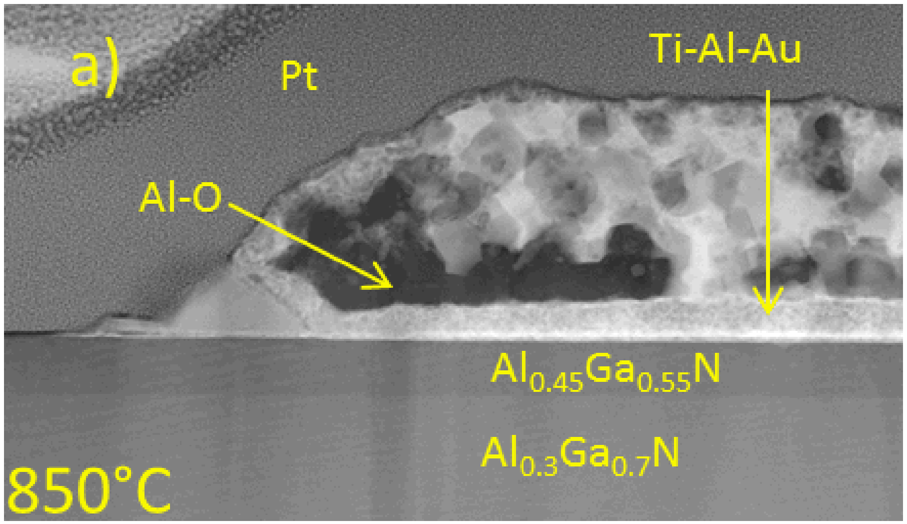


HAADF STEM, Z-Contrast

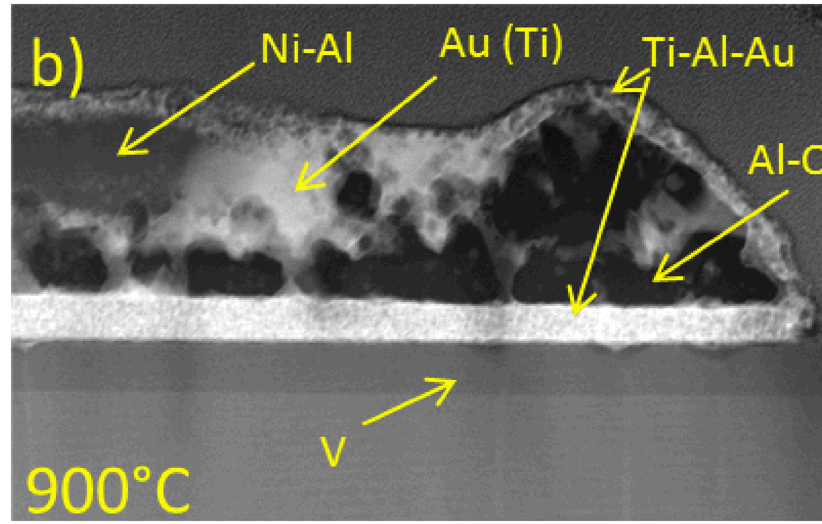
TEM RTA Temperature Comparison

Ti/Al/Ni/Au

Schottky Contacts



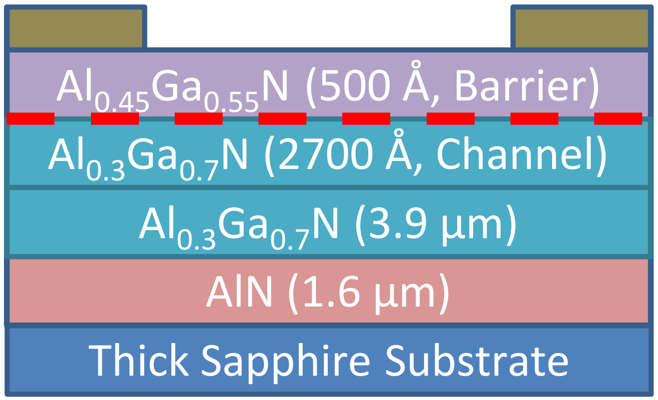
Ohmic Contacts

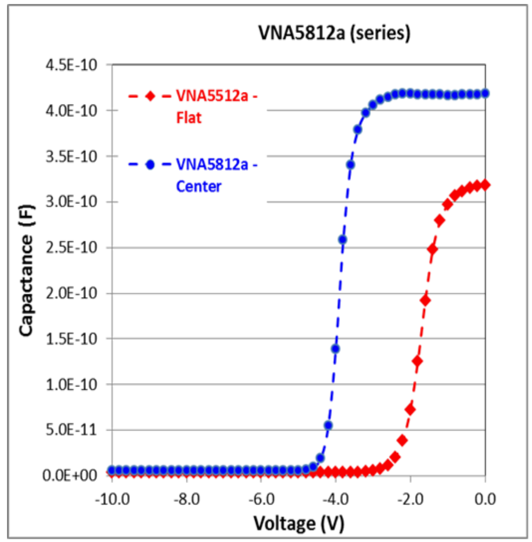


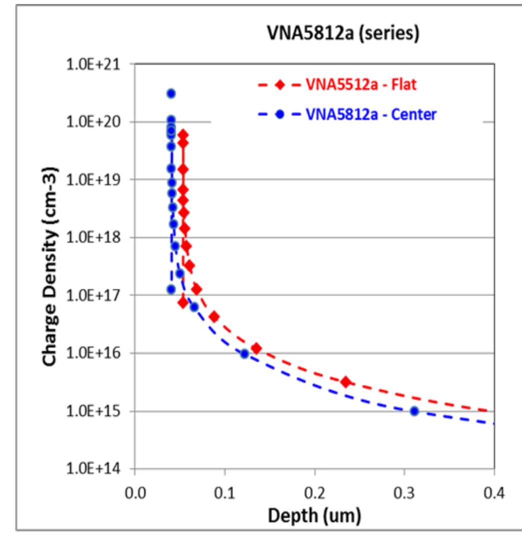
- AlGaN-Metal interface has Ti-Al-Au
- No obvious spiking in area viewed; smooth interface
- V-defects observed on 900°C might be promoting Ohmic contacts
- Grains of Al-O and Ni-Al
- “Au diffusion barrier” metal (Ni) is not a barrier for 850°C or 900°C anneal

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

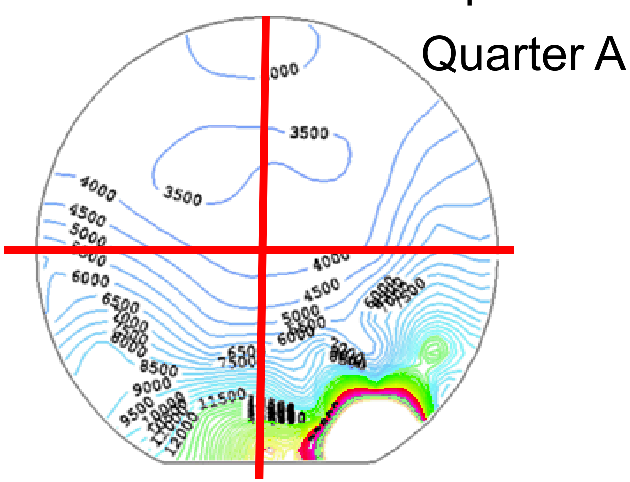
HEMT Device



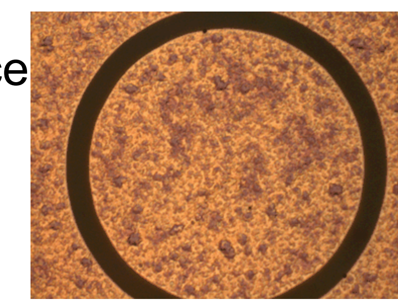




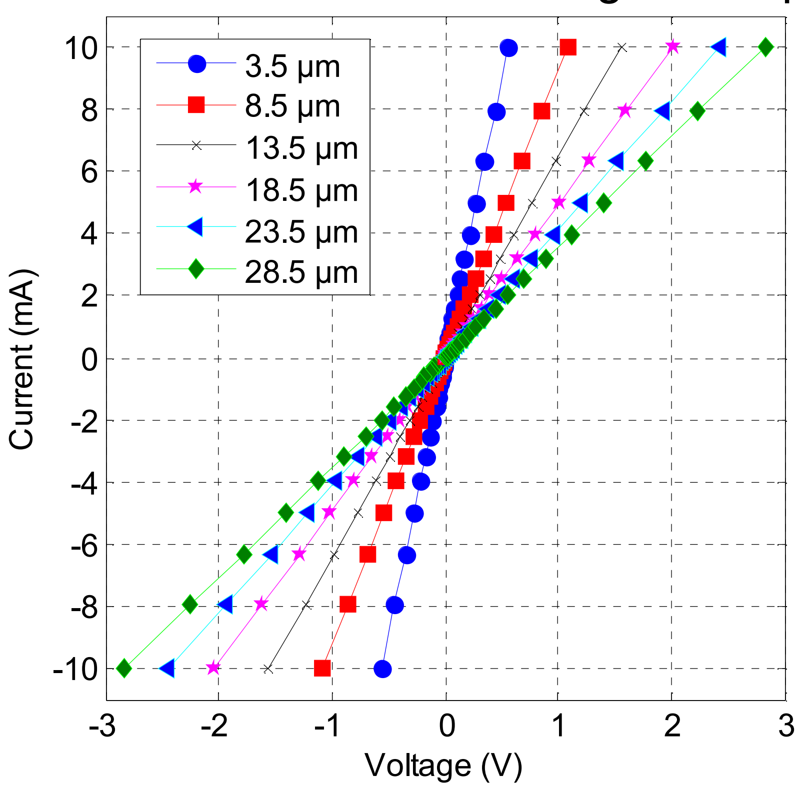
Sheet resistance map

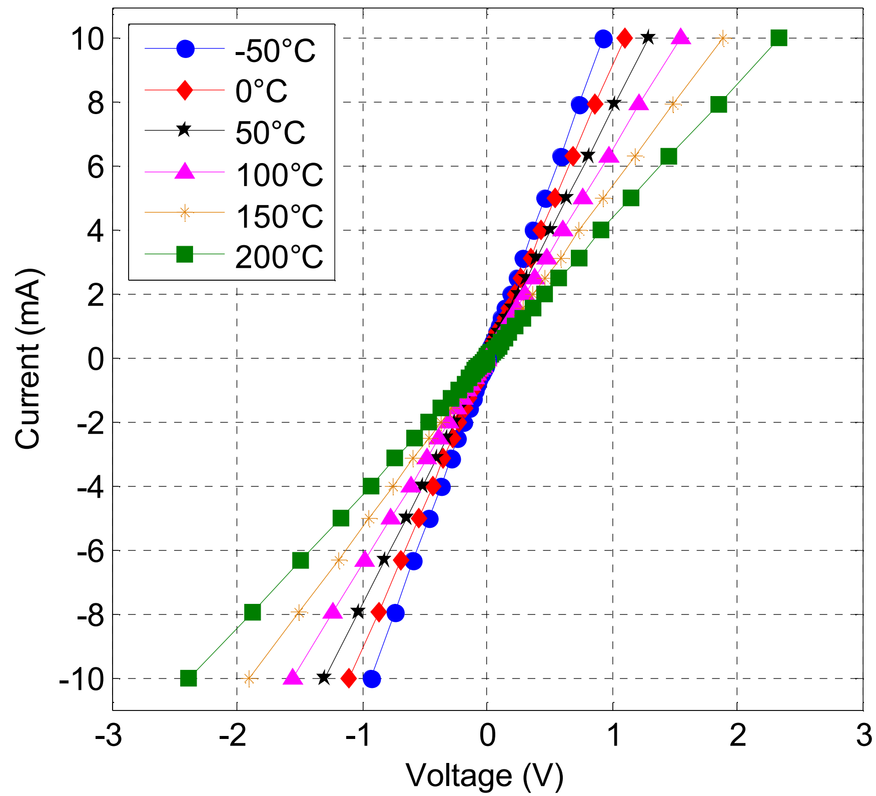


- HEMTs fabricated on a quarter of a 2” wafer with uniform sheet resistance
- Ti/Al/Ni/Au annealed at 900 and 950°C, 30 s, nitrogen ambient
- Post-anneal metal surface morphology was rough



CTLM Results for Device Wafer



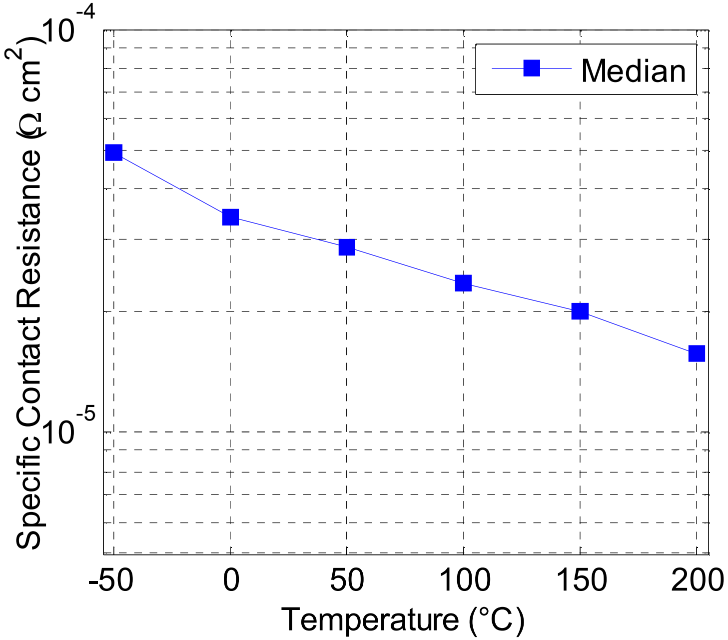


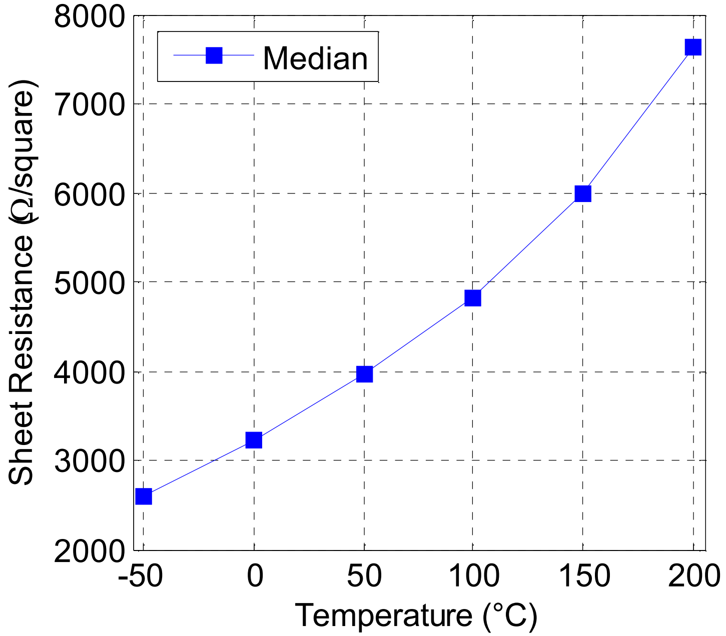
- Linear current voltage sweeps at 0°C
- Current compliance set to 10 mA

- Current-Voltage sweeps performed at multiple temperatures
- 8.5 µm CTLM pad spacing

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

Temperature Dependence of Contacts



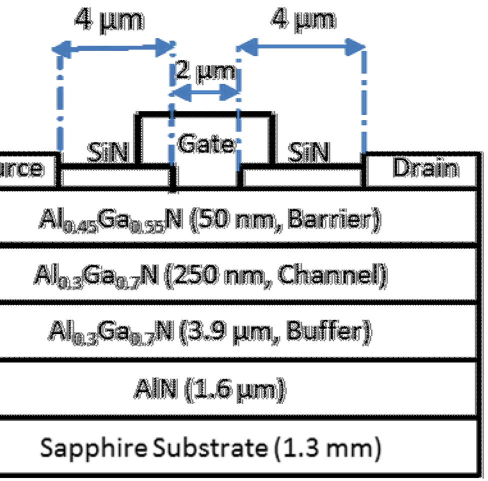


With increasing temperature from -50 to 200°C:

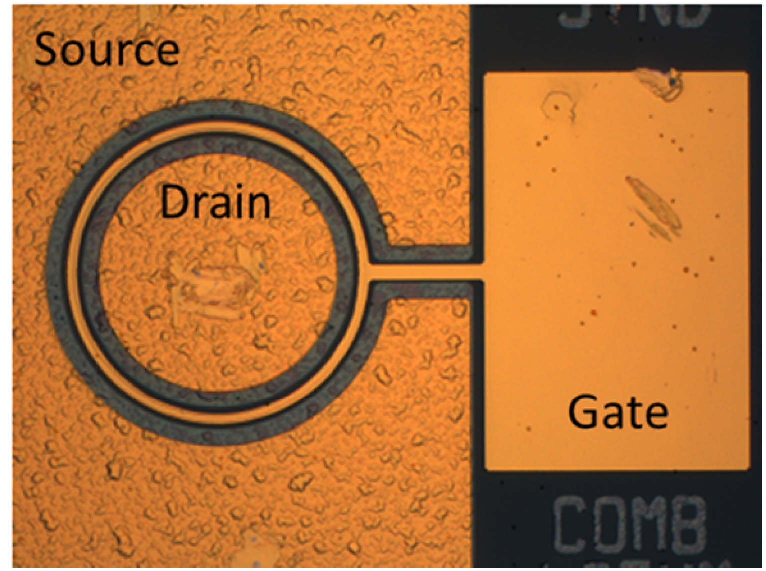
- Specific contact resistance improves (3x improvement)
  - →Conduction mechanism attributed to thermionic emission
- Sheet resistance degrades

HEMT Device

a)



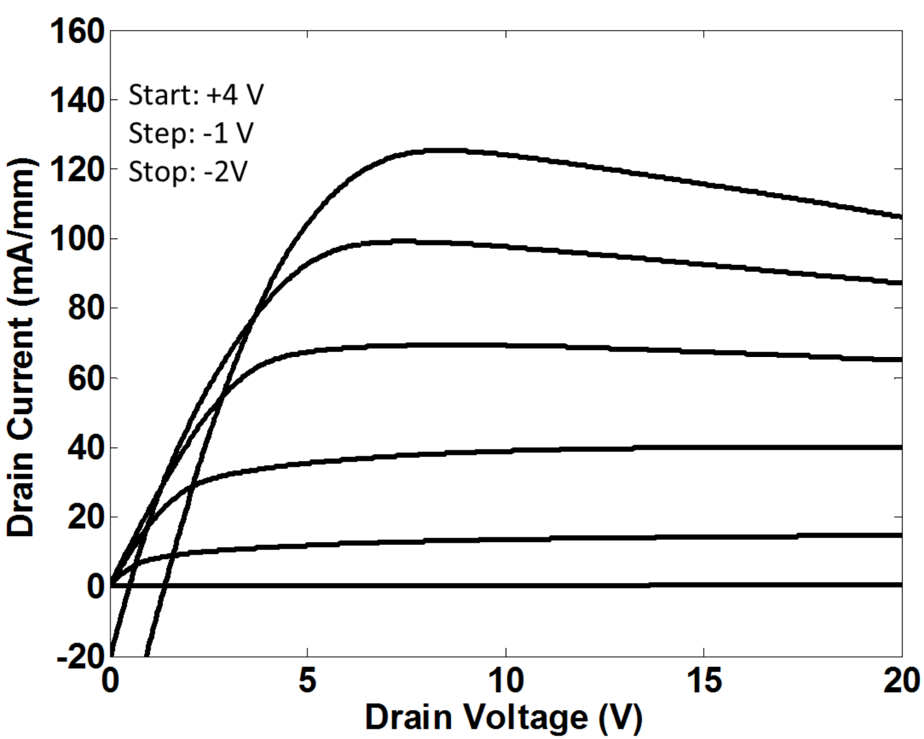
b)

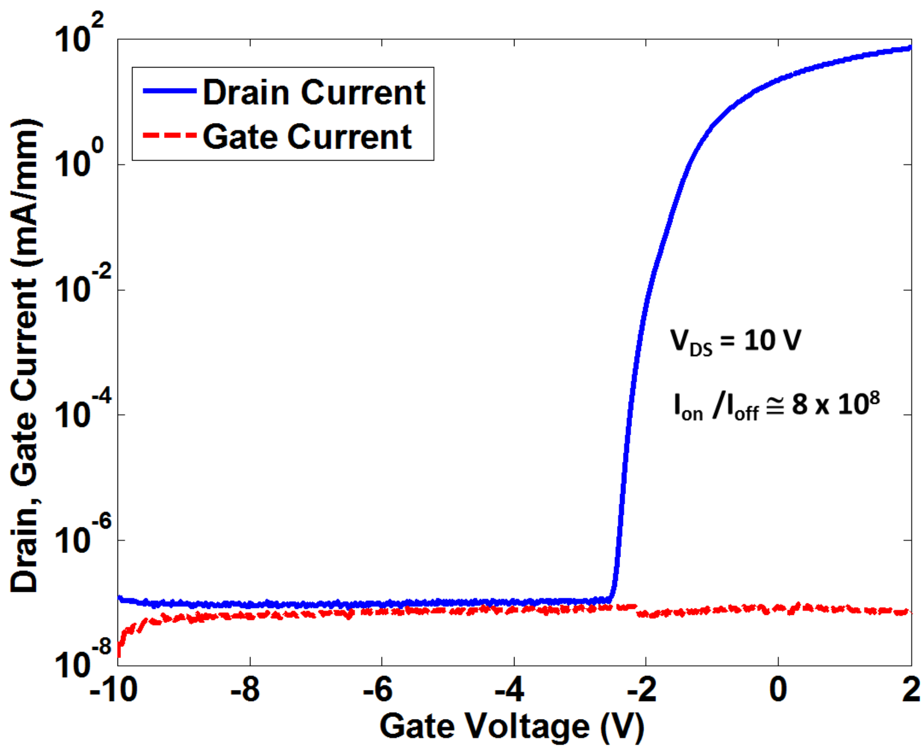


- Room temperature averages:
  ρ_c = 2.5 x 10^{-5} Ω cm^2
  R_{SH} = 3.9 kΩ / □

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

HEMT Device Results

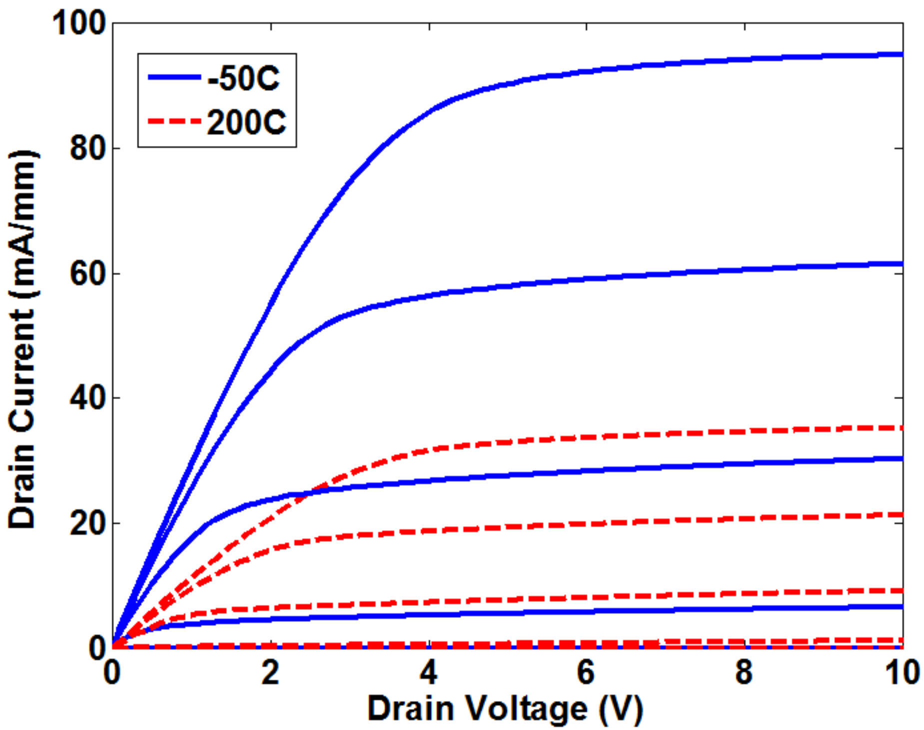


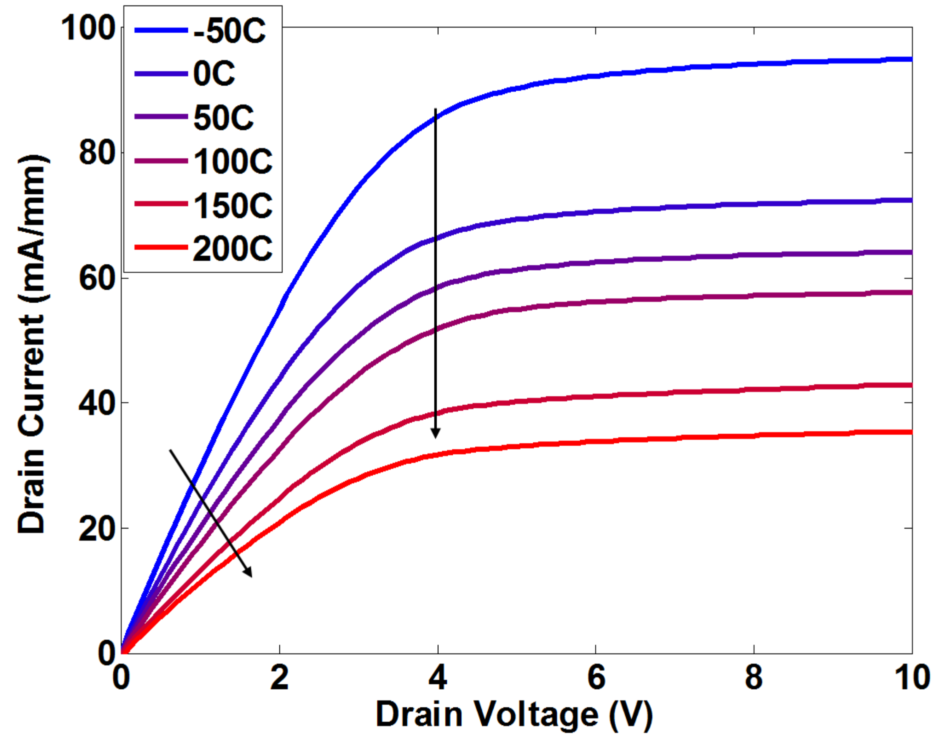


- Drain current = 125 mA/mm (4Vgate), 70 mA/mm (2Vgate)
- $I_{ON}/I_{OFF} \approx 8 \times 10^8$

Baca, A. G., (2017). ECS Journal of Solid State Science and Technology **6**(11): S3010-S3013.

HEMT Device Results

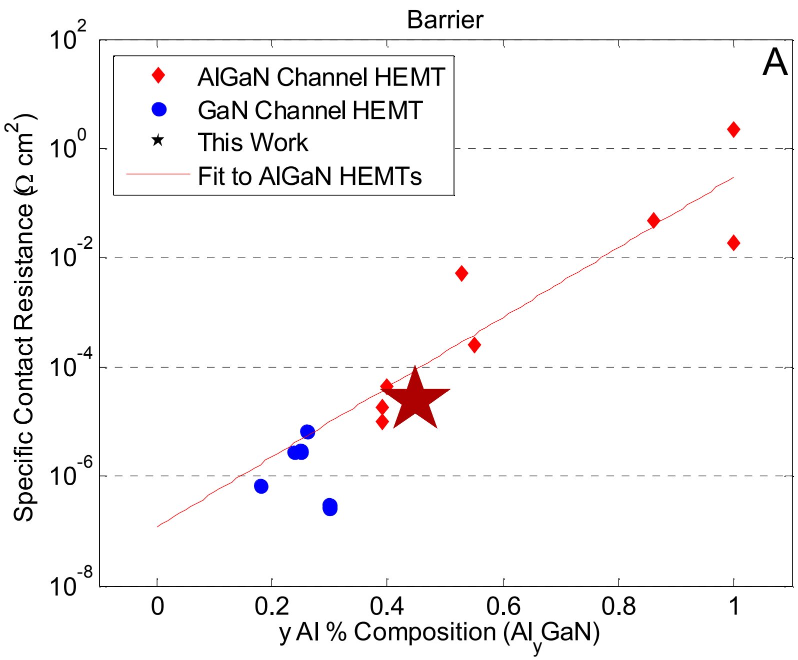


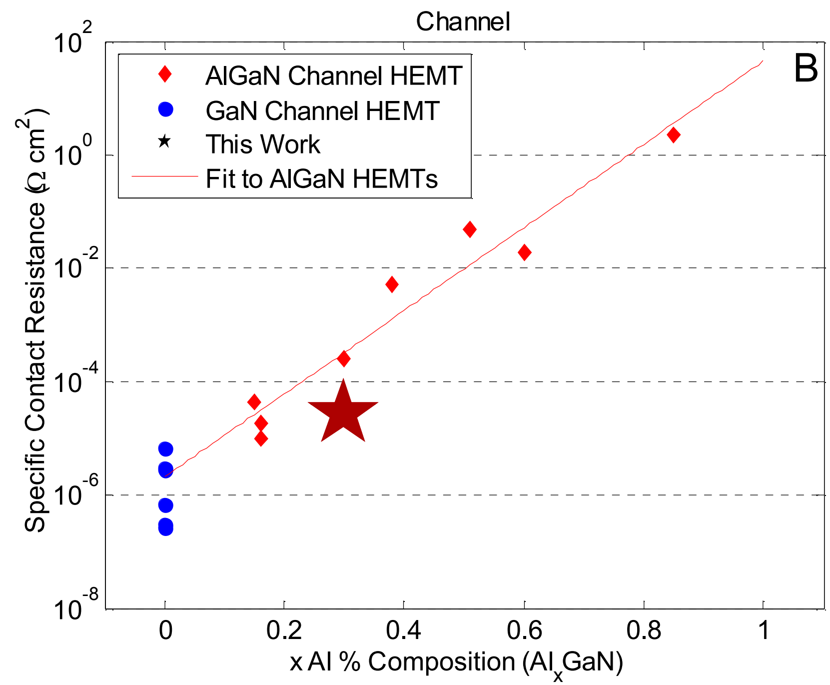


- Drain current drops (by a factor of 2.7) with increasing temperature
- High-temperature operation limited by transport properties

Baca, A. G., (2017). ECS Journal of Solid State Science and Technology **6**(11): S3010-S3013.

HEMT Contact Resistance Overview





Specific Contact Resistance $2.5 \times 10^{-5}\ \Omega\ \mathrm{cm}^2$

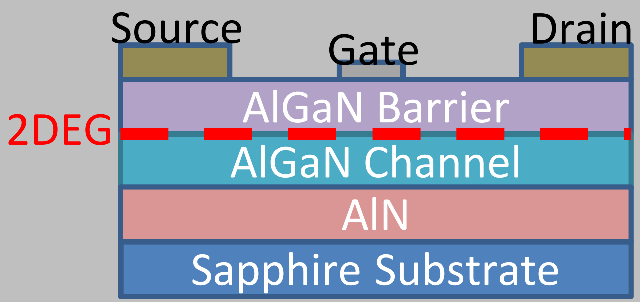
Conclusions

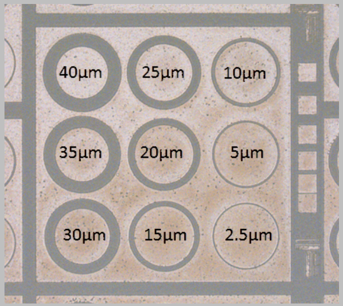
- Evaluated five planar Ohmic contact metals for $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ HEMT
    - Ti/Al/Ni/Au selected

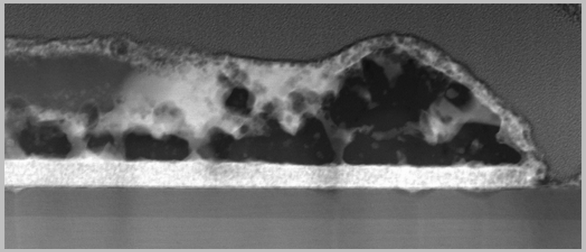
- TEM analysis of Ti/Al/Ni/Au for 850 and 900°C anneal temperature
    - Smooth Ti-Al-Au/AlGaN interface with a few v-defects
    - No indication of metal spiking

- The Ti/Al/Ni/Au Ohmic contacts were used in final HEMT devices:
    - Current densities up to 70 mA/mm at V_{GATE} = 2 V,
      125mA/mm at V_{GATE} = 4 V
    - Specific contact resistance = 2.5 x 10^{-5} Ω cm²
    - Sheet resistance = 3.9 kΩ / □

- Temperature dependence of contacts
    - Thermionic emission
    - Improvement in specific contact resistance with increasing temperature
    - Degradation in sheet resistance with increasing temperature







Low-resistance Ohmic contacts to $Al_{0.45}Ga_{0.55}N/\ Al_{0.3}Ga_{0.7}N$ HEMTs

B. Klein, A.G. Baca, A.M. Armstrong, A.A. Allerman, E.A. Douglas,
C.A. Sanchez, P. Kotula, M. Miller, S. Reza

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Map of HEMT maximum current (mA) at Vg = 2 V

Red = good , Green = bad

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	10.485	4.4503	19.748	19.211																				
2	7.7338	4.5165	20.658	20.069																				
3	9.1821	6.3642	21.213	20.784																				
4	6.8283	10.115	22.666	22.338	21.315	20.98	20.943	20.916																
5	5.3267	8.6025	21.736	23.262	21.638	21.409	20.954	21.297																
6	11.889	9.8501	23.218	22.623	21.614	21.648	20.885	21.263																
7	10.393	8.8898	23.55	23.381	22.052	21.387	21.472	21.667	21.356	21.946	22.076	22.023												
8	6.8452	7.3875	23.97	23.274	21.916	21.895	21.201	21.494	21.242	21.045	21.901	22.19												
9	9.2829	8.8707	23.561	22.935	22.37	22.116	21.493	21.373	21.254	20.999	21.837	21.974												
10	12.835	6.1437	24.698	24.224	22.774	21.986	21.979	21.747	21.488	21.971	21.48	21.587	22.642	21.933	22.774	22.113								
11	9.6967	5.6818	24.623	23.961	22.353	22.672	22.161	21.754	22.176	21.877	21.886	21.892	22.733	22.348	22.762	22.752								
12	13.091	6.6745	24.978	24.621	22.888	22.203	21.907	21.994	22.327	21.872	21.8	22.091	22.125	22.31	22.344	22.129								
13	9.6237	5.9302	24.903	24.449	24.085	23.002	22.65	22.524	22.785	22.122	22.236	22.17	22.521	22.192	21.935	21.826								
14	8.2829	5.9321	25.043	24.9	23.339	22.877	22.548	22.611	22.773	22.297	22.213	21.867	22.177	21.93	21.775	21.62								
15	9.8578	6.4162	25.282	25.029	23.496	23.383	22.524	22.99	22.619	22.676	22.849	21.876	22.429	21.961	21.587	21.796								
16	3.8839	7.5488	25.794	25.2	23.626	23.753	23.433	23.224	23.173	22.852	22.648	22.597	22.284	22.128	21.724	21.503	20.823	20.987	19.695	18.825				
17	3.2956	6.3233	25.677	25.103	23.958	23.389	23.606	23.404	23.068	23.095	22.568	22.291	22.073	22.884	21.703	21.401	21.431	21.07	19.746	20.293				
18	3.4509	8.9311	23.399	25.148	24.253	23.606	23.08	23.104	23.072	22.551	22.144	22.47	23.128	22.541	21.731	21.707	20.9	20.423	20.176	19.867				
19	3.1463	10.63	26.269	25.894	24.41	24.187	23.514	23.046	23.489	23.254	23.341	23.362	21.997	21.985	20.07	21.72	20.017	19.606	19.115	18.223				
20	3.4359	9.5552	25.679	25.015	24.685	23.954	23.721	23.585	23.042	23.663	23.319	22.809	22.213	22.54	21.899	21.521	20.066	20.102	19.347	18.318				
21	3.9354	12.064	25.229	25.839	24.21	24.145	23.574	23.607	23.514	23.105	23.237	22.894	21.625	21.922	21.238	21.471	20.089	17.985	19.17	18.647				
22	4.1417	12.655	25.882	25.929	24.892	23.931	24.603	24.28	24.322	23.56	22.554	23.132	22.631	21.991	21.777	21.409	20.283	19.392	18.31	17.777	12.553	6.0317	1.4583	1.0427
23	3.1466	10.937	26.004	26.021	24.398	24.654	24.786	24.374	23.814	23.239	22.823	22.813	22.13	21.237	21.4	21.461	20.769	19.387	18.642	18.065	12.899	6.0303	1.5933	1.0935
24	3.4788	10.1	25.925	25.564	24.345	24.541	24.537	24.026	23.903	23.234	23.399	23.283	21.972	22.382	21.484	20.961	20.129	19.988	18.559	18.286	12.682	5.8588	1.7611	1.1816
25	2.2044	17.172	25.963	25.195	24.775	25.019	24.129	23.817	23.216	23.22	23.114	23.257	21.953	22.201	21.576	21.328	19.556	18.818	17.585	99.999	5.9989	4.1525	2.6052	2.7487
26	2.3368	7.3721	25.935	25.315	25.03	25.006	24.084	24.272	24.191	24.201	23.321	22.525	22.402	22.475	21.512	21.789	19.888	19.396	18.31	19.511	5.4445	3.7351	2.9285	2.9012
27	2.7292	8.0068	25.791	25.635	24.448	23.656	24.191	24.008	23.83	23.384	23.626	22.775	21.652	22.315	21.961	20.111	20.085	18.683	18.196	99.999	4.643	3.5858	2.4762	3.0222
28	1.2288	4.0935	21.708	23.651	24.689	24.668	39.245	24.821	8.4472	23.459	23.406	23.131	22.27	22.503	21.507	20.26	18.431	16.225	5.4406	99.999	4.7589	4.4286	6.6282	8.0068
29	0.88227	3.3145	16.923	18.866	24.227	25.206	24.584	24.458	23.659	24.117	22.812	22.65	22	22.009	21.407	20.93	14.945	11.981	6.4924	99.999	3.9718	3.4674	4.3232	7.7959
30	1.1727	3.256	11.978	12.163	25.332	24.897	24.613	24.402	24.317	24.103	23.185	22.246	21.741	21.658	21.049	18.455	9.5433	7.98	4.2875	2.8895	2.7747	2.4314	3.9176	9.8126
31	10.987	7.3615	1.2672	1.7127	6.7439	2.7028	2.5573	2.5664	3.5511	4.1533	2.3731	1.8452	2.0527	1.6714	1.1612	1.0728	0.79958	0.78759	3.2675	7.9353	15.736	16.023	13.147	13.074
32	13.239	7.2229	1.2112	2.4886	1.5491	1.0729	1.3109	1.9871	1.9478	1.8995	1.4199	1.3962	0.98091	0.84412	1.3641	1.6288	0.81077	1.311	7.8801	15.243	15.481	15.86	13.214	13.509
33	0	11.307	3.4975	8.0648	1.1857	1.093	1.6234	4.1151	1.3617	1.3229	1.8314	2.9813	2.2435	0.85088	1.8706	4.4938	2.4967	3.5218	16.648	16.927	15.173	14.344	12.869	13.468

Lower currents on edge of wafer attributed to annealing