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GaN / AlGaN high electron mobility transistor characteristics after 10^{16} n_{eq} neutron irradiation

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1) NRC Canada 2) Carleton U. 3) STFC-RAL 4) U. Birmingham 5) Jozef Stephan Inst. 6) CNM

Global deployment of GaN technology is significant… and still accelerating

- Communications (cell phone chips, 5G base stations, LEO satellites, CATV, PtP radio, VSAT, power cubes & wireless chargers)
- Automotive (LiDAR for autonomous vehicles; power switch/converter for hybrids and EVs, ultra-high fidelity infotainment systems, power distribution)
- Aerospace (power amplifiers, radiation-hardened RF electronics)
- Military and defense (radar, electronic warfare EW, and military communications)
- Oil and gas, geothermal power generation

(a) (b) (c) (d) (e)

Fig 1. Main AlGaN/GaN HEMT applications are in: (a) Communications, (b) Automotive, (c) Aerospace, (d) Military/defense, (e) Oil and gas/geothermal.

Two GaN HEMT epitaxial structures: AlGaN barrier on GaN, and InAlN barrier on GaN

A high-mobility 2D-electron gas (2DEG) forms at the interface between GaN and AlGaN or InAlN

- polarization effects provide free electrons
  - ❑ no intentional dopant atoms → no ionized impurity scattering
- GaN is an ordered alloy, but $Al_xGa_{1-x}N$ is a random alloy
  - ❑ 1nm AlN "spacer" between GaN and AlGaN (not shown) provides shift of 2DEG centroid away from AlGaN
  - ❑ 2DEG intensity in AlGaN ~ 10% of peak → reduces alloy scattering

Net result for GaN/AlGaN 2DEG properties at RT:

mobility ~ 2000 cm^2/V-s → potential for high speed devices

density ~ $10^{13}/cm^2$ → potential for high current devices

"Engine" for high electron mobility transistors → 2DEG

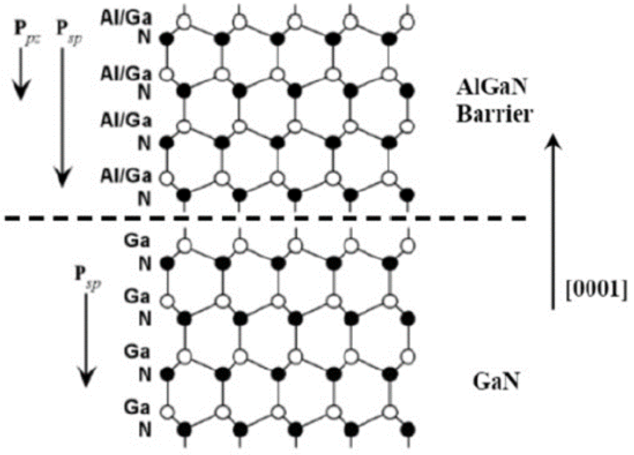


Figure 2. Spontaneous and piezoelectric polarization vectors in a metal-face wurtzite AlGaN/GaN heterostructure.

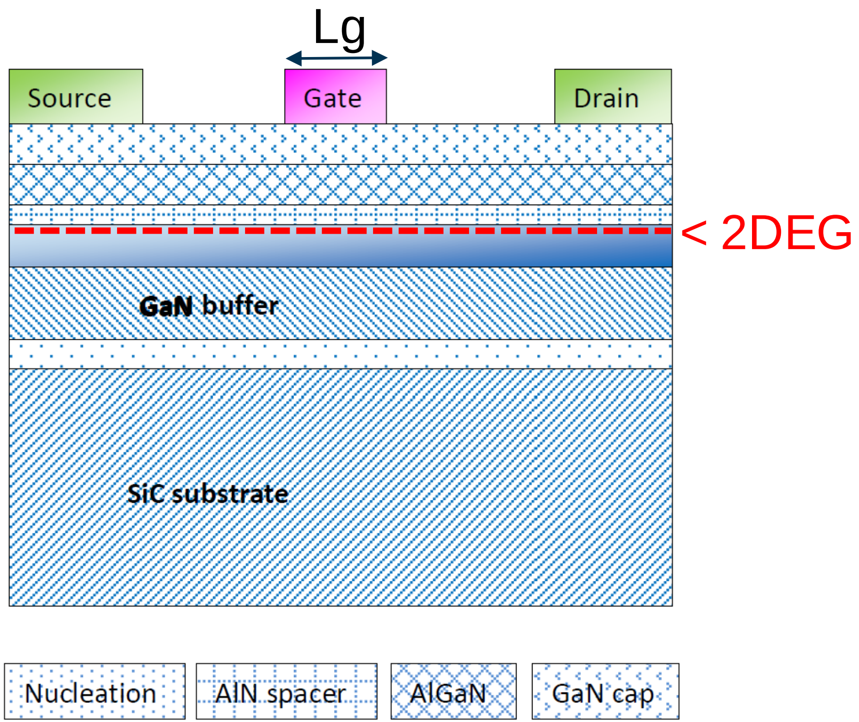
Depletion-mode (normally ON) HEMT cross-section

Drain bias positive relative to source (ground)

- Vds = +10V for all presented results

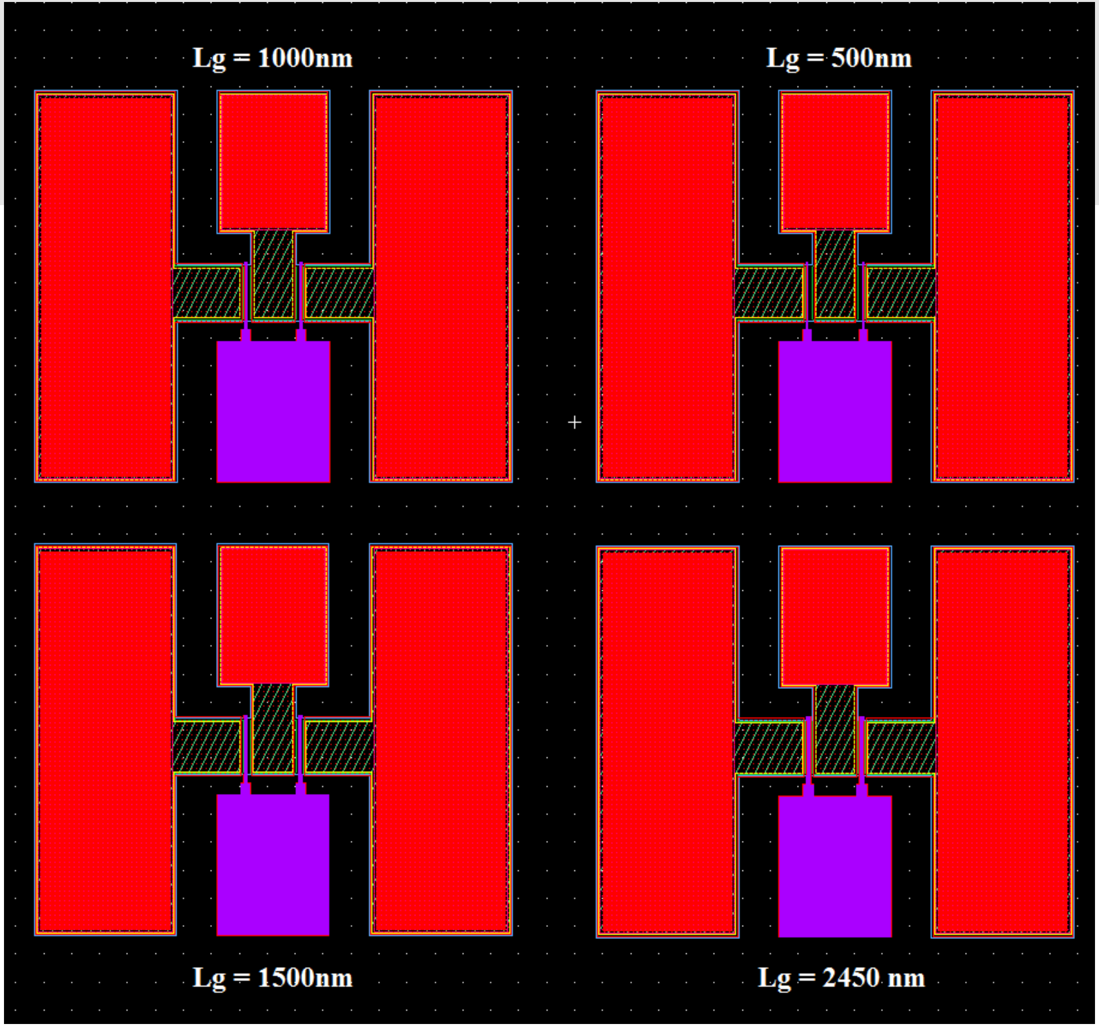
Gate bias controls electron flow from source to drain

- Vgs variable from -10V (OFF) to +2V (ON)
- 2DEG depletion under gate occurs at Vgs = -4V → drain current cut-off
- unipolar device



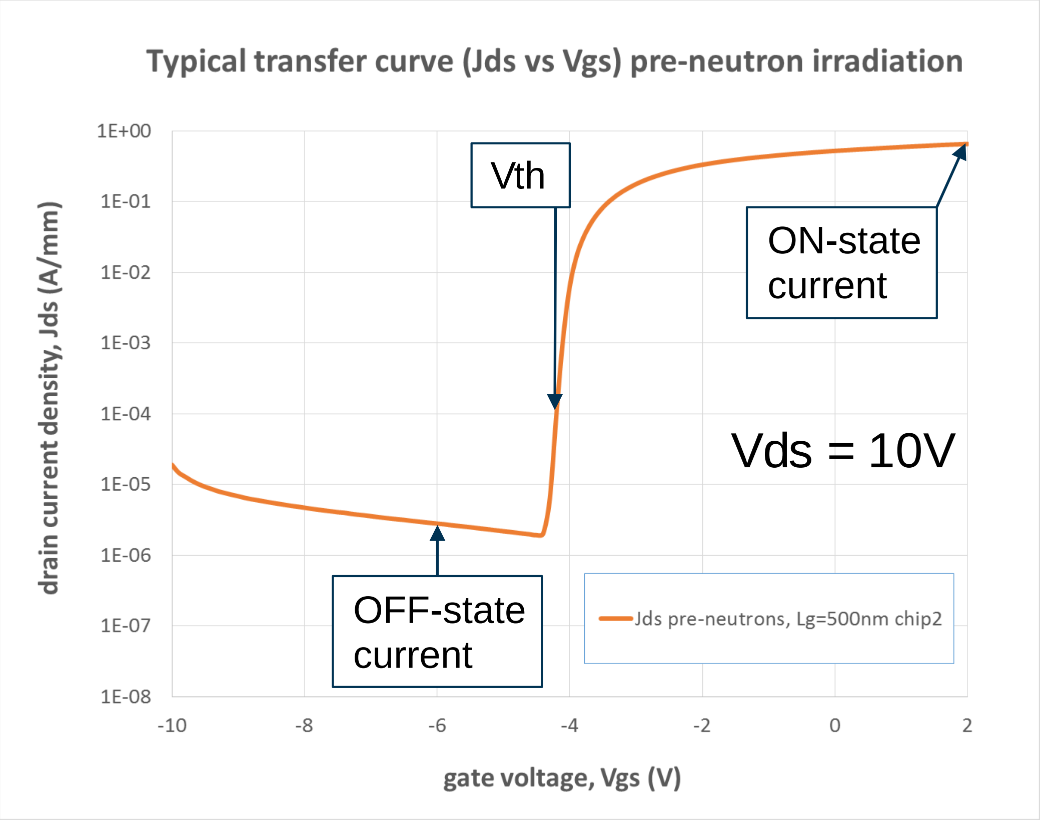
HEMT cross-section (not to scale)

Overall chip layout



Pre-neutron irradiation transfer curve

All HEMTs (30) had similar curves prior to irradiation; no correlations with Lg

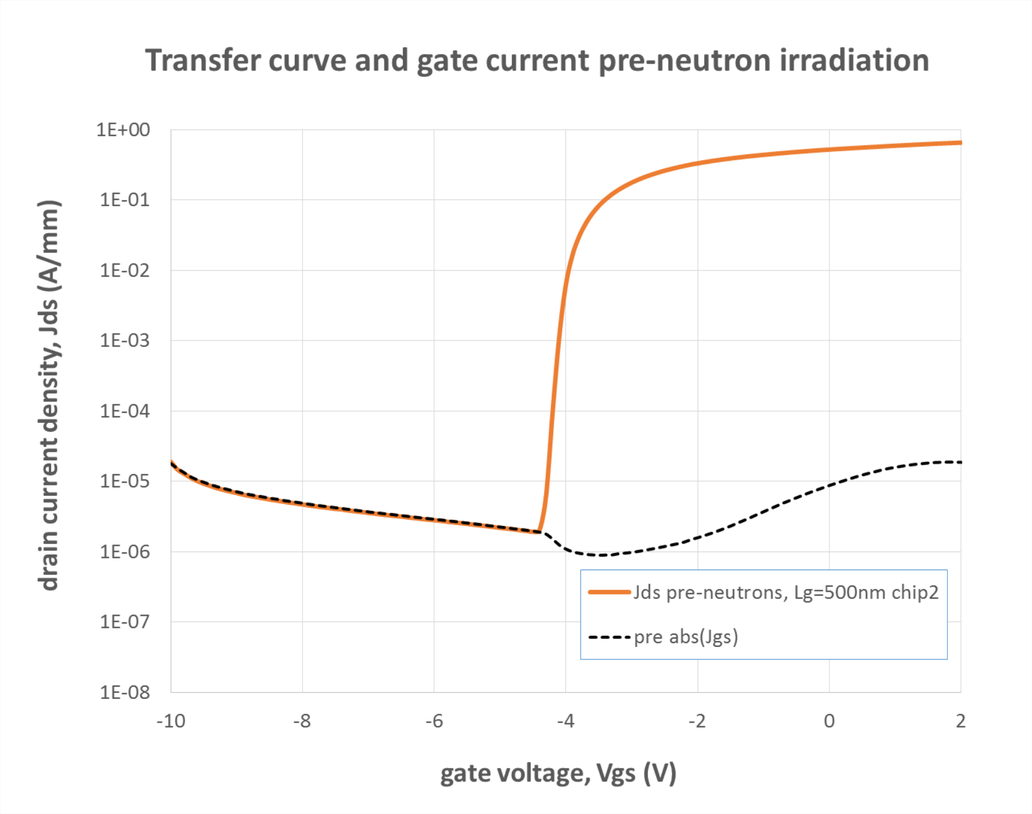


Pre-neutron irradiation transfer curve and current in gate circuit: reveals issues with epi growth or processing

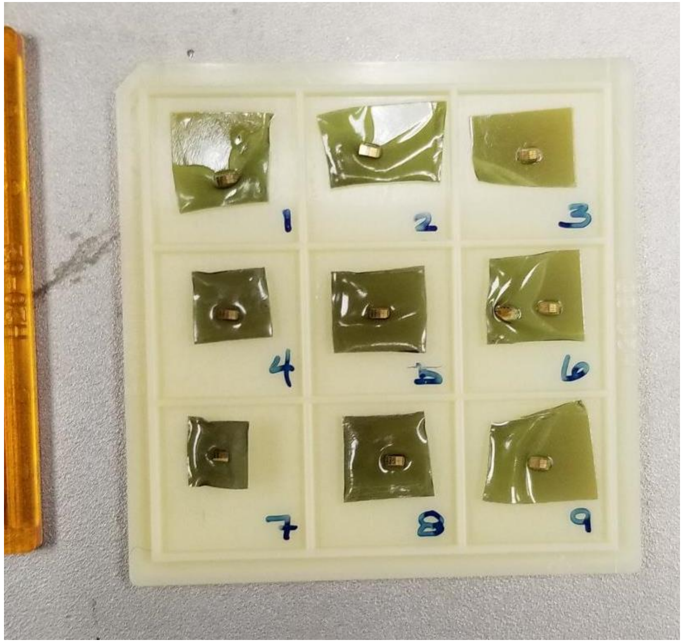
Below Vth, the gate circuit current in a good quality HEMT precisely tracks drain circuit current

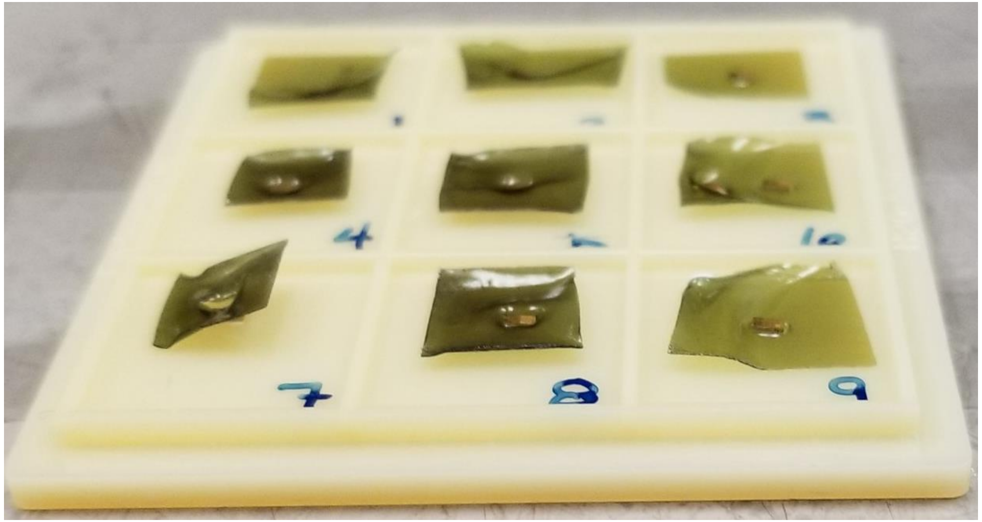
Drain current >> gate current indicates epi quality problem

Gate current >> drain current indicates gate process issue



Chips as-received after neutron irradiation at Jozef-Stephan Institute





Chips were mounted on clear double-sided tape in chip tray to facilitate shipping and exposure to beam. Dark, wrinkled tape with some “tilted” chips resulted.

Pre- and post-neutron irradiation transfer curves and gate currents

Effects of 10^{16} n_{eq} neutrons:

Drain leakage current reduced (i.e. improved)

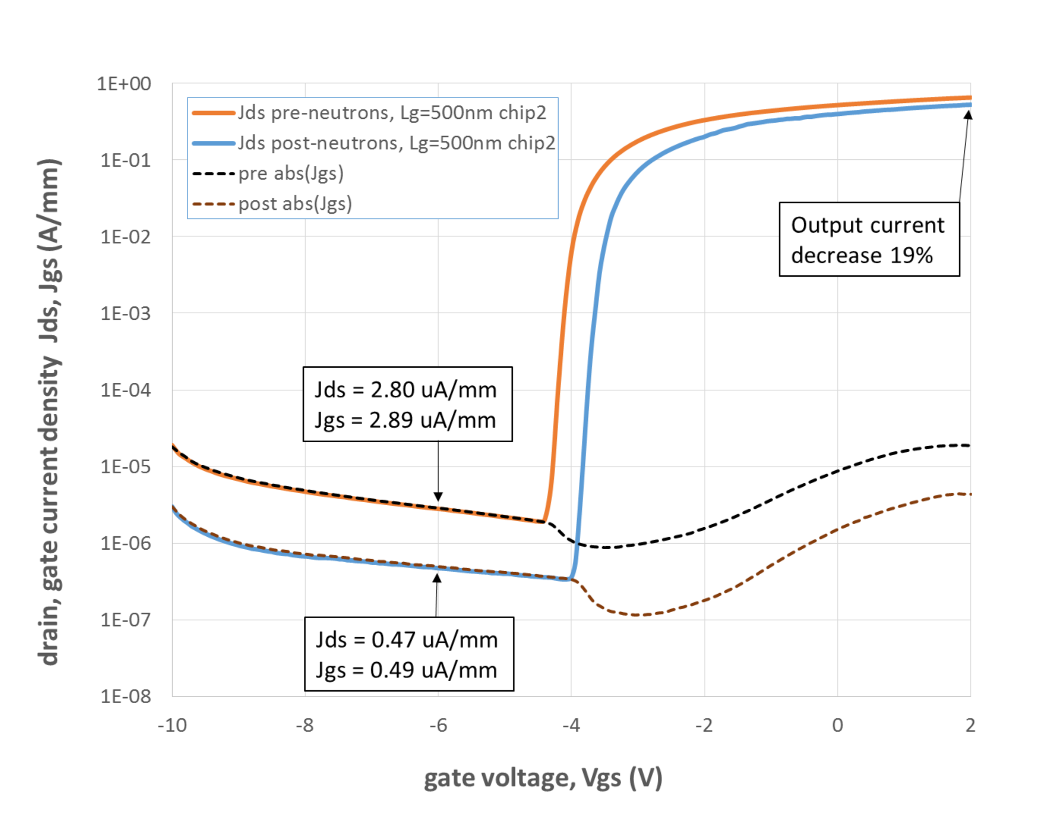
- corresponding differences b/w Jds and Jgs are consistent

Vth shifted + 0.4V

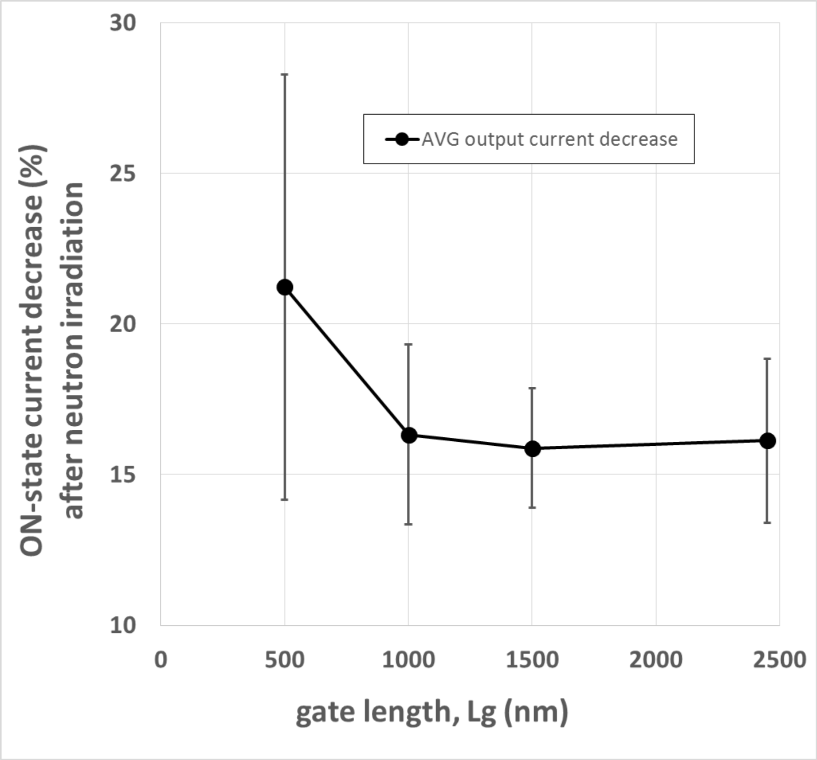
- acceptable within IC design limits

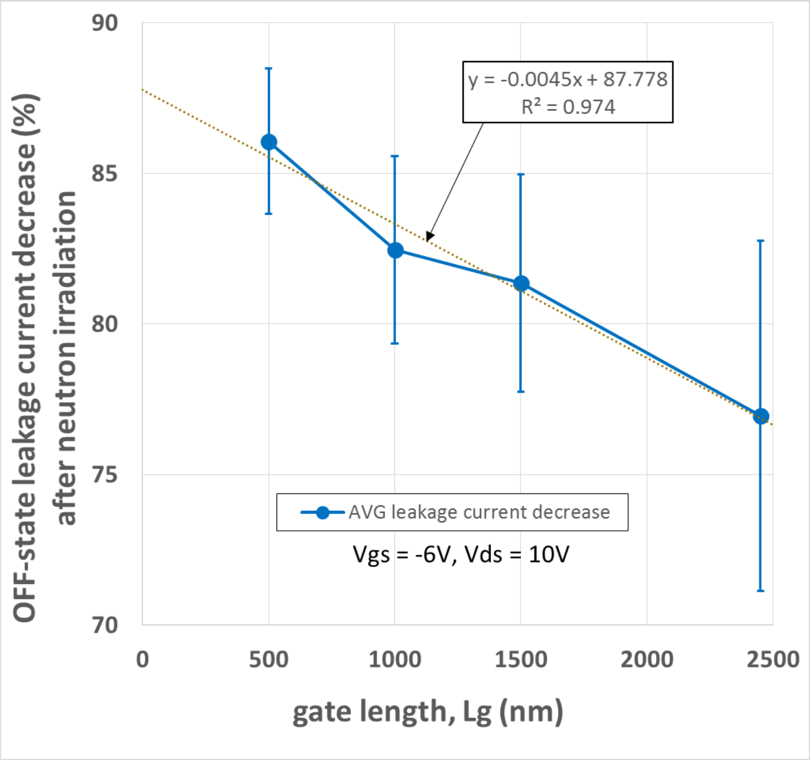
Output current decreased 19%

- lower than expected for standard HEMTs, i.e. no fab process improvements

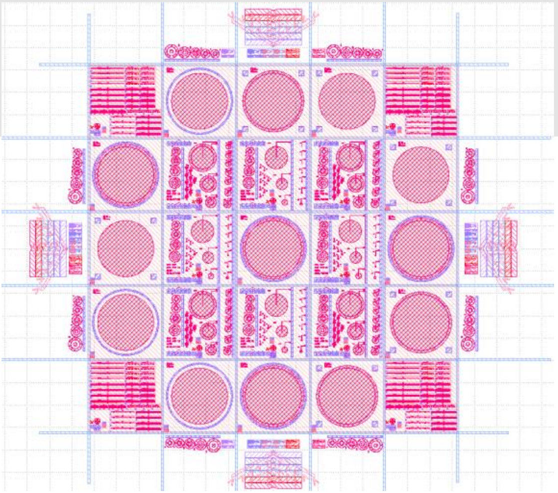


Summary Plots:
ON-state current, OFF-state current vs Lg





2” GaN on GaN Schottky work



PLAN

Specify and procure 4 wafers from Kyma (at $5k US each)

2 wafers each to go to CNM, NRC for Schottky processing

Mask layouts were shared, toward a common one

RESULTS so far: a “rough” start

CNM processed one wafer → poor Schottky diodes (more like resistors)

- determined that the epi surface was very rough

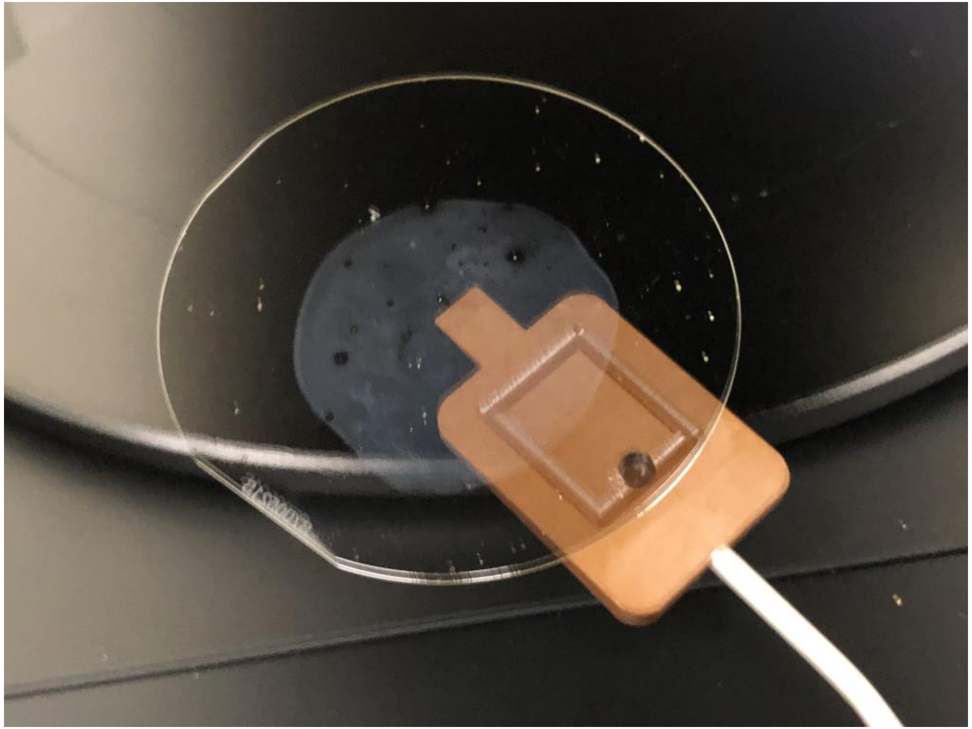
Wafer pucks as-received from Kyma were not yet opened at NRC

- fab tool issues caused major delays
- wafer inspection was done promptly upon CNM’s news
- disappointing results for inspection…

2” GaN on GaN work: incoming wafer inspection

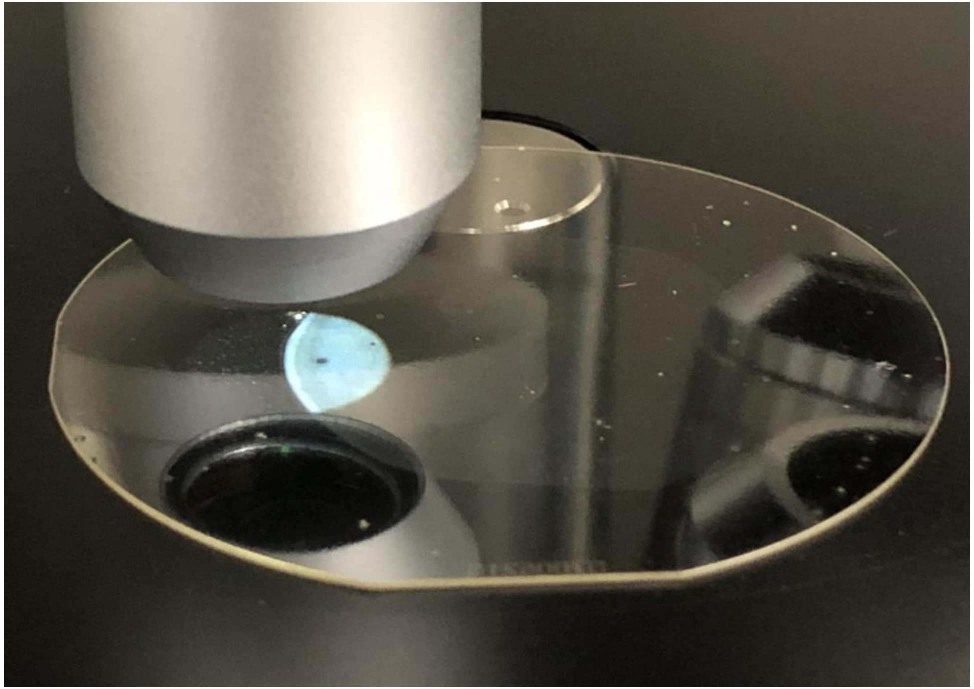
Macroscopic defects visible to the unaided eye upon 1st inspection

Large circular blemish on backside



2" GaN on GaN work: circular back side feature

Microscope illumination from the objective lens reveals strong light scattering in the circular backside blemish



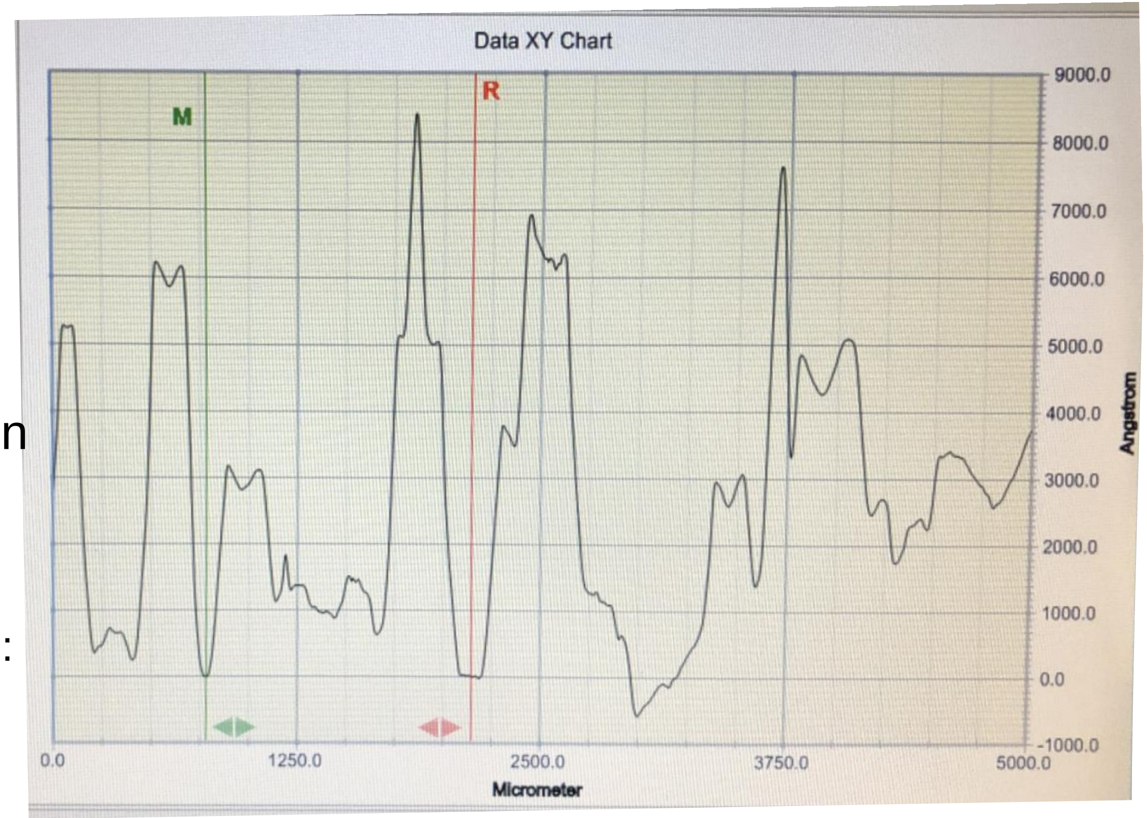
2” GaN on GaN work: profilometer scans

Clear peripheral area and centre area with strong light scattering gave similar results by profilometer:

- 5mm scan shows peak-valley roughness of ~ 0.8um

Kyma admitted hillock formation occurred during epi and

- “wafers should have been polished post-epi”
- polishing now done on 2 wafers: 3um of 10um epi removed

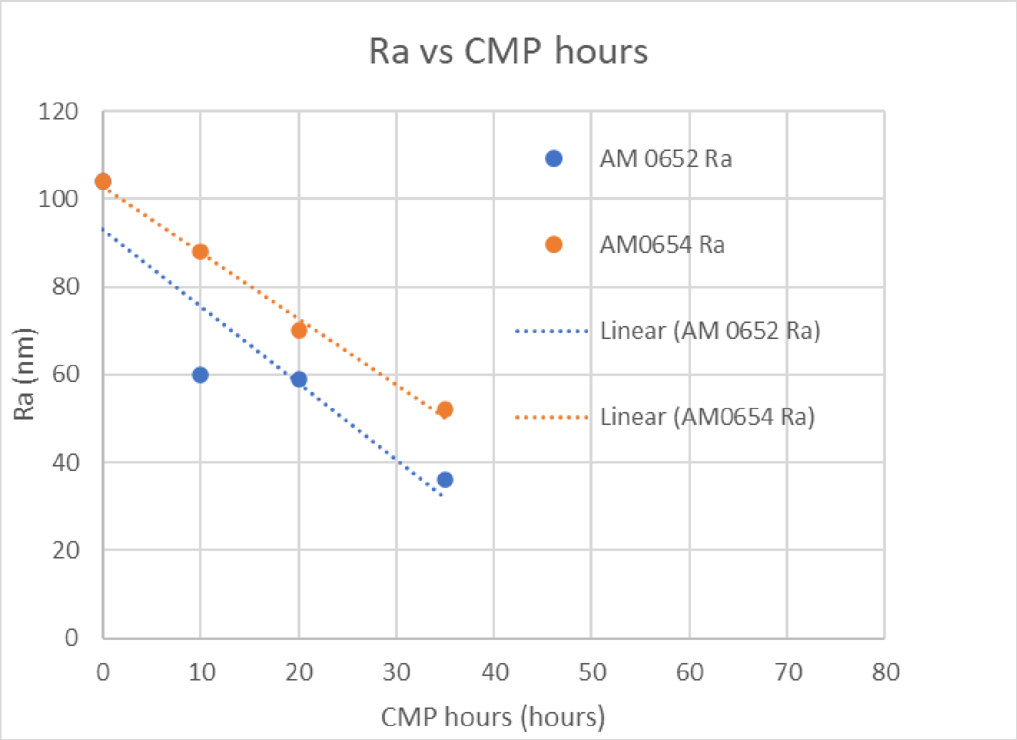


2” GaN on GaN work: roughness after polishing

Roughness after 35 hours of chemical-mechanical polishing down to ~ 40nm – 50nm.

- better than 800nm RMS as-grown value, but nowhere near their own spec of 2nm RMS!

GaN HEMT epi on SiC from all three well-established vendors to NRC is routinely < 2nm RMS surface roughness



Outlook and next steps

Perform RF measurements on neutron-irradiated HEMTs to compare with post fab final test data from 2017, if coplanar waveguide probes can be made to work on existing chips adhered to damaged/tilted tape

- Lg= 500nm pre-irradiation values were f_t = 18 GHz, f_{max} = 36 GHz

Start fab runs for Schottky diodes on two polished Kyma wafers

- one wafer for CNM fab, one for NRC fab
- send third wafer (currently at CNM) to Kyma for polishing, as a spare

Start fab run for GaN HEMTs (possibly ICs, e.g. TIA for hybridizing with Si LGADs), this time incorporating fab process modifications with demonstrated robustness during 500°C aging

- expect better radiation-hardness than measured in the present work: **aim for 10^{17} n_{eq} neutrons**

Longer term…monolithically-integrated GaN HEMT ICs and particle detectors

THANK YOU