Detection and modeling of electrical leakage current in AlGaN-based deep ultraviolet light-emitting diodes

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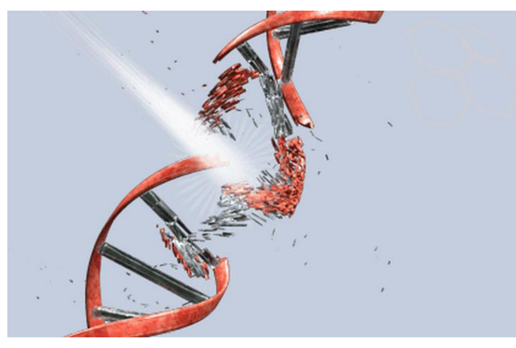
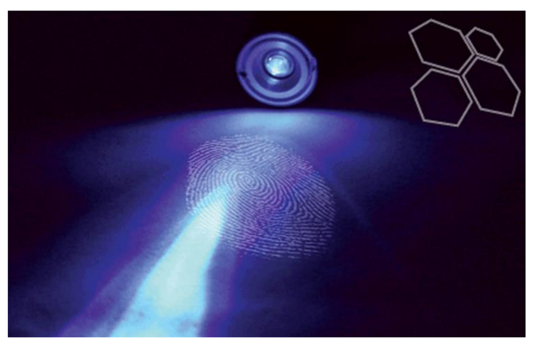
Deep UV applications

- Biological agent detection
- Air and water purification
- Optical data storage
- Photolithography





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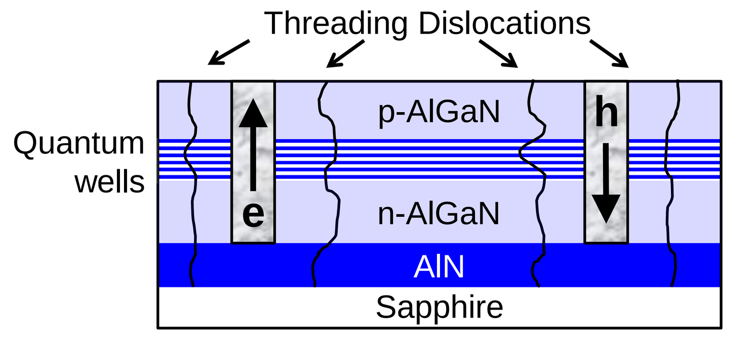
Background – Threading dislocations

- Generated through heteroepitaxy
- Act as non-radiative recombination centers
- Function as electrical current leakage paths

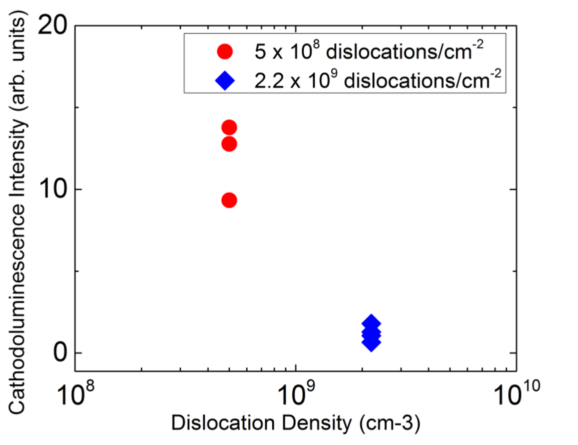


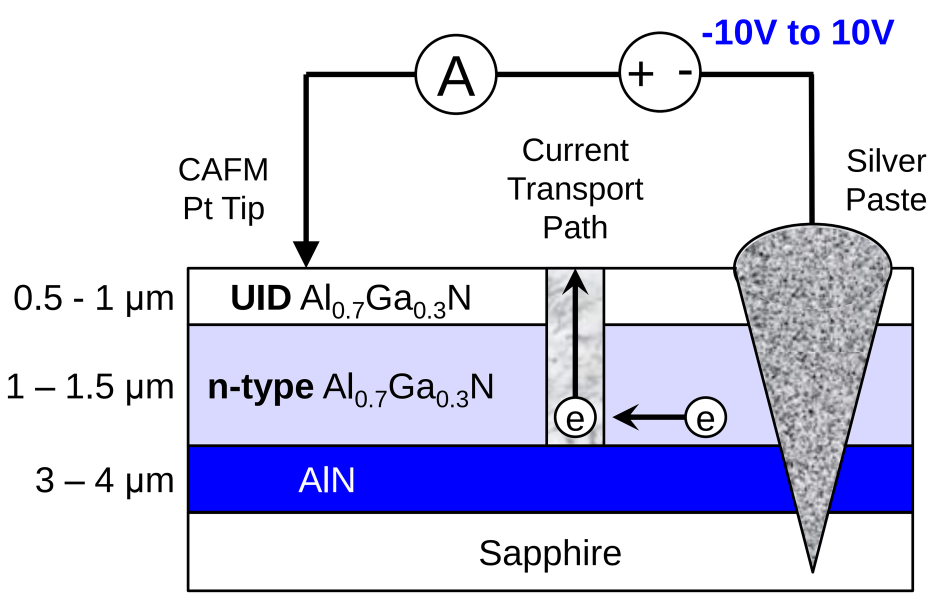
Typical MQW UV-LED Structure

Motivation – SNL UV-LEDs

- Photoluminescence, cathodoluminescence in SNL UV-LEDs tracks dislocation density
- Electroluminescence and SNL UV-LED optical output power independent of dislocation density
- Carrier injection efficiency reduced by electrical current leakage

SNL UV-LED CL vs Dislocation Density





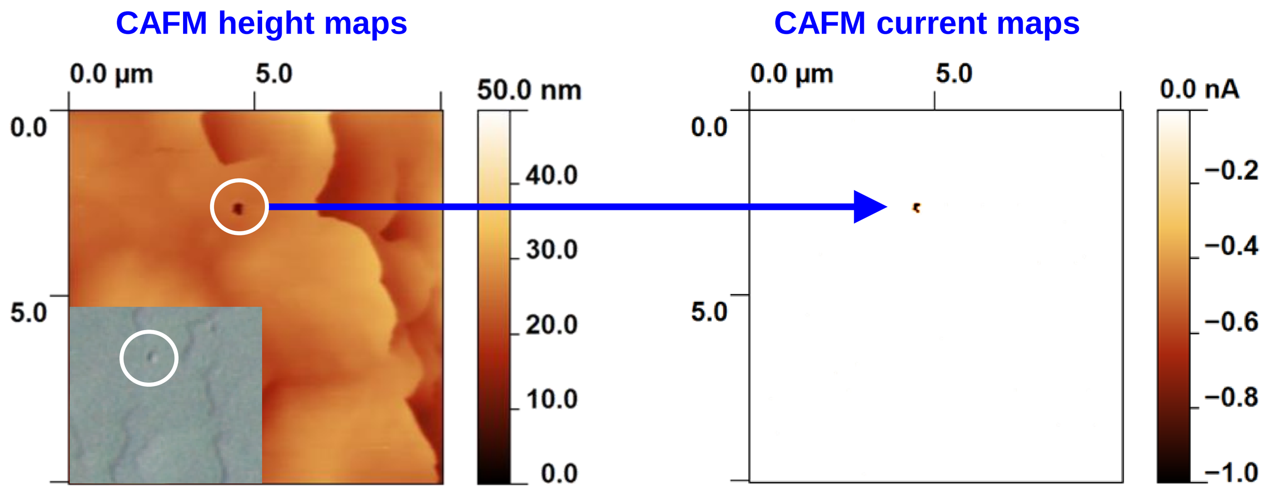
CAFM used to search for current flow through UID $Al_{0.7}Ga_{0.3}N$

Electrical Current Leakage and CAFM

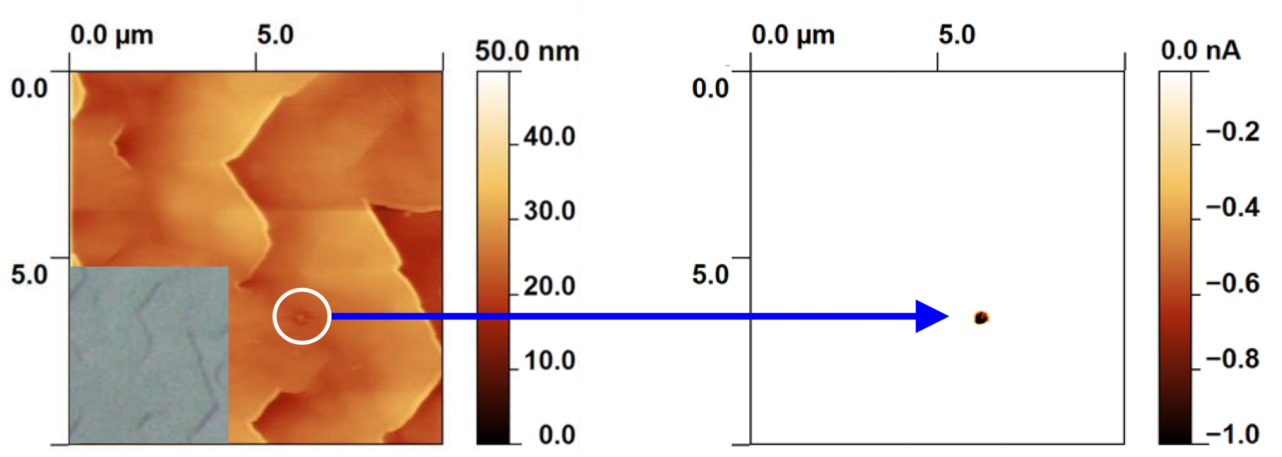
- Charge carriers could bypass QWs and cross junction without radiatively recombining
- **Conductive AFM** would reveal these leakage paths
- UID AlGaN layer confirmed to be insulating
- Any current detected is leakage through UID layer

Two locations of an as-grown 70% AlGaN template

10 µm x 10 µm CAFM height maps — 10 µm x 10 µm CAFM current maps



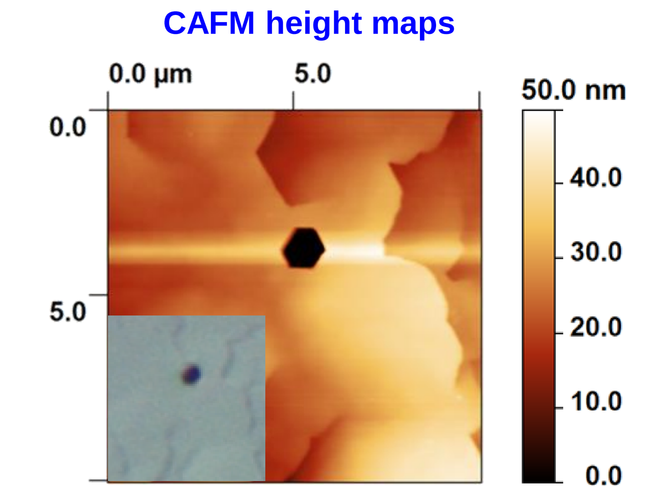
Current flow through UID $Al_{0.7}Ga_{0.3}N$ detected at a pit, which is also visible in an optical microscope.



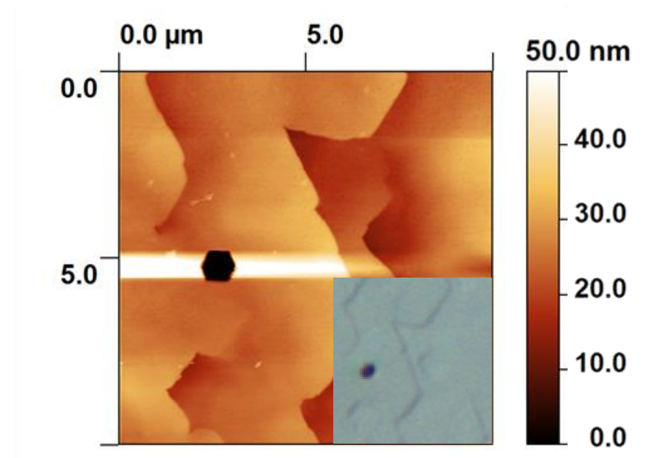
Current flow detected, but no feature observed in optical microscope

After defect-sensitive etching in 160 °C H_3PO_4

10 µm x 10 µm CAFM height maps



Hexagonal pits formed at sites of current transport

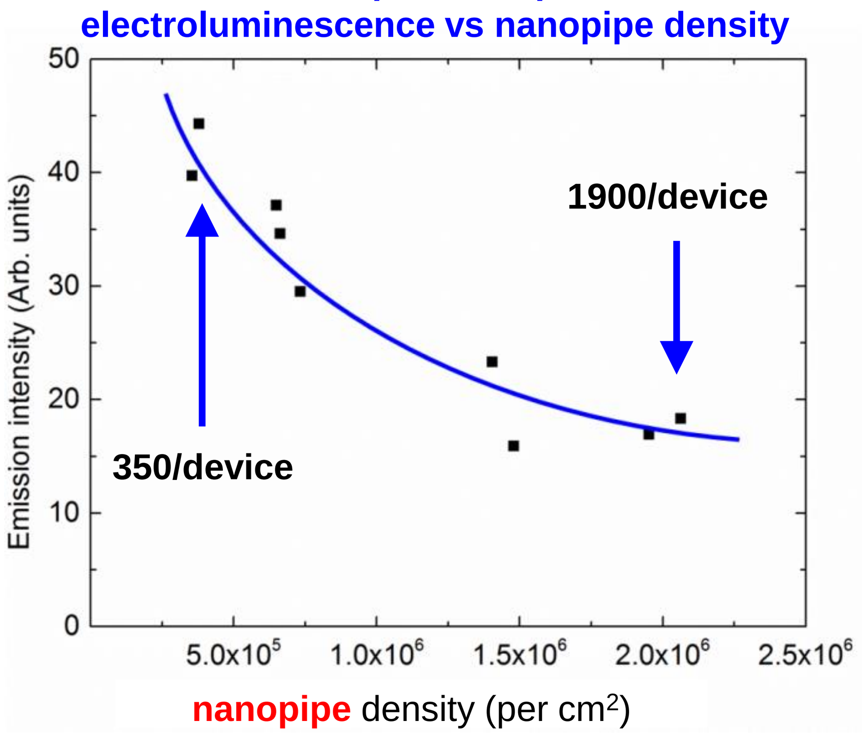


Hexagonal pits formed at sites of current transport

Open-core threading dislocations

- Also known as "nanopipes"
- Hollow tubes in (1010) facets
- Diameter range from 2 nm to 50 nm
- Oxygen along walls form conductive impurity band, enabling current leakage
- **Etched anisotropically along the inner walls by hot H3PO4, forming a hexagonal pit**

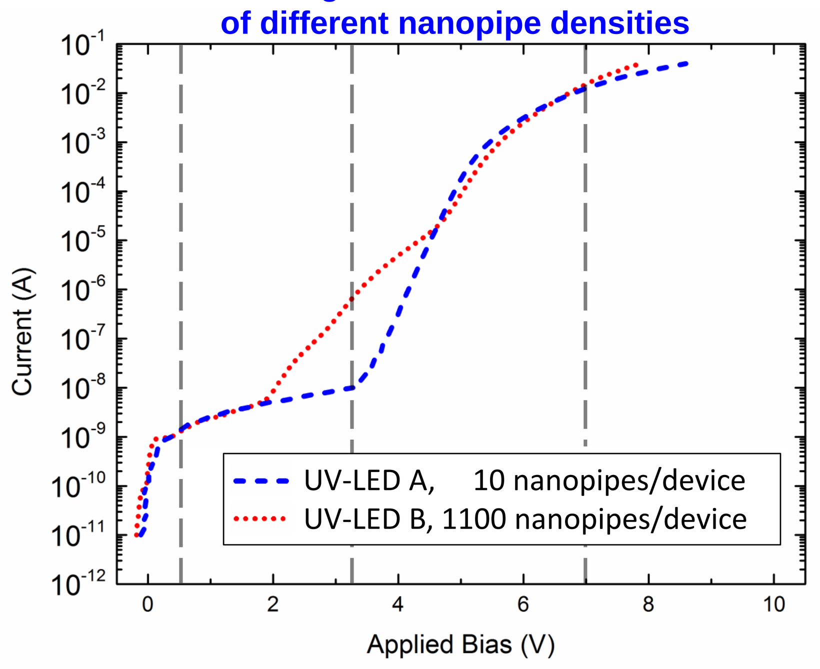
On-wafer 300 µm x 300 µm UV-LED electroluminescence vs nanopipe density



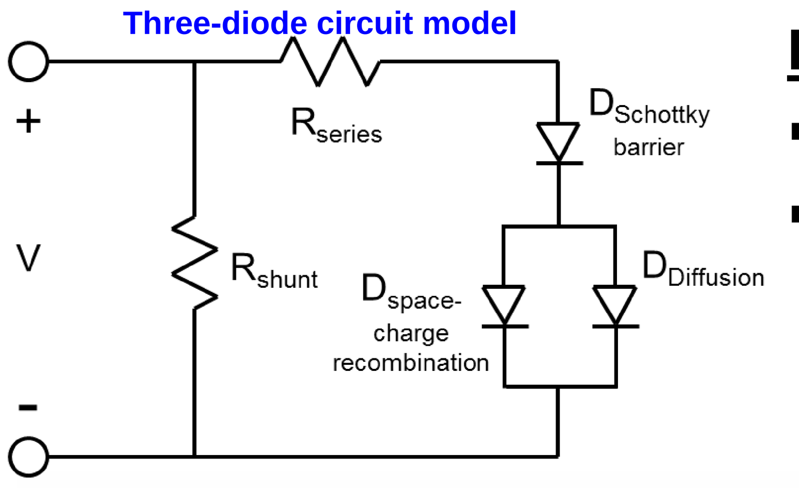
UV-LED IV characteristics

- Two deep-UV 280nm LEDs
- Same total threading dislocation density of 3×10^9 cm^{-2}
- Densities of nanopipes differed by two orders of magnitude **(10/device vs. 1100/device)**
- Evidence of current leakage in high nanopipe density UV-LED

Current-voltage characteristics for UV-LEDs of different nanopipe densities

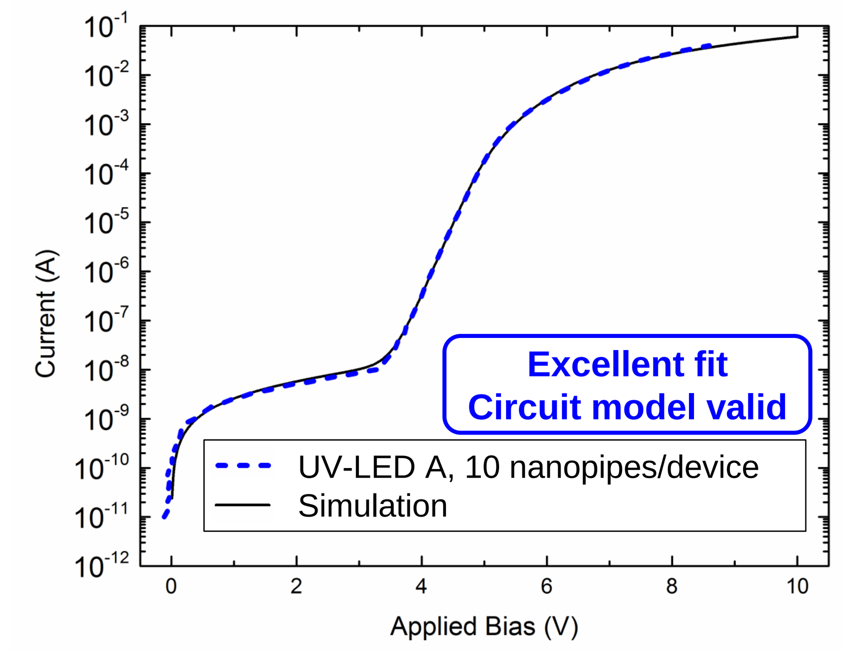


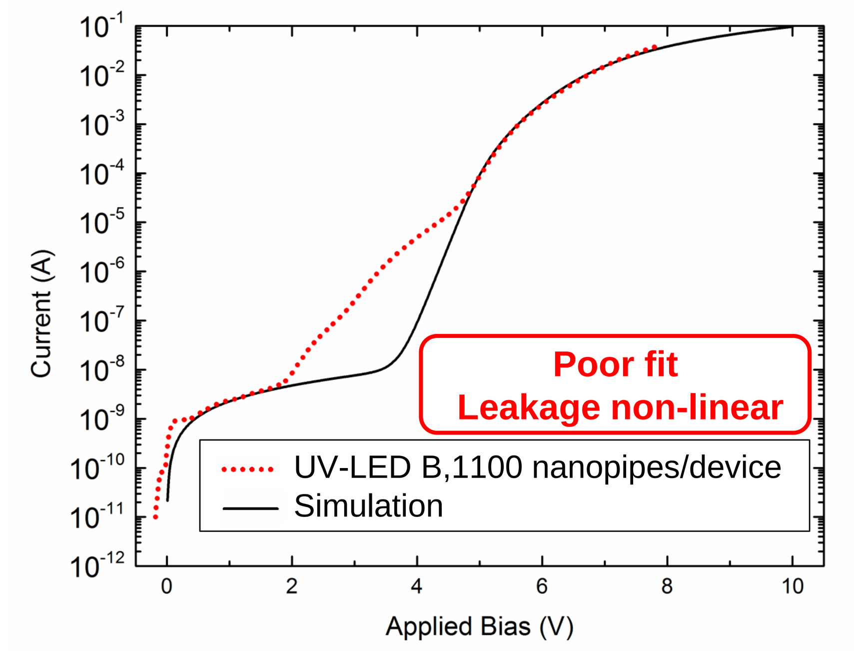
Three-diode circuit model



IV characteristic SPICE simulations

- Three-diode circuit
- Diodes represent recombination in the space charge region, main ideal diode diffusion, and a Schottky barrier at the contact

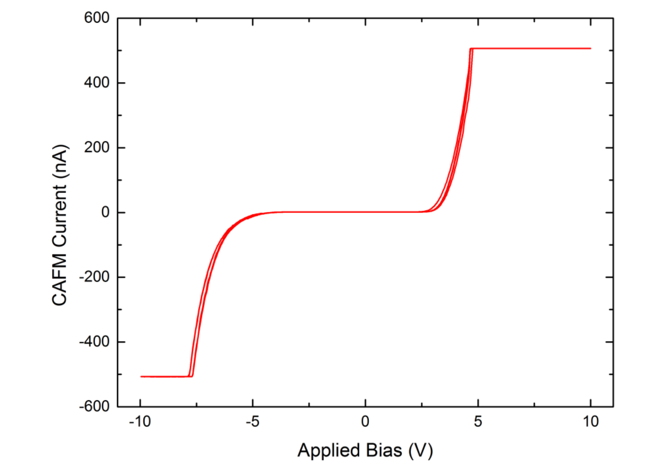




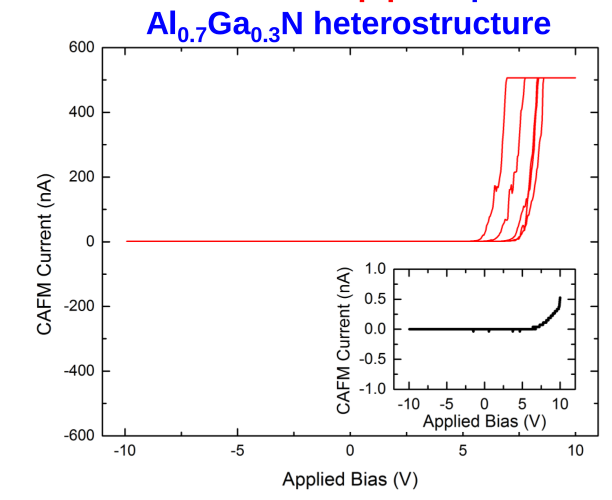
Single-nanopipe IV characteristics

- Nanopipes should behave linearly as resistors
- CAFM tip used to probe individual nanopipes
- Comparison of nanopipes in n-type to nanopipes in p-n junctions
- **Rectification observed in nanopipes in p-n junctions**
- Nanopipes hypothesized to terminate at or in p-material

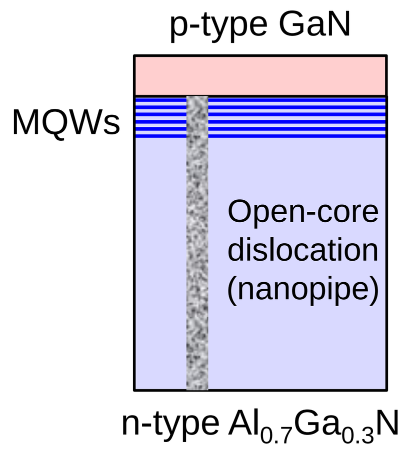
CAFM IV of a nanopipe in n-type $Al_{0.7}Ga_{0.3}N$



CAFM IV of a nanopipe in p-GaN / n-$Al_{0.7}Ga_{0.3}N$ heterostructure



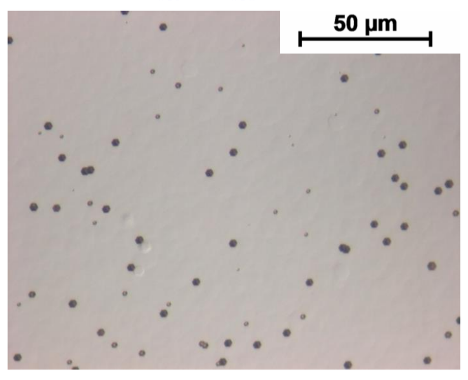
Proposed nanopipe termination model



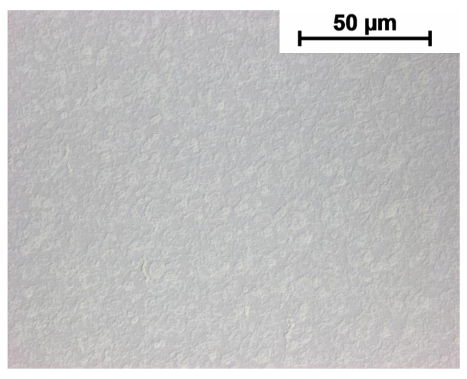
Defect-sensitive etching

- H_3PO_4 revealed nanopipes at in the n-type $Al_{0.7}Ga_{0.3}N$ layer
- **No decorated pits at the surface of the p-GaN / n-type $Al_{0.7}Ga_{0.3}N$ heterostructure**

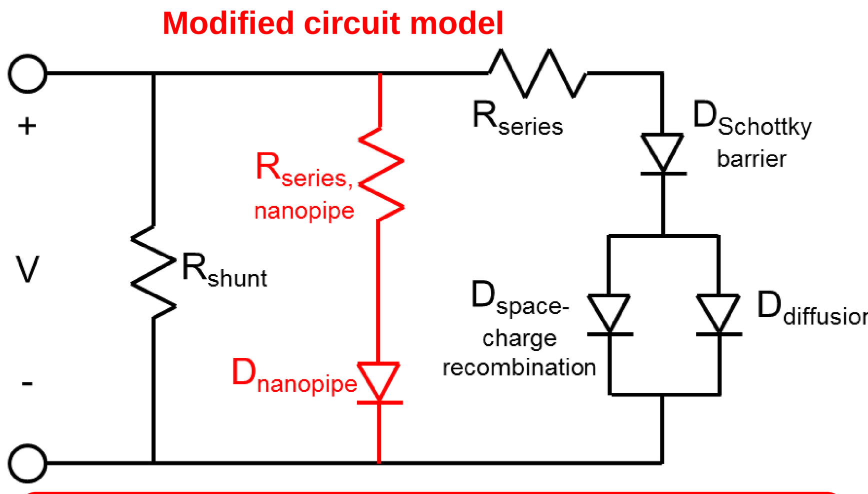
H_3PO_4-etched n-$Al_{0.7}Ga_{0.3}N$ layer



H_3PO_4-etched p-GaN / n-$Al_{0.7}Ga_{0.3}N$ heterostructure

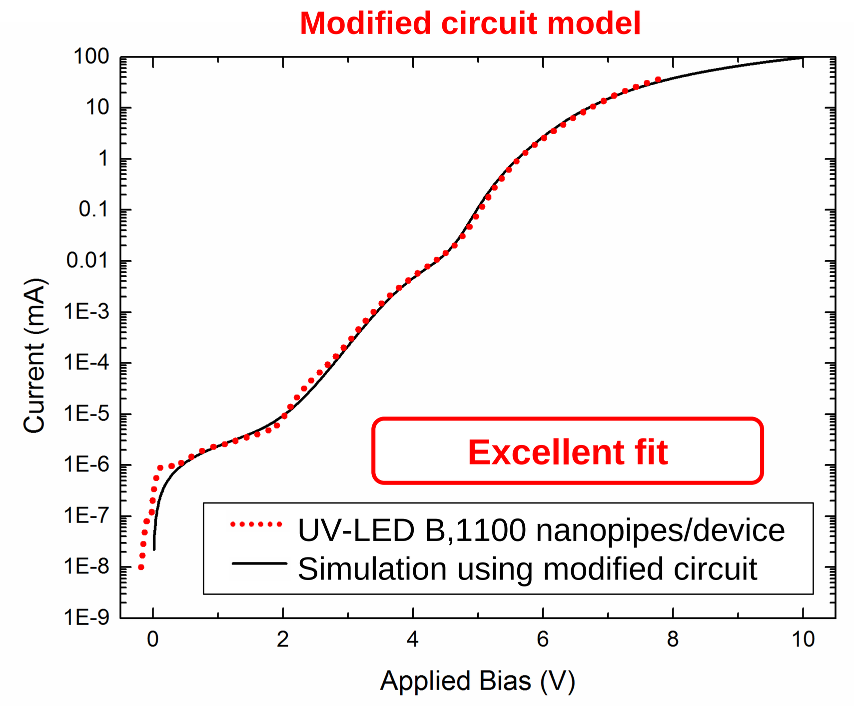


Modified circuit model



Additional diode and resistor to emulate p-n junction at nanopipe / p-GaN interface

Modified circuit model



Conclusions

- **Nanopipes play a major role in UV-LED performance reduction**
- Hot H_3PO_4 etching is a rapid method of nanopipe quantification
- **Nanopipe-related leakage paths rectifying in p-n junctions**
- p-Region in LED structures responsible for nanopipe termination

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