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# *In-Operando* Imaging of Field Spreading and Carrier Transport in GaN-Based pin Diodes

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**University of Notre Dame**
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# Application space for GaN in power electronics

high power • high temperature • high frequency • low power losses • low weight and volume

## Data Centers

gizmodo.com

## Aerospace

nasa.gov

## Energy

ge.com solarcity.com energy.gov

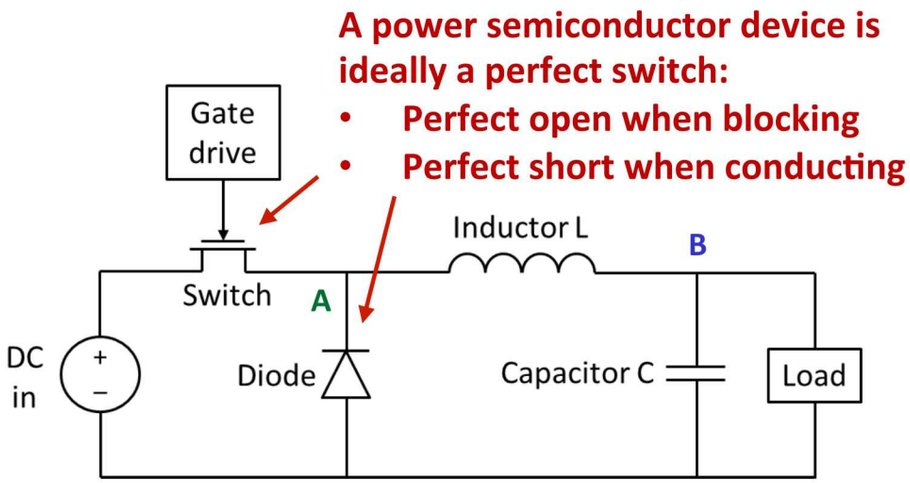
## Transportation

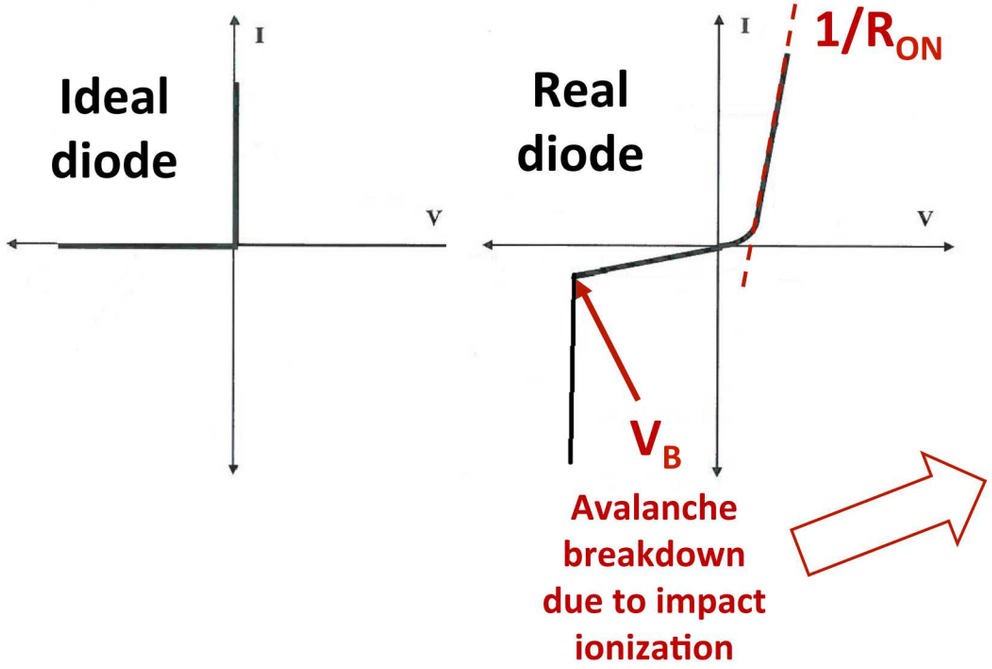
tesla.com

## Consumer Electronics

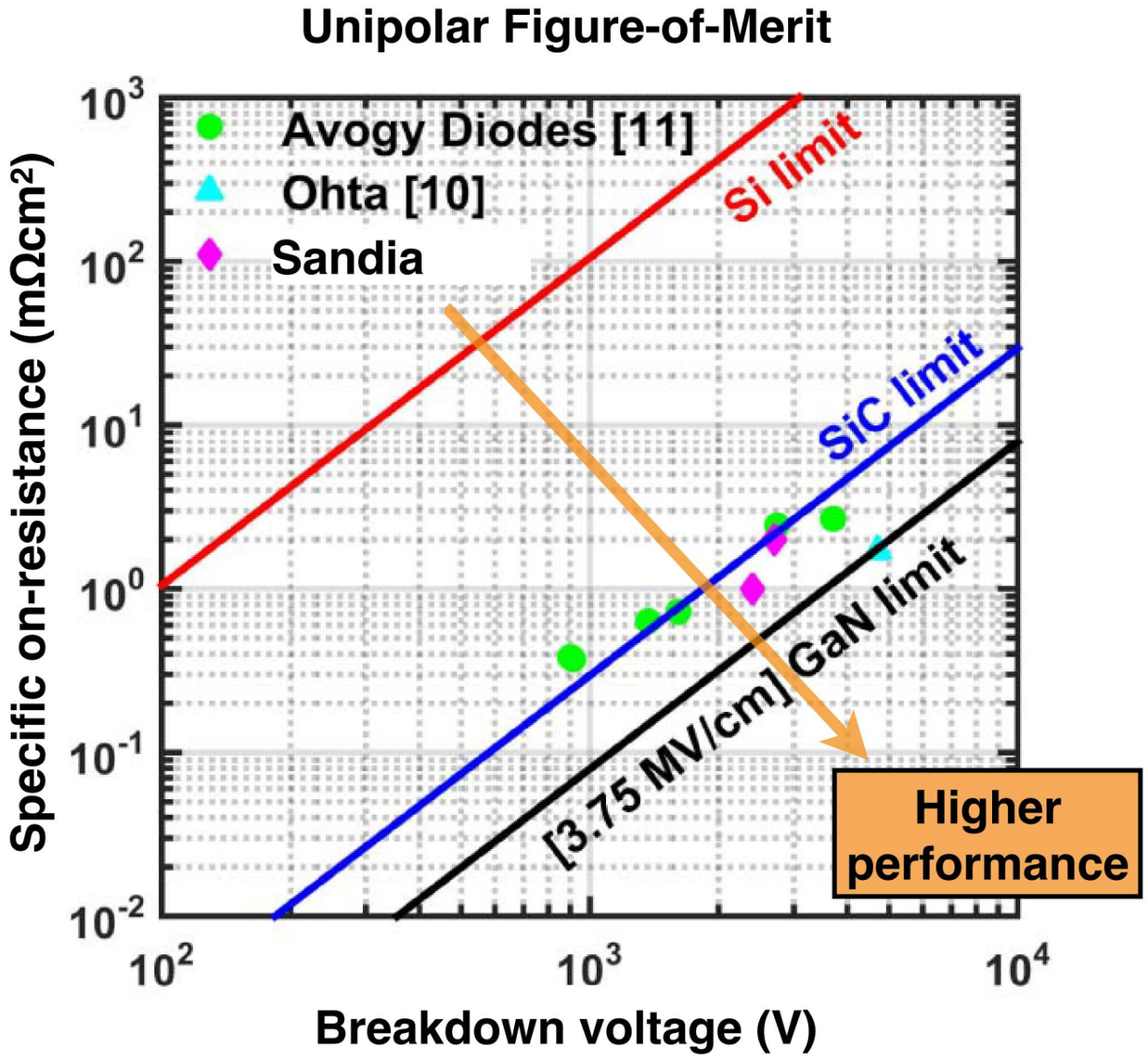
apple.com

# State-of-the-art devices do not achieve the theoretical limits of performance



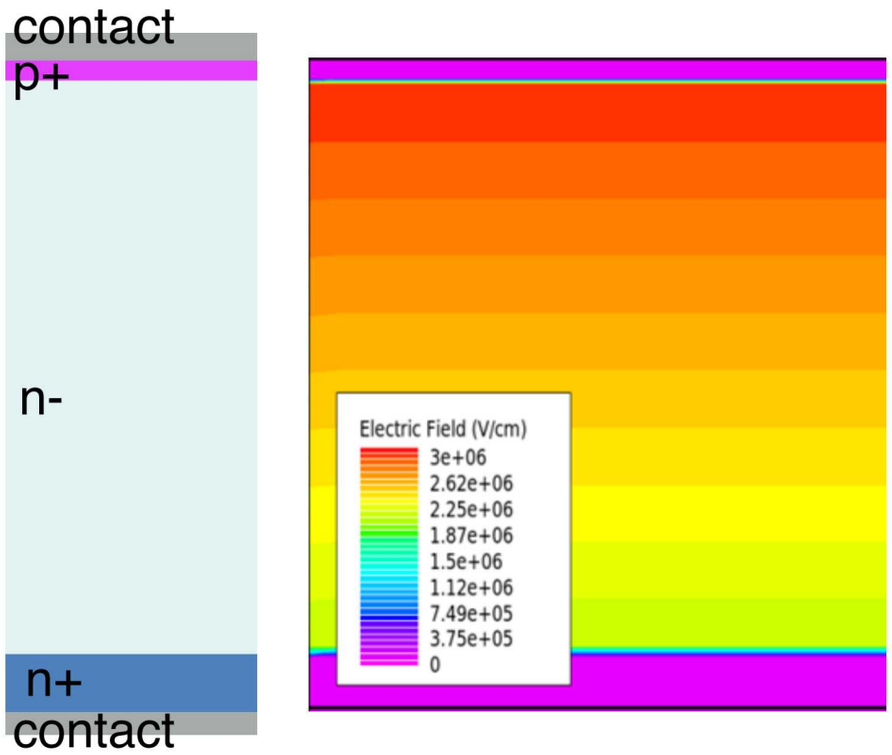

Courtesy of R. J. Kaplar



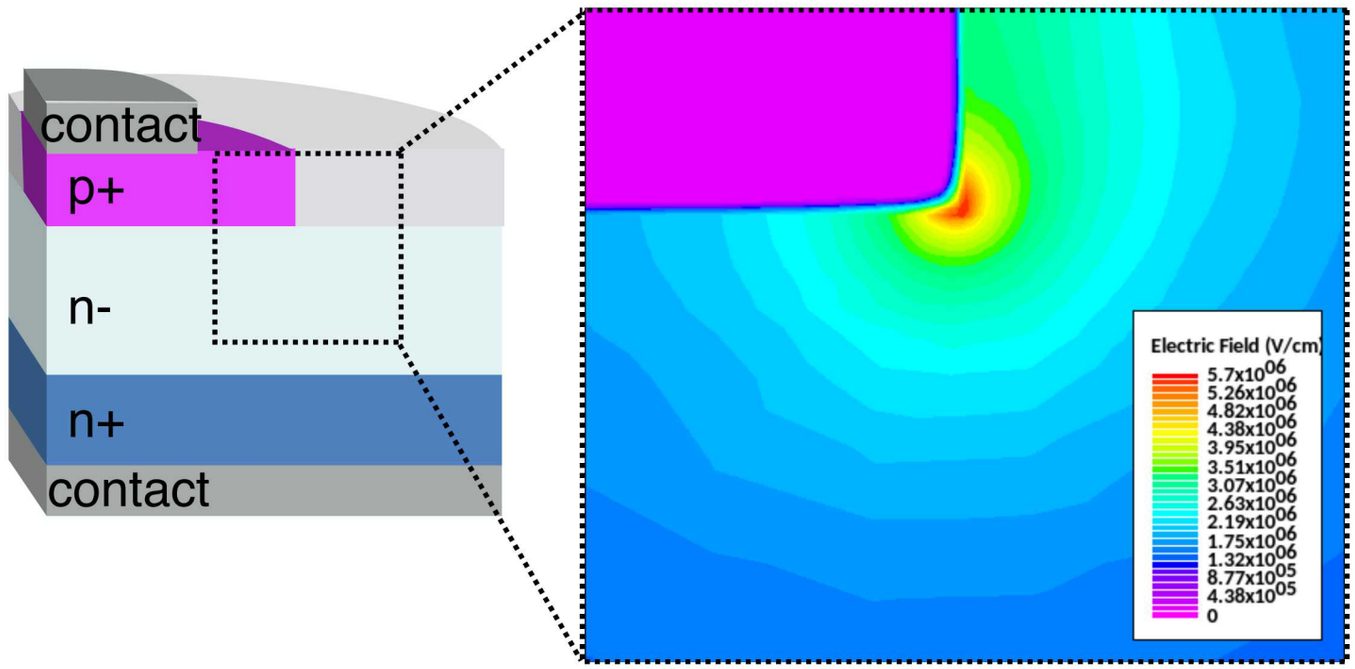

J. R. Dickerson et al., IEEE Trans. Electron Dev., 2016

# Field crowding leads to premature breakdown, below the theoretical limit of planar junctions

Ideal parallel plane junction:



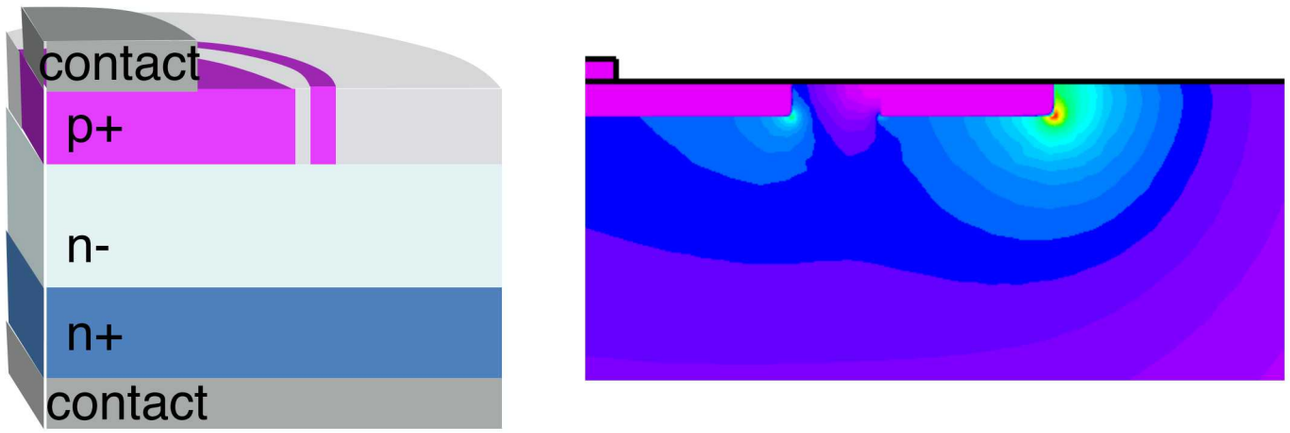

Real junction has edges where field crowding occurs:



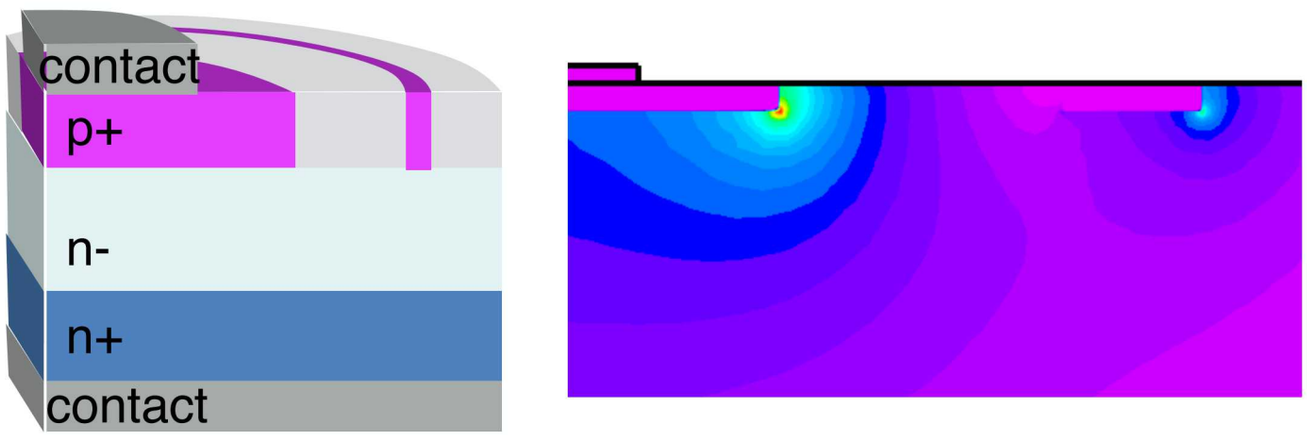

Numerical calculations courtesy of J. R. Dickerson

# Edge terminations are used to mitigate field crowding

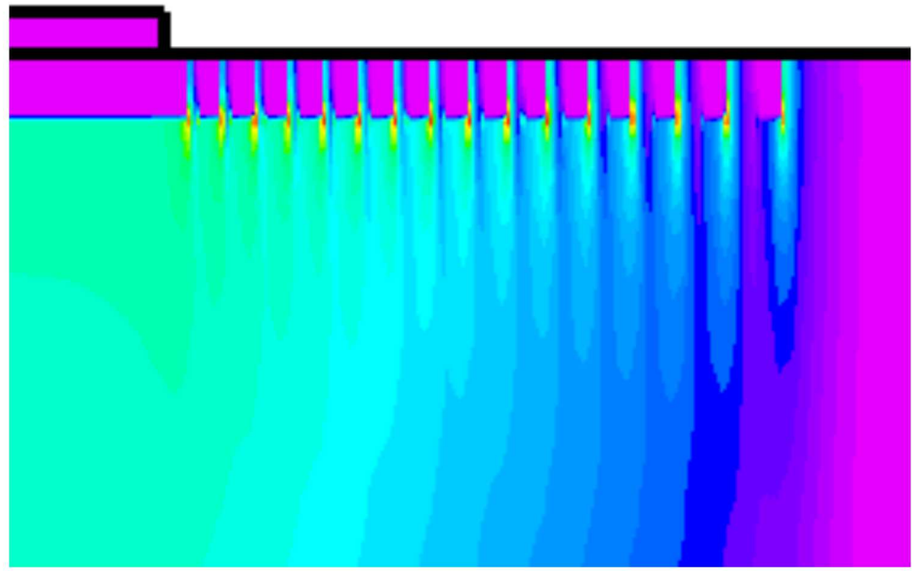
Guard ring too close:

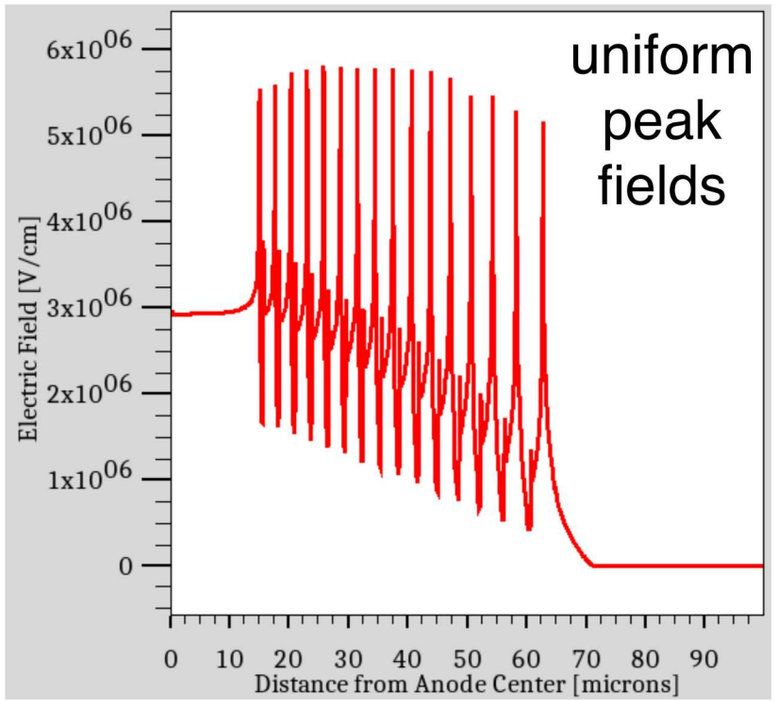



Guard ring too far:




Optimized 15 ring design:

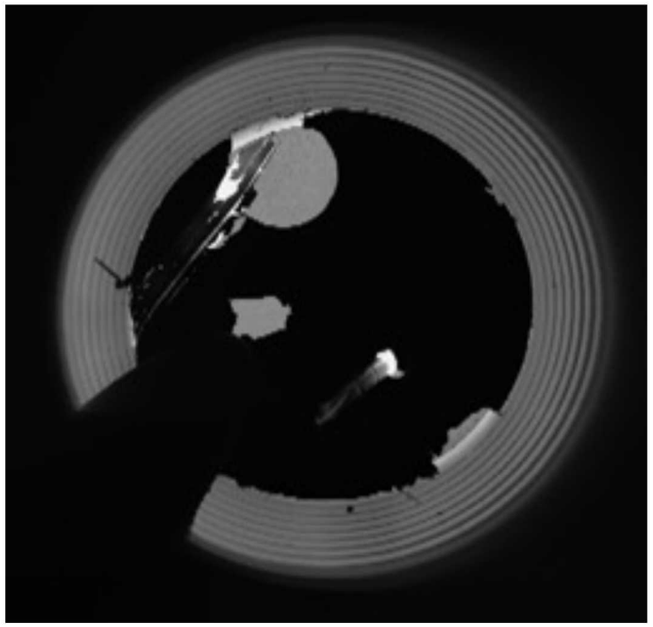


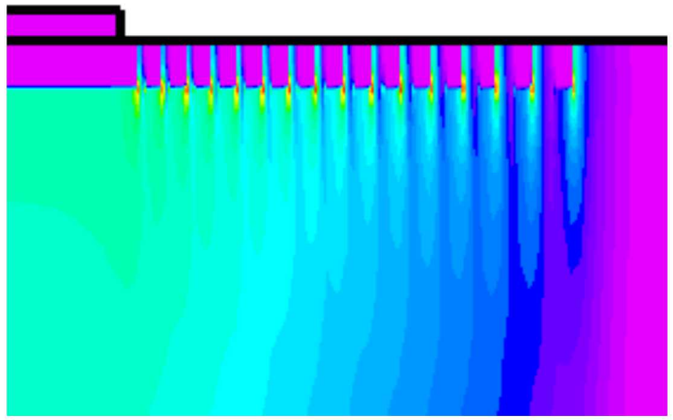


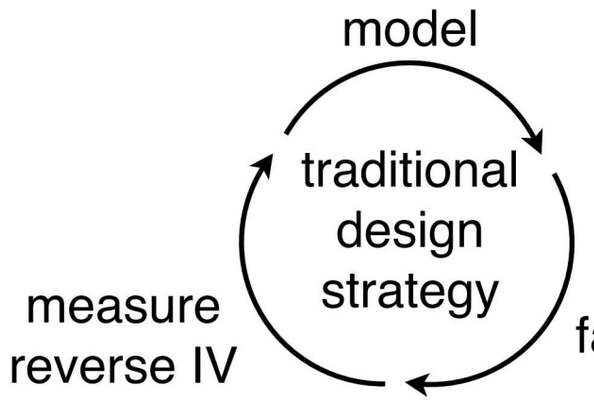

Numerical calculations courtesy of J. R. Dickerson

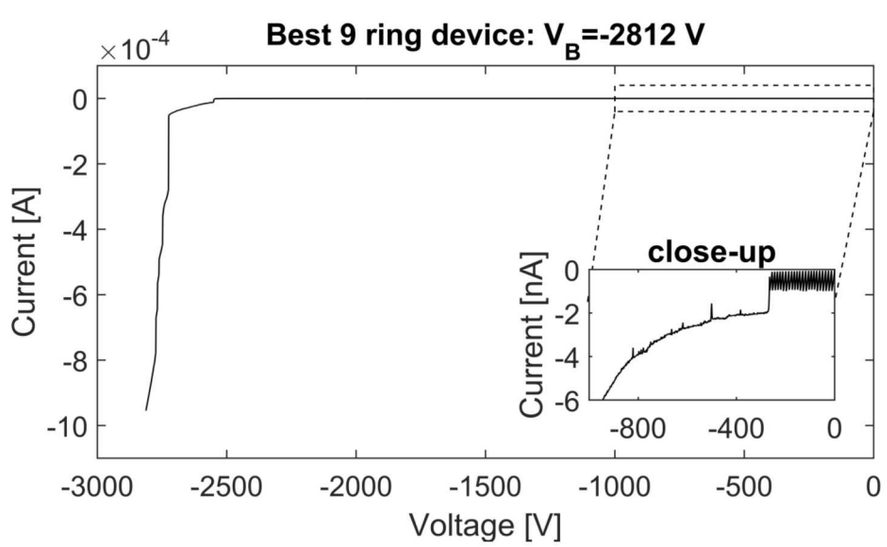
# Our work focuses on gaining a more nuanced understanding of edge termination performance

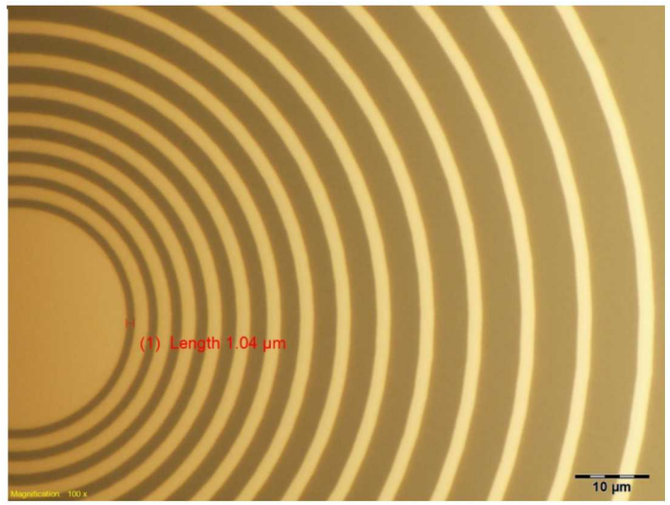
map electric field spreading with EBIC/OBIC





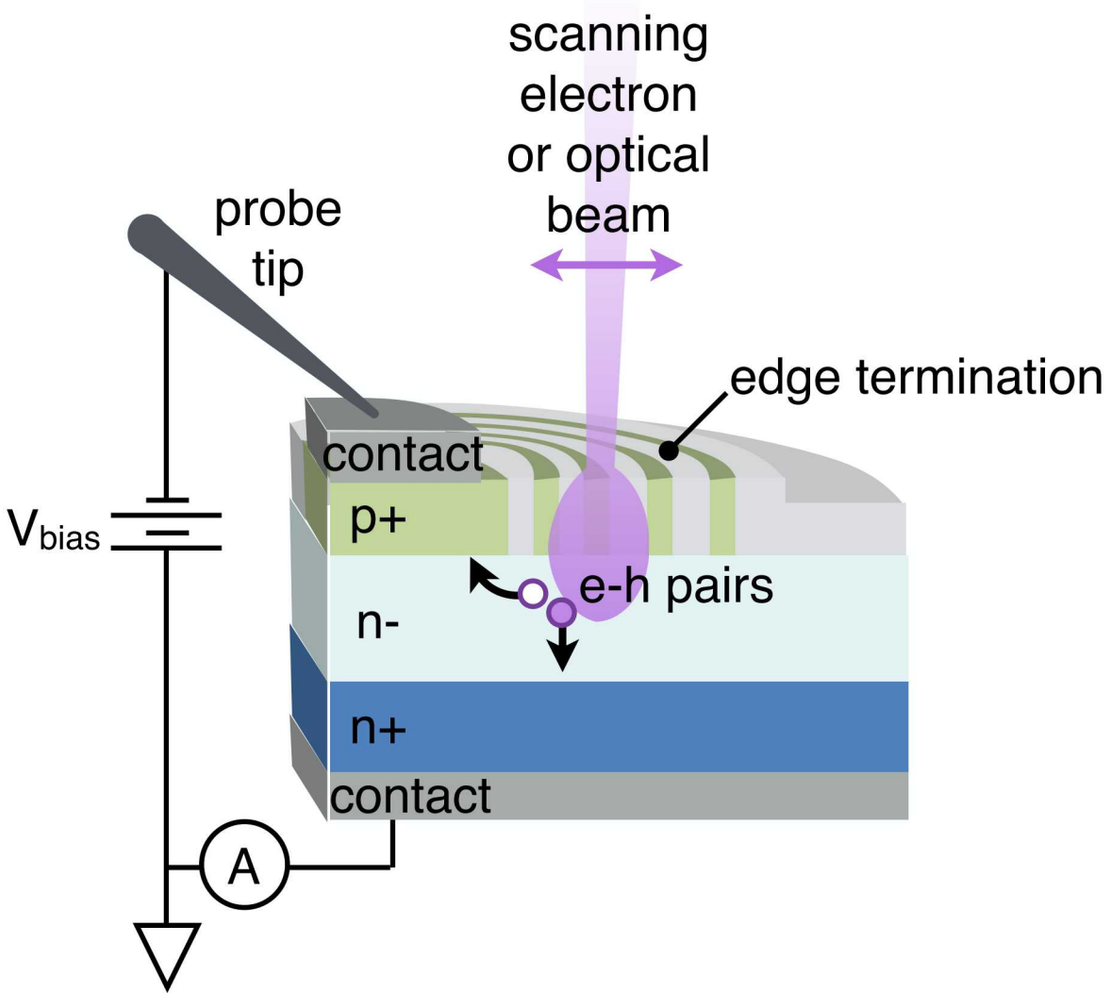


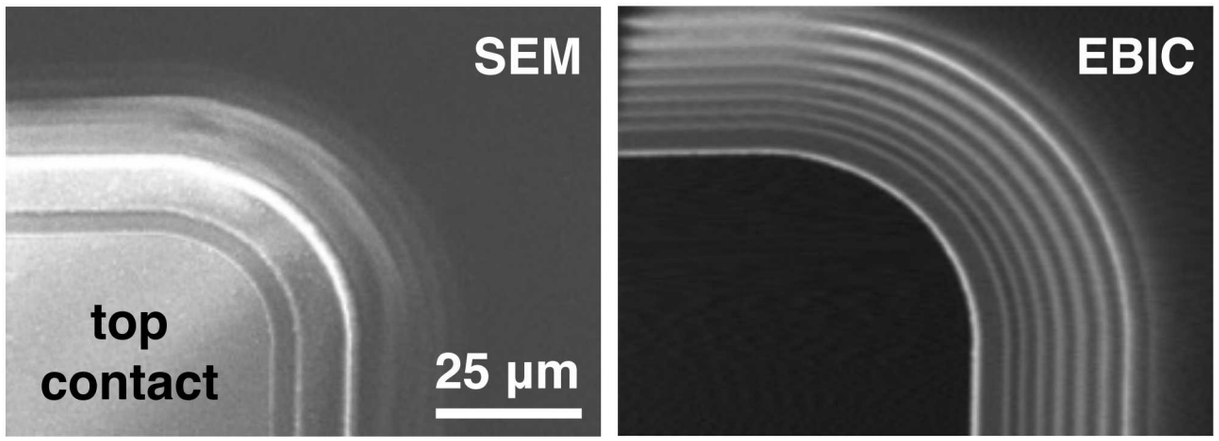




Courtesy of J. R. Dickerson

# *In-operando* beam-induced-current methods show electric field spreading and more!



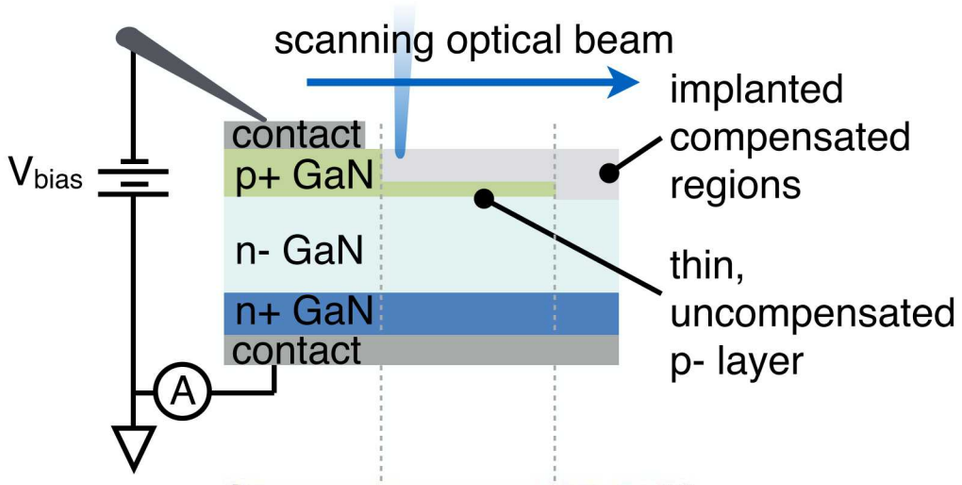

**OBIC = Optical-Beam-Induced Current**
**EBIC = Electron-Beam-Induced Current**

Beam-induced-current map shows . . .

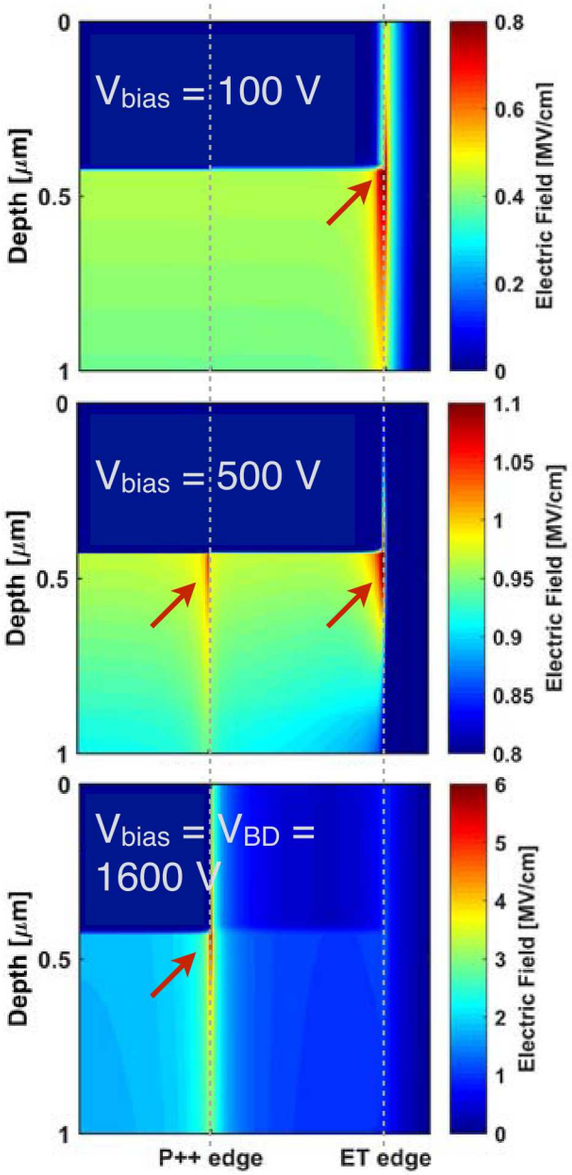
- extent of space-charge region (field spreading)
- in the case of high fields, field-induced charge multiplication (field strength)
- carrier diffusion length
- recombination centers
- areas prone to breakdown
- device non-uniformities

We will highlight each of these with studies on GaN and AlGaN devices

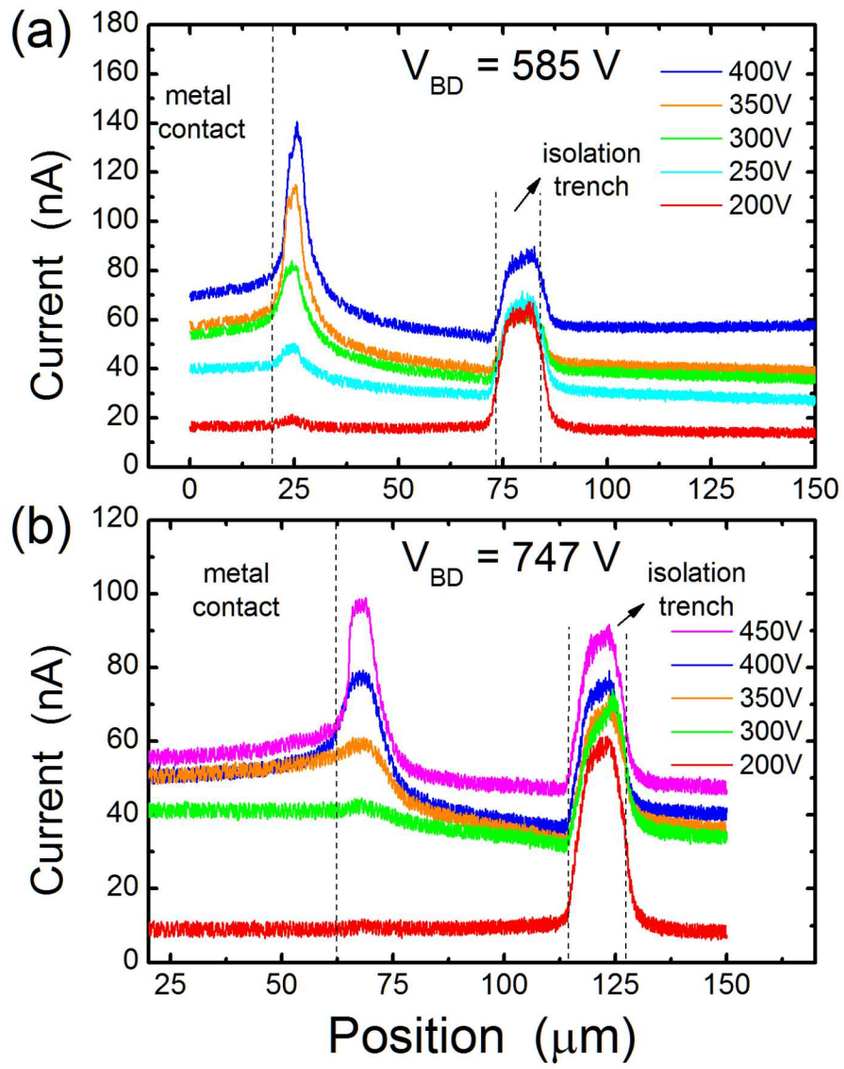
# Detection of shifting E-field peak location with bias




Model:



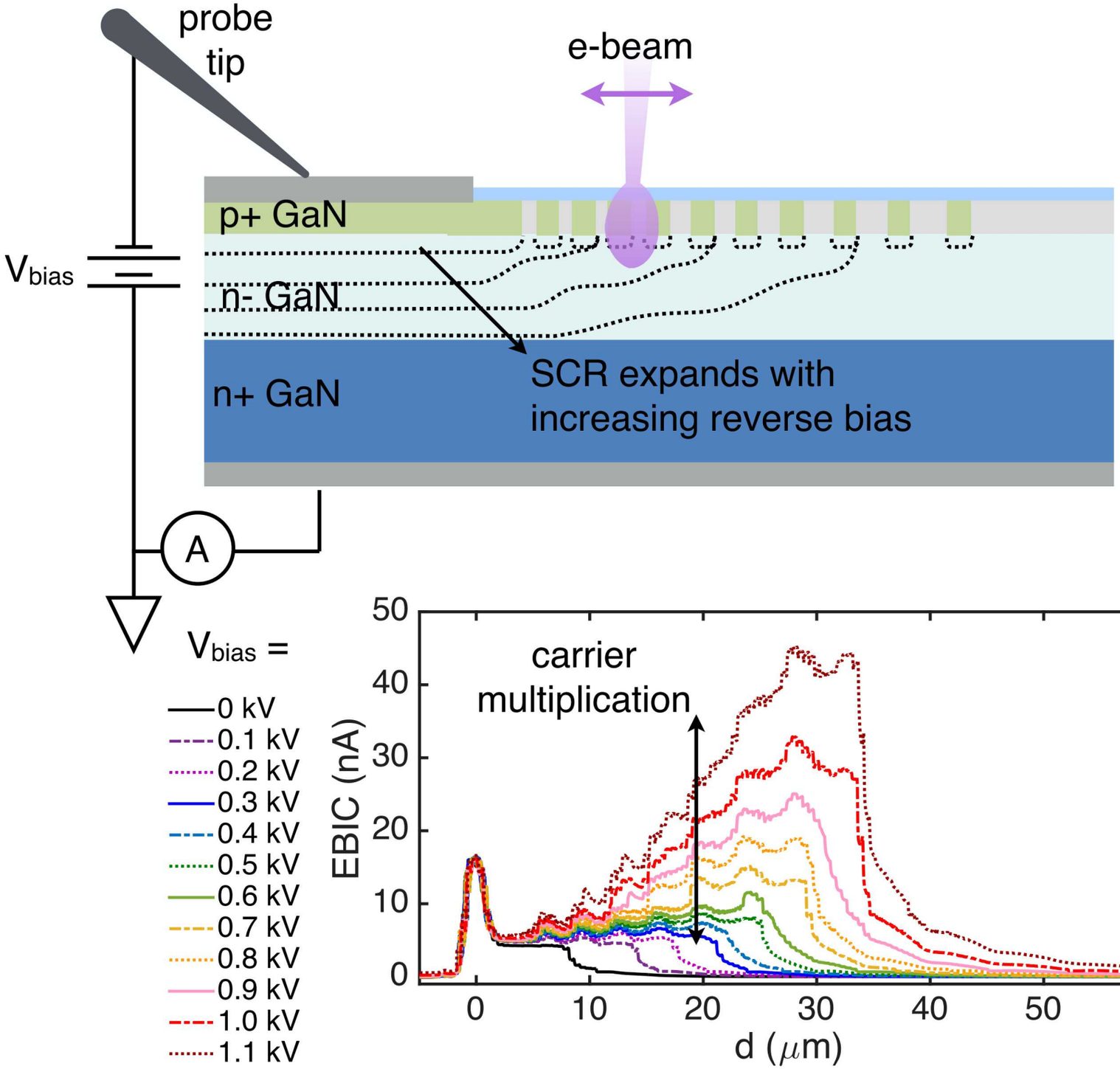

OBIC measurements:

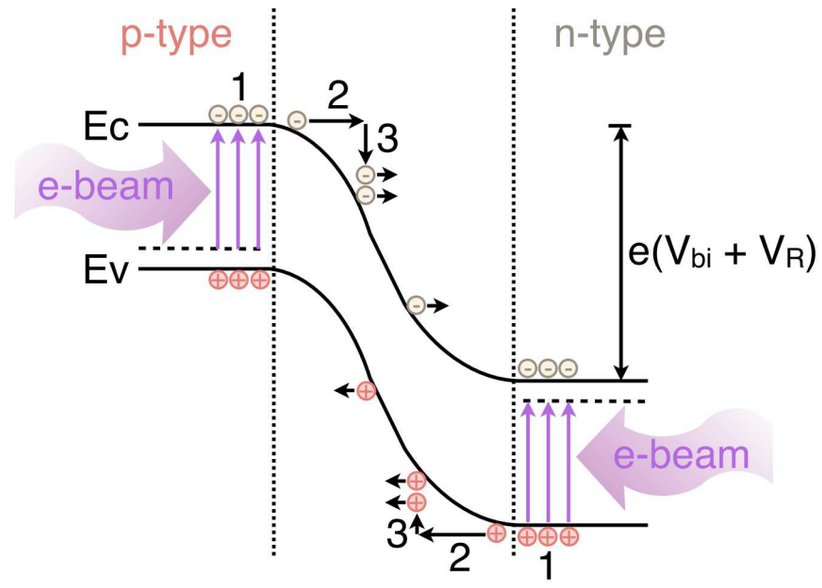



- Model predicts movement of E-field peak from end of edge termination towards contact with increasing bias
- Confirmed by OBIC measurements

F. Léonard et al., IEEE Electron Device Lett., 2016

# Detection of field-induced charge multiplication gives an indication of local electric field strength

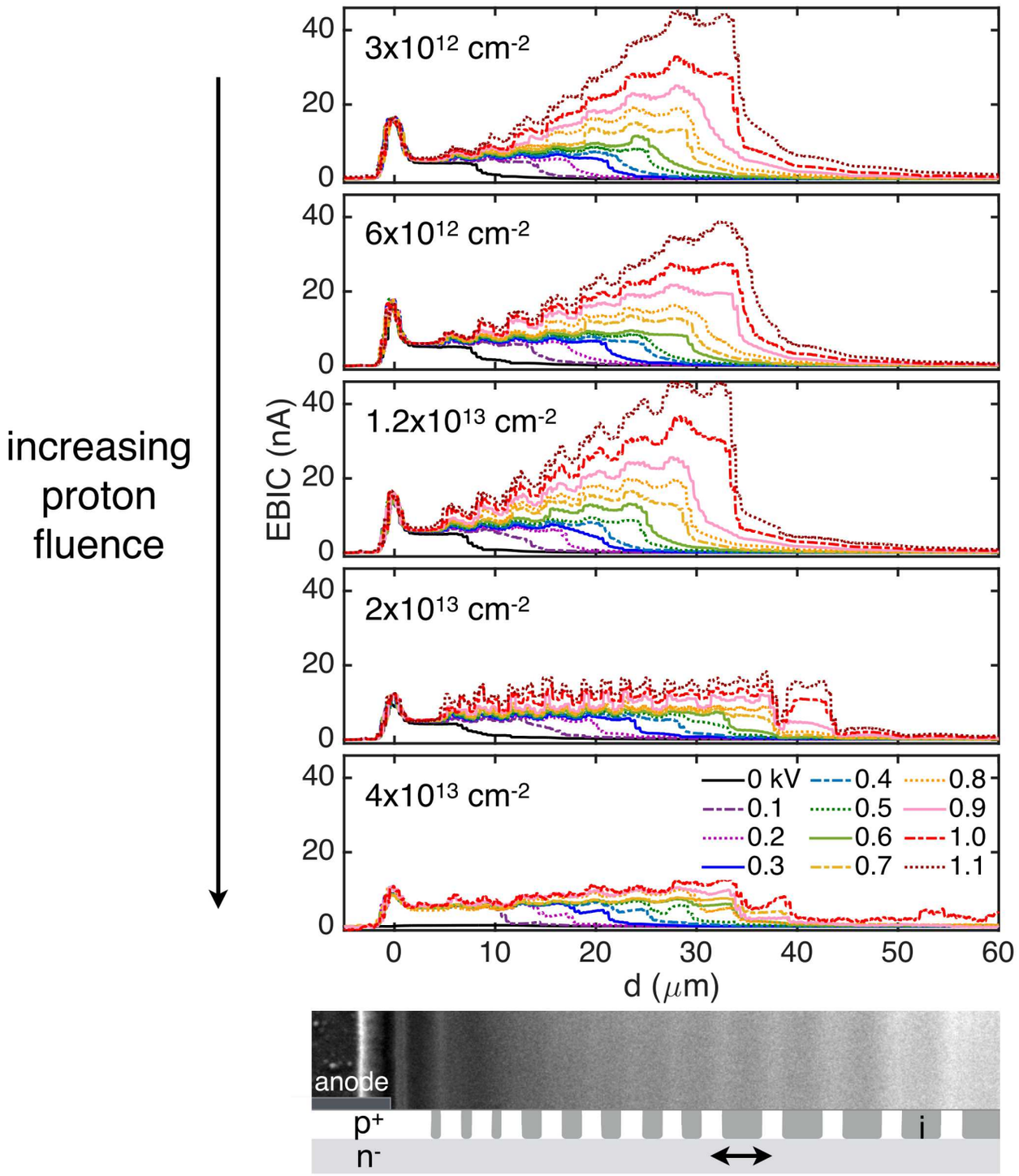



Device courtesy of Avogy, Inc.

K. C. Collins et al., IEEE Electron Device Lett., 2017

# Measuring field spreading and strength provides insights into edge termination performance following irradiation

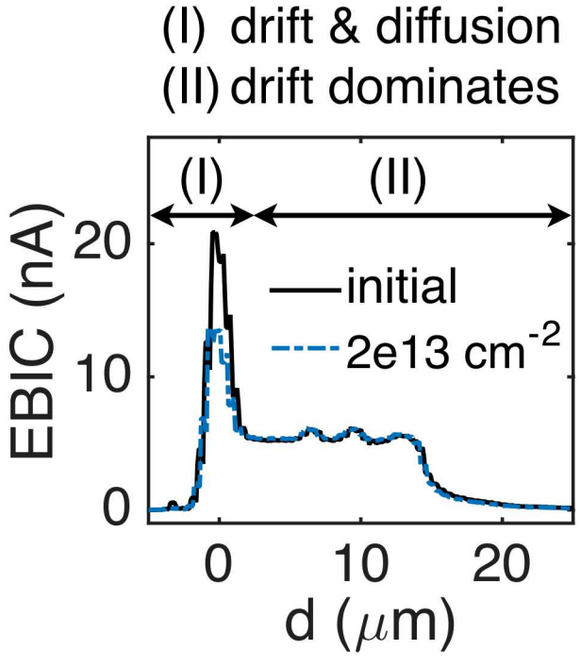


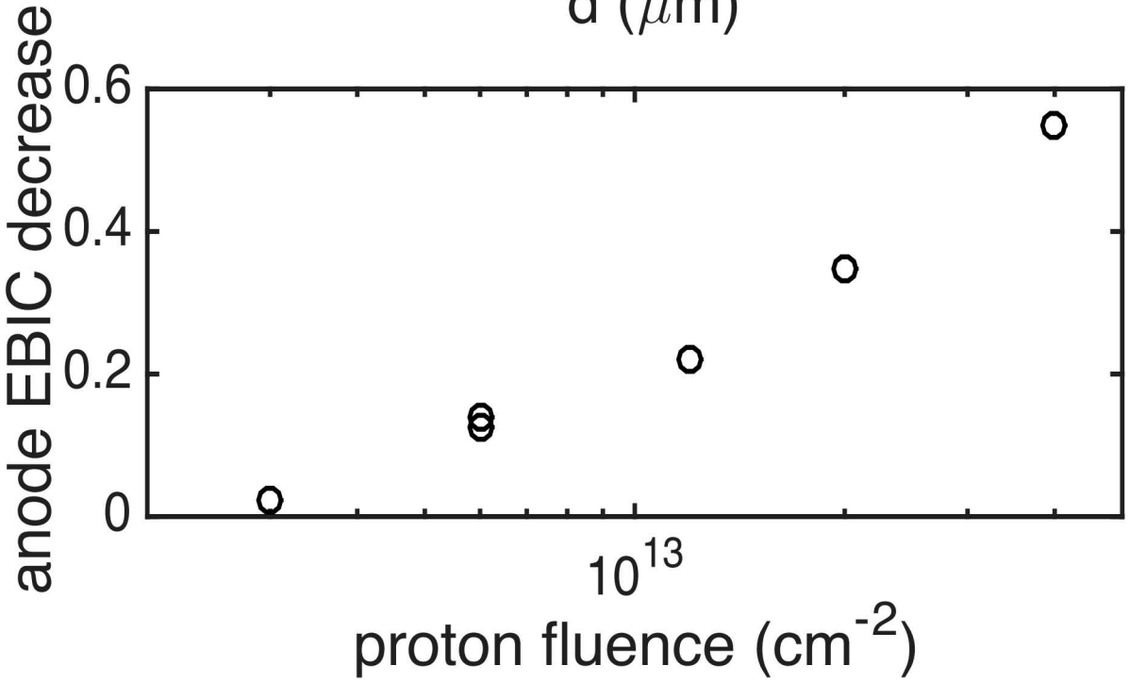

large gap between 8th and 9th p-rings

Device courtesy of Avogy, Inc.

K. C. Collins et al., IEEE Electron Device Lett., 2017

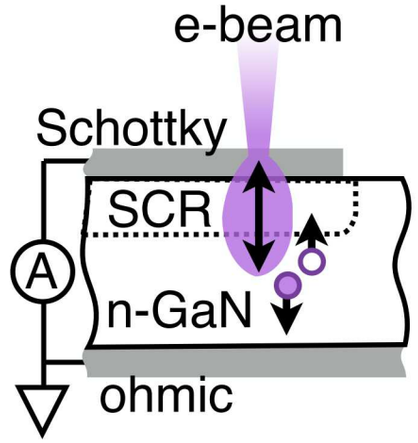
# Irradiation decreases free carrier diffusion lengths, and the effect is apparent in the near-contact EBIC magnitude

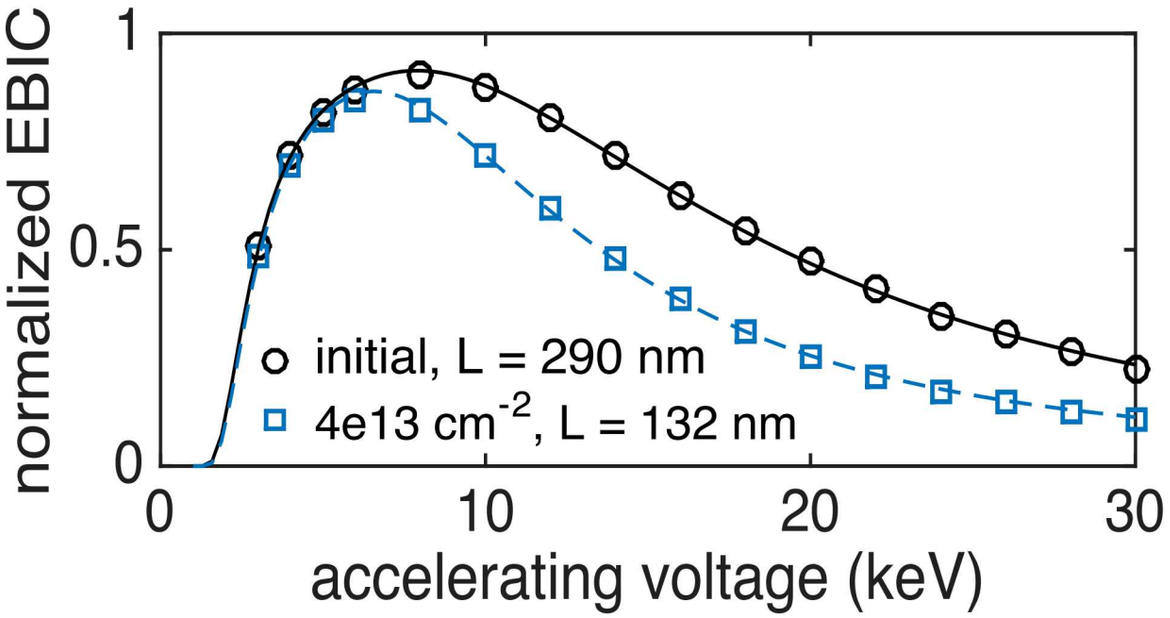



55% decrease in anode EBIC peak height

## Quantifying carrier transport



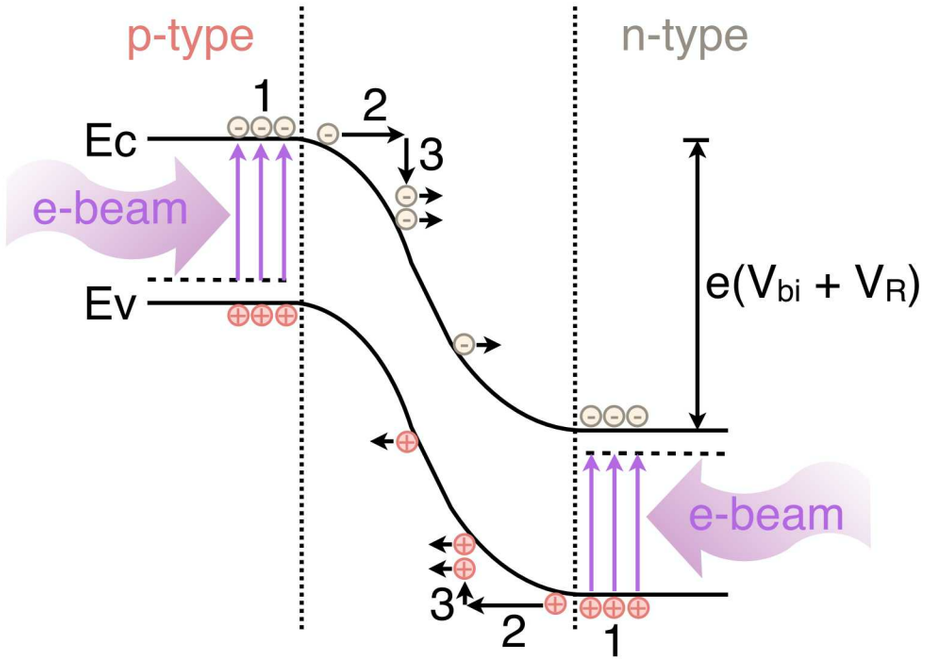



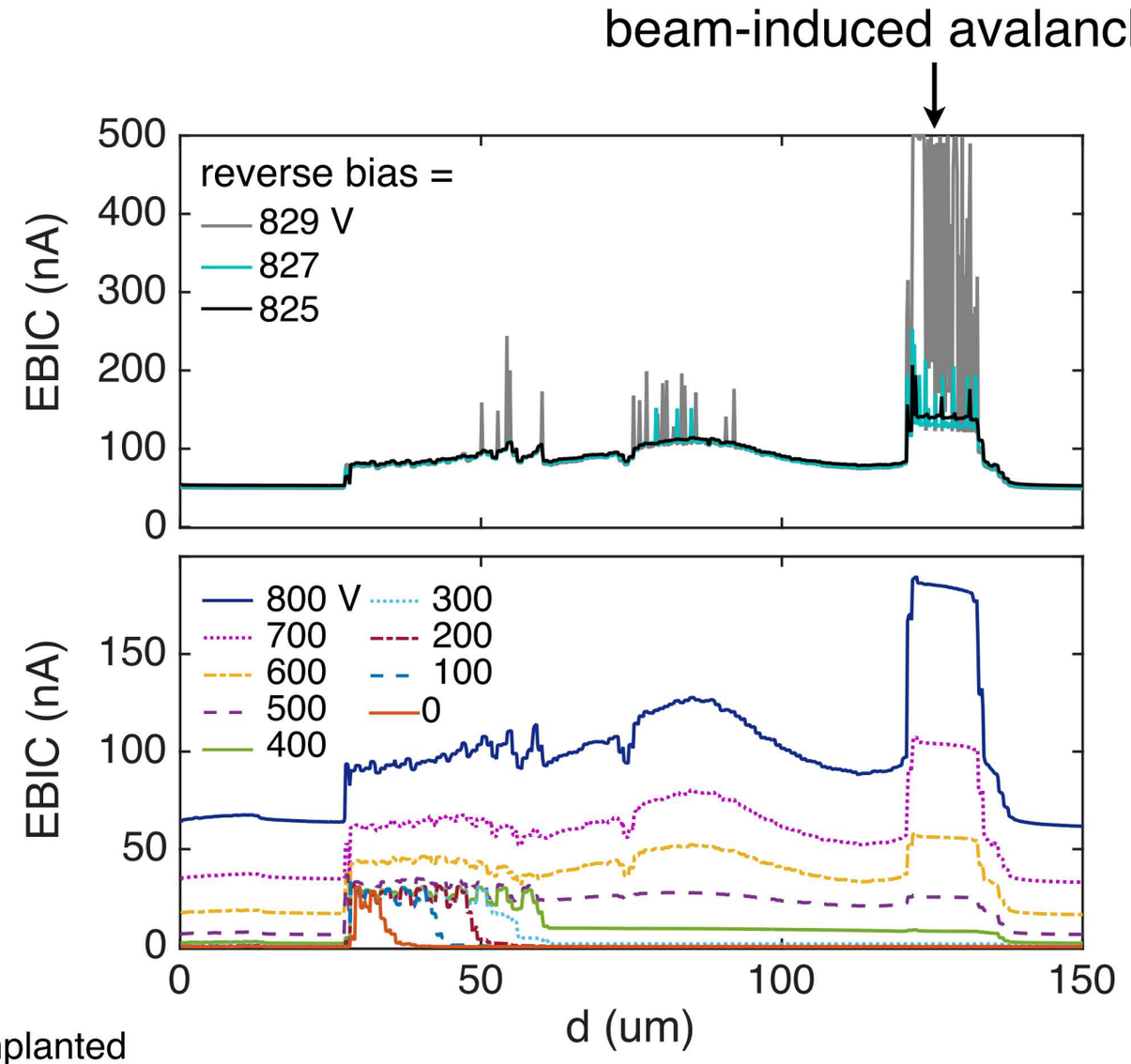

55% decrease in hole diffusion length

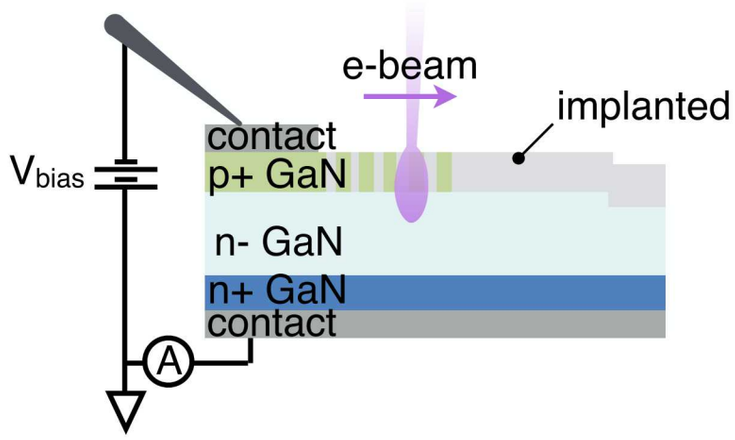
K. C. Collins et al., IEEE Electron Device Lett., 2017

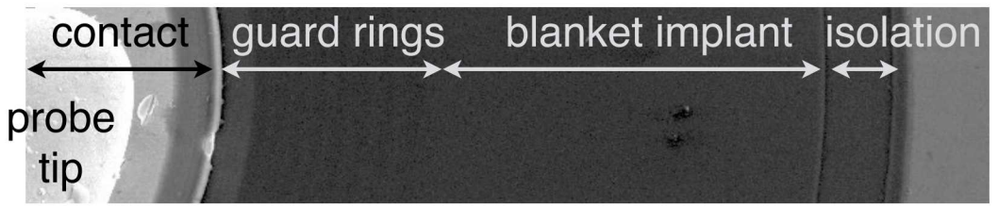
# Identifying high field regions prone to avalanche initiation

locally inducing avalanche with carrier injection from e-beam



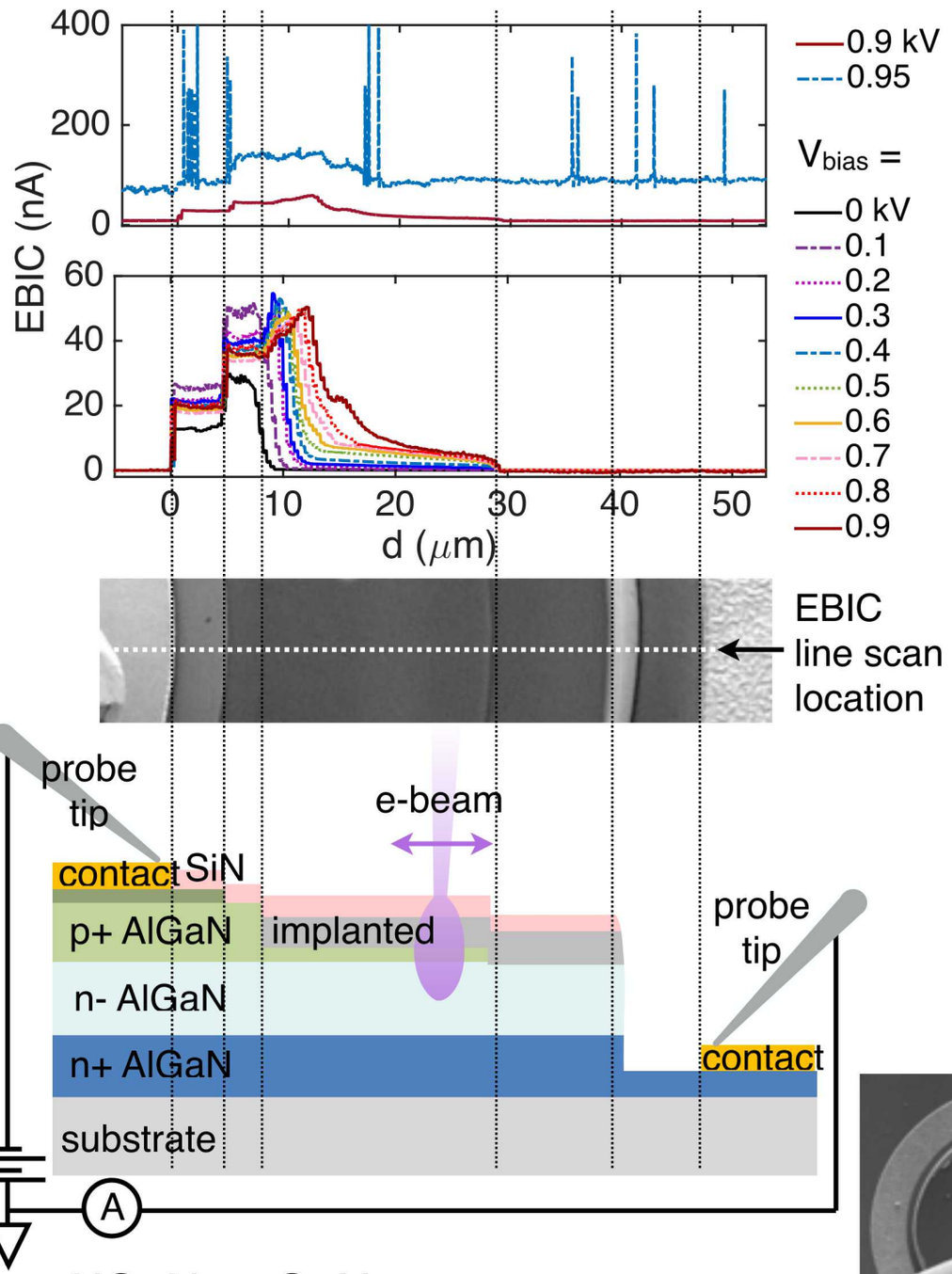



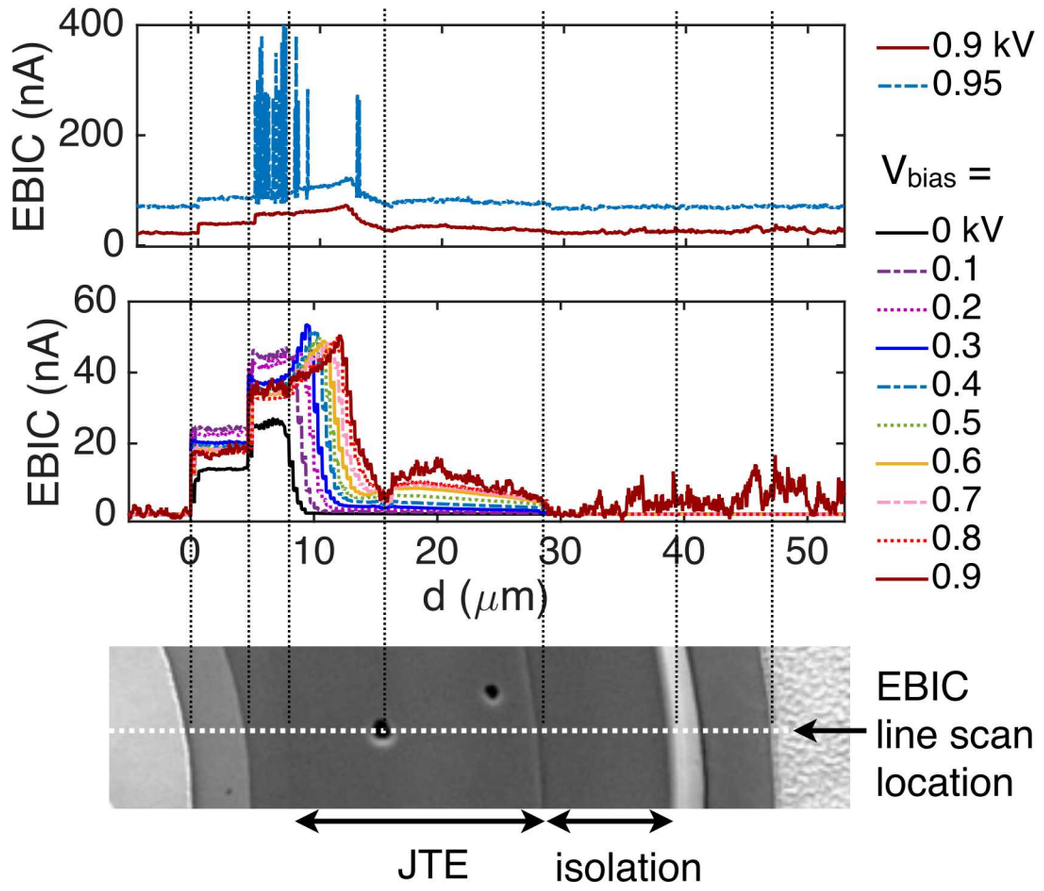



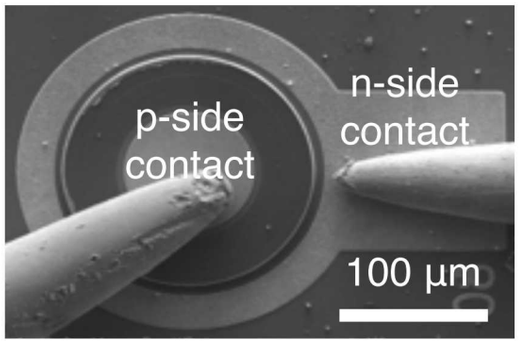

R. J. Kaplar et al., Elect. Dev. Fail. Anal., 2017

# Investigating defects: a nanopipe in AlGaN




- Drop in EBIC at nanopipe suggests that pipe extends into n- region, so there is no junction under the pipe

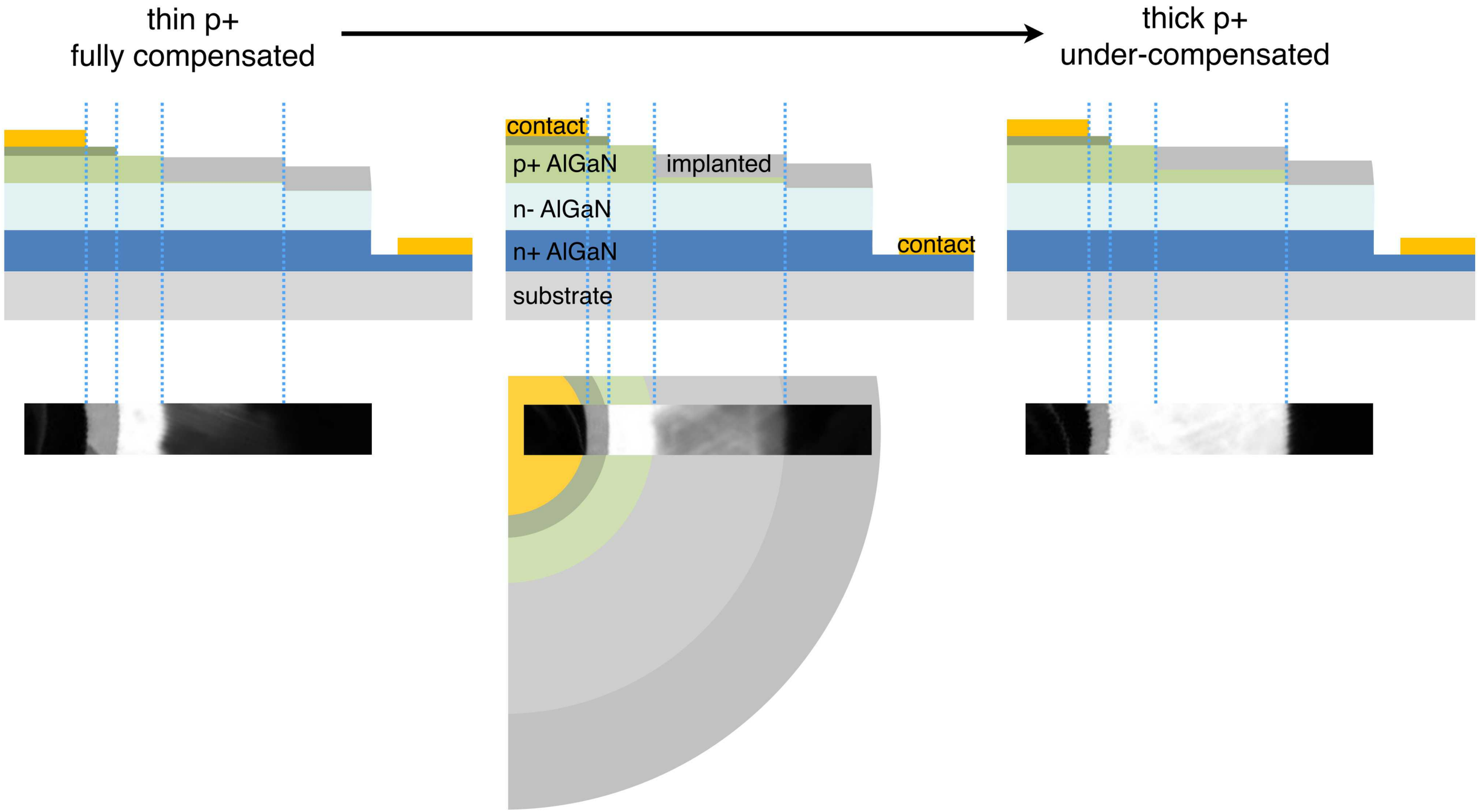



AlGaN vs GaN . . .

- mismatched epitaxy
- insulating substrate & front side contacts
- higher dislocation density and more point defects

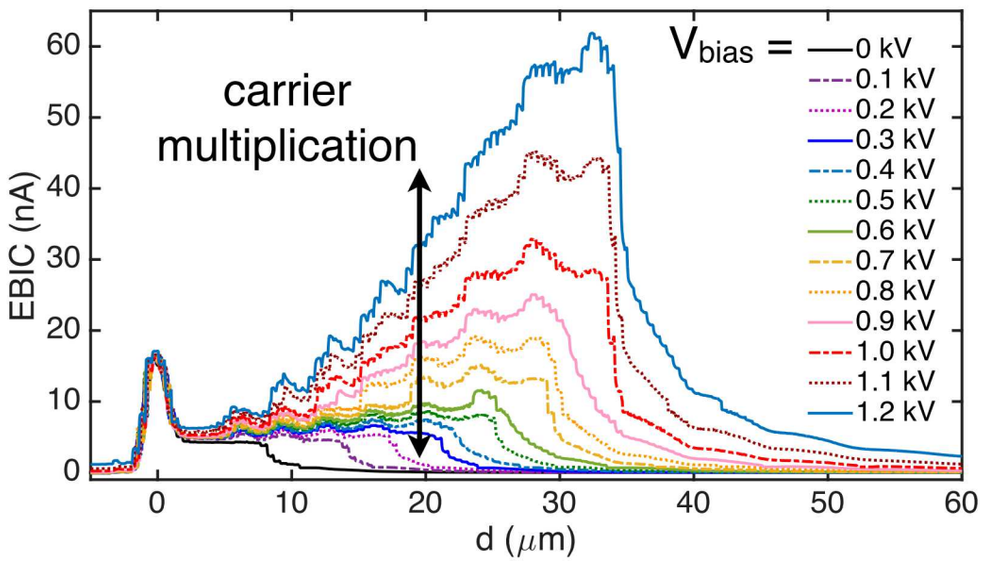
R. J. Kaplar et al., Elect. Dev. Fail. Anal., 2017

# Non-uniform p-layer thickness leads to non-uniform carrier compensation by ion implantation

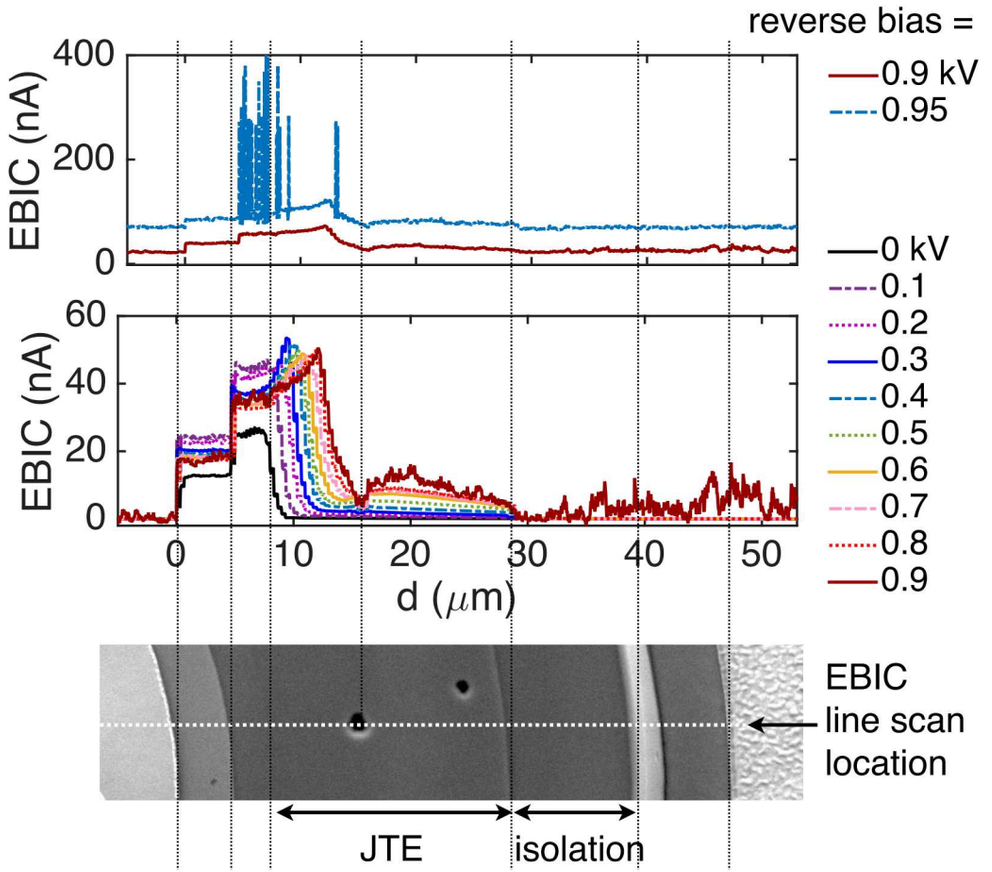


# In summary, EBIC and OBIC are useful diagnostic tools

Measuring field spreading and field strength *in-operando*:

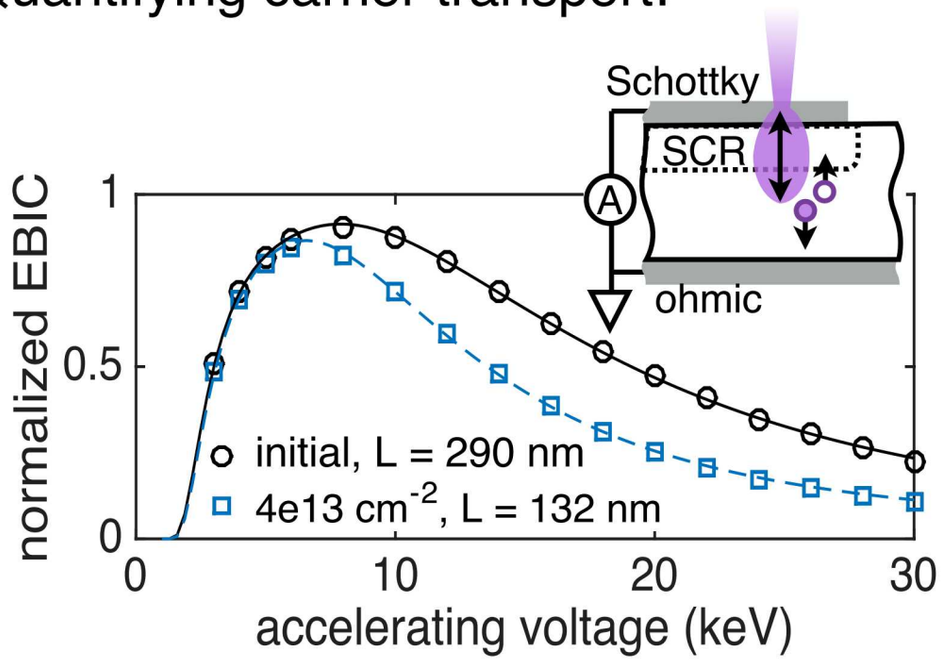



Identifying regions prone to avalanche:




Understanding defects:

Quantifying carrier transport:




Revealing device non-uniformities: