SAND2016-8406C

Exceptional service in the national interest

Sandia National Laboratories

Electron beam induced current study of minority carrier diffusion length in homoepitaxial GaN

Kimberlee Collins[1], Andrew Armstrong[2], Andrew Allerman[2], François Leonard[1], and A. Alec Talin[1]

[1]Sandia National Laboratories, Livermore, CA
[2]Sandia National Laboratories, Albuquerque, NM

SPIE. CONNECTING MINDS. ADVANCING LIGHT.

San Diego, CA
August 30, 2016

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

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

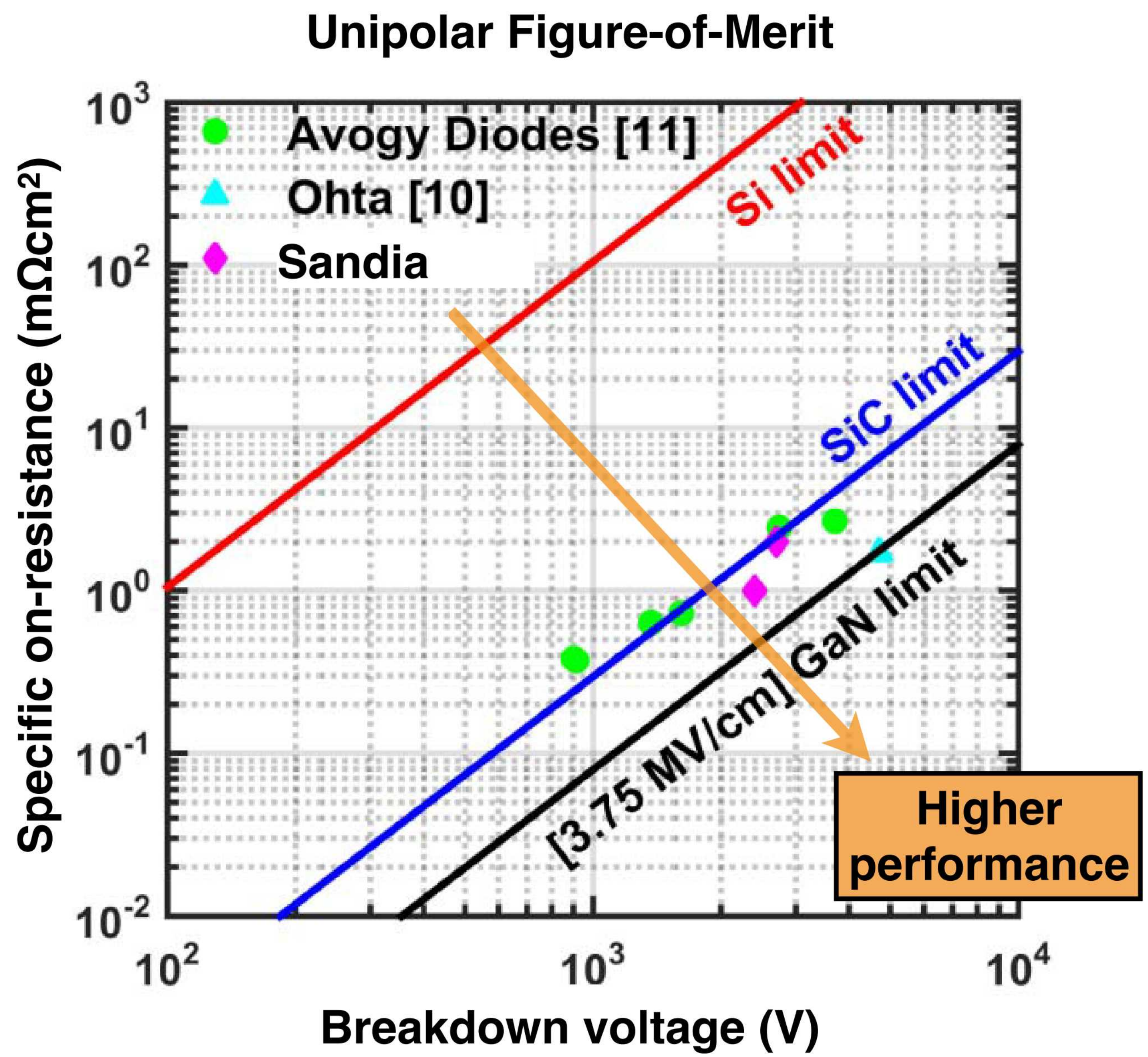
tesla.com

Consumer Electronics

apple.com

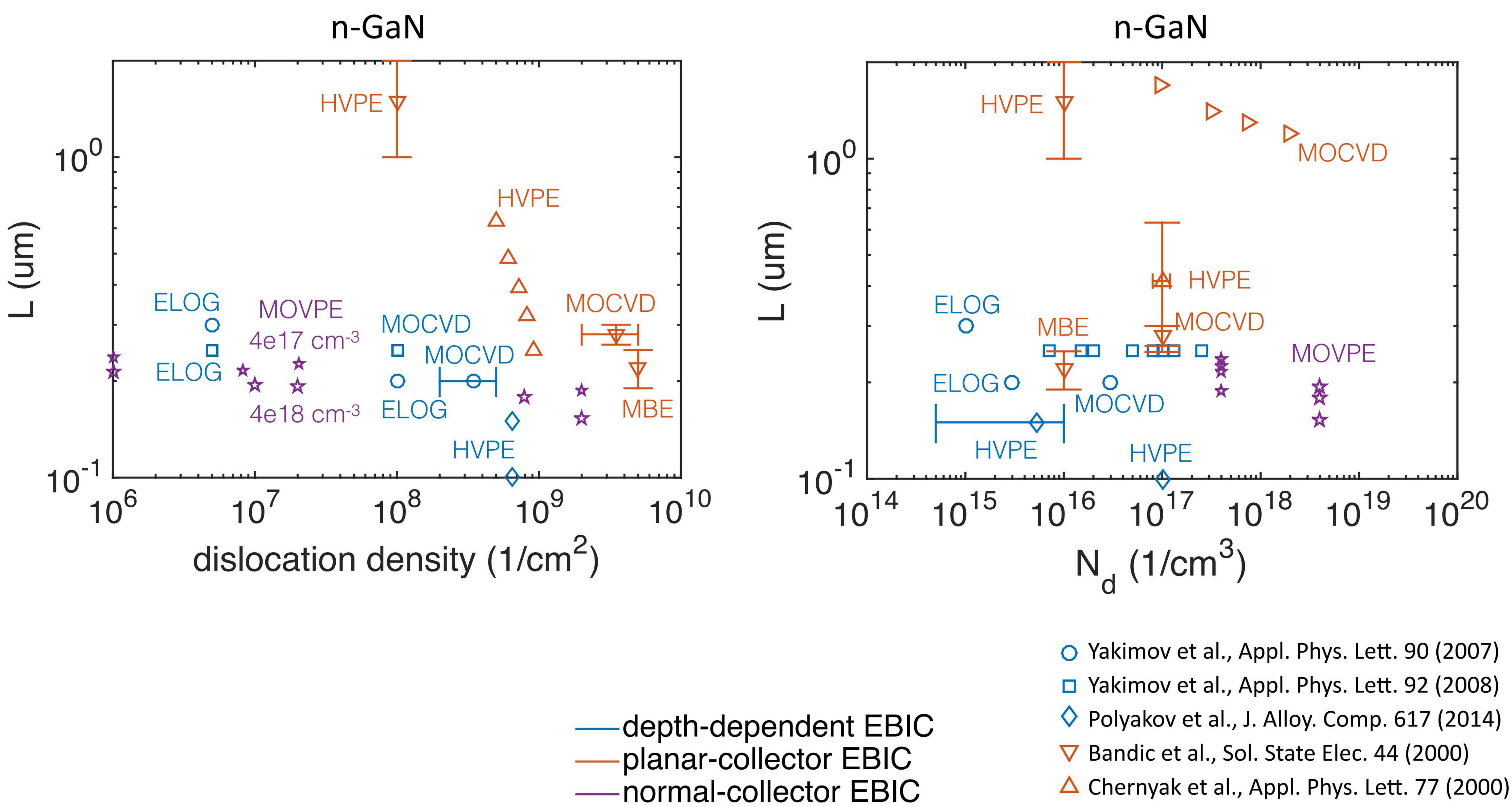
Understanding minority carrier diffusion length is important for improving device performance

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



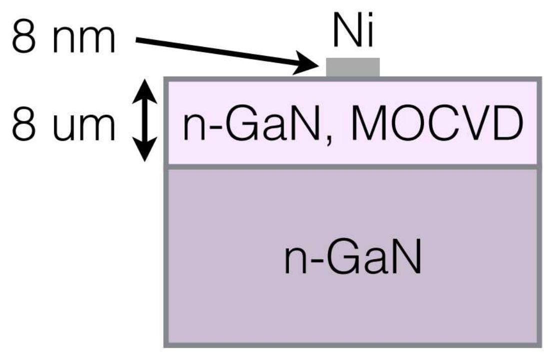
Dickerson et al., IEEE Trans. 63, (2016)

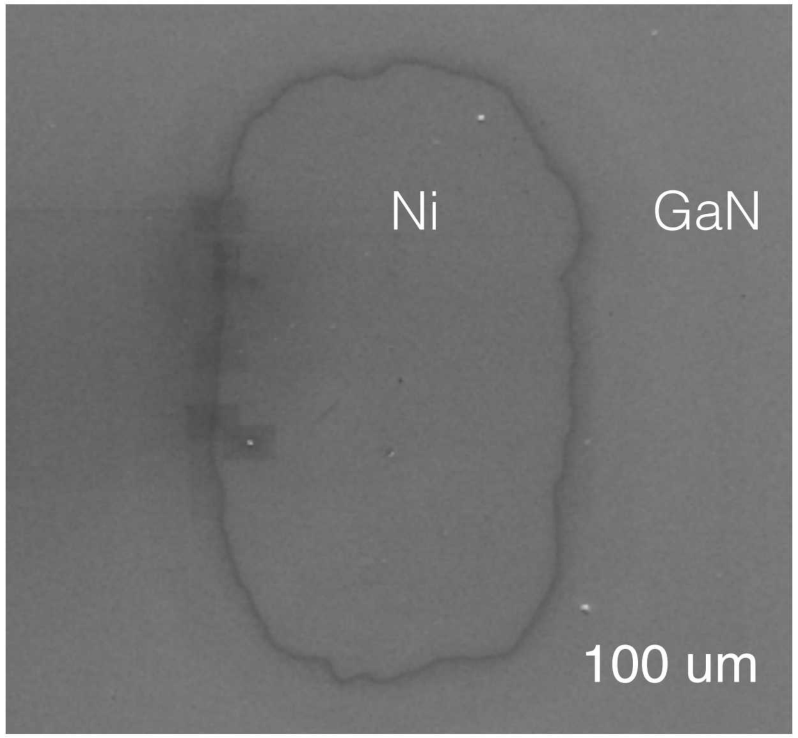
Literature reports of GaN diffusion length, L, vary



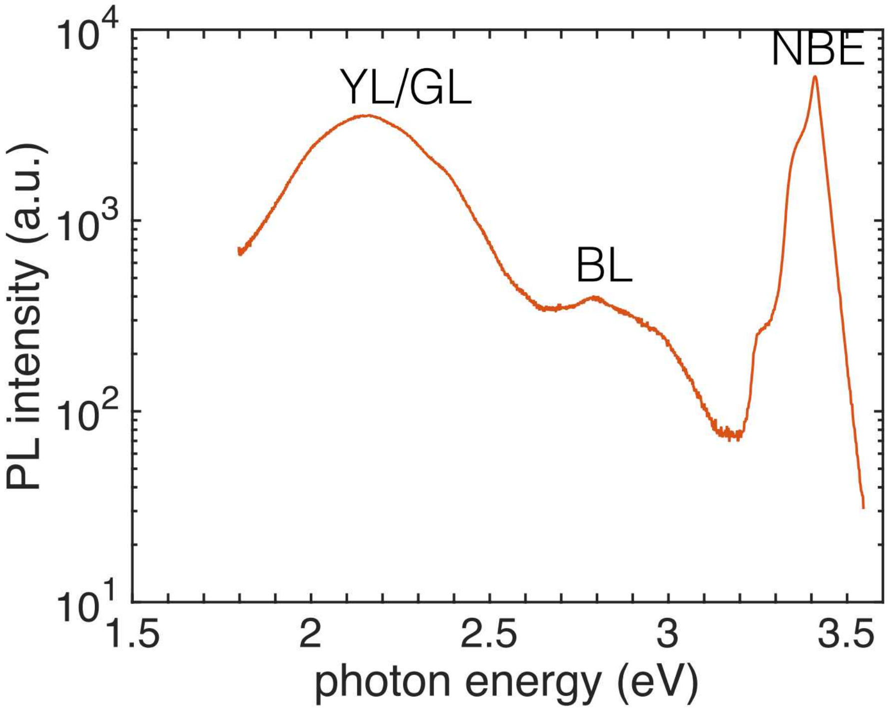
- ○ Yakimov et al., Appl. Phys. Lett. 90 (2007)
- □ Yakimov et al., Appl. Phys. Lett. 92 (2008)
- ◇ Polyakov et al., J. Alloy. Comp. 617 (2014)
- ▽ Bandic et al., Sol. State Elec. 44 (2000)
- △ Chernyak et al., Appl. Phys. Lett. 77 (2000)
- ▷ Chernyak et al., Appl. Phys. Lett. 69 (1996)
- ☆ Kumakura et al., Appl. Phys. Lett. 86 (2005)

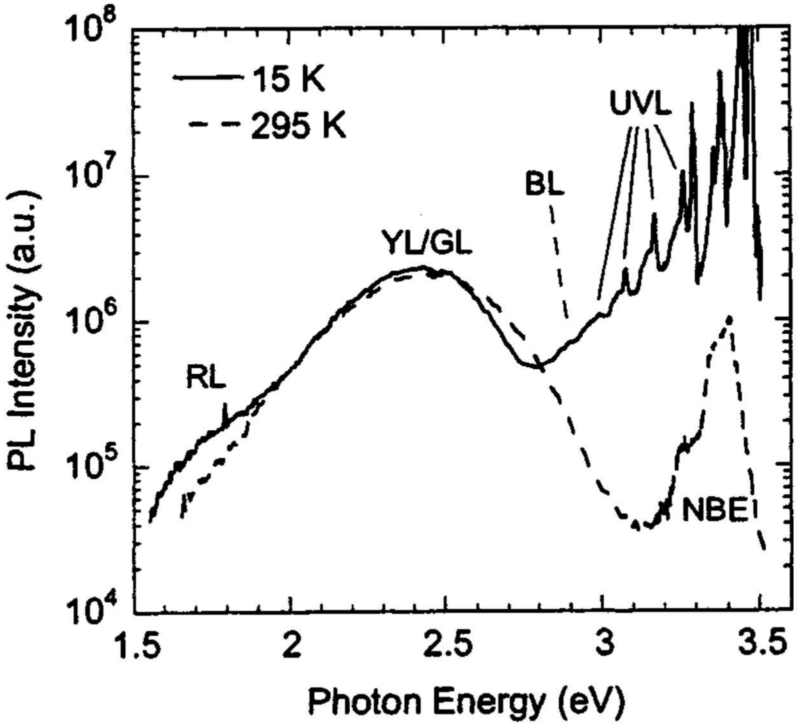
Sample: Ni Schottky on n-GaN





Photoluminescence spectrum comparable to high quality HVPE GaN:

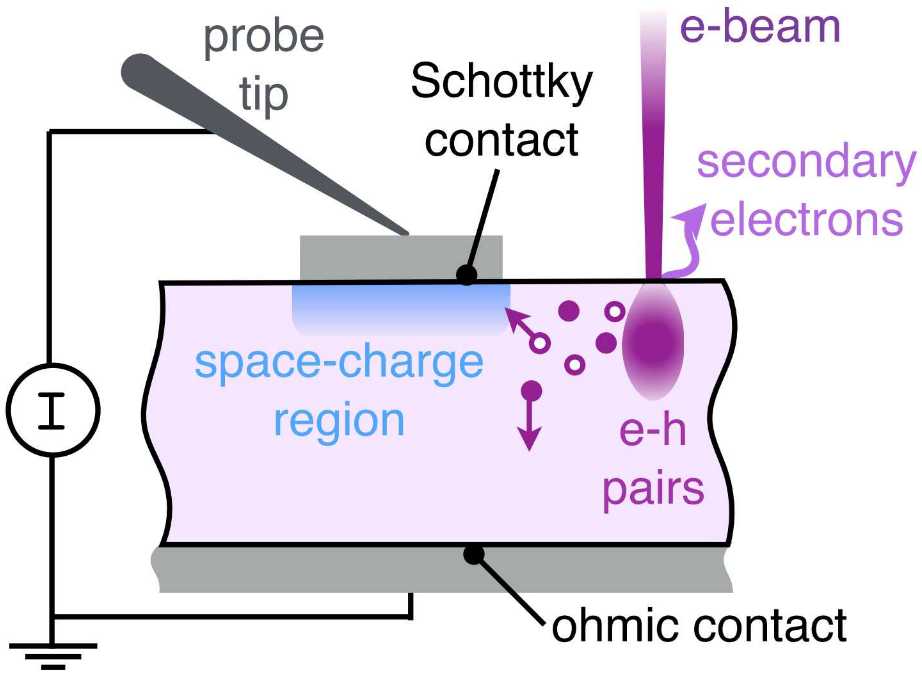


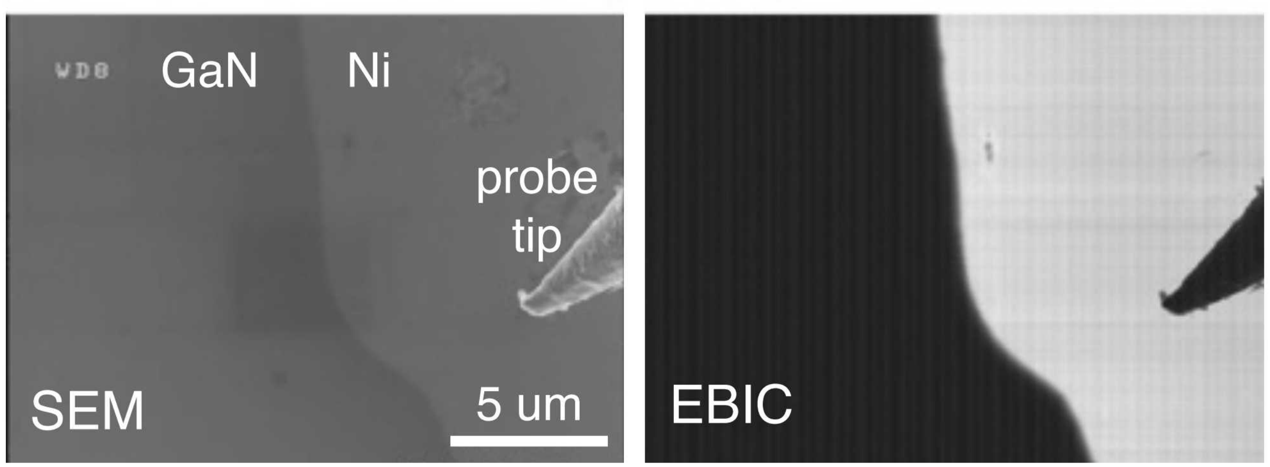


Reshchikov and Morkoc, J. Appl. Phys. 97, (2005)

Configurations for diffusion length measurements

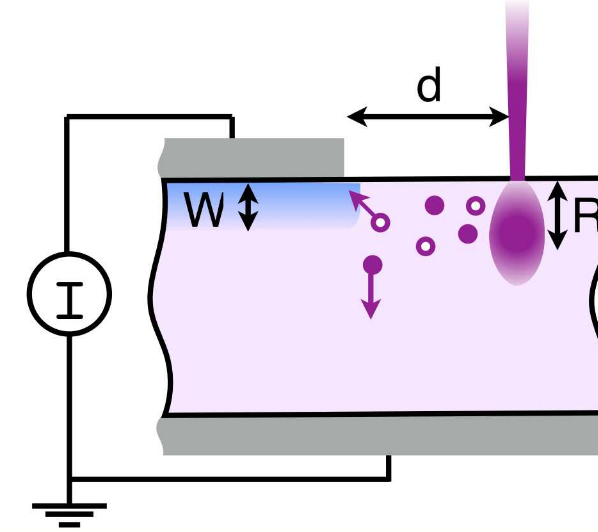
Electron Beam Induced Current (EBIC)





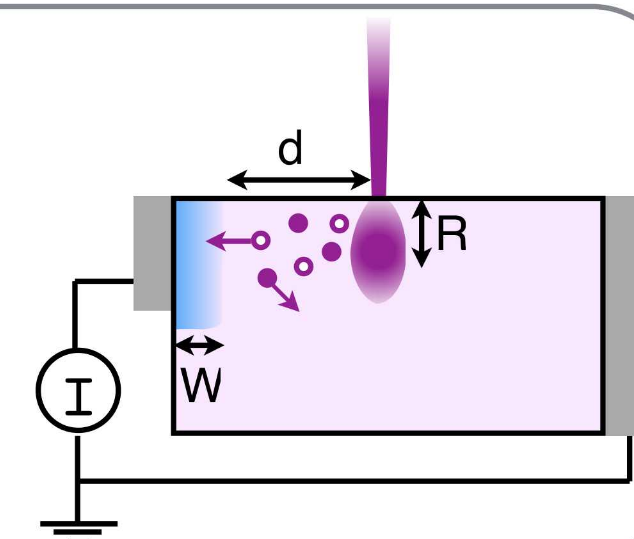
Planar-Collector Configuration

- Vary d
- Straightforward implementation
- Simple model



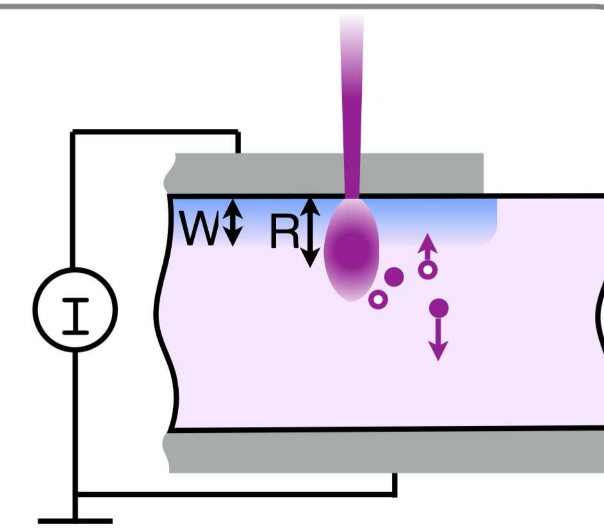
Normal-Collector Configuration

- Vary d
- Challenging implementation
- Simple model

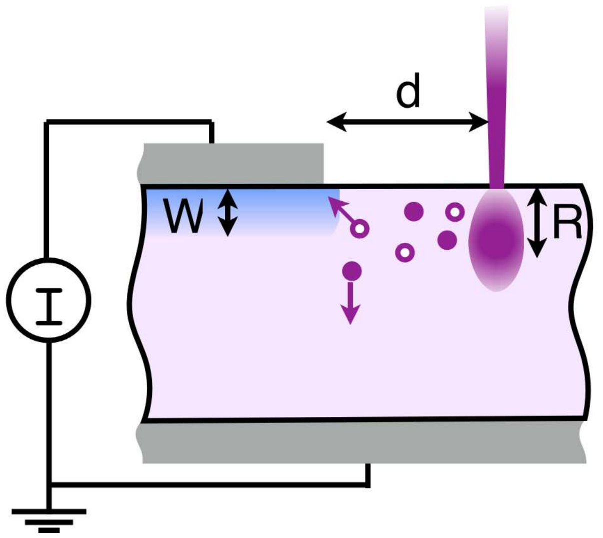


Depth-Dependent Configuration

- Vary R
- Straightforward implementation
- More complex model



Conventional approach: planar-collector EBIC



Simple, commonly used model:

$$\boxed{I(d) = \exp(-d/L)\cdot d^{-n}}$$

n = 0.5 for slow surface recombination ($v \rightarrow 0$)
n = 1.5 for fast surface recombination ($v \rightarrow \infty$)

Main assumptions:

- R >> W
- d >> R
- d >> L
- Generation at a point source

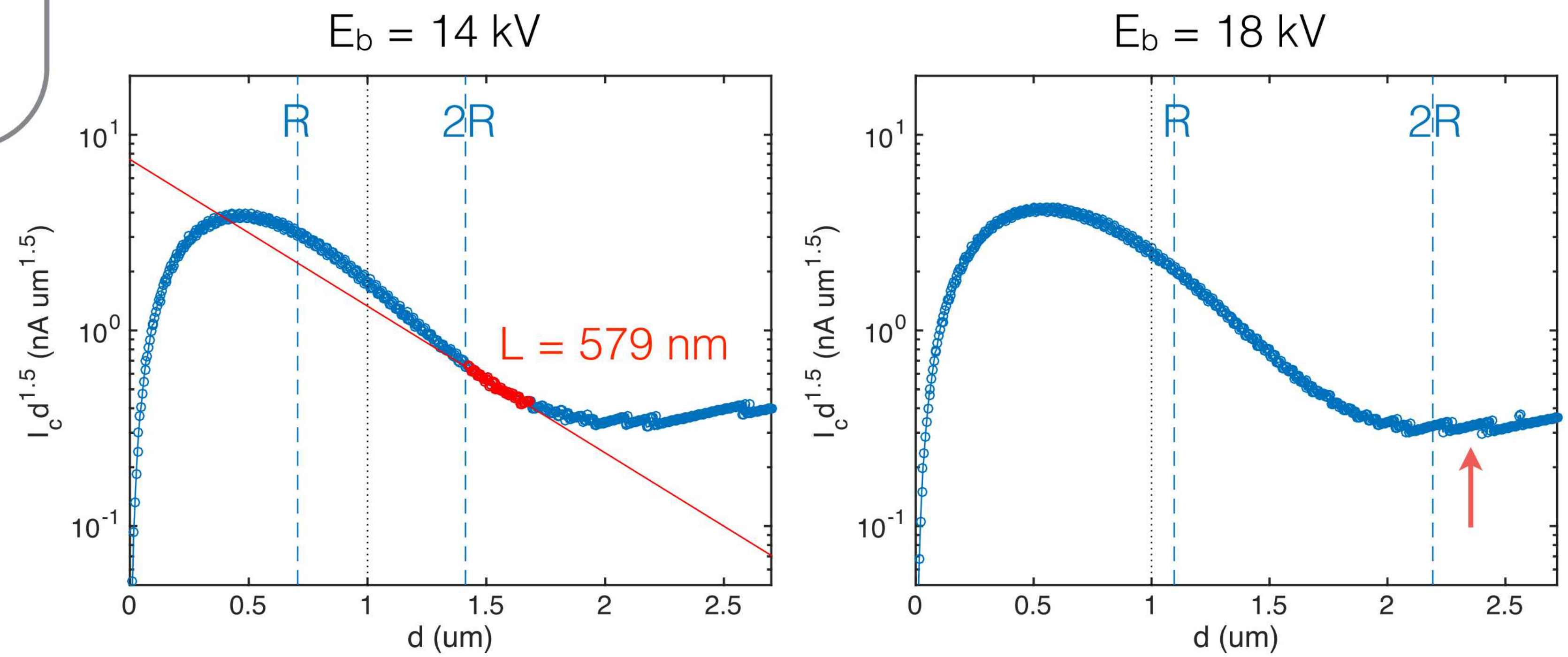
Advantages:

- Straightforward implementation
- Same configuration used for studying defects
- Simple model

Disadvantages:

- Model assumptions difficult to satisfy for materials with small L

d >> R is difficult to satisfy due to signal-to-noise issues



Typical values for GaN Schottky diodes:

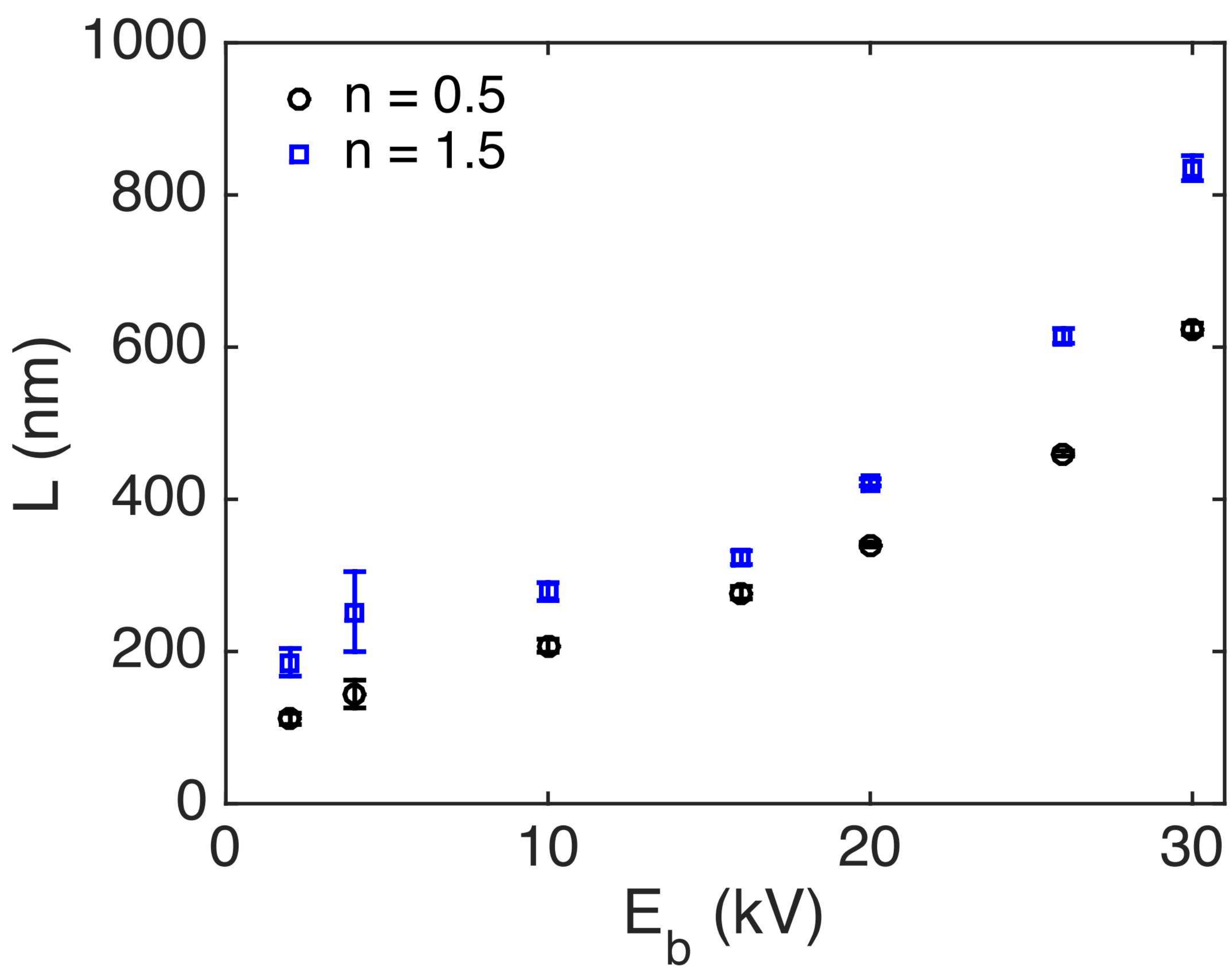
- W ~ 100 nm
- 100 nm < L < 1 um

Yakamov, J. Alloy. and Comp. 627 (2015)

Fitting regardless of model assumptions gives high, inconsistent values for L

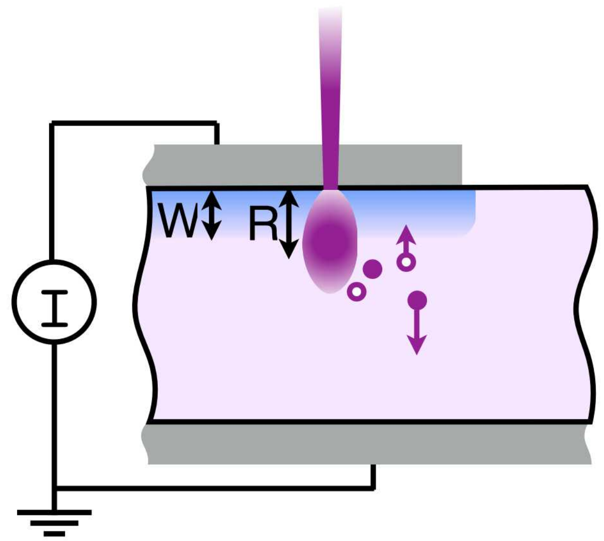
$$I(d) = \exp(-d/L)\cdot d^{-n}$$

n = 0.5 for slow surface recombination ($v \rightarrow 0$)
n = 1.5 for fast surface recombination ($v \rightarrow \infty$)



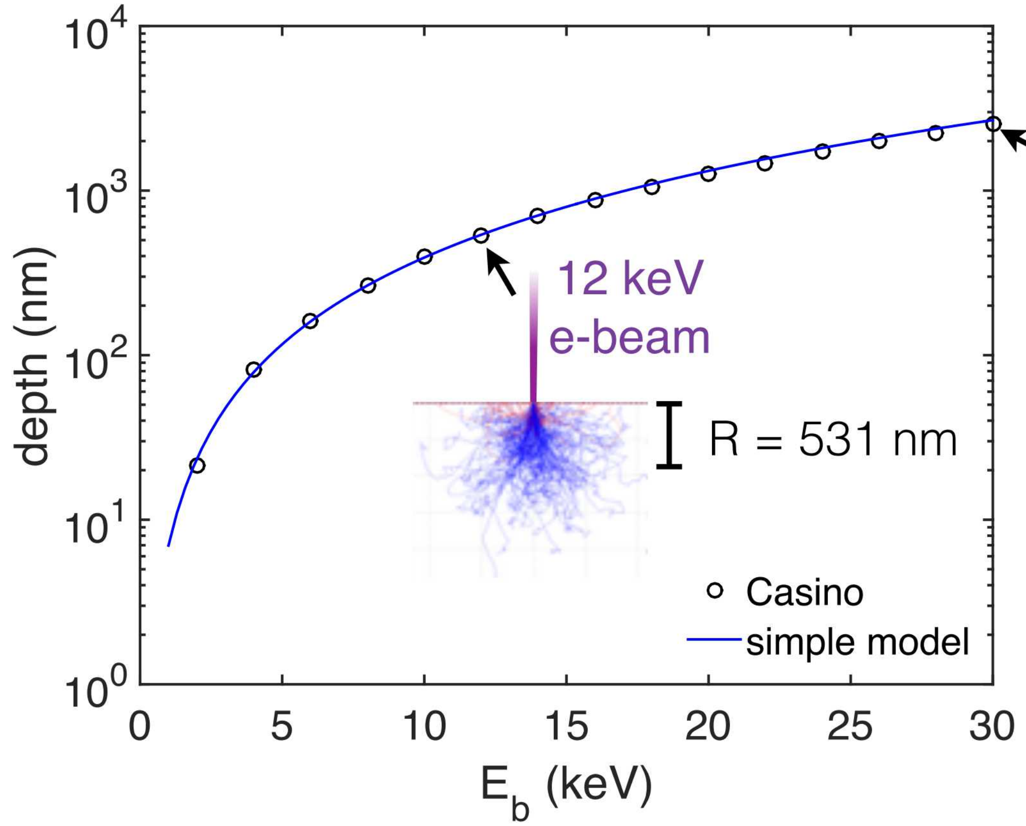
Alternate approach: depth-dependent EBIC

Vary R by changing accelerating voltage, E_b

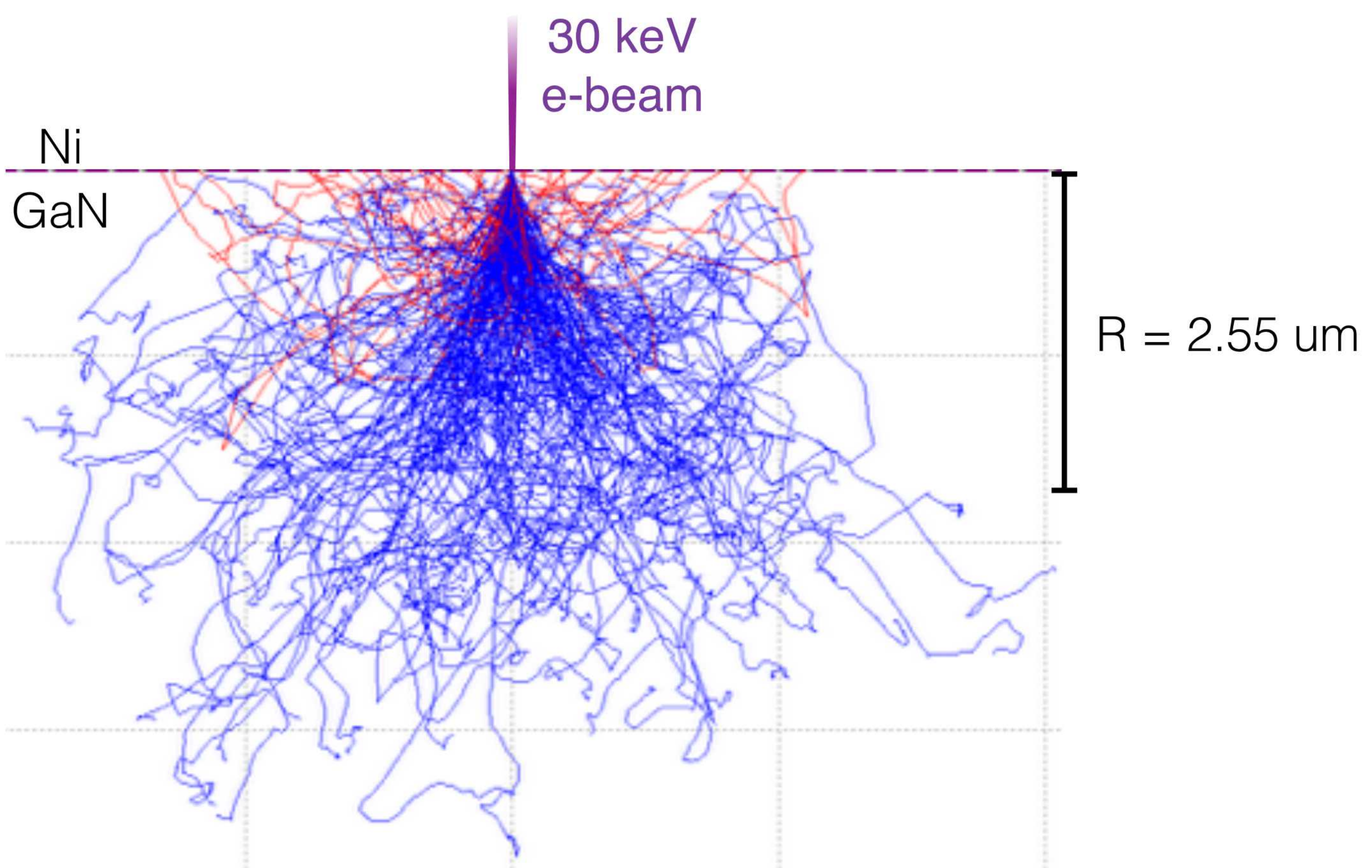


Advantages:
- Straightforward implementation
- Insensitive to surface recombination

Disadvantages:
- More complex model

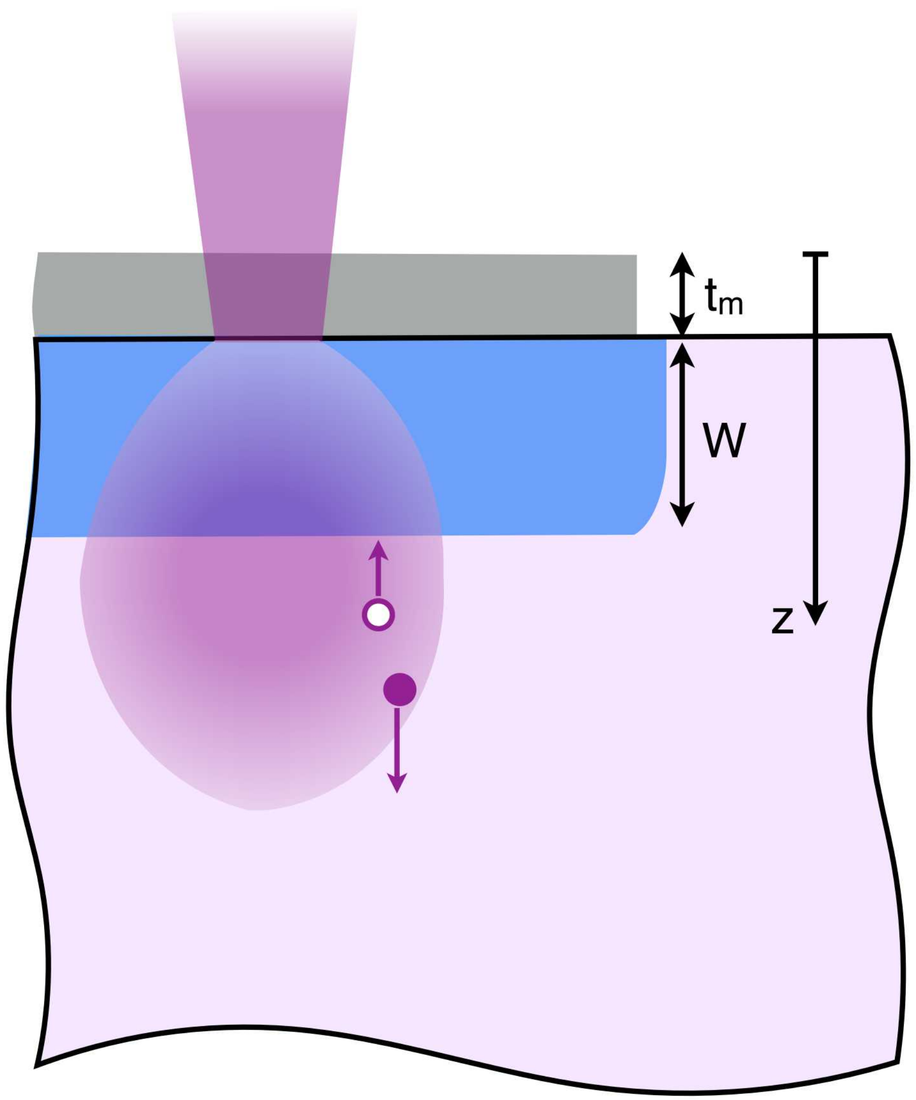


Casino (Monte Carlo) simulation of electron trajectories:



www.gel.usherbrooke.ca/casino/download2.html

Model for collected current in depth-dependent EBIC



h(z) = depth-dose dependent e-h generation rate

collected current

$$I_c = e\beta\left\{\boxed{\int_{t_m}^{W} h(z)dz} + \boxed{\int_{W}^{\infty} h(z)\exp[-(z-W)/L]dz}\right\}$$

total number of e-h pairs created by e-beam

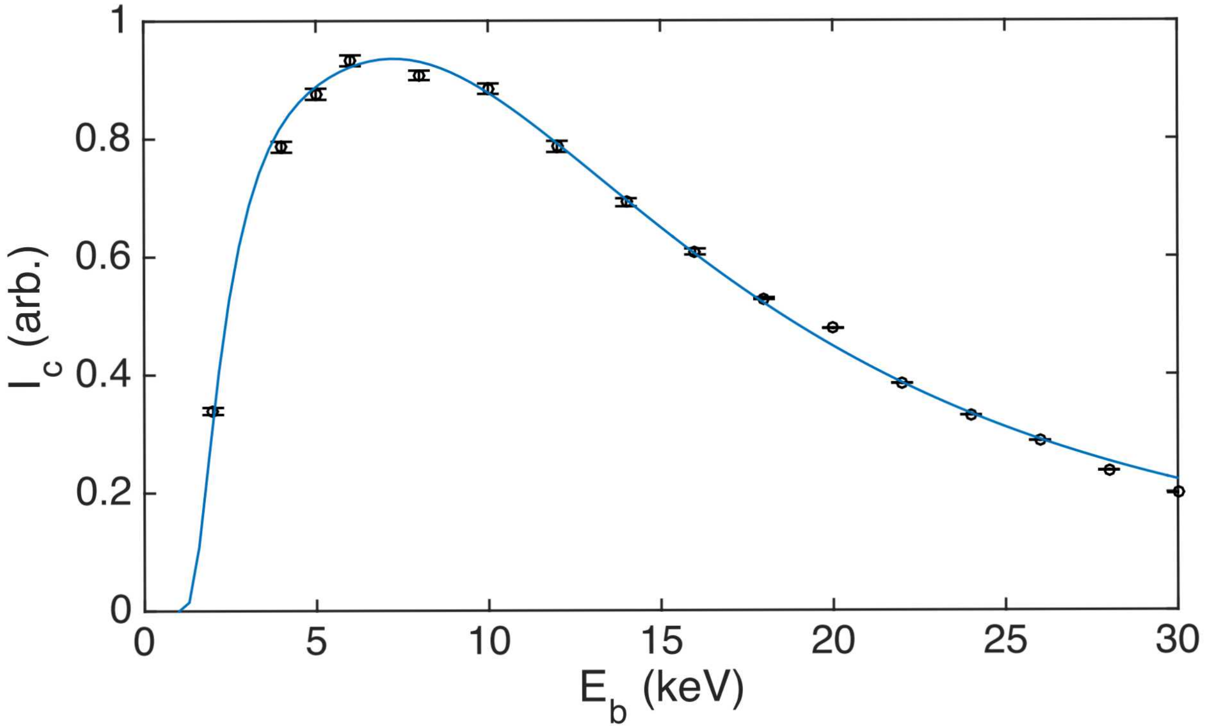
All carriers generated in the space-charge region are collected

Carriers generated in the bulk semiconductor must diffuse to the space-charge region to be collected

Yakamov, J. Alloy. and Comp. 627 (2015)

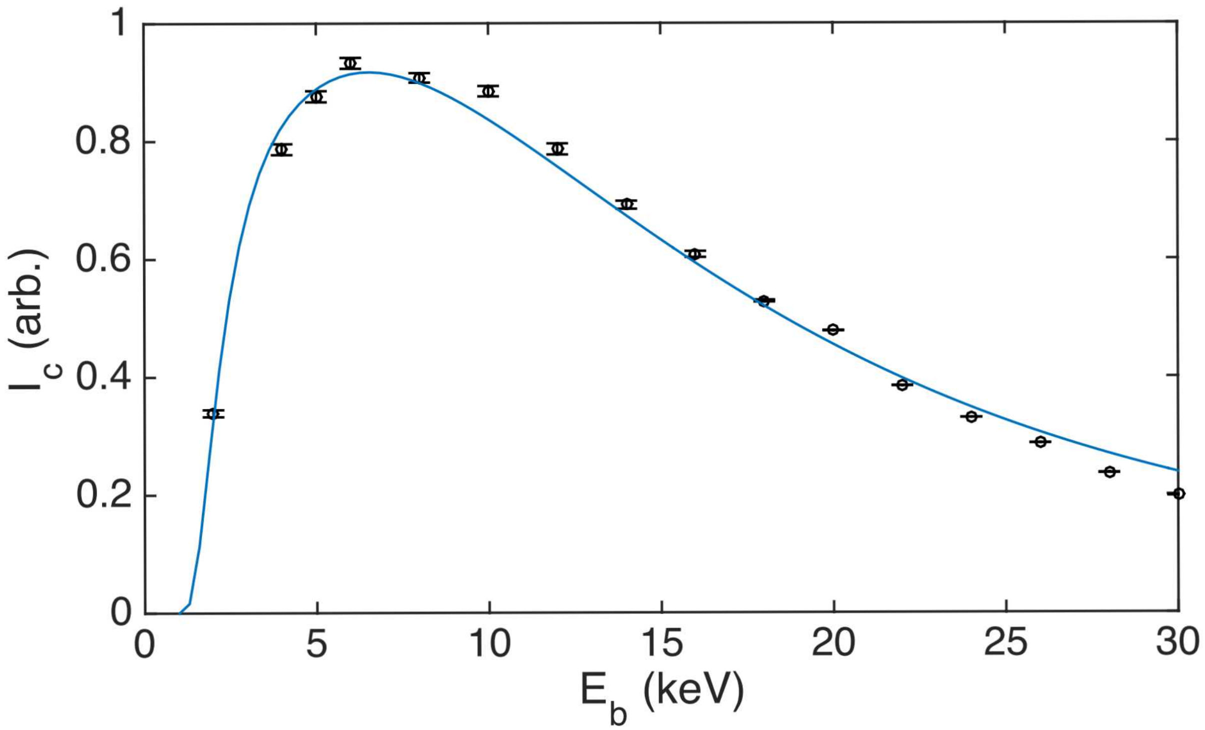
Data and model fitting results

Fitting simultaneously for t_m, W and L:



t_m = 10.6 nm
W = 153.6 nm
L = 282.4 nm

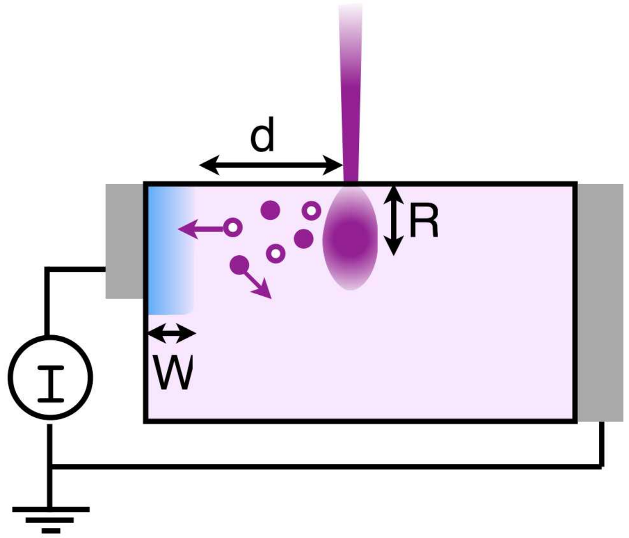
Fitting for t_m and L, assuming W = 100 nm:

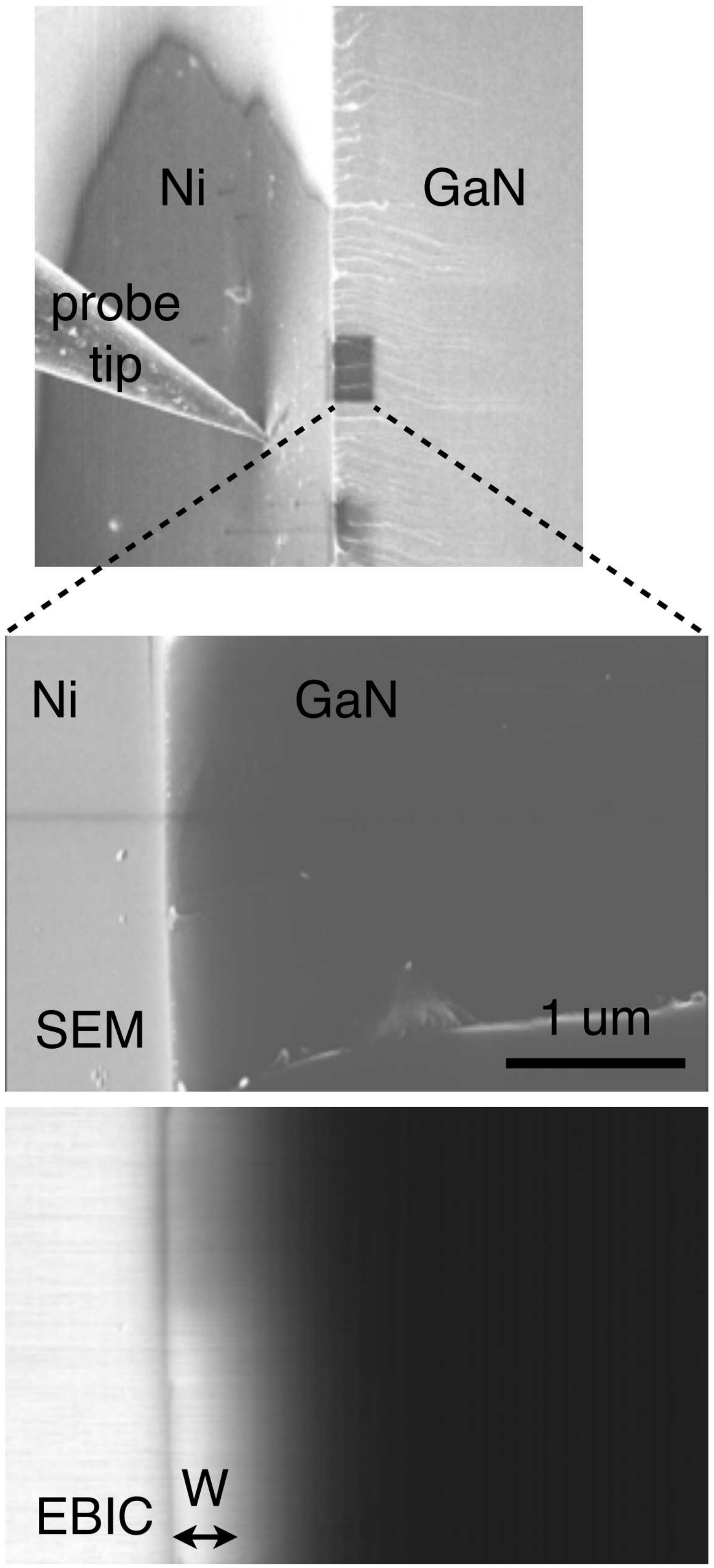


t_m = 10.5 nm
L = 366.4 nm

- Metal thickness target was 8 nm
- Independent measurements found W ~ 100 nm

Comparison to normal-collector shows good agreement





$$I(d) \propto \exp(-d/L)$$

Requires:

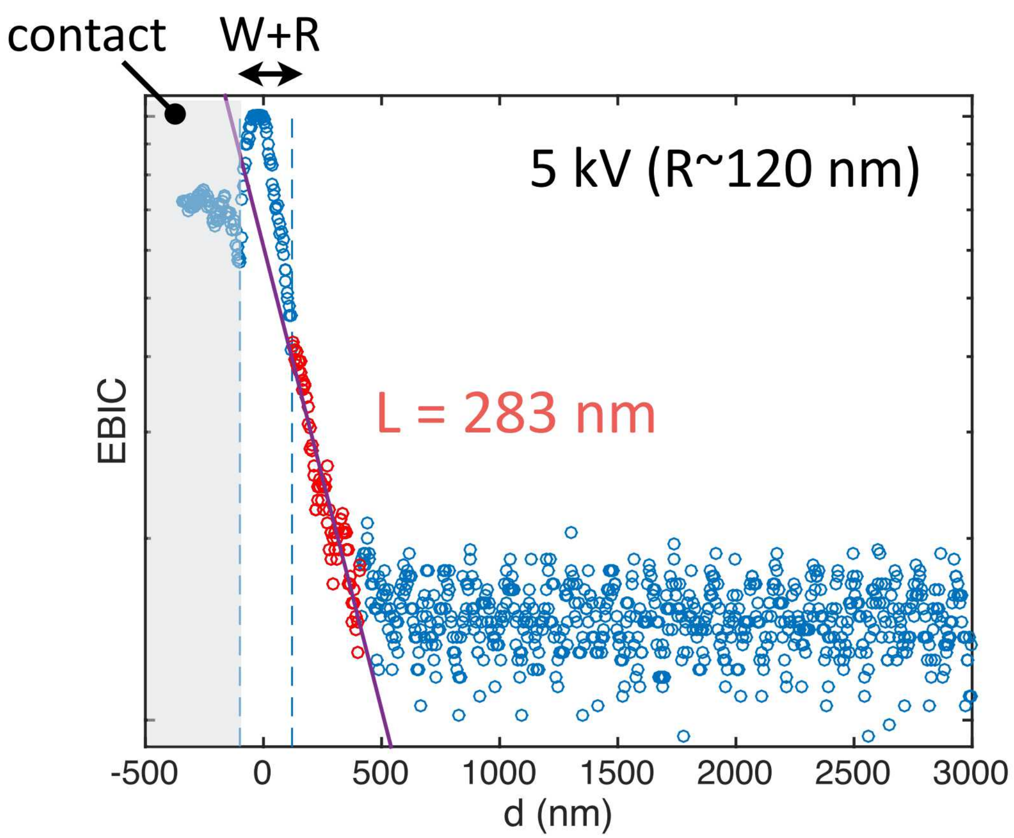
- d > R
- R << L
- R/L < 4
- Negligible surface recombination (v → 0)

Advantages:

- Simple model

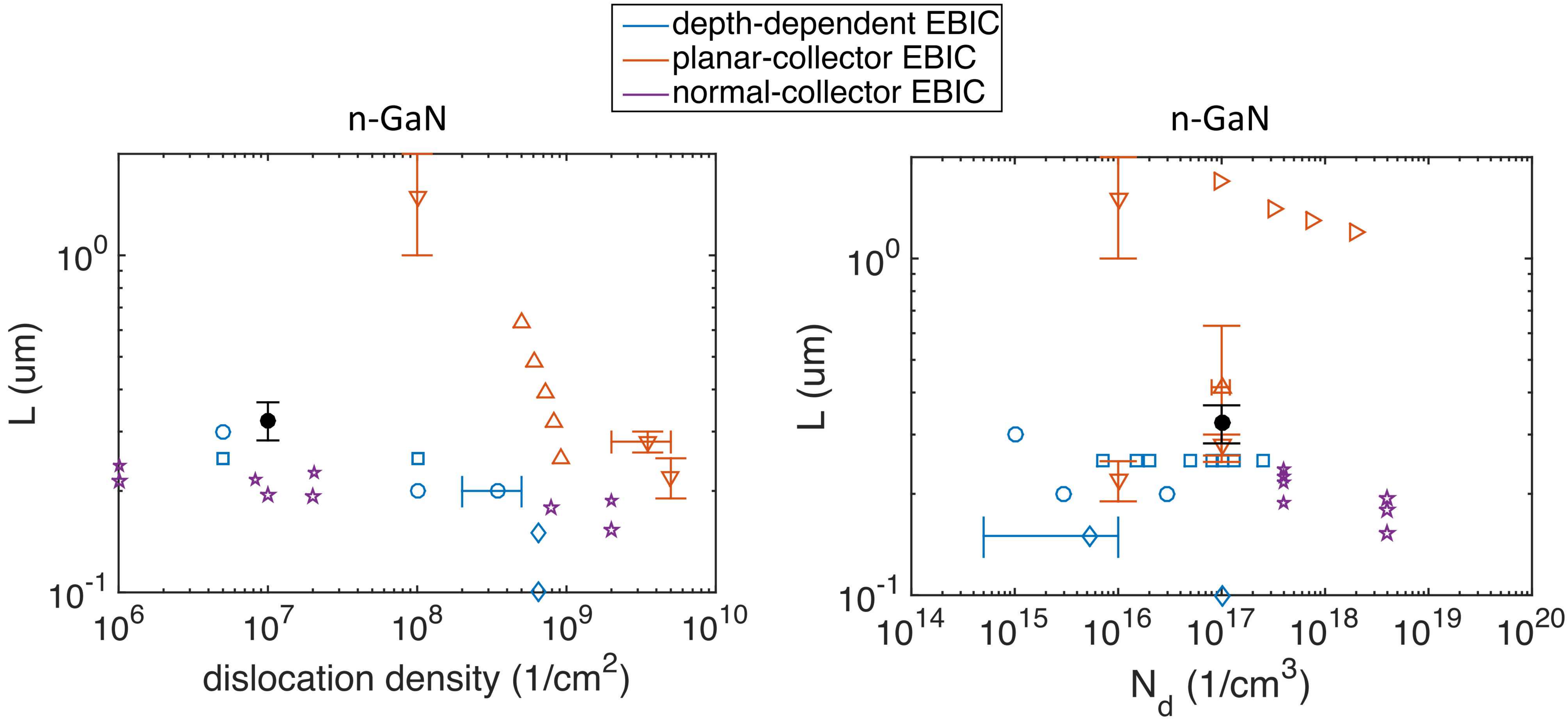
Disadvantages:

- Challenging implementation



Luke et al., J. Appl. Phys. 57 (1985)
Ong et al., Solid-State Elec. 37 (1994)

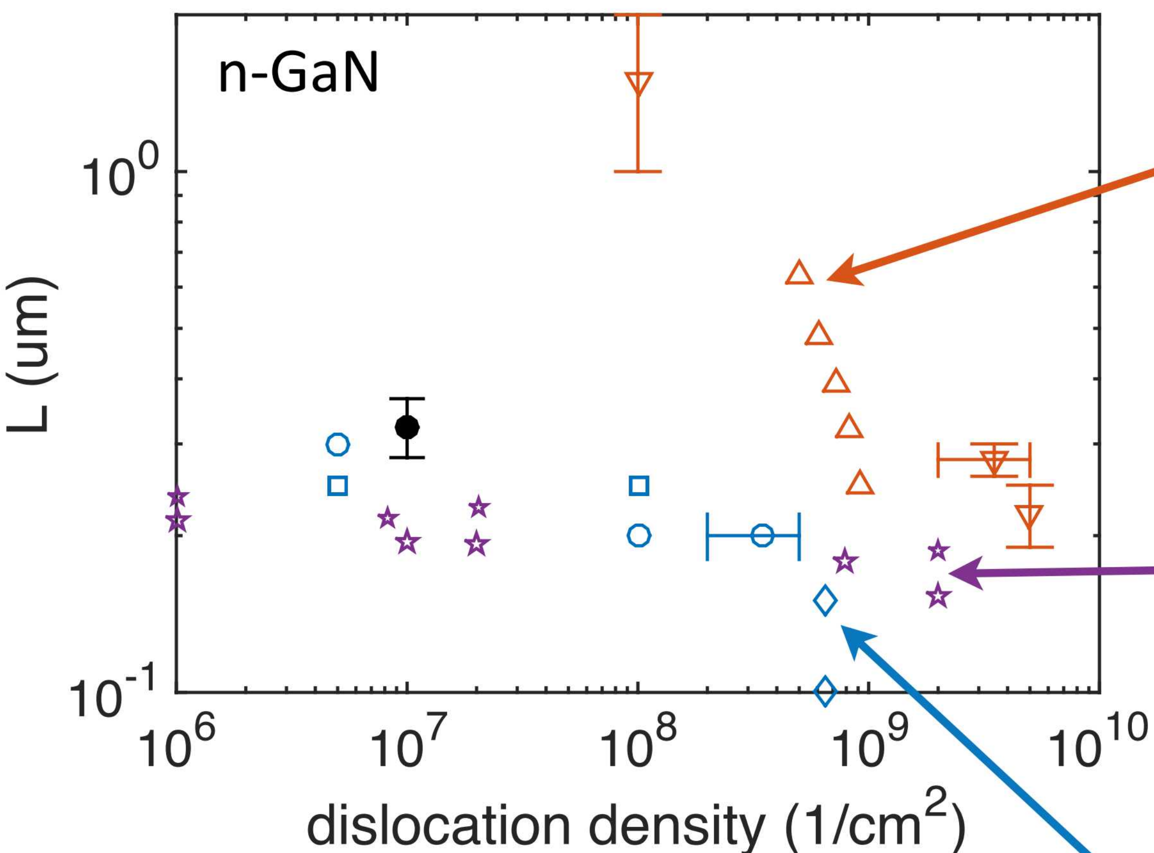
Comparison to literature

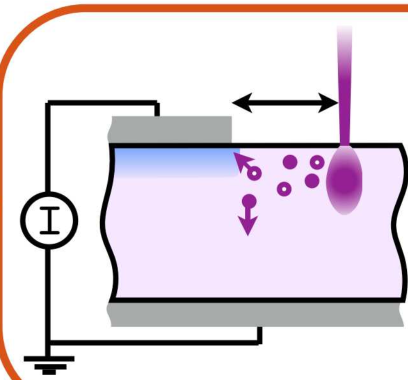


- ○ Yakimov et al., Appl. Phys. Lett. 90 (2007)
- □ Yakimov et al., Appl. Phys. Lett. 92 (2008)
- ◇ Polyakov et al., J. Alloy. Comp. 617 (2014)
- ▽ Bandic et al., Sol. State Elec. 44 (2000)
- △ Chernyak et al., Appl. Phys. Lett. 77 (2000)
- ▷ Chernyak et al., Appl. Phys. Lett. 69 (1996)
- ☆ Kumakura et al., Appl. Phys. Lett. 86 (2005)

Summary

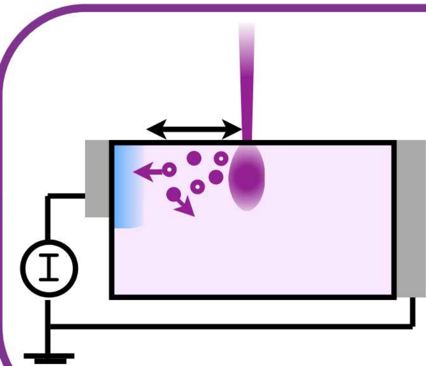
- We use EBIC to measure the hole diffusion length for high-quality homoepitaxial GaN, and explore three measurement implementations.





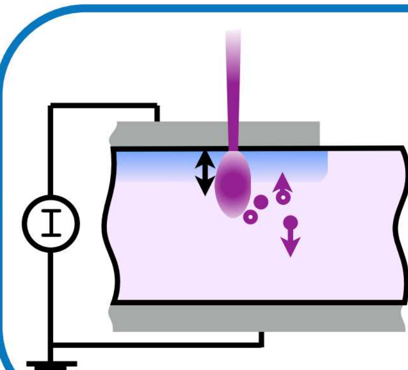
Planar-Collector Configuration

- Use with caution!
- Not a good choice for low L materials.
- Gives high, inconsistent L values.



Normal-Collector Configuration

- Use if possible
- Challenging implementation, but reliable results



Depth-Dependent Configuration

- Best choice
- Straightforward implementation and reliable results that are consistent with the normal-collector configuration