Simulation and Investigation of Electrothermal Effects in Heterojunction Bipolar Transistors

SAND2019-9967C

Xujiao (Suzey) Gao*, Gary Hennigan, Lawrence Musson, Andy Huang, Mihai Negoita
* xngao@sandia.gov, Sandia National Laboratories, Albuquerque, NM

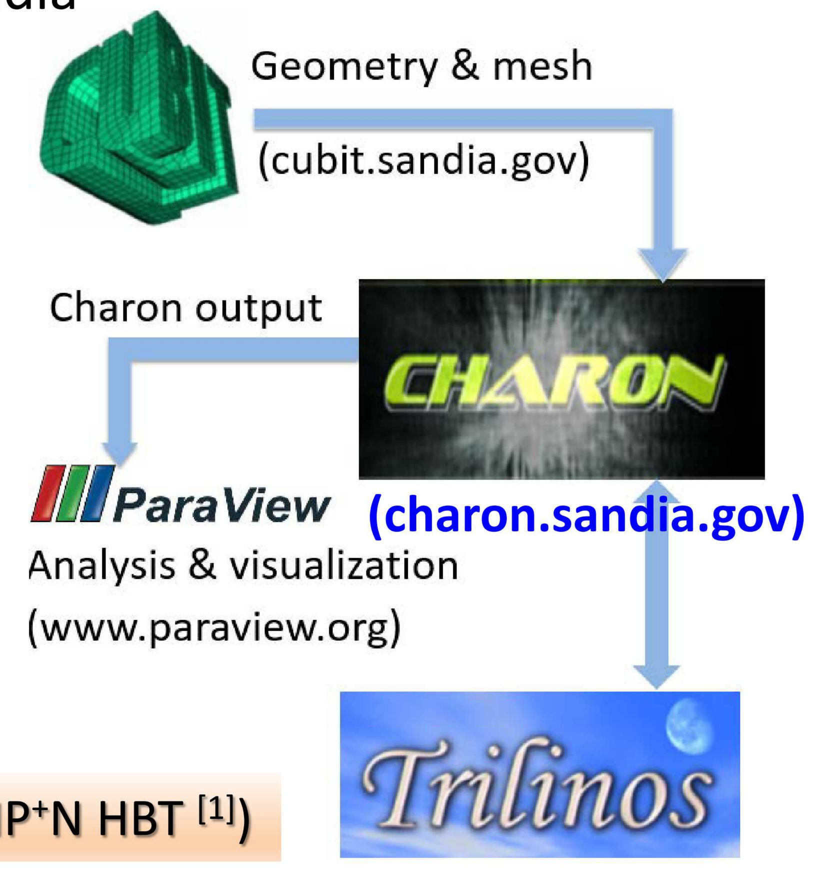
Introduction and Motivation

- InGaP/GaAs heterojunction bipolar transistors (HBTs) are widely used in mobile and space applications
- Physics of electrothermal effects in III-V HBTs is not well understood because existing HBT compact models do not work well for modeling self-heating and breakdown effects
- This work presents **a deep dive into self-heating and impact ionization effects** in InGaP/GaAs HBTs via TCAD simulations, potentially enabling us to improve circuit compact models for III-V HBTs

Modeling Approach

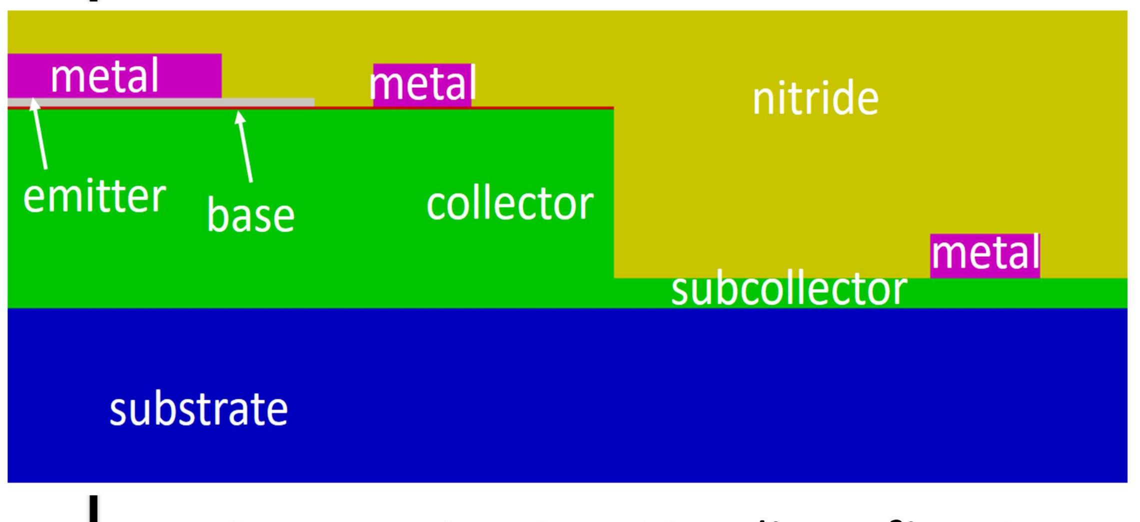
Simulations were done using **Charon**, a 2D/3D **MPI-parallel** TCAD device simulator developed at Sandia

- Coupled drift-diffusion & lattice heating simulation
- Temperature dependent material property models
- Include impact ionization
- Thermionic emission and tunneling at heterojunction
- Thermal resistance boundary conditions



Simulation Device ($In_{0.5}Ga_{0.5}P/GaAs$ NP^+N HBT [1])

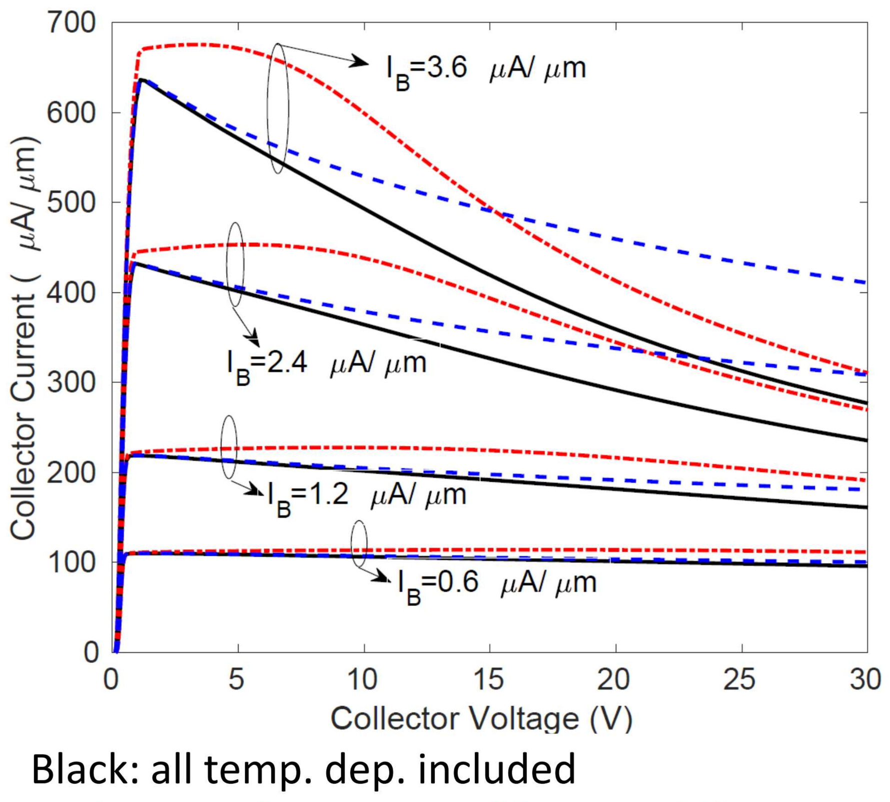
Connected to Gs = 200 W/(K.cm^2) obtained from fitting simulated responses to experiment data

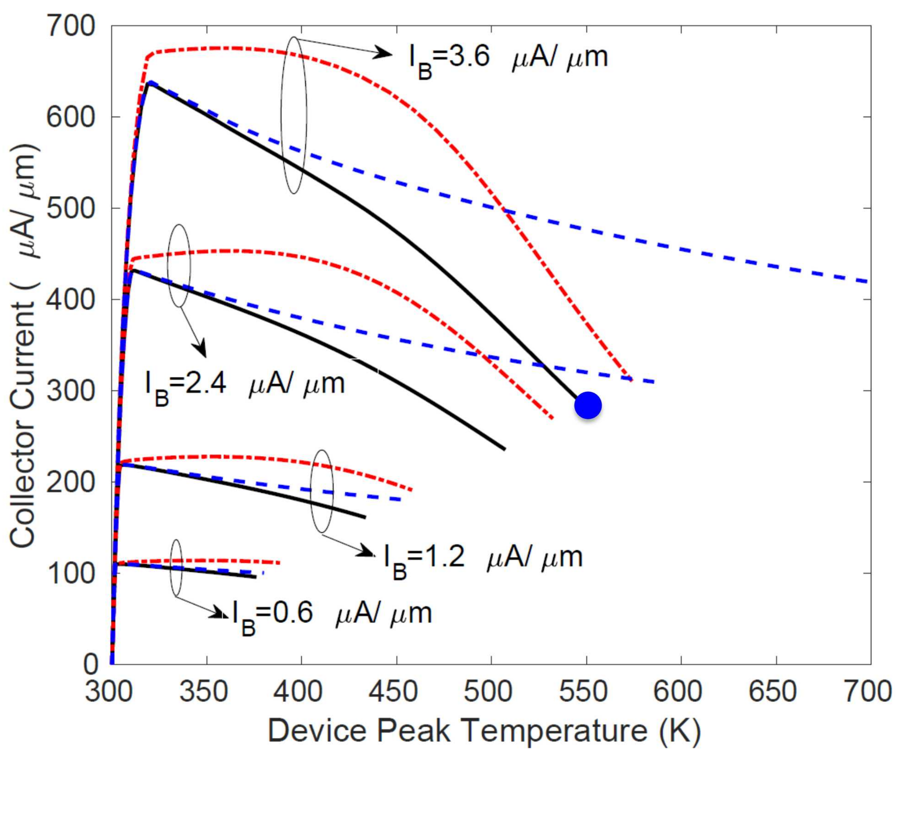


Connected to Gs = 10 W/(K.cm^2) estimated from substrate thickness and GaAs thermal conductivity

Results and Discussions

Self-Heating (SH) Effects for Constant Base Current (I_B)





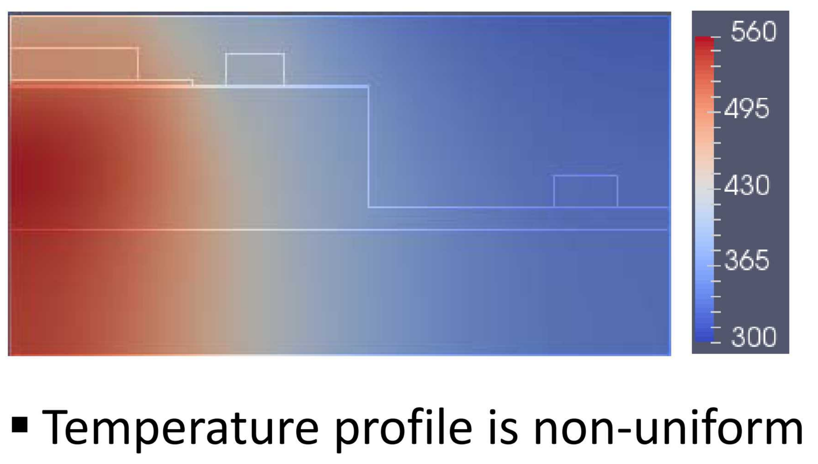
Black: all temp. dep. included
Red: temp. dep. removed from mobility
Blue: temp. dep. removed from the base-to-emitter hole back injection

$$J_{TE,p} = A_p^* T^2 \left[\frac{p_E}{N_{V,E}} - \frac{p_B}{N_{V,B}} \exp\left(-\frac{\Delta E_V}{k_B T}\right)\right]$$

At low V_{CE}, I_C shows a power-law temp. dep. → mobility reduction dominates

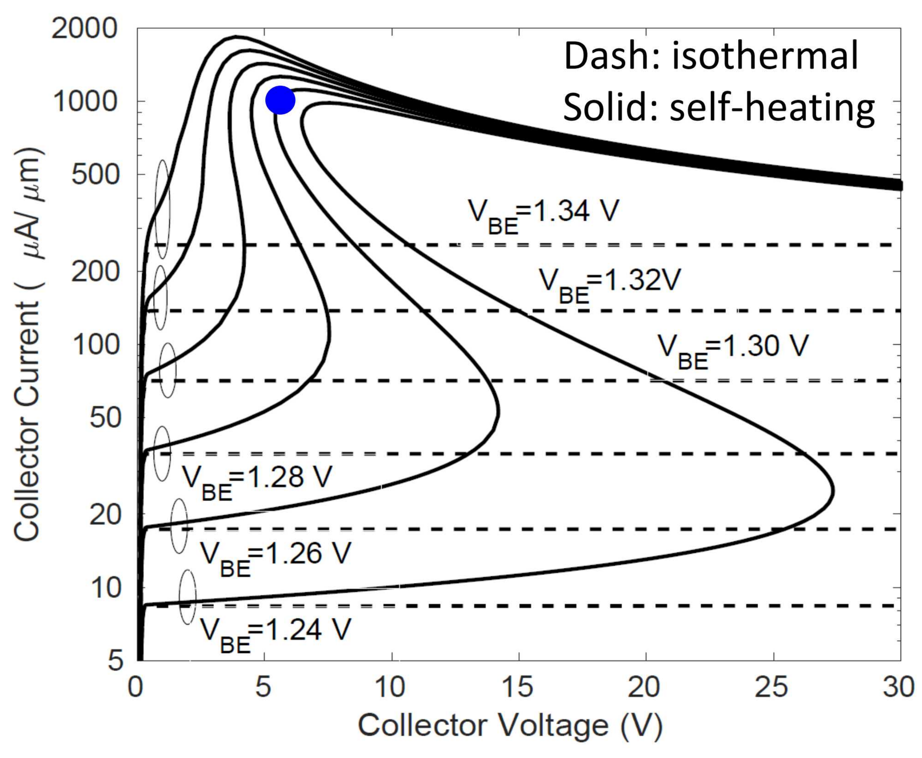
At high V_{CE}, I_C shows an exponential dep. on temp. → base-to-emitter hole back injection dominates I_C reduction

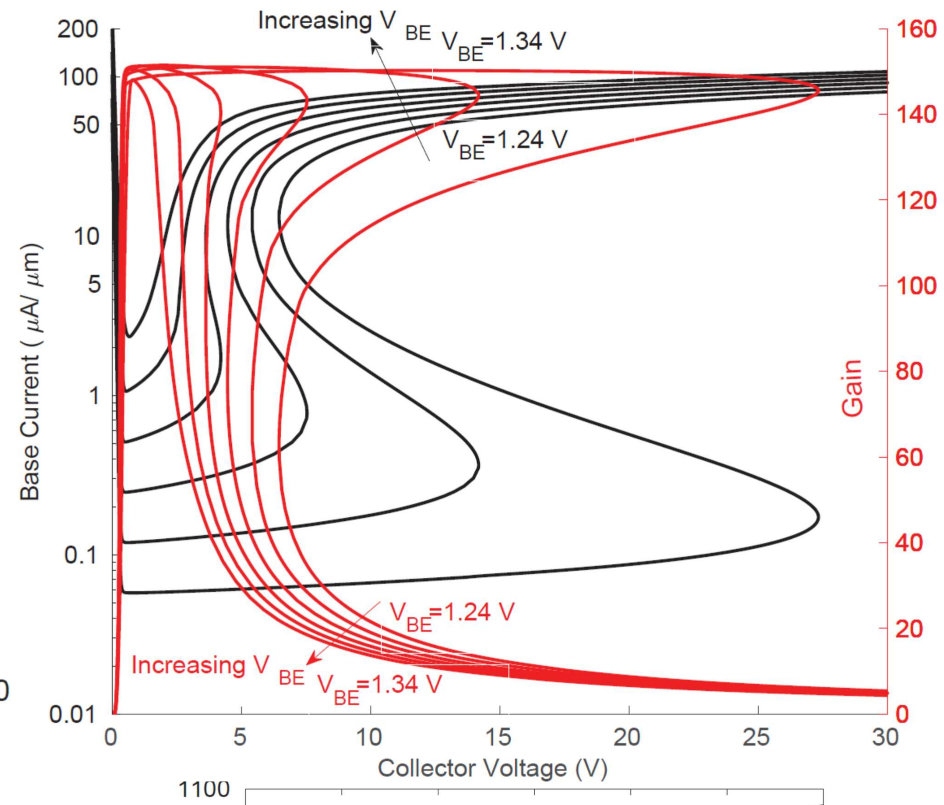
Device temperature profile (●)



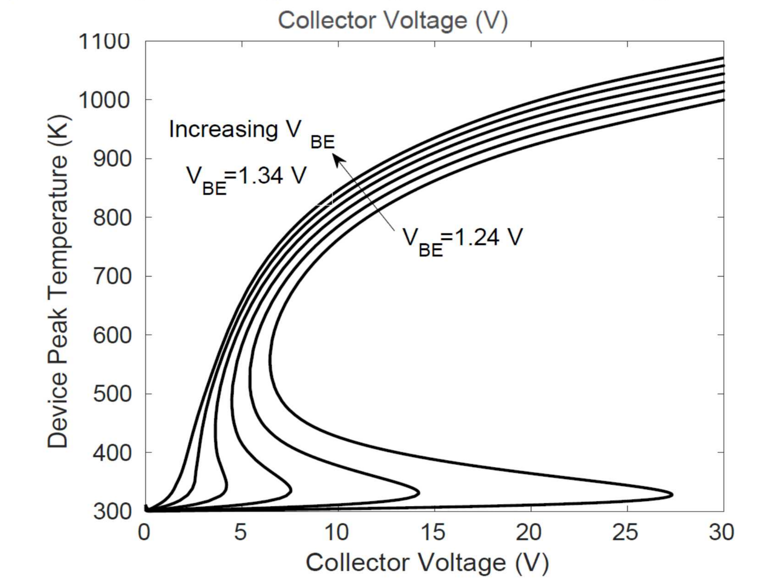
- Temperature profile is non-uniform
- The device is heated up mostly in the active region below the emitter.

Self-Heating (SH) Effects for Constant Base-Emitter Voltage (V_{BE})



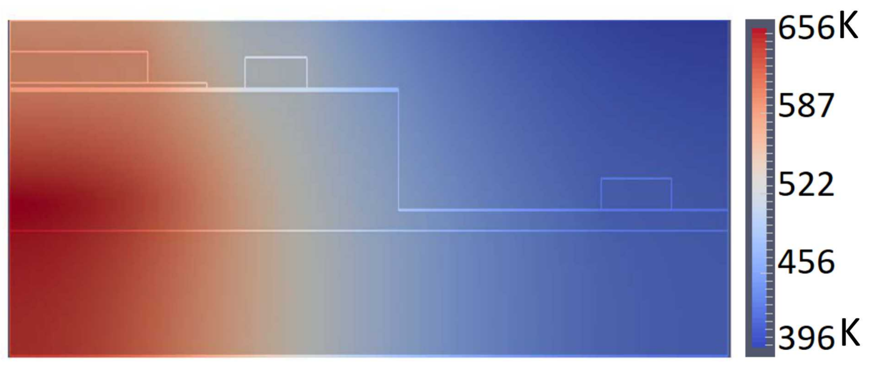


- Fly-back occurs at low V_{BE}, not at high V_{BE}
- Similar fly-back observed by others[2]
- I_C converged at high temp. due to hole back injection as in the constant I_B case
- Fly-back never occurs for constant I_B

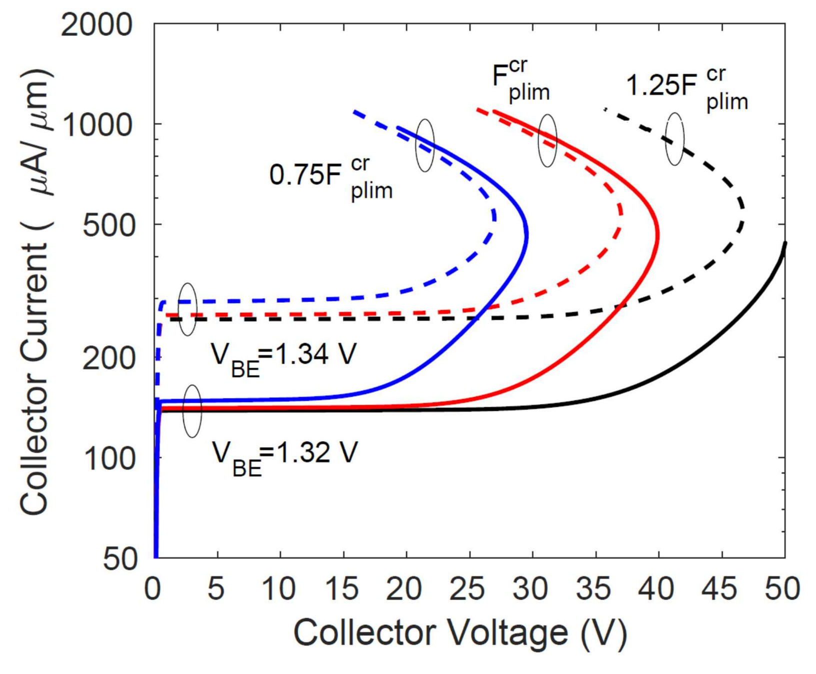


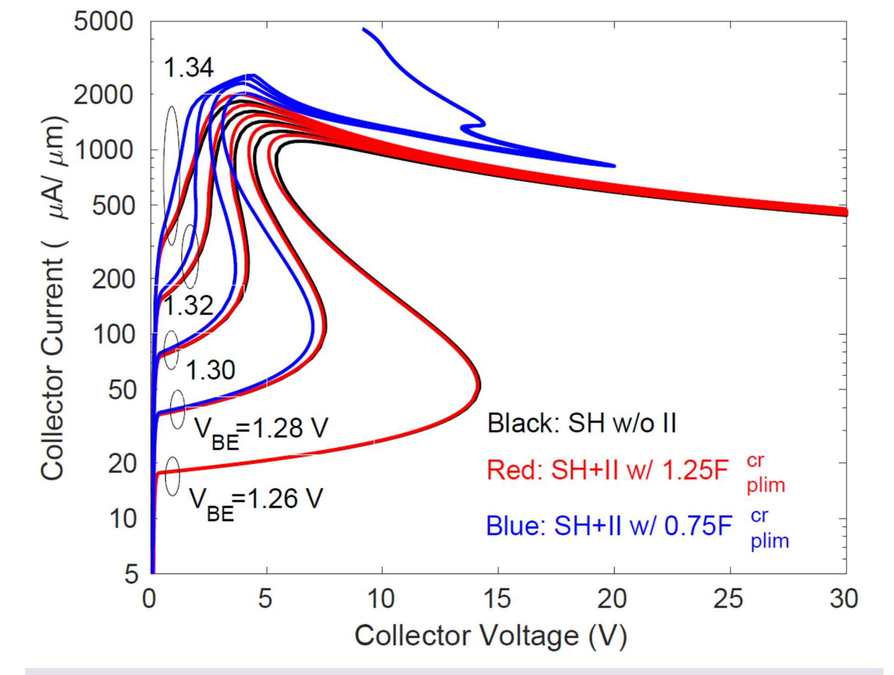
SH induced fly-back is due to competing processes of thermal gen. & carrier recomb. At high V_{BE}, strong injection obscures thermal generation, so NO fly-back[4].

Temperature profile at the peak current (●)



Impact Ionization (II) Effects for Constant V_{BE} Voltage





- Isothermal with the Plimmer II model[3]
- II induced fly-back is due to avalanche generation (thermal gen. in the SH case)
- Fly-backs occur at much higher voltages

- Self-heating with the Plimmer II model
- Multiple fly-backs occur when the II critical field is reduced by 25% (blue)
- Device fails due to SH well before the II induced fly-back occurs

Conclusions

- Negative slopes in the output responses of InGaP/GaAs HBTs are found due to carrier mobility reduction and **the increased base-to-emitter hole back injection** with increasing temperature.
- Both SH and II can **cause fly-backs** in the output responses of HBTs under constant base-emitter voltages.
- Fly-backs are resulted from **competing processes** of carrier recombination and SH and/or II induced carrier generation.
- Device failure under quasi-DC operation is **dominated by SH** since II induced fly-backs occur at much higher voltages.

[1] S. Choi *et al.*, IEEE Trans. Compon., Packag., Manuf. Technol., **6**, 740 (2016).
[2] N. Rinaldi and V. d'Alessandro, IEEE Trans. Electron Devices **52**, 2009 (2005), and IEEE Trans. Electron Devices **53**, 1683 (2006).
[3] S. A. Plimmer *et al.*, Semicond. Sci. Technol. **15**, 692 (2000).
[4] X. Gao *et al.*, submitted to J. Rad. Eff., Res. and Engr., June 2019.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.