Translating and Supplementing Si Based Radiation Effects Knowledge to the Wide Band-Gap Devices of Tomorrow's Space Flight Missions

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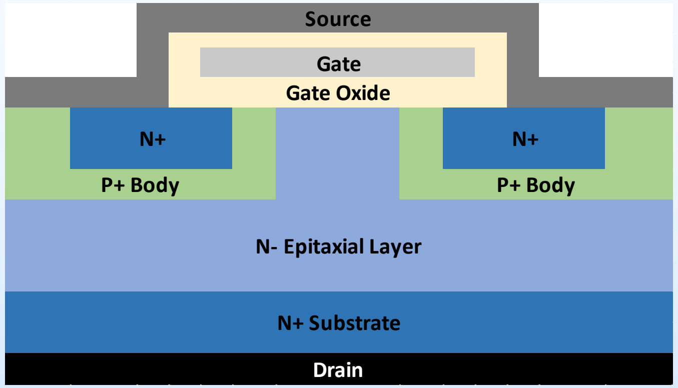
Acronyms

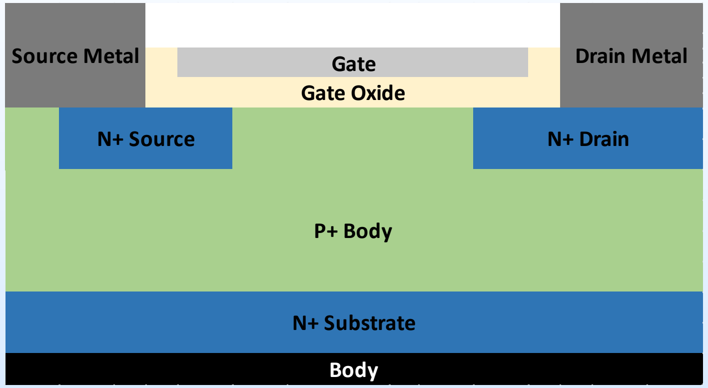
- BJT: Bipolar Junction Transistor
- DDD: Displacement damage dose
- DUT: Device Under Test
- EPC: Efficient Power Conversion
- FET: Field Effect Transistor
- GSFC: Goddard Space Flight Center
- HEMT: High Electron Mobility Transistor
- HV: High Voltage
- JBS: Junction Barrier Schottky
- LBNL: Lawrence Berkeley National Lab
- LET: Linear Energy Transfer
- NEPP: NASA Electronics and Packaging Program
- REAG: Radiation Effects and Analysis Group
- SEB: Single Event Burnout
- SEDR: Single Even Dielectric Rupture
- SEE: Single Event Effects
- SEGR: Single Event Gate Rupture
- SELC: Single Event Leakage Current
- SBIR: Small Business Innovation Research
- SRIM: Stopping Ranges of Ions in Matter
- TID: Total Ionizing Dose
- WBG: Wide Band Gap

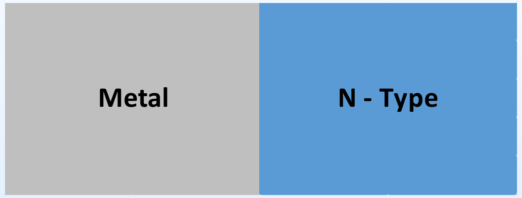
Outline

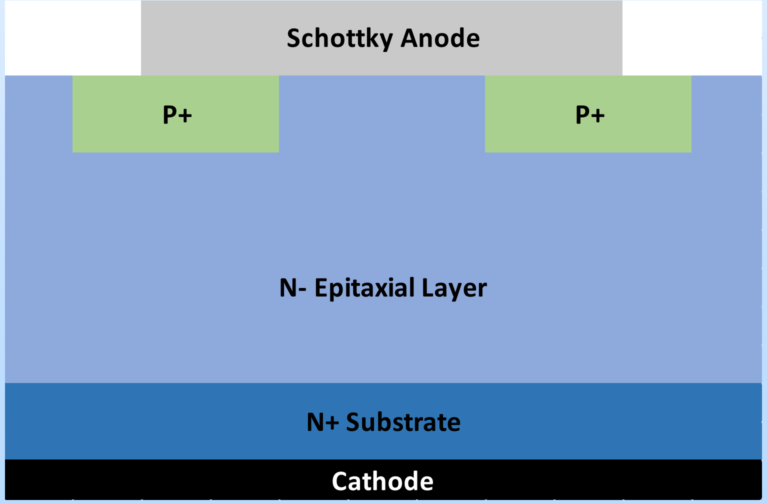
- Total Ionizing Dose (TID)
- Displacement Damage Dose (DDD)
- Single Event Effects (SEE) in Si
- Wide Band Gap (WBG) Material properties
- SiC
- GaN
- GaOx
- Other Materials
- Conclusion/Questions

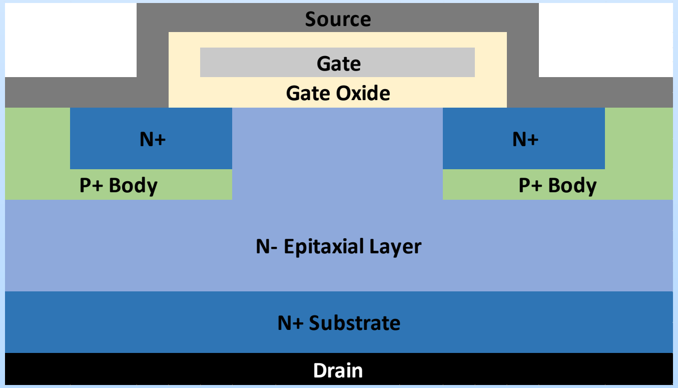
Silicon Power Devices

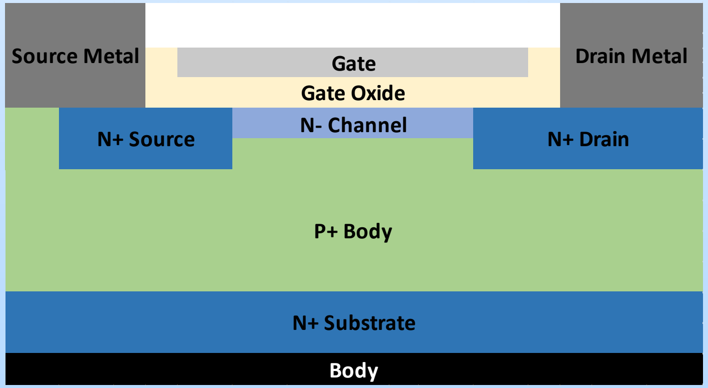






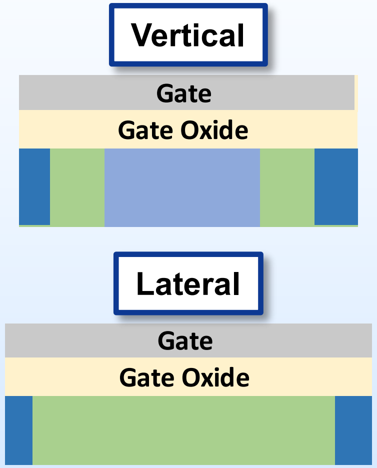


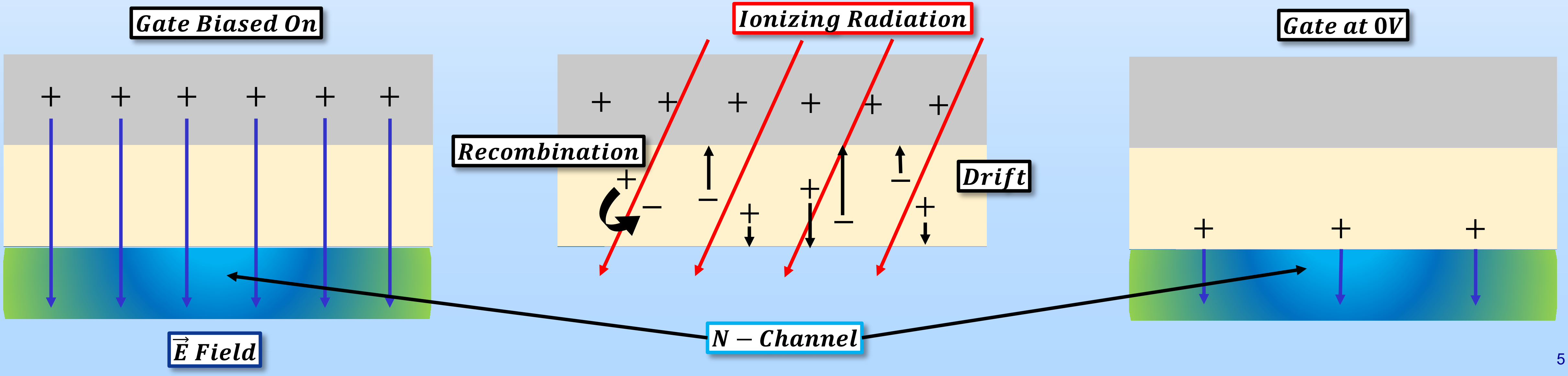




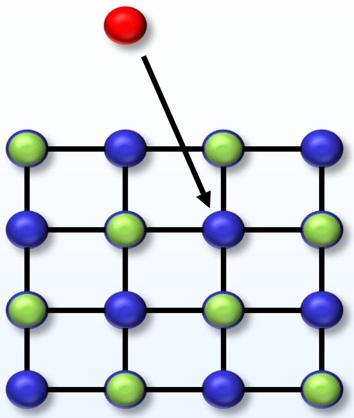
Total Ionizing Dose (TID)

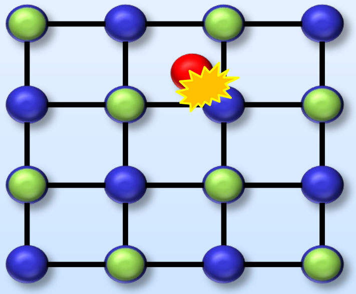
- Ionizing radiation creates charge in the oxide layer
- Bias conditions allow for charge drift
- Negative charges are moved towards the positively biased gate and swept out
- Accumulation of trapped positive charge in the oxide layer
  - Cumulative Effect
- Gate threshold voltage will shift downward towards zero as charge accumulates
- Power devices have thick oxides
- No gate oxide in diodes or HEMTs



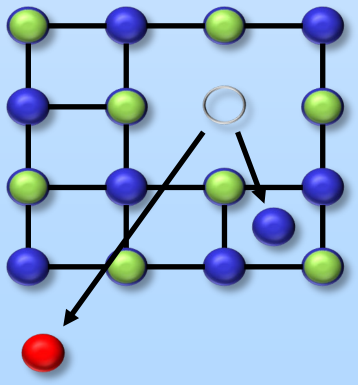


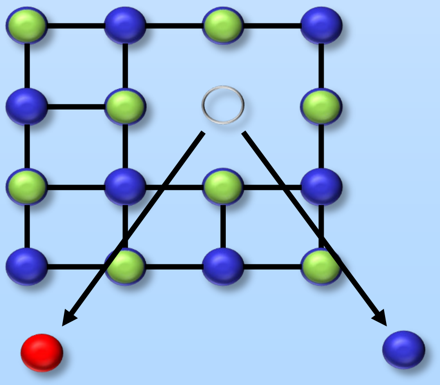
Displacement Damage Dose (DDD)

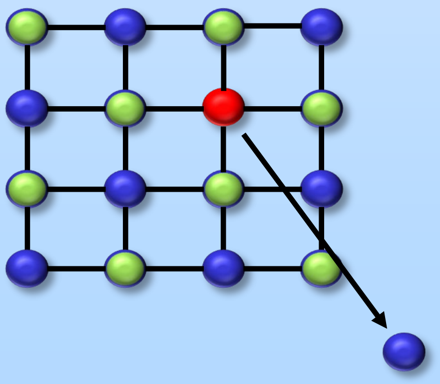


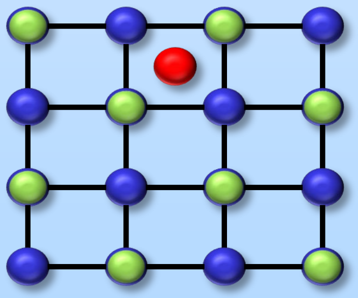


- Displacement of atoms from the lattice
  - Vacancies, interstitials, Frenkel Pairs
- Primarily from Protons and Neutrons
- Cumulative Effect
- Parametric shifts as you change the properties of the semiconductor



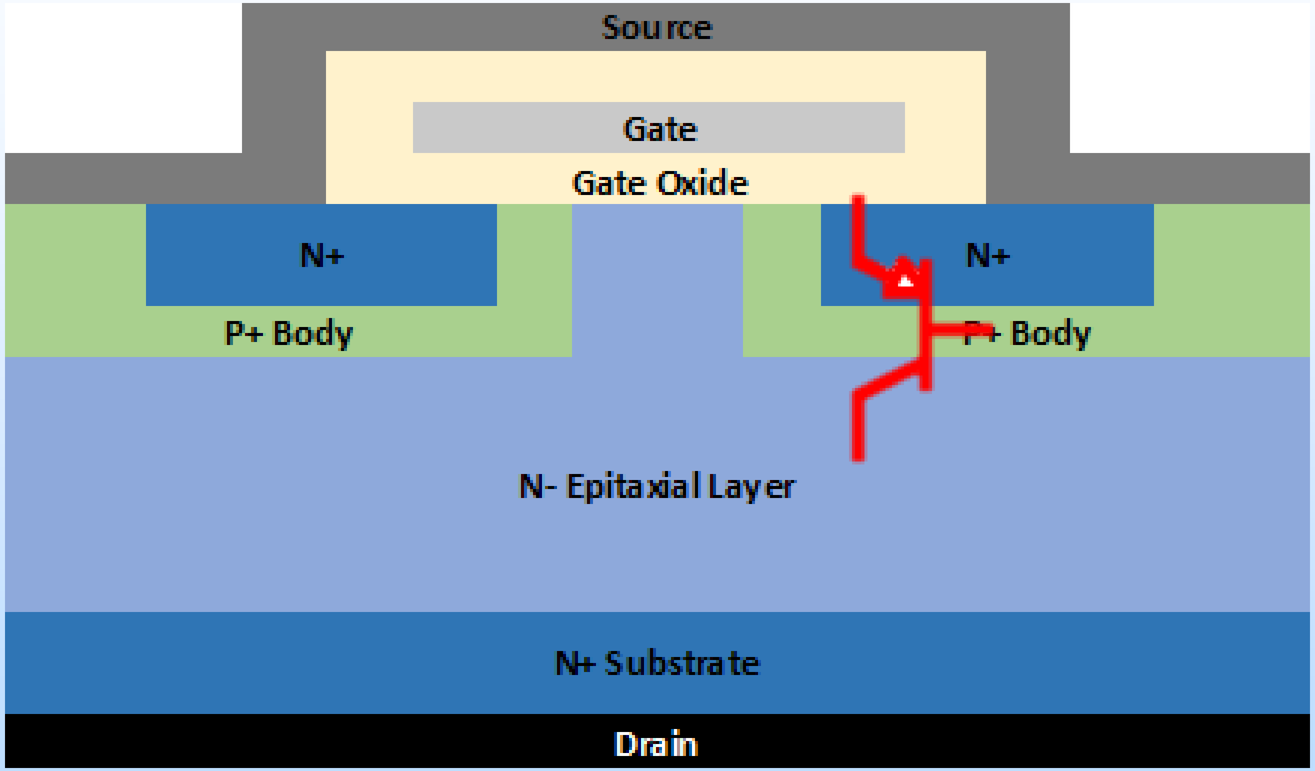






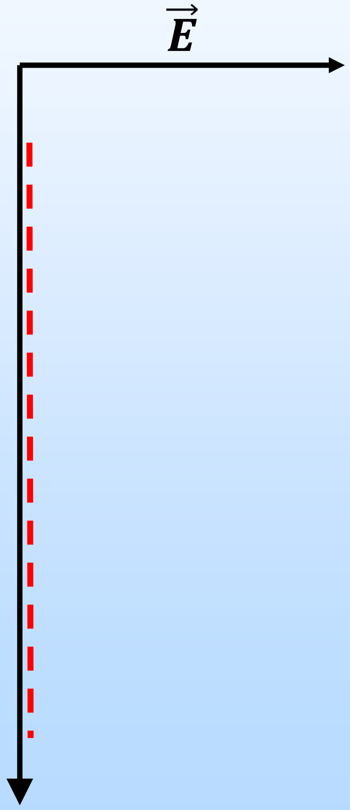
SEE in Si - SEB

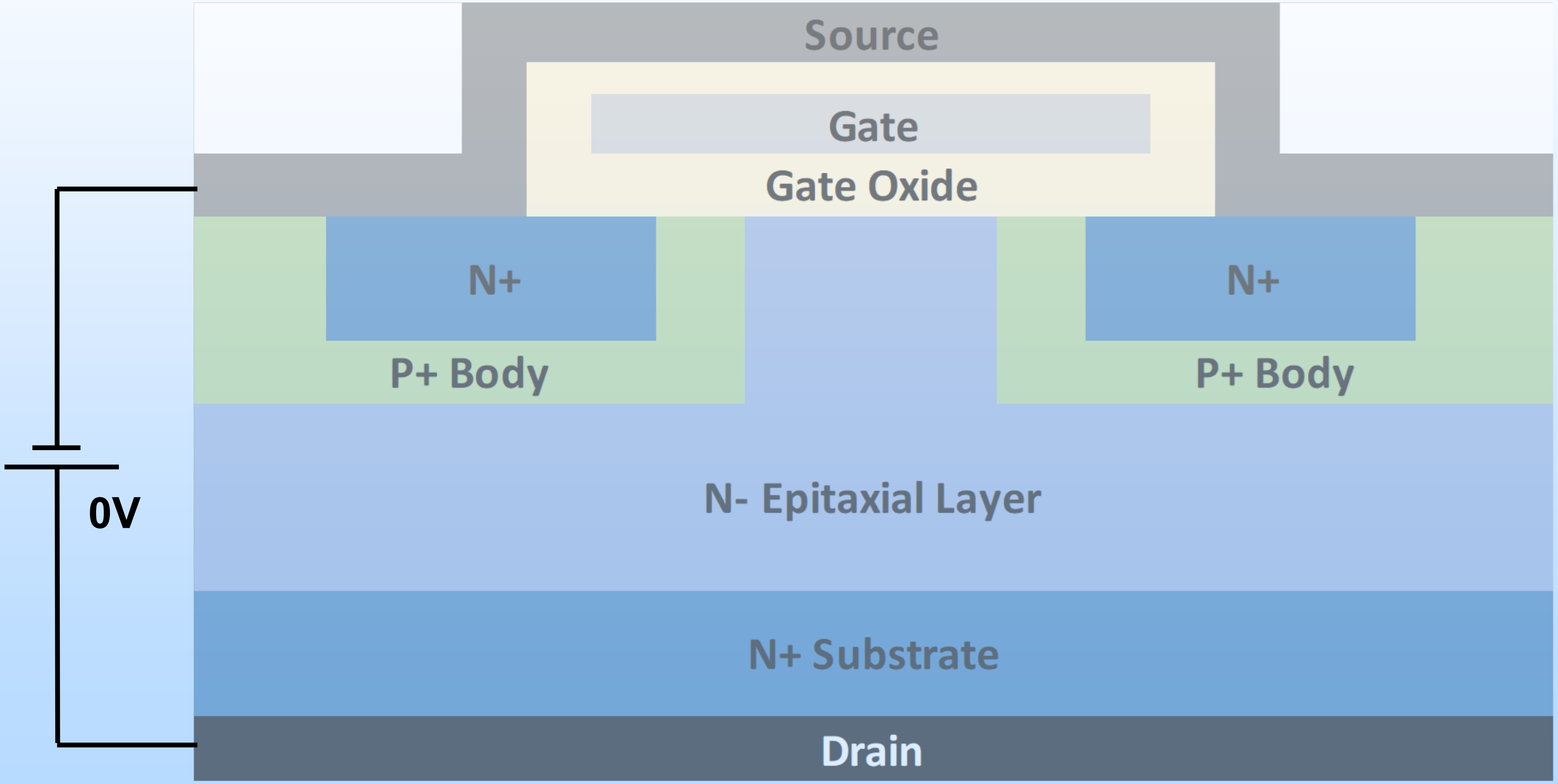
- Parasitic BJT formed by N well, P Body and N Epi layer
- Ionization causes BJT to turn ON due to charge in the body region, resulting in current flow from drain to source
- Positive feedback loop



SEE in Si-SEGR

- **MOSFETs**





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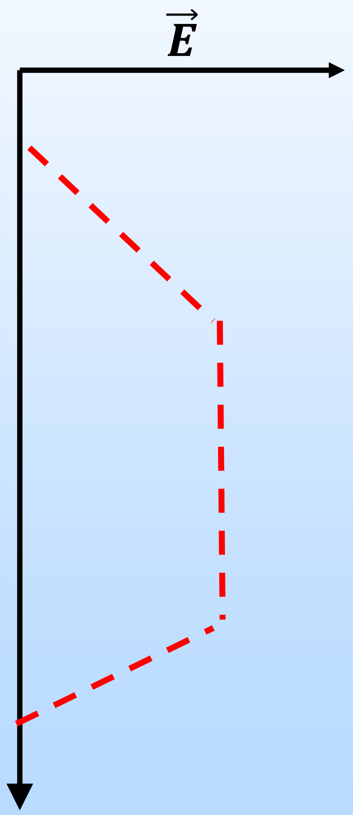

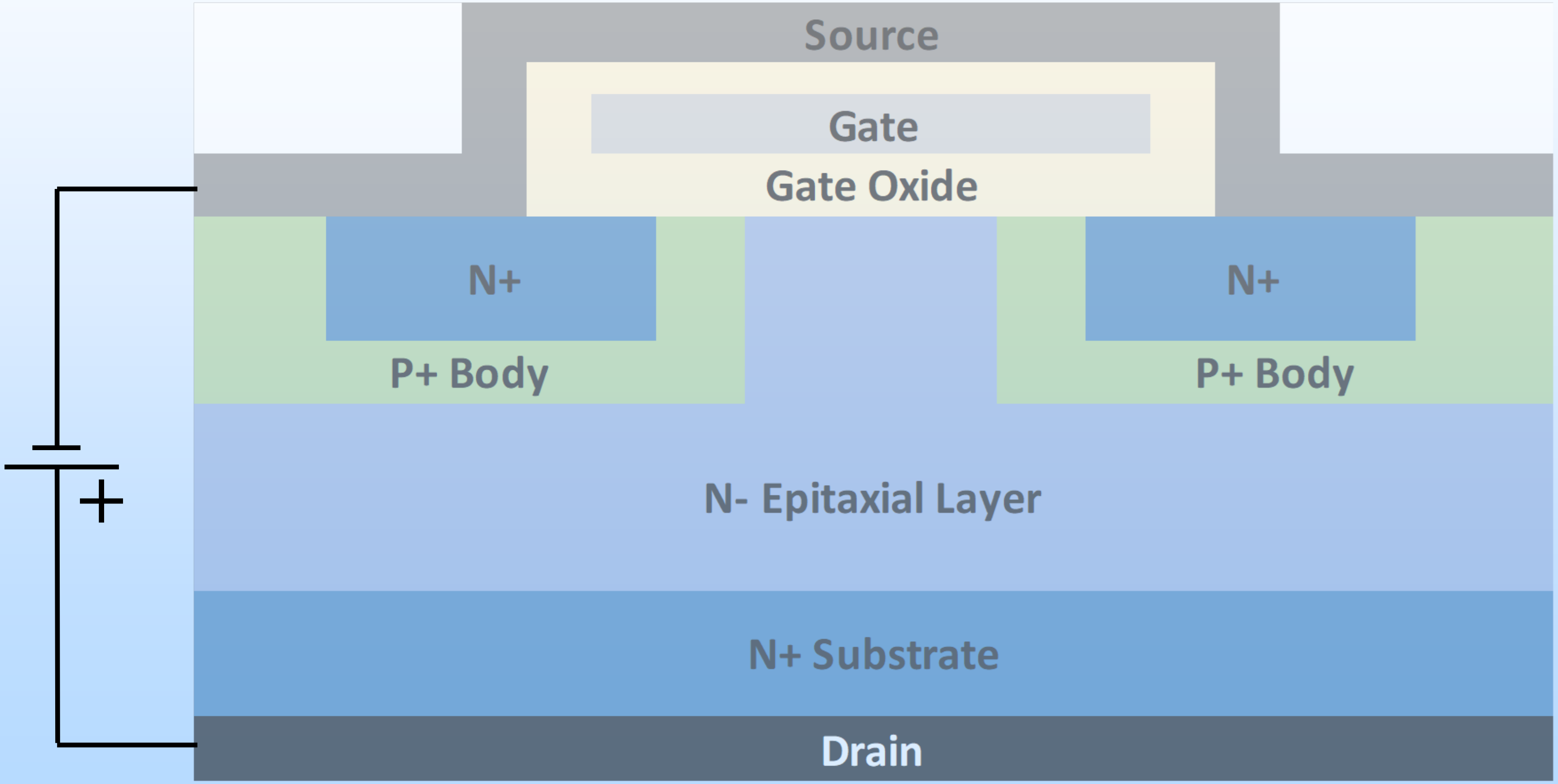

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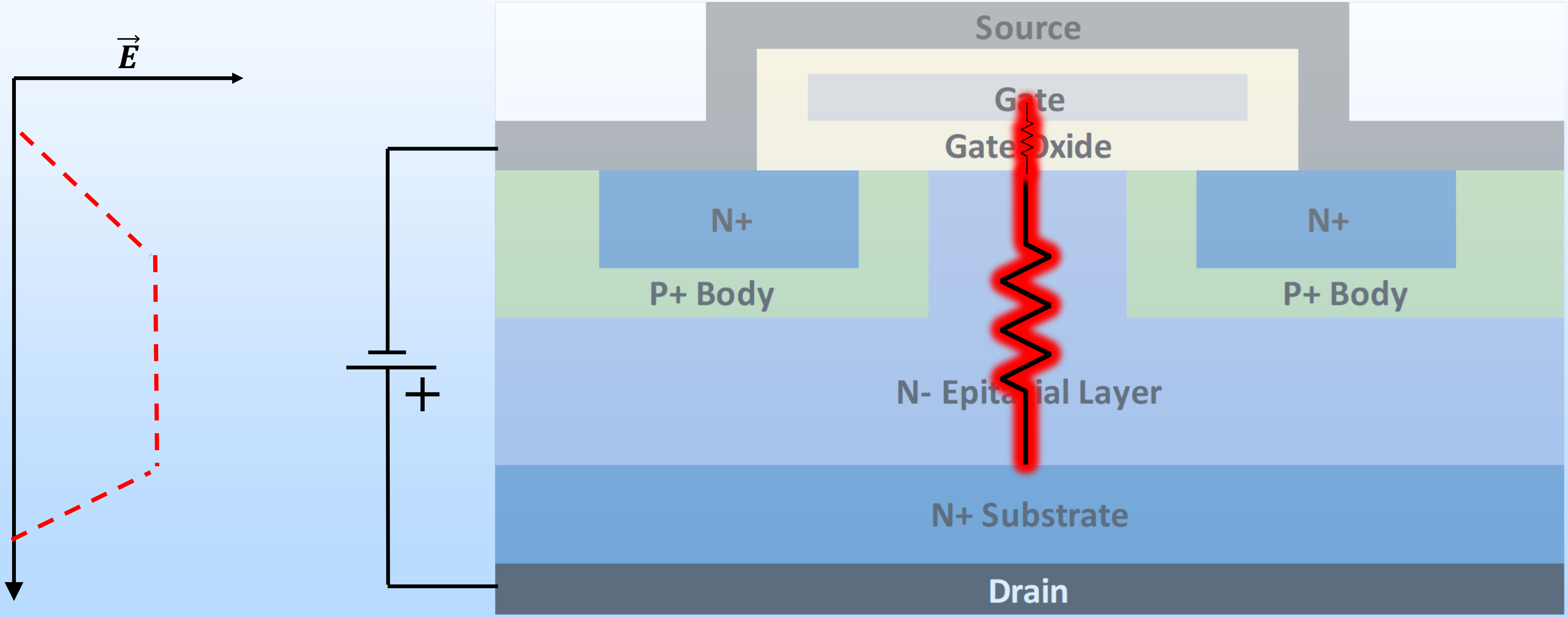

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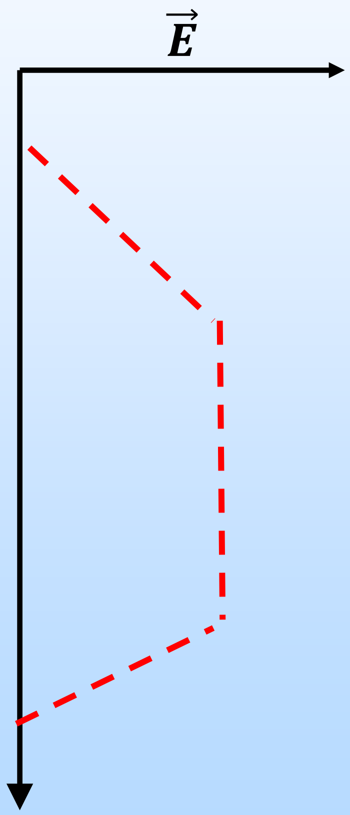

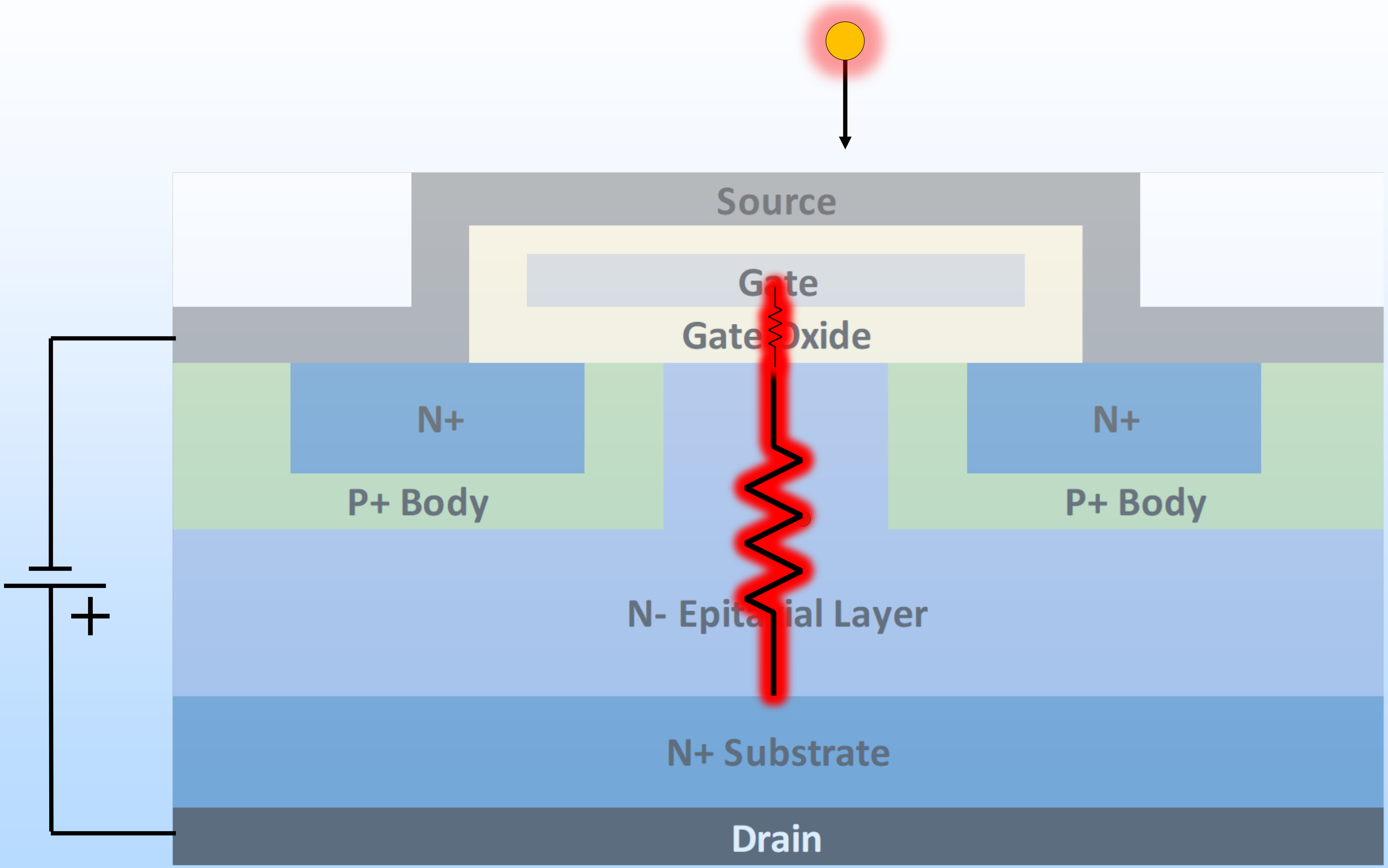

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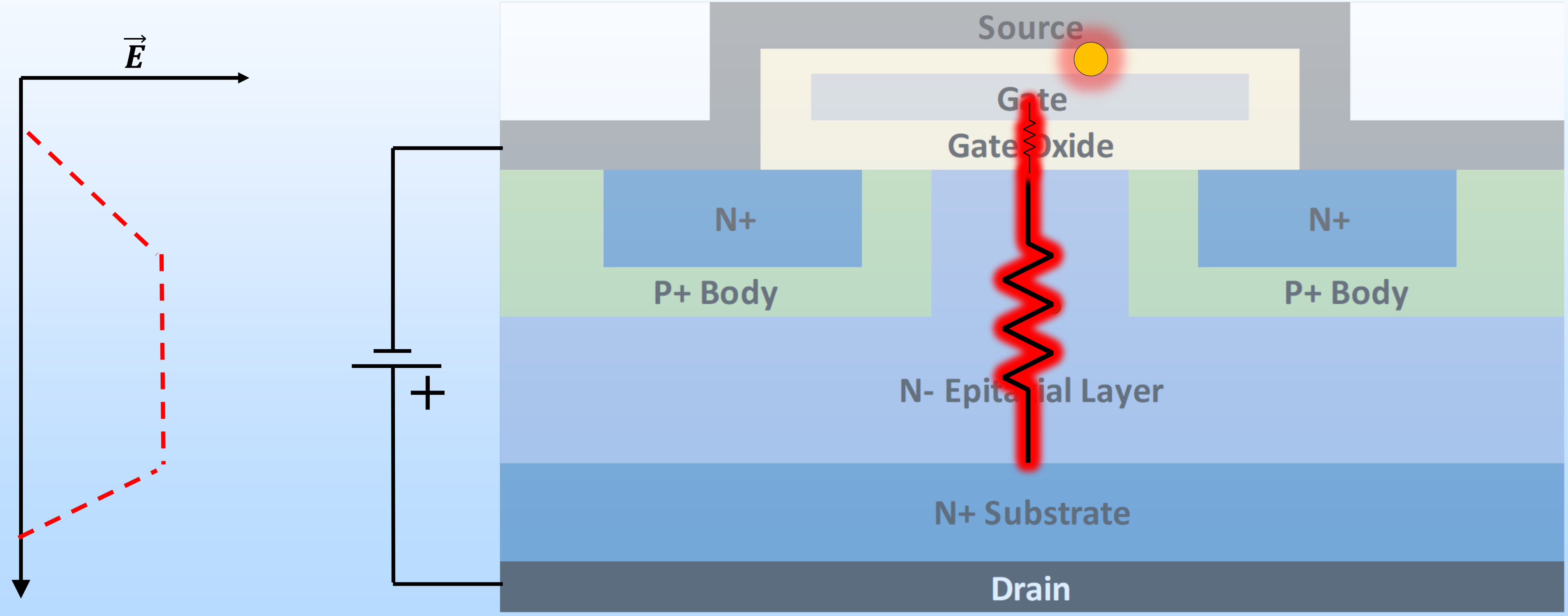

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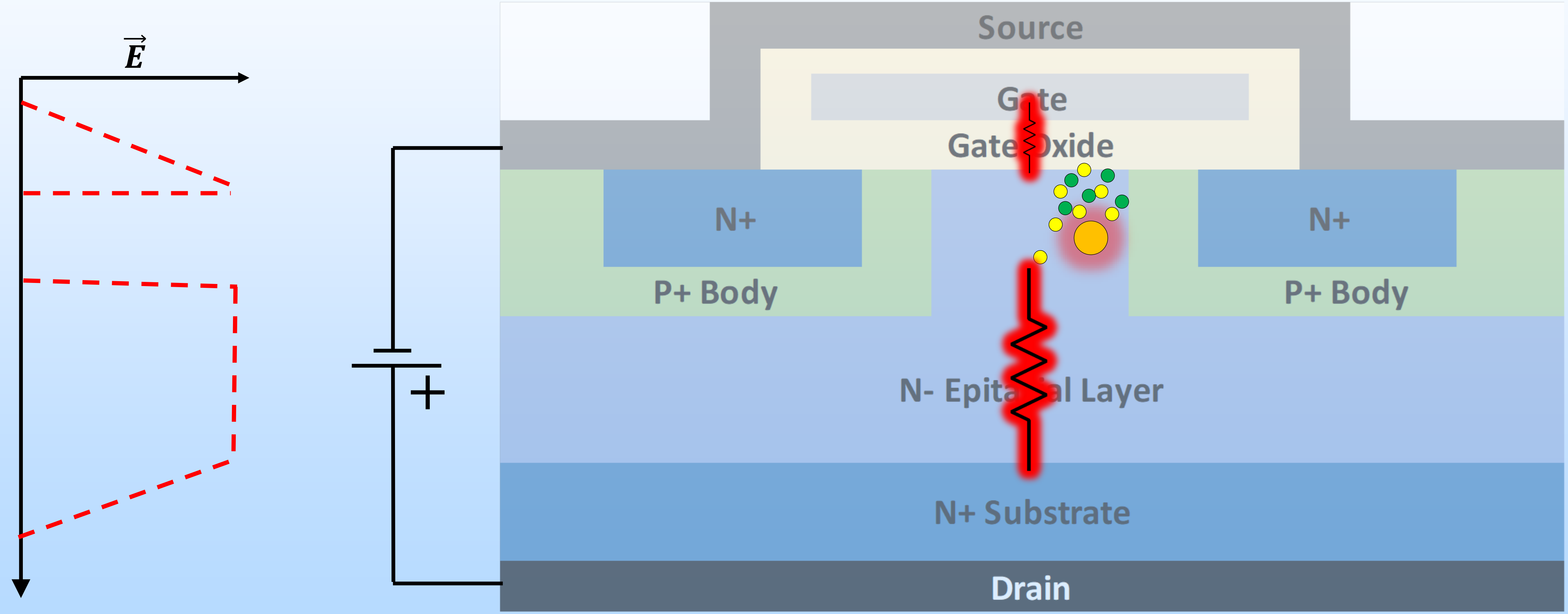

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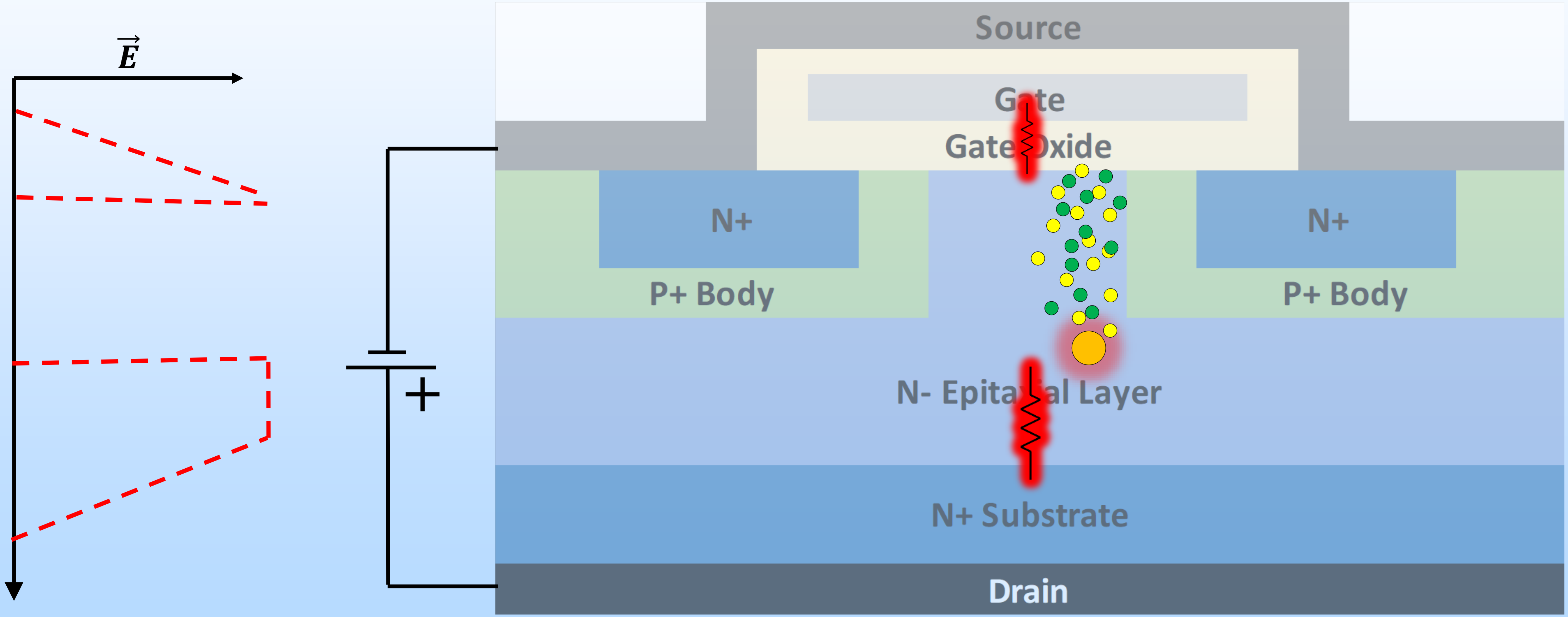

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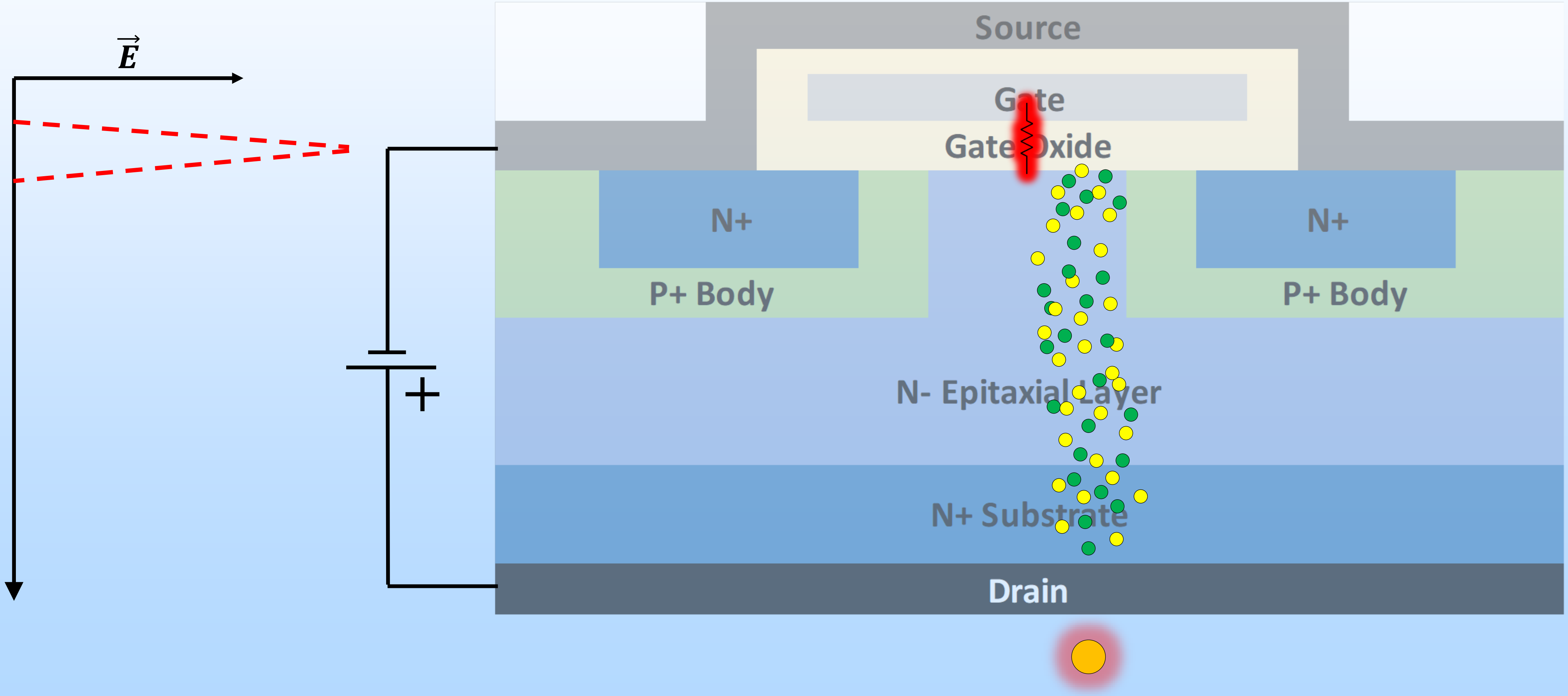
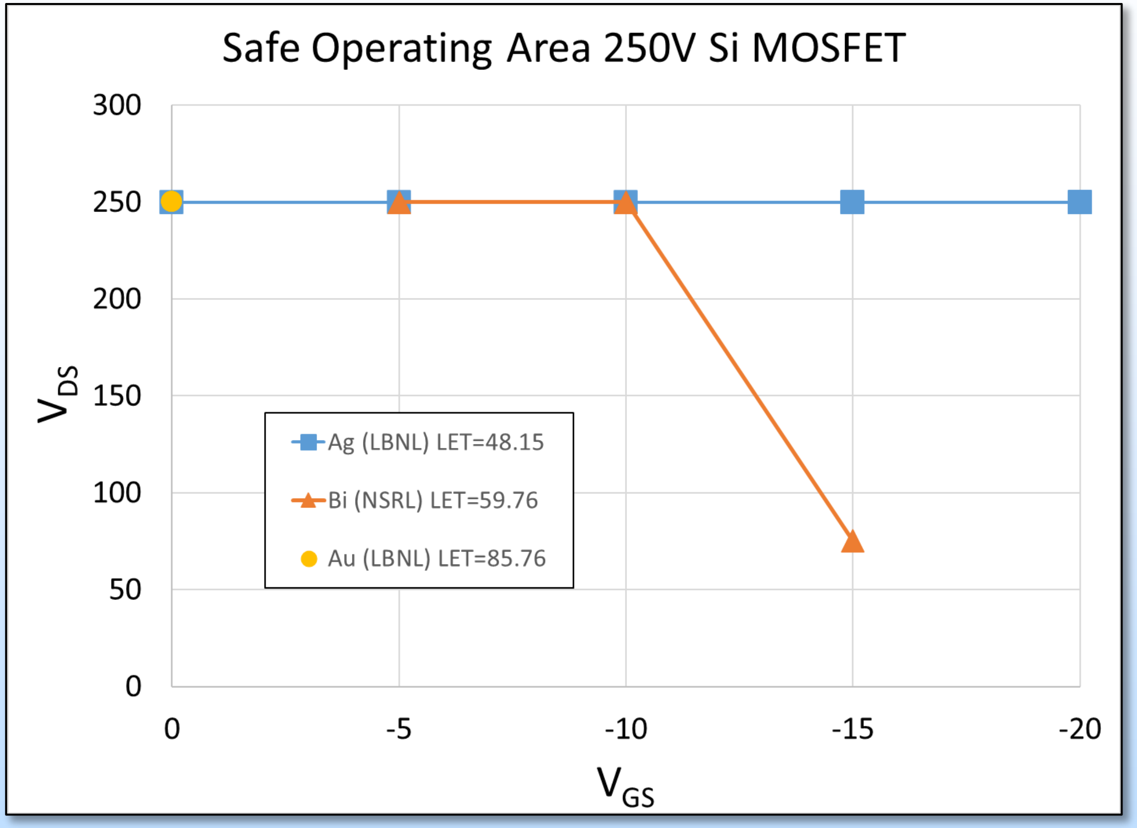


Single Event Effects (SEE) in Silicon

- **Single Event Burnout (SEB)**
  - Catastrophic failure, Drain-Source Short
  - Influenced by ion LET and V_{DS}
  - Diodes and MOSFETs

- **Single Event Gate Rupture (SEGR)**
  - Catastrophic failure, destruction of gate oxide
  - Influenced by ion LET, V_{DS}, and V_{GS},
  - MOSFETs only

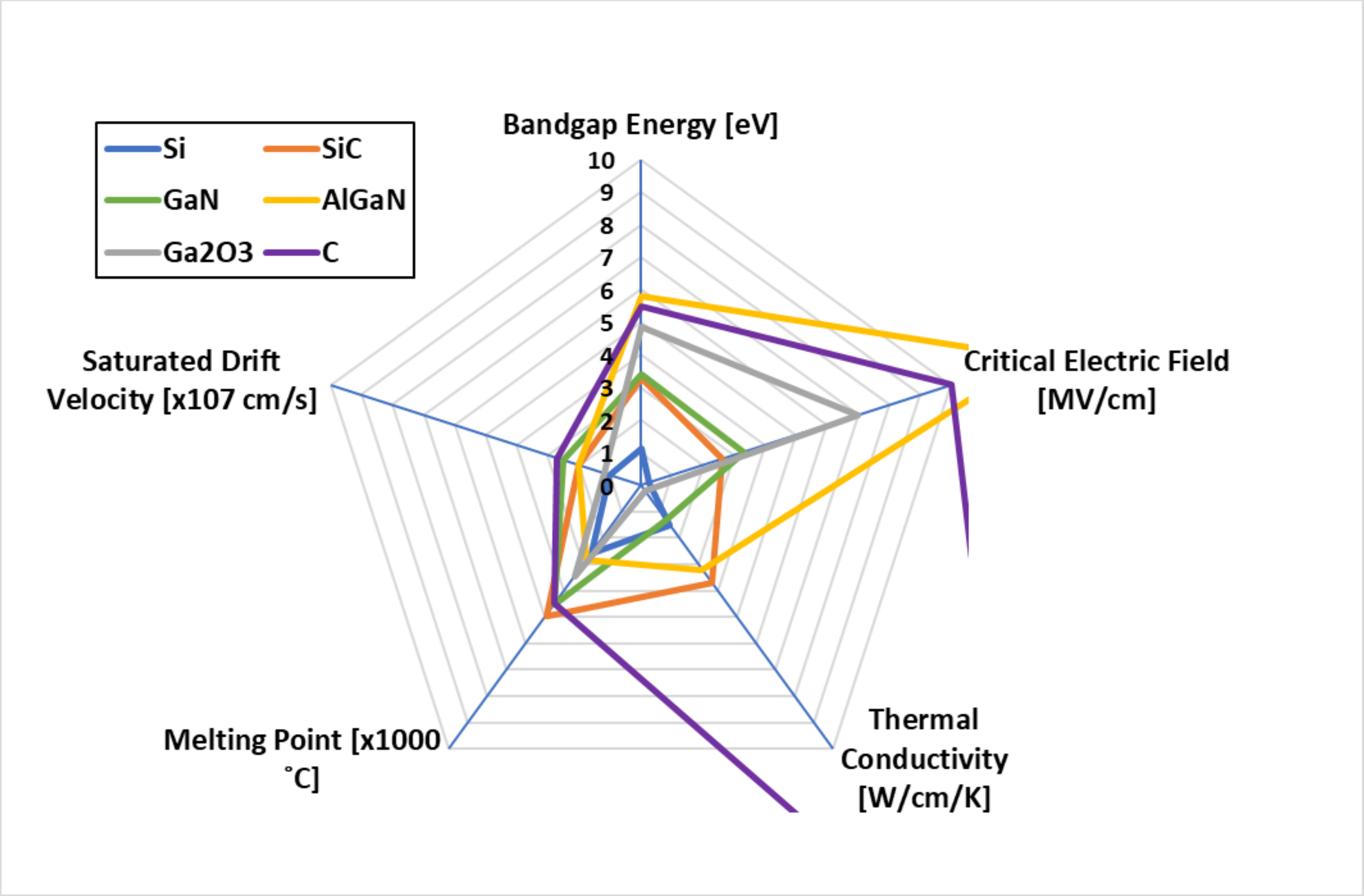
***Angle, strike location, and penetration depth need to be considered to ensure worst-case test conditions**



Wide Band Gap (WBG) Materials

- **High Voltage Applications**
  - Bandgap Energy, Critical Electric Field
- **High Temperature Applications**
  - Thermal Conductivity, Melting Point
- **Fast Switching**
  - Saturated Drift Velocity

	Bandgap Energy [eV]	Critical Electric Field [MV/cm]	Thermal Conductivity [W/cm/K]	Melting Point [x1000 ˚C]	Saturated Drift Velocity [x10^7 cm/s]
Si	1.12	0.25	1.5	2.57	1
GaAs	1.43	0.3	0.5	2.26	1
SiC	3.3	2.6	3.7	4.946	2
GaN	3.4	3.3	1.3	4.532	2.5
C	5.5	10	20	4.5	2.7
AlGaN	5.8	12.7	3.2	2.83	2
Ga_2O_3	4.85	7	0.2	3.452	1.2



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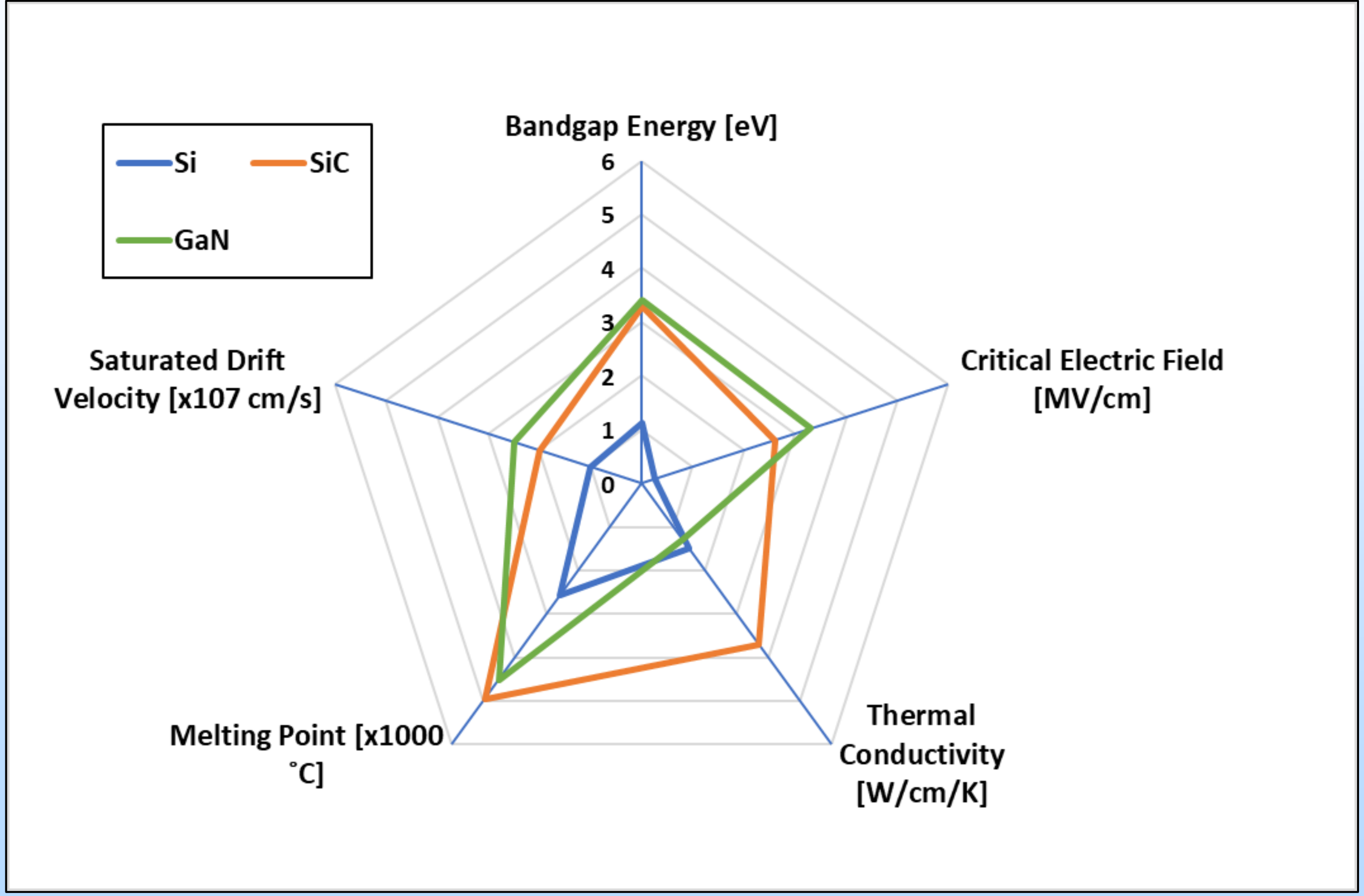
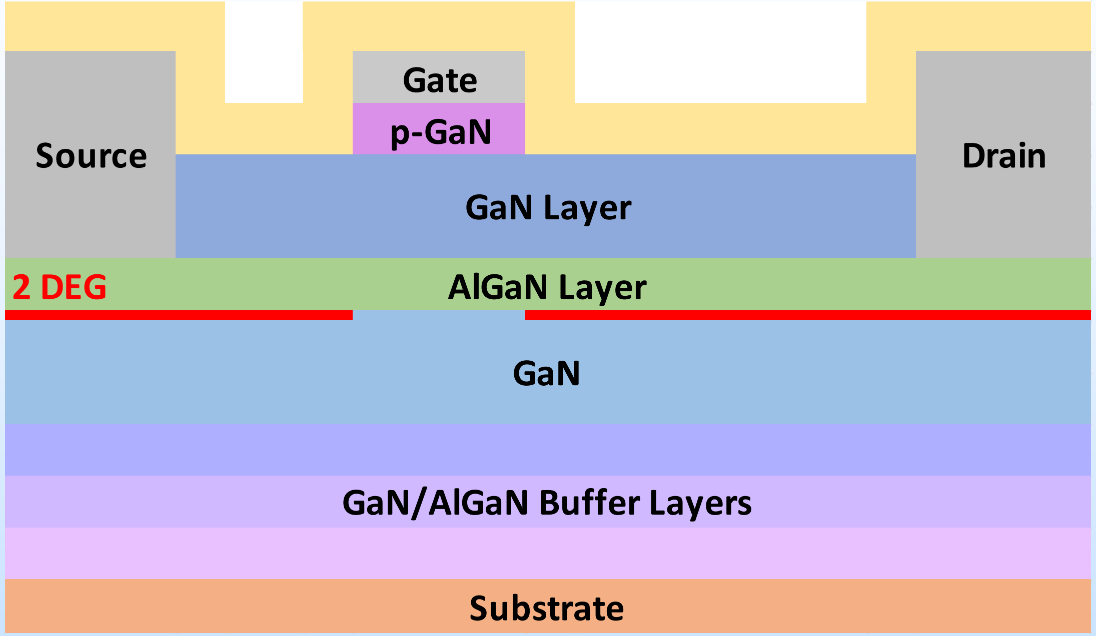


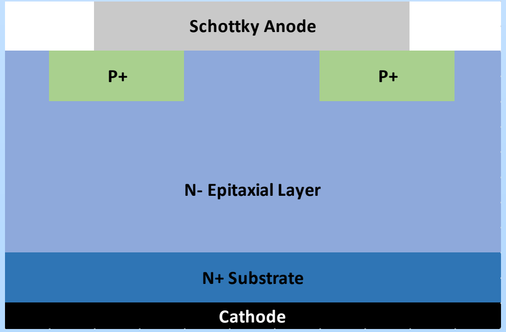
WBG Uses: Size Weight and Power (SWaP)

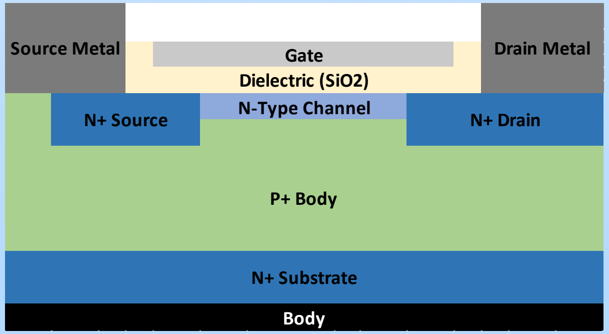
- Chargers
- Power conversion
- Power Management and Distribution (PMAD) (Lunar/Martian)
- Voltage and Current Capabilities

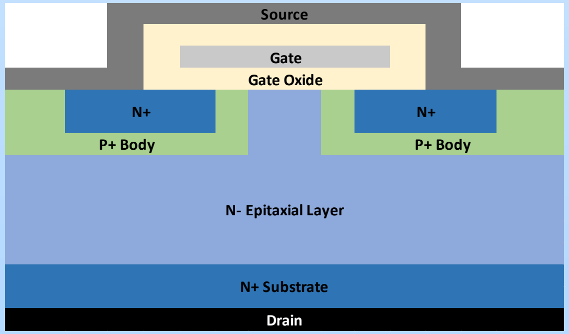
WBG Topologies

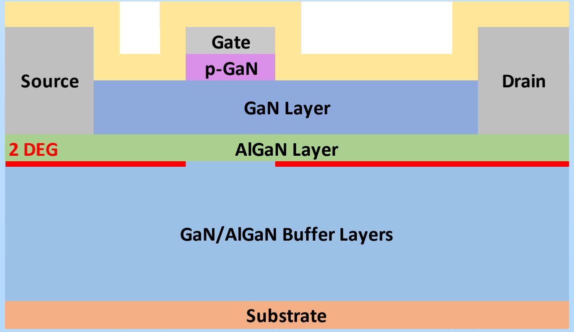
- PN, Schottky, and JBS Diodes
- Vertical and Lateral MOSFET structures
- High Electron Mobility Transistors (HEMTs)
- Possible new topologies



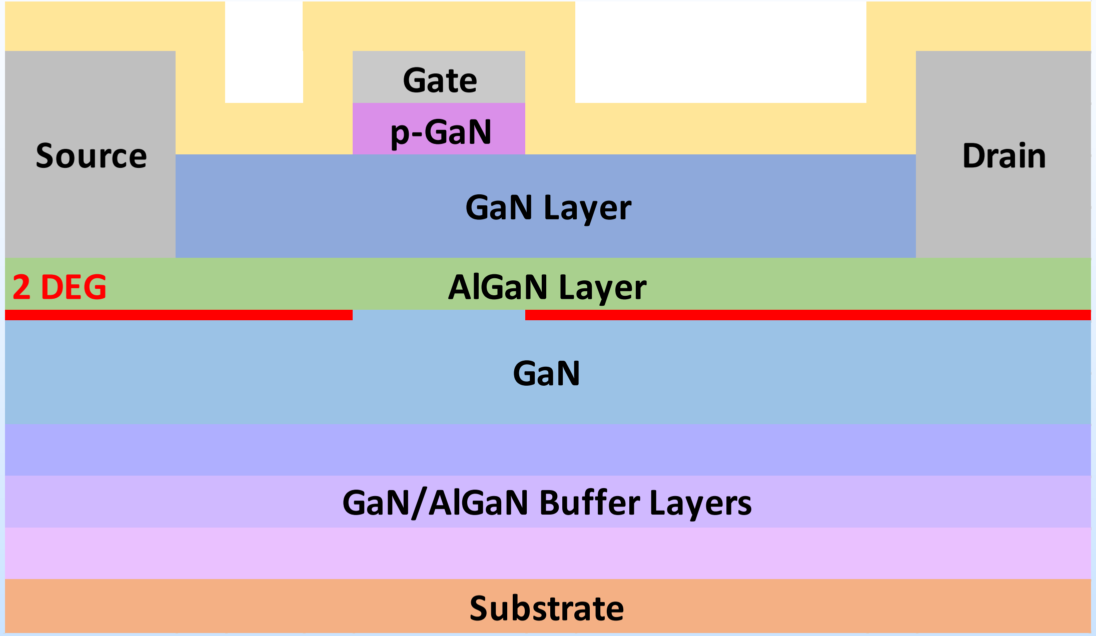


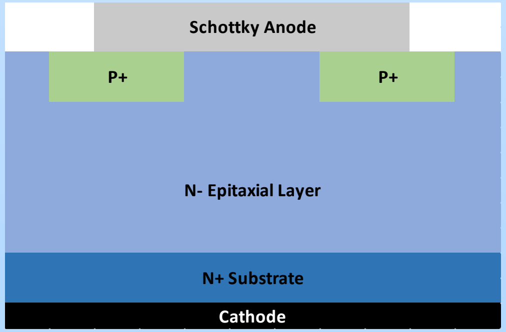


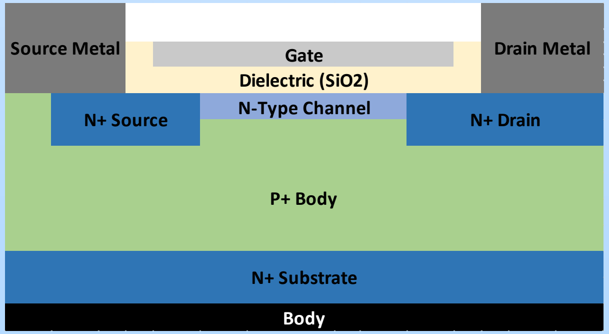


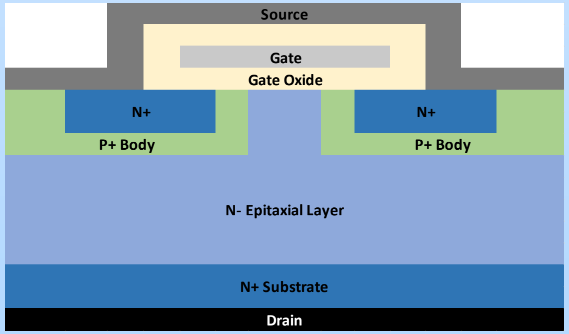


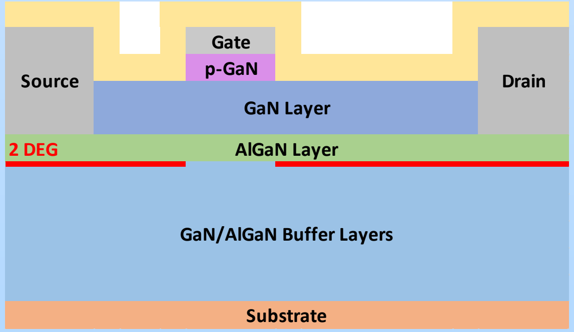
WBG Topologies











Break for Questions

Total Ionizing Dose (TID)	Displacement Damage Dose (DDD)
Single Event Effects (SEE) in Silicon	Wide Band Gap (WBG) Materials

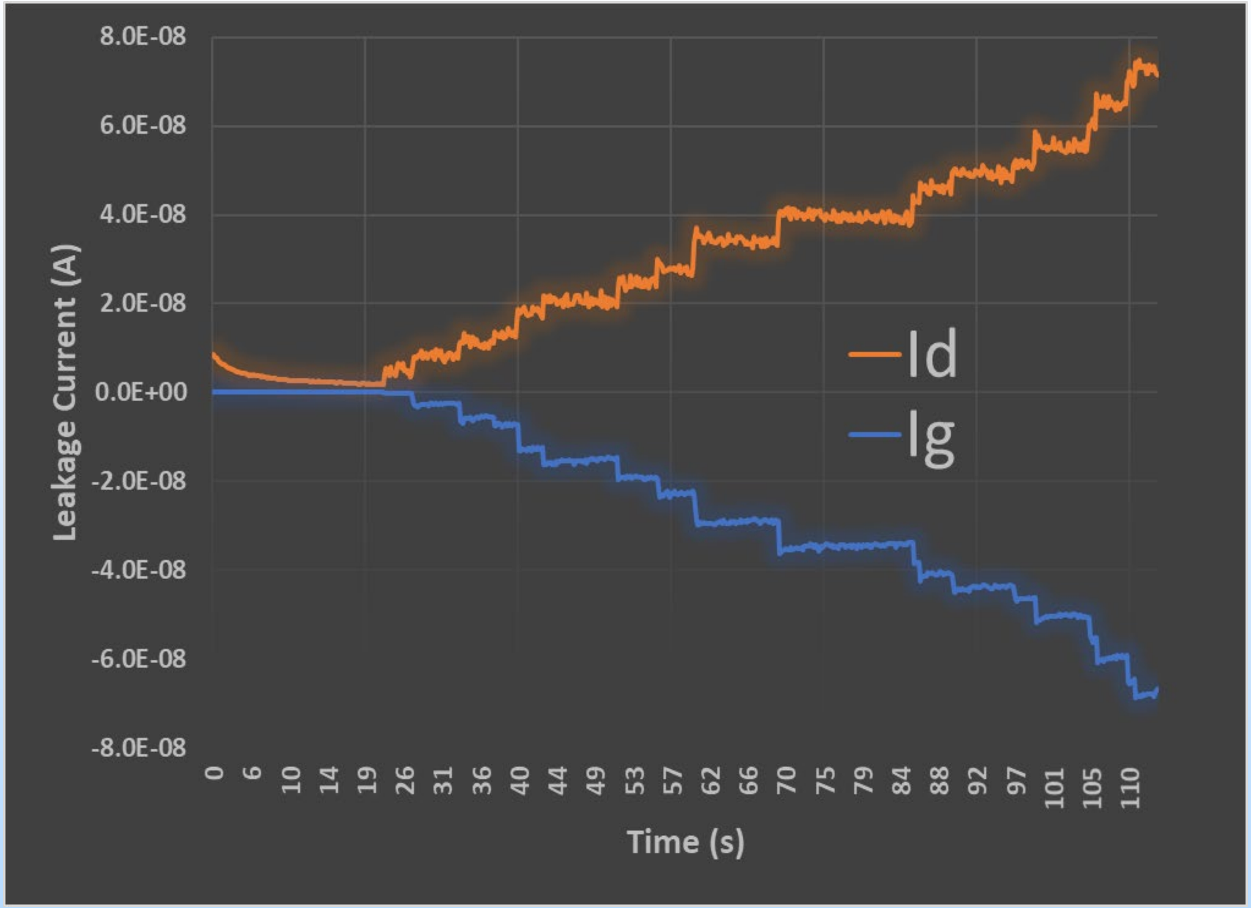
SEE in SiC - Diodes

- No Gate = No SEGR
- SEB
- Reverse Leakage Degradation
- Can be predictive of SEB in similarly rated SiC MOSFETs
  - We will discuss in a moment what implications this has on the SEB mechanism compared to Si

- ****LuSTR*
  - *See later presentation by A. Sengupta*

SEE in SiC - MOSFETs

- **MOSFETs**
  - **Multiple "non-catastrophic" regions**
  - **SEB**
  - **Similar onset VDS**
  - **Low LET -> fewer regions**



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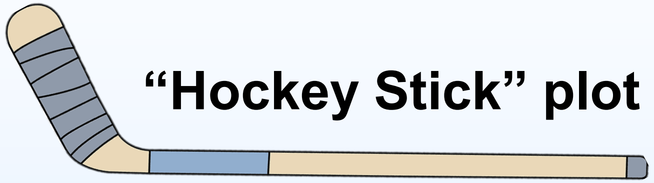
SEE in SiC

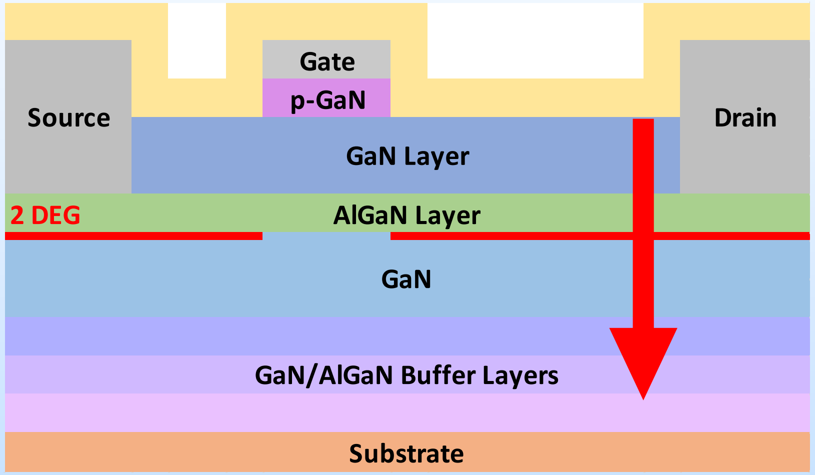


“Hockey Stick” plot

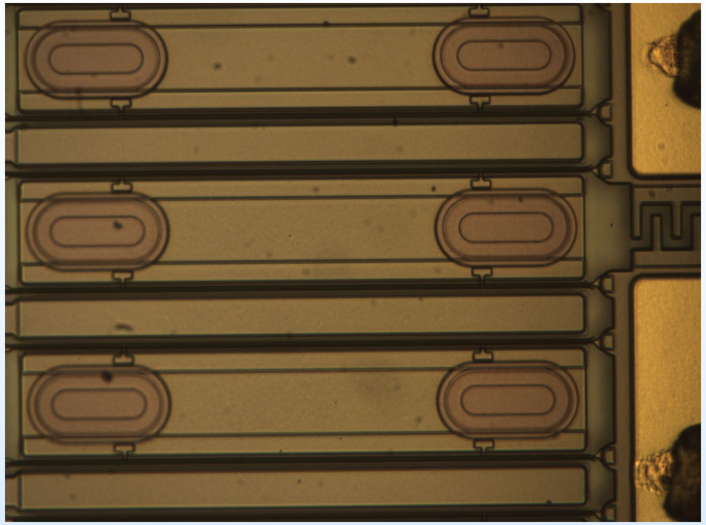
- Diodes and MOSFETs show similar SEB response and degradation onset
- SEB threshold voltage seems to saturate for LET >10 MeV-cm^2/mg
- Degradation raises the question of when is a device catastrophically failed?
- Similarity in diode and MOSFET threshold suggest SEB mechanism is NOT from a parasitic BJT

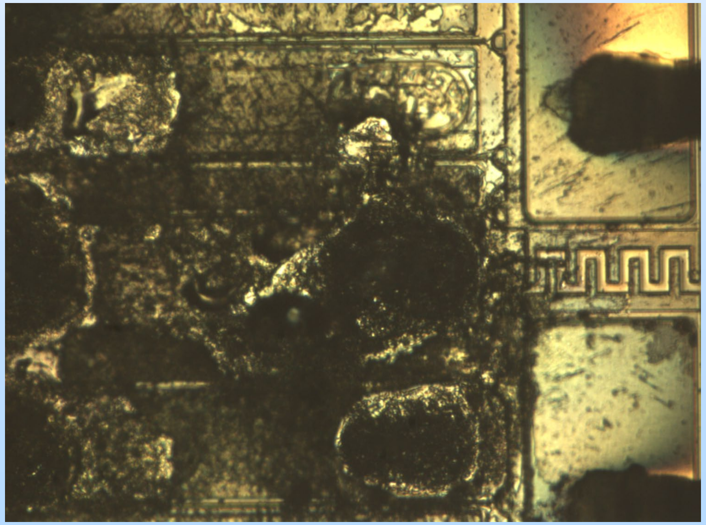
SEE in GaN-SELC

- **RF GaN HEMTs operate at relatively low voltages compared to normally-off (enhancement mode)**



SEE in GaN-SEB



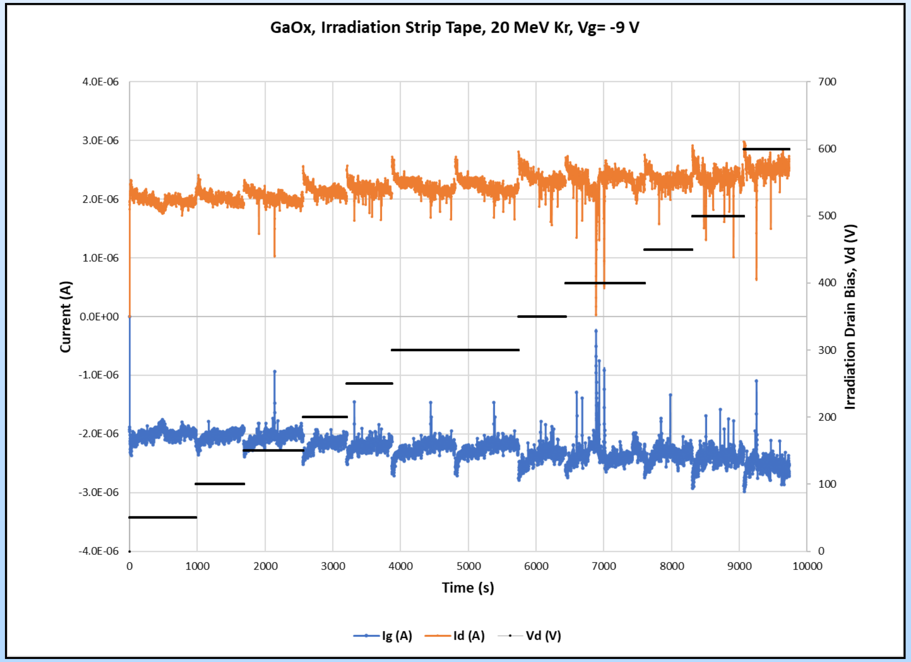


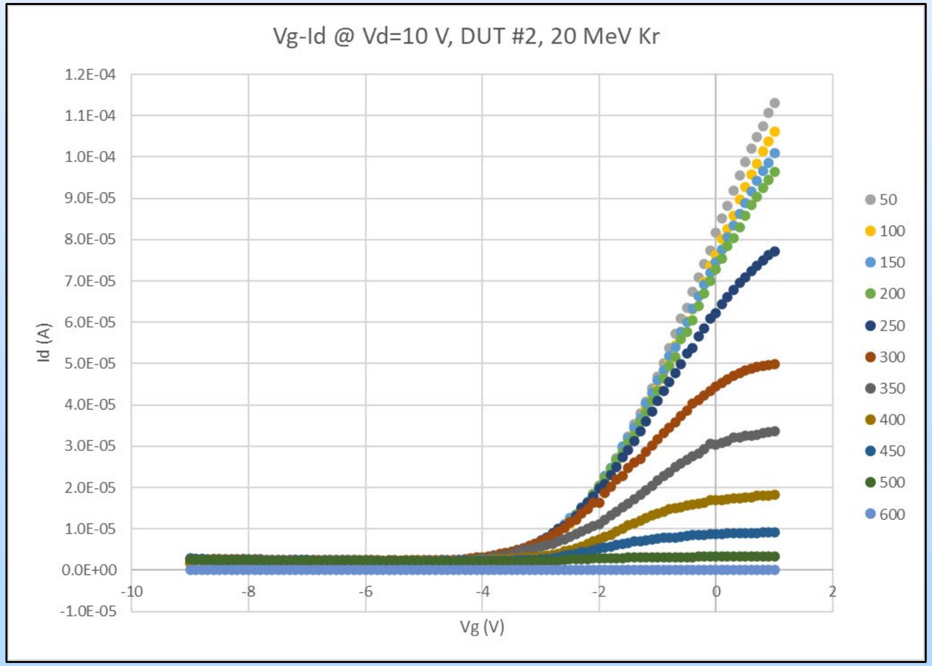
SEE in GaN-SEDR

- We don’t see “SEGR” because there is no gate oxide to rupture. However there is a dielectric that can rupture -> SEDR

Recent GaOx testing

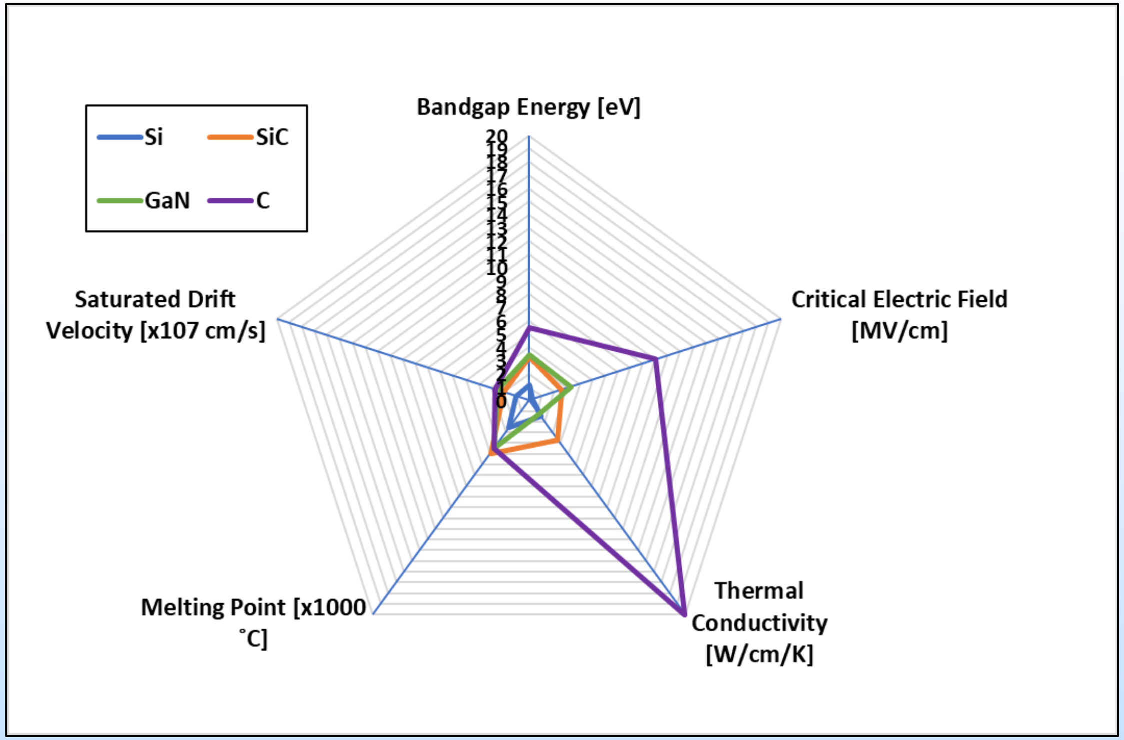
- Initial results are promising up to a few hundred volts
- Possible different failure mechanisms
- Fail ON vs. Fail OFF?
- Different topologies could introduce not only new mechanisms but possibly new failure states which could be used to our advantage





Diamond, and Others

- Diamond proposals have been funded
  - SBIR Phase II
- Challenges with commercial adoption
  - Cost
  - Large scale production
  - Wafer size
- While Diamond has some of the most attractive electrical characteristics it suffers from the challenges mentioned most dramatically



- Some of these characteristics may only be available in certain conditions or topologies limiting the application space

Conclusions

- “Rad-hard” is a not a well defined term and must be clearly understood in the context in which it is being used
- Properties of WBG semiconductors can provide advantages in electrical performance as well as thermal but some of the very attributes that enable these capabilities also increase their susceptibility to SEE
- We can use Si test methodologies as a starting point to evaluate the radiation tolerance of WBG devices but given the new topologies and new types of SEE observed we must work to broaden our toolchest and write new standards and methods specific to WBG power devices
- In addition to the technical hurdles there are some logistic issues with some technologies like wafer availability, adoption/development by the commercial market, and materials cost.

Special Thanks To…

- NASA Electronics Parts and Packaging (NEPP) Program
- NASA Goddard Space Flight Center (GSFC) Code 561

References

[1] https://7id.xray.aps.anl.gov/calculators/crystal_lattice_parameters.html

[2] S. J. Pearton, Fan Ren, Marko Tadjer, and Jihyun Kim, "Perspective: Ga2O3 for ultra-high power rectifiers and MOSFETS", Journal of Applied Physics 124, 220901 (2018) https://doi.org/10.1063/1.5062841

[3] J. -M. Lauenstein, M. C. Casey, R. L. Ladbury, H. S. Kim, A. M. Phan and A. D. Topper, "Space Radiation Effects on SiC Power Device Reliability," 2021 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, USA, 2021, pp. 1-8, doi: 10.1109/IRPS46558.2021.9405180.

[4] M. Zerarka, P. Austin, A. Bensoussan, F. Morancho and A. Durier, "TCAD Simulation of the Single Event Effects in Normally-OFF GaN Transistors After Heavy Ion Radiation," in IEEE Transactions on Nuclear Science, vol. 64, no. 8, pp. 2242-2249, Aug. 2017, doi: 10.1109/TNS.2017.2710629.

[5] S. Kuboyama et al., "Single-Event Damages Caused by Heavy Ions Observed in AlGaN/GaN HEMTs," in IEEE Transactions on Nuclear Science, vol. 58, no. 6, pp. 2734-2738, Dec. 2011, doi: 10.1109/TNS.2011.2171504.

[6] A. Sengupta et al., "Impact of Heavy-Ion Range on Single-Event Effects in Silicon Carbide Power Junction Barrier Schottky Diodes," in IEEE Transactions on Nuclear Science, vol. 70, no. 4, pp. 394-400, April 2023, doi: 10.1109/TNS.2023.3242223.

[7] Tsao, J. Y. et al., "Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges," in Adv. Electron. Mater. 2018, 4, 1600501. https://doi.org/10.1002/aelm.201600501

[8] D. R. Ball et al., "Ion-Induced Energy Pulse Mechanism for Single-Event Burnout in High-Voltage SiC Power MOSFETs and Junction Barrier Schottky Diodes," in IEEE Transactions on Nuclear Science, vol. 67, no. 1, pp. 22-28, Jan. 2020, doi: 10.1109/TNS.2019.2955922.

Questions?