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Implementation of the Axness-Kerr Photocurrent Model

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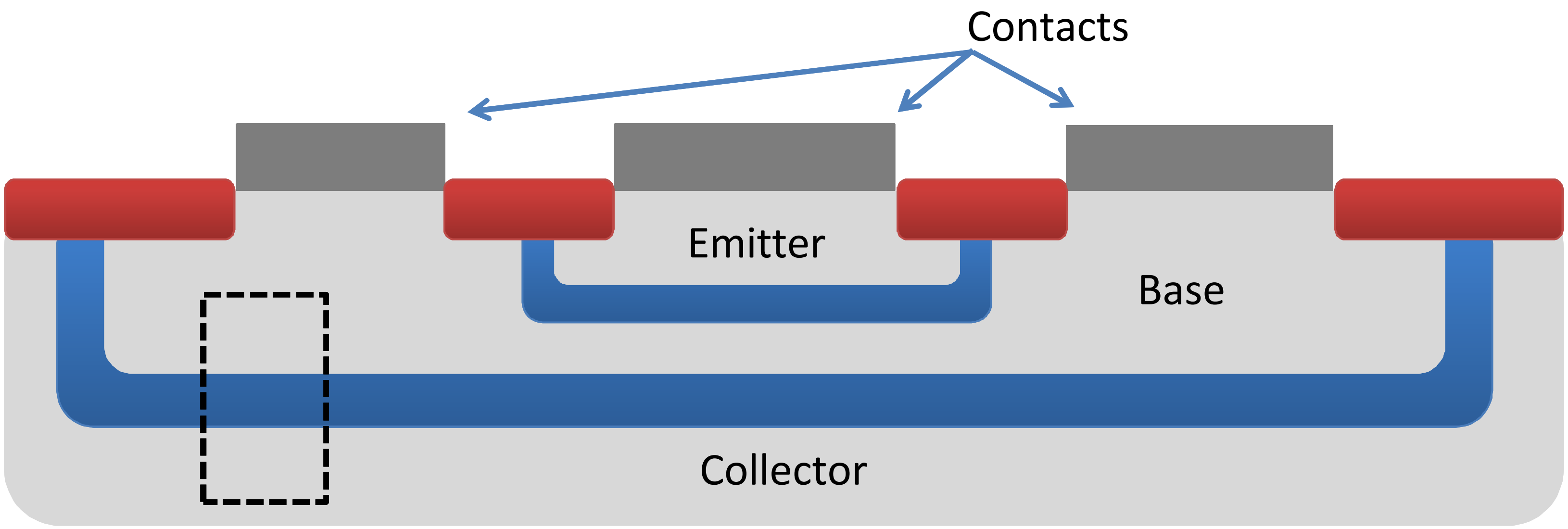
Introduction

- **QASPR – Qualification Alternatives to the Sandia Pulsed Reactor**
  - **SPR decommissioned**
  - **Need for high-fidelity predictive models**
  - **My work concerned models for silicon BJTs. Comparing:**
    - *Data from operational irradiation facilities (Medusa Linac and Little Mountain Linac)*
    - *Science-Based Modeling*
      - TCAD (Technology Computer Aided Design) Models
      - Compact Models
  - **My Focus: Photocurrent models**
    - *Also, effects of neutron damage on photocurrent generation*

TCAD vs. Compact Models

- **TCAD**
  - *Medici*
  - *Silvaco*
  - *Charon*
  - – **Highly accurate - Numerically solve carrier transport equations on finite mesh**
  - – **1D, 2D, and 3D capabilities**
  - – **Device level calculations**
  - – **Computationally Expensive – Long runtimes for single devices**
- **Compact models**
  - – **Modular components of large scale circut simulators**
    - *Xyce – Designed for simulation of large systems using high performance computing (i.e. parallel computing)*
  - – **Need to be much smaller and faster running**
  - – **Only support 1D modeling**
  - – **Require more calibration then TCAD models**

Photocurrent Background



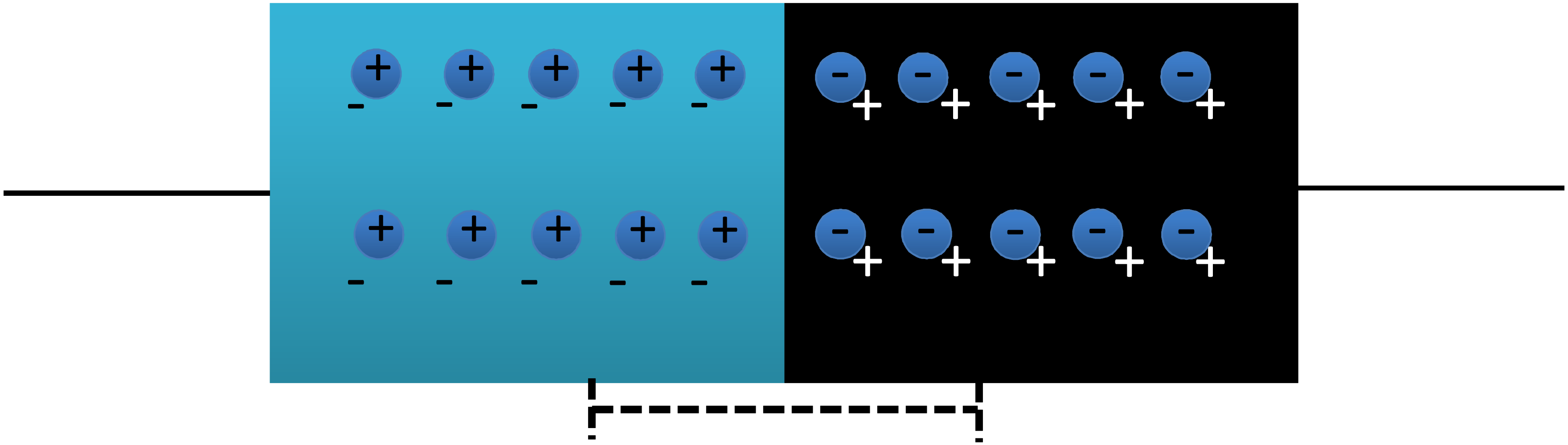
BJT (Bipolar Junction Transistors):
-Silicon Substrate
-Doped with Boron and Phosphorous
-Considering NPN device (Emitter and Collector are N-type material, Base is P-type)
-From a photocurrent perspective, the junctions can be treated as (separate) diodes

Photocurrent Background (Continued)

Base
-Doped with Boron (Group III)
-Missing valence electrons
-Excess holes (positively charged majority carrier)
-P type material

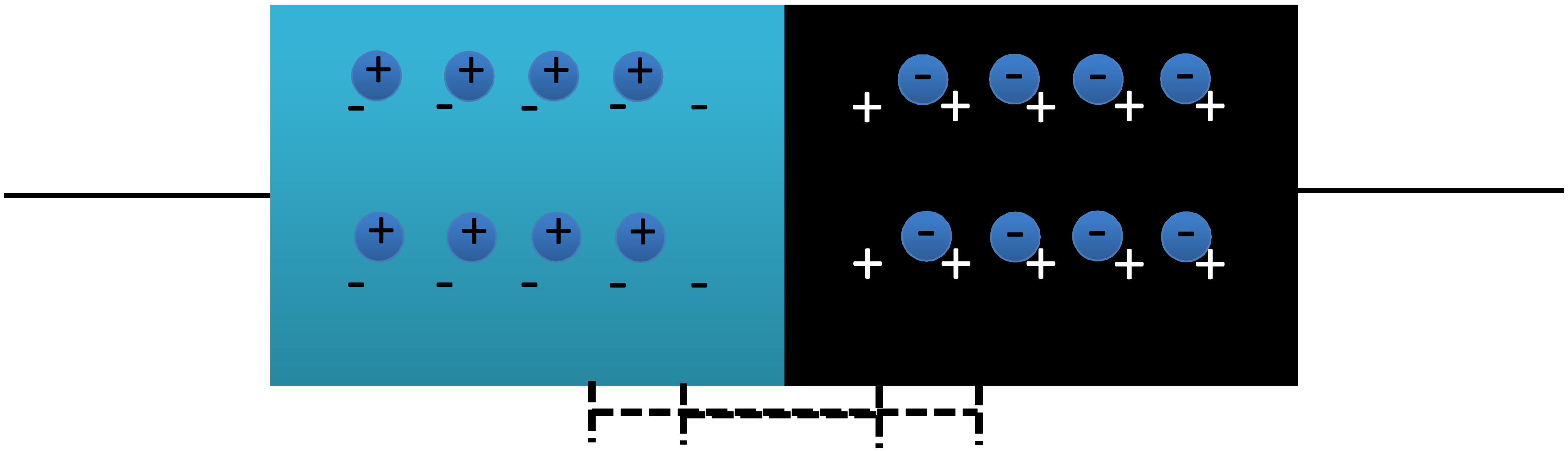
Collector
-Doped with Phosphorous (Group V)
-Has extra valence electrons
-Excess electrons (negatively charged majority carrier)
-N type material

Photocurrent Background (Continued)



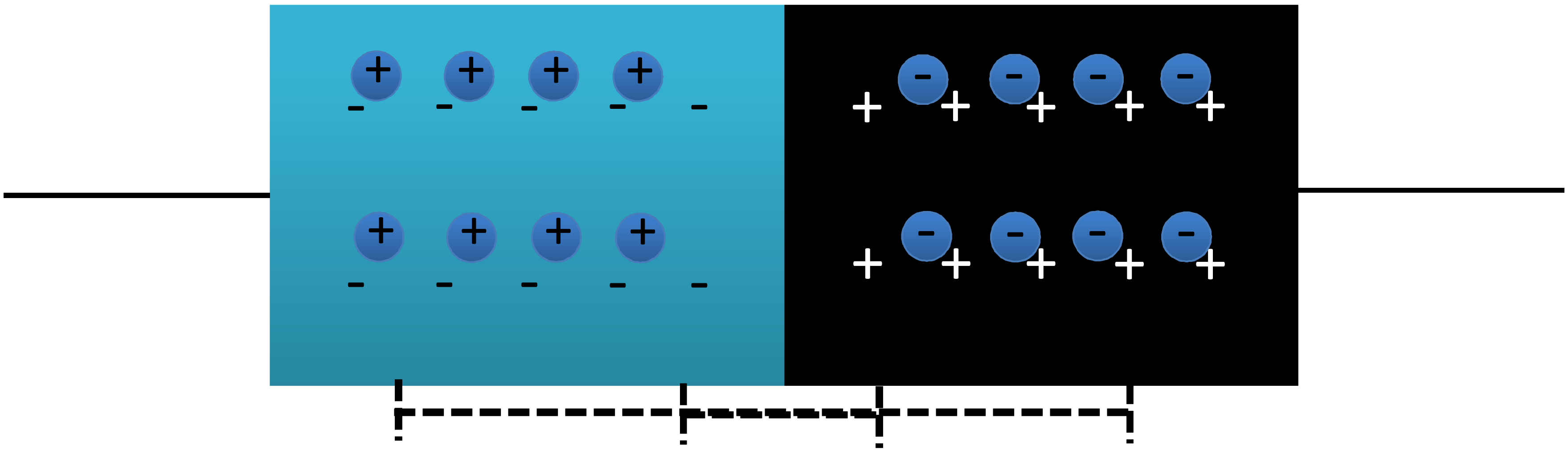
-Diffusion causes electrons to move from high concentration to low concentration. Creates electric field that prevents more charge from flowing (equilibrium state)

Photocurrent Background (Continued)



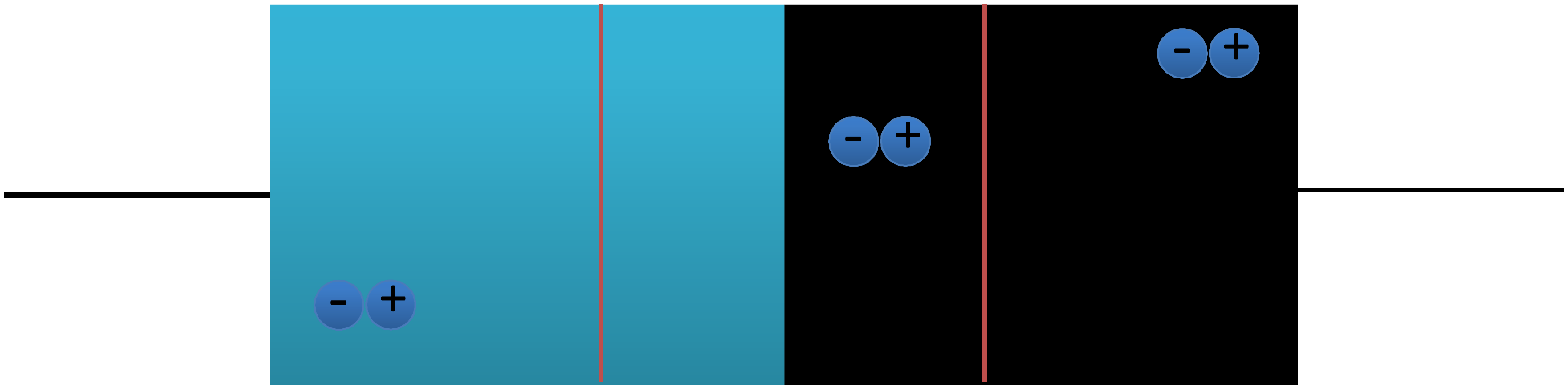
-Applying a forward bias shrinks the depletion region and allows more current to flow

Photocurrent Background (Continued)



-Applying a reverse bias enlarges the depletion region, decreasing the output current

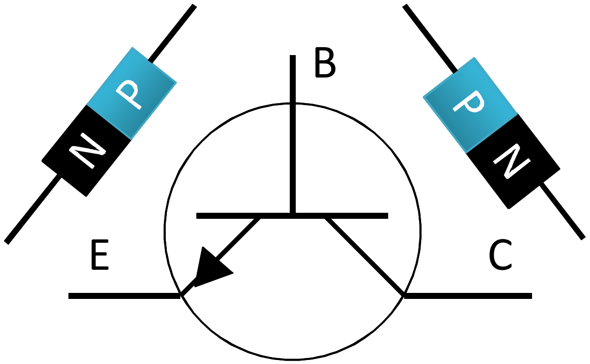
Photocurrent Background (Continued)



-Photocurrent is induced when ionizing radiation strikes the device and creates an electron-hole pair.
-In the depletion region a high electric field separates the pair and accelerates them.
-In the quasi-neutral (undepleted) regions diffusion (and sometimes a small electric field) move the pairs.

Compact Photocurrent Model

- **Express photocurrent as current source from two diodes running in parallel to transistor.**
- **Photocurrent model is separate from regular operation model of BJT**
- **Does not fully solve transport equations:**
  - Utilizes 1D Ambipolar Diffusion equation to approximate current contributions from quasi-neutral regions of device

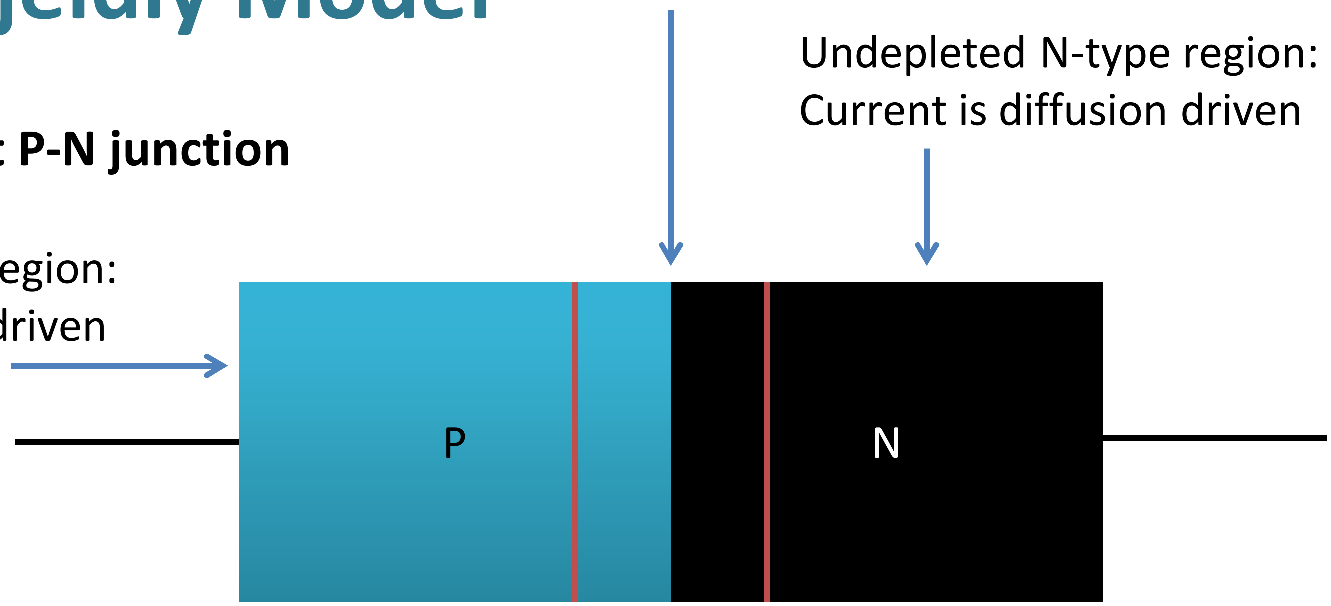


$$\frac{\partial u}{\partial t} = D_a \frac{\partial^2 u}{\partial x^2} - \mu_a E \frac{\partial u}{\partial x} - \frac{1}{\tau} u + g(t)$$

u = excess carrier density
D = ambipolar diffusion coefficient
E = Electric field
μ = ambipolar mobility
τ = carrier lifetime
g = e-h pair generation rate

The Tor Fjeldly Model

- **Assume abrupt P-N junction**



- **Assume majority of voltage drop is across depletion region**
  - **Field strength high enough to move carriers to terminals immediately after generation**
    - *Assume recombination is negligible in depletion region*
    - *No delay in prompt photocurrent*
- **Diffusion current is determined by the ADE**
- **Decay tails (residual current after pulse ends)**
  - **Approximated by a calibrated RC circuit model**

Limitations of the Tor Fjeldly Model

- **Does not actually solve the Ambipolar Diffusion Equation**
  - Only derives steady state solution
  - Time dependent effects utilize RC circuit approximation
- **RC circuit model of current decay tails difficult to calibrate**
  - Carrier diffusivities and lifetimes had to be calibrated well outside physical boundaries in order to match experimental data
- **No mechanism to accommodate damage to device during γ-irradiation**
  - Need reliable way to model photocurrent response during neutron pulse

The Axness-Kerr Photocurrent Model

- **Also solves ADE for an abrupt P-N junction**
- **Uses Fourier series to derive partial closed form solution to ADE**
  - Solutions for various irradiation profiles
    - *Step functions*
    - *Square pulses*
    - *Piecewise linear generation rates*
- **Mathematics developed to include description of effects on photocurrent response due to abrupt changes in carrier lifetimes**
  - Neutron pulses can create interstitial defects in semiconductor lattice- leads to electron hole recombination sites and changes in carrier lifetimes
- **Includes description of delay in photocurrent generated in depletion region**
- **Will include updated model of current generation from the subcollector**
- **Currently working on:**
  - Approximation to moving boundary problem for a piecewise linear/piecewise constant device bias.
  - Convergence analysis to communicate with solvers in XYCE

Implementation

- **Started with standalone version written in standard C**
  - Goal is to calibrate parameters in model using CHARON
  - Then we can run comparisons between the A-K model, the Tor Fjeldly model, TCAD models, and experimental data
- **Working on version in C++ to ultimately integrate into XYCE**
  - The photocurrent 'sources' run in parallel to the normal function of the transistor, so they can be implemented alongside other models.
  - Currently considers the BJT as two connected diodes
  - Template functions designed to utilize the SACADO automatic differentiation library
    - *Used to find voltage-derivatives for use in XYCE's solvers*

Newton's method iterates and SACADO

- **SACADO is a C++ library developed at Sandia as part of the Trilinos Package**
  - Uses template features in C++ to build derivative functions at compile time.
  - We are using forward mode AD, essentially a chain rule process
- **Derivatives do not need to be recomputed if code/model is changed, functions need only be properly templated**
- **Derivatives of current with respect to voltage are used by XYCE to calculate voltages at each node in the system**
  - Solving n-by-n system generated using Kirchhoff's current rule ($\sum_k I_k = 0$)
  - Uses Newton's method to find zeros of: $F : \vec{V} \rightarrow \vec{I}$
  - $J_F(V_m)\Delta V = -F(V_m)$ where J_F is the Jacobian of F, $J_{ij} = \left[\frac{\partial F_i}{\partial V_j} \right]$

    $V_{m+1} = V_m + \Delta V$

Current and Future Work

- **Account for changing device bias.**
  - Piecewise linear
  - Piecewise constant
- **On-the-fly error analysis**
  - Communicating a measure of convergence to XYCE
- **Modify standalone code to fit into XYCE**
- **Calibrate parameters using TCAD models**
- **Run comparisons between different compact models, TCAD models, and data.**

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Questions