Abstract—The paper demonstrates a finite-element method (FEM) simulation model of semiconductor devices operation. Classical semiconductor equations employing drift, diffusion and generation-recombination transport of charge carriers are established and variational forms for FEM assembly are derived in detail, including a basic voltage and current boundary conditions. Mathematically, a system of mutually coupled nonlinear equations need to be solved, which requires extensive use of nonlinear iteration solver. The derived model was coded in Python by strict use of open source tools, mainly grouped around FEniCSx project. Graphic output figures and characteristics for basic semiconductor structures are presented to demonstrate the functionality of model.

An ultimate goal of presented effort is derivation and verification of simplified semi-analytical model of Insulated-gate bipolar transistor (IGBT), including precise transient behavior.

This kind of model should be calibrated by use of measurement-obtained data, so the qualitative behavior of device physics at reasonable computational cost is of primary interest of presented FEM model as opposed to commercial device development tools aiming at precise quantitative outputs; which need to be experimentally calibrated even so.

As an additional step to simplified one-dimensional model usability verification, results of unusual way of experimental estimation of minority-carrier excess charge within power bipolar transistor collector and base during on-state is presented and compared to simulation result.

Index Terms—Power BTJ model, power BJT switching, IGBT transient model, transistor switching measurement, semiconductor device simulation, finite element method, lumped charge model

I. INTRODUCTION

A. Semiconductor Equations

Let’s establish the basic semiconductor equations governing the main phenomena in semiconductor devices, as described numerous times in literature ([1], [2], [3], [4]), following the notation listed below:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon )</td>
<td>Permittivity of material (silicon)</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Electric potential</td>
</tr>
<tr>
<td>( \mathbf{E} )</td>
<td>Electric field intensity ( \mathbf{E} = -\nabla \psi )</td>
</tr>
<tr>
<td>( q )</td>
<td>Elementary charge</td>
</tr>
<tr>
<td>( p, n )</td>
<td>Holes and electrons concentration respectively</td>
</tr>
<tr>
<td>( n_i )</td>
<td>Intrinsic carrier concentration for given material</td>
</tr>
<tr>
<td>( N_A, N_D )</td>
<td>Acceptors and donors concentration (^1)</td>
</tr>
<tr>
<td>( \mathbf{J}_p, \mathbf{J}_n )</td>
<td>Hole and Electron current pre unit area</td>
</tr>
<tr>
<td>( \mu_p, \mu_n )</td>
<td>Hole and electron mobility</td>
</tr>
<tr>
<td>( D_p, D_n )</td>
<td>Diffusion constants (Fick’s Law)</td>
</tr>
<tr>
<td>( R_p, R_n )</td>
<td>Recombination-generation rate of holes and electrons</td>
</tr>
<tr>
<td>( \tau_p, \tau_n )</td>
<td>hole and electron recombination lifetime</td>
</tr>
<tr>
<td>( k )</td>
<td>Boltzmann’s constant</td>
</tr>
<tr>
<td>( T )</td>
<td>Thermodynamic temperature</td>
</tr>
<tr>
<td>( kT )</td>
<td>Thermal Voltage ((25, 9 \text{ mV at room temperature}))</td>
</tr>
<tr>
<td>( \mathbf{n} )</td>
<td>Facet normal pointing in direction out of the boundary</td>
</tr>
</tbody>
</table>

Poisson’s Equation \((\text{Gauss’s Law})\):

\[
\nabla \cdot (\varepsilon \nabla \psi) = -q(p - n + N_D - N_A)
\]

Carrier transport - drift-diffusion equations:

\[
\mathbf{J}_p = q\mu_p \mathbf{E} - qD_p \nabla p
\]

\[
\mathbf{J}_n = q\mu_n \mathbf{E} + qD_n \nabla n
\]

Continuity equations for hole and electron current:

\[
\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot \mathbf{J}_p - R
\]

\[
\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_n - R
\]

\(^1\)For simplicity, all dopant atoms are considered fully ionised.

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The drift current - as embodied in any conductor - is driven by electric field, with velocity given by mobility of charged particle, while diffusion current is driven by carrier concentration gradient, as given by Fick’s Law of any kind of diffusion.

The Recombination-generation term \( R \) is dependent on holes and electrons concentration and doping profile (impurity atoms concentration) and should not be omitted as it affects the PN-junction conditions significantly, though there is no one generally valid yet simple model. Carrier recombination originates in number of different physical mechanisms. The main ones like trap-assisted “Shockley-Read-Hall” (SRH), “Auger”, band-to-band and surface recombination effects are not negligible. The number of independent variables in \( R \) increases with particular model complexity.

Typically a Shockley-Read-Hall recombination (SRH) model is used if no special effects are needed to be accounted, expressed by form [3], [4]:

\[
R = \frac{n \cdot p - n_i^2}{\tau_p(n + n_0) + \tau_n(p + p_0)}
\]

where \( n_i \) stands for intrinsic carrier concentration in given material, \( p_0, n_0 \) for thermal equilibrium concentrations of holes and electrons and \( \tau_p, \tau_n \) for holes and electron recombination lifetimes respectively.

Considering \( E = -\nabla \psi \), equations (1) - (4) can be rearranged into 3-equation system with unknowns \((\psi, p, n)\) as follows:

\[
\nabla \cdot (\varepsilon \nabla \psi) = -q(p - n + N_D - N_A)
\]

\[
\frac{\partial p}{\partial t} = \nabla \cdot (p \mu_p \nabla \psi + D_p \nabla p) - R
\]

\[
\frac{\partial n}{\partial t} = \nabla \cdot (-n \mu_n \nabla \psi + D_n \nabla n) - R
\]

Equations (7) - (9) present a system of mutually coupled nonlinear partial differential equations, that can be discretized, assembled and solved numerically by finite elements method.

II. FEM MODEL

For purpose of this paper only a static semiconductor equations (steady state) need to be solved, i.e. the left-hand side of (4) and (5) equals zero.

To solve the system of coupled equations a mixed FEM needs to be utilized, where the unknown variables are treated as components of one possibly multidimensional “vector” variable. Using the mixed function space allows avoiding the manual and computationally expensive decoupling of equations by any kind of splitting scheme.

A. Scaling the Equations

Since the set of variables \((\psi, p, n)\) as well as physical constants exhibit values difference of many orders of magnitude, it is advantageous to scale the equations [5] and geometric domain so that the problem becomes dimensionless. The values can be easily scaled back to physical dimensions after the solution by multiplying the dimensionless value by its scaling constant according to:

\[
X = \frac{X_{\text{orig}}}{X_0}
\]

where \( X \) stands for the scaled dimensionless value, \( X_{\text{orig}} \) for dimensional physical value and \( X_0 \) is the scaling factor.

For compact notation, all variables and values used in equations are considered scaled in the remainder of this paper unless indexed explicitly as “orig”. The differential operators also need to be scaled accordingly. The same applies for time in transient case solution.

Consider the original Poisson’s equation (7) with dimension-emphasizing notation:

\[
\nabla \cdot (\varepsilon \nabla \psi_{\text{orig}}) = -q(p_{\text{orig}} - n_{\text{orig}} + N_{D, \text{orig}} - N_{A, \text{orig}})
\]

After utilization of scaled quantities

\[
\psi_{\text{orig}} = \psi \cdot \lambda \quad p_{\text{orig}} = p \cdot \lambda \\
n_{\text{orig}} = n \cdot \lambda \\
N_{A, \text{orig}} = N_A \cdot \lambda \\
N_{D, \text{orig}} = N_D \cdot \lambda
\]

we get a scaled equation:

\[
\lambda_0 \nabla \cdot (\varepsilon \nabla \lambda \psi) = -(p - n + N_D - N_A)
\]

where

\[
\lambda_0 = \frac{\varepsilon \psi_0}{X_0^2 q N_0}
\]

Similarly the continuity equations (4),(5) at steady state \((\frac{\partial n}{\partial t} = 0, \frac{\partial p}{\partial t} = 0)\) become:

\[
0 = \lambda_1 \nabla \cdot (p \mu_p \nabla \psi + D_p \nabla p) - \lambda_1 R
\]

\[
0 = \lambda_1 \nabla \cdot (-n \mu_n \nabla \psi + D_n \nabla n) - \lambda_1 R
\]

with

\[
\lambda_1 = \frac{N_0 \psi_0 \mu_0}{X_0^2}
\]

and

\[
\mu_{\text{p, orig}} = \mu_p \cdot \mu \quad \mu_{\text{n, orig}} = \mu_n \cdot \mu \\
D_{\text{p, orig}} = D_p \cdot D_0, \text{ where } D_0 = \frac{kT}{q \mu_0} \\
D_{\text{n, orig}} = D_n \cdot D_0
\]

The equation \( \frac{D}{p} = \frac{kT}{q} \) used in (18) is known as Einstein’s relation known from kinetic theory.
The basic approach in order to maintain the scaled variables roughly close to unity is to normalize each quantity to its “typical” value, though it is strictly not possible (for example, \( p, n, N_A, N_D \) typically exhibit different values of at least an order of magnitude). The set of scaling factors used in presented model, partly inspired by [6], [4], [7] and [3], is summarized in Tab. I.

### B. Problem Statement

Let us state the **boundary-value problem** according to (13), (15), (16) within a spatial domain \( \Omega \):

\[
\begin{align*}
\lambda_0 \nabla \cdot (\nabla \psi) &= -(p - n + N_D - N_A) \quad \text{in} \ \Omega \quad (19) \\
0 &= \lambda_1 \nabla \cdot (p\mu_p \nabla \psi + D_p \nabla p) - \lambda_1 R(p, n) \quad \text{in} \ \Omega \quad (20) \\
0 &= \lambda_1 \nabla \cdot (-n\mu_n \nabla \psi + D_n \nabla n) - \lambda_1 R(p, n) \quad \text{in} \ \Omega \quad (21)
\end{align*}
\]

with boundary conditions

\[
\begin{align*}
\psi &= \psi_{BC} \quad \text{on} \ \Gamma_{D0} \quad (22) \\
p &= p_{BC} \quad \text{on} \ \Gamma_{D1} \quad (23) \\
n &= n_{BC} \quad \text{on} \ \Gamma_{D2} \quad (24) \\
n \cdot \nabla \psi &= g \quad \text{on} \ \Gamma_{N0} \quad (25)
\end{align*}
\]

Here, \( \psi, p, n \) are unknown functions, \( N_D, N_A, \mu_p, \mu_n, D_p, D_n \) are normalized (scaled) material constants, \( \lambda_0, \lambda_1 \) the scaling factors and \( R(p, n) \) the source term as defined by (6). \( \Omega \) represents the spatial domain (device geometry) composed by subdomains with diverse material properties matching the various doping regions in device; and \( \partial \Omega = \Gamma_{D0} \cup \Gamma_{D1} \cup \Gamma_{D2} \cup \Gamma_{N0} \) is the domain boundary emphasizing the Dirichlet and Neumann type of individual boundaries.

### C. Variational Forms

The unknown variables are approximated by set of piecewise **trial functions** \( (\psi, p, n) \). System of equations (19) - (21) represent a strong form, i.e. the continuous **differential form** of equations with exact solution. To be able to get an approximate piecewise solution by FEM, the problem must be formulated into weak form by multiplying by corresponding **test functions** \( (v_0, v_1, v_2) \) - sometimes called the weight functions - and integrating over the whole domain. Moreover, the continuous **trial** and **test** function spaces must be replaced by discrete function spaces to enable the numerical approximate solution.

Doing so, the mixed function-space variational problem can be phrased as follows: find \( (\psi, p, n) \in V_0 \times V_1 \times V_2 \) such that

\[
a((\psi, p, n), (v_0, v_1, v_2)) = L(v_0, v_1, v_2) \quad (26)
\]

for all \( (v_0, v_1, v_2) \in \hat{V}_0 \times \hat{V}_1 \times \hat{V}_2 \); where

\[
a((\psi, p, n), (v_0, v_1, v_2)) = \\
- \int_{\Omega} \lambda_0 \nabla \psi \cdot \nabla v_0 \, dx \\
- \int_{\Omega} D_p \nabla p \cdot \nabla v_1 \, dx - \int_{\Omega} \mu_p p \nabla \psi \cdot \nabla v_1 \, dx \\
- \int_{\Omega} D_n \nabla n \cdot \nabla v_2 \, dx + \int_{\Omega} \mu_n n \nabla \psi \cdot \nabla v_2 \, dx
\]

\[
L(v_0, v_1, v_2) = \\
- \int_{\Omega} (p - n + N_D - N_A) v_0 \, dx - \int_{\Gamma_{N0}} g v_0 \, ds \\
+ Rv_1 \, dx \\
+ Rv_2 \, dx
\]

and \( \hat{V}_0 \times \hat{V}_1 \times \hat{V}_2 \subset V_0 \times V_1 \times V_2 \) form a discrete **mixed function space** for test and trial (to be approximated) functions. Each of the subspaces represents a classic Lagrange “\( P_i \)” finite element.

The differential elements \( dx \) and \( ds \) denote integration over the domain \( \Omega \) and over the domain boundary \( \partial \Omega \) respectively. That means the surface integral over \( \Omega \) and line integral over \( \partial \Omega \) in the two-dimensional geometry.

### D. Boundary Conditions

Among others, the two basic types of boundary conditions appear in semiconductor simulations literature: so called **voltag**e and **current** boundary conditions to emphasize which of the external circuit value is forced to the device. Particular boundary conditions for semiconductor equations variables \( (\psi, p, n) \) need to be treated accordingly along with the type of contact that interfaces the device with external circuit - ohmic (metal), Schottky or insulator contact [4, 3] being the basal ones.

1) **Voltage Boundary Conditions**: The Dirichlet boundary conditions (22), (23), (24) constitute the basic form of ohmic-contact **voltage-type** boundary conditions. The value \( v_{BC} \) equals simply the value of electric potential applied to given contact (minus the **built-in potential** [8] which corresponds to equilibrium potential across PN-junctions and is compensated by semiconductor-metal contact potential in physical reality when device terminals are shorted). For \( p_{BC}, n_{BC} \) values, several strategies have been published; as a very basic one, the equilibrium concentration values can be used, that assumes the boundaries to be distant enough from PN-junction depletion region so that all excess charge caused by forward bias can be considered to recombine, which is valid up until significant current or unusual geometries.

2) **Current Boundary Conditions**: Neumann boundary condition (25) or more sophisticated one must be derived for forced-current contacts.

Total current in any position equals:

\[
\mathbf{J} = \mathbf{J}_p + \mathbf{J}_n \quad (29)
\]
Substitution of (2), (3) for \( \mathbf{J}_p \) and \( \mathbf{J}_n \) yields

\[
\frac{\mathbf{J}}{q} = \nabla \psi \left( -\mu_p n - \mu_n p \right) - D_p \nabla p + D_n \nabla n \tag{30}
\]

From (30) we get the following expression for normal component of electric potential gradient as a Neumann condition, and we call it \( g \):

\[
g = n \cdot \nabla \psi = \frac{D_n \nabla n \cdot n - D_p \nabla p \cdot n - \frac{J}{q} \cdot n}{\mu_n n + \mu_p p} \tag{31}
\]

It may be worth noting \( p \) and \( n \) represent scalar fields so that \( \nabla p, \nabla n \) and \( J \) are all vector quantities and the dot product with normal vector \( n \) produces scalar values.

All of the other boundaries are treated as natural “reflective” boundaries with zero gradient of quantities in normal direction.

**E. Solver and Initial Conditions**

Since the system is non-linear, the bilinear form (26) should be reformulated into semilinear form \( F \)

\[
F((\psi, p, n); (v_0, v_1, v_2)) = 0 \\
\forall (v_0, v_1, v_2) \in \mathcal{V}_0 \times \mathcal{V}_1 \times \mathcal{V}_2
\tag{32}
\]

such that

\[
F = a - L = 0 \tag{33}
\]

with no need to treat the unknowns \( (\psi, p, n) \) specially as trial functions in direct method; an appropriate iteration solver needs to be employed instead - most commonly the Newton’s method.

Dividing by function derivative in a standard single variable Newton’s method must be replaced by multiplication by system’s inverse \( k \times k \) Jacobian matrix.

Setting the initial conditions consists of assigning certain values to unknown functions \( \psi, p, n \) prior to performing Newton’s iterations. To make solver general, the initial guess values should be provided algorithmically, possibly violating the physical sense. Of course, consistency with Dirichlet boundary conditions is desirable whenever possible.

In proposed model, zero potential \( (\psi = 0) \) and majority charge carriers equal to doping profile \( (p = N_A, n = N_D) \) are used as initial guess. For situations greatly exceeding the equilibrium conditions, the stepping of bias voltage, current or even carrier concentrations is preformed to preserve convergence.

### III. IMPLEMENTATION

The FEM model is coded in Python by use of open source tools, mainly grouped around FEniCSx project [9], [10]. It is comprised of the libraries UFL [11], Basix [12], [13], FFCx [14] and DOLFINx. All of the project components are accessible via high-level Python and C++ interfaces.

The variational forms are formulated in UFL language and DOLFINx provides most of the methods for defining mesh, tagging individual FEM cells, assigning material properties and boundary conditions according to cell tag, input/output file handling, direct methods for solving linear problem formulated in UFL and even automated method for computing of Jacobian matrix and evaluating of residua (with boundary conditions taken into account) via function NonLinearProblem.

For illustration, the variational forms defined by (26) can be transcribed into almost 1:1 Python/UFL code as follows:

```python
# Poisson:
a0 = inner(\text{grad}(\psi), \text{grad}(v0)) * dx - 1/\text{lmda0} * (Nd - Na-n+p + EPS) * v0 * dx # EPS to avoid zero
# Neumann BC on boundary tag_bc_B
g = (Dn*inner(\text{grad}(n), nn) - Dp*inner(\text{grad}(p), nn) - Jb) / (mob_n*n + mob_p*p)
L0 = - g * v0 * ds(tag_bc_B)
# Recomeration / Generation rate
RG = (ni**2-n*p) / (Tau_p*(n+n_eq) + Tau_n*(p+p_eq))
# Continuity p:
a1 = -D_p*inner(\text{grad}(p), \text{grad}(v1)) * dx - mob_p*\text{grad}(p)*v1 + EPS) * v1 * dx
L1 = RG * v1 * dx
# Continuity n:
a2 = -D_n*inner(\text{grad}(n), \text{grad}(v2)) * dx + mob_n*\text{grad}(n)*v2 + EPS) * v2 * dx
L2 = RG * v2 * dx
F = a0+a1+a2 -L0-L1-L2
```

The domain, mesh, subdomain tags and boundary conditions tags for all cells are created in gmsh [15].

Post-processing and visualizations are made directly in python program by use of matplotlib library [16] using output data formatted by appropriate DOLFINx and numpy [17] functions.

### IV. DEMONSTRATION - PN JUNCTION DIODE

To demonstrate the model functionality, an PN-diode of rectangular subdomains representing uniformly doped P-type and N-type regions was modeled. N-region is background doped by acceptors equal to P-region doping concentration, emulating the P-type base material in device manufacturing process.

![Fig. 1. Simulated static V-A characteristic of simple PN diode. Horizontal axis represents an external applied voltage i.e. with built-in voltage accounted. Current axis is normalized by arbitrary choice of device cross-section area.](image)

**A. Geometry Domain and Subdomains**

Geometry and material properties of simulation subdomains is defined as follows:
• P-region:
  \[ N_D = 0, \ N_A = 1.3 \cdot 10^{16} \text{ cm}^{-3}, \ \text{length 1.25 \mu m} \]
• N-region:
  \[ N_D = 1.6 \cdot 10^{16} \text{ cm}^{-3}, \ N_A = 1.3 \cdot 10^{16} \text{ cm}^{-3}, \ 1.25 \mu m \]

The simulation results are scalable through cross-section area, so there is no need to define an exact cross-section dimension.

**B. Boundary Conditions**

- P-side: *current* BC with value sweep,
- N-side: *voltage* BC set to \( \psi_{BC,N} = 0 \) (cathode grounded)

**C. Simulation Results**

The thermal equilibrium results of PN-junction electrostatics, which are virtually the same as reverse bias (except the depletion region width and potential extent) due to existence of built-in potential, are depicted on Fig. 2. The depletion region free of mobile carriers - thus non-zero net charge \( q(p-n+Nd-Na) \) - is formed at junction vicinity. A positive drift current is perfectly compensated by negative diffusion current and vice versa at any position.

In contrast, a forward biased PN-junction results are shown on Fig. 3. The depletion region is reduced greatly, minority carriers are injected from opposite regions and total current \( J = J_p + J_n \) is constantly flowing through device from P-anode to N-cathode.

A sequence of steady state situations like this with parametric sweep of total current can be arranged into current-voltage characteristic as shown on Fig. 1.

**V. NP\textsubscript{\nu}N POWER TRANSISTOR - ON-STATE EXCESS CHARGE STORAGE**

**A. Background and 1D Model**

NP\textsubscript{\nu}N nomenclature signifies a presence of very lightly doped so called N-drift region [18] in collector to support high voltage during reverse bias of base-collector junction. An example of such structure - representing one of many cells incorporated in real power transistor chip - is depicted on Fig. 4. Essentially the same structure is employed in any IGBT transistor. N-drift region has significant impact on transistor’s static characteristic and slows-down switching as it can store a huge amount of excess charge.

**B. Power BJT Domain Geometry and Boundaries Definition**

Simplified analytical one-dimensional models, often called the lumped-charge models, that model an excess charge within
device are widely used for explanation of power transistor operation [19], [20], being essentially an extension of traditional charge-control approach introduced by device modelling pioneers like Gummel [21].

A brief analysis 1D model of power BJT as shown on Fig. 5 is presented in our previous work [22]. The article introduces an experimental way of stored-charge estimation based on analysis of base drive current during turn-off transient. Due to inability to access the base current within IGBT, a power BJT was chosen for characterization to support the simplified model experimentally.

One of the outputs examining the stored charge under variable collector current and showing the transition between active and quasi-saturation mode of operation is presented on Fig. 6. The rationalisation of shape of the curves is discussed in [22] and is not an objective of this paper. Here only a physical simulation support for the experiment is supplied.

B. 2D Simulation Model

Simulation domain adheres geometry, subdomains and boundaries depicted on Fig. 4. The subdomains are uniformly doped according to:

<table>
<thead>
<tr>
<th>Layer Width</th>
<th>N⁺ Emitter</th>
<th>P Base</th>
<th>N⁻ drift</th>
<th>N⁺ Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 µm</td>
<td>5 · 10¹⁸</td>
<td>1 · 10¹⁵</td>
<td>1 · 10¹⁵</td>
<td>1 · 10¹⁸</td>
</tr>
<tr>
<td>6 µm</td>
<td>1 · 10¹⁷</td>
<td>1 · 10¹⁷</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Voltage boundary condition $\psi_{BC}$ was applied on emitter contact. Parametric sweep of base and collector voltage boundary conditions were performed to achieve any of the operation modes as shown on current-voltage characteristic on Fig. 10. An example of solution of unknown functions $(\psi, p, n)$ at quasi-saturation bias mode is shown on Fig. 8 and visualisation of vector-valued variables $J, J_p, J_n$ are shown on Fig. 9 - the transistor effect causing current amplification is clearly apparent.

VI. CONCLUSION

The simulation outputs validate the feasibility of building an open-source implementation of semiconductor device physical model. It is demonstrated on simplified uniformly doped semiconductor structures, mainly for geometry and mesh coding.
simplicity; though it fully validates of numerical approach as well as qualitative explanation of device internal physics in sufficient detail.

The basic comparison with real measurement data of excess charge storage within power BJT shows good qualitative correlation with simulation data proving the FEM model to serve as good validation tool for analytical assumptions in further development of simplified models.

The main appeal in latter model version can be defined as:
- initial guess accuracy improvement for arbitrary bias conditions, being apparently one of the most crucial factors affecting the numerical convergence,
- more reasonable physics-based boundary conditions for any bias,
- extension of static transport equations to time dependent problem using either backwards Euler or any advanced scheme, allowing to model the transient behavior,
- more realistic non-uniform doping profiles and material properties definitions,
- advanced physical and/or empirical models of physical parameters (mobility, recombination, etc.).

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REFERENCES