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Diode_CMC model v2.0.0

Klaus-Willi Pieper, Infineon Technologies AG
Agenda

› Introduction
› Features of diode models
› Application of Juncap2 and Diode_CMC
› Scaling of Juncap2 and Diode_CMC
› High injection in Diode_CMC v2.0.0
› Reverse Recovery Effect in Diode_CMC v2.0.0
  – Calculation of charge storage
  – NQS modeling
› New model parameters in Diode_CMC v2.0.0
› Measurement and simulation of reverse recovery effect
› Comparison of characteristics Diode_CMC v1.0.0 and v2.0.0
› Documentation and Si2 web page
› What’s next?
Available Diode models (ordered from low to high complexity)

› **Berkeley-SPICE Diode** (1975, University of Berkeley, often called level 1)

› Fowler-Nordheim Diode (often implemented as diode level 2)

› Lauritzens VerilogA models [link](http://www.ee.washington.edu/research/pemodels/)
  - with reverse recovery, with forward and reverse recovery, with voltage-dependent reverse recovery and power diode with forward and reverse recovery

› **Juncap2** model (NXP, 2009)

› **Diode_CMC model v1.0.0**
  - CMC standard of Compact Modeling Coalition (CMC) in 2010

› **Diode_CMC model v2.0.0**
  - Implementation by Hiroshima University, CMC production release in Sept 2015 (verilogA model)
Features of diode models

› Features of Berkeley-SPICE model
  - Forward DC characteristics, reverse leakage current, temperature dependent saturation current, series resistance, diffusion capacitance, nonlinear depletion capacitance, charge storage with transit time parameter, reverse breakdown, flicker noise

› Additional features of Juncap2 model
  - Geometrical scaling: bottom, STI-edge, and gate-edge components
  - Shockley-Read-Hall generation/recombination current, both in forward and reverse mode of operation
  - Trap-assisted tunneling current, both in forward and reverse mode of operation
  - Band-to-band tunneling current
  - Avalanche and breakdown
  - Shot noise

Published Literature: The Physical Background of JUNCAP2
Scholten, A.J.; Smit, G.D.J.; Durand, M.; van Langevelde, R.; Klaassen, D.B.M.
Features of diode models

- **Additional features of Diode_CMC v1.0.0**
  - Series resistors that scale with bottom well area, gate edge and STI edge perimeters plus non-scaling part
  - Temperature dependence of series resistor RS
  - Junction flicker noise, shot noise and resistor thermal noise
  - Temperature dependence of saturation current as a function of XTI (PT)
  - Non-ideality factor NFACTOR for ideal current component
  - Temperature dependence of reverse breakdown voltage
Diode models

- Additional features of Diode_CMC v2.0.0
  - High injection mode for forward diode current
  - Reverse recovery effect (scaling with bottom area only)
  - Compatible to Diode_CMC v1.0.0, if v1.0.0 parameters are used only

Implementation by Hiroshima University, addition of high injection and reverse recovery modelling concepts from HiSIM-Diode model, production release in Sept 2015 (verilogA model)

Original published literature:
Juncap2, Diode_CMC v1.0.0 and v2.0.0

Scaling

Suitable for drain-bulk/source-bulk junctions as well as for standalone diodes

Scaling parameters

› Bottom area AB
› Length of gate edge LG
› Length of STI-edge LS

Figures taken from documentation of Juncap2 version 200.3, 4/2009
Juncap2, Diode_CMC v1.0.0 and v2.0.0

› Application for Juncap2 and Diode_CMC v1.0.0
  - PN junction

› New application of Diode_CMC v2.0.0 model
  - PN junction with low doped N⁻ (or P⁻) region

Fig. 1. Target device structures: (a) actual target, (b) example application.

Figure taken from documentation of Hiroshima University
Diode_CMC v2.0.0 High injection region

- New implementation of high injection region

- **blue line**: v1.0.0 with serial resistance=326 Ohm
- **red line**: v2.0.0 with high injection parameters and serial resistance=1.5 Ohm (correct value)
- **red symbols**: measurement
Model parameters for high injection region

<table>
<thead>
<tr>
<th>scaling with</th>
<th>Diode_CMC/Juncap2 parameters</th>
<th>additional Diode_CMC v2.0.0 parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>bottom area AB</td>
<td>IDSATBOT</td>
<td>NFABOT (default=1)</td>
</tr>
<tr>
<td>STI length LS</td>
<td>IDSATSTI</td>
<td>NFASTI (default=1)</td>
</tr>
<tr>
<td>gate length LG</td>
<td>IDSATGAT</td>
<td>NFAGAT (default=1)</td>
</tr>
</tbody>
</table>

High injection is activated ...

- for bottom area scaling (AB), if NJH > NFABOT
- for STI edge scaling (LS), if NJH > NFASTI
- for GAT edge scaling (LG), if NJH > NFAGAT
High injection region Diode_CMC v2.0.0

- High injection region for different temperatures

Temp = -40, 25, 100, 150, 200°C

Symbols: measured
Lines: simulated

Log y-axis

Linear y-axis
Reverse Recovery Effect in Diode_CMC v2.0.0

What is the reverse recovery effect?

- carrier storage time $t_s$ is big
  - for long dimensions (WI)
  - for long lifetime of minority carriers (TAU)
Reverse Recovery Effect in Diode_CMC v2.0.0
Calculation of charge storage

\[ I = I_j + \frac{dQ_j}{dt} \]

\[ I_j: \text{junction current} \]

› Diode_CMC v1.0.0 or v2.0.0 with CORECOVERY=0

\[ Q_j = Q_{junction} + TT \ I_j \]

\[ TT: \text{transit time} \]

› Diode_CMC v2.0.0 with CORECOVERY=1

\[ Q_j = Q_{junction} + Q_{RR} \]
Reverse Recovery Effect in Diode_CMC v2.0.0
Calculation of charge storage

› Charge calculation $Q_{rr}$

Forward operation

During reverse recovery process

Diffusion Length

$$L_a = \sqrt{\frac{\tau_{HL} D_a}{\tau_{KR}}}$$

with

$$\tau_{HL} = TAU \left( \frac{T_{KD}}{T_{KR}} \right)$$
Reverse Recovery Effect in Diode_CMC v2.0.0
Calculation of charge storage

- Injected charge carrier densities with corrections near $V_{HA} / V_{HK}$ (anode and cathode)

\[
q_A = AB q \left\{ p_{n0,bot} M_{ID,bot}^{\text{INJ1}} \exp \left[-\text{INJ2}(V_{AK} - V_{HA})^2 \left( \frac{T_{KR}}{T_{KD}} \right)^{\text{INJT}} \right] - p_{n0,bot} \right\}
\]

\[
q_K = AB q \left\{ p_{n0,bot} \exp\{k\}^{\text{INJ1}} \exp \left[-\text{INJ2}(V_{AK} - V_{HK})^2 \left( \frac{T_{KR}}{T_{KD}} \right)^{\text{INJT}} \right] - p_{n0,bot} \right\}
\]

$V_{HA}, V_{HK}$: threshold voltages for high injection (anode and cathode)
$T_{KR}$: reference temperature
$T_{KD}$: device temperature
$p_{n0}$: minority carrier density at thermal equilibrium
Reverse Recovery Effect in Diode_CMC v2.0.0

NQS modeling

› Delay in charge density \( q_A / q_K \) and width of depletion region \( W_{depA} \)

实施 R/NQS 或 DEPNQS

Example:
Abrupt change of \( q_{qs} \)

\[
\frac{q_A}{NQS} = \frac{q_{A\_nqs}}{NQS} + \frac{dq_{A\_nqs}}{dt}
\]

same for \( q_K \) and \( W_{depA} \)

\( q_A \rightarrow q_{A\_nqs}, \quad q_K \rightarrow q_{K\_nqs}, \quad W_{depA} \rightarrow W_{depA\_nqs} \)
Reverse Recovery Effect in Diode_CMC v2.0.0
Calculation of charge storage

Total charge $Q_{rr}$

\[
Q_{nexA,nqs} = - \int_{W_{depA,nqs}}^{\text{WI}} q_{A,nqs} \exp\left(-\frac{x}{L_a}\right) dx
\]

\[
Q_{nexK,nqs} = - \int_{W_{depA,nqs}}^{\text{WI}} q_{K,nqs} \exp\left(-\frac{\text{WI} - x}{L_a}\right) dx
\]

$L_A$: diffusion length

$Q_{n0} = q \ AB \ NDIBOT \ WI$

\[
Q_{rr} = -(Q_{nexA,nqs} + Q_{nexk,nqs} + Q_{n0})
\]
New model parameters in Diode_CMC v2.0.0

› Reverse recovery effect
  - is activated by a new parameter \( \text{CORECOVERY} = 1 \)
  - scaling is with bottom area only

› Parameters influencing reverse recovery effect
  - \text{NFABOT, NJH, NJDV, NDIBOT} (high injection parameters, can be extracted at DC)
  - \text{WI} (length of drift region)
  - \text{NQS, DEPNQS} (carrier / depletion width delay times)
  - \text{TAU} (carrier life time)
  - \text{INJ1, INJ2} (carrier densities at high injection)
  - \text{TAUT} (temperature coefficient of carrier life time)
  - \text{INJT} (temperature coefficient of carrier densities at high injection)

To be extracted at reverse recovery current at room temperature
Measurement and simulation of reverse recovery effect

- reverse recovery effect

Simulation and measurement circuit

Forward current IF=100mA

symbols: measurements
lines: simulations

$V_{REV} = -5.16V$
$V_{REV} = -8.94V$
$V_{REV} = -16.40V$
$V_{REV} = -24.05V$
$V_{REV} = -31.63V$

Forward operation TLP switched to reverse operation

0 10 20 30 40 50
forward operation TLP switched to reverse operation timenu

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Comparison of characteristics Diode_CMC v1.0.0 and v2.0.0

CORECOVERY = 0

CORECOVERY = 1
Comparison of characteristics Diode_CMC v1.0.0 and v2.0.0

CORECOVERY = 0

CORECOVERY = 1
Comparison of characteristics Diode_CMC v1.0.0 and v2.0.0
Diode_CMC model code and documentation are publically available and can be found on the public part of Si2-CMC page at “CMC Open Standards”
What’s next? (ideas for the future)

› What happen structure (n-p-n or p-n-p) ?
  - Influence of the third layer?
  - Where does the stored charge flow?
  - Implementation of RR into a bipolar model?
› Temperature dependence of Reverse Recovery Effect
› Forward Recovery Effect
› Self heating
Acknowledgments

› Masataka Miyake (Model developer at HiSIM Research Center, Hiroshima University)

› Mitiko Miura-Mattausch (Prof. at HiSIM Research Center, Hiroshima University)
Part of your life. Part of tomorrow.
High injection region Diode_CMC v2.0.0

- Emission coefficient is increasing with voltage $V_{AK}$ from NFA to NJH, if NJH $\leq$ NFA, then NJ = const = NFA

$$\text{High-injection } \textbf{threshold voltage} \quad V_{HA} = \phi_{TD} \ NFA \ \ln\left(\frac{NDI}{p_{n0}(\text{temp})}\right)$$

Same equations for BOT, STI and GAT scalings.
High injection region Diode_CMC v2.0.0

› Diode_CMC v1.0.0

Diode_CMC v2.0.0

DC current \( I_D = (M_{ID} - 1) IDSAT \)

\[
M_{ID} = \begin{cases}
\exp\left(\frac{V_{AK}}{NFA \phi_{TD}}\right) & \text{if } V_{AK} < VMAX \\
(1 + \frac{V_{AK} - VMAX}{NFA \phi_{TD}}) \exp\left(\frac{VMAX}{NFA \phi_{TD}}\right) & \text{if } V_{AK} \geq VMAX
\end{cases}
\]

› Diode_CMC v2.0.0

\[
M_{ID} = \begin{cases}
\exp\left(\frac{V_{AK}}{nj(V_{AK}) \phi_{TD}} + vha \left(\frac{nj(V_{AK}) - NFA}{NFA \ NJH}\right)\right) & \text{if } V_{AK} < VMAX \\
\left(1 + \frac{V_{AK} - VMAX}{\phi_{TD}} dVMAX\right) \exp\left(\frac{VMAX}{nj(VMAX) \phi_{TD}} + vha \left(\frac{nj(VMAX) - NFA}{NFA \ NJH}\right)\right) & \text{if } V_{AK} \geq VMAX
\end{cases}
\]

with \( dVMAX = \frac{nj(VMAX) - VMAX}{nj(VMAX)^2} \left(\frac{dnj}{dV}\right)_{VMAX} + vha \left(\frac{dnj}{dV}\right)_{VMAX} \)

› For NJH<=NFA: \( nj(V_{AK})=NFA \) (same equations in both versions)
The model documentation of Diode_CMC v2.0.0 consists of two documents:

- Juncap2 document (April 2009, NXP)
- Diode_CMC document (Sept 2\textsuperscript{nd} 2015, HU)
Recovery Model in Diode_CMC (Version 2.0.0 Level 2002)

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Equations implemented in 2009 can be found in appendix of Diode_CMC document.
Measurement and simulation of reverse recovery effect

The transmission line models the effect of an 75 cm long cable.