



Aging model for a 40 V Nch MOS, based on an innovative approach

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- **WHAT IS AGING MODELING:**

- Aging modeling is a tool to simulate devices performance after a long period of operation (years)
- Simulated degradation depends on both time and operating conditions

- **PURPOSE:**

- To estimate the possible degradation of a device during its life
- To allow the designers to take into account the reliability issues at design level

- **MAIN FEATURES:**

- The effect of a DC or periodic stress can be simulated.
- Different degradation mechanisms may be considered:
 - Hot carrier injection
 - NBTI
 - PBTI

Introduction (1)



- Commercial aging simulation tools (Eldo UDRM, RelXpert) work using the following scheme:

- Stress calculation:**

- A function “stress rate” $s(V)$ is defined for each degraded instance
- During a transient simulation, s is integrated to give “Total Stress” S :

$$S(T_s) = \int_0^{T_s} s(V(t)) dt \quad (1)$$

- Assuming a periodic stress waveform, Cumulated Stress at the end of the device lifetime (even years) is extrapolated:

$$S(Time) = \frac{Time}{T_s} \left(\int_0^{T_s} s(V(t)) dt \right) \quad (2)$$

- Post-stress simulation**

- Parameters value after degradation is computed as a function of S :

$$\Delta P = f(S) \quad (3)$$

- “Degraded” circuit is simulated

Introduction (2)



- With this flow, degradation during AC Stress is accurately modelled only if DC parameter degradation kinetic is of the form:

$$\Delta P_{DC} = f\left(\frac{t}{\tau(V)}\right) \quad (4)$$

where only the characteristic time τ depends on bias

- Then, degradation after a generic (periodic) stress is given by:

$$\Delta P = f\left(\int \frac{dt}{\tau(V(t))}\right) \quad (5)$$

- i.e., comparing it with (2) : Stress rate: $s(V) = 1 / \tau(V)$ (6.a)

$$\text{Parameters update: } \Delta P = f(S) \quad (6.b)$$

- This is a **limitation**: not all the experimental cases satisfy this condition
- We propose a way to **extend** aging model to a wider class of kinetics

Introduction (3)



- **Improvement:** if DC drift is written as the sum of components, each of which has the required form...

$$\Delta P_{DC} = f_1\left(\frac{t}{\tau_1(V)}\right) + f_2\left(\frac{t}{\tau_2(V)}\right) + f_3\left(\frac{t}{\tau_3(V)}\right) + \dots \quad (7)$$

- ...Then a periodic stress can be accurately simulated, treating each component as **independent**:

$$S_1(T_s) = \int_0^{T_s} s_1(V(t)) dt = \int_0^{T_s} \frac{dt}{\tau_1(V(t))} \quad S_2(T_s) = \int_0^{T_s} s_2(V(t)) dt = \int_0^{T_s} \frac{dt}{\tau_2(V(t))} \quad (8)$$

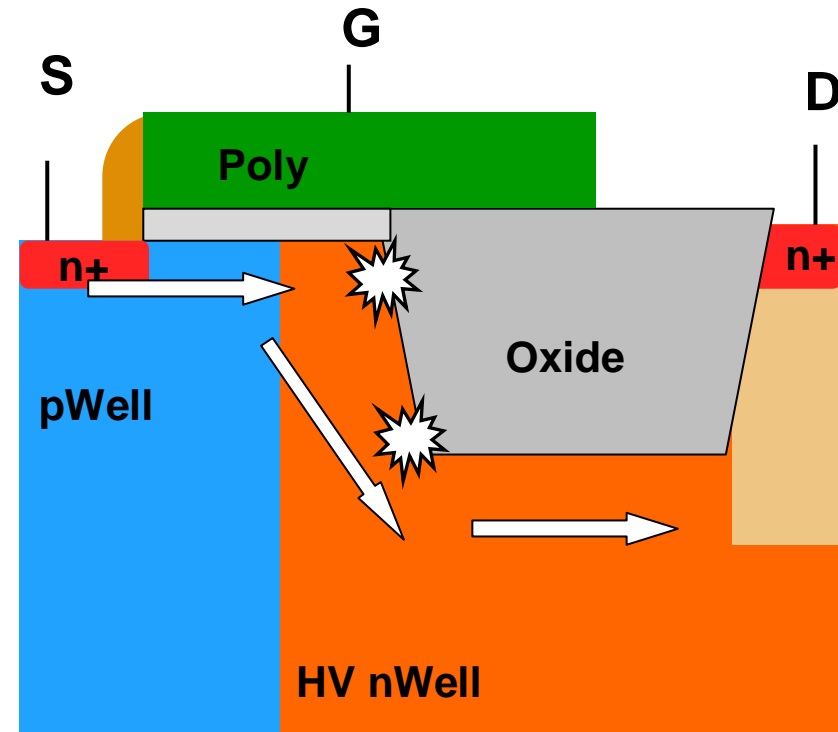
$$\Delta P = f_1(S_1) + f_2(S_2) + \dots \quad (9)$$

- We developed a **physical model** for HCI-induced Ron drift (adopting a dispersive first-order kinetics) in which degradation kinetics satisfy this condition (if some physical assumption are satisfied)

New method (1)



- Target:
To model **HCI-induced Ron drift**
- Ron drift is due to the **activation of defects** at Si/SiO₂ interface or in SiO₂
- Defects are activated by **hot carriers** injection (electron or holes) in hotspots
- **One or more** hotspots may be present; they're assumed to be independent



New method (2)



- Physical assumptions:
 - Ron Drift is proportional to the **number** of activated defects
 - No new defects generated during stress
 - Rate depends on defect **activation energy**, which has a distribution $D(\phi)$ (dispersive kinetics)

$$\Delta Ron(t) = \alpha \int_{\phi=0}^{\infty} D(\phi) p(\phi, t) d\phi \quad (10)$$

$D(\phi)$ = defect **energy distribution**
 $p(\phi, t)$ = **probability** that a defect of energy Φ has been activated at the time t .

- Activation rate is given by a 1st order kinetics

$$\frac{dp(\phi, t)}{dt} = k(\phi, V(t))(1 - p(\phi, t)) \quad (11)$$

$k(\phi, V(t))$ = **rate constant of activation reaction**
Depends on instantaneous device bias

- Calculation is shown for one hotspot; if more hotspots are present the extension is straightforward – drifts are plainly summed

New method (3)



- From the above equations we have:

Probability
$$p(\phi, t) = 1 - \exp\left(-\int_0^t k(\phi, V(t')) dt'\right) \quad (12)$$

Drift
$$\Delta Ron(t) = \alpha \int_{\phi=0}^{\infty} D(\phi) \left[1 - \exp\left(-\int_0^t k(\phi, V(t')) dt'\right)\right] d\phi \quad (13)$$

- During DC stress, time integral is trivial and degradation reduces to:

$$\Delta Ron_{DC}(t) = \alpha \int_{\phi=0}^{\infty} D(\phi) [1 - \exp(-k(\phi, V_{DC})t)] d\phi \quad (14)$$

Thus, DC drift kinetics would **not** satisfy condition (4) $\Delta P_{DC} = f(t/\tau(V))$

- Indeed, the energy integral may be discretized in a **sum**:

$$\Delta Ron_{DC}(t) = \alpha \sum_{i=0}^N D(\phi_i) [1 - \exp(-k(\phi_i, V_{DC})t)] \Delta\phi = \alpha \sum_{i=0}^N \Delta Ron_i^{DC} \Delta\phi \quad (15)$$

New method (4)

- Then, total Ron is **the sum of independent contributions**, each of which is due to defects of a given energy

- A single “energy level” contributes with a term:

$$\Delta Ron_i^{DC} = D(\phi_i)[1 - \exp(-k(\phi_i, V_{DC})t)] \quad (16)$$

- Each single contribution can be **implemented** in a simulator since it is in the form:

$$\Delta P_{DC} = f\left(\frac{t}{\tau(V_{DC})}\right) \quad \text{having} \quad \tau(V_{DC}) = \frac{1}{k(\phi_i, V_{DC})} \quad (17)$$

- Total Ron drift is then the **sum of elements of the form $f(t/\tau(V))$** :
→ it satisfies condition (7)
- It can thus be integrated in the simulator like in eqs. (8), (9) (even if condition (4) is not satisfied)

Aging model implementation (1)



- This method was used to implement an aging model in “**Eldo UDRM**” , the reliability simulation tool supplied with Eldo simulator (by Mentor Graphics)
 - The same flow could be applied to other commercial aging simulators, as long as they follow the same simulation scheme
 - The implementation in “**RelXpert**”, by Cadence, could be less straightforward because its aging API is quite rigid
- Range of defects energies is divided in a given number of intervals (e.g. 50)
- **For each energy interval, a stress rate s_i is defined**; it represents the contribution to the degradation of the defects with energy in the interval

Aging model implementation (2)



- As usual, aging simulation is performed in two steps.

- Stress calculation**

Let's consider a transient simulation, with a periodic signal (having period T).

For each energy value, stress rate s_i is computed, depending on device bias and energy; stress rates is then integrated (see eq. (8)), giving stress parameters $S_1 \dots S_N$.

$$S_1(t_s) = \int_0^{t_s} s_1(V(t)) dt = \int_0^{t_s} \frac{dt}{\tau_1(V(t))} = \left(\frac{t_s}{T}\right) \int_0^T k(\phi_1, V(t')) dt' \quad (18)$$

$$S_i(t_s) = \left(\frac{t_s}{T}\right) \int_0^T k(\phi_i, V(t')) dt'$$

Periodic signal → integral over 1 period
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- In “usual” aging model, there would be a single stress parameter S; now, **one per each energy value**

Aging model implementation (3)



- **Model parameters update:**

- The contribution to Ron drift of every component is then calculated...

$$\Delta Ron_i(t) = D(\phi_i)[1 - \exp(-S_i)] \quad (18)$$

- ...and summed giving total degradation

$$\Delta Ron(t) = \alpha \sum_{i=0}^N Ron_i \Delta \phi = \alpha \sum_{i=0}^N D(\phi_i)[1 - \exp(-S_i)] \Delta \phi \quad (19)$$

- Ron increment is added to the **drain series resistance**
- We obtained **an accurate description of Ron drift during AC stress**
- **Drawback:** simulation requires more **computational resources** than usual aging models (50 stress integrations vs. 1)
 - may be an issue for CMOS (Millions devices in a chip), less for HV devices
- **Possible upgrade:** the same method could be extended to models beyond 1st order kinetics, as long as is valid that:

$$\frac{dp(\phi, t)}{dt} = k(\phi, V(t))g(p(\phi, t)) \quad (20)$$

HCI on 40V Nch drift – model details



- Our method was applied to describe the **Ron degradation of a 40V Nch drift**
- Electrical model: complex subcircuit including **BSIM3 MOS model**
- Modeling equations used:
 - **Two hotspots**: one of electrons, one of holes
 - Modeling functions used:

Defect energy distributions: **Gaussian**

$$D(\phi) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(\phi - \langle\phi\rangle)^2}{2\sigma^2}\right) \tag{21}$$

Rate of defect activation $k(\phi, V)$: (modified) “Lucky electron”

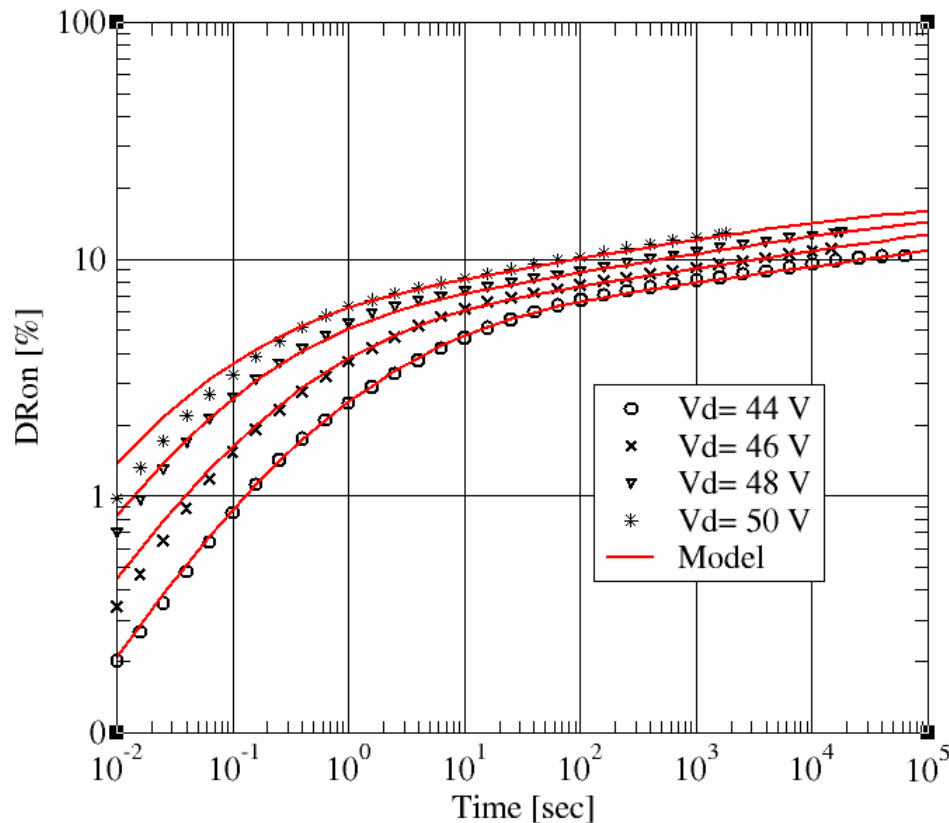
$$k(\phi, V) = Kn(V_{DS}, V_{GS}) \exp\left(-\frac{\phi}{q\lambda F(V_{DS}, V_{GS})}\right) \tag{22}$$

n=carriers density at hotspot
 F=Effective electrical field at hotspot
 λ =carriers mean free path

F, n from **TCAD** simulation
 λ “conventional”
 $\langle\phi\rangle$, σ , K fitted to **experimental data**

HCI on 40V Nch drift – model results (1)

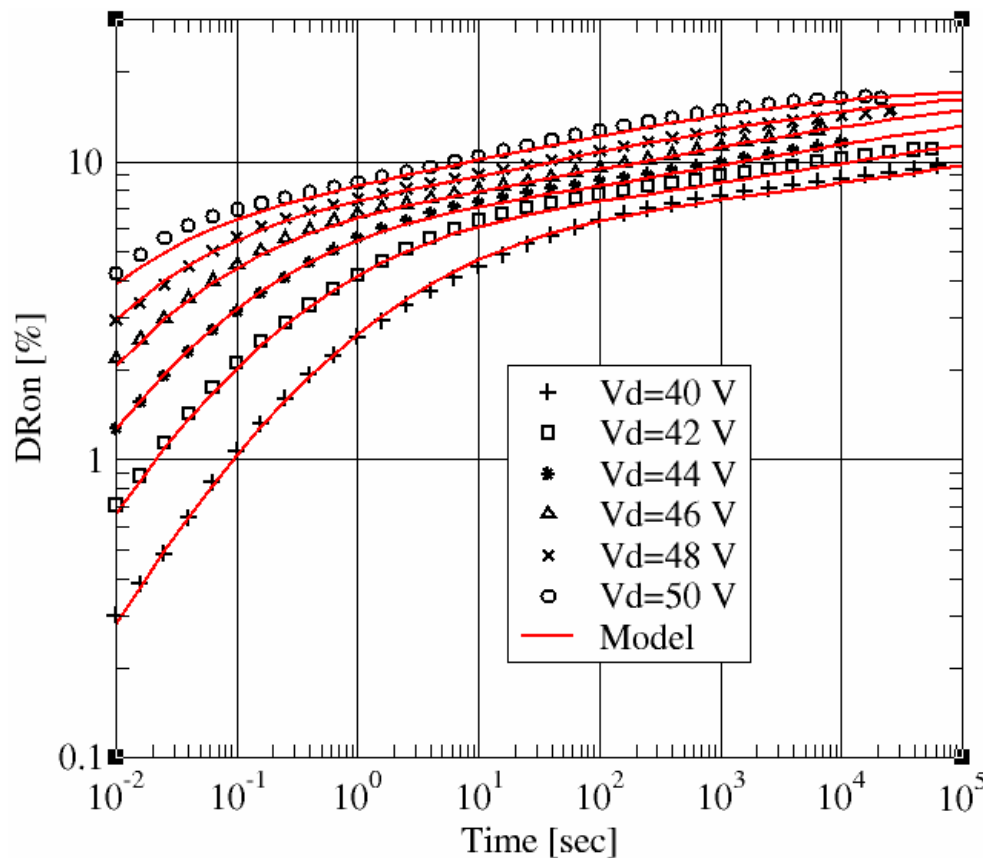
- Drift of **On-state resistance** measured at:
 - $V_{gs}=3.3V$, $V_{ds}=0.1V$



- DC measure vs. model
- Simulator: **Eldo**
- Stress conditions:
 - $V_{gs}-V_{th}=0.25\text{ V}$
 - $V_{ds}=44 \rightarrow 50\text{ V}$ step 2 V

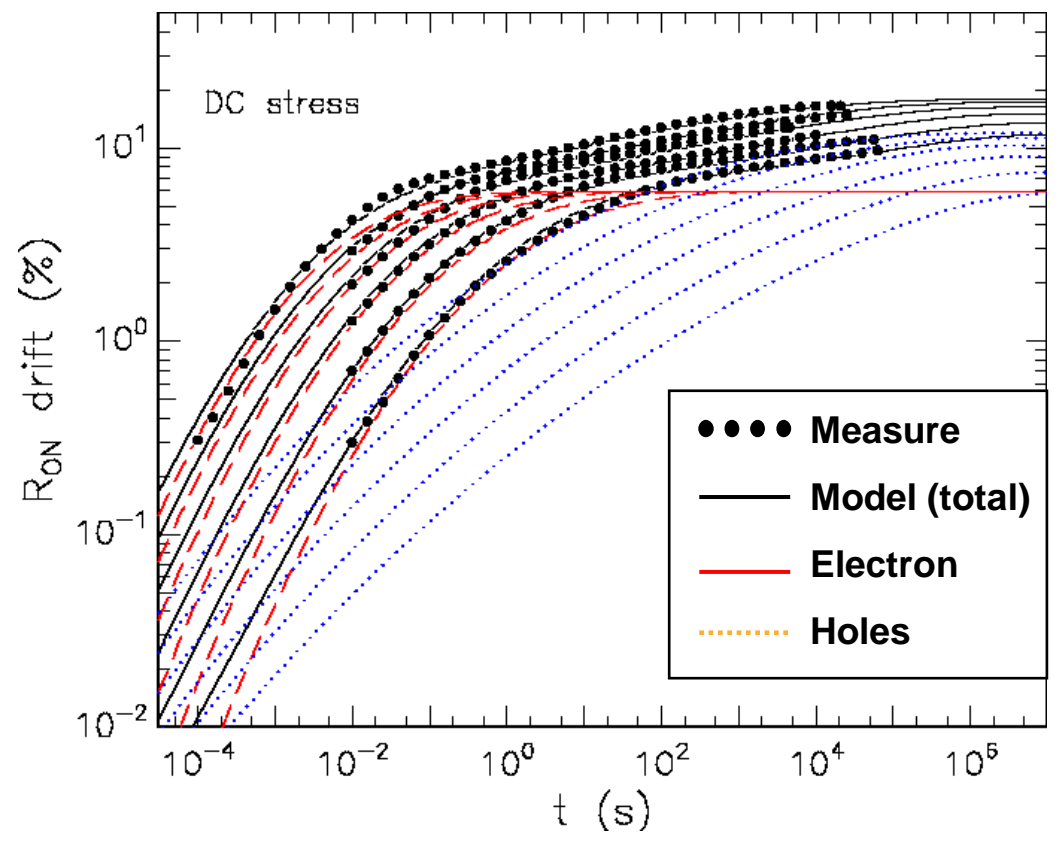
HCI on 40V Nch drift – model results (2)

- Drift of **On-state resistance** measured at:
 - $V_{gs}=3.3V$, $V_{ds}=0.1V$



- DC measure vs. model
- Simulator: **Eldo**
- Stress conditions:
 - $V_{gs}-V_{th}=1 V$
 - $V_{ds}=40 \rightarrow 50 V$ step 2 V

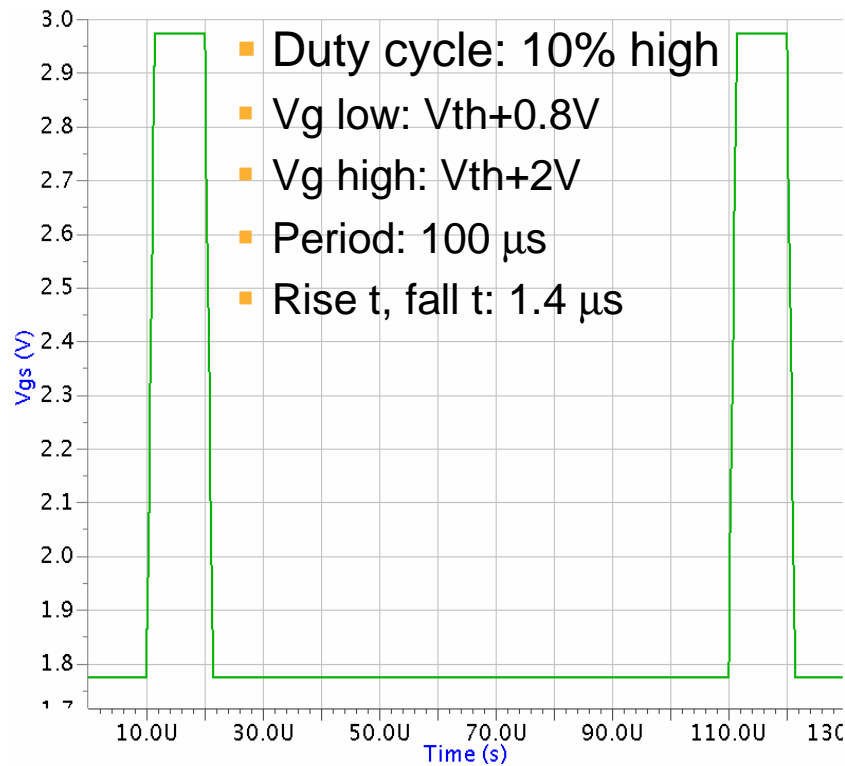
HCI on 40V Nch drift – model results (3)



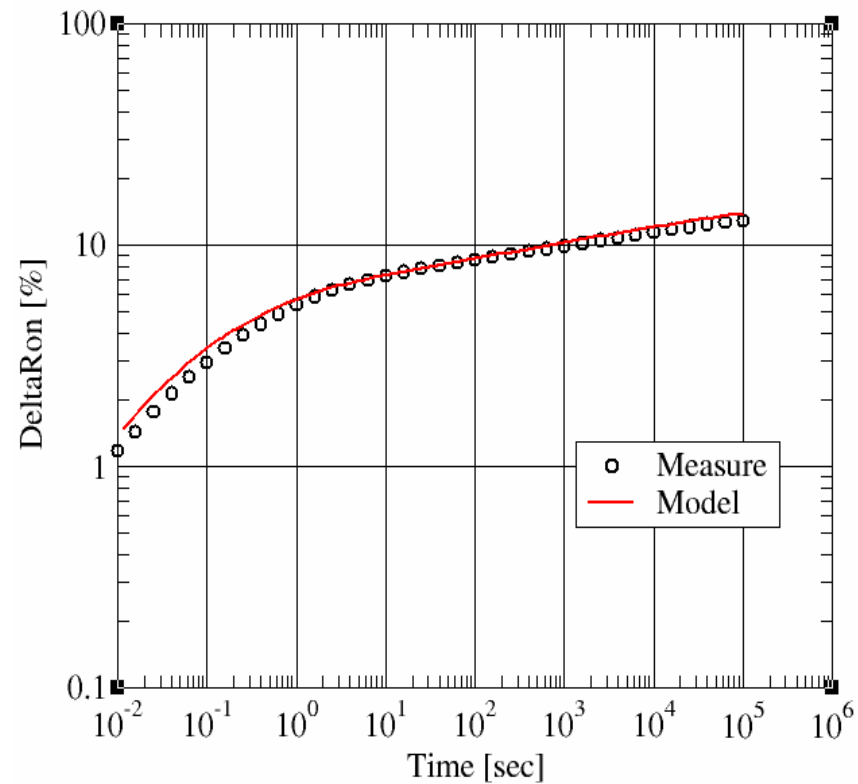
- DC measure vs. model
 - $V_{gs}-V_{th}=1$ V
 - $V_{ds}=40 \rightarrow 50$ V step 2
- Electrons and holes contributions (2 different hotspots) are shown

HCI on 40V Nch drift – model results (4)

- Measure/model comparison during a **periodic stress**
- $V_d=44V$
- V_g **pulsed (trapezoial wave)**



Vgs waveform

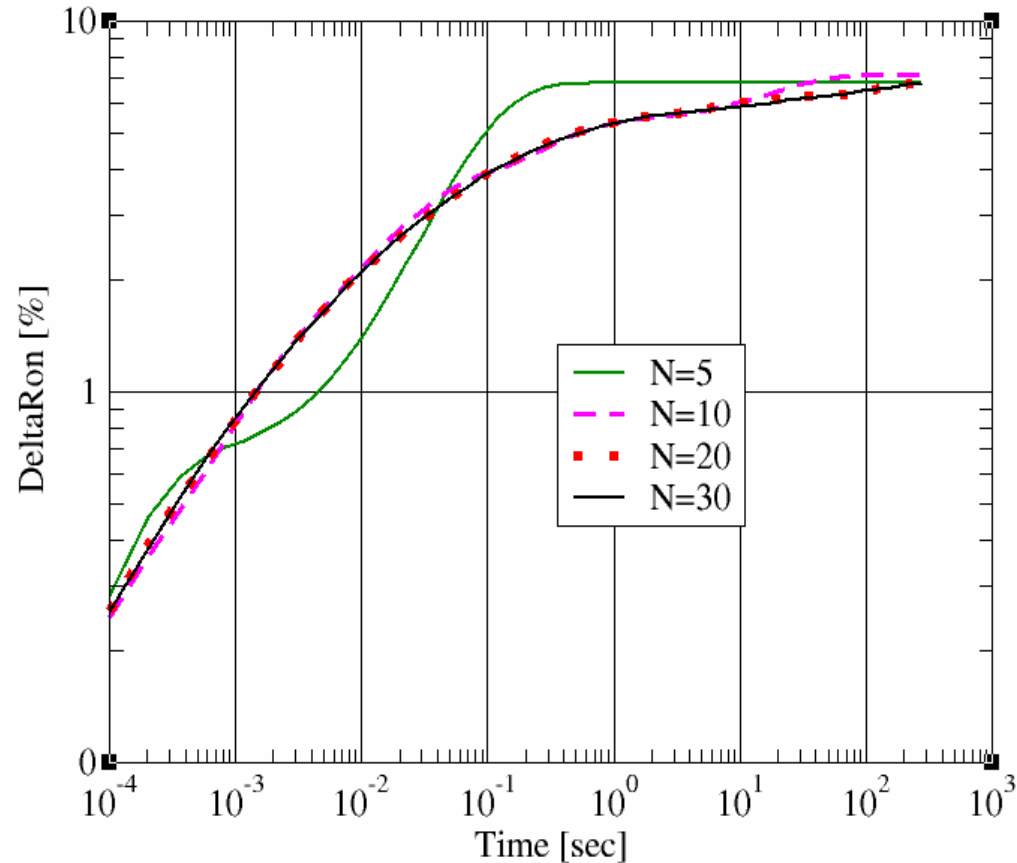


ΔRon vs stress time

HCI on 40V Nch drift –Discretization of the energy integral



- Ron drift vs time (Vds=36V, OVD=1V)
- Different number N of discretization levels in energy integral



- Only a slight improvement changing from 20 to 30 levels
- → **N>30** ensures a good approximation of the integral

- A model for **hot-carriers-induced Ron drift** has been developed, based on the assumptions that
 - Drift is due to the activation of **pre-existing defects**, with a given activation energy distribution
 - Kinetics is described by a **1st order equation**
(dispersive 1st order kinetics approach)
- The model is suitable for the **implementation in a simulator** (Eldo) even if DC kinetics doesn't satisfy the condition $\Delta R_{on}=f(t/\tau(V))$
 - Implementation in RelXpert not straightforward
- The methodology has been applied to a 40V NMOS Drift
 - Model has been extracted by DC measurements and shows a sufficient accuracy even during a AC test

References



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