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

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Aging modeling

- **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:

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

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

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

  - **Post-stress simulation**
    - Parameters value after degradation is computed as a function of S:

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

    - "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:

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

where only the characteristic time τ depends on bias

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

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

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

  Parameters update: $\Delta P = f(S)$ *(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...

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

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

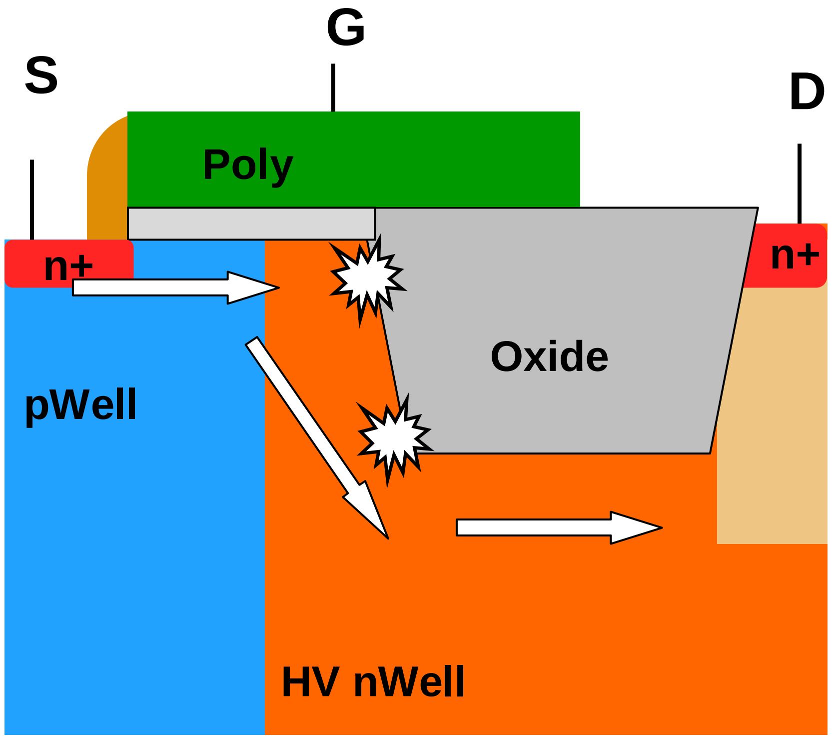
$$S_1(T_s) = \int_0^{Ts} s_1(V(t))dt = \int_0^{Ts} \frac{dt}{\tau_1(V(t))} \qquad S_2(T_s) = \int_0^{Ts} s_2(V(t))dt = \int_0^{Ts} \frac{dt}{\tau_2(V(t))} \qquad (8)$$

$$\Delta P = f_1(S_1) + f_2(S_2) + \ldots \qquad (9)$$

- 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/SiO_2 interface or in SiO_2
- 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(ϕ) (dispersive kinetics)

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

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

  - Activation rate is given by a 1^{st} order kinetics

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

k(ϕ,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**:

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

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:

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

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

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

- Total Ron drift is then the **sum of elements of the form f(t/τ(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 $S_1 \ldots S_N$.

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

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

Periodic signal
→integral over
1 period

- 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…

$$\Delta Ron_i(t) = D(\phi_i)\left[1 - \exp(-S_i)\right] \tag{18}$$

  - …and summed giving total degradation

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

- 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:

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

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**

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

Rate of defect activation k(ϕ,V): (modified) "Lucky electron"

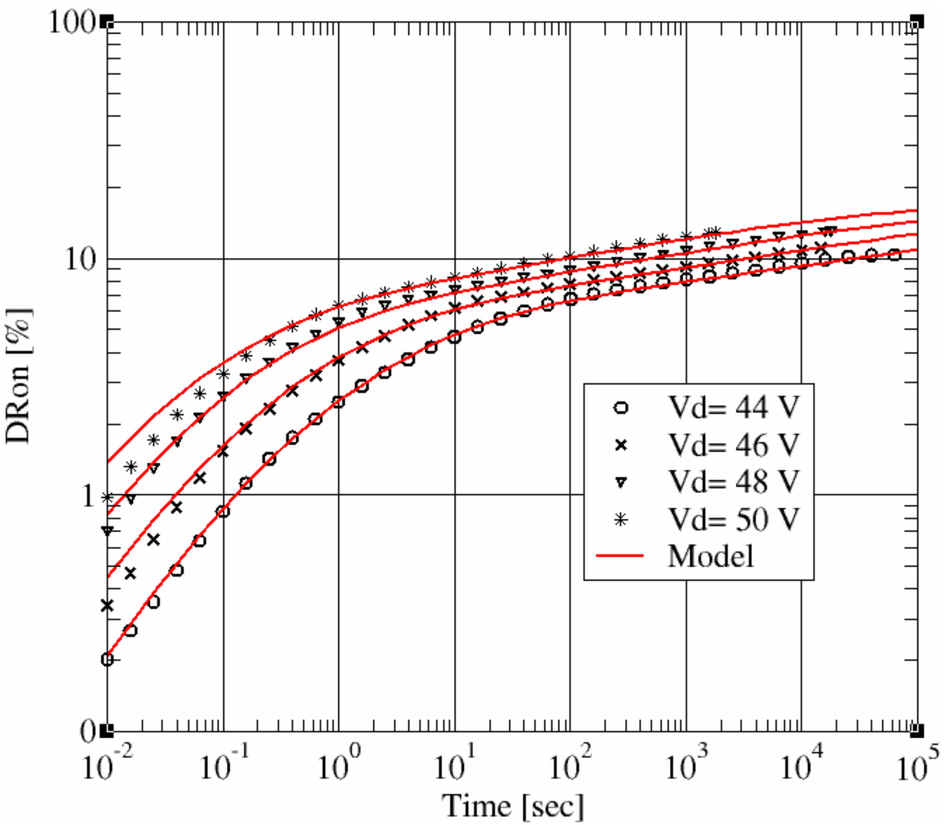
$$k(\phi, V) = Kn(V_{DS}, V_{GS}) \exp\left(-\frac{\phi}{q\lambda F(V_{DS}, V_{GS})} \right) \qquad (22)$$

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

F,n from **TCAD** simulation
λ "conventional"
<ϕ>, σ, K fitted to **experimental data**

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

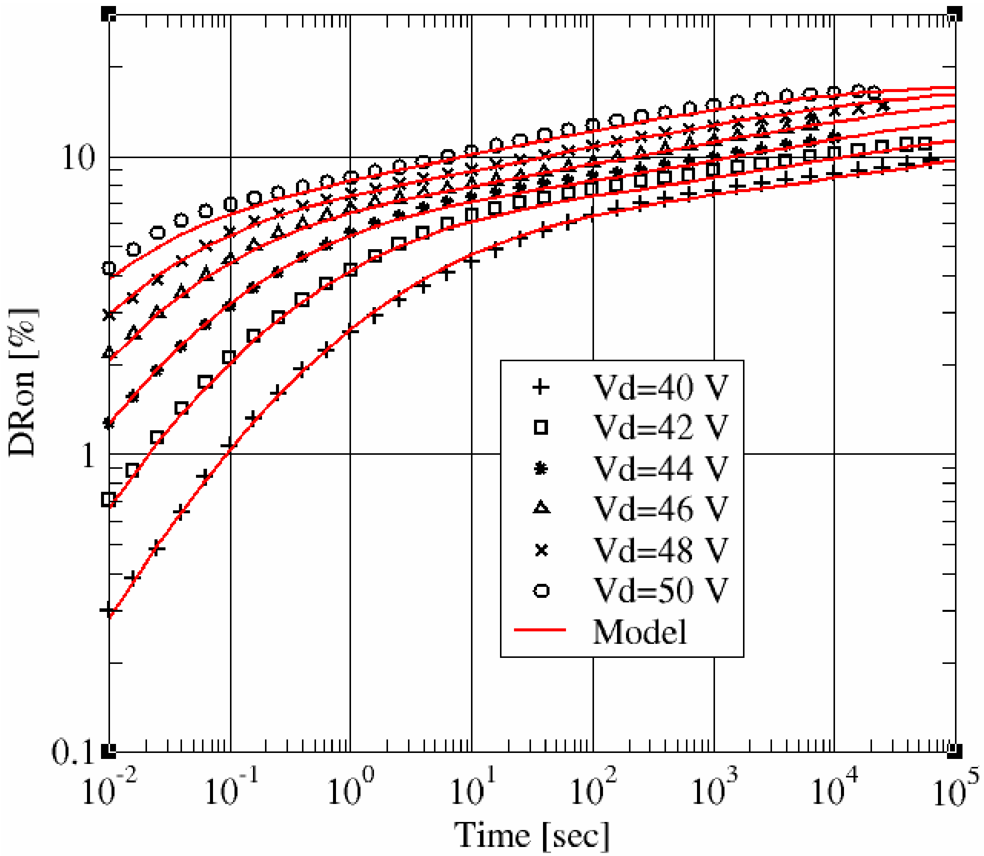
- Drift of **On-state resistance** measured at:
  - Vgs=3.3V, Vds=0.1V



- DC measure vs. model
- Simulator: **Eldo**
- Stress conditions:
  - Vgs-Vth=0.25 V
  - Vds=44→50 V step 2 V

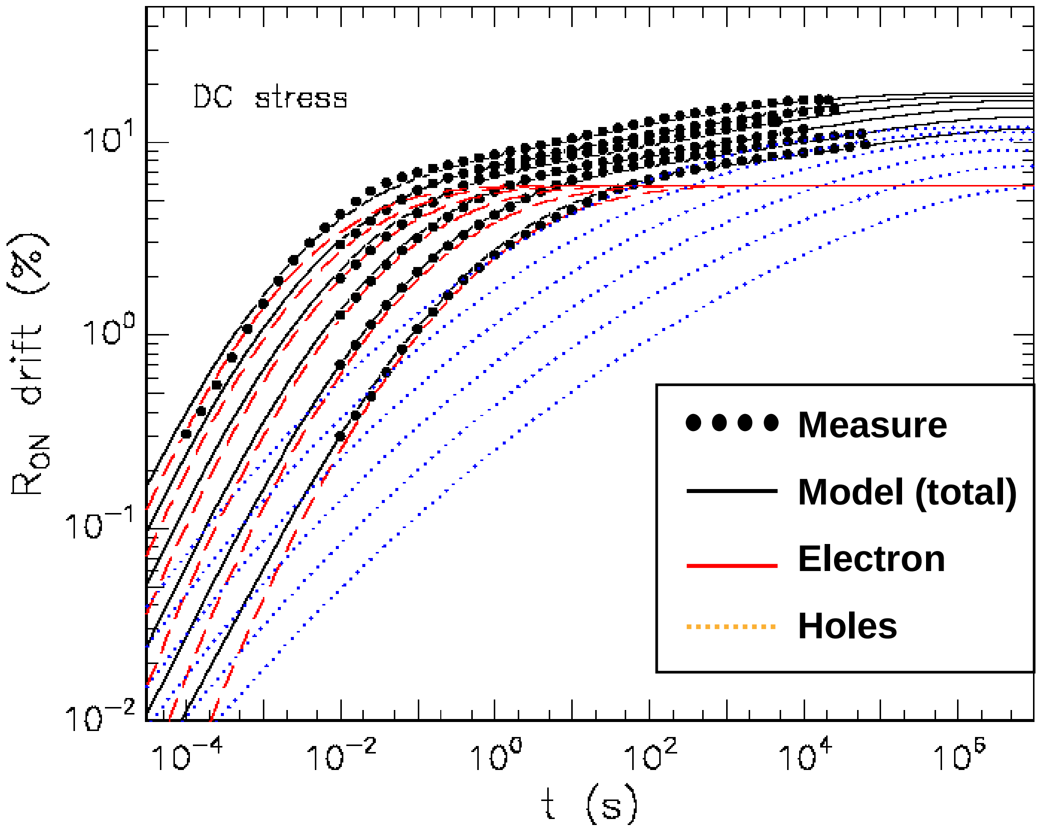
HCI on 40V Nch drift – model results (2)

- Drift of **On-state resistance** measured at:
  - Vgs=3.3V, Vds=0.1V



- DC measure vs. model
- Simulator: **Eldo**
- Stress conditions:
  - Vgs-Vth=1 V
  - Vds=40→50 V step 2 V

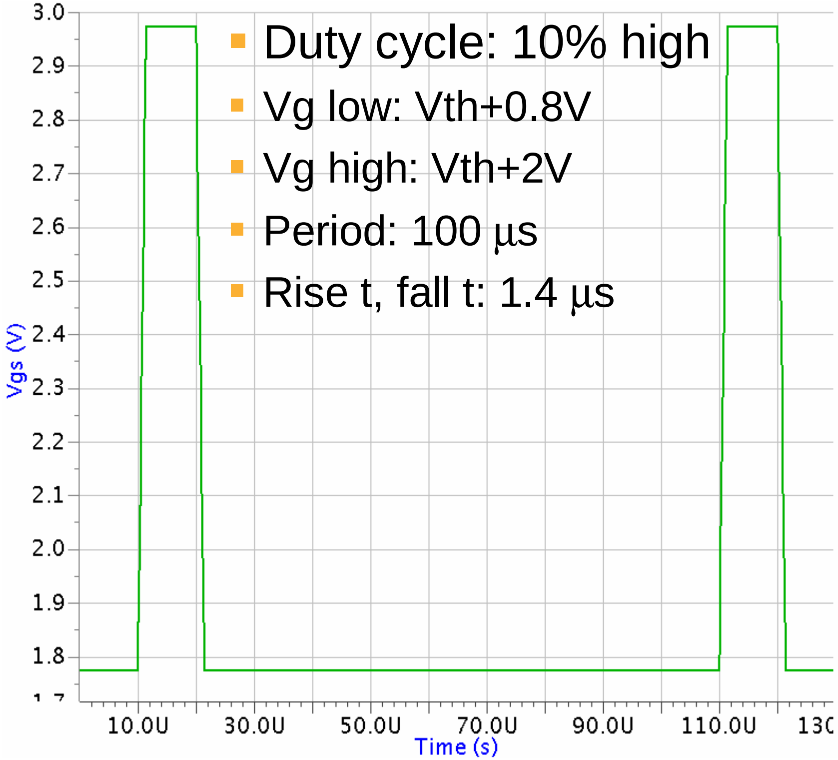
HCI on 40V Nch drift – model results (3)



- DC measure vs. model
  - Vgs-Vth=1 V
  - Vds=40→50 V step 2
- Electrons and holes contributions (2 different hotspots) are shown

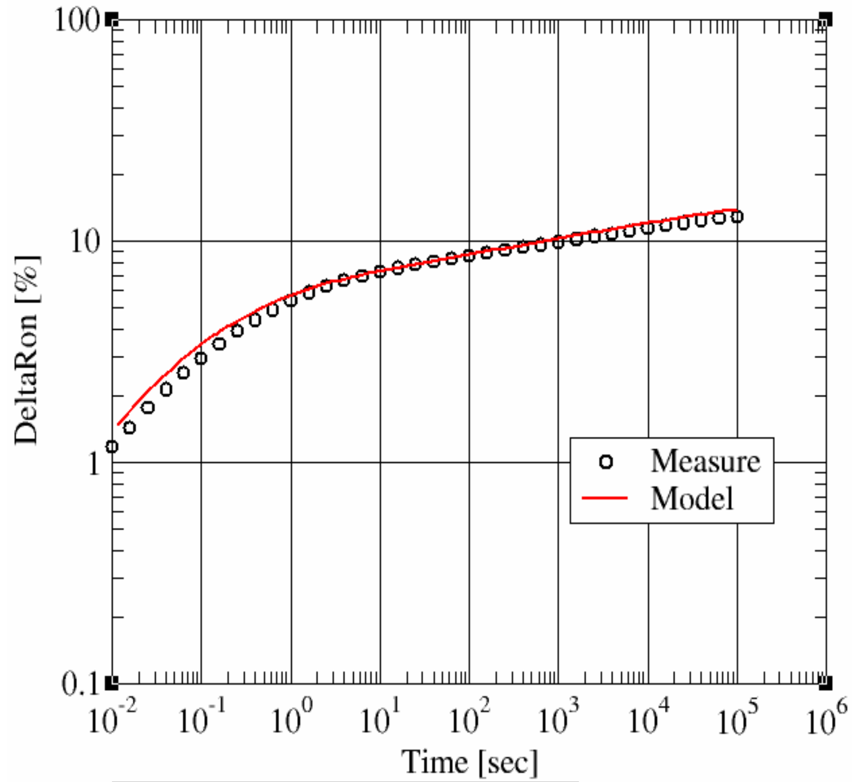
HCI on 40V Nch drift – model results (4)

- Measure/model comparison during **a periodic stress**
- Vd=44V
- Vg **pulsed (trapezoial wave)**



- Duty cycle: 10% high
- Vg low: Vth+0.8V
- Vg high: Vth+2V
- Period: 100 µs
- Rise t, fall t: 1.4 µs

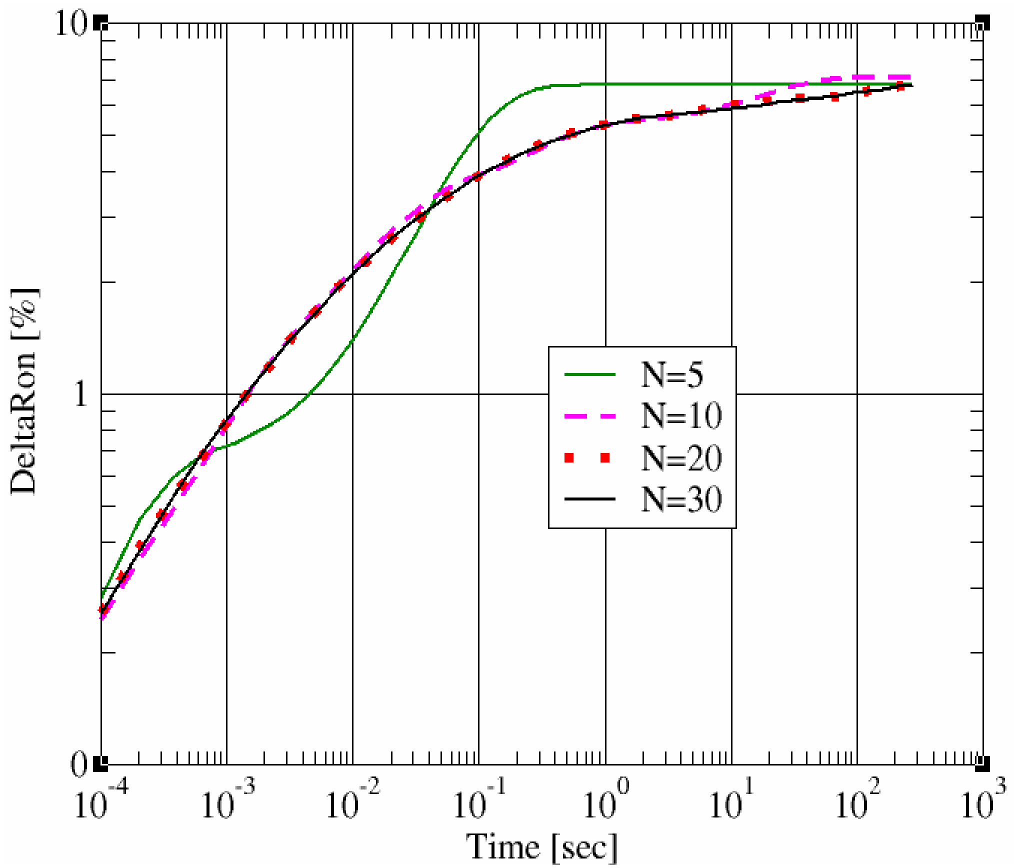
Vgs waveform



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

Conclusions

- 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 ΔRon=f(t/τ(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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