Theory of the transient current induced by laser illumination in FD-SOI CMOS inverter responsible of a bitflip

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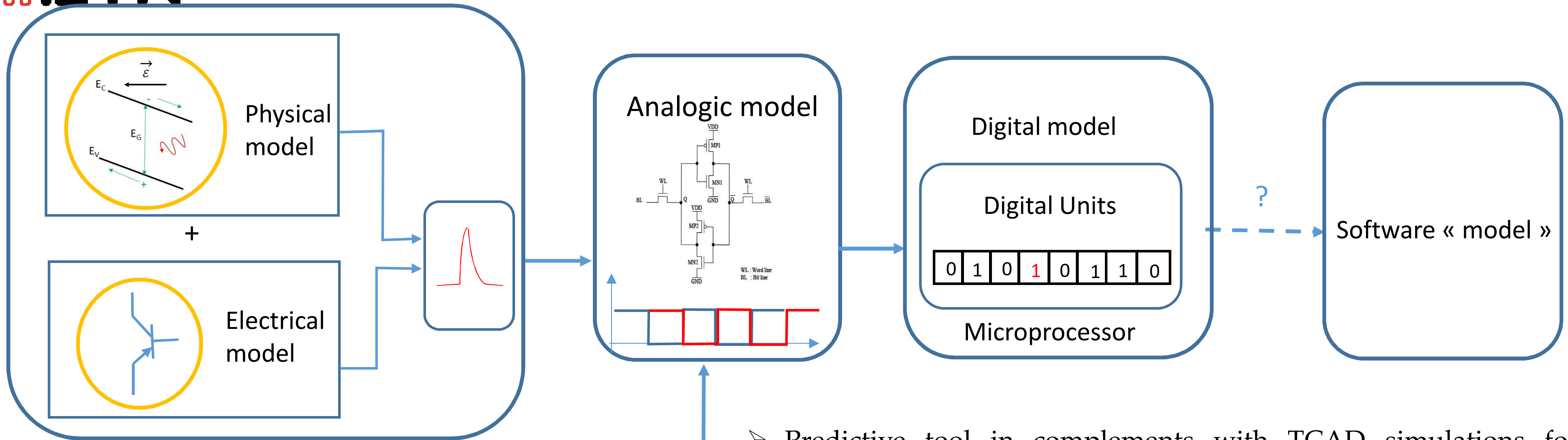
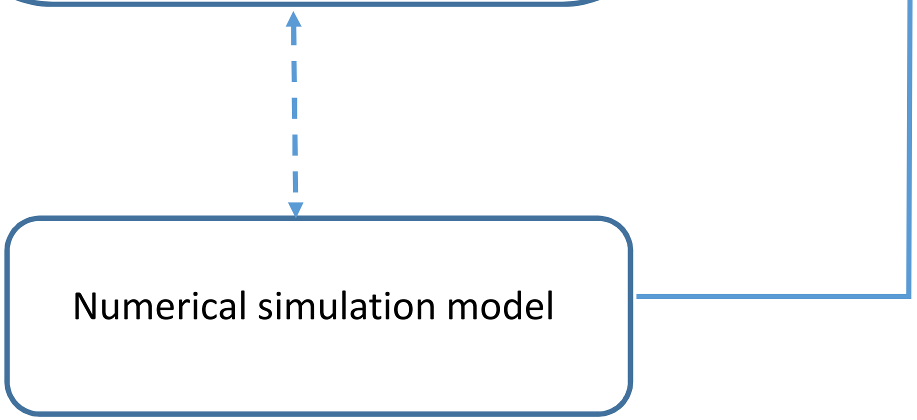
Objectives of theoretical model





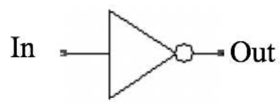
- Predictive tool in complements with TCAD simulations for studies of vulnerability analysis in advanced FD-SOI silicon technologies
- To enable parametric analysis of physical phenomena related to the technology
- Anticipate experimental studies of the vulnerability by laser fault injection of complex electronic systems

Outline

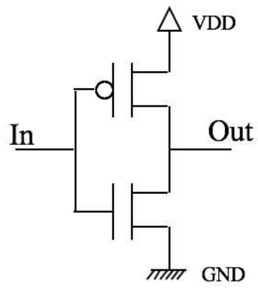
- Bitflip in SRAM cell memory under laser illumination
- Theory of the transient photocurrent in MOSFET under laser illumination
- Incident laser power density for a bitflip
- Comparison with TCAD simulations
- Electrical simulation of a bitflip
- Conclusion

- Bitflip in SRAM cell memory under laser illumination

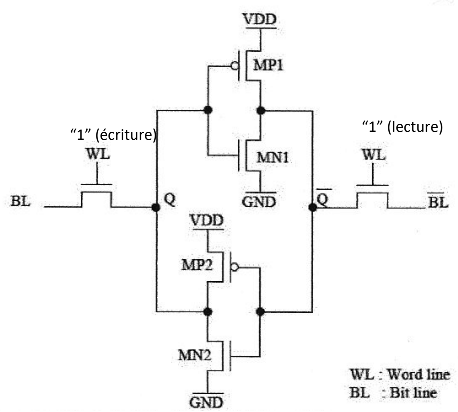
CMOS inverters



In	Out
0	1
1	0
X	X

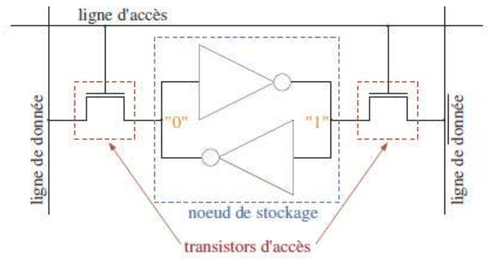


SRAM cell memory (6 MOS transistors)

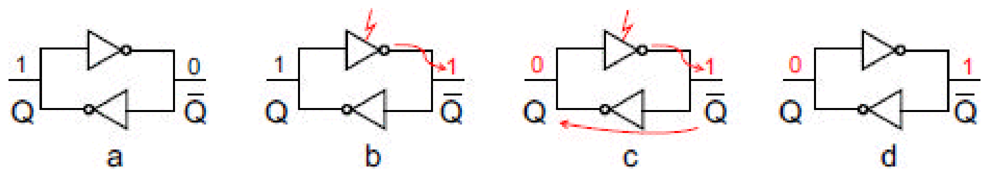


6 MOS transistors:

- 4 transistors forming two cross coupled inverters performing the memory function,
- 2 other transistors for writing or reading the stored bit.



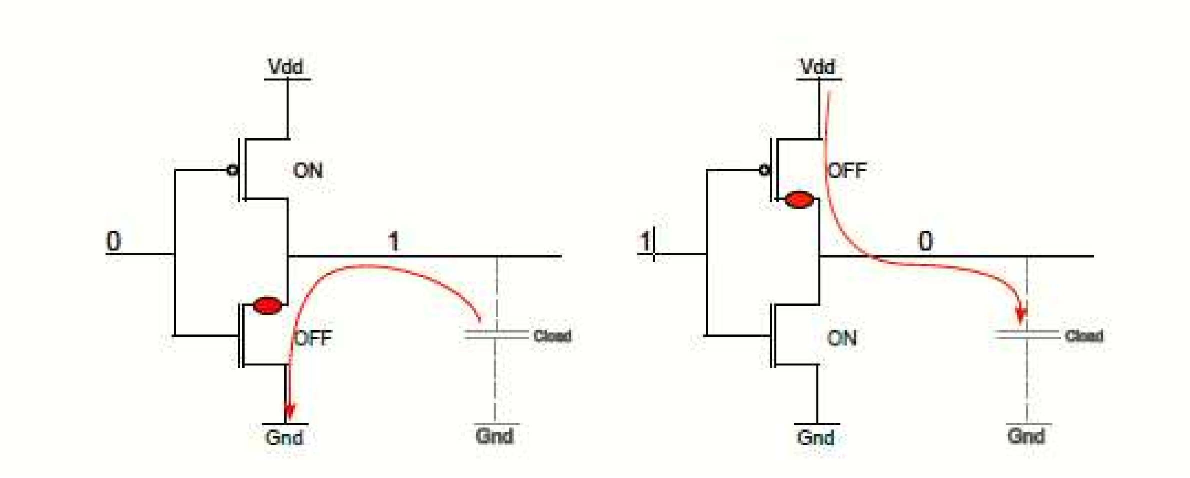
The circuit retains one of the two states through cross-coupling. These two stable states correspond to the two values (0 or 1) of the associated bit.



Laser fault injection (Bit flip Q = 0 → 1, or Q = 1 → 0)

- Bitflip in SRAM cell memory under laser illumination

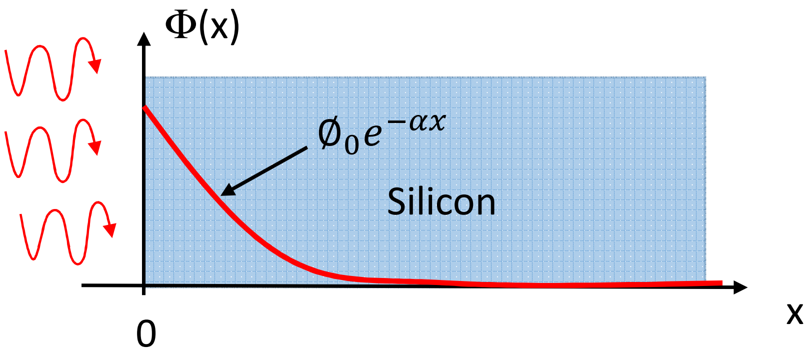
The injection of the fault (simulated by laser) on the OFF transistors ("High impedance"), allows to make the transistor "On" in a transient way



Sensitive area under laser illumination

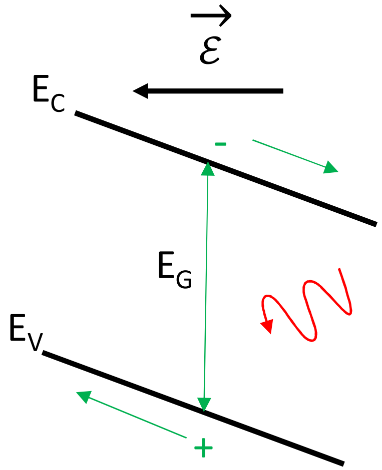
- Theory of the transient photocurrent in MOSFET under laser illumination

Absorption of photons under laser illumination (generation of hole/electrons pairs)



Photons absorption = electron/hole pairs generation

α: absorption parameter dependent on the doping level

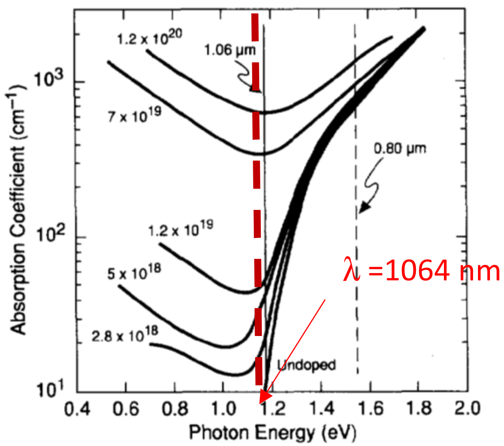


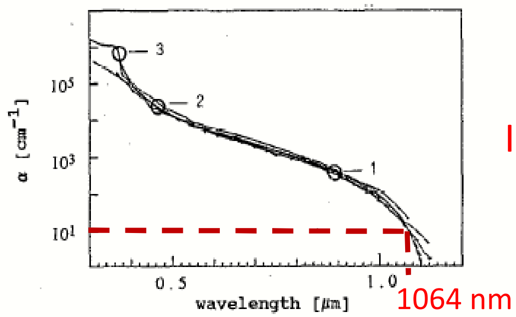
$E_{Photon} = hc/\lambda \geq E_G$

Silicon:

E_G = 1,1 eV

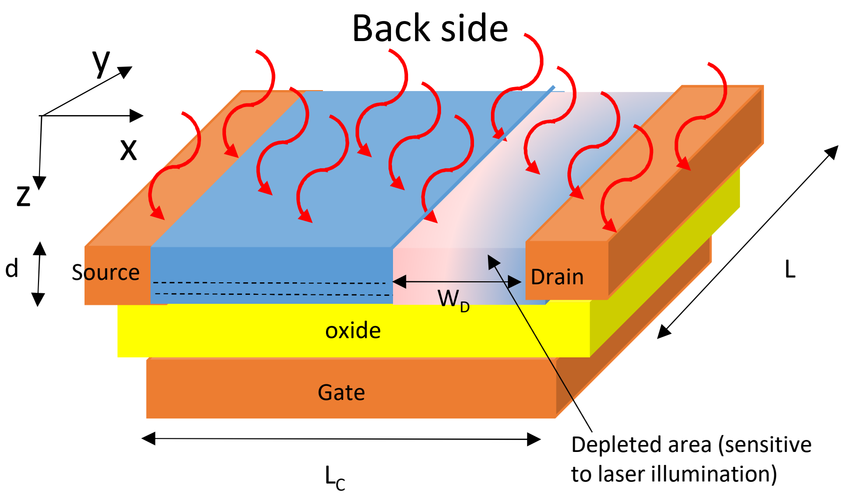
$\lambda \leq$ 1,1µm





IR pulsed laser source

IETR - Theory of the transient photocurrent in MOSFET under laser illumination



The current transient responsible for a bitflip results from **the generation of electron/holes pairs in the space charge region of the reverse biased channel/drain junction**

$$J_{Géné} = \int_0^{W_D} qGdx = qG(z,t)W_D$$

W_D : space charge zone width ($W_D \leq L_C$).

Hypothesis : for advanced technologies (small sizes) the space charge zone extends over the entire length of the channel ($W_D = L_C$), and over the entire thickness of the (IR-light) sensitive active layer (FD SOI devices)

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- Theory of the transient photocurrent in MOSFET under laser illumination

Incident surface power density

Incident power density homogeous in the bulk of the devices

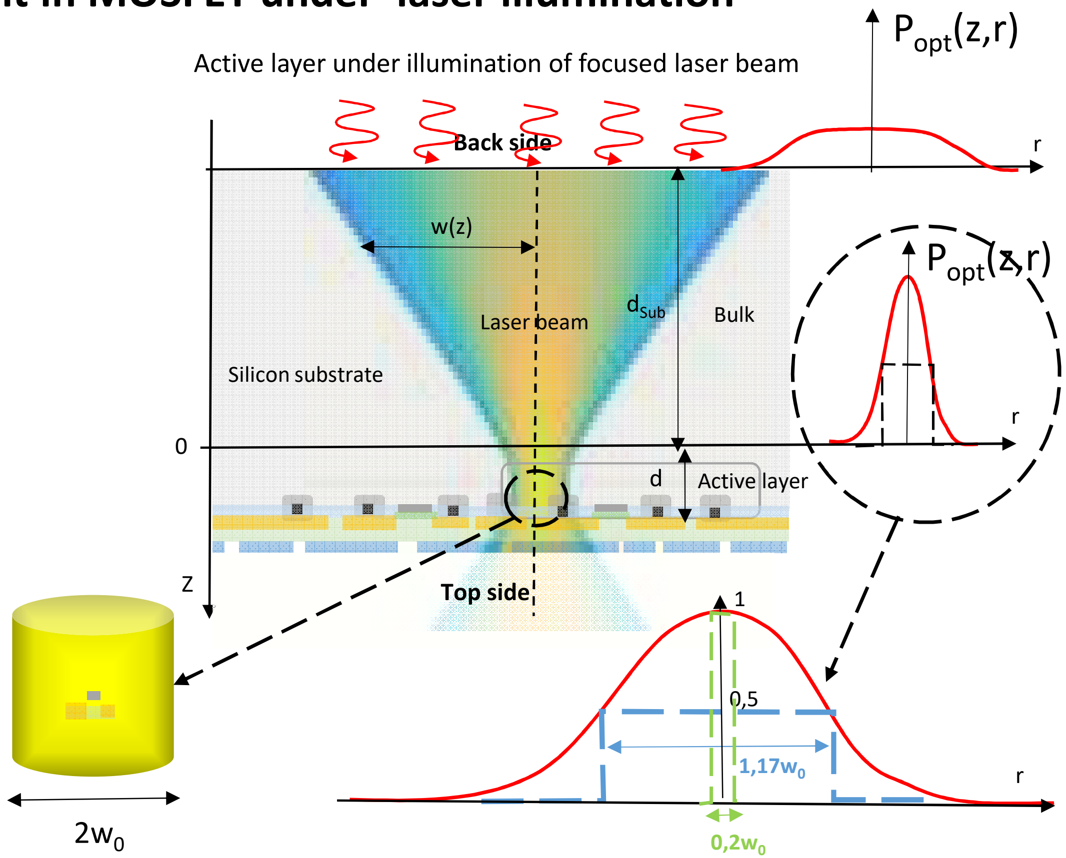
$$P_{opt}(z,r) = \frac{P}{\pi w(z)^2} e^{-\frac{2r^2}{w(z)^2}} e^{-\alpha(z+d_{Sub})}$$

Gaussian beam width:

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_0}\right)^2} \quad , z_0 = \frac{\pi w_0^2}{\lambda}$$

$2w_0$: diameter of the laser beam (1 – 5µm)
P : laser power

In small size MOSFET: $W = L_C$
W_D : depleted area width
L_C : geometrical length of the channel
L_C (W) << $2w_0$, r

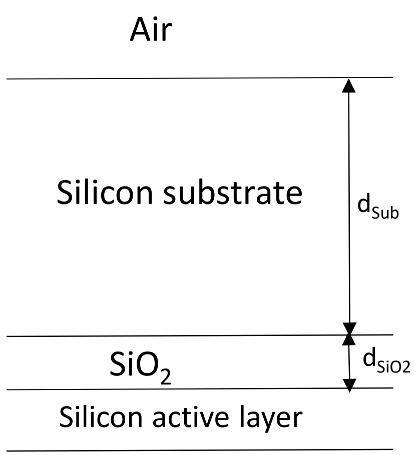


Variation of P_{opt} lower than 10% for $2r \leq 0{,}46w_0$ (ex with $2w_0$ = 1µm, for r = 50 nm, ie W_D = 100 nm = $0{,}2w_0$, $\Delta P_{opt}/P_{opt}$ = 2 %)
The incident surface power density (at z = 0):

$$P_{opt} = P_{opt}(0,r) \cong \frac{P}{\pi w_0^2} e^{-\alpha d_{Sub}}$$

- Theory of the transient photocurrent in MOSFET under laser illumination

Optical transmission coefficient



$$T_{air,Si} = \frac{n_{Si}}{n_{air}}\left(\frac{2n_{air}}{n_{air}+n_{Si}}\right)^2 = 70\%$$

$$T_{Si,SiO_2} = \left(\frac{2n_{Si}}{n_{SiO_2}+n_{Si}}\right)^2 \times \frac{n_{SiO_2}}{n_{Si}} = 83{,}3\%$$

$$T_{SiO_2,Si} = \left(\frac{2n_{SiO_2}}{n_{Si}+n_{SiO_2}}\right)^2 \times \frac{n_{Si}}{n_{SiO_2}} = 83{,}3\%$$

Parameter	Value
Silicon refractive index (n_{Si})	3,48
Silicon dioxide refractive index (n_{SiO2})	1,46
Air refractive index (n_{air})	1
Buried oxide thickness (d_{SiO2})	10 nm
Silicon subtrate thickness (d_{sub})	100 µm
Optical aborption coefficient of silicon (α)	10 cm^{-1}
Optical absorption coefficient of silicon dioxide (α_{SiO2})	10^{-5} cm^{-1}

Bulk CMOS devices

$$T = T_{air,Si} \times e^{-\alpha d_{Sub}} = 63\%$$

$$P_{opt}T = \frac{P}{\pi w_0^2} \times 0{,}63$$

FDSOI devices

$$T = T_{air,Si} \times e^{-\alpha d_{Sub}} \times T_{Si,SiO_2} \times e^{-\alpha SiO_2 d_{SiO2}} \times T_{SiO_2,Si} = 44\%$$

$$P_{opt}T = \frac{P}{\pi w_0^2} \times 0{,}44$$

- Theory of the transient photocurrent in MOSFET under laser illumination

Homogeneous flow of incident (absorbed) photons over the entire surface of the device

$$\frac{dn}{dt} = G_0(z) - \frac{n - n_0}{\tau}$$

Time dependent charge carrier concentration relation

$$G_0(z) = -\frac{\mathrm{d}\emptyset(z)}{\mathrm{dz}}$$

: Rate of absorbed photons = rate of electron/hole pairs generated ($cm^{-3}\ s^{-1}$)

$\Phi(z)$: Incident photon flux ($cm^{-2}\ s^{-1}$)

$$\emptyset(z) = \emptyset_0 e^{-\alpha z} \quad \Rightarrow \quad G_0(z) = \alpha\emptyset(z) = \alpha\emptyset_0 e^{-\alpha z} = \alpha\ \frac{P_{opt}}{hc/_{\lambda}}\, e^{-\alpha z}$$

P_{opt} : incident power density of the laser ($W\ cm^{-2}$)

λ: laser wavelength

IETR

- Theory of the transient photocurrent in MOSFET under laser illumination

$$\frac{dn}{dt} = G_0(z) - \frac{n - n_0}{\tau}$$

t_p : pulse duration

Generation rate

$$G(z,t) = \frac{n(z,t)}{\tau}$$

$-For\ 0 \le t \le t_p$ **Under laser illumination**

$$n(t,z) = G_0(z)\tau\left(1 - e^{-t/\tau}\right) + n_0$$

$$J_{Photo} = \int_0^{W_D} qG\,dx = \frac{q}{\tau}\left[G_0(z)\tau\left(1 - e^{-t/\tau}\right) + n_0\right]W_D$$

$$I_{Photo} = \int_0^d \int_0^L J_{Photo}\,dy\,dz$$

$$I_{Photo} = q\phi_0\left(1 - e^{-\alpha d}\right)\left(1 - e^{-t/\tau}\right)LW_D + \frac{qn_0 dLW_D}{\tau}$$

I_{Ph} Photocurrent (generation)

I_C leakage current (darkness)

$-For\ t \ge t_p$ **After laser illumination**

$$n(t,z) = G_0(z)\tau\left(e^{t_p/\tau} - 1\right)e^{-t/\tau} + n_0$$

$$J_{Photo} = \int_0^{W_D} qG\,dx = \frac{q}{\tau}\left[G_0(z)\tau\left(e^{t_p/\tau} - 1\right)e^{-t/\tau} + n_0\right]W_D$$

$$I_{Photo} = \int_0^d \int_0^L J_{Photo}\,dy\,dz$$

$$I_{Photo} = q\phi_0\left(1 - e^{-\alpha d}\right)\left(e^{t_p/\tau} - 1\right)e^{-t/\tau}LW_D + \frac{qn_0 dLW_D}{\tau}$$

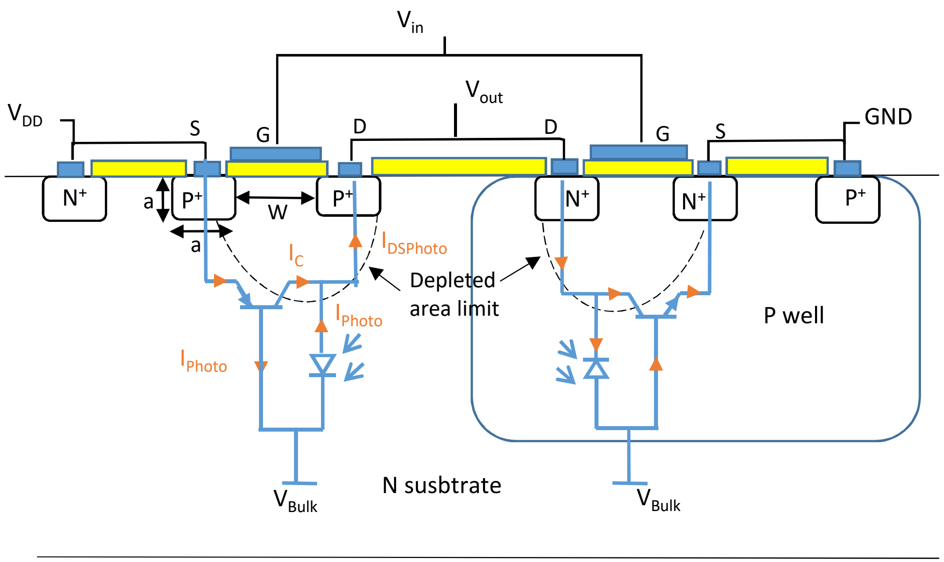
I_{Ph} Photocurrent (recombinationn)

I_C leakage current (darkness)

IETR - Theory of the transient photocurrent in MOSFET under laser illumination

Parasitic bipolar effect transistor

Each Off-State (high impedance) MOSFET acts alternatively as **bipolar phototransistor for (lateral) size MOSFET**



Under laser illumination **bipolar parasitic is triggered**

$$I_{DSPhoto} = \beta_0 I_{Photo} + I_{Photo} = (\beta_0 + 1) I_{Photo} \cong \beta_0 I_{Photo}$$

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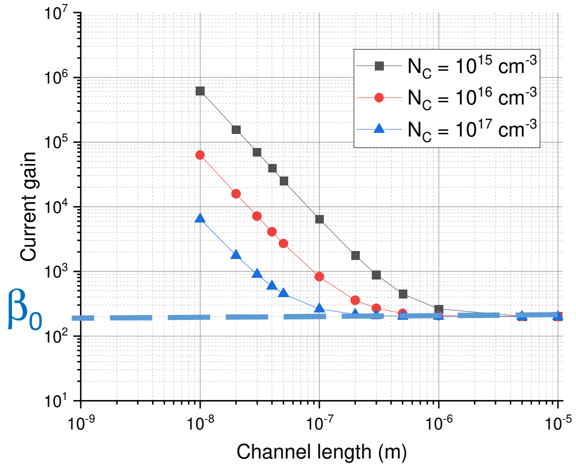
- Theory of the transient photocurrent in MOSFET under laser illumination

Early effect in the parasitic bipolar transistor



$$\beta_t = \beta_0\left(1 + \frac{V_{DD}\varepsilon_S}{2qNcW^2}\right)$$

β_0 : technological current gain

N_c = channel doping level

Current gain of the parasitic bipolar transistor strongly dependent of the length and (low) doping level of the channel

Transient current model

- For $0 \leq t \leq t_p$

$$I_{DSPhoto} = q\lambda\frac{P_{opt}T}{hc}\beta_t(1-e^{-\alpha d})\left(1-e^{-t/\tau}\right)LW + \beta_t\frac{qn_0dLW}{\tau}$$

- For $t \geq t_p$

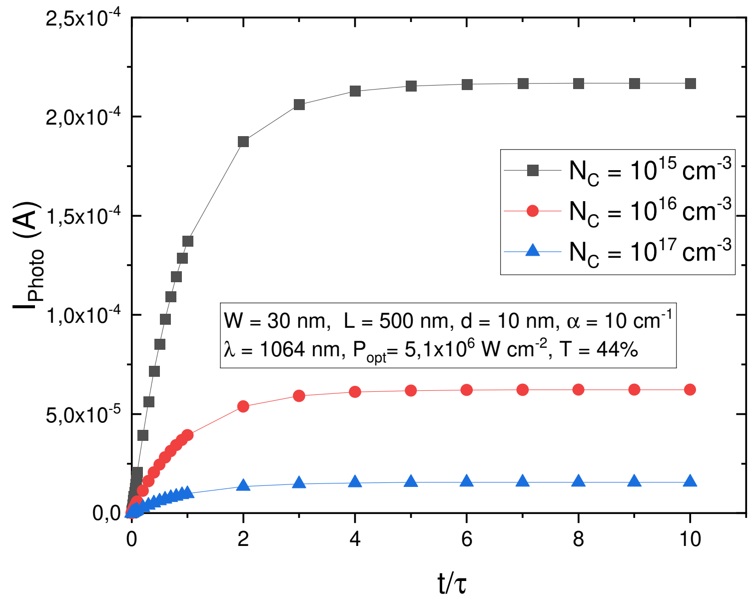
$$I_{DSPhoto} = q\lambda\frac{P_{opt}T}{hc}\beta_t(1-e^{-\alpha d})\left(e^{t_p/\tau}-1\right)e^{-t/\tau}LW + \beta_t\frac{qn_0dLW}{\tau}$$

Relevant (adjusting) parameters : λ, P_{opt}, t_p, T, α, $\beta_t(N_C)$ L, W_D, d

- Theory of the transient photocurrent in MOSFET under laser illumination

Photocurrent in FD SOI devices

$\lambda = 1064\text{nm}$, $P_{opt} \approx$ 5,1x10^{6} W cm^{-2} (5,1x10^{10} W m^{-2}), $\alpha \approx$ 10 cm^{-1}, W = 30 nm, L = 500 nm, d = 10 nm, T = 0,44%



Results compatible with those reported in FD-SOI CMOS inverter (W = 30 nm, L = 500 nm):

J.M. Dutertre *et al.*, « Sensitivity to Laser Fault Injection: CMOS FD-SOI vs. CMOS Bulk », *IEEE Transactions on Device and Materials Reliability*, vol. 19, nº 1, p. 6-15, mars 2019, doi: 10.1109/TDMR.2018.2886463.

- Incident laser power density for a bitflip

Condition for a bitflip : when the photocurrent level reaches that across the MOSFET in on mode given by:

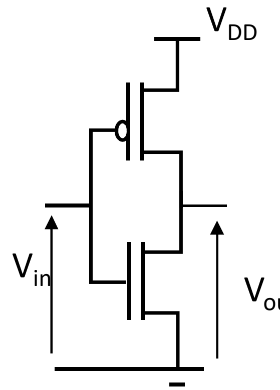
$$V_{GS} - V_T \approx V_{DS} \approx \frac{V_{DD}}{2}$$

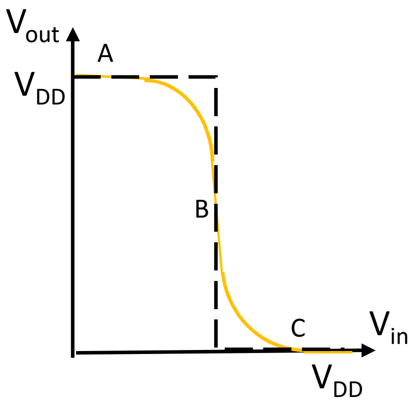
$$I_{DS} = \mu C_I \frac{L}{W_D}(V_{GS} - V_T)V_{DS} = \beta_{NP}\frac{V_{DD}^2}{4}$$

$$I_{DS} = G_M(V_{GS} - V_T) = G_M\frac{V_{DD}}{2}$$

G_M: transconductance of the MOSFET

(10^{-6} S $\leq G_M \leq 10^{-2}$ S)





A : N MOS Cut off, P MOS On (linear mode)
B : N MOS Saturation mode, P MOS Saturation mode
C : N MOS On (linear mode), P MOS Cut off

$$I_{DSPhoto} = q\lambda\frac{P_{opt}T}{hc}\beta_t\left(1 - e^{-\alpha d}\right)\left(1 - e^{-t/\tau}\right)LW \cong G_M\frac{V_{DD}}{2}$$

- Incident laser power density for a bitflip

$$q\lambda \frac{P_{opt}T}{hc}\beta_t\left(1-e^{-\alpha d}\right)\left(1-e^{-t/\tau}\right)LW \cong G_M\frac{V_{DD}}{2}$$

Pulse duration of the laser

$$\frac{t_p}{\tau} = -Ln\left[1-\frac{G_M\frac{V_{DD}}{2}}{q\lambda\frac{P_{opt}T}{hc}\beta_t\left(1-e^{-\alpha d}\right)LW_D}\right]$$

Duration of the pulse related to the technological node

Incident power density

$$P_{opt} = \frac{G_M\frac{V_{DD}}{2}}{q\lambda\frac{T}{hc}\beta_t\left(1-e^{-\alpha d}\right)\left(1-e^{-t_p/\tau}\right)LW_D}$$

Energy of the laser

$$E/\pi r^2 = \frac{G_M\frac{V_{DD}}{2}\tau}{q\lambda\frac{T}{hc}\beta_t\left(1-e^{-\alpha d}\right)LW_D}\left[\frac{t_p}{\tau}+Ln\left(1-e^{-\frac{t_p}{\tau}}\right)\right]$$

Laser incident power density related to the technological node (P_{opt} increases as k^{-1})

- Incident laser power density for a bitflip

Bitflip in bulk CMOS

Results from simulations in 0,25um CMOS techno, laser nanosecond, pulse duration 50ns, laser power 1,6 W, diameter 1 um ($P_{opt} = 2x10^8$ cm^{-2})

After C. Roscian et al "Fault Model Analysis of Laser-Induced Faults in SRAM Memory Cells" (2013) DOI 10.1109/FDTC.2013.17

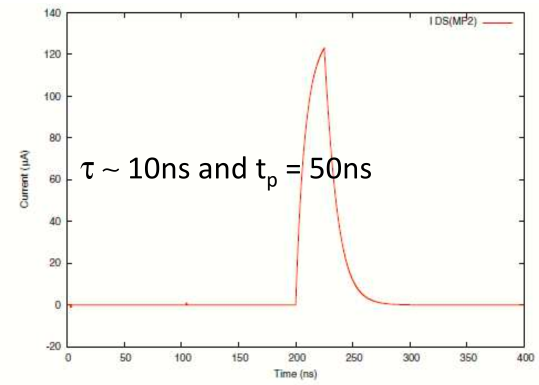
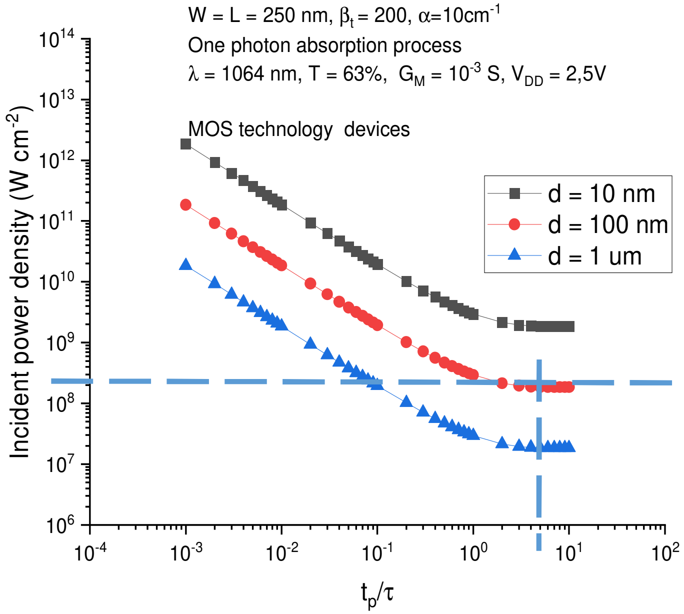
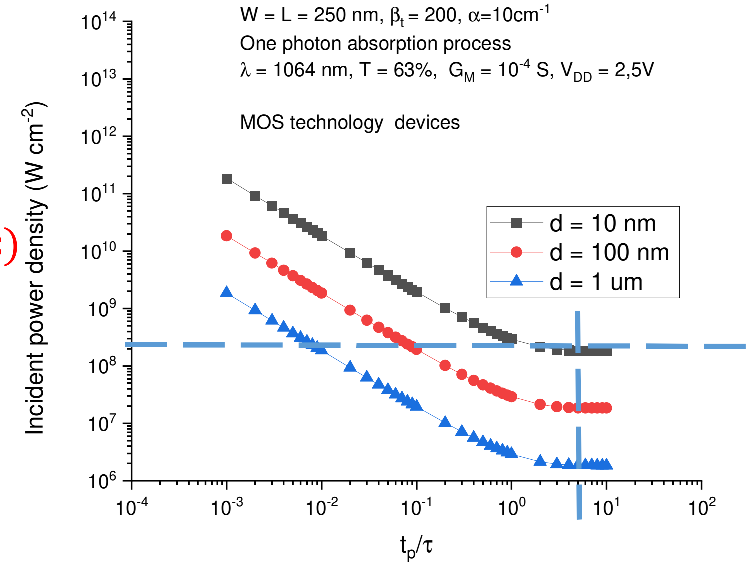


Figure 15. Simulation of *MN2*'s photo-current (upper part) and *MP2*'s current (bottom part) in state "0".



10^{-4} S $\leq G_M \leq 10^{-3}$ S
(typical intermediate values)

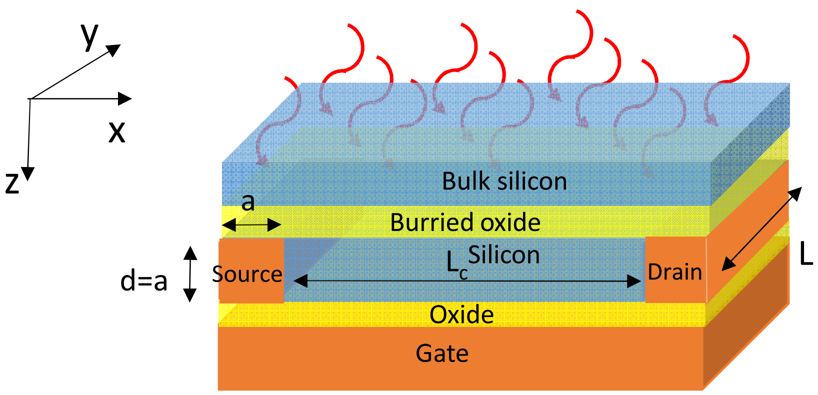
T = 63 %



Critical incident surface power density for a bitflip decreases as the thickness of bulk substrate increases due to a higher contribution of the induced photocurrent

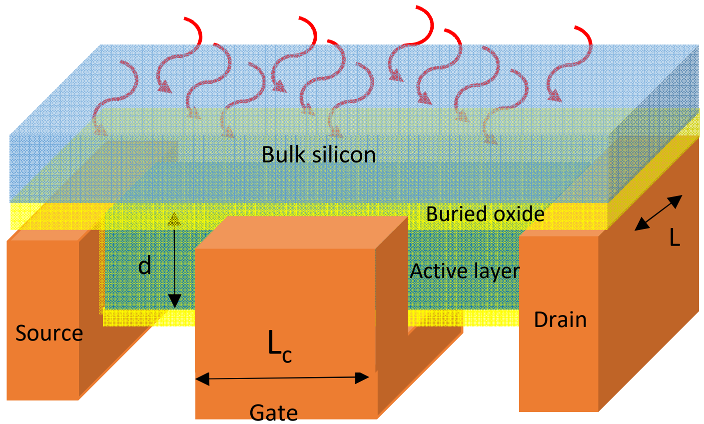
IETR - Incident laser power density for a bitflip

Bitflip in FD SOI devices



UTBOX

($d \leq 20$ nm)



FinFET

$L_c = W \geq L$, $d \geq L$

No contribution of the substrate current because of the burried oxide layer

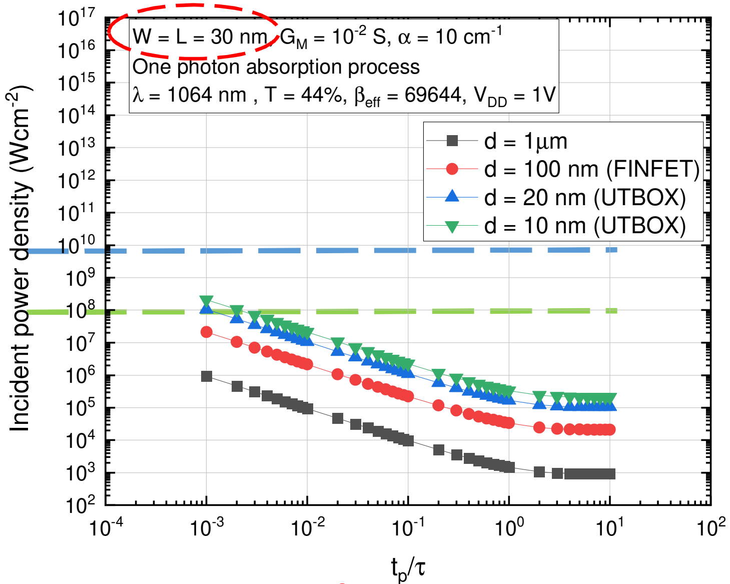
IETR

- Incident laser power density for a bitflip

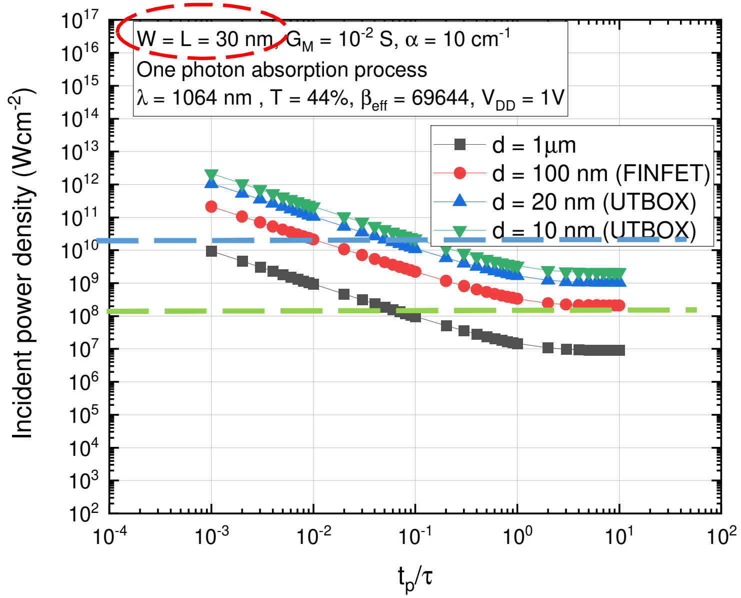
Bitflip in FDSOI MOS devices

Incident power density for picosecond laser (Alphanov): ~ 10^{10} W cm^{-2}

Incident power density for nanosecond laser (Alphanov): ~ 10^{8} W cm^{-2}



G_M (= 10^{-6} S)



G_M (= 10^{-2} S)

Critical incident power density decreases with the decrease of the of the channel thickness (sensitive active layer)

In UTBOX configuration critical P_{opt} is higher while for FINFET configuration it is lower due to the higher volume of the active area of the transistor

No BITFLIP for UTBOX configuration at high values of G_M using nanosecond laser .

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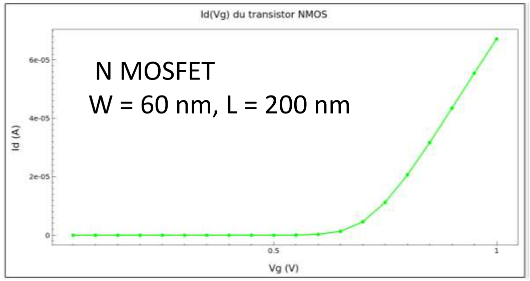
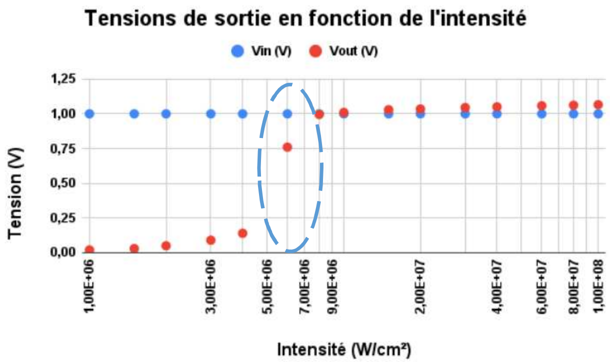
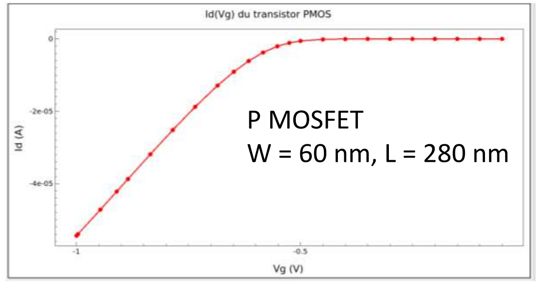
- Comparison with TCAD simulation



$G_M = 2,2 \times 10^{-4}$ S, $N_C = 10^{18}$ cm^{-3}



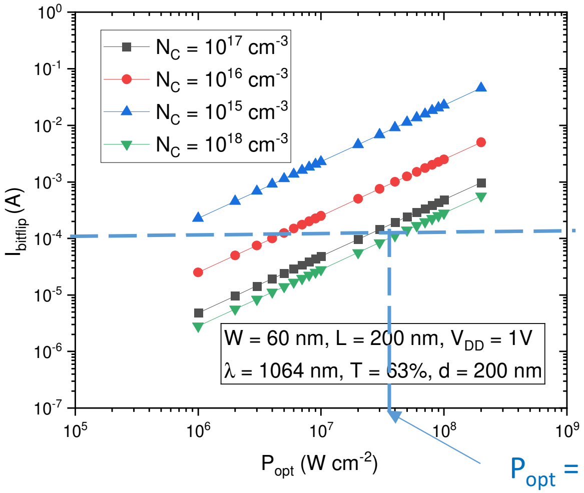
$P_{opt} \approx 6x10^6$ Wcm^{-2}



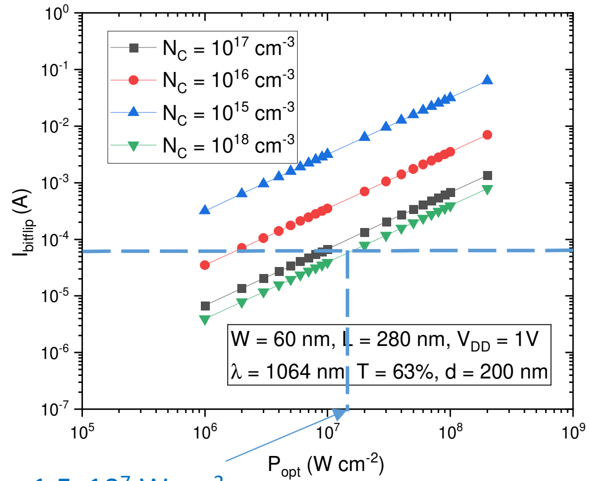
$G_M = 1,2 \times 10^{-4}$ S, $N_C = 10^{18}$ cm^{-3}

Our model

Inversion of the output



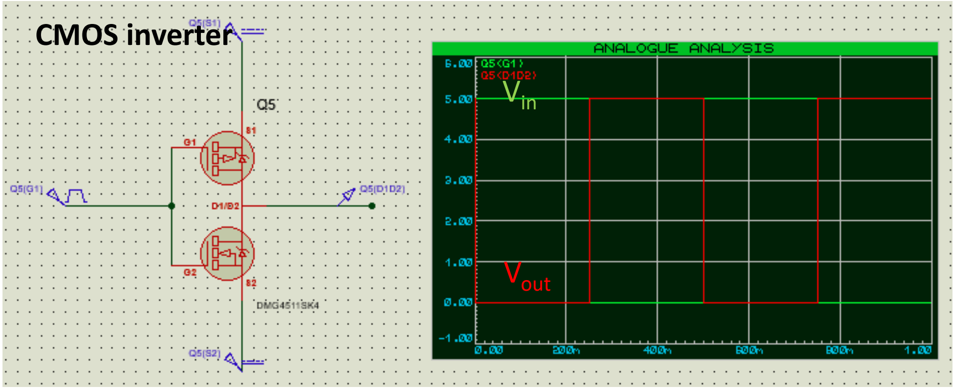
$P_{opt} = 4x10^7$ Wcm^{-2}

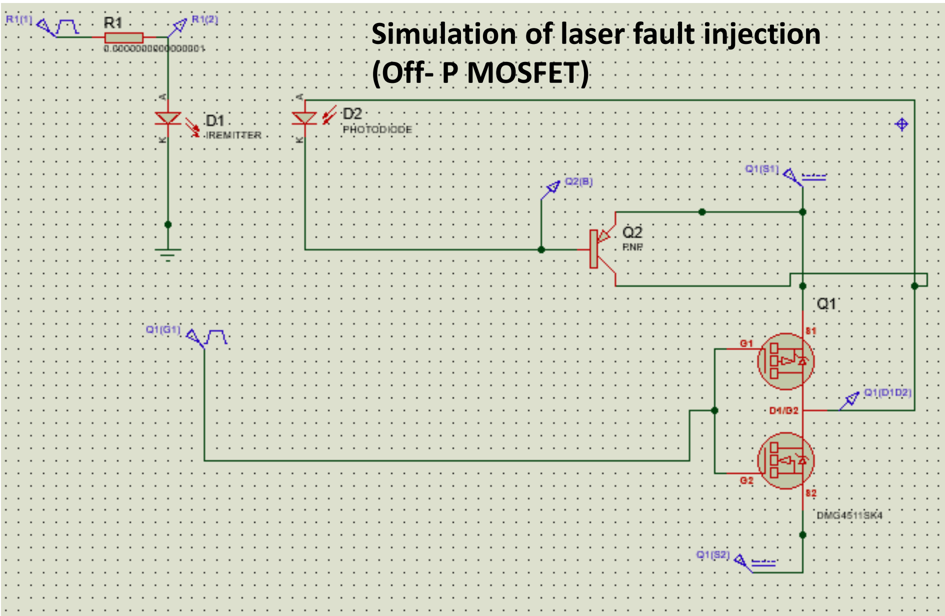


$P_{opt} = 1,5x10^7$ Wcm^{-2}

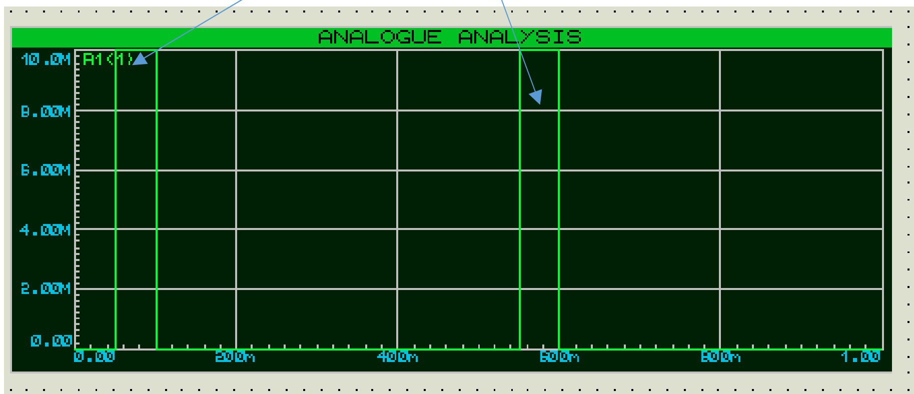
Theoretical results compatible with TCAD simulation

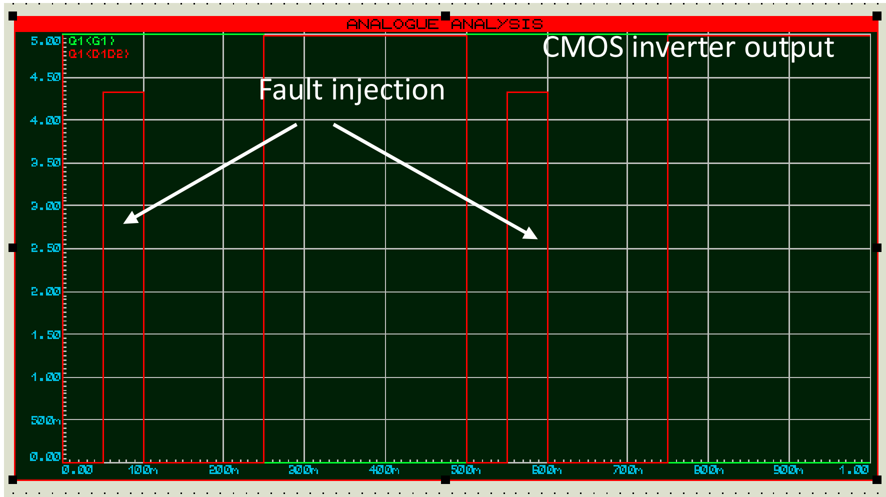
- Electrical simulation of a bitflip



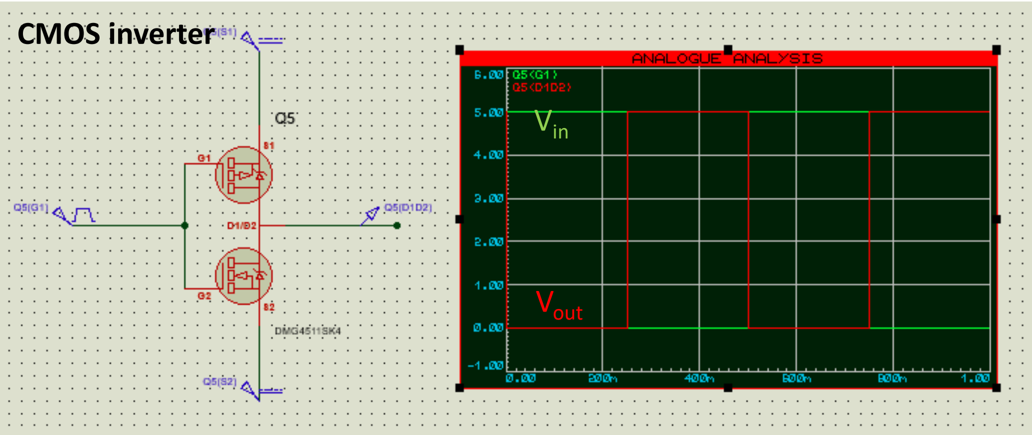


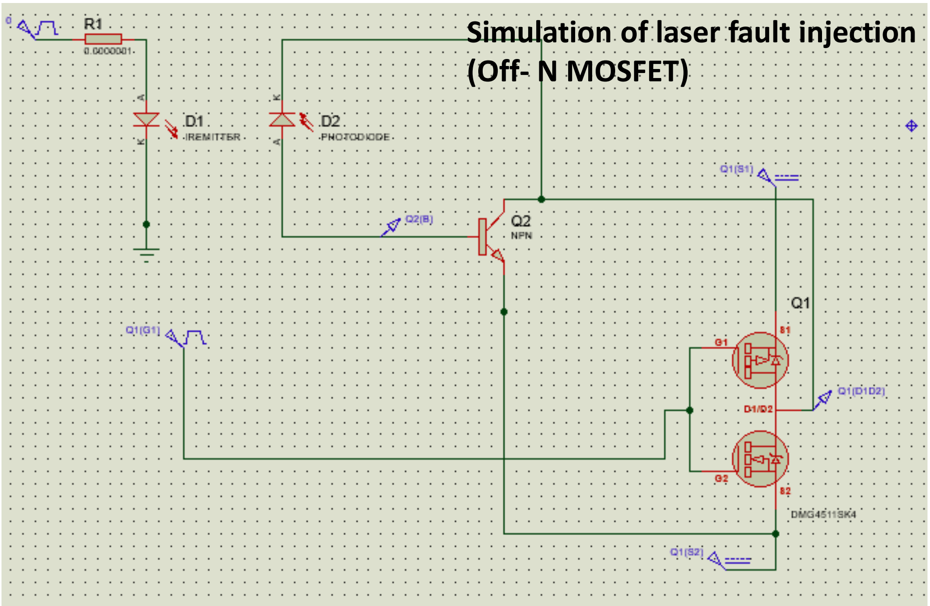
Fault injection
Simulation of laser pulse by an IR LED



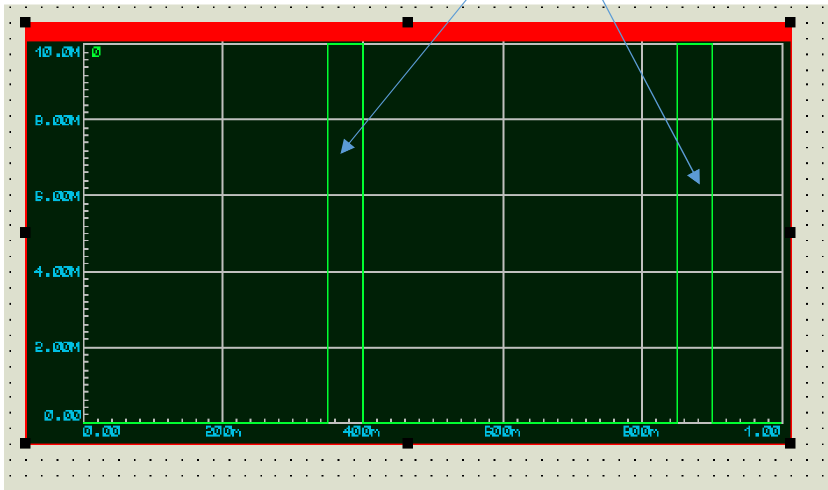


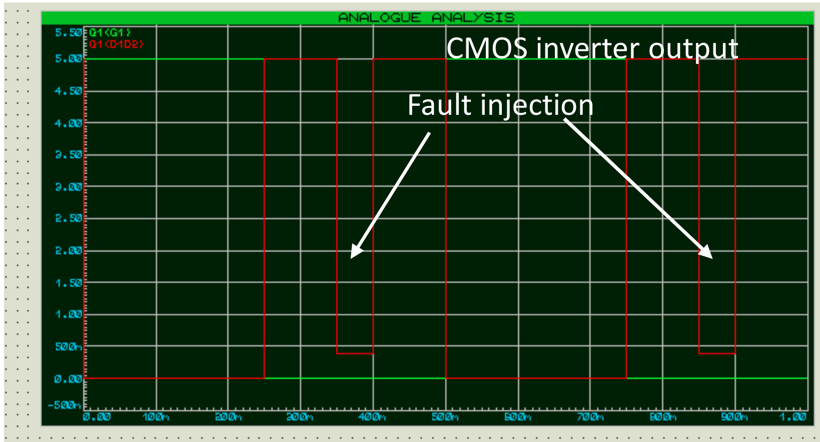
IETR - **Electrical simulation of a bitflip**



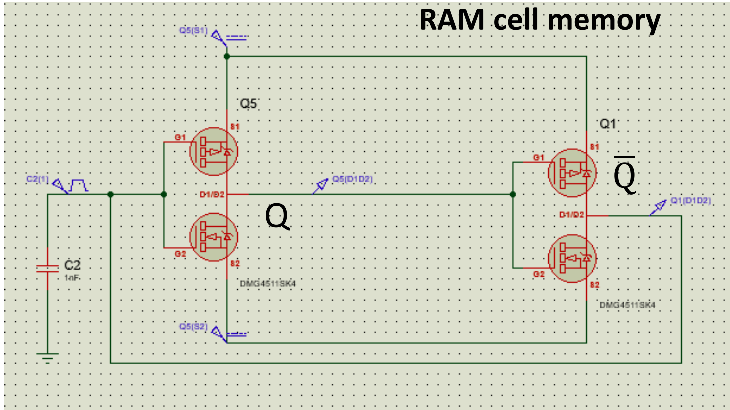


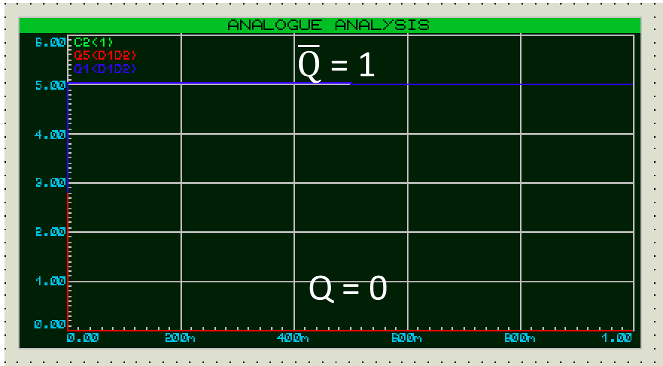
Fault injection
Simulation of laser pulse by an IR LED

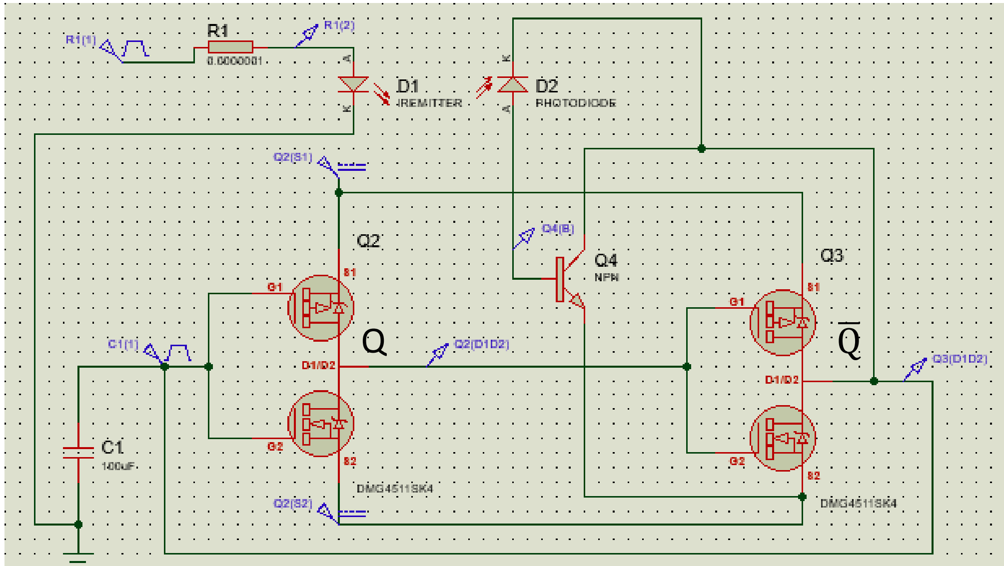




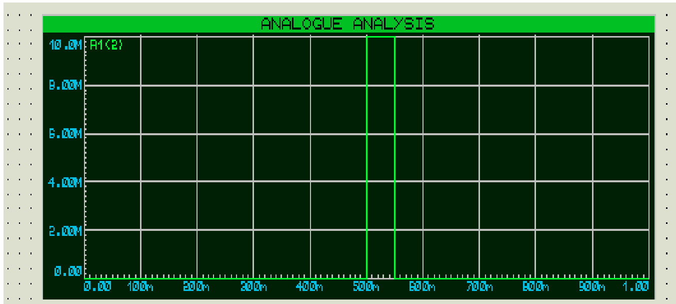
IETR - Electrical simulation of a bitflip

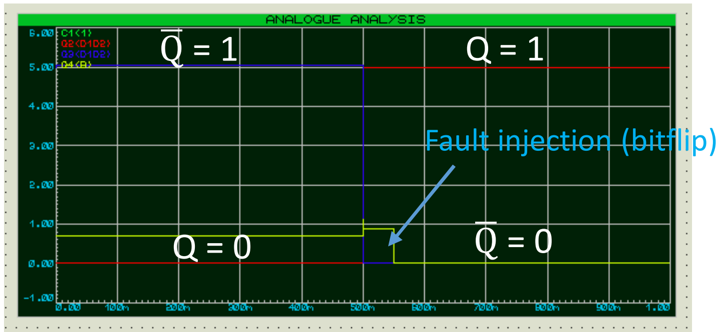






Simulation of fault injection in a RAM cell memory





- Conclusion

- The Theoretical model predicts an estimation of the incident power surface density of the laser required to create a bitflip in CMOS FD-SOI electronic circuitry.

- This model is based on the physical effect of the laser interaction with the semiconductor material (silicon) including:

- ➢ the laser characteristics,
- ➢ the physical properties of the silicon,
- ➢ the geometrical and technological parameters.

- The model takes into account the amplification of the photocurrent induced by the parasitic bipolar transistor combined with the effects of size reduction (length of the transistor channel).

- It highlights the volume effects making the devices more sensitive to fault injection by pulsed IR laser, particularly for conventional CMOS technologies and FD-SOI technologies based on FINFETs.

- Physical and electrical model as complements with TCAD simulation studies of photocurrent generation in silicon simulating laser fault injection on basic logic units (2-transistor CMOS inverters) in advanced silicon technologies

– Allow to anticipate experimental studies of the vulnerability of complex electronic systems (STM32 microcontrollers, FPGA, RISC-V).

Thank you for your attention

- Theory of the transient photocurrent in MOSFET under laser illumination

- For $0 \leq t \leq t_p$

$$I_{DSPhoto} = q\lambda \frac{P_{opt}T}{hc} \beta_t \left(1 - e^{-\alpha d}\right)\left(1 - e^{-t/\tau}\right) LW + \beta_t \frac{q n_0 d L W}{\tau}$$

- For $t \geq t_p$

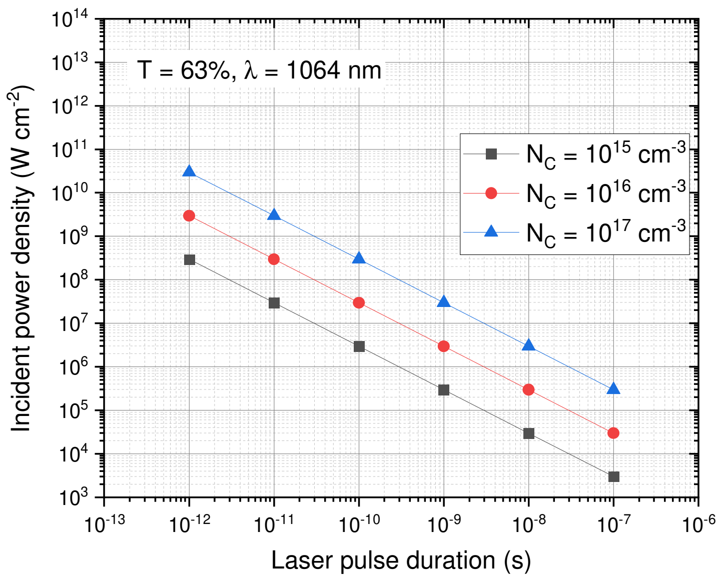
$$I_{DSPhoto} = q\lambda \frac{P_{opt}T}{hc} \beta_t \left(1 - e^{-\alpha d}\right)\left(e^{t_p/\tau} - 1\right) e^{-t/\tau} LW + \beta_t \frac{q n_0 d L W}{\tau}$$

To make sure that our theoretical model is applied correctly, contribution of the leakage current must be negligible.

Criteria: $I_{DSPhoto} \geq 10 \times I_{Leak}$

- $t_p \geq \tau$ ⇒ $P_{opt} \geq \dfrac{hc10n_0}{\lambda T \alpha t_P}$

Use of nano- or pico-second laser sources



Minimum of the incident surface power density