Non-volatile memory using Optically-Gated Carbon Nanotube FET: Description of carrier mobility model in P3OT and hopping mechanism at SiO_2-P3OT interface

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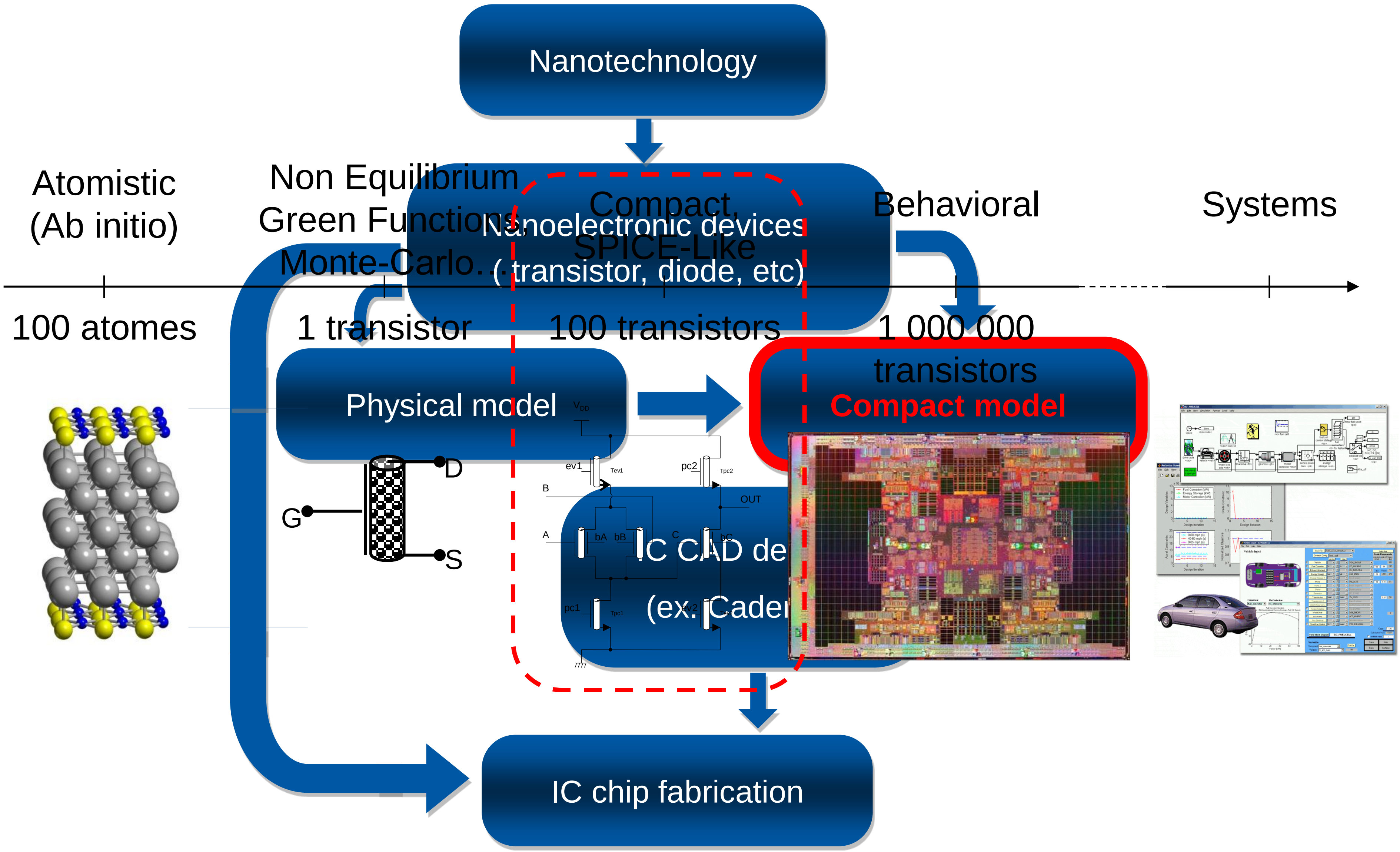
General purpose

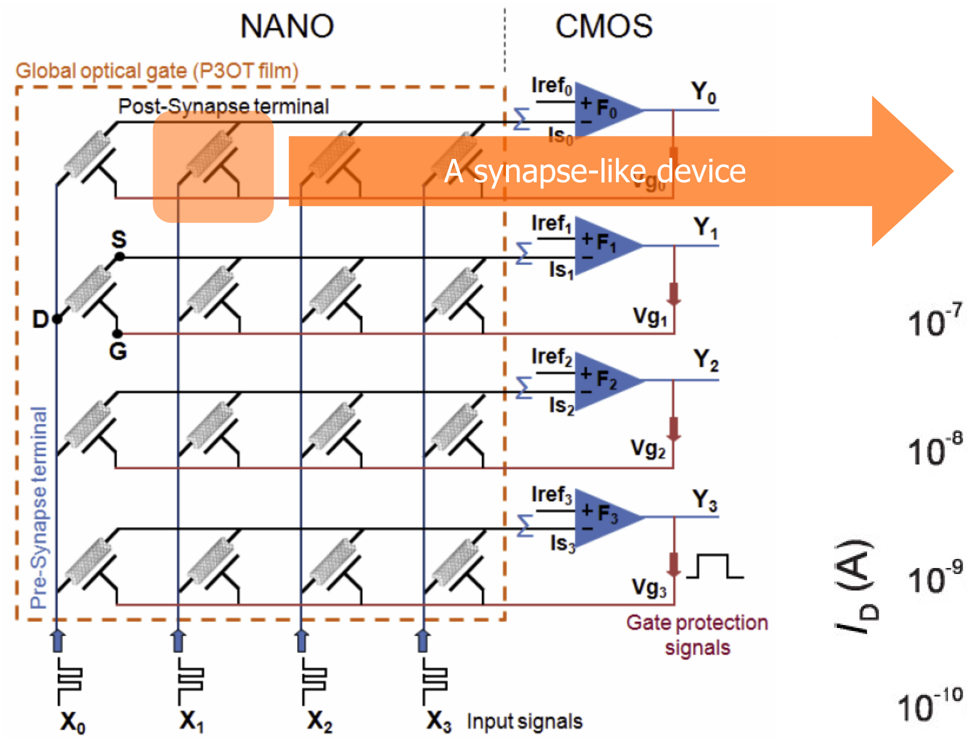


Outline

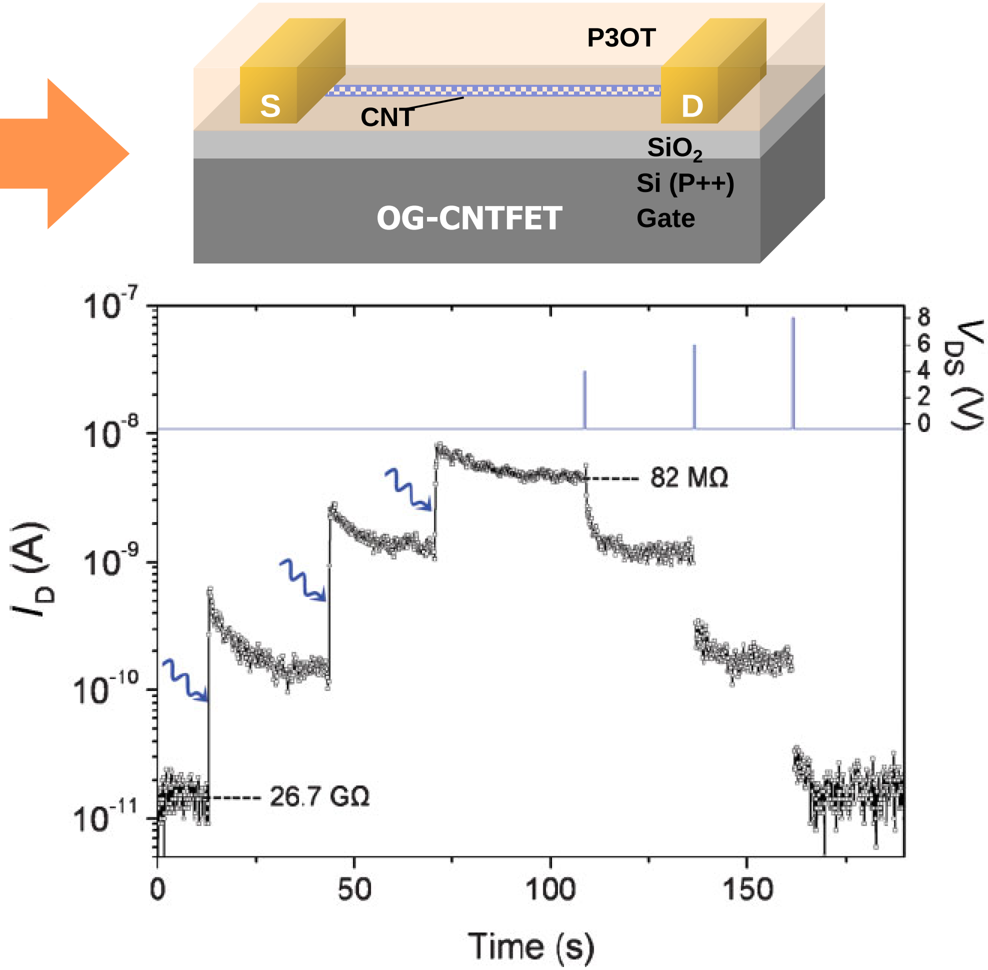
- Part 1 : The modeling of Non-volatile memory using Optically-Gated Carbon Nanotube FET (OG-CNTFET)
  - Memory operations description & modeling
  - Electrical equivalent circuits
- Part 2 : Description of carrier mobility model in P3OT and hopping mechanism at SiO_2-P3OT interface
- Part 3 : Including Schottky Barrier at the drain/source contact of the OG-CNTFET modeling

What is OG-CNTFET ?

Crossbar system of a neuromorphic circuit*



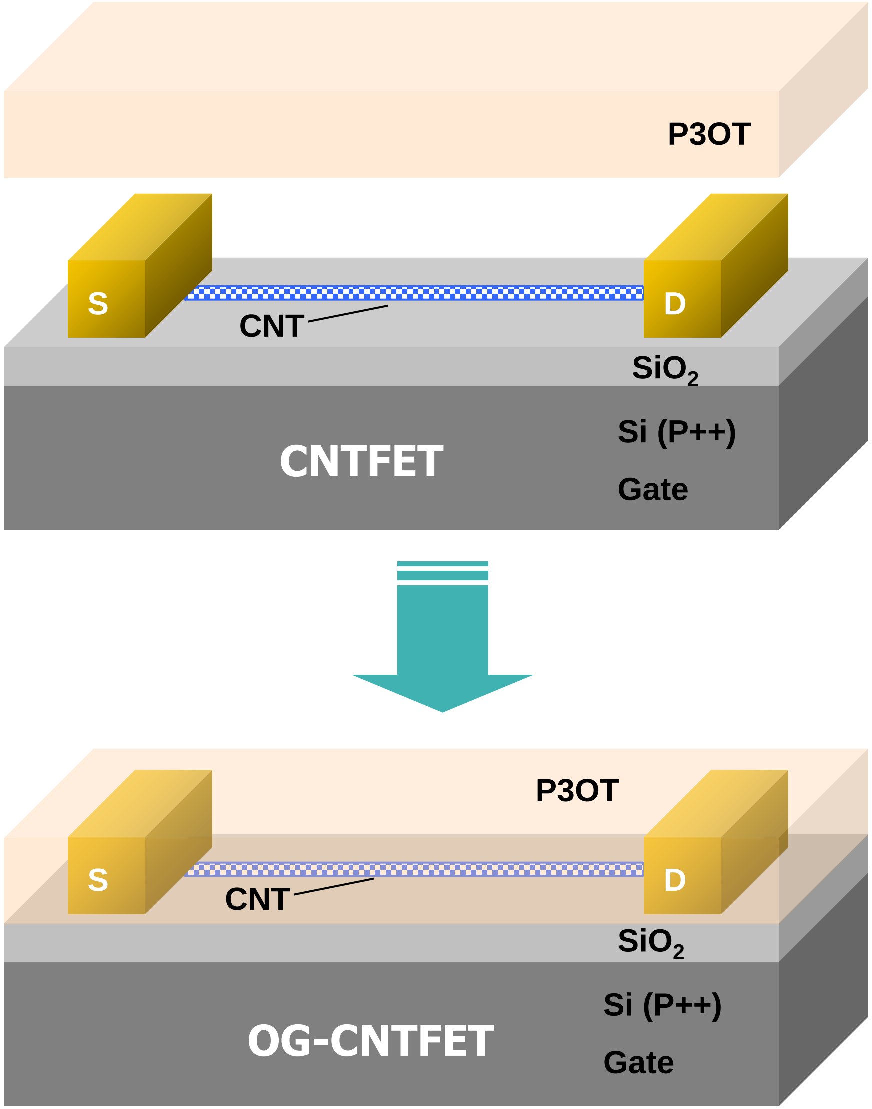
Non-volatile memory operation (R/W/E)**



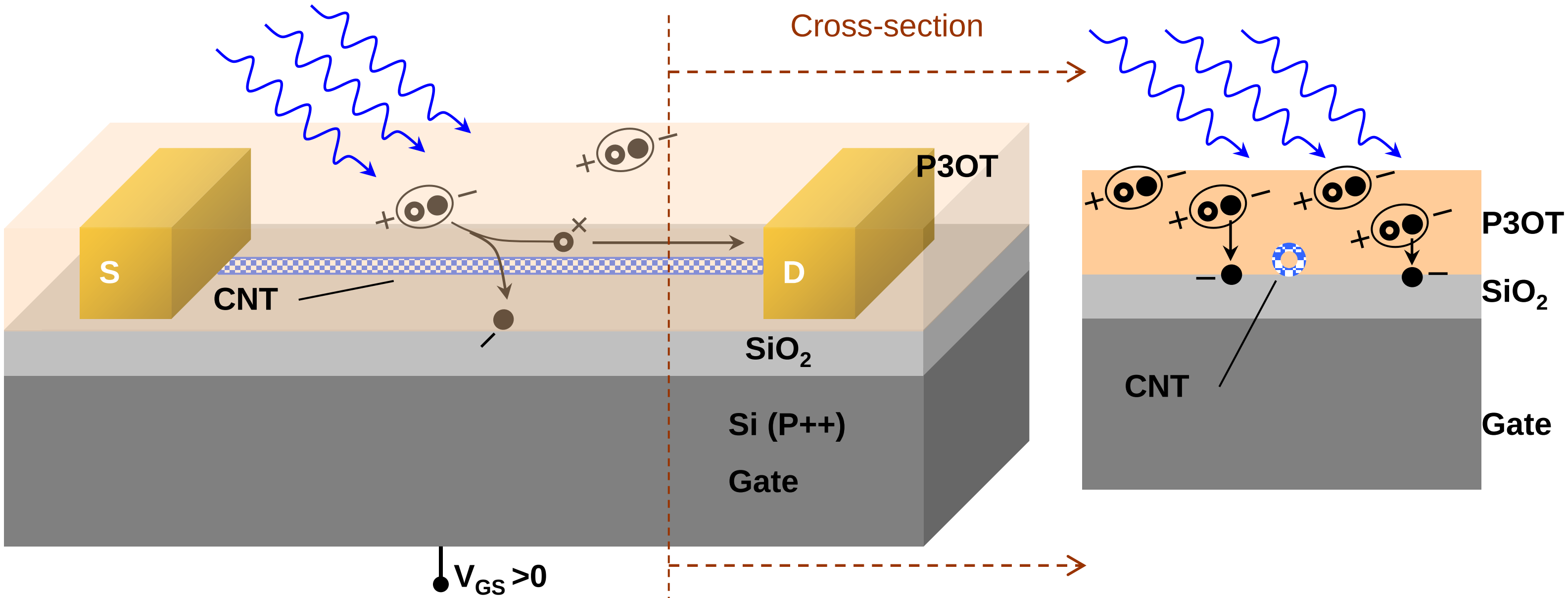
* W.-S. Zhao et al. *Nanotechology*, 2010, **21**, 175202.

** G. Agnus et al. *Adv. Mater.*, 2010, **22**, 702-706.

From CNTFET to OGCNTFET

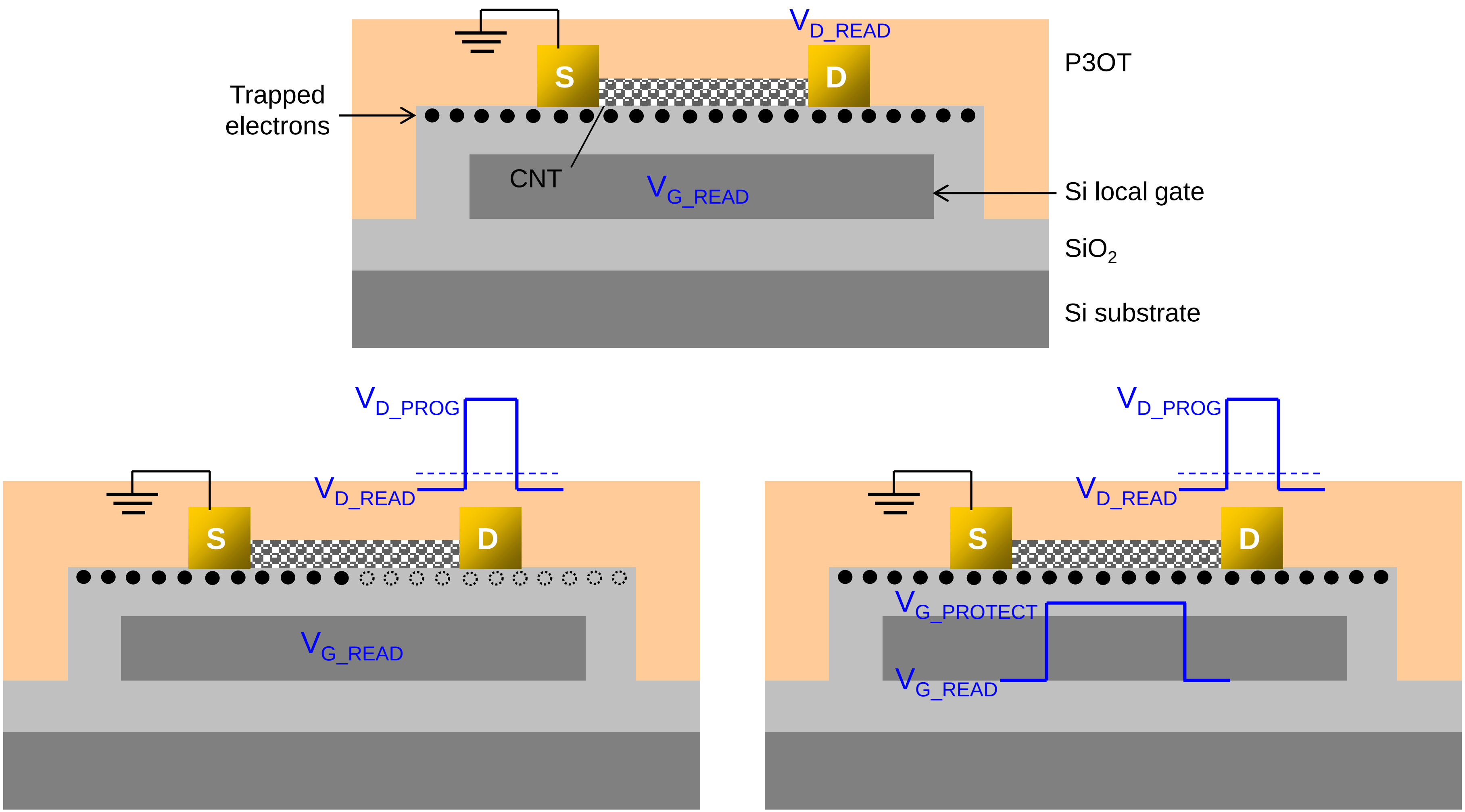


Optically write an OG-CNTFET memory



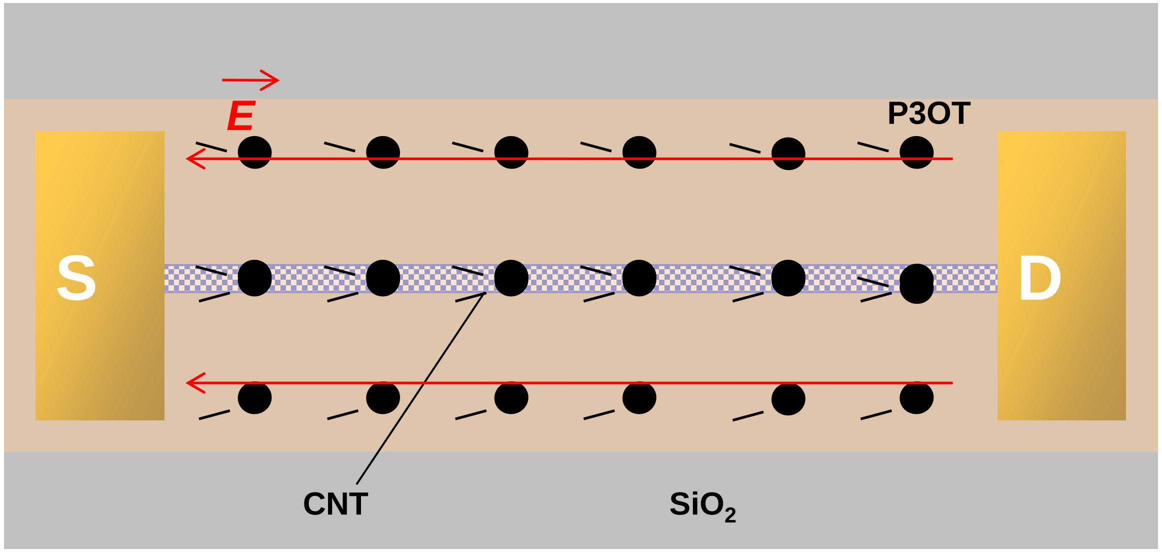
Program the conductance level of OG-CNTFET

(a) AFTER ILLUMINATION



(b) V_D PULSE PROGRAMMING

(c) GATE-PROTECTED: NO PROGRAMMING



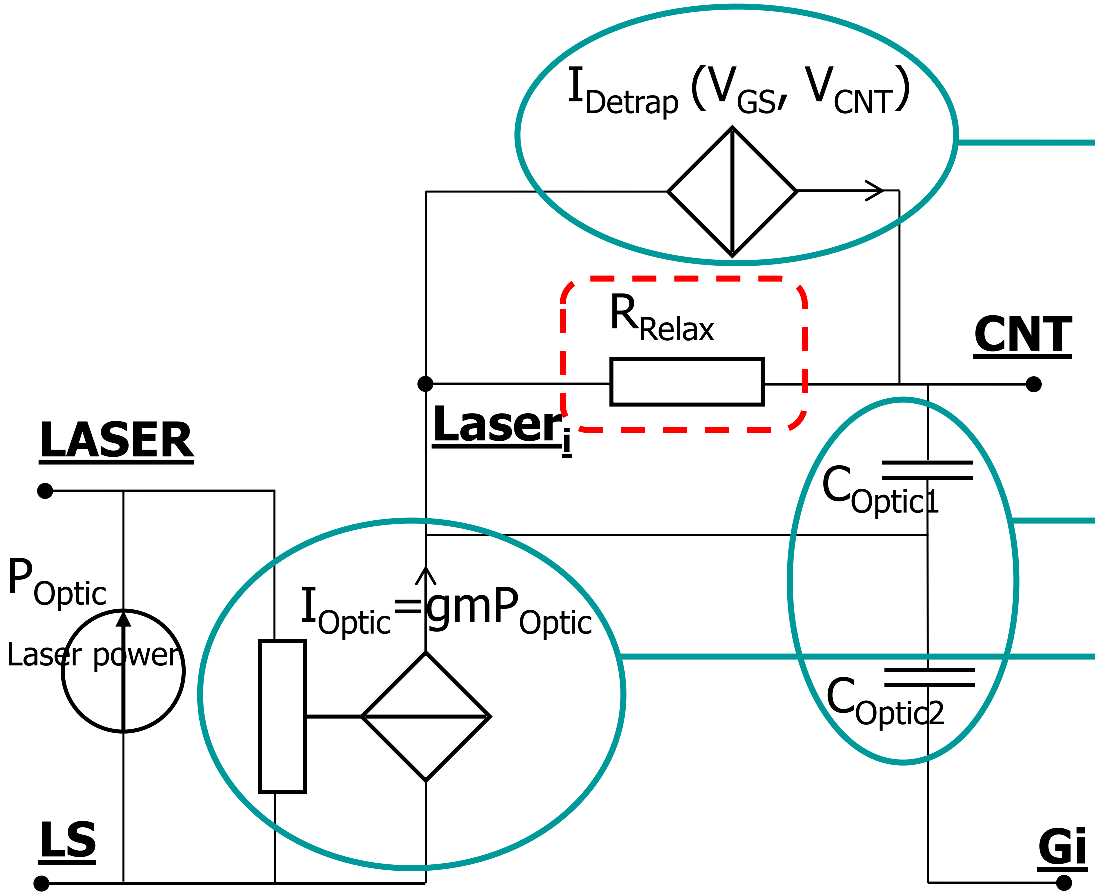
Hypotheses:

- Positive V_{DS} modulates the positive V_{CNT} which homogenously detraps interface charges in the near channel zone.
- Charge evacuations pass through the CNT channel.

Modeling:

- The current source of Shockley-Read-Hall (SRH) surface recombination depends on V_{DS} and V_{GS}.

Electrical equivalent sub circuit



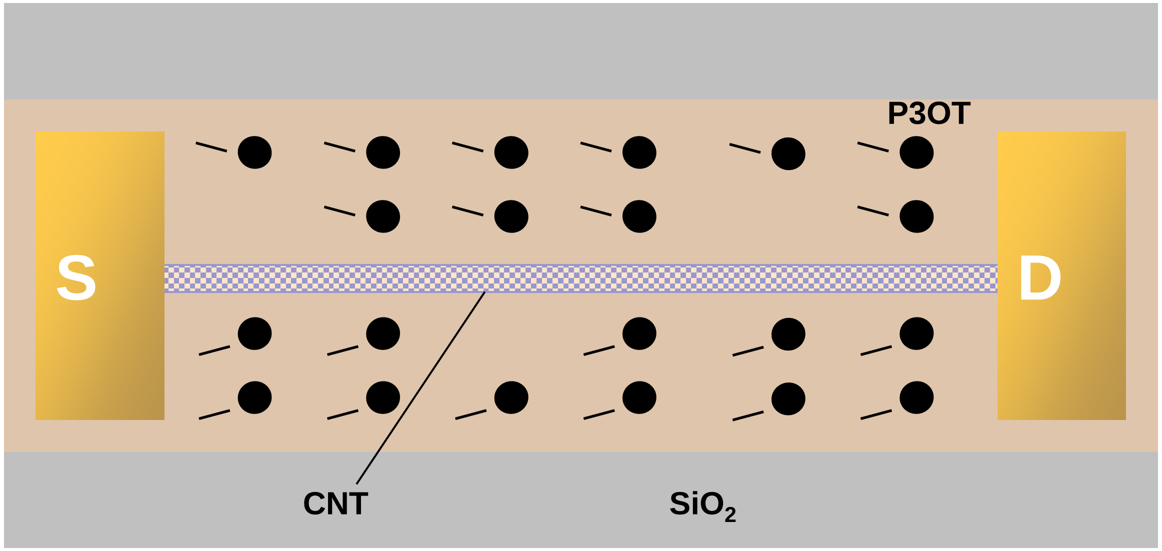
Detrapping current source I_{Detrap}, depends on V_{GS} and V_{CNT}.

Interface trap relaxation time constant $R_{Relax} * C_{Optic1} = Tau_{Relax}$.

Interface traps between SiO_2 and P3OT.

"Optical writing" current source.

- Part 1: The modeling of Non-volatile memory using OG-CNTFET
- Part 2: Description of carrier mobility model in P3OT and hopping mechanism at SiO_2-P3OT interface
  - Description of electron hopping and carrier mobility in P3OT
  - Electron mobility modeling
  - Relaxation current modeling
- Part 3 : Including Schottky Barrier (SB) at the drain/source contact of the OG-CNTFET modeling



- Electron mobility of P3OT in low field range.
- Relaxation current :

$$I_{relax} = (V_{Laseri} - V_{CNT}) \div R_{P3OT} \cdot Rate_{relax} = (V_{Laseri} - V_{CNT}) \cdot Y_{P3OT} \cdot Rate_{relax}$$

$$with \frac{1}{R_{P3OT}} = Y_{P3OT} = \sigma_{P3OT} \frac{Area}{length}$$

Electron hopping probability

- Conductivity of P3OT :

$$\sigma_{P3OT} = N_m e \mu_{P3OT} \approx N_d e \mu_{P3OT} = N_{trap} e \mu_{P3OT}$$

Electron mobility modeling in P3OT

Pool-Frenckel model (PF):

- The mobility is described as a electric field and temperature assisted detrapping process of a carrier from the Coulomb potential of a charge trap.
- Pros: good fitting in wide electric field range
- Cons: no physical clue about the nature of the process

$$\mu = \mu_0 \exp\left(-\frac{E_0 - \alpha\sqrt{F}}{kT_{eff}}\right)$$

$$with\,\frac{1}{T_{eff}} = \frac{1}{T} - \frac{1}{T_R}$$

Gaussian disorder model (GDM):

- GDM transport is supposed to proceed by means of hopping in a Gaussian site-energy distribution, caused by fluctuation in conjugation lengths and structural disorder.
- Pros: point out clearer the physics
- Cons: validation only in high electric field range

$$\mu(F,T) = \mu_\infty \exp\left(-\left(\frac{2\sigma}{kT}\right)^2 + C\left[\left(\frac{\sigma}{kT}\right)^2 - \Sigma^2\right]\sqrt{F} \right)$$

Ref : V. Kazukauskas et al., *Eur. Phys. J. Appl. Phys.*, **37** (2007) 247-251.

- Hypothesis:
  - Non-volatile relaxation = null bias = null field

$$\mu_{P3OT} \approx \mu_0 \exp\left(-\frac{E_0}{kT_{eff}}\right) = \mu_0 \exp\left(-\frac{E_0}{kT}\cdot\frac{T_R - T}{T_R}\right)$$

$$\sigma_{P3OT} \approx N_{trap} e \mu_0 \exp\left(-\frac{E_0}{kT}\cdot\frac{T_R - T}{T_R}\right)$$

- Relaxation of P3OT is temperature depended:

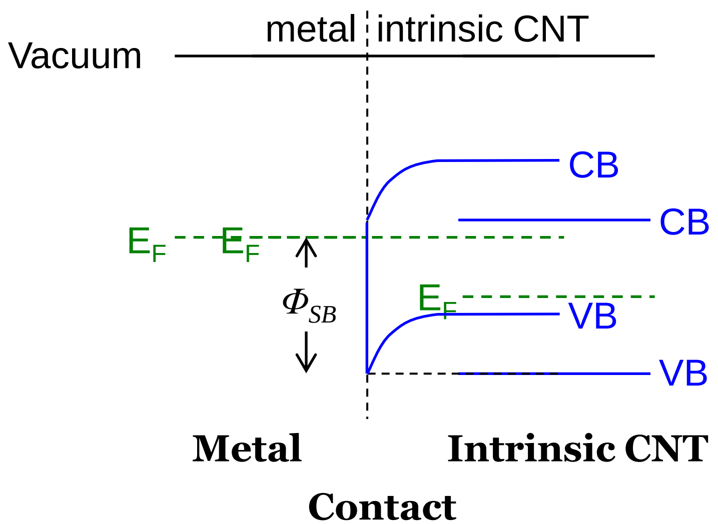
$$I_{relax} = \left(V_{Laseri} - V_{CNT}\right)\cdot \boxed{N_{trap} e \mu_0 \exp\left(-\frac{E_0}{kT}\frac{T_R - T}{T_R}\right)\frac{L_G d_{CNT}}{length}}\cdot Rate_{relax}$$

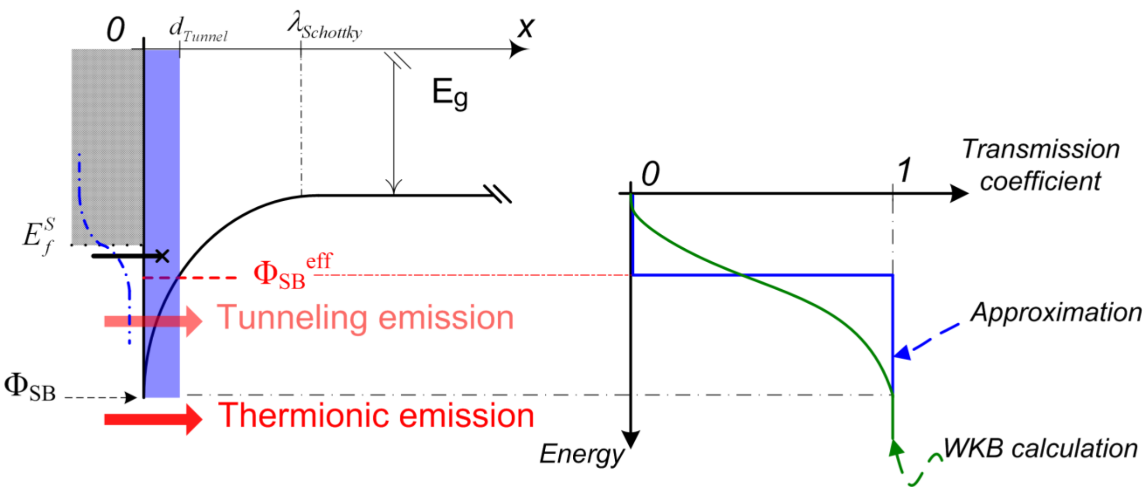
P3OT conductance under low electric field

- Part 1: The modeling of Non-volatile memory using OG-CNTFET

- Part 2: Description of carrier mobility model in P3OT and hopping mechanism at SiO2-P3OT interface

- Part 3:Including Schottky Barrier (SB) at the drain/source contact of the OG-CNTFET modeling
  - Modeling the Schottky barrier by the effective SB approach
  - Simulation result analysis



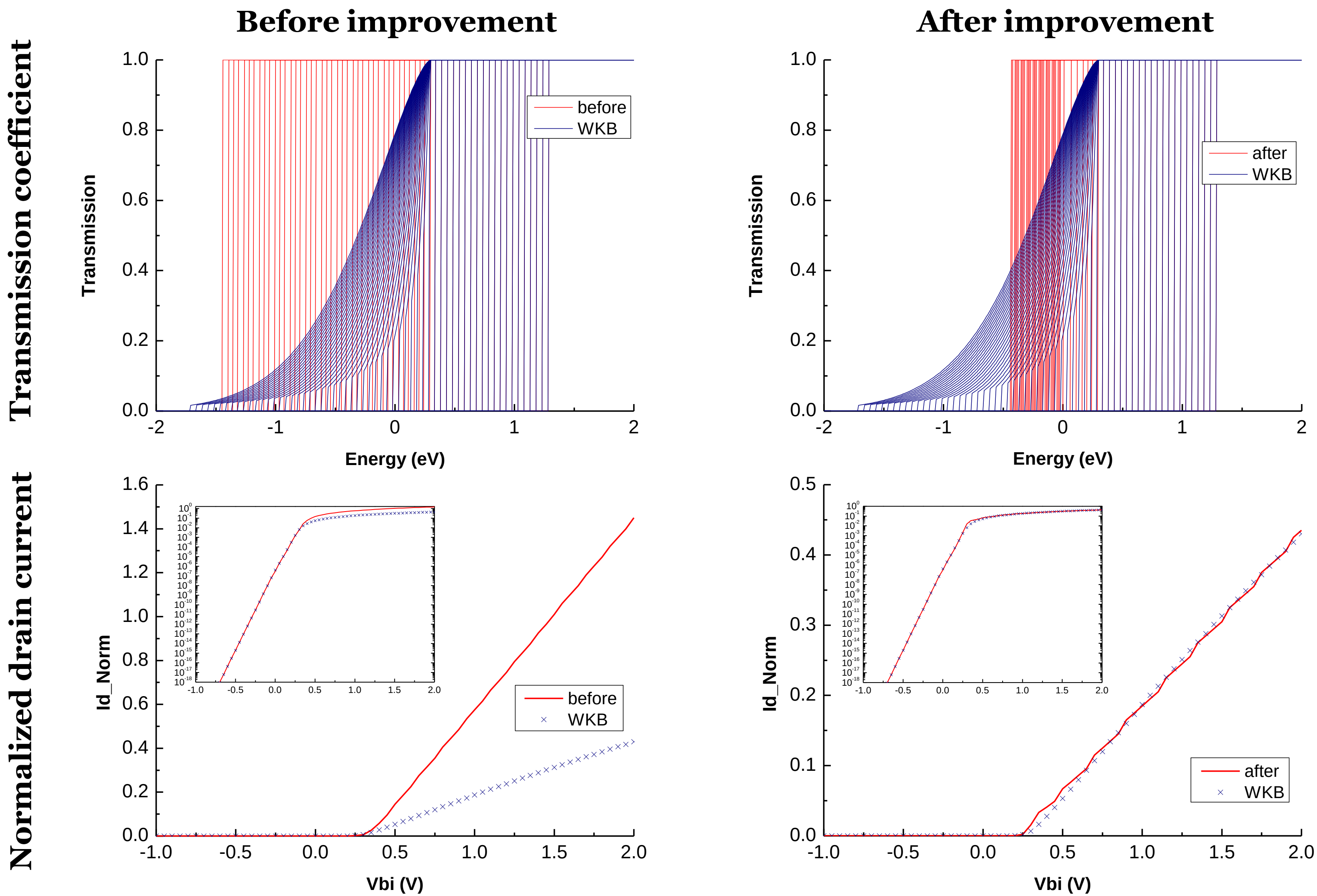


- Effective Φ_{SB} :
  - $0 > E_{injection} > \Phi_{SB\_eff}$, T (transmission propability) = 0; else, T = 1.
  - Charge injection computing starts from Φ_{SB_eff} .

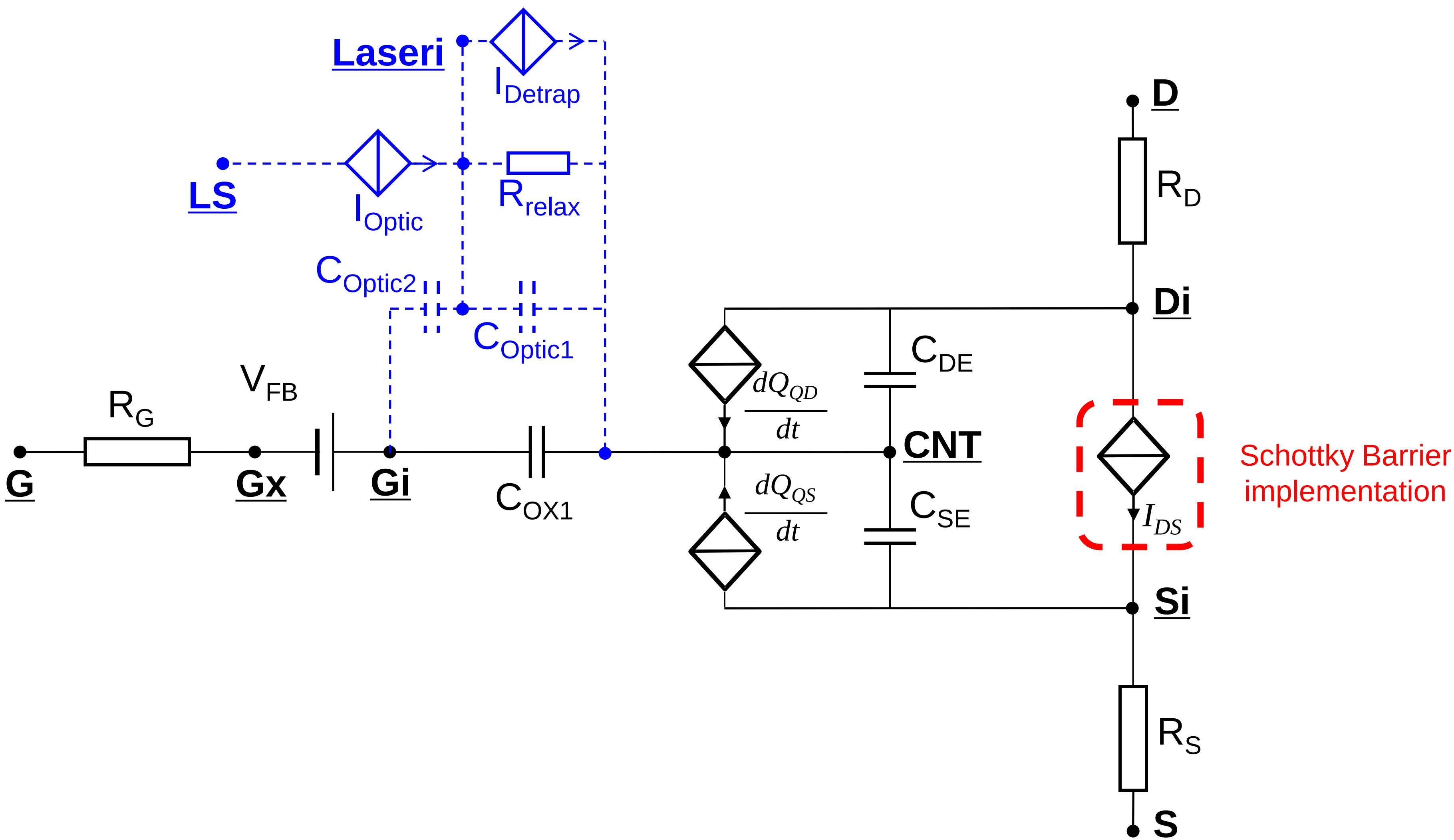
$$\Phi_{SB}^{eff} = \left(\Phi_{SB} - \left(\Phi_G + \Phi_{bi}\right)\right) \exp\left(\frac{-d_{tunnel}}{\lambda_{Schottky}}\right) + \left(\Phi_G + \Phi_{bi}\right)$$

Ref : J. Knock et al., *Phys. Stat. Sol. (a).*, **205**, 4, 679-694, 2008.

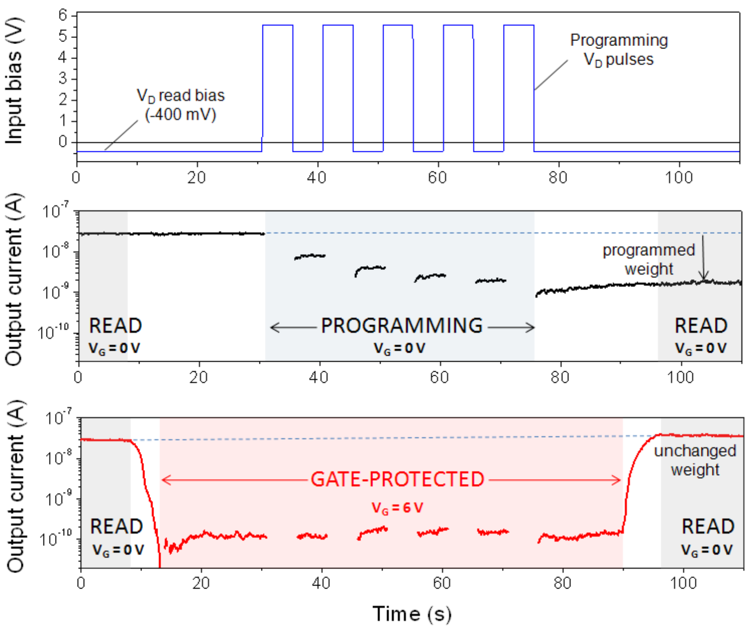
Improvement of Schottky barrier modeling



Electrical equivalent circuit of OG-SB-CNTFET

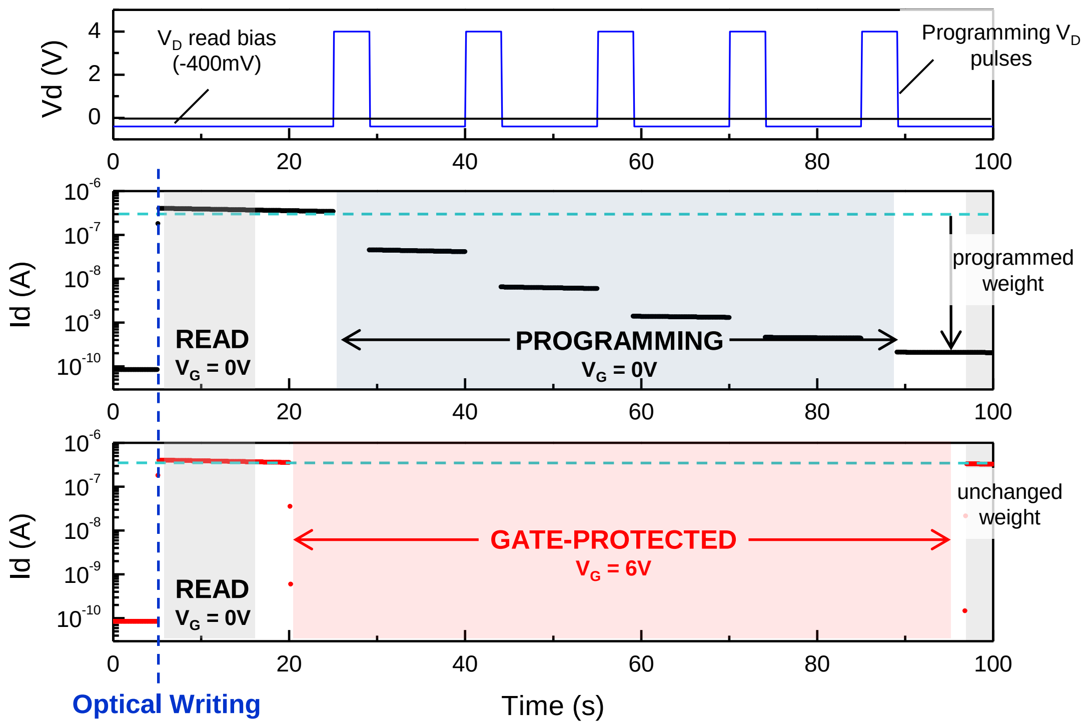


Measurements after optical writing

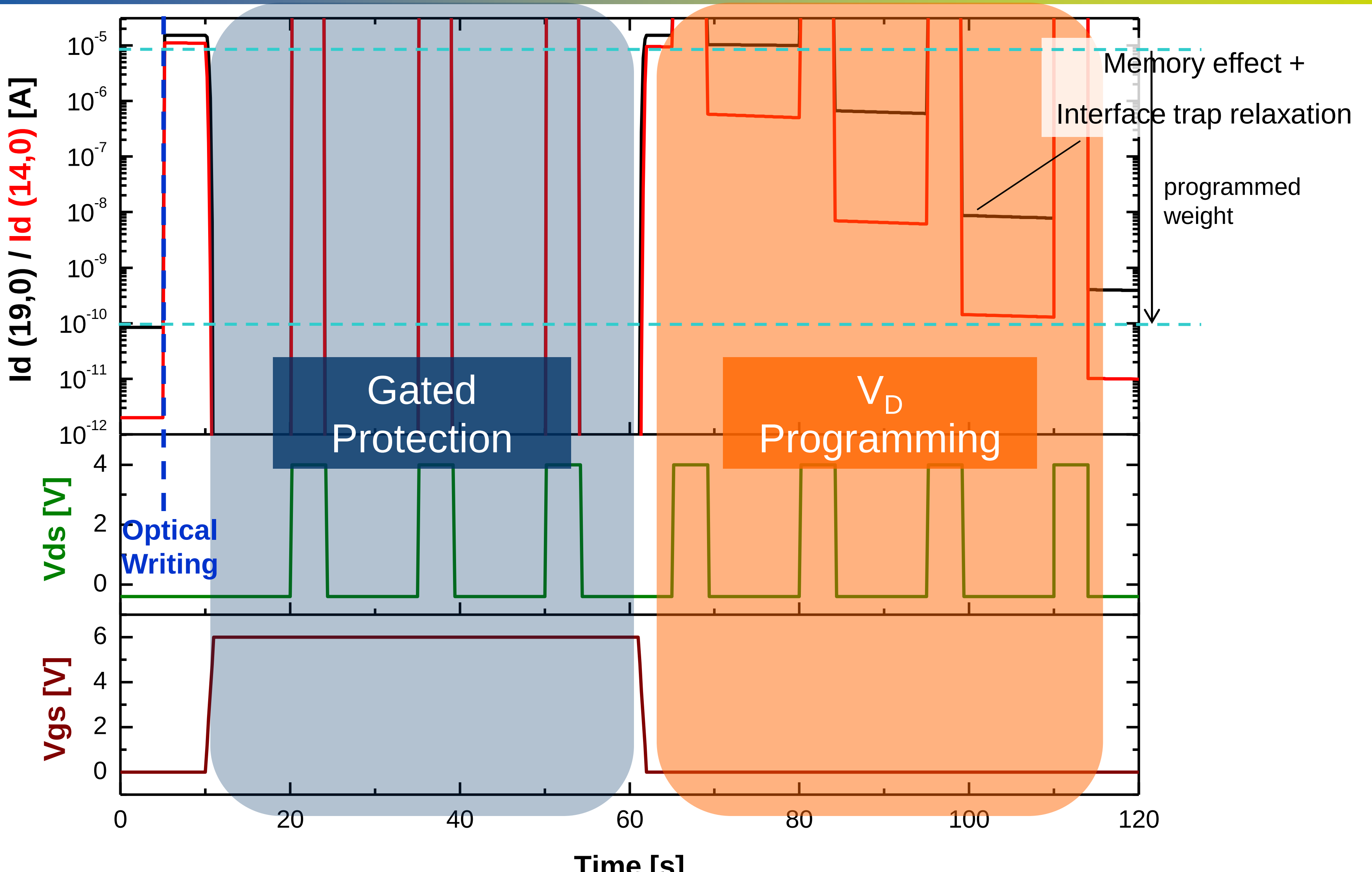


W.-S. Zhao et al. *Nanotechology*, 2010, **21** (2010) 175202.

Simulation results



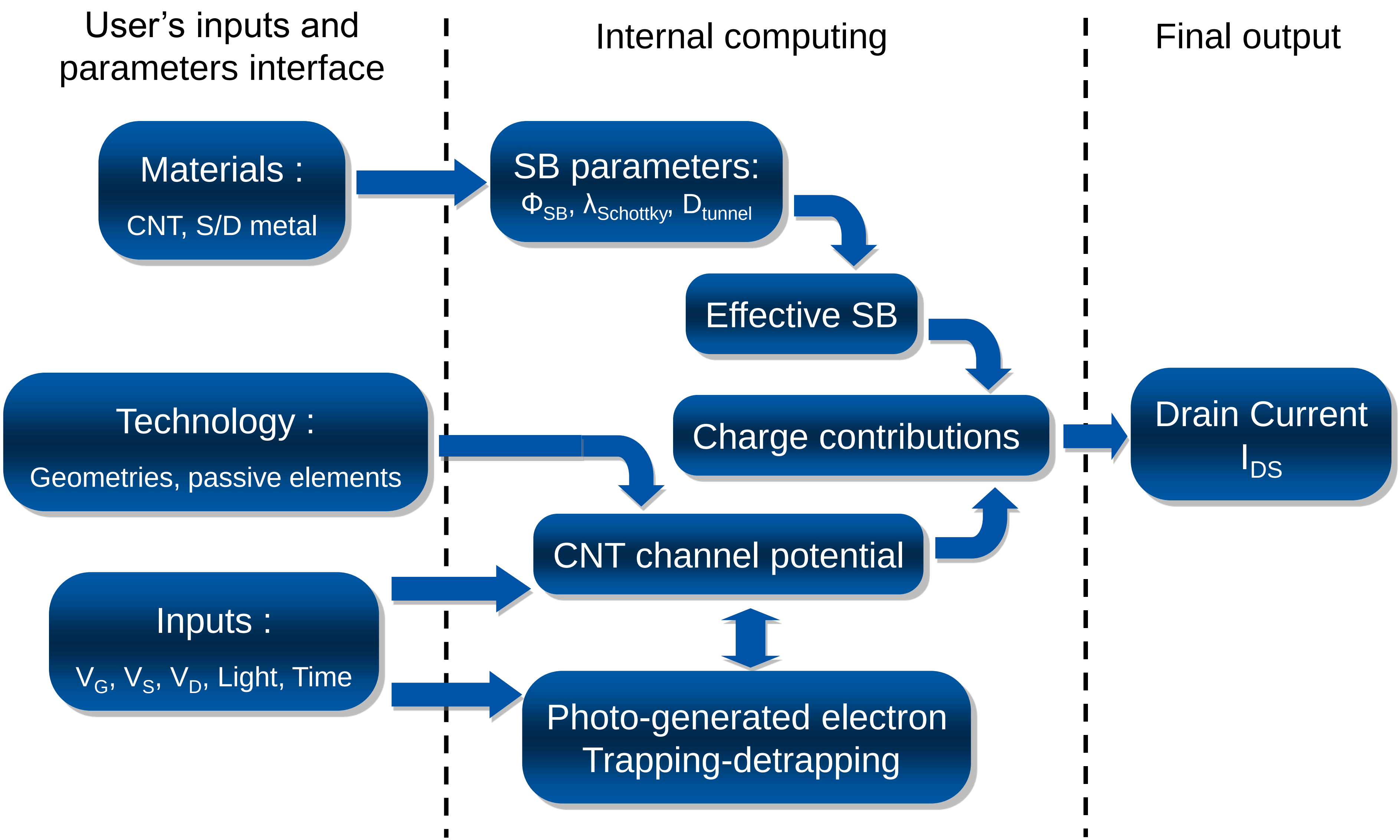
Comparison: Influence of Schottky contacts



Conclusion

- OG-CNTFET Modeling :
  - Optical gating, V_D programming, and gate bias protection of programming are physically modeled.
  - The compact model is adapted for ADS and Cadence.
- Description of mobility in P3OT and electron hopping :
  - The trapped electron relaxation is modeled by hopping mechanism at SiO_2/P3OT interface.
  - Pool-Frenckel mobility model is adapted for P3OT conductivity under non-volatile memory condition.
- Including drain-source Schottky contacts in OG-CNTFET :
  - The Schottky barrier is converted to effective Schottky barrier on the channel potential.
  - The effective Schottky barrier computing is improved for not only the OG-CNTFET bias range, but also for the one of normal CNTFET.

From inputs/parameters to outputs



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Thanks for your attention