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# MOSFET Channel Engineering and Scaling Study using COMSOL® Multiphysics Simulation Software

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# Overview

- Structure of MOSFET
- Short Channel effect
- FIBMOS and its Structure
- Methods
- Results
- Conclusion

# MOSFET

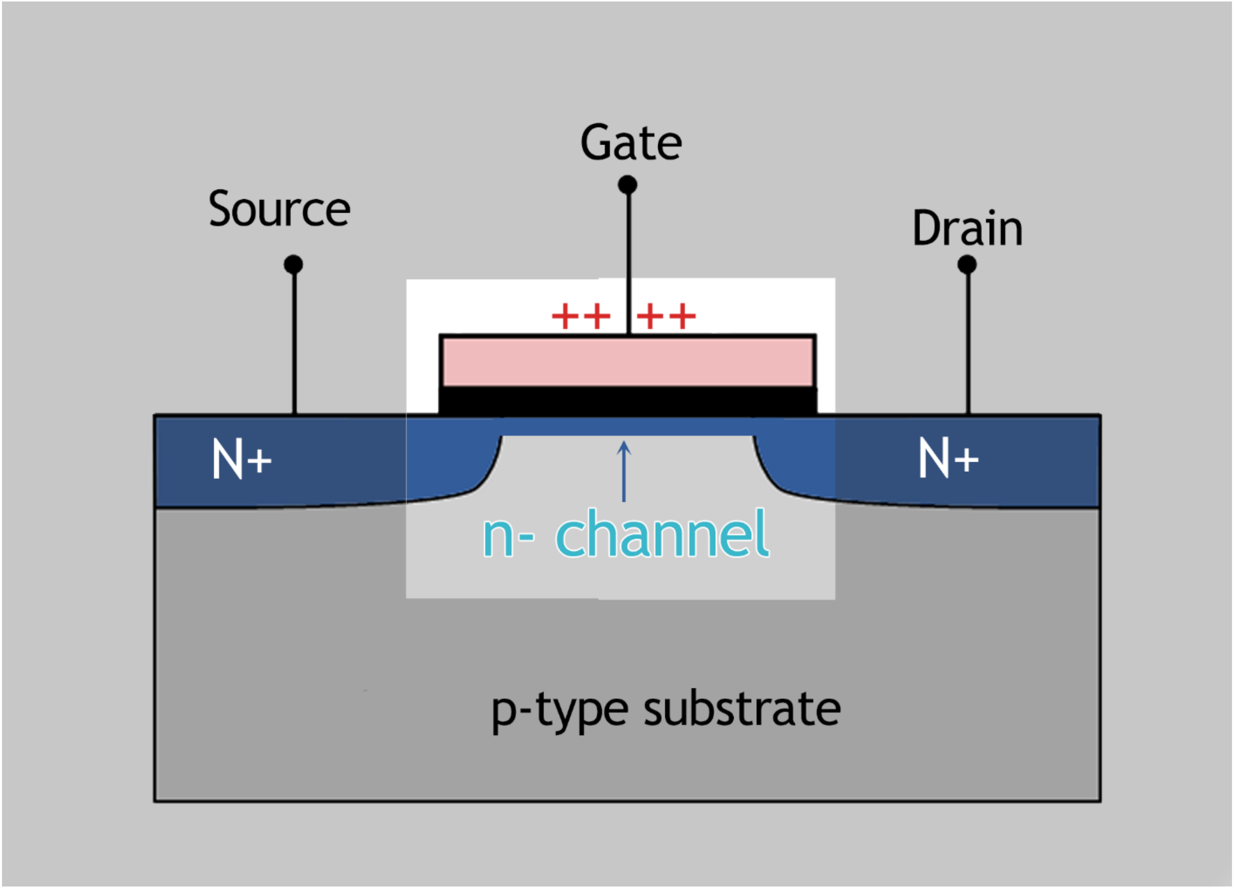


Fig 1. Structure of an n-type MOSFET

# Short Channel Effects

- Threshold instability
- Punchthrough effect
- Reduced Output resistance
- Hot electron degradation

# FIBMOS

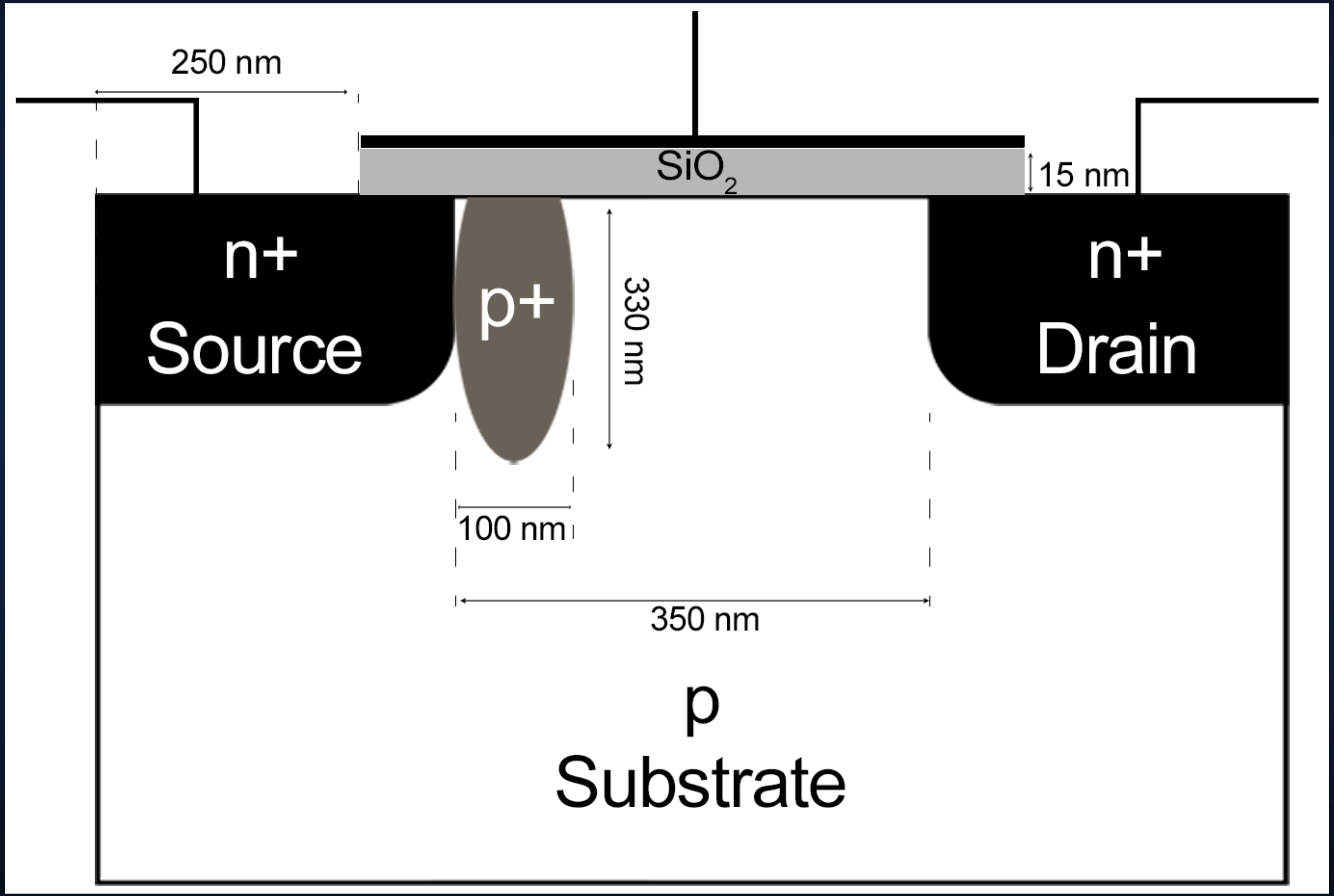


Fig 2. Device Structure of FIBMOS

# Device Parameters

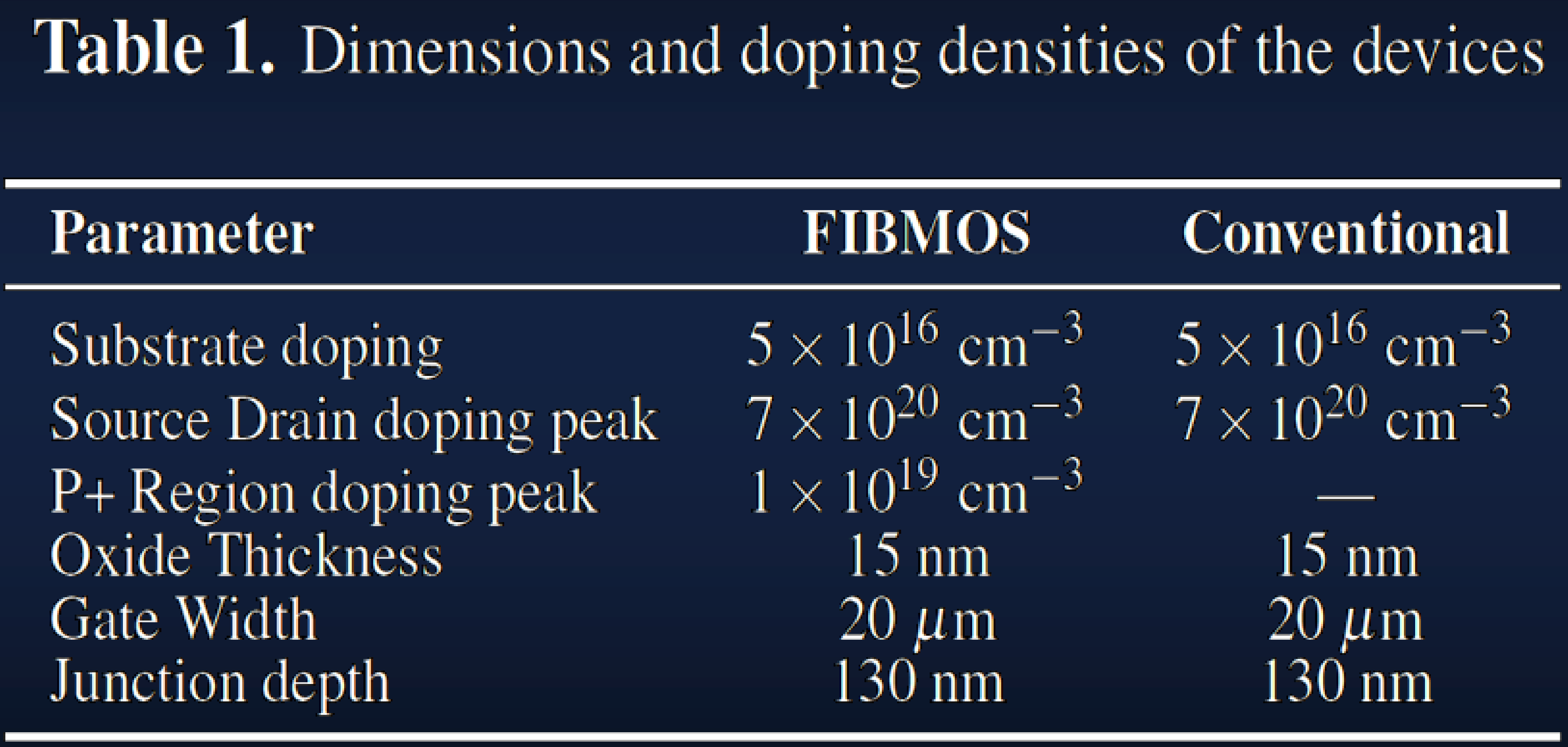


**Table 1.** Dimensions and doping densities of the devices

| **Parameter** | **FIBMOS** | **Conventional** |
|---|---|---|
| Substrate doping | $5 \times 10^{16}$ cm$^{-3}$ | $5 \times 10^{16}$ cm$^{-3}$ |
| Source Drain doping peak | $7 \times 10^{20}$ cm$^{-3}$ | $7 \times 10^{20}$ cm$^{-3}$ |
| P+ Region doping peak | $1 \times 10^{19}$ cm$^{-3}$ | — |
| Oxide Thickness | 15 nm | 15 nm |
| Gate Width | 20 $\mu$m | 20 $\mu$m |
| Junction depth | 130 nm | 130 nm |

# Constant Field Scaling

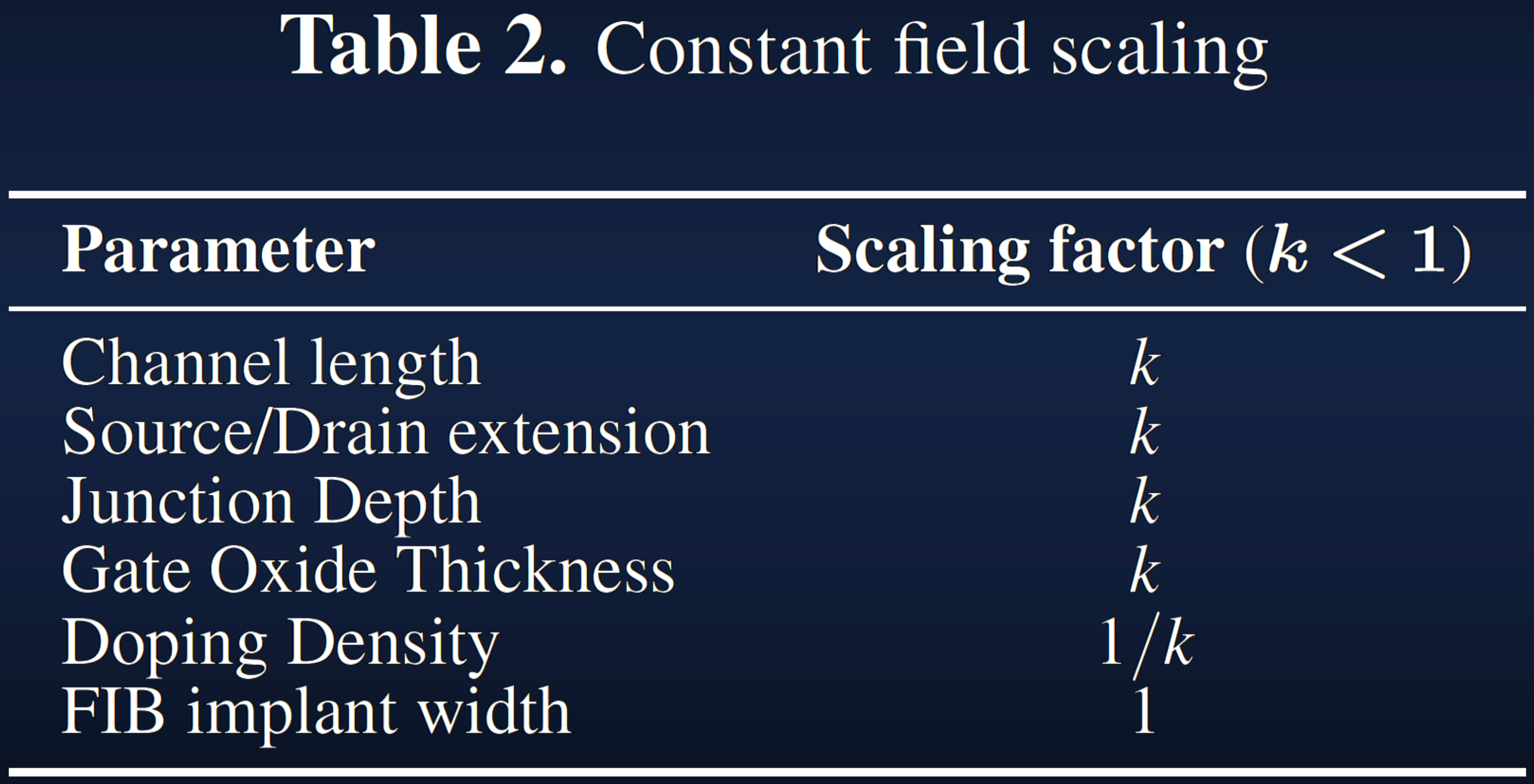


**Table 2.** Constant field scaling

| **Parameter** | **Scaling factor** ($k < 1$) |
|---|---|
| Channel length | $k$ |
| Source/Drain extension | $k$ |
| Junction Depth | $k$ |
| Gate Oxide Thickness | $k$ |
| Doping Density | $1/k$ |
| FIB implant width | $1$ |

# METHODS

- Semiconductor Module was used in order to design the devices and perform study on them
- 350-nm devices were designed and were scaled further down by factor of k = {0.7, 0.5, 0.35} that is channel length of {245-nm, 175-nm, 122.5-nm} using parametric sweep
- Two different user-defined mesh were made according to needs of the simulation
- Mobility Model and Recombination Model were implemented to increase fidelity of the physics
- Solver settings were changed accordingly to facilitate the models used and to converge to a solution
- Fermi-Dirac Distribution of particle was implemented

# Equation Used

- Poisson Equation

$$\boldsymbol{\nabla}\cdot\left(-\epsilon_0\epsilon_r\,\boldsymbol{\nabla V}\right)=q\left(p-n+N_d^{+}-N_a^{-}\right)$$

- Continuity Equation

$$\frac{\partial n}{\partial t}=\frac{1}{q}\left(\boldsymbol{\nabla}\cdot\boldsymbol{J_n}\right)-U_n$$

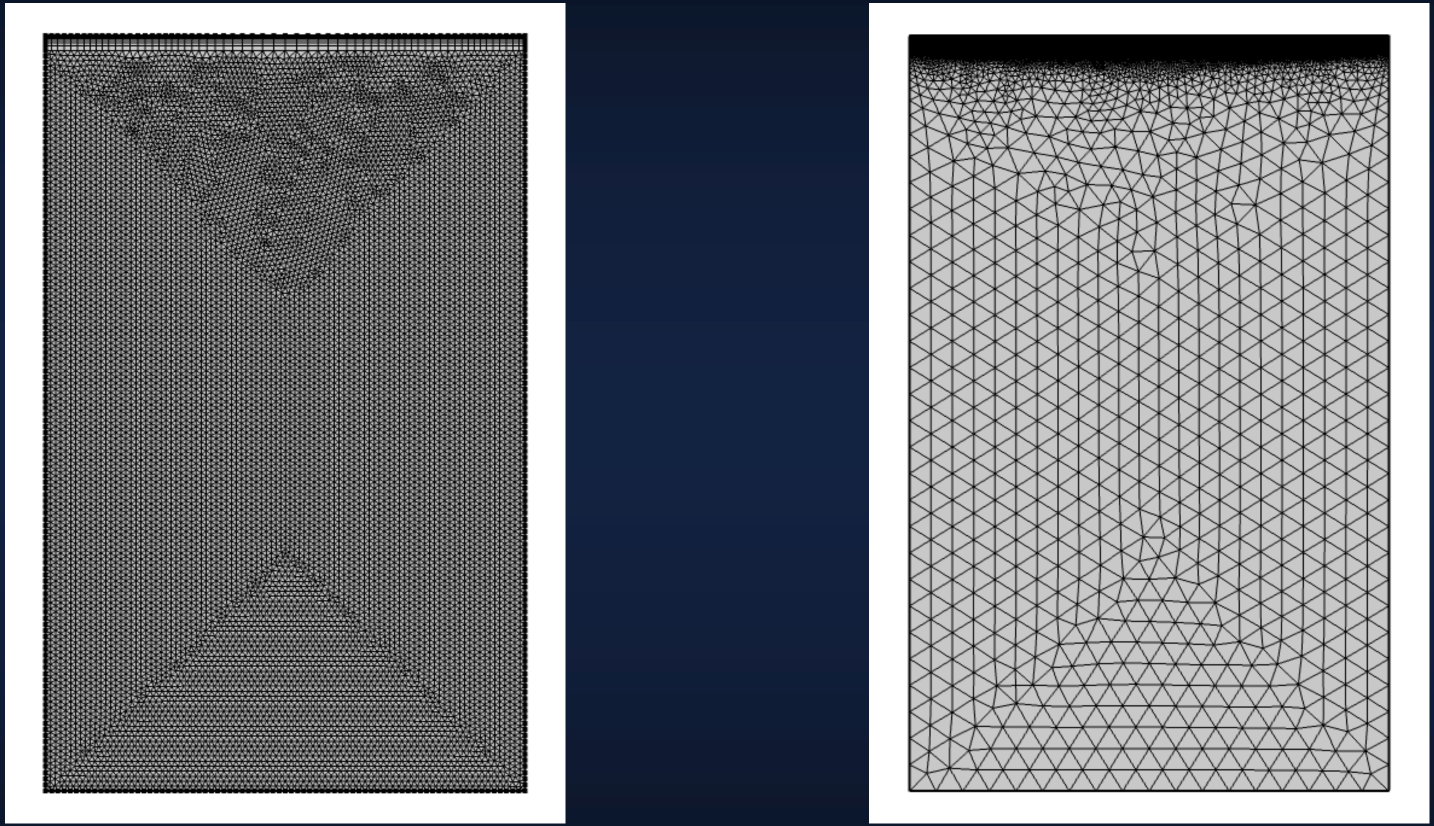
$$\frac{\partial p}{\partial t}=-\frac{1}{q}\left(\boldsymbol{\nabla}\cdot\boldsymbol{J_p}\right)-U_p$$

- Energy-Transport Model

$$\boldsymbol{J_n}=qn\mu_n\boldsymbol{\nabla E_c}+\mu_n k_B T G\left(\frac{n}{N_c}\right)\boldsymbol{\nabla}\mathbf{n}+\mathrm{qnD}_{n,\mathrm{th}}\boldsymbol{\nabla}\,\boldsymbol{ln(T)}$$

$$\boldsymbol{J_p}=qp\mu_p\boldsymbol{\nabla E_v}+\mu_p k_B T G\left(\frac{p}{N_v}\right)\boldsymbol{\nabla}\mathbf{p}-\mathrm{qpD}_{\mathrm{p,th}}\boldsymbol{\nabla}\,\boldsymbol{ln(T)}$$

# Mesh

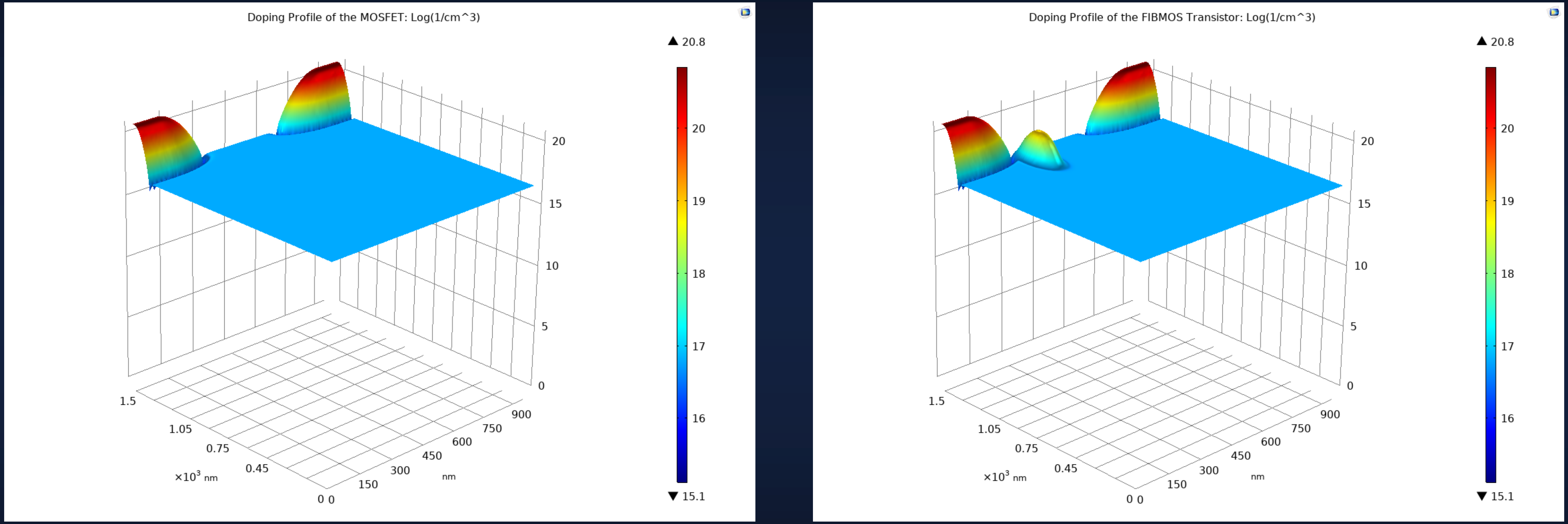


24592 domain elements
398 boundary elements

25910 domain elements
1068 boundary elements

Fig 3. User-defined meshes

# Doping Profile



Doping Profile of the MOSFET: Log(1/cm^3)

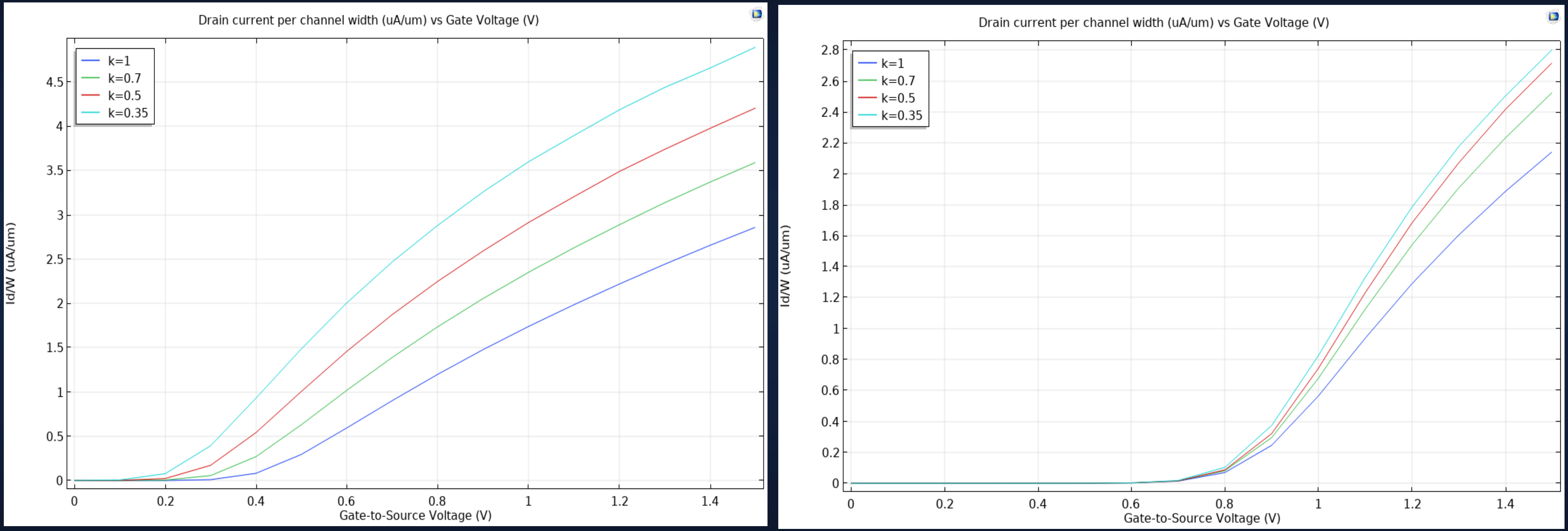
Doping Profile of the FIBMOS Transistor: Log(1/cm^3)

(a)

(b)

Fig 4. Doping Profile of (a) MOSFET and (b) FIBMOS device

# Transfer Characteristics



(a)

(b)

Fig 5. Transfer Characteristics of (a) MOSFET and (b) FIBMOS device

# Subthreshold Conduction

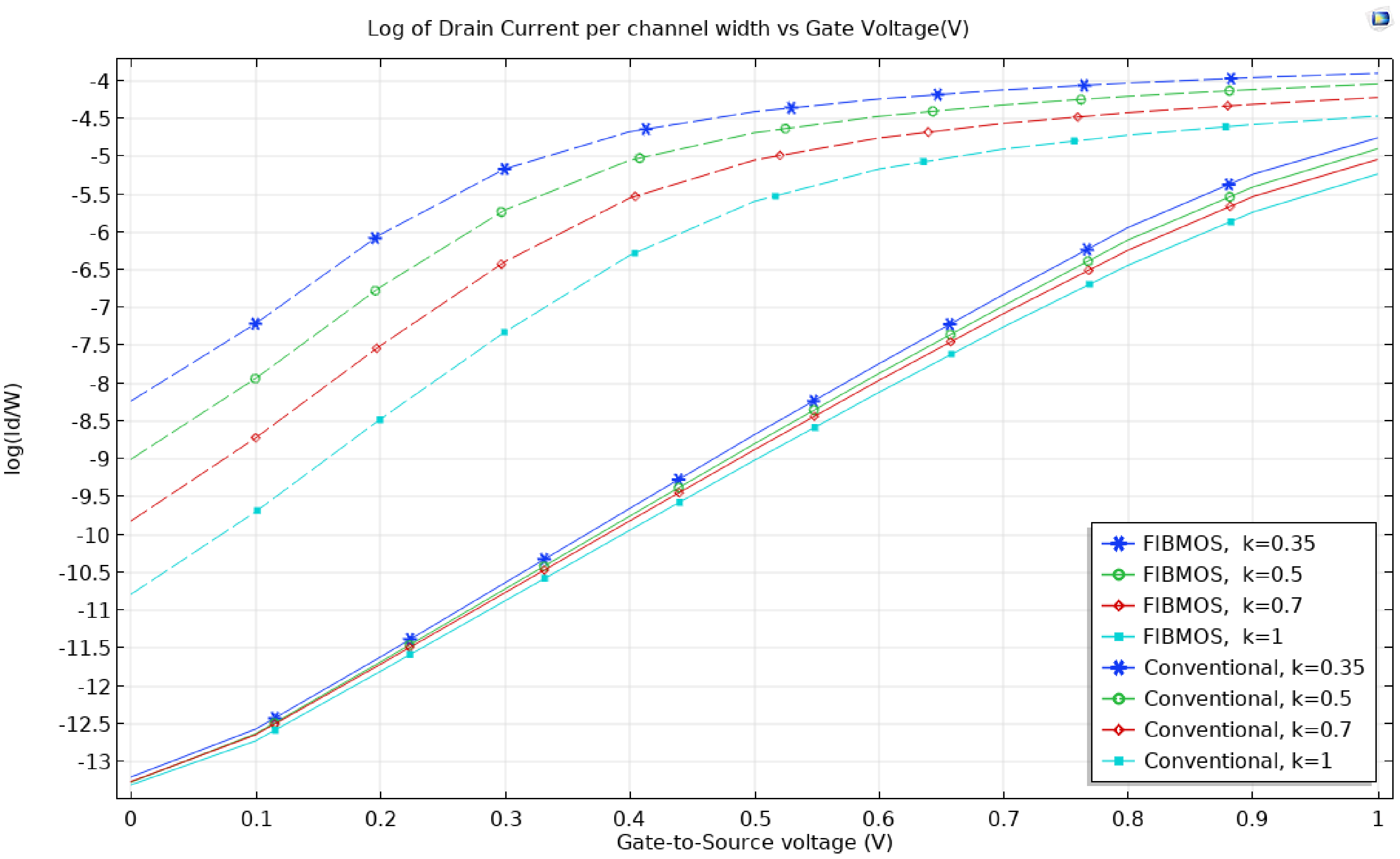
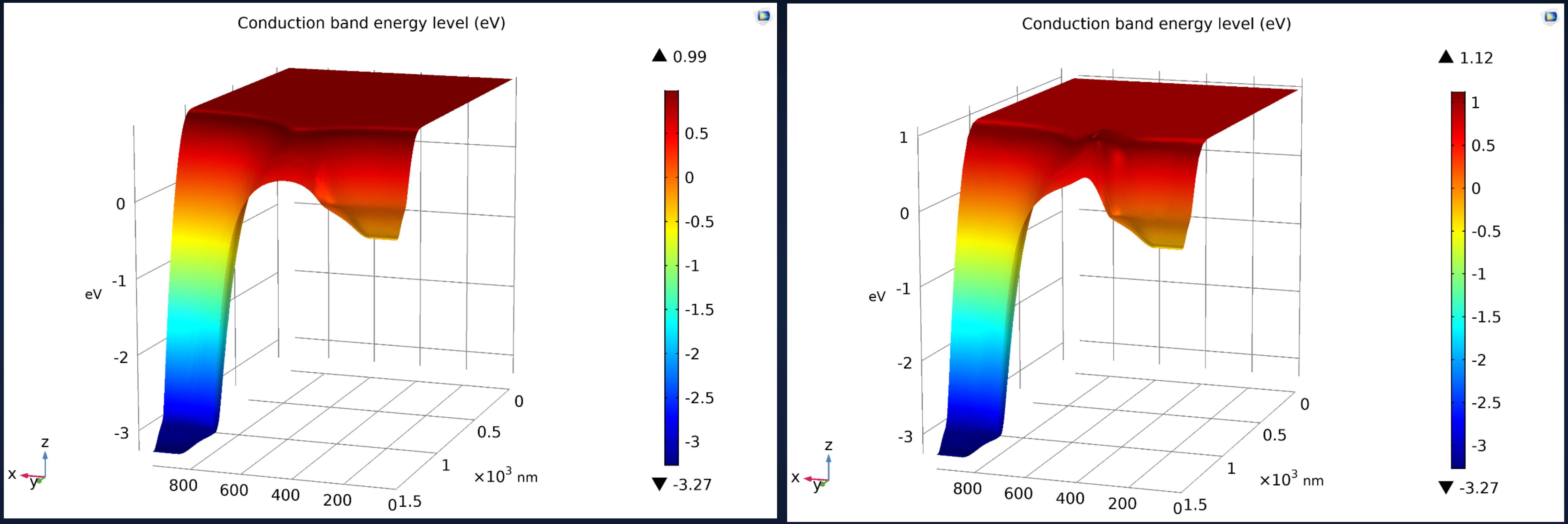


Fig 6. Subthreshold current of MOSFET (dashed) and FIBMOS device (solid)

# Conduction band energy level



(a)

(b)

Fig 7. Conduction band energy level of (a) MOSFET and (b) FIBMOS device

# Output Characteristics

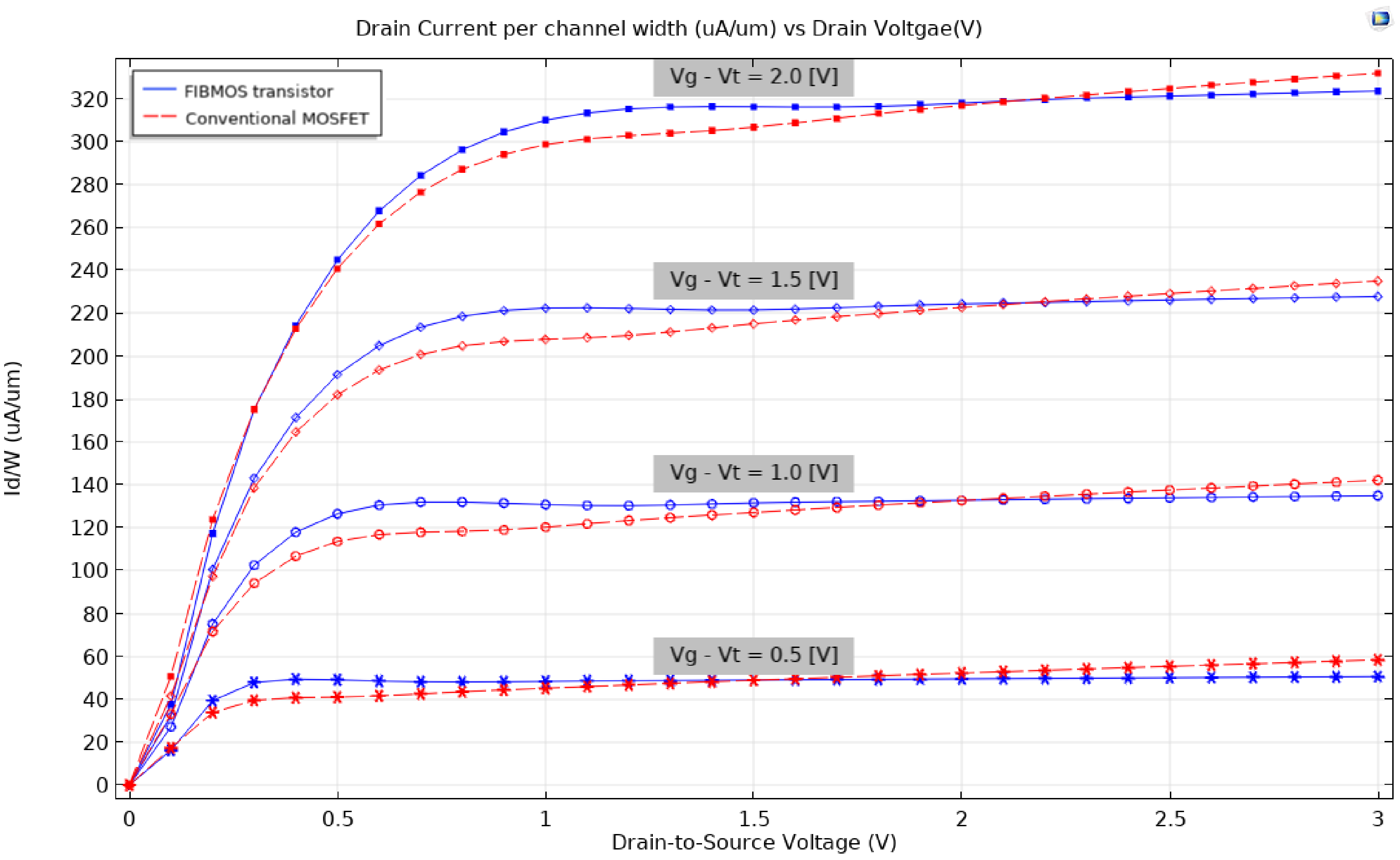


Fig 8. Output Characteristics of MOSFET (red) and FIBMOS device (blue)

# Lateral Electrical Field

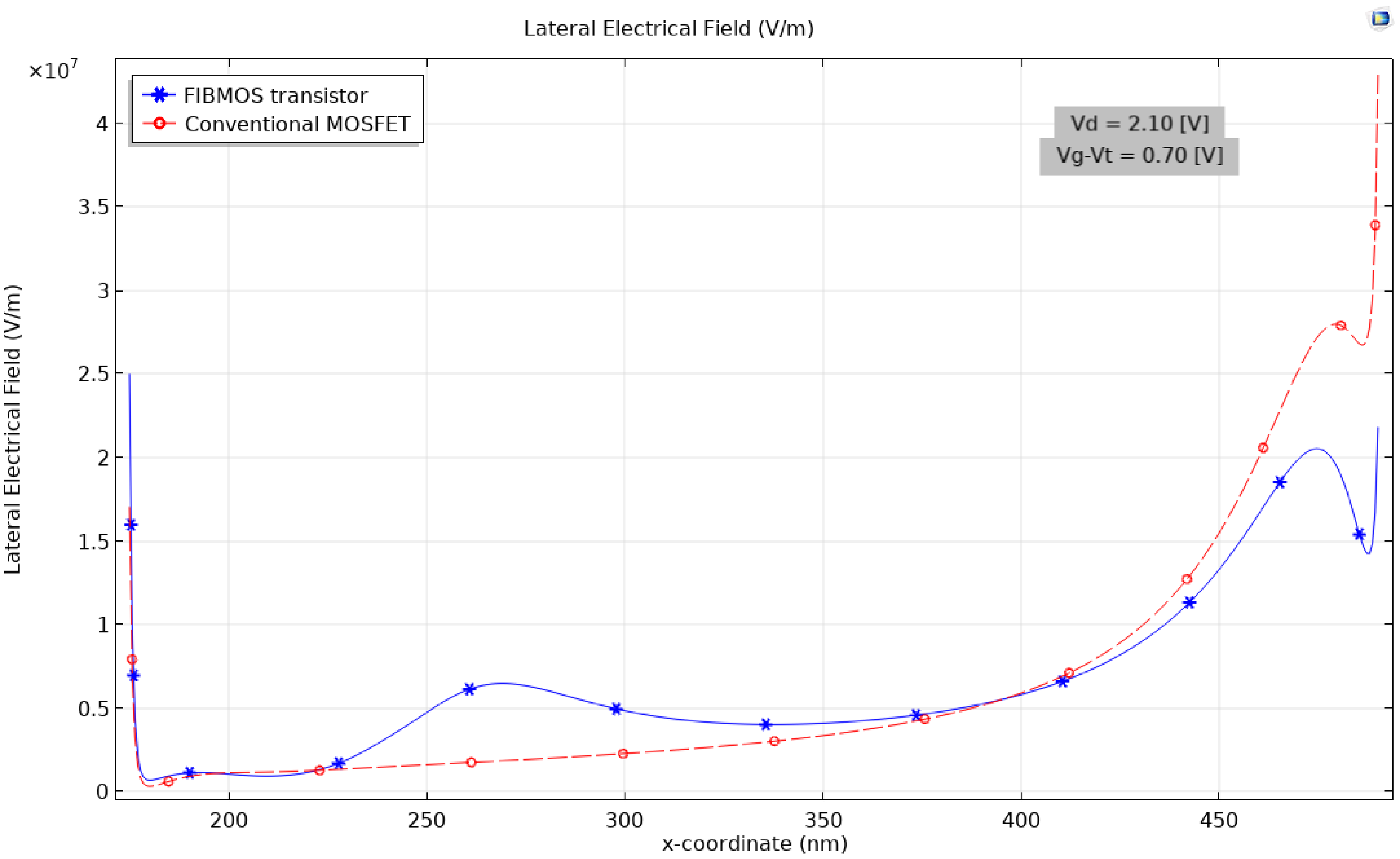


Fig 9. Lateral Electrical Field inside the channel of MOSFET (red) and FIBMOS device (blue)

# Electron Concentration inside the channel

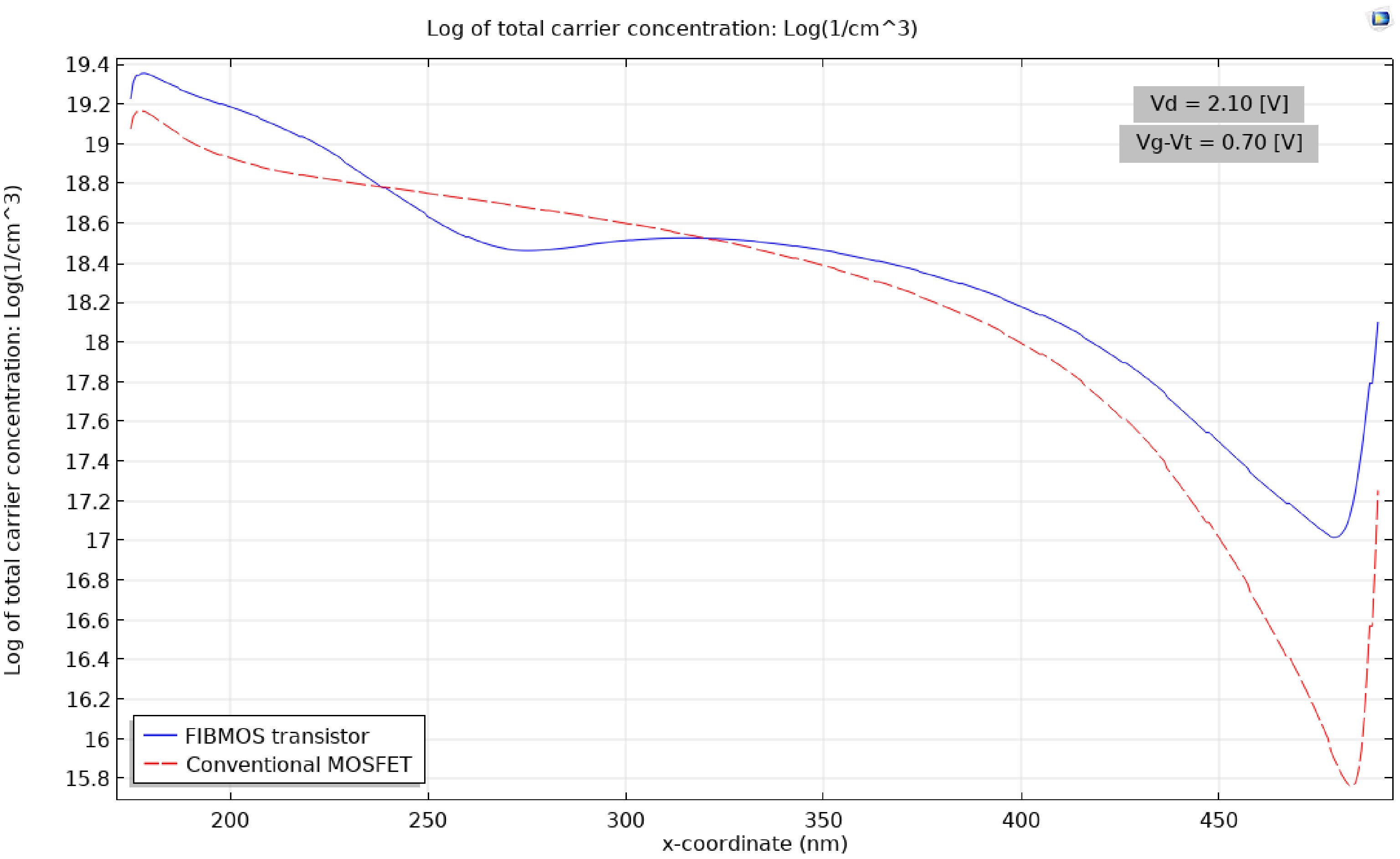


Fig 10. Electron Concentration inside the channel of MOSFFET (red) and FIBMOS device (blue)

# Conclusion

- Threshold stability
- Greater resistance against Punchthrough effect
- Higher Output resistance
- Greater resistance against Hot electron degradation
- Hence, FIBMOS shows characteristics closer to ideal transistors

# References

- Chih-Chieh Shen, J. Murguia, N. Goldsman, M. Peckerar, J. Melngailis, and D.A. Antoniadis. Use of focused-ion-beam and modeling to optimize submicron MOSFET
- Donald A. Neamen. Semiconductor Physics And Devices: Basic Principles. McGraw-Hill, 2012.
- J Kang, X He, D Vasileska, and D K Schroder. Optimization of FIBMOS Through 2d Silvaco ATLAS and 2d Monte Carlo Particle-based. VLSI Design, 13(1-4):251–256, 2001.
- Kevin Kramer and W. Nicholas G. Hitchon. Semiconductor Devices: A Simulation Approach. Prentice Hall PTR, 1997.

# THANK YOU

Question?

# Appendix

# Mobility Model

- Arora Mobility Model
  - Phonon scattering and Impurity scattering
- Fletcher Mobility Model
  - Carrier-carrier scattering
- Lombardi Mobility Model
  - Surface scattering (Perpendicular Electrical Field)
- Caughey-Thomas Mobility Model
  - High Field Velocity Scattering (Lateral Electrical Field)

$$\mu_{total} = \mu_E(\mu_S(\mu_C(\mu_{LI})))$$

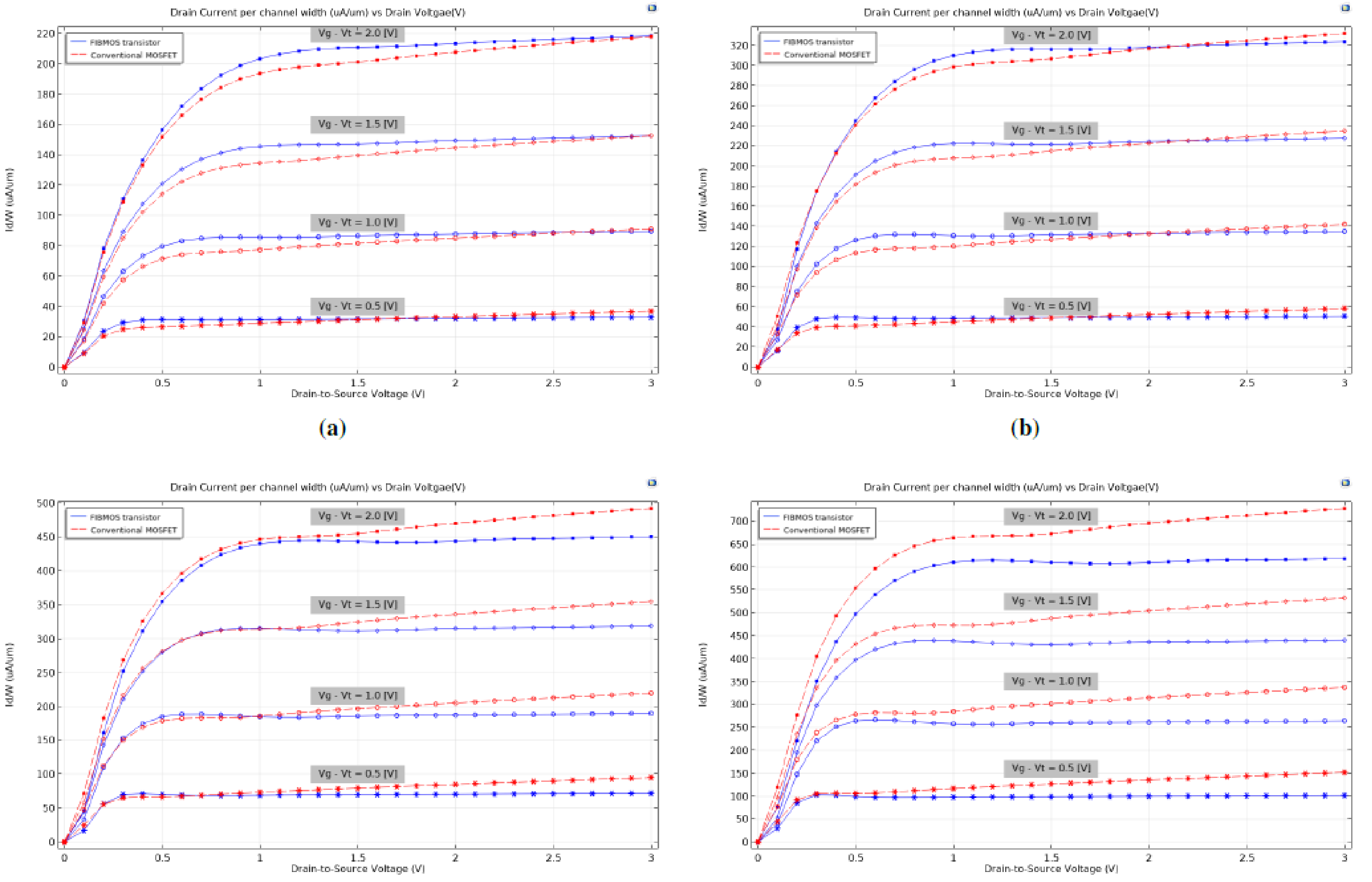


**Figure 5.** Output Characteristics of FIBMOS device and conventional MOSFET for channel length of (a) 350-nm, (b) 245-nm, (c) 175-nm, and (d) 122.5-nm

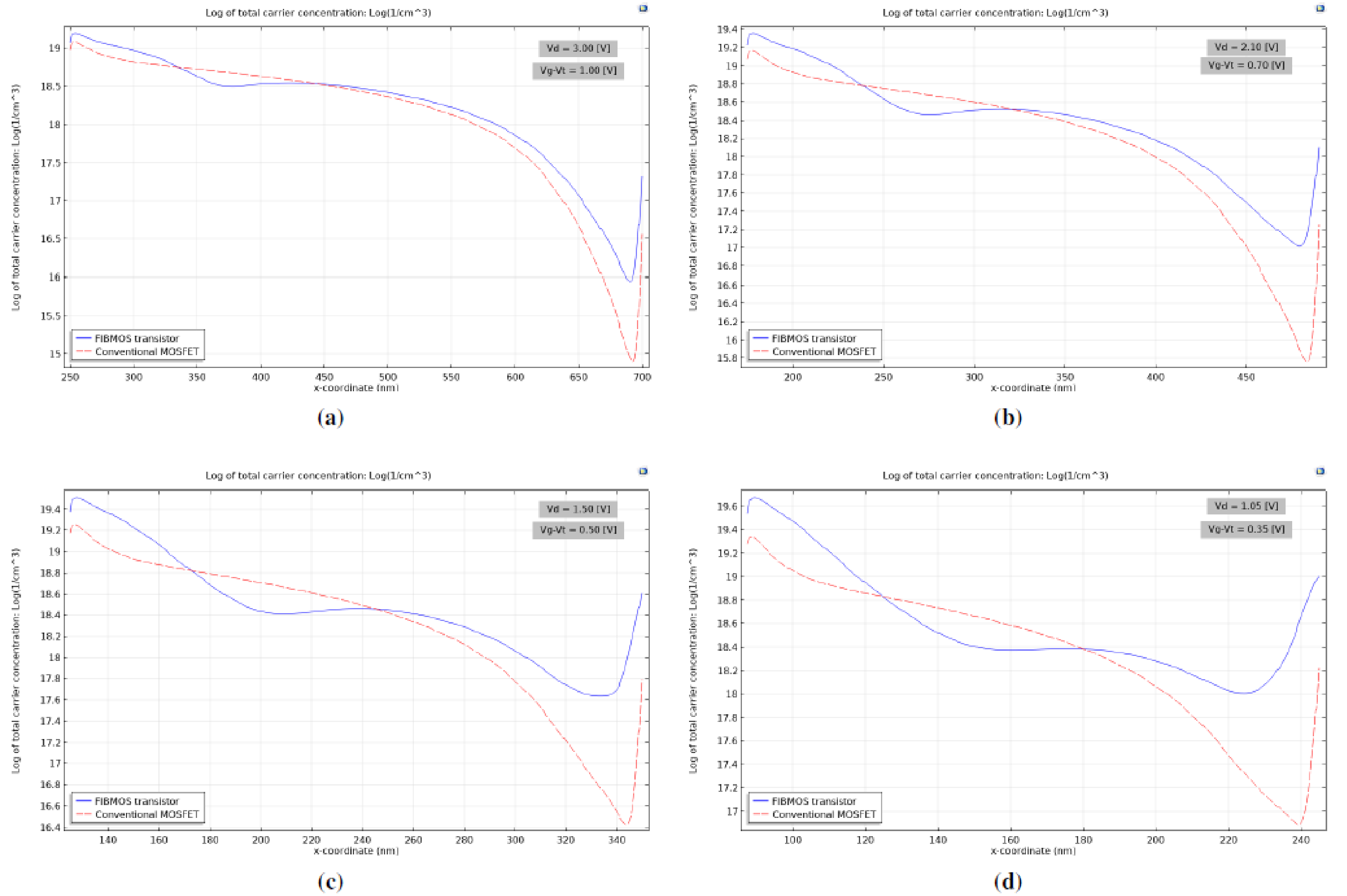
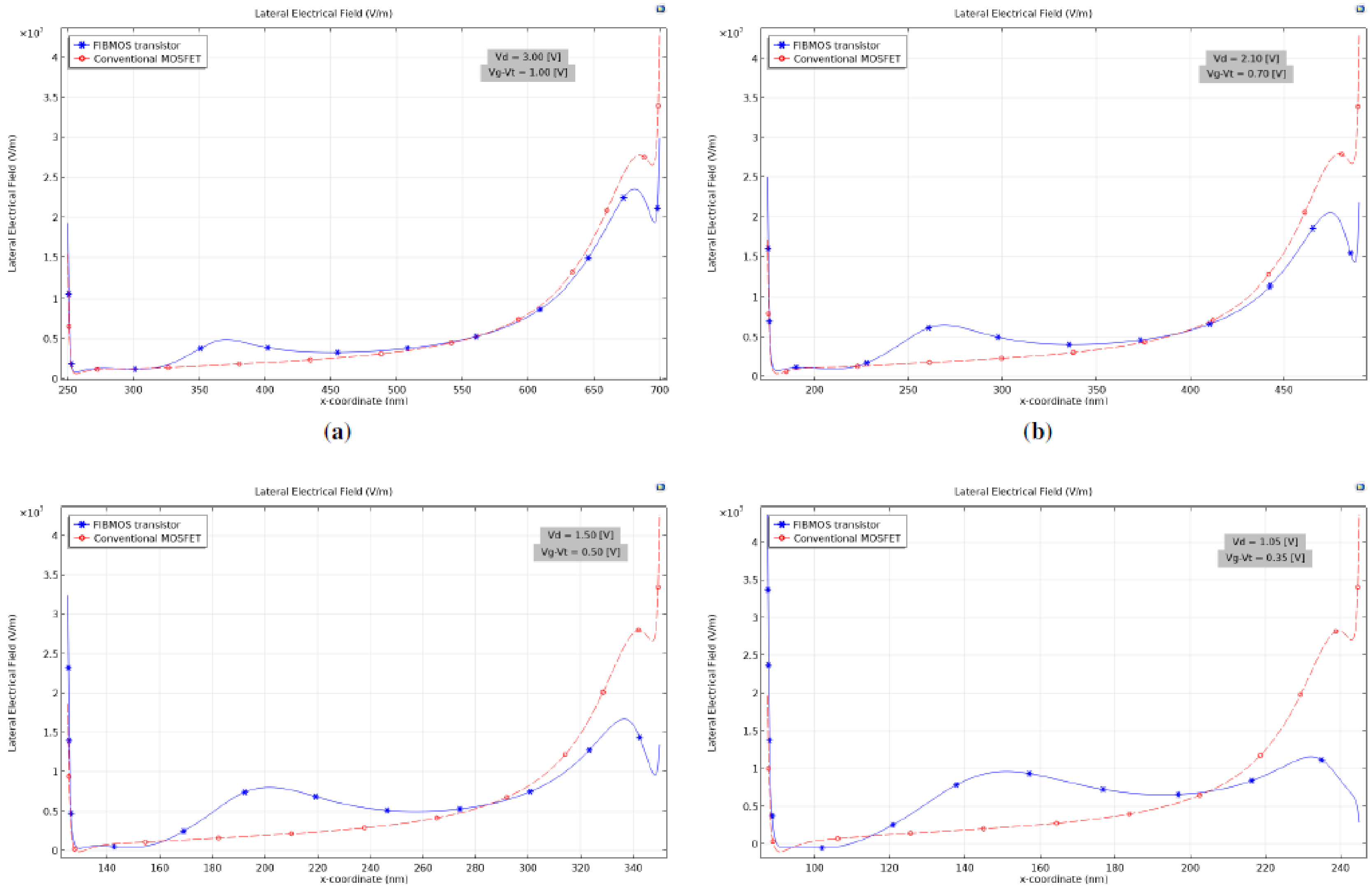


**Figure 8.** Electron concentration at surface near gate of FIBMOS device and conventional MOSFET for channel length of (a) 350-nm, (b) 245-nm, (c) 175-nm, and (d) 122.5-nm



(a) (b)

(c) (d)

**Figure 9.** Lateral Electrical Field at surface near gate of FIBMOS device and conventional MOSFET for channel length of (a) 350-nm, (b) 245-nm, (c) 175-nm, and (d) 122.5-nm

$$f(E) = \frac{1}{1 + exp(\frac{E - E_F}{kT})}$$

$$G(\alpha) = \frac{\alpha}{F_{-\frac{1}{2}}(F_{\frac{1}{2}}^{-1}(\alpha))}$$

$$F_j(x) = \frac{1}{\Gamma(j+1)} \int_0^\infty \frac{t^j}{e^{t-x} + 1} \, dt, \qquad (j > -1)$$