Modeling the Inversion Electron Tunneling Currents through Ultrathin Oxides/Gate Stacks

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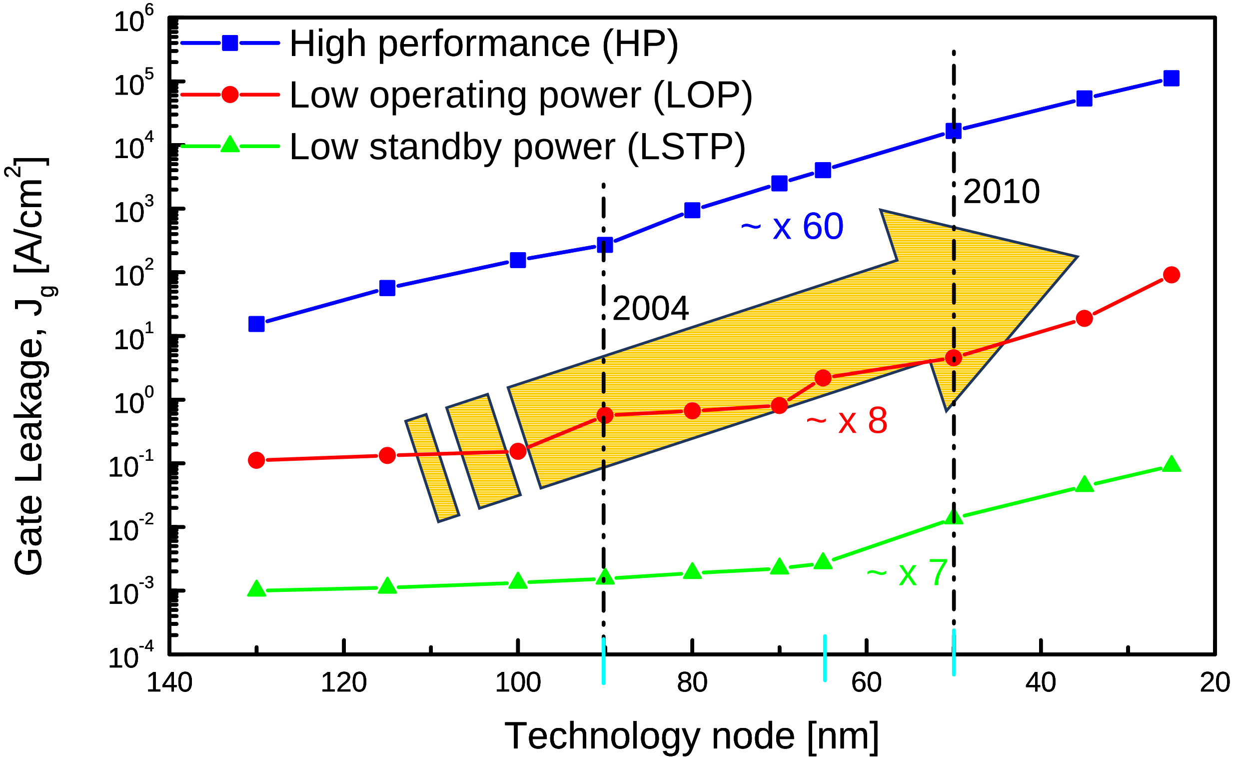
Outline

- Introduction
- Modeling Approach
- Results & Discussion
- Conclusion

Introduction

Gate Leakage Requirements

- Increase at each generation
- HP requirements could be met with SiO_2/SiON
- LOP/LSTP: introduction of high-k dielectrics is necessary
- High-k deposition → interfacial layer → gate dielectric stacks



Need for effective dual layer/multilayer tunneling current models

Outline

- Introduction
- Modeling Approach
    - 2D charge density & subbands energy levels
    - Effective field and potential balance equations
    - Inversion layer as a quasibound states (QBS) system
- Results & Discussion
- Conclusion

Charge Density & Subbands Energy Levels

Modeling Approach

- 2D subbands charge density

$$N_{ij} = n_{v,i} m_{d,i} \frac{k_B T}{\pi \hbar^2} \cdot \ln\left(1 + \exp\left(\frac{E_F - E_{ij}}{k_B T}\right)\right) \qquad (1)$$

- Subbands energy levels and centroids

  (triangular approximation)

$$E_{ij} = \left(\frac{\hbar^2}{2m_{i,\perp}}\right)^{1/3} (A_j q F_{eff})^{2/3} \qquad z_{ij} = \frac{2E_{ij}}{3F_{eff}} \qquad (2)$$

- Aggregates: inversion charge density and centroid

$$N_{inv} = \sum_{i,j} N_{ij} \qquad z_{av} = \sum_{i,j} \frac{z_{ij} N_{ij}}{N_{inv}} \qquad (3)$$

Charge Density & Subbands Energy Levels

Modeling Approach

- 2D subbands charge density

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[Stern, Phys.Rev B 5(12), 1972; Mueller & Schulz, T-ED 44(9), 1997]

Effective Field and Potential Balance

Modeling Approach

- Effective field

$$F_{eff} = F_{depl} + \eta F_{inv} \quad (4)$$

$$\eta = \eta_0 \frac{1 + \tanh\left(\dfrac{\psi_S - 2\Phi_B}{2(k_B T / q)}\right)}{2}$$

- Potential balance

$$\psi_S = \psi_D + q\frac{N_{inv} z_{av}}{k_{Si}\varepsilon_0} + \frac{k_B T}{q} \quad (5)$$

$$V_G = \psi_S + V_{ox} + \psi_P + \phi_{MS} \quad (6)$$

Tunneling Current as a Decaying QBS

Modeling Approach

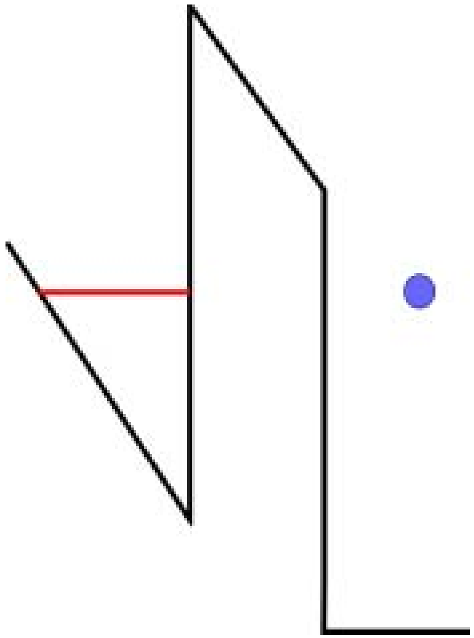
- Quasibound state lifetime

  (semiclassical formulation)

$$\frac{1}{\tau(E)} = f(E) \cdot T(E)$$

f(E) – impact frequency

T(E) – tunneling probability



[*Tiwari et al, APL 69(8), 1996*]

- Inversion layer tunneling current

$$J_{2D,inv} = q \sum_{i,j} \frac{N_{ij}}{\tau(E_{ij})}$$

Carriers statistics

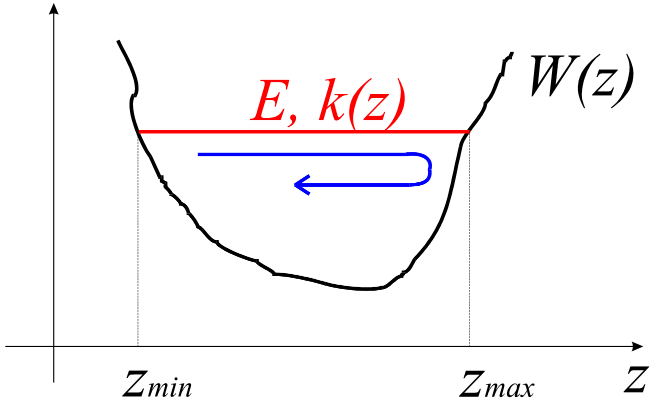
Tunneling

Impact Frequency & Tunnel Probability

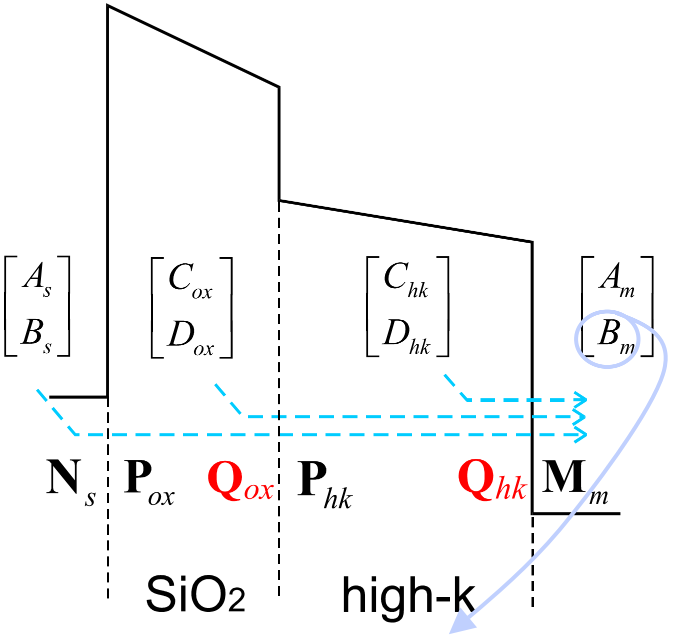
Modeling Approach

- Impact Frequency

$$f = \frac{1}{2\int_{z_{\min}}^{z_{\max}} \frac{m_{i,\perp}\,\mathrm{d}z}{\hbar k_{\perp}(z)}}$$



- Tunneling Probability
  - Transfer matrix method based on Airy functions
  - Single pair of Airy functions per physical dielectric layer (generalization of Gundlach approach)
  - Exact expression of the tunneling probability (under the barrier, ideal dielectrics)



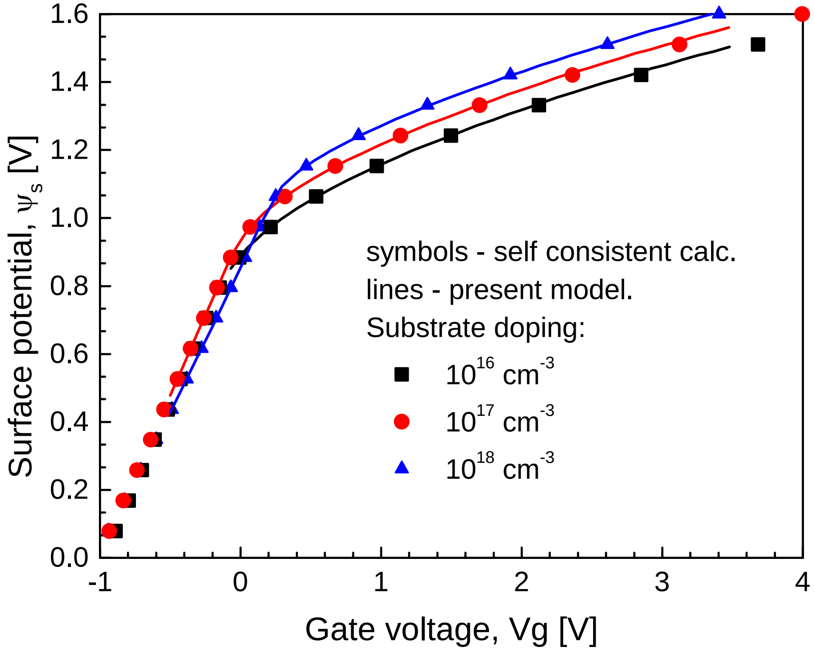
Set to 0, no reflection from ∞

Outline

- Introduction
- Modeling Approach
- Results & Discussion
    - Comparison with self-consistent (SC) results
    - Experimental validation
    - QBS lifetimes
    - Influence of high-k material parameters
- Conclusion

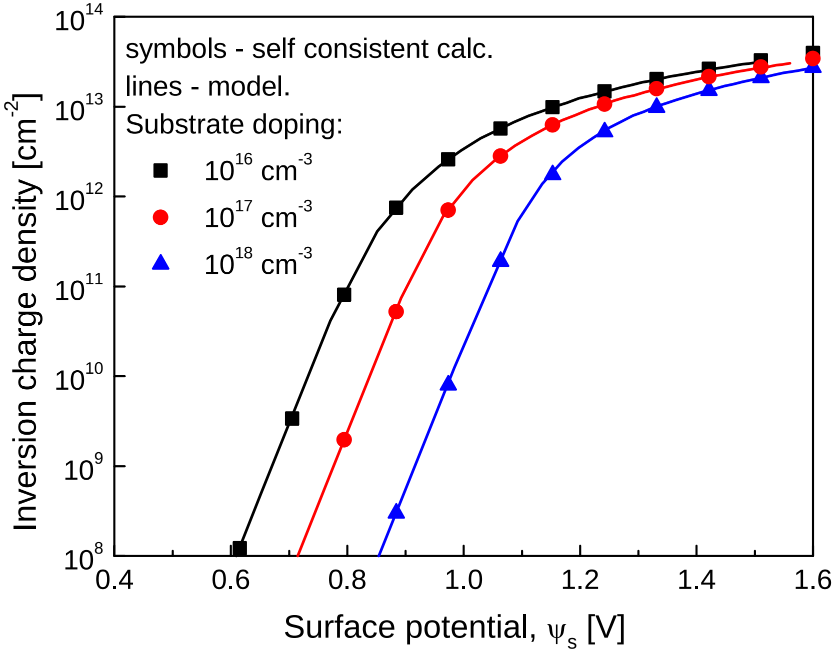
Comparison with SC Results

Results & Discussion



Surface Potential

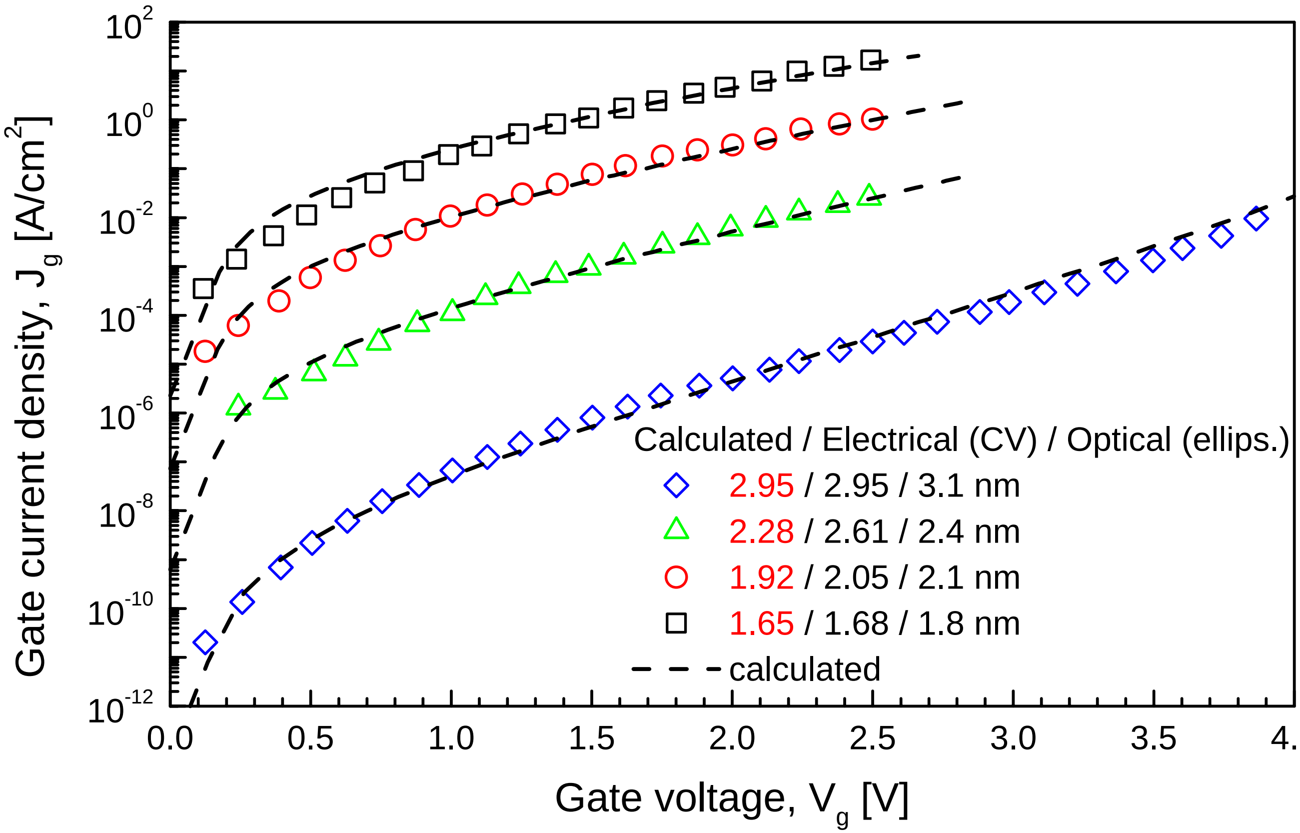
Inversion Charge



[SC: http://www-device.eecs.berkeley.edu/]

Experimental Validation

Results & Discussion



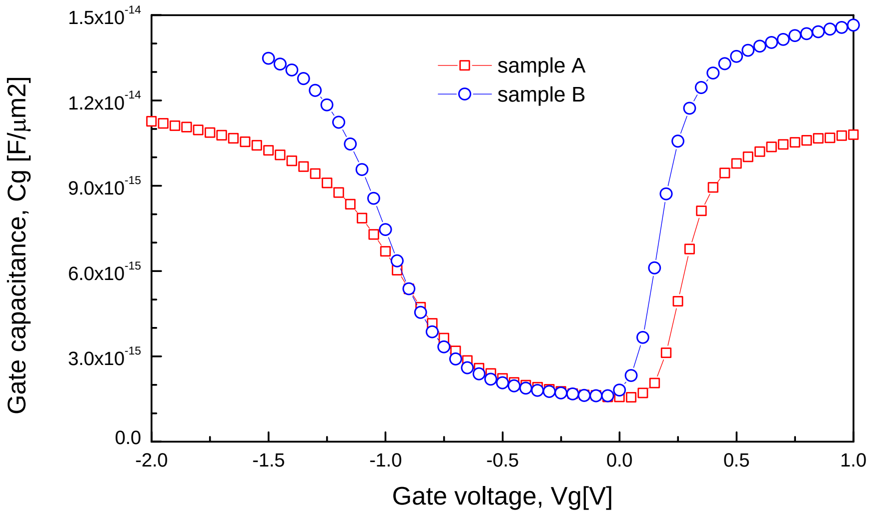
[*Data: Clerc et al: SSE 46(3), 2002*]

SiO$_2$ parameters: $m_{ox} = 0.5\ m_0$, $\Phi_{B,ox}$=3.15 eV.

Experimental Validation

Results & Discussion

RPN Oxynitrides



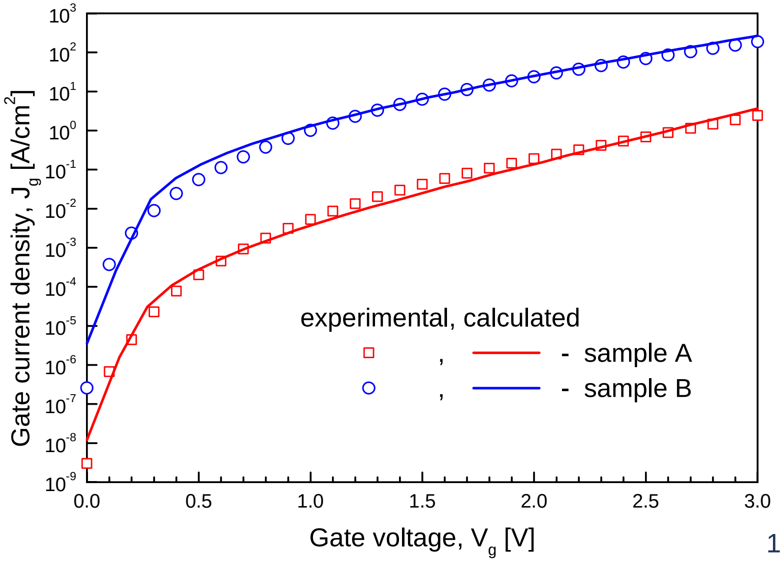
extracted EOT:

2.53 nm (A)

1.81 nm (B)

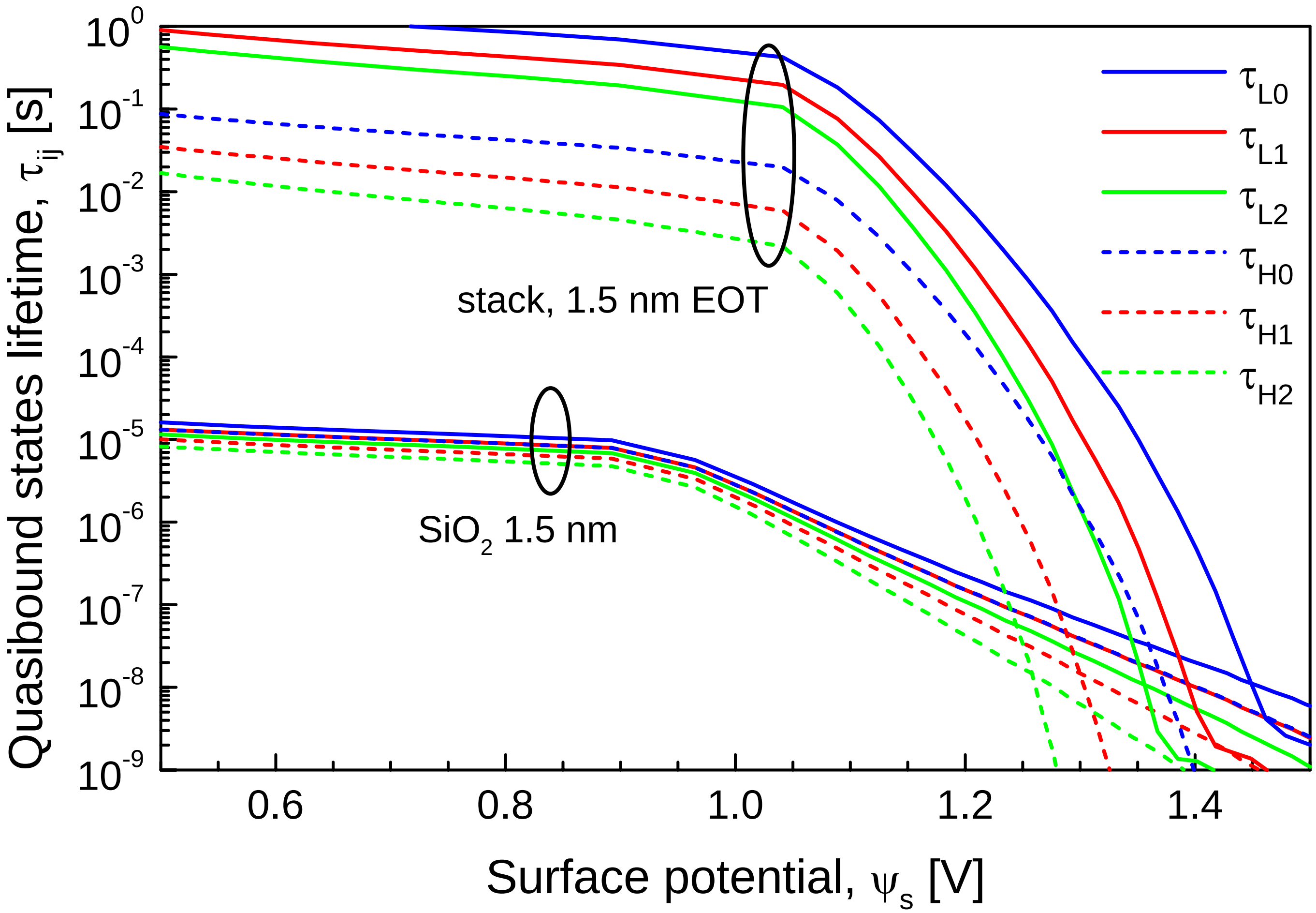
Effective k ~ 4.3

$\Phi_B \sim 3.0$ eV



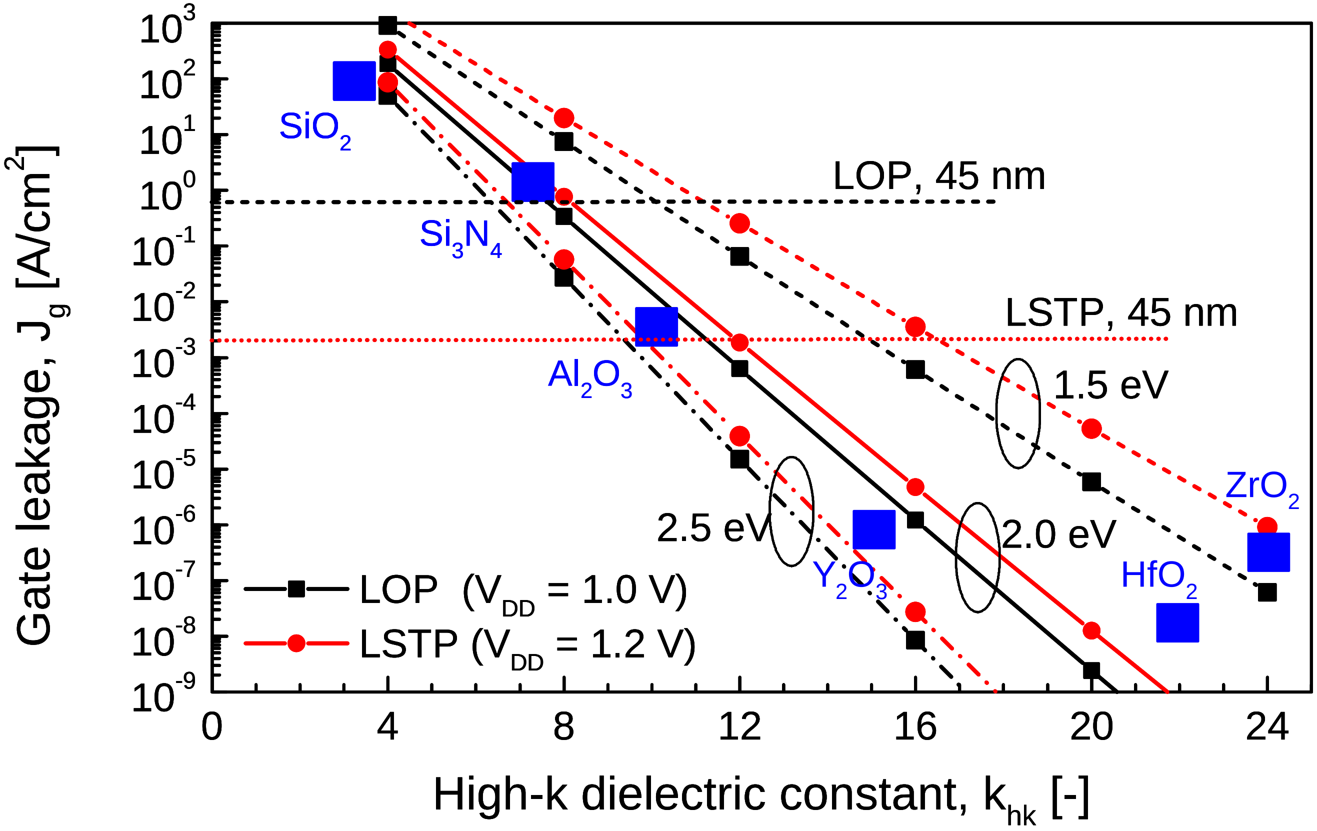
Quasibound States Lifetimes

Results & Discussion



Influence of the High-k Dielectric Constant

Results & Discussion



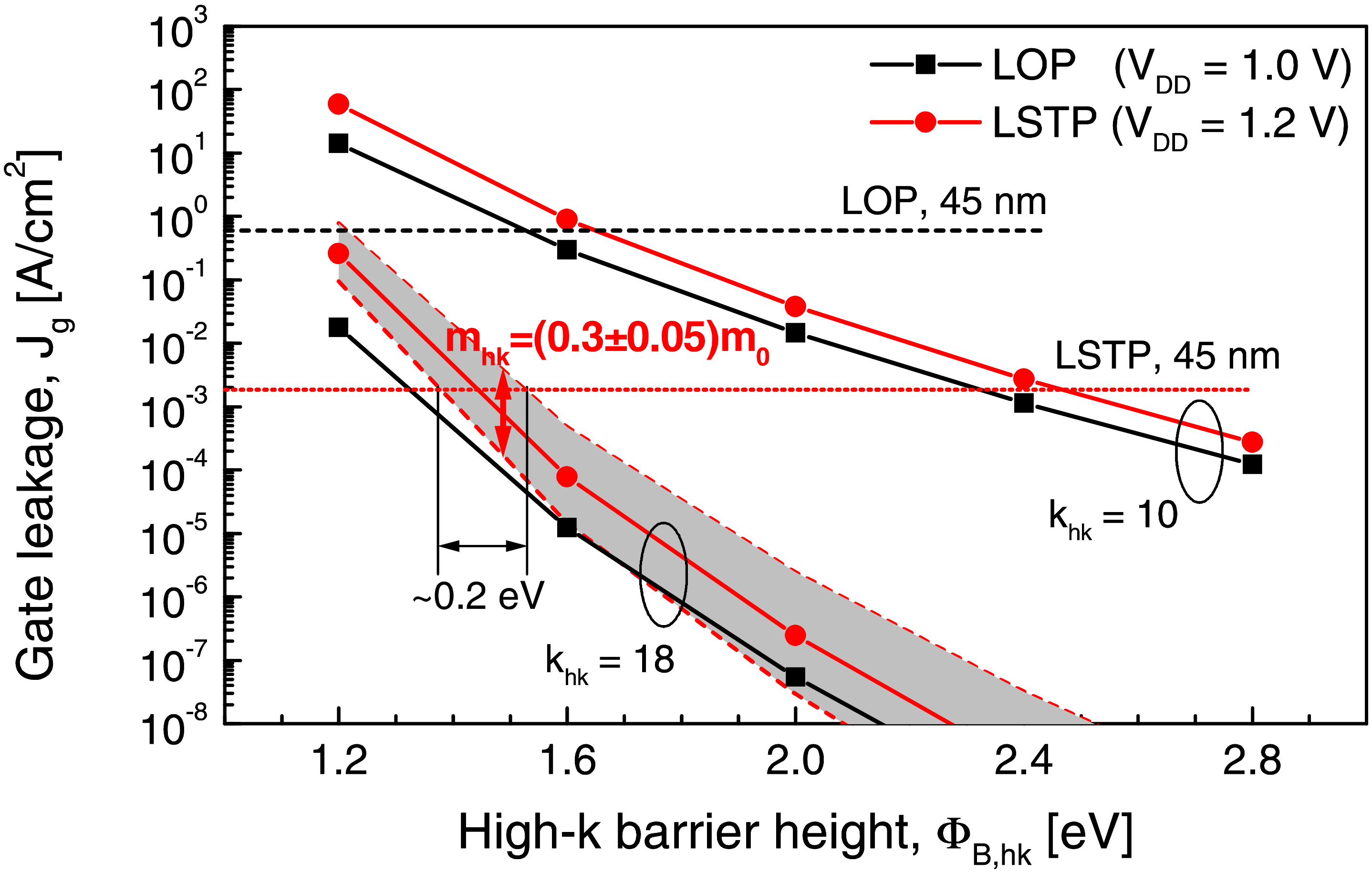
Large current variations of up to 10 orders of magnitude

“k” is key for selecting a suitable material, but…

Govoreanu et al – ULIS 2003

Influence of the High-k Barrier Height

Results & Discussion



High-k barrier height should also be considered for material selection.

Uncertainty in the high-k effective mass affects the scaling projections.

Conclusion

- A simple and effective inversion layer tunneling current model for multilayer stacks has been developed
- Contributions from higher energy subbands should be included in the calculation of the tunneling gate leakage current through high-k stacks
- The high-k barrier height should be also considered for selecting a suitable high-k material
- The gate leakage projections are affected by the uncertainty in the effective mass

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