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TCAD investigation on hot-electron injection in new-generation technologies

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Outline

- Introduction and motivations
- Test structures
- Experimental characterization
- Modeling approach
- Conclusions

Introduction and motivations

BCD gate oxide reliability: Hot-carrier injection in the gate oxide of high-voltage MOSFETs is a complicated issue

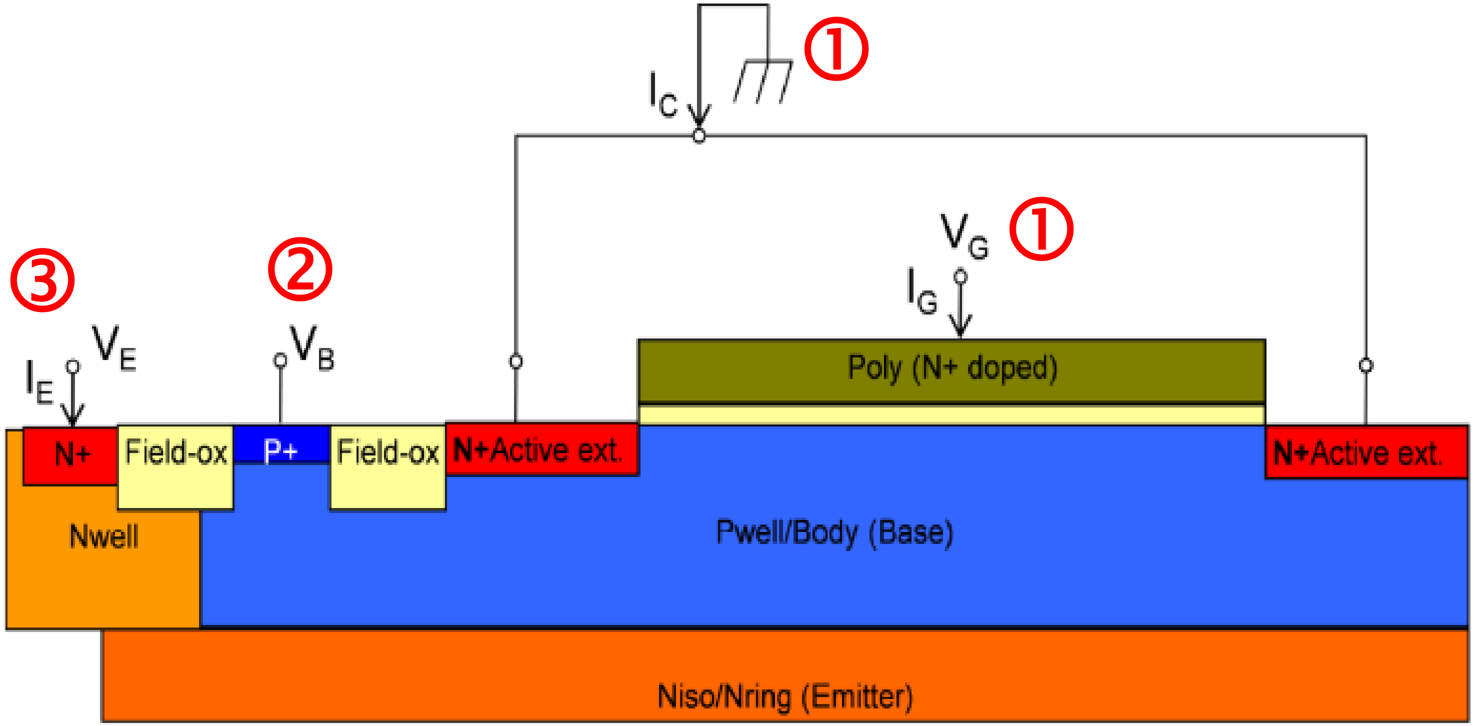
→ **TCAD prediction as a tool for technology support**

Open issues: new-generation technologies feature the nitrogen-monoxide annealing at the Si/SiO_2 and larger electric fields in the channel

→**Analysis of the model accuracy:**

1. Boltzmann Transport Equation solution in the frame of the Spherical Harmonics Expansion method (SHE-BTE)
2. Gate-current model parameters

Test structures



Structure setup

✓ Conventional nMOS with additional emitter region to control the hot-electron injection into the body

Experiments

① V_{DS}=0; V_{GS}=1.4 ÷7 V

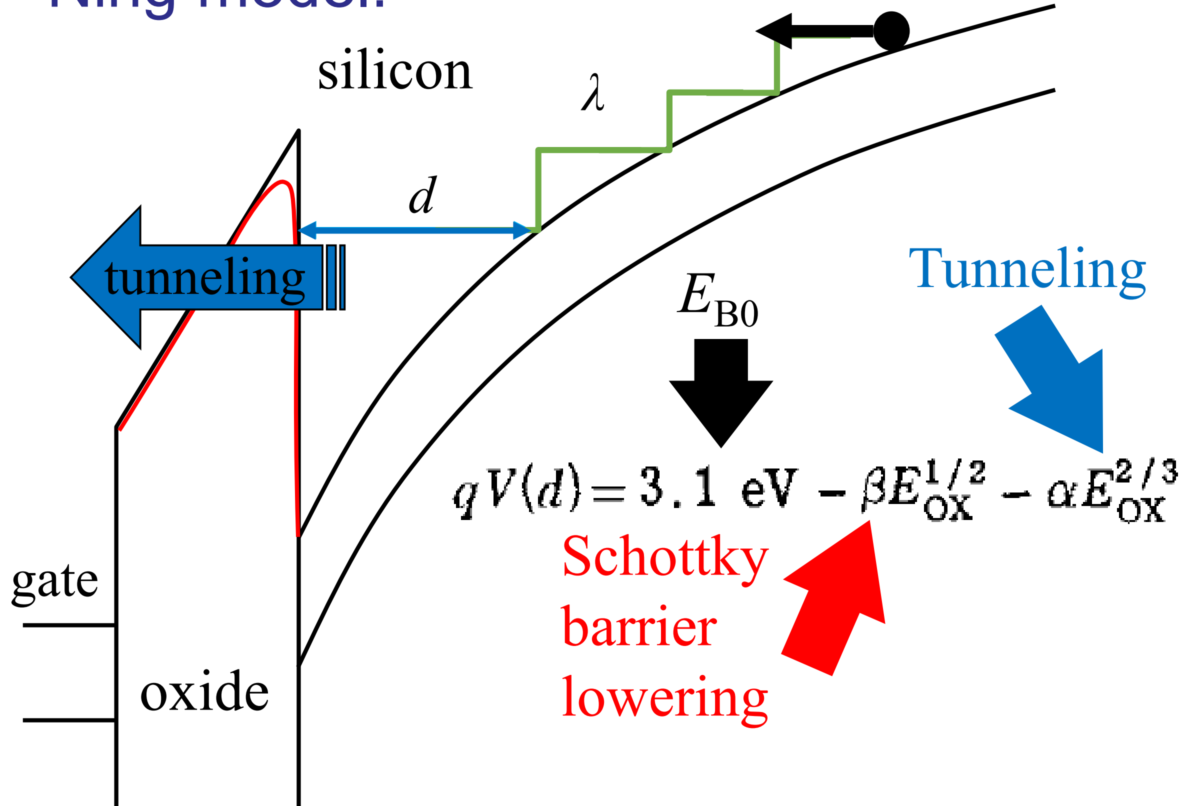
② V_B=0 ÷-5 V

③ I_E= -100 μA

✓ I_C, I_B and I_G are monitored → $P_{inj} = I_G / I_C$

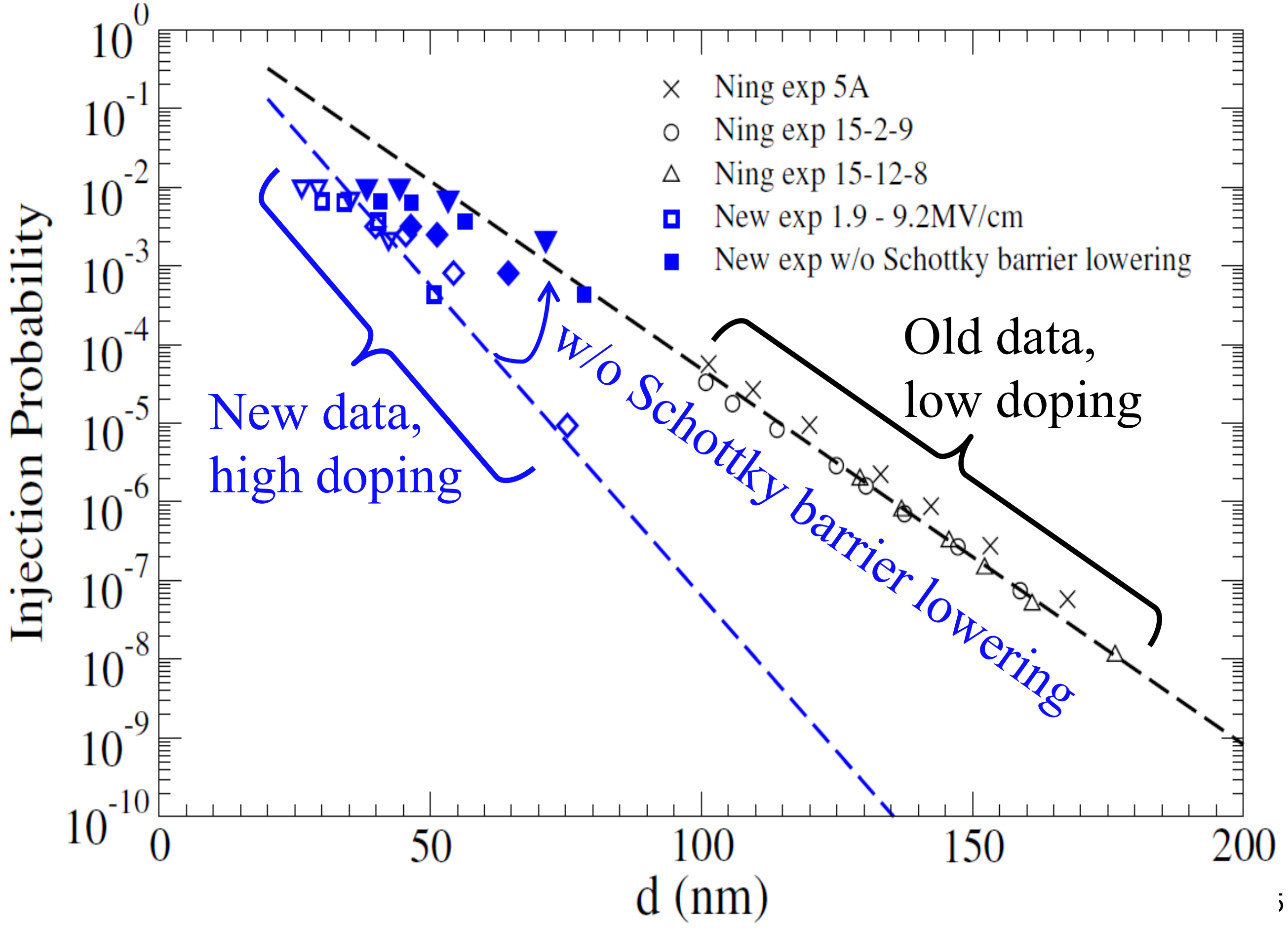
Injection probability: new vs. old experiments

Ning model:



$$qV(d) = 3.1\ \text{eV} - \beta E_{OX}^{1/2} - \alpha E_{OX}^{2/3}$$

$$P_{inj} = A \exp(-d/\lambda)$$



λ — mean free path for optical-phonon scattering (in bulk silicon)

TCAD study: the SHE-BTE solution

SHE-BTE solution using the silicon full-band structure:

✓ Deterministic solution through the spherical-harmonics expansion of the BTE:

- lowest order expansion nicely compares with high-order results at high fields

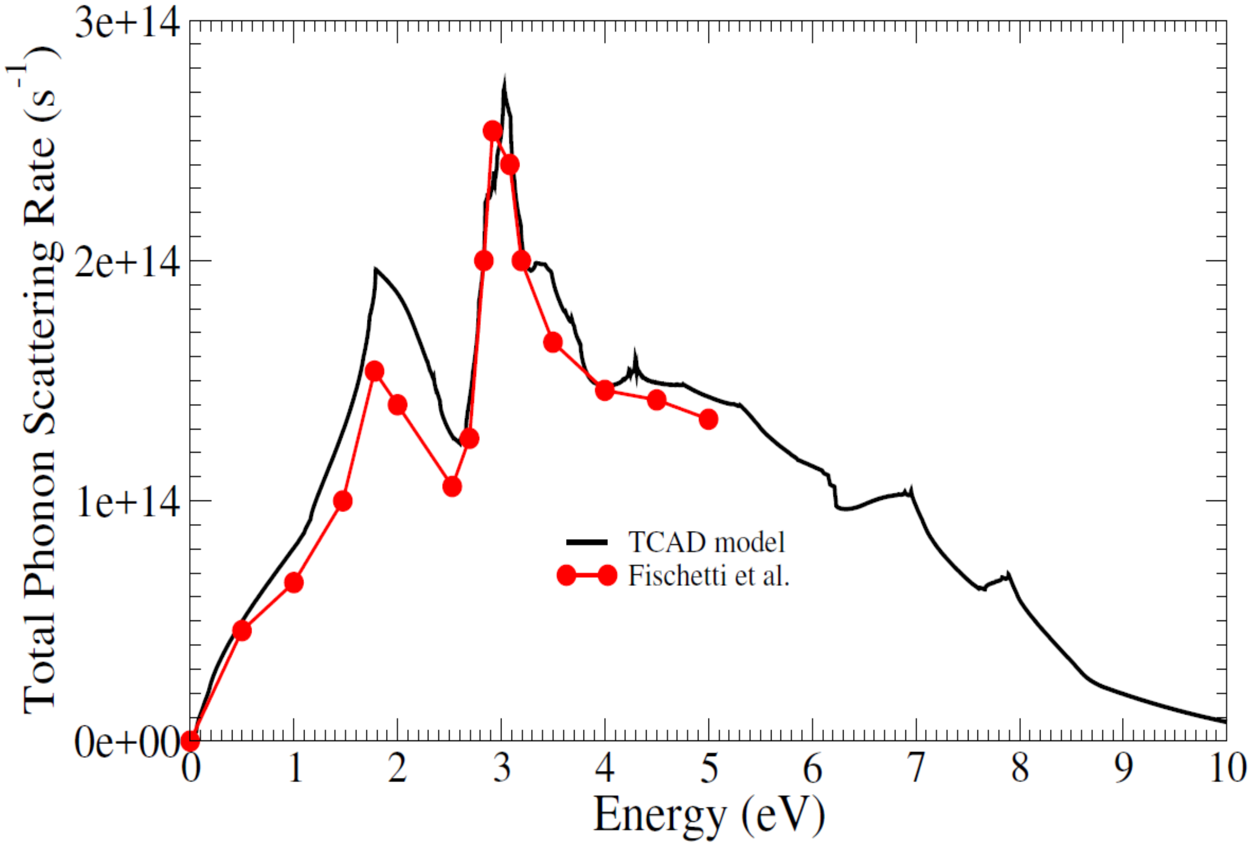
✓ Full-band structure obtained from the nonlocal empirical pseudopotential method:

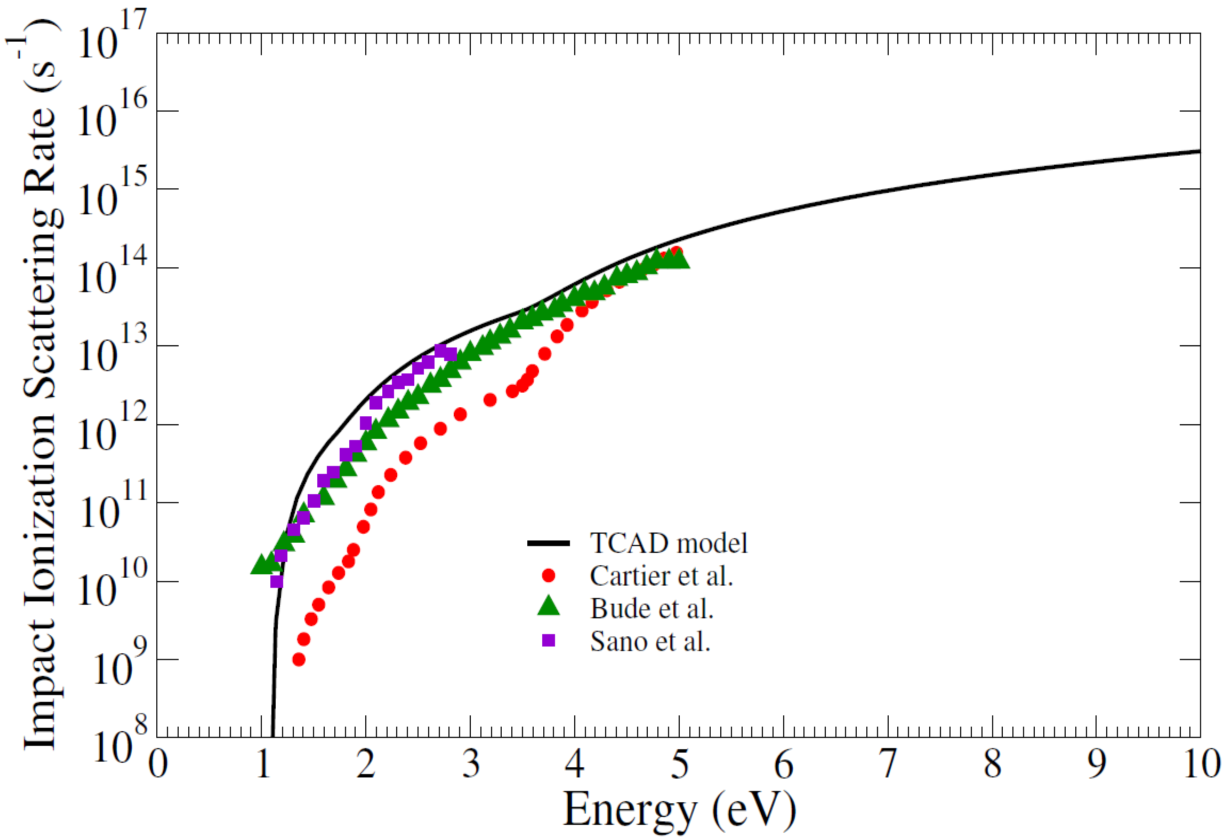
- up to the fourth band starting at ~ 3.23 eV

SHE-BTE microscopic scattering rates (bulk silicon):

- $1/\tau_c$ is the Coulomb scattering rate.
- $1/\tau_{ii}$ is the impact ionization scattering rate.
- $1/\tau_{ac}$ is the acoustic phonon scattering rate.
- $1/\tau_{ope}$ is the scattering rate due to optical phonon emissions.
- $1/\tau_{opa}$ is the scattering rate due to optical phonon absorptions.

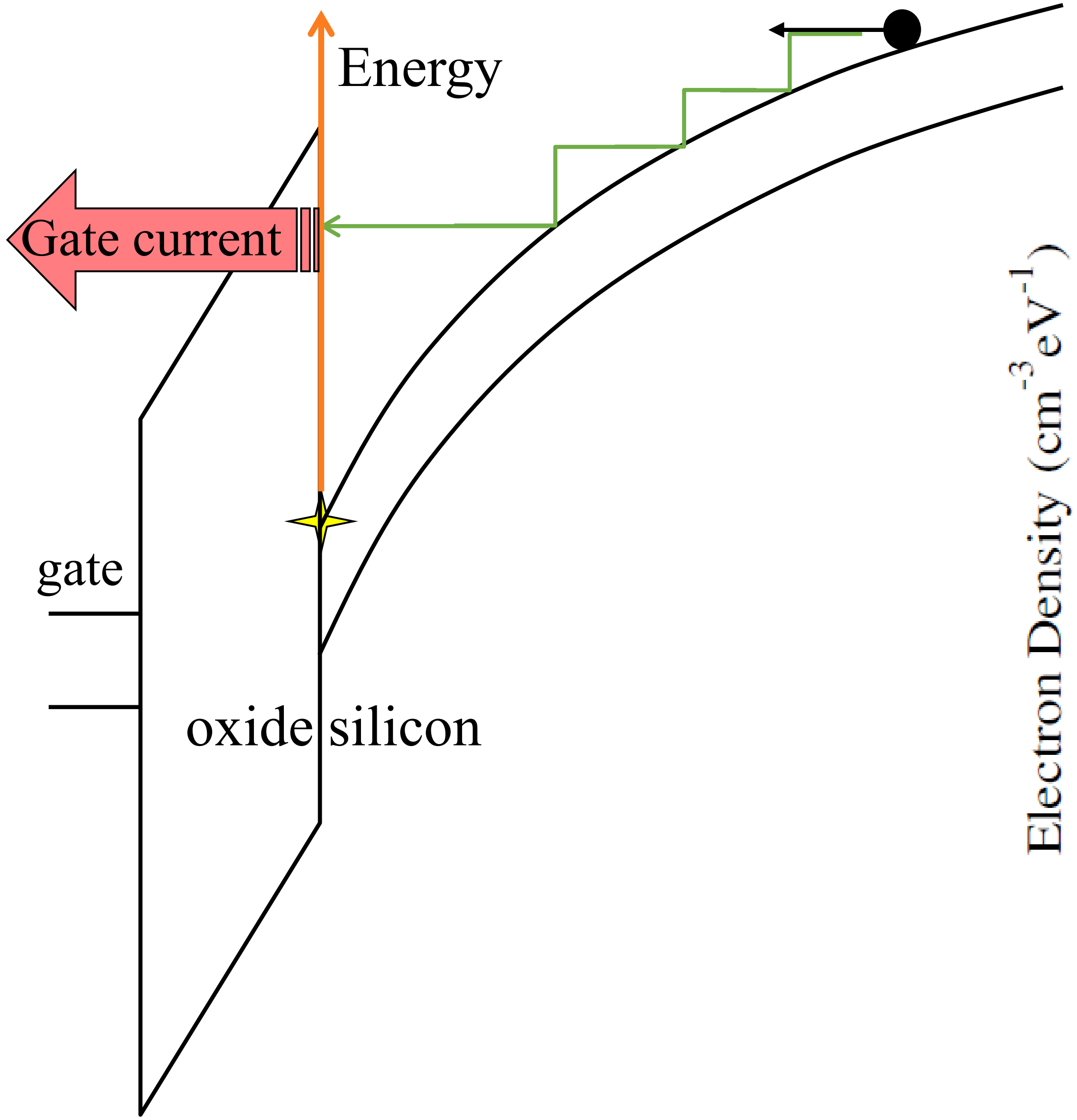
Modeling approach: the microscopic rates

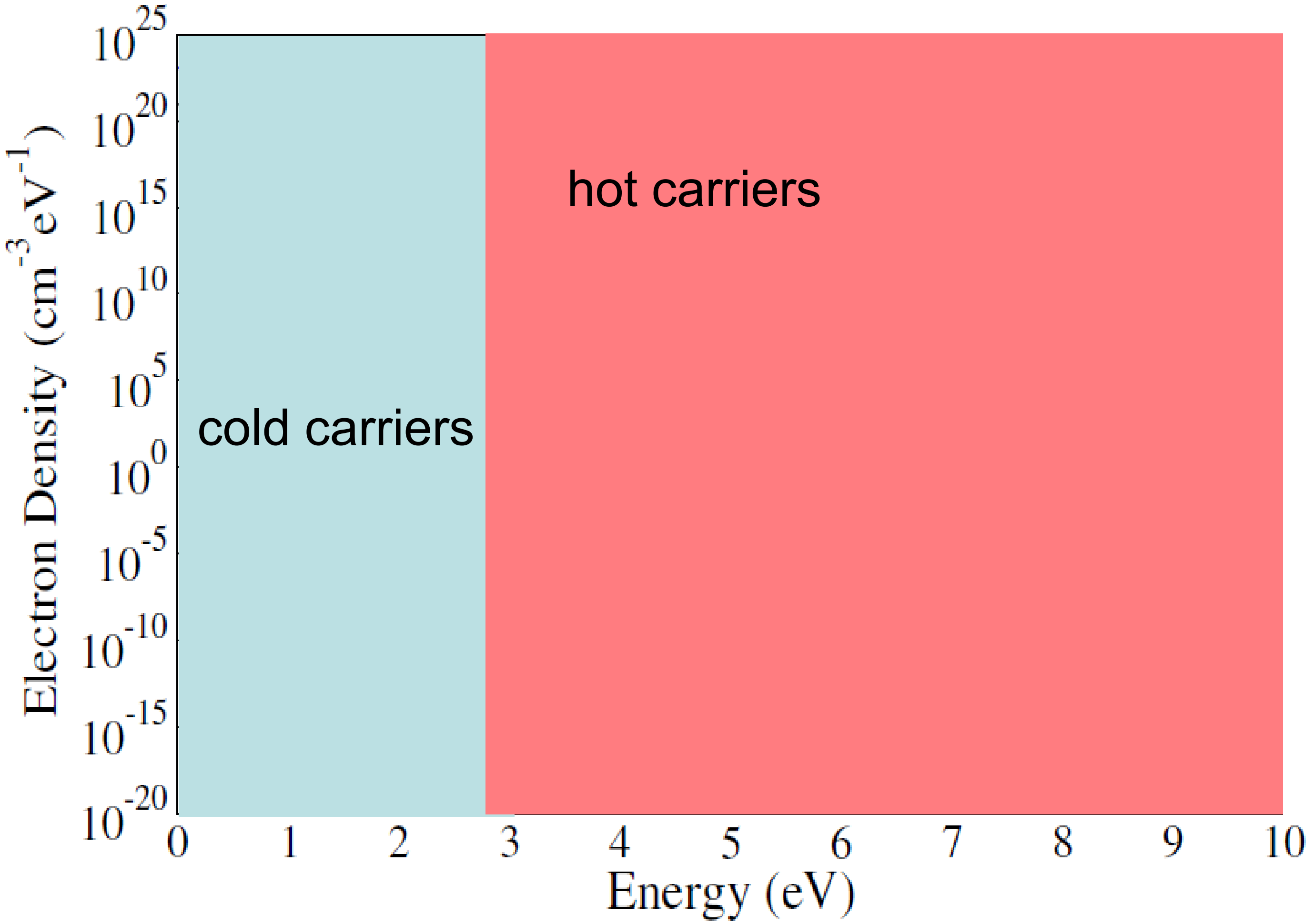




- ✓ The phonon-scattering rate nicely compares with Monte Carlo data up to 5 eV
- ✓ The reported ii-scattering rates have been demonstrated to give ii-coefficient, ii-quantum yield and soft X-ray photoemission spectroscopy→ new fitting

Electron distribution functions





TCAD study: the gate-current model

SHE-Distribution Hot-Carrier Injection (S. Jin et al., 2009)

$$I_g = \frac{2qAg_v}{4}\int P_{ins}\left[\int_0^\infty g(\varepsilon)v(\varepsilon)f(\varepsilon)\left(\int_0^1 \Gamma\left[\varepsilon - \frac{h^3 g(\varepsilon)v(\varepsilon)x}{8\pi m_{ins}}\right]dx\right)d\varepsilon\right]ds$$

1) Microscopic current density calculated at the Si/SiO_2 interface using the SHE-BTE distribution function

m_{ins} → spherical band approximation for SiO_2

E_B with image-potential barrier lowering

2) Tunneling probability: WKB approximation taking into account the parallel momentum conservation

TCAD study: the gate-current model

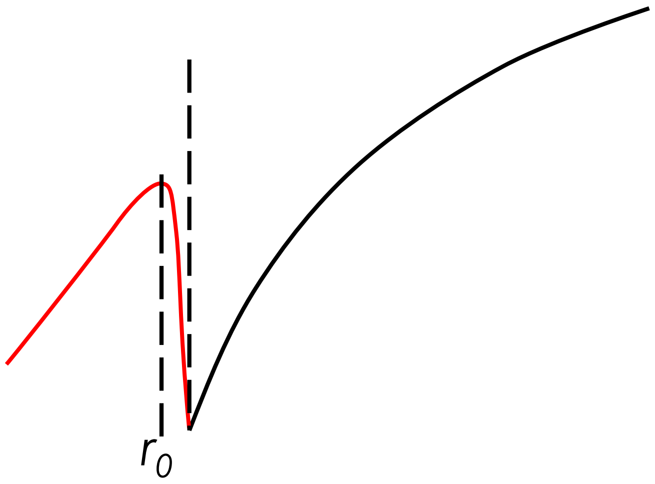
SHE-Distribution Hot-Carrier Injection (S. Jin et al., 2009)

$$I_g = \frac{2qAg_v}{4}\int P_{ins}\left[\int_0^{\infty} g(\varepsilon)v(\varepsilon)f(\varepsilon)\left(\int_0^1 \Gamma\left[\varepsilon - \frac{h^3 g(\varepsilon)v(\varepsilon)x}{8\pi m_{ins}}\right]dx\right)d\varepsilon\right]ds$$

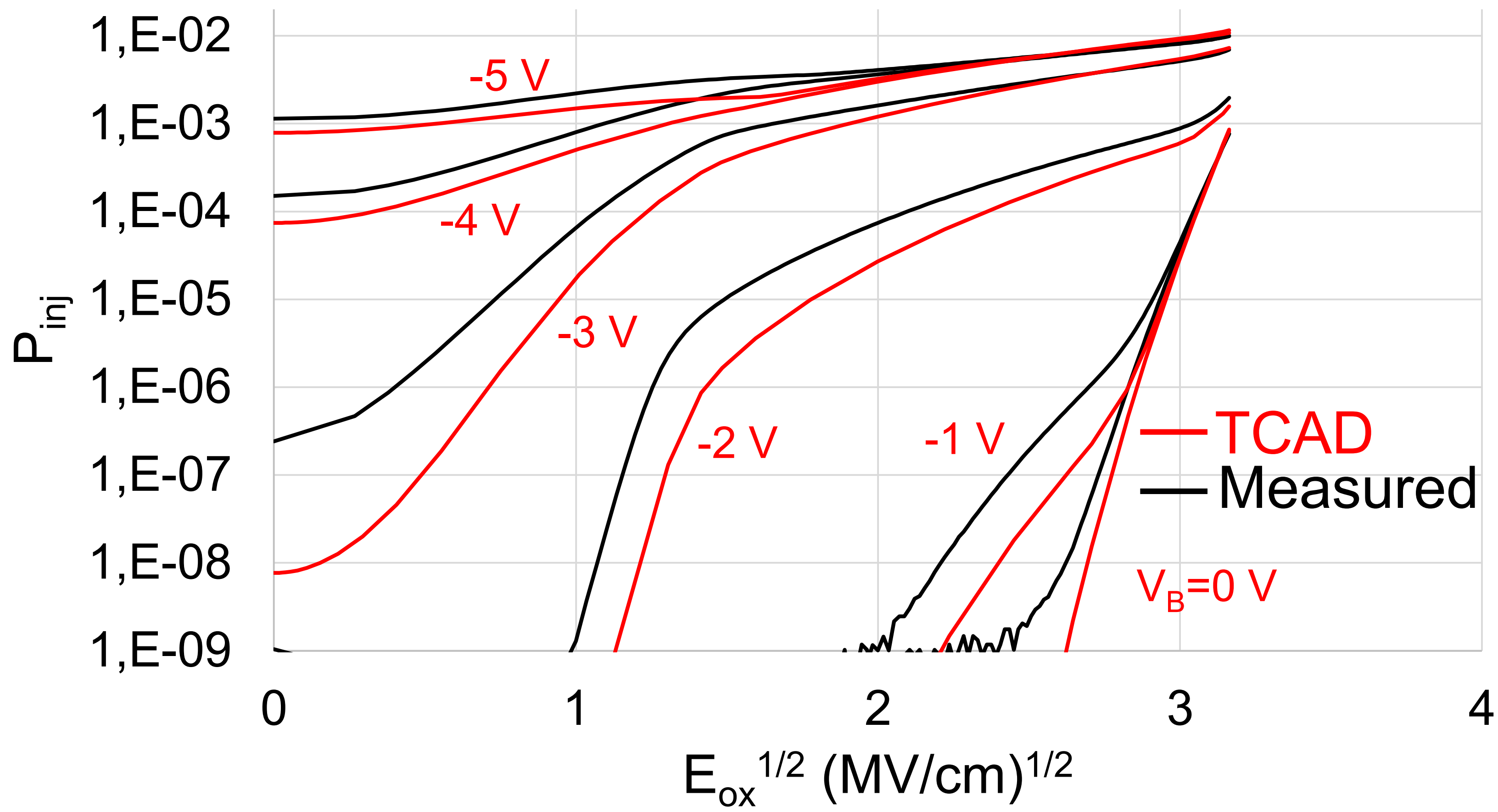
3) Effect of scattering in the SiO_2 barrier:

$P_{ins} = \exp\left(-r_0/\lambda_{ins}\right)$

r_0 is the distance from the interface to the barrier peak,
λ_{ins} is the mean free path in the insulator

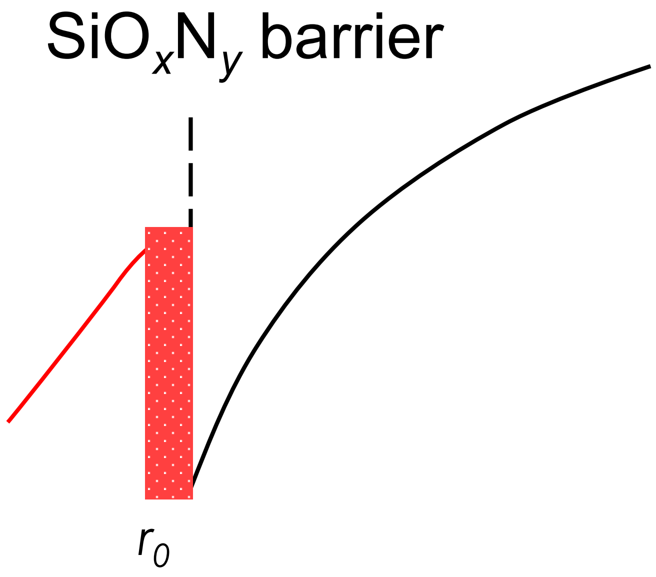


Injection probability: TCAD results



P_{inj} vs. $E_{ox}^{1/2}$

- λ_{ins}=0.3 nm
- No barrier-lowering effect



✓ Very nice agreement for the tunneling component @low |V_B|, high V_G

✓ Very nice agreement for the hot-carrier injection @high |V_B|, high V_G

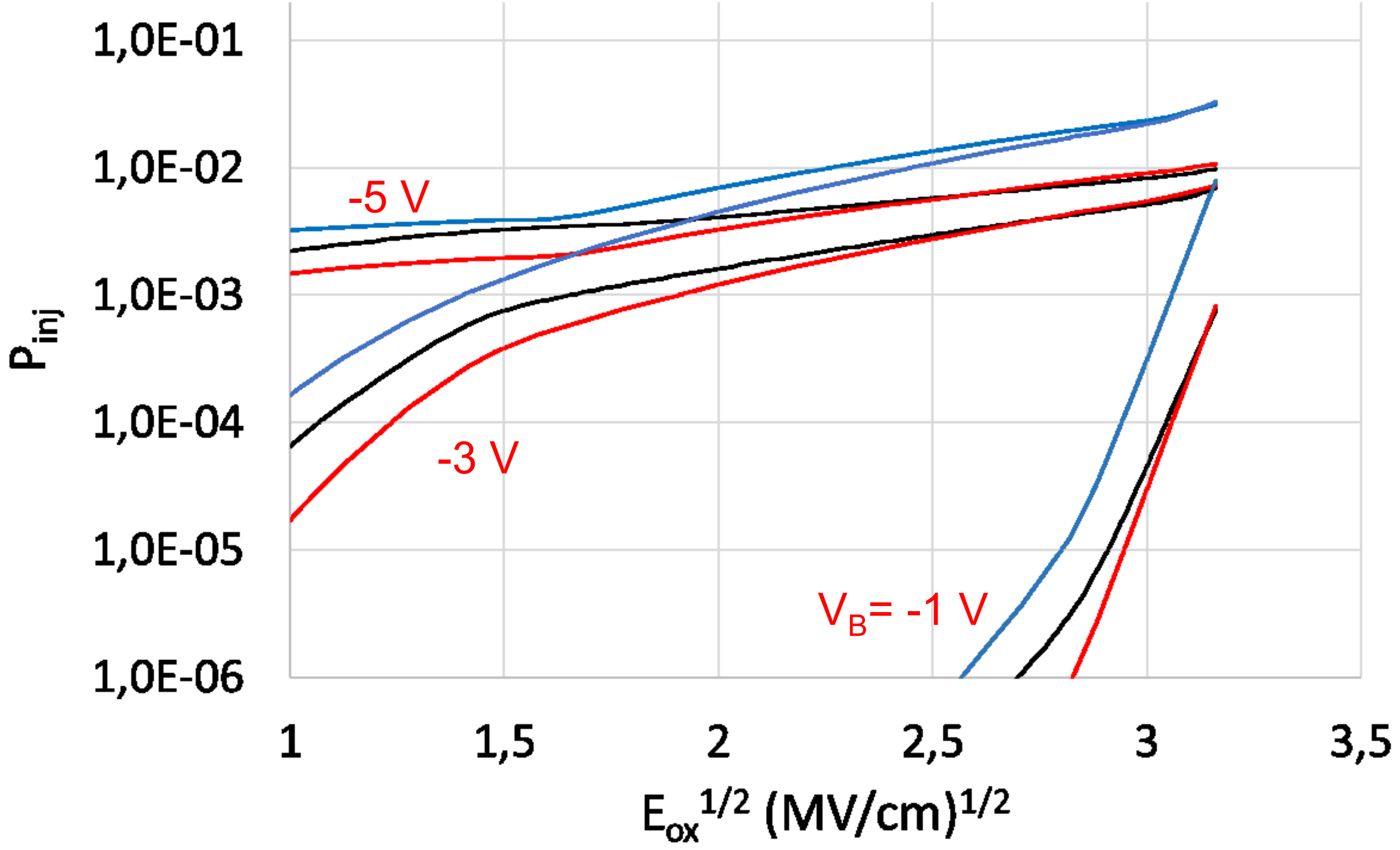
Injection probability: the role of barrier lowering

The observed slope of hot-electron injection is too weak to be explained through a Schottky barrier lowering effect:

— TCAD w/o barrier lowering

— TCAD with barrier lowering

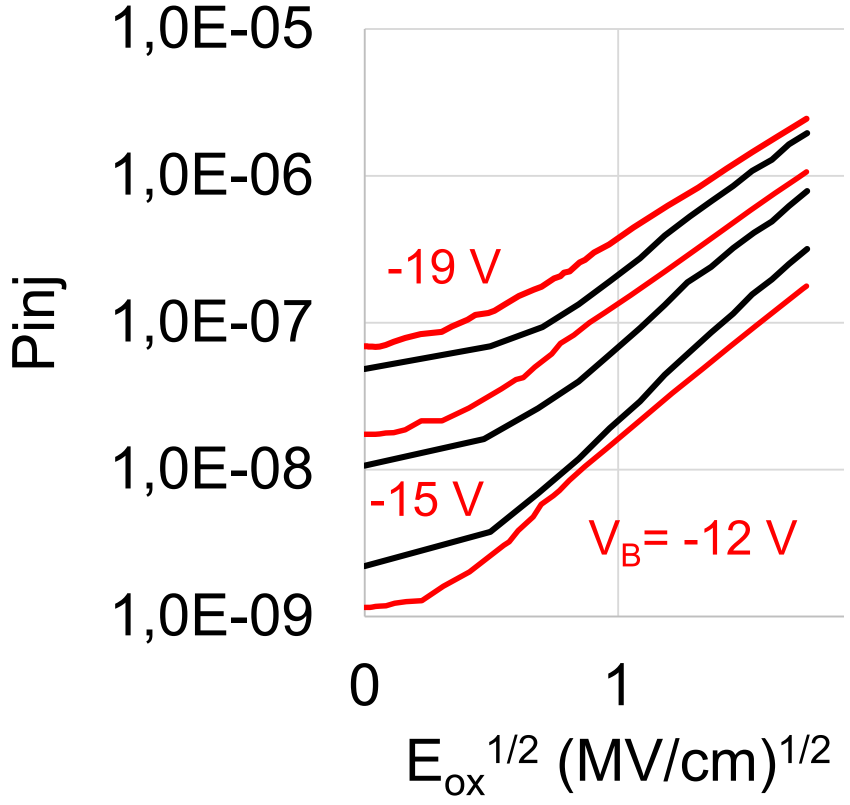
— Experiments

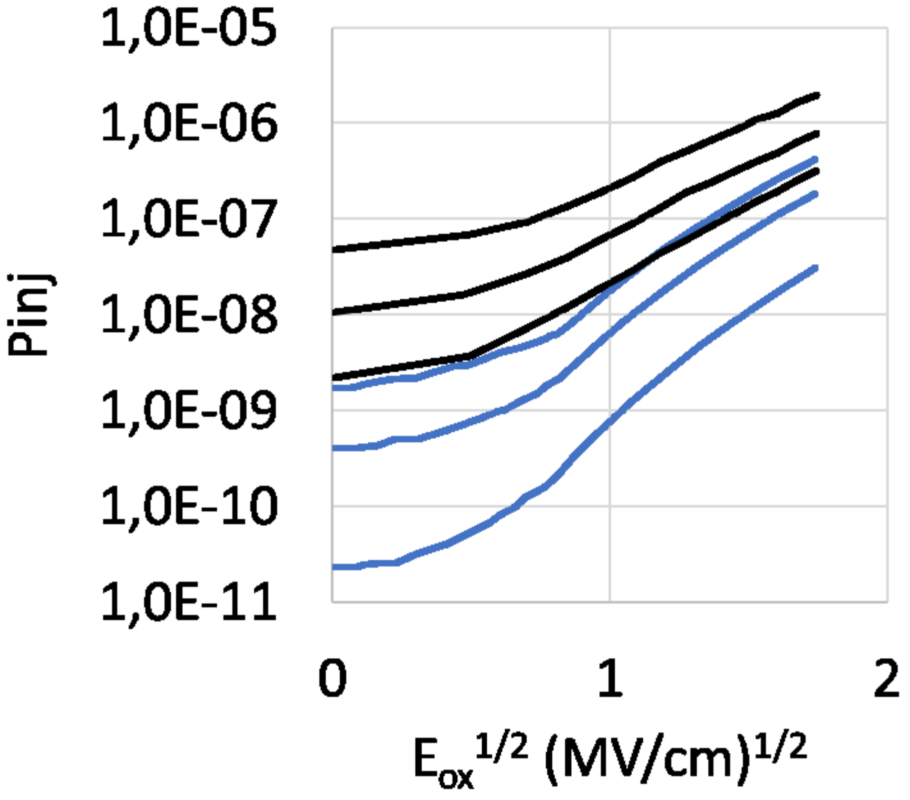


Injection probability: old experiments

✓ **Ning data**:

- No thermal nitridation → **lower scattering rate at the SiO_2 barrier: λ_{ins}=2 nm**



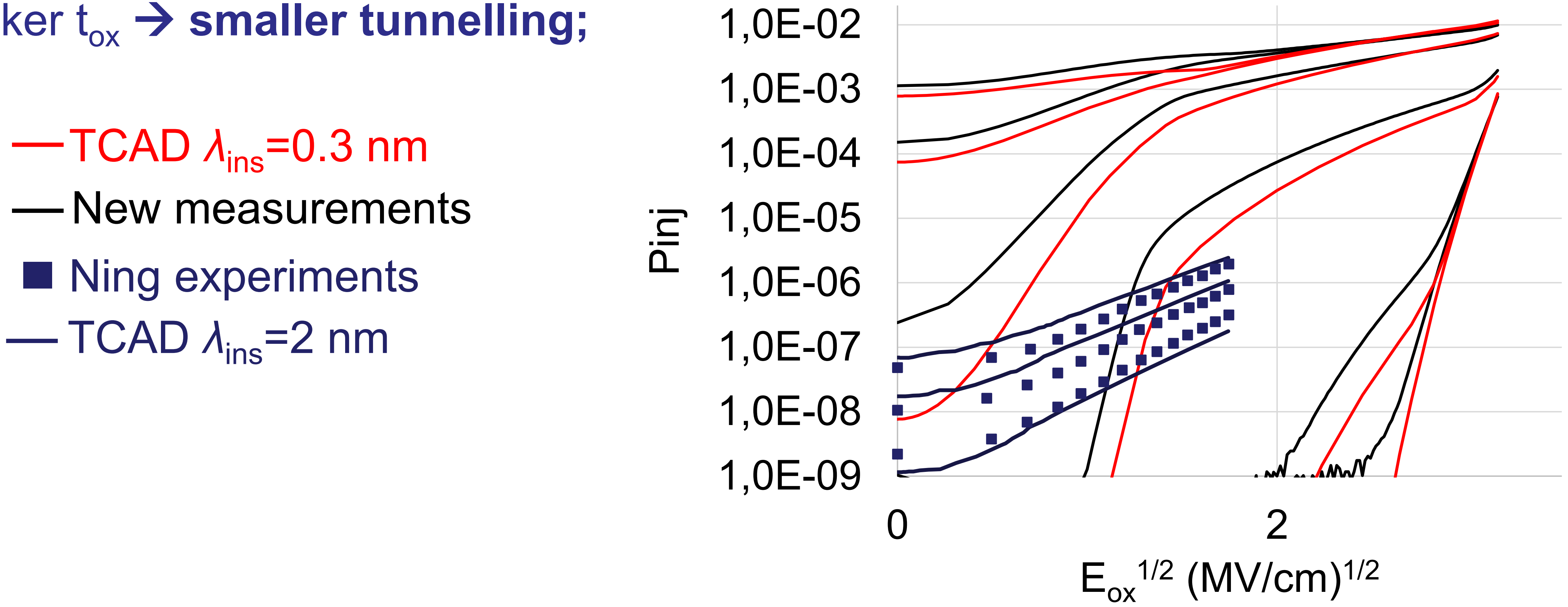


✓ Nice agreement without barrier lowering

Diode breakdown: role of the DLC passivation

✓ **Ning data**:

- No thermal nitridation → **lower scattering rate at the SiO_2 barrier: λ_{ins}=2 nm;**
- lower doping → **smaller electric field;**
- thicker t_{ox} → **smaller tunnelling;**



Conclusions

- The hot-electron injection model presently available in the TCAD tool has been investigated:
  - Predictability in the context of new-generation BCD technologies.
  - Electron emission extended to very high electric fields as expected in power LDMOS devices at the onset of avalanche breakdown.
- The TCAD analysis clearly showed that the new Si/SiO_2 interfaces experience different features with respect to the old ones, but it can accurately capture the relevant features of electron injection.