Defect Generation and Reliability of Ultra-thin SiO_2 at Low Voltage

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The microelectronics industry owes its considerable success largely to the existence of the thermal oxide of silicon. However, recently a concern has been raised that the reliability of ulrathin SiO2 layers may limit the continued scaling of gate oxides less than about 2nm. In this talk we will review the physics of oxide breakdown. Electrons tunneling through the gate oxide generate defects until a critical density is reached and the oxide breaks down. The critical defect density is explained by the formation of a percolation path of defects across the oxide. Only < 1% of the these paths ultimately lead to destructive breakdown, and the microscopic nature of these defects is not known. The rate of defect generation decreases exponentially with supply voltage, below a threshold voltage of about 5V for hot electron induced hydrogen release. However, the tunnel current also increases exponentially with decreasing oxide thickness, leading to a diminishing margin for reliability as device dimensions are scaled.

D. J. DiMaria

D. J. DiMaria graduated from Lehigh University with a B.S., M.S., and Ph.D. in Physics in 1968, 1970, and 1973, respectively. For the following 28 years he has been employed at IBM's Research Division working in the areas of insulator physics and material science for semicondutor based devices . He originally formed and managed the Insulator Physics Group at the T. J. Watson Resarch Center for 15 years. His current interests involve reliability limits of scaling for gate insulators.

J.H. Stathis

J.H. Stathis received a bachelor's degree in Physics (Summa Cum Laude) from Washington University in St. Louis in 1980, and a Ph.D. in Physics from the Massachusetts Institute of Technology in 1986, joining the IBM Research Division the same year. The focus of his work at IBM has been the electrical properties of point defects in SiO2, including basic studies of defect structure using magnetic resonance and electrical measurement techniques, and the role of defects in wearout and breakdown. He is the author of more than 70 research papers.

Defect Generation and Reliability of Ultra-thin Silicon Dioxide at Low Voltage

D. J. DiMaria and J. H. Stathis
IBM Research

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Outline

- History-relationship to point defect generation.
- IEDM '98 predictions for n-FETs.
- Revised predictions-long term stress expts.
- What produces defects?
  - Hot electron energy delivered to anode
    - Hydrogen release
    - Holes (anode injection)
  - Oxide electric field
- What about p-FETs?

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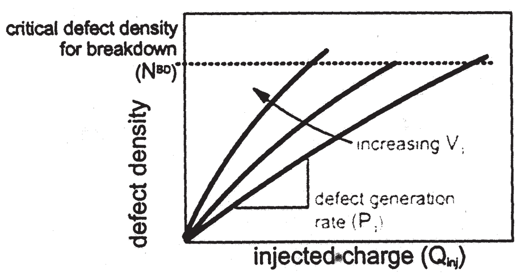
Defect Generation to breakdown

gate voltage ➡ energetic electrons ➡ oxide damage ➡ dielectric breakdown

gate voltage	energetic electrons	oxide damage	dielectric breakdown
▸ direct tunneling (<3V) ▸ fowler-nordheim (>3V)	▸ 5V trap creation threshold ▸ ~8V anode hole injection ▸ ~12V impact ionization	▸ electron traps ▸ interface states ○ fast and slow ▸ generation/ recombination centers	▸ sudden increase in leakage ○ hard or soft



critical defect density
- strong t_{ox} dependence

defect generation rate
- strong V_g dependence

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Charge to breakdown

- fundamental relationship for Q_{BD}:
  - critical defect density at breakdown (N^{BD})
  - defect generation rate (P_g)

$$\boxed{Q_{BD} = N^{BD} / P_g}$$

DiMaria, Cartier, and Arnold, J. Appl. Phys. 73, 3367 (1993

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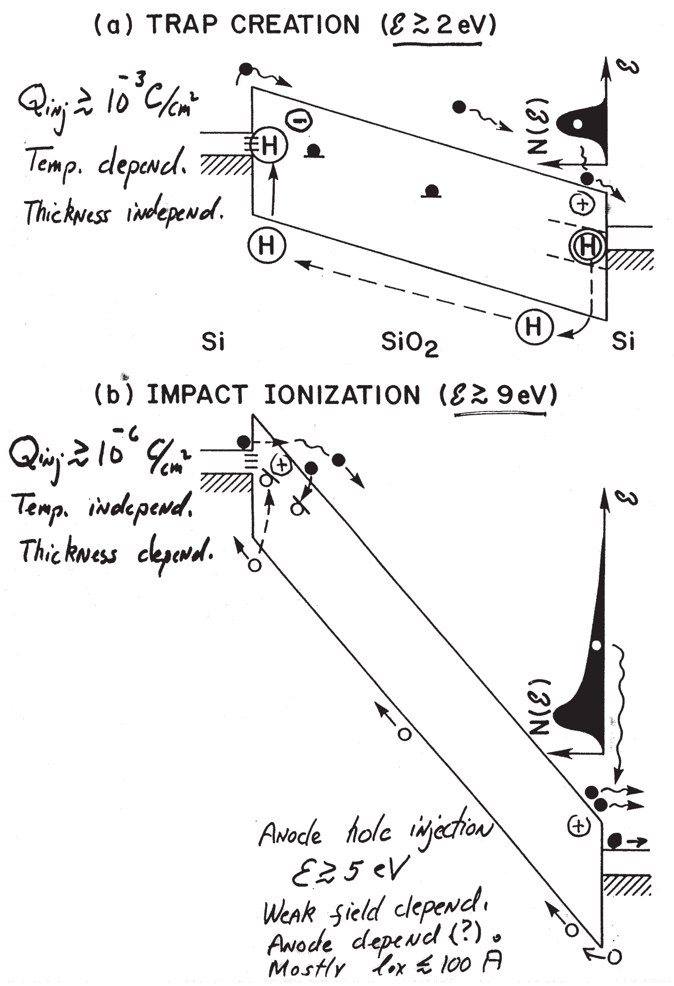

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Experimental techniques

- n- and p-FETs
  - fully integrated CMOS
  - t_{ox} ~1.4 - 5 nm
- measure defect generation to breakdown
  - SILC (stress-induced leakage current) (≤ 5 nm)
    - **neutral electron traps**
    - **only technique below 4 nm**
  - CV stretch out (≥ 4 nm)
  - V_t and sub-thres. slope
  - Charge pumping
  - Gated-diode
- generation rate (P_g)
  - P_g = slope (linear region)
    $= (\Delta J/J_0) / \Delta Q_{inj}$
    or
    $= \Delta N_s / \Delta Q_{inj}$
- final defect density at breakdown (N^{BD})
  - N_n^{BD} (neutral traps)
  - N_s^{BD} (interface states)
- charge to breakdown
  - $Q_{BD} = N^{BD} / P_g$

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Defect generation to breakdown

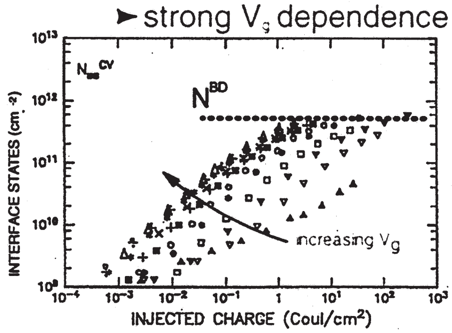
$$\boxed{Q_{BD} = N^{BD} / P_g}$$

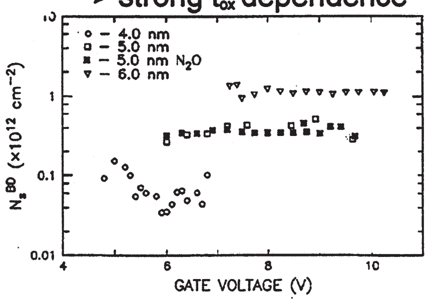
defect generation rate

➤ strong V_g dependence

critical defect density

➤ strong t_{ox} dependence





D.J. DiMaria and J.H. Stathis, Appl. Phys. Lett. **70**, 2708 (1997)

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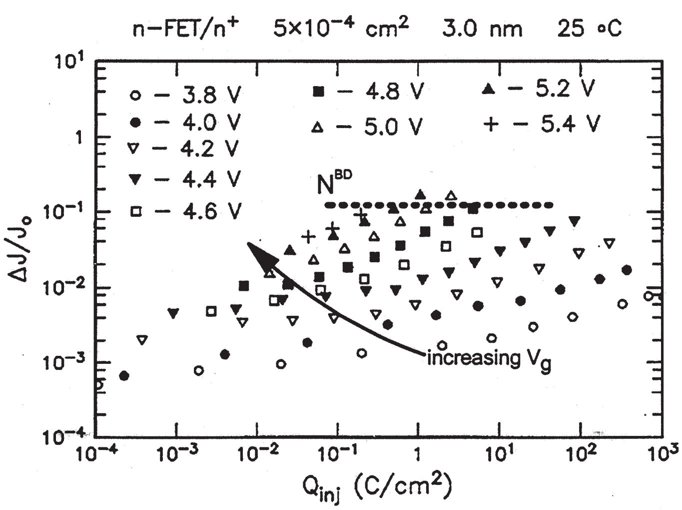
Defect generation to breakdown

- Stress-induced leakage current (SILC)
  - proportional to trap density



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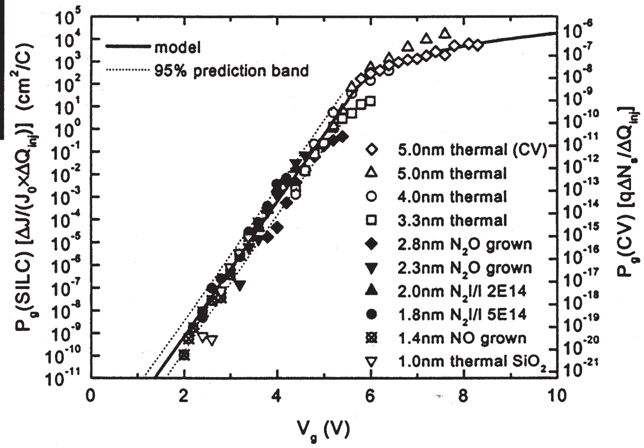
defect generation rate (P_g)

- subthreshold generation below 5V
- single mechanism
  - single exponential
- universal behavior with V_g



QM thickness

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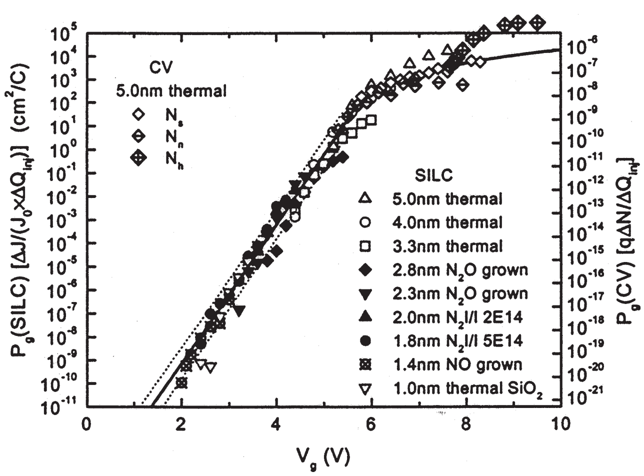
defect generation rate (P_g) (hydrogen release and anode hole injection thresholds)

- "trap creation" (hydrogen release) threshold ~ 5V
- hole injection threshold ~ 8V



QM thickness

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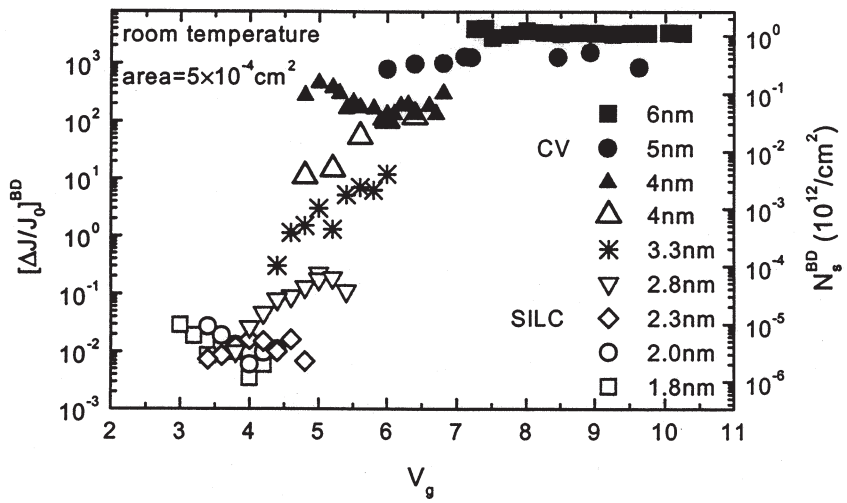
Critical defect density at breakdown



QM thickness

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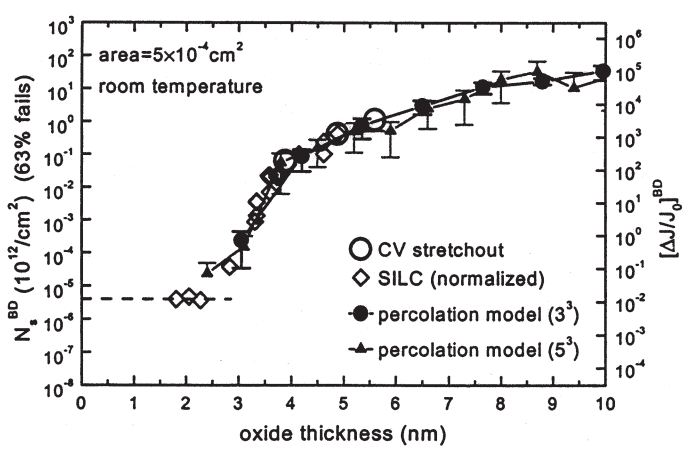
Critical defect density (N^{BD}) vs. thickness

- defect "diameter" ≈ 3.5nm
- breakdown probability ≈ 10^{-3}



QM thickness

J.H. Stathis, J. Appl. Phys. **86**, 5757 (1999).

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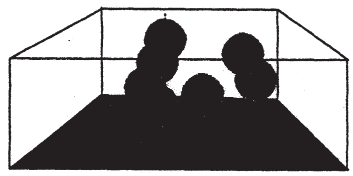
Critical defect density at breakdown

- Suñe *et al.* 1990
  - gives correct extreme-value statistical behavior
  - thickness dependence of N^{BD} not predicted
- IMEC group (Degraeve *et al.*) IEDM extended abstract 1995
  - introduced percolation approach
  - explains thickness dependence as a geometrical/statistical effect
    - connecting path more likely for thinner films



- N^{BD} independent of stress condition
  - DiMaria and Stathis, Appl. Phys. Lett. **70**, 2708 (1997).
  - Y. Kamakura *et al.* IEDM 97; K. Umeda and K Taniguchi, J. Appl. Phys. **82**, 297 (1997).
  - E. Vincent *et al.*, Microelectron. Reliab. **37**, 1499 (1997).
  - Degraeve *et al.*, IEEE Trans. Electron Dev. **45**, 904 (1998).

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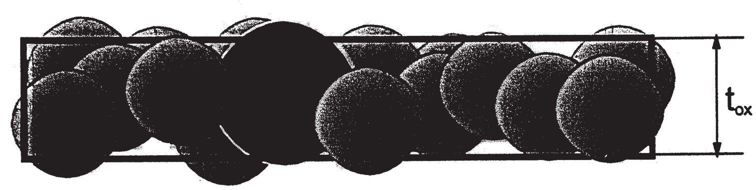
Q_{BD} vs. stress voltage

$T_{BD} = Q_{BD} / J$

"Participating" defect fraction *f*

- <1% of defects participate in breakdown
- *f* may be temperature dependent
  - DiMaria and Stathis, Appl. Phys. Lett. **74**, 1752 (1999).



- see also:
  - S. Lombardo *et al.*, J. Appl. Phys. **86**, 6382 (December, 1999)
    - Density of "weak spots" ≈1% of defect density at breakdown

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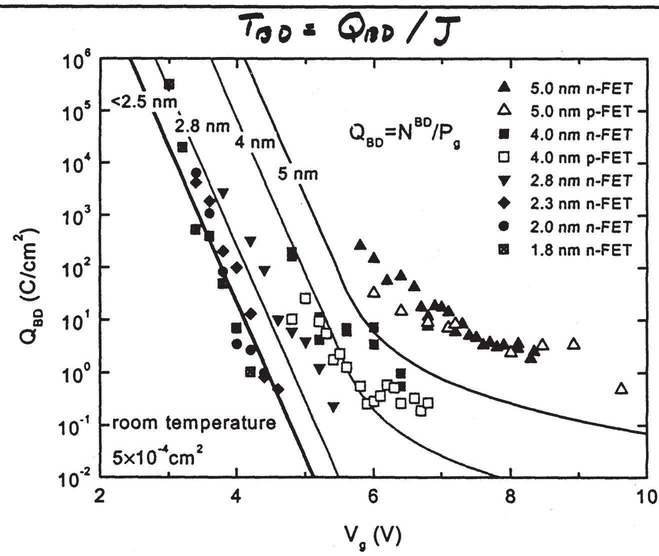
Q_{BD} vs. stress voltage



QM thickness

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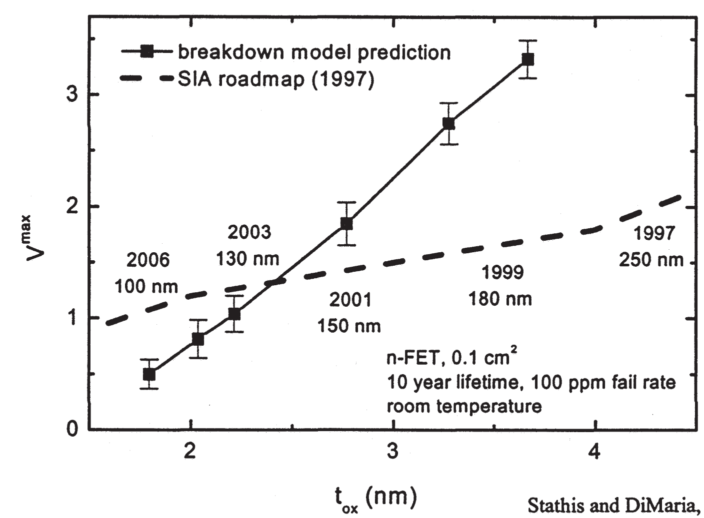
V_{dd}^{max} predictions (IEDM '98)

- reliability as a limiter for CMOS scaling



Stathis and DiMaria, IEDM '98, p. 167.

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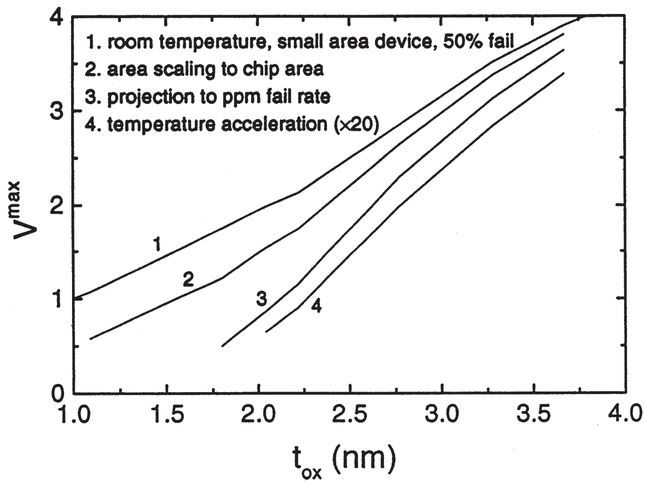
Illustration of various factors which enter into lifetime projection



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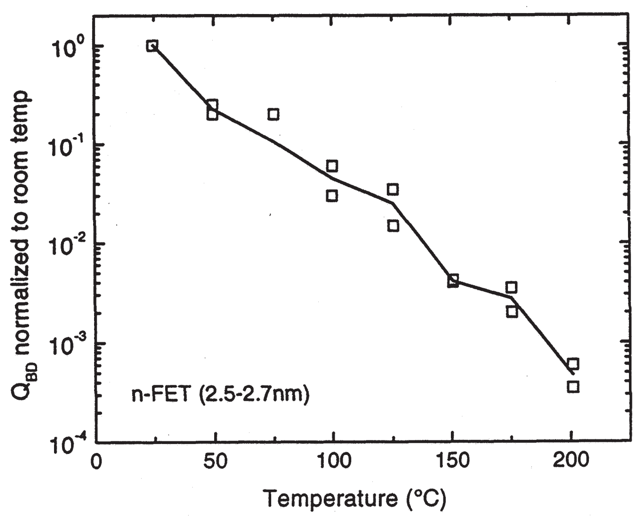
Temperature dependence of Q_{BD}



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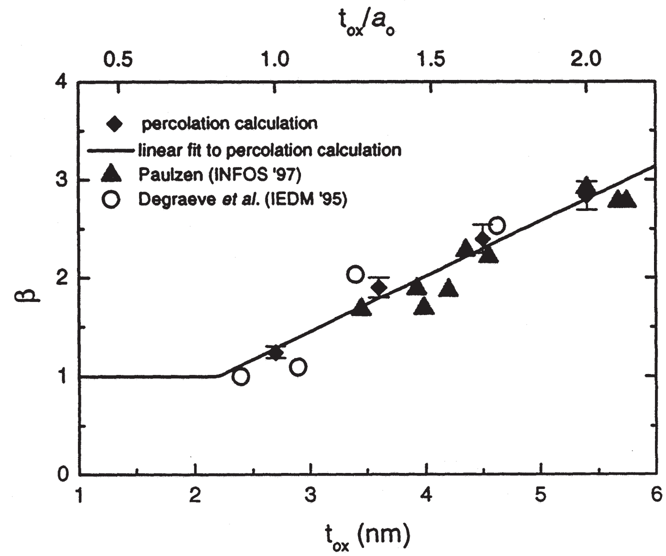
β dependence on t_{ox}



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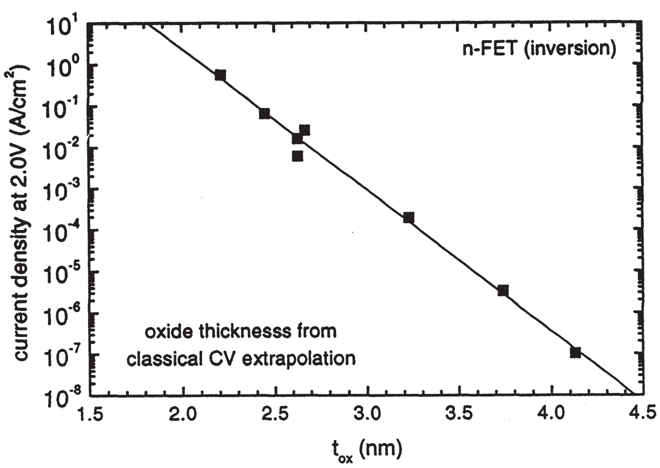
Strong thickness dependence of tunnel current



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Is there a loophole?

- P_g
  - unlikely

extend to 1.25V
unify FN, SHE, CHE
only hot e in Si, not oxide field

- N^{BD}
  - maybe?
- Device operation after soft breakdown
  - controversial

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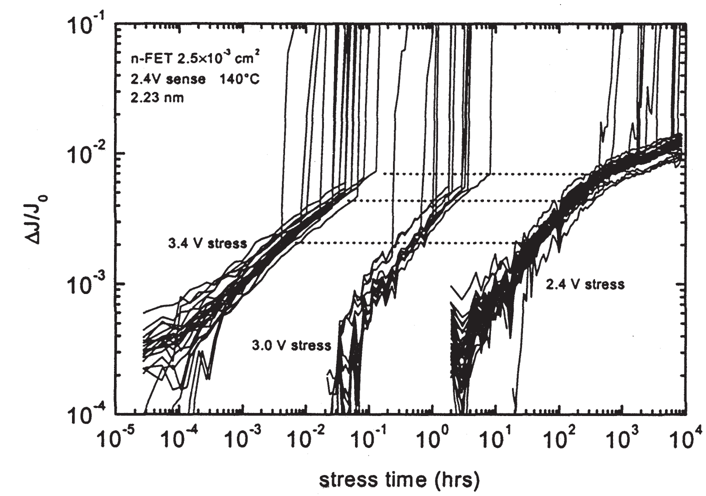
long-term stress experiments on bonded chips



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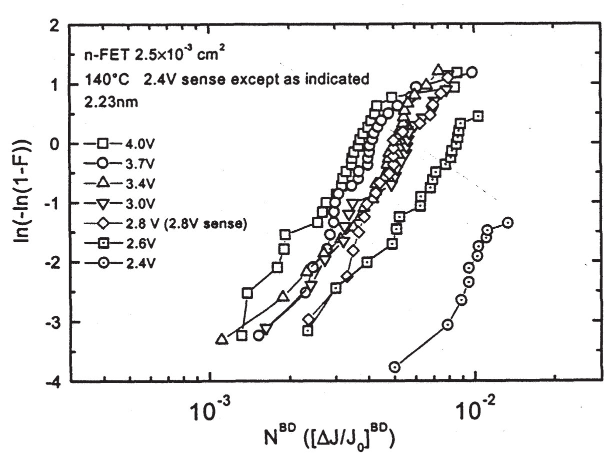
Cumulative failure distributions of N^{BD}



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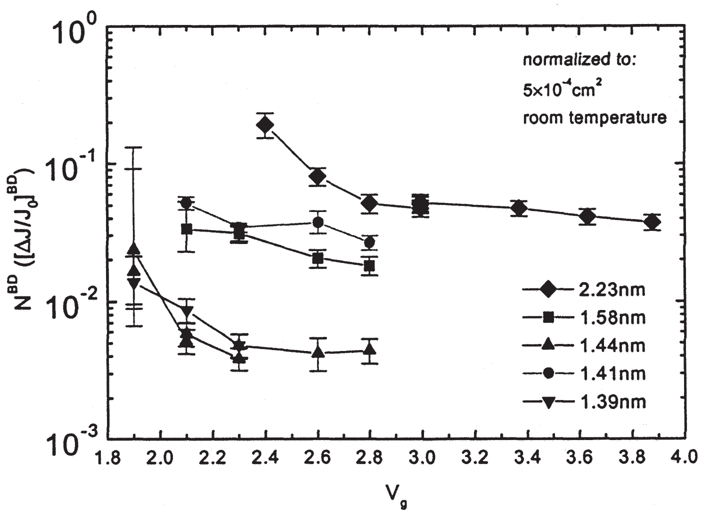
voltage dependence of critical defect density



QM thickness

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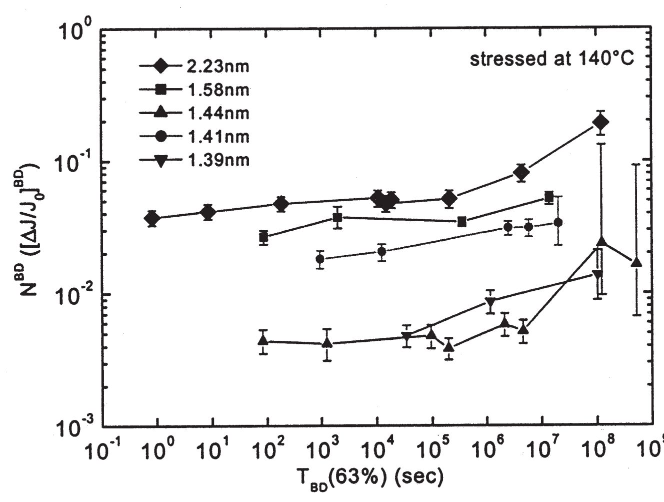
critical defect density vs. breakdown time



QM thickness

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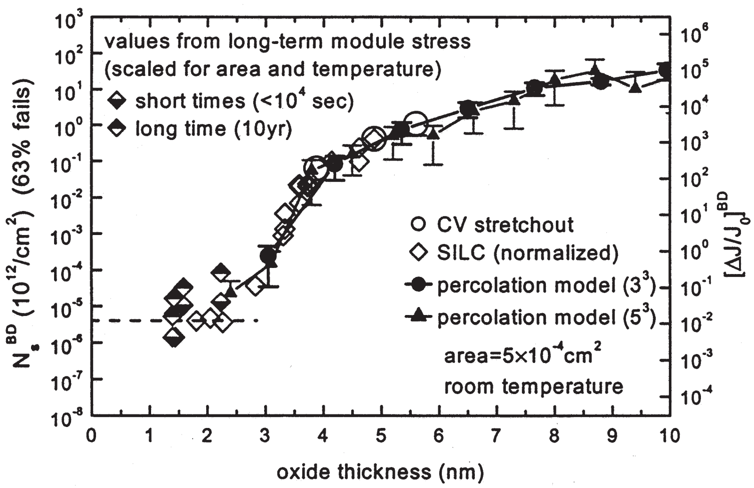
Critical defect density (N^{BD}) vs. thickness



QM thickness

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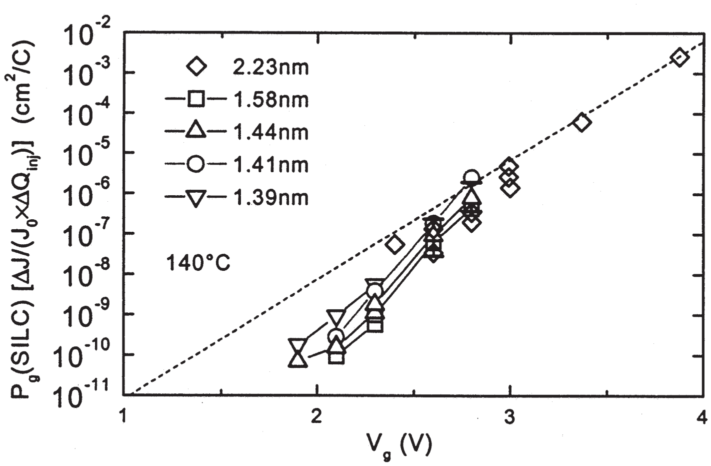
non-exponential (sigmoidal) Pg behavior



QM thickness

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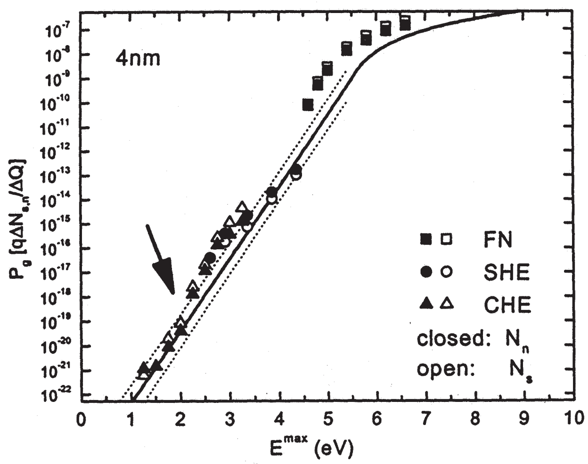
SHE and CHE injection experiments



- similar inflection for SHE/CHE as for long-term FN stress data

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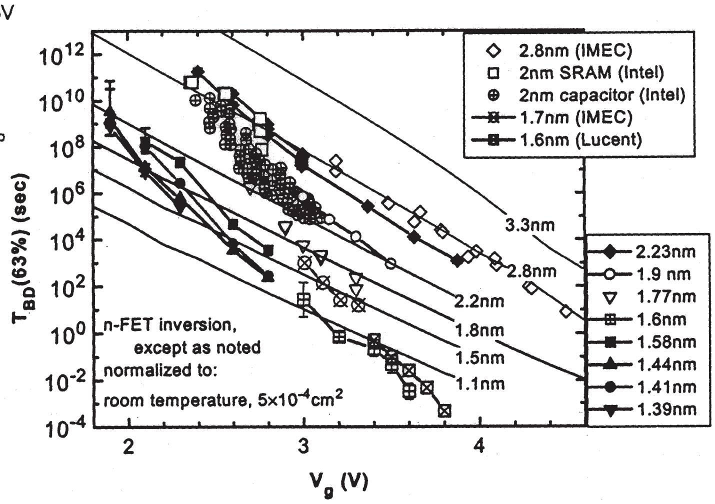
T_{BD} data and comparison to model

- lines are from IEDM'98 model
- good agreement >3V
  - except for very high fields e.g. 1.6nm >3.5V
- higher T_{BD} <3V from P_g inflection plus N_{BD} increase



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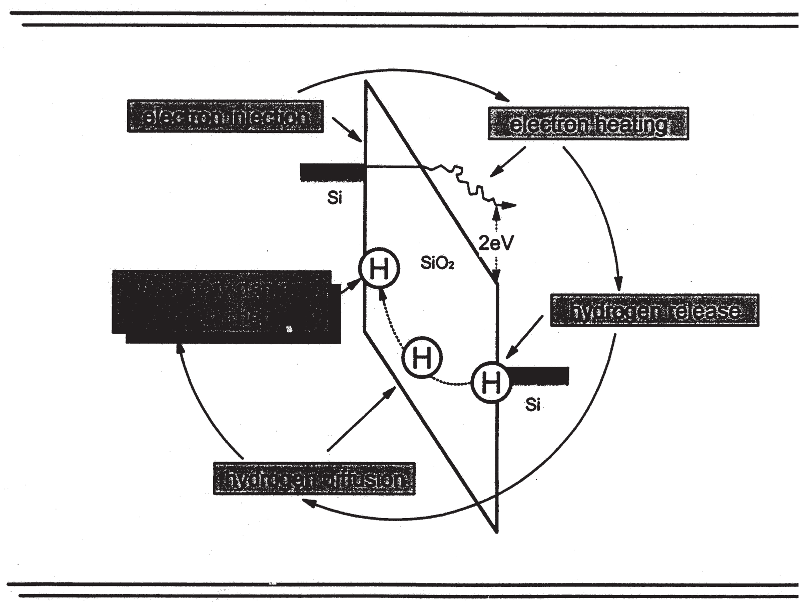
hydrogen mechanism of oxide degradation



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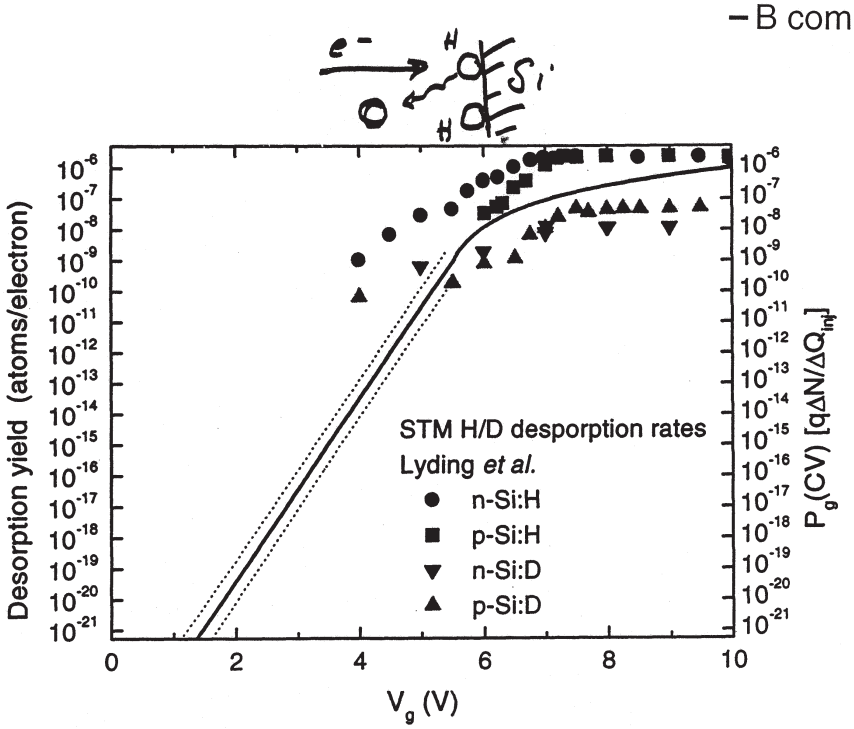
Hydrogen Release

- NRA-motion of hydrogen from anode to cathode.
- Hydrogen/deuterium desorption expts.
- Comparison to atomic hydrogen exposure of ungated films.
- Hydrogen related defects
  - P_b
  - B compensation

KN-31



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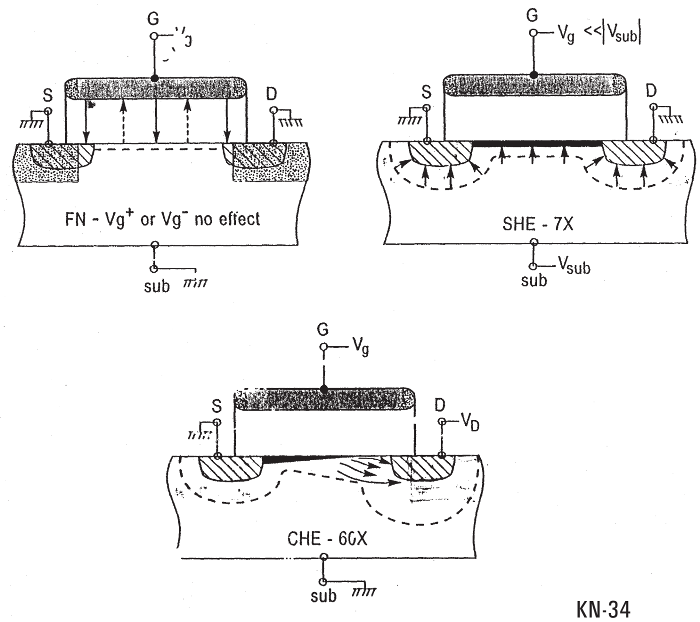
Deuterium Replacement

- Deuterium replacement of hydrogen
  - Desorp. expts.-100x(100%), 2x(50%).
  - Deuterium motion restricted (undoped).
  - Hydrogen removal / back annealing.
- D_2 annealing (400-450 C)
  - Nitride sidewalls blocking
- D_2O oxidation (high temp)
  - Oxide source of deuterium
- Correlation to P_g (bulk traps / interface)
  - CHE - 60x (non-uniform using D_2)
  - SHE - 7x (non-uniform using D_2)
  - FN - 2x or less (uniform using D_2O)

KN-33

GIANT DEUTERIUM ISOTOPE EFFECT
(Hess, Lyding, Kizilyalli, et al.)

- N-FETS annealed at 450 °C for 3 hr. in 100% H_2 or % D_2
  t_{ox} = 65 Å L = 0.35 μm
- Stress by FN, SHE, or CHE
  Sense by charge pumping - ΔN_{it} from 10^8-10^{12} cm^{-2}



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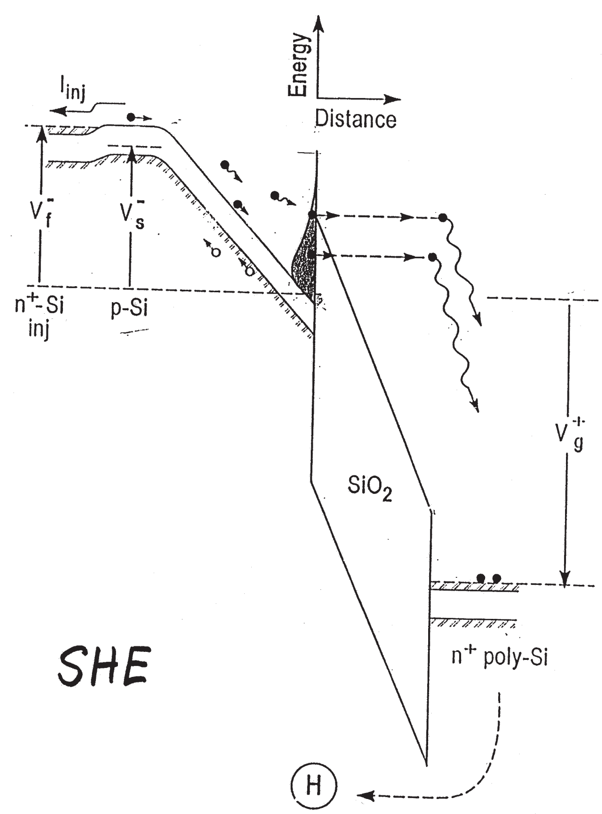
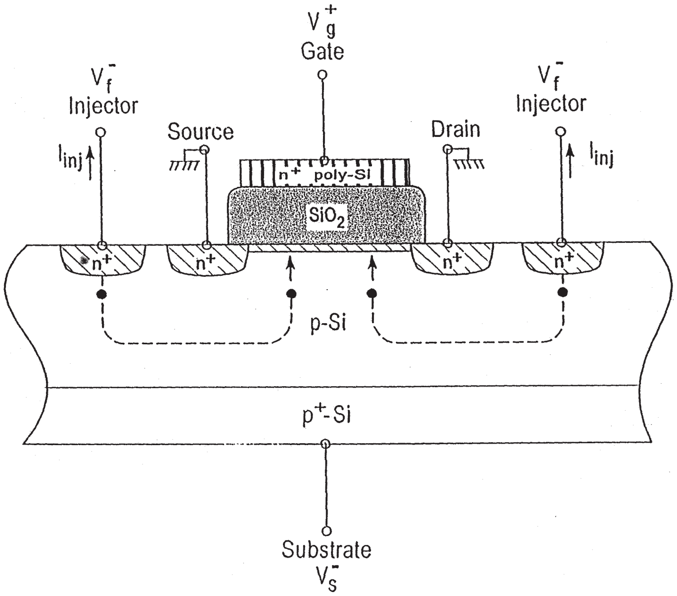
Electric field/Anode hole

- ▸ Oxide electric field.
  - SHE-no dependence on oxide field.
  - Energy delivered to Si layer near interface independent of stress (FN, SHE, CHE).
  - Fields exceeding 25 MV/cm?
- ▸ Anode hole injection.
  - Energy delivered to Si layer.
  - Hole current comparable to electron current.

KN-35



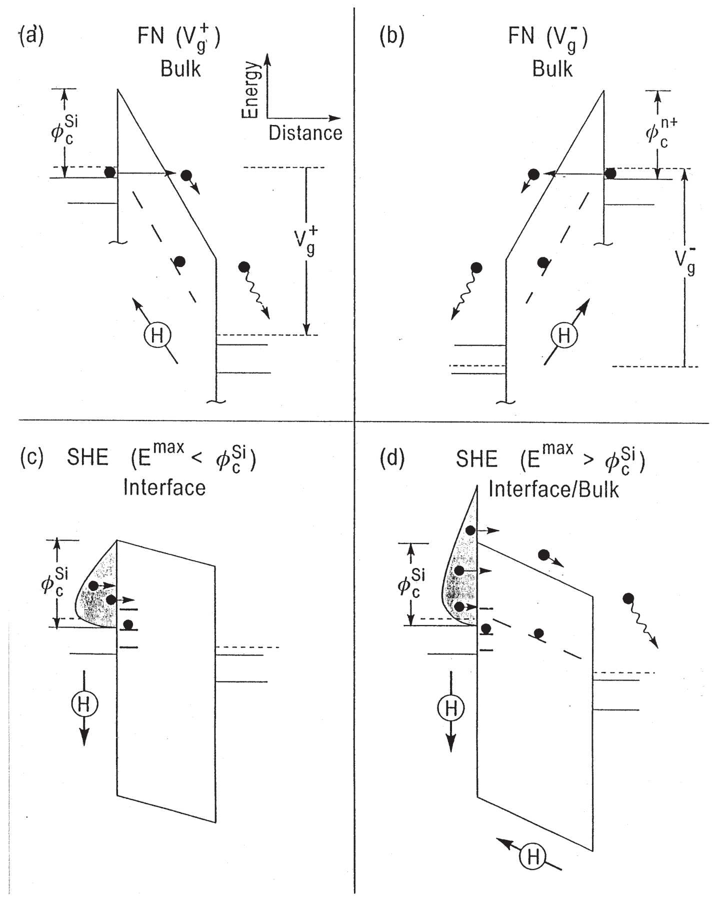
KN-36



n-FET/n$^+$ with n$^+$/p Inj.

SHE

KN-37



Bulk oxide traps

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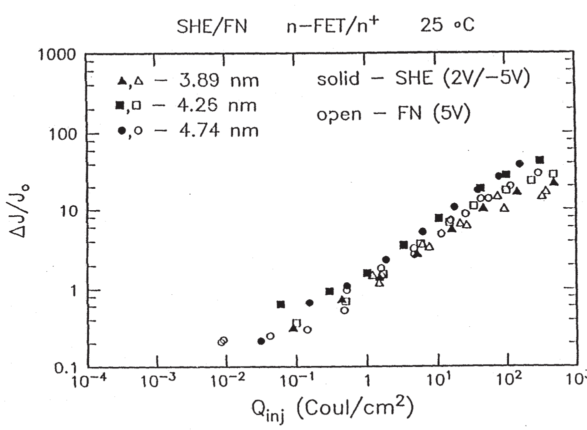

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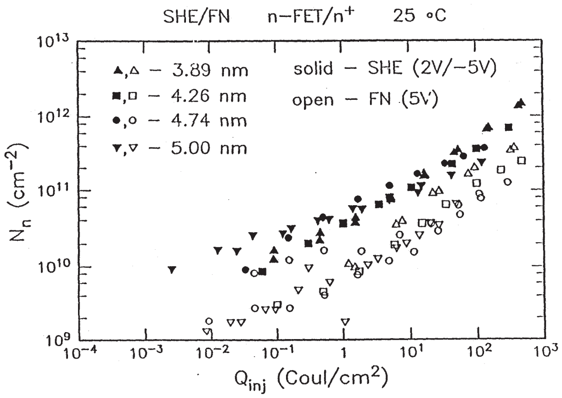
Acceptor-like



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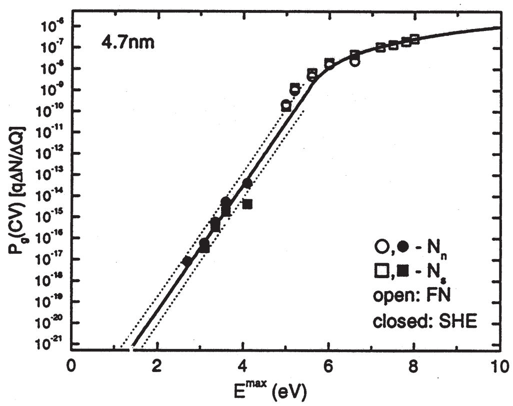
SHE injection experiment

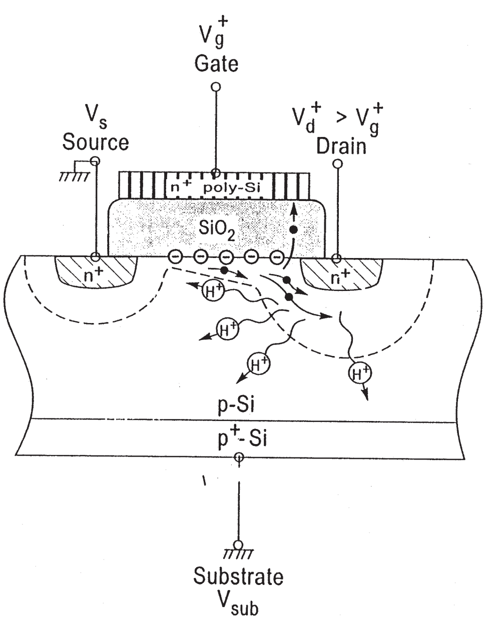


- E^{max}(SHE) = q(V_s+ϕ_{np})
- interface state creation from electrons hitting substrate/oxide interface
- same electron energy dependence as FN injection

D.J. DiMaria, to be published, J. Appl. Phys.

KN-41

CHE



n-FET/n+ under CHE

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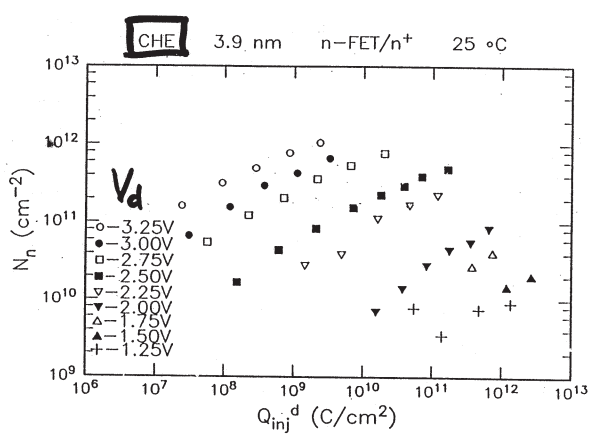
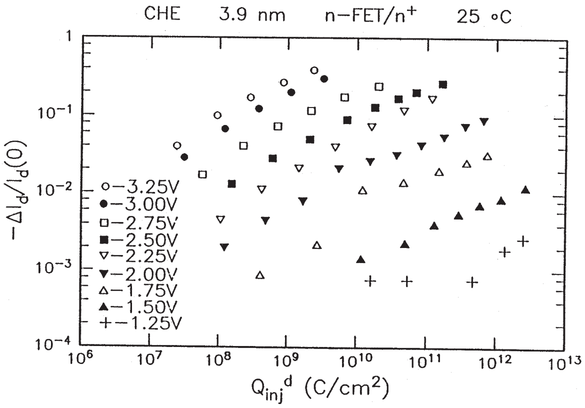
Acceptor-like



KN-43



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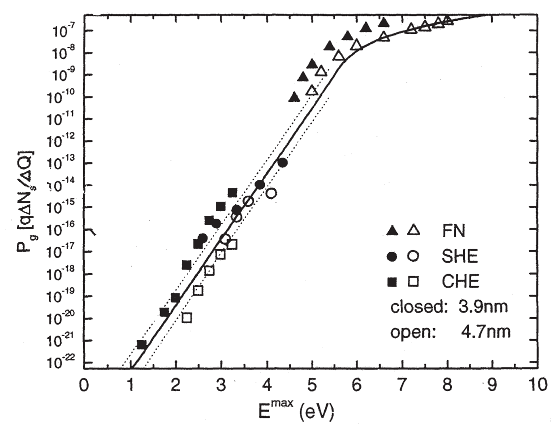
SHE and CHE injection experiments



- E^{max}(SHE) = q(V_s+ϕ_{np})
- E^{max}(CHE) = qV_d
- interface state creation from electrons hitting substrate/oxide interface
- same electron energy dependence as FN injection

D.J. DiMaria, to be published, Appl. Phys. Lett.

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CHE and SHE stress experiments

- Generation Prob. same for SHE, CHE, FN
- Hydrogen release by hot electrons in Si layers
  - poly-Si gate: FN (+)
  - Si-sub: FN (-)
  - Si-sub: SHE
  - Si-sub near drain: CHE
- Universal Behavior for all Degradation Modes:
  - uniform (FN and SHE) and non-uniform (CHE)
  - Modes additive

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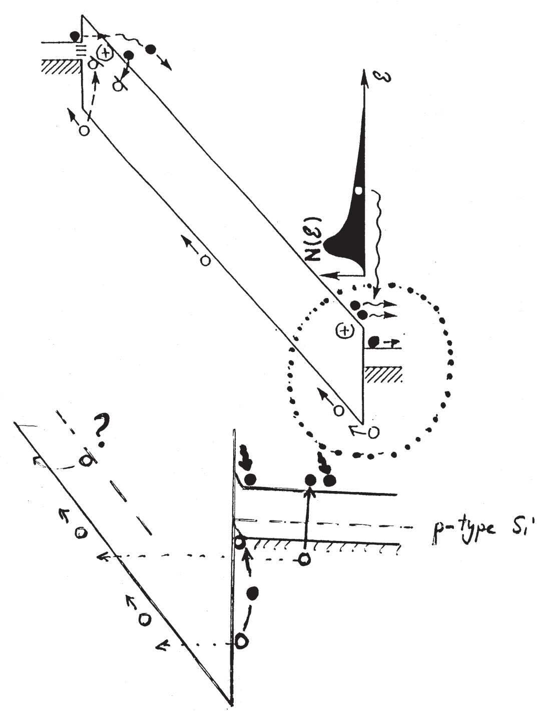
ANODE HOLE INJECTION



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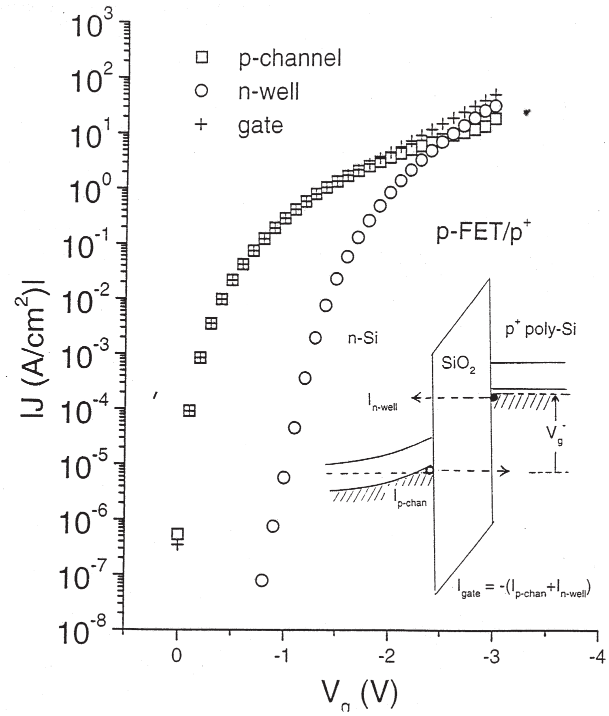
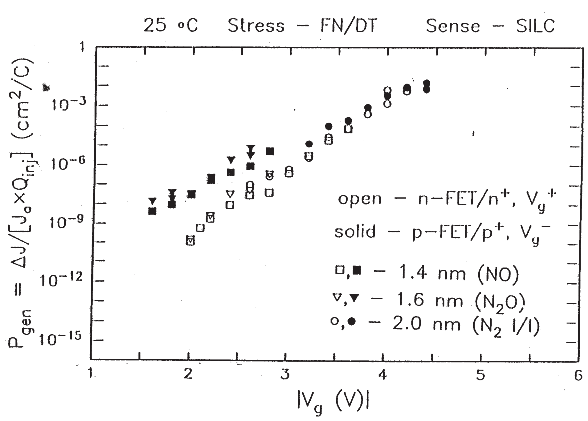
Anode Hole Injection

- Defect generation only due to hole injection?
  - Ultrathin oxide p-FETs under inversion
  - Hole current comparable or dominant
  - Energy delivered to cathode (thin oxide)
- SHH experiments
  - Hot holes similar to thermal
  - Energy delivered to anode (thick oxide)
- Comparison to models for n-FET
  - Hot-electron-induced hole current- too small
  - Hydrogen release by hot carriers in Si

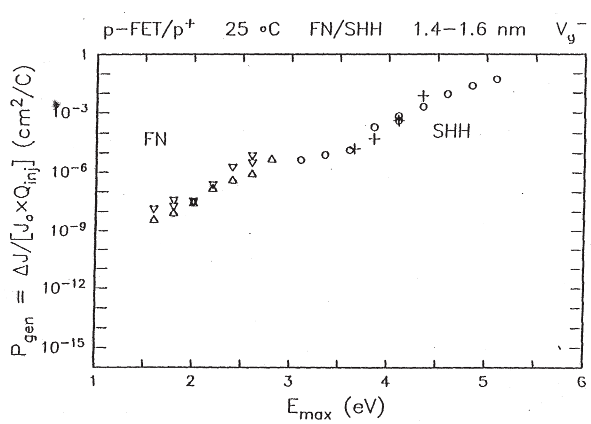
KN-48



KN-49



KN-50



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