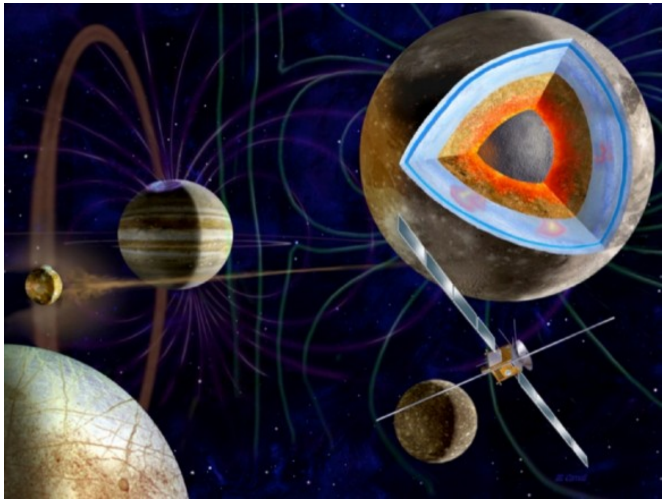
Dose and Dose-Rate Effects in Micro-Electronics

Pushing the Limits to Extreme Conditions

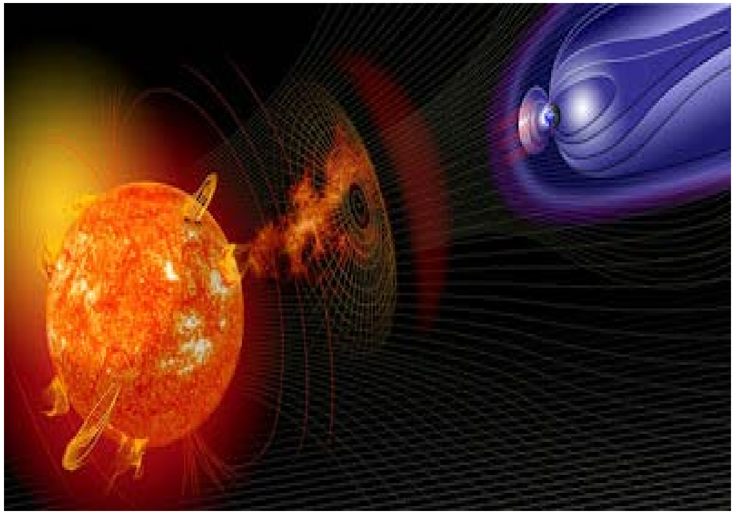
Philippe Adell, PhD., NASA-JPL, USA

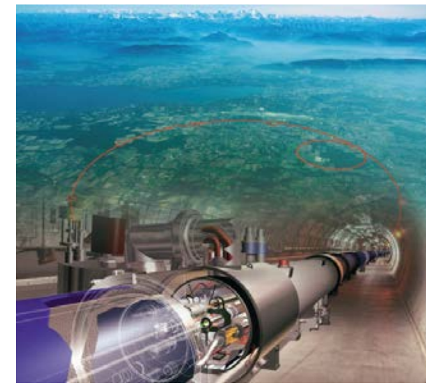
Background



- Earth missions:
  - LEO, MEO and GEO
- Planetary missions:
  - Asteroids, Moon and Mars missions
  - High Dose Missions: Europa (planning) and Juice
- Agencies are looking into:
  - Flying commercial technologies
  - Flying electronics out of the “warm box”
  - Flying CubeSat technologies as secondary payload or tech-demo

The Problem of Total Ionizing Dose (TID)





- Degradation in integrated circuits due to ionizing radiation exposure can deteriorate the circuit characteristics, potentially leading to system failure

- Most space electronics, nuclear plant systems, implantable medical devices, and radiation/accelerator facility instrumentation therefore require hardness TID.

Dose Definition …

- The SI unit for TID is Gray: 1 Gy = 1 J/kg
  The radiation effects community still uses most often the old unit, the rad (radiation-absorbed dose): 1 Gy = 100 rad

- TID is a cumulative effect.
  Cumulative effects are gradual effects taking place during the whole lifetime of the electronics operating in a radiation environment.

<u>example:</u> 10 krad mission → approximately 1.10^{17} ehps.cm^{-3}

Carriers density cm^{-3}

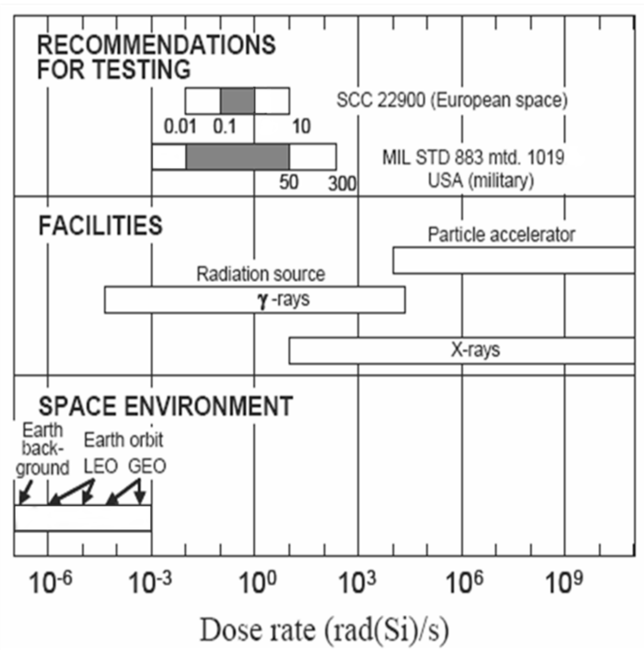
#0	10^{14} à 10^{19}	10^{22}
Insulator	Semiconducteur	Metal

» Dose effects are mainly due to charge trapping in oxides.

… and Dose Rate

The dose rate is the amount of dose received in a certain period of time. It is usually measured in rad/s or krad/h.

Space



Nuclear

Ageing irradiation to be used for qualification (Reactor Building) (for equipment sensitive to ageing if equipment is not sensitive, ageing irradiation is not taken into account for qualification)		
Equipment environmental condition range	Equipment location	Ageing irradiation (depends on the frequency of replacement of sensitive components)
1 to 6	Accessible zone	0.7 kGy per 10 year period
	Restricted zone	35 kGy per 10 year period
	"Red" zone	250 kGy

Fundamental Safety Overview, volume 2: Design and Safety, "Qualification of Electrical and Mechanical Equipment for Accident Conditions". http://www.epr-reactor.co.uk/

For a mission, dose rates range over several orders of magnitude. For ground testing, dose rates are higher.

Mission Types

Mission	Radiation rad/100 mils-Al	Cold (^oC)	Hot (^oC)	Thermal Cycling (^oC)	Duration (Years)	Dominant Species
Europa	2-3 Mrad	-160	-	-	> 9	e^-(hard)
Titan	30 krad	-180	-	-	14	-
Venus	20 krad	-	487	-	2	-
Moon	10 krad	-230	-130	Yes	20	-
Mars	10 krad	-128	-	Yes	>2	p^+
Earth (GEO-1 year)	30 krad	-	-	-	10	e^-(soft)
Earth (MEO-1 year)	2krad - 2 Mrad	-150	-	-	10	p^+
Earth (LEO-1 year)	1 krad	-150	-	-	10	p^+
Deep Space	1-10 krad	-	-	-	10	p^+

Variations in environment make total dose qualification practices more challenging.

Outline

- **Dose and Dose-Rate Effects in Electronics**
  - TID and damage processes in SiO_2
  - Effects in MOS devices
    - Annealing, time dependent and dose rate effects
    - TID and CMOS scaling
  - Effects in Bipolar Devices
    - Update on ELDRS: mechanism and modeling
    - Hydrogen contamination
    - Aging
- **Pushing the limits to extreme conditions**
  - Low temperature to improve TID performance
  - Challenges for high dose environments
  - Radiation hardness assurance

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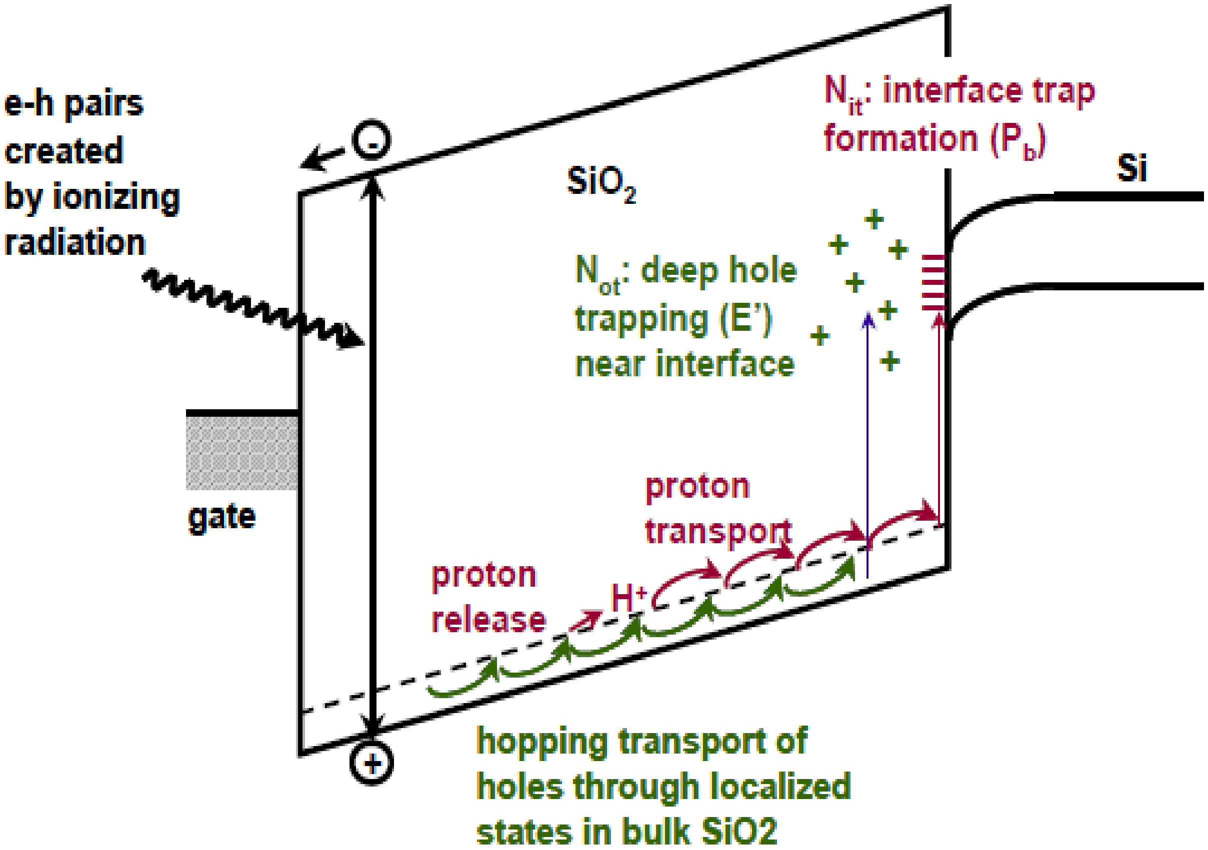
Overview of TID Damage Processes in SiO_2

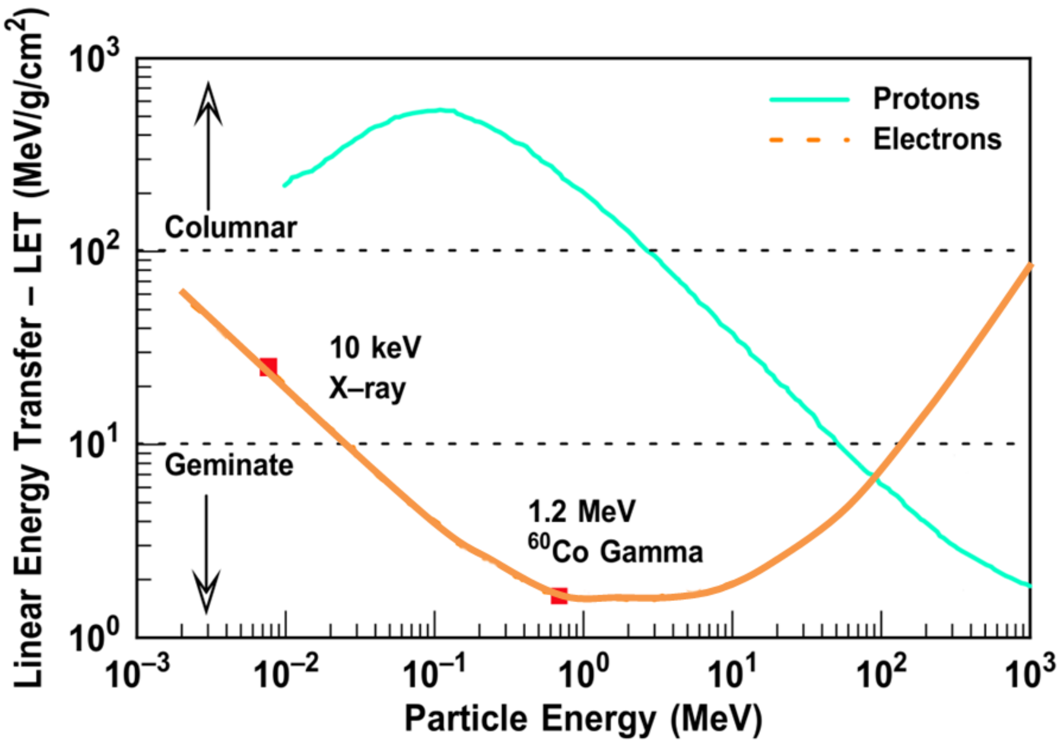


(after McLean and Oldham, HDL-TR-2129 1987)

Processes

1. EHP Generation
2. EHP Recombination
3. Hole and H+ transport
4. Defect formation:
   - **Fixed oxide-trapped-charge (N_{ot})**
   - **Interface traps (N_{it})**
5. => Then annealing takes place

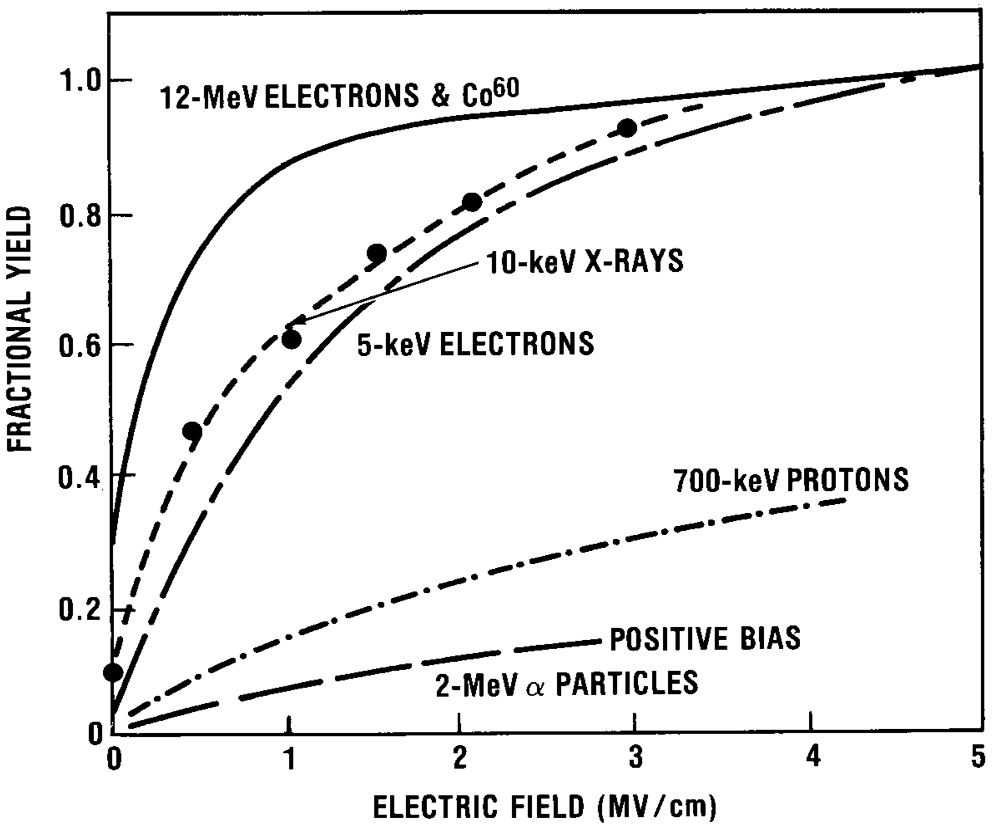
EHP Generation
Electronic Stopping Power



- Linear Energy Transfer (LET) measures energy deposited into a material by ionizing radiation
- LET depends on energy and radiation source
- TID is a measure of energy deposited through ionization

(after Paillet et al., IEEE TNS 2002)

EHP Recombination



(after McLean and Oldham, HDL-TR-2129 1987)

Fraction of holes surviving prompt recombination (f_y) is a function of type and energy of radiation as well as electric field

Charge Yield varies with radiation source types

Defect Formation

Fixed oxide-trapped-charge (N_{ot}) depends on:

- oxide thickness
- electric field
- oxide quality

Interface traps (N_{it}) depends on:

- oxide thickness
- hydrogen

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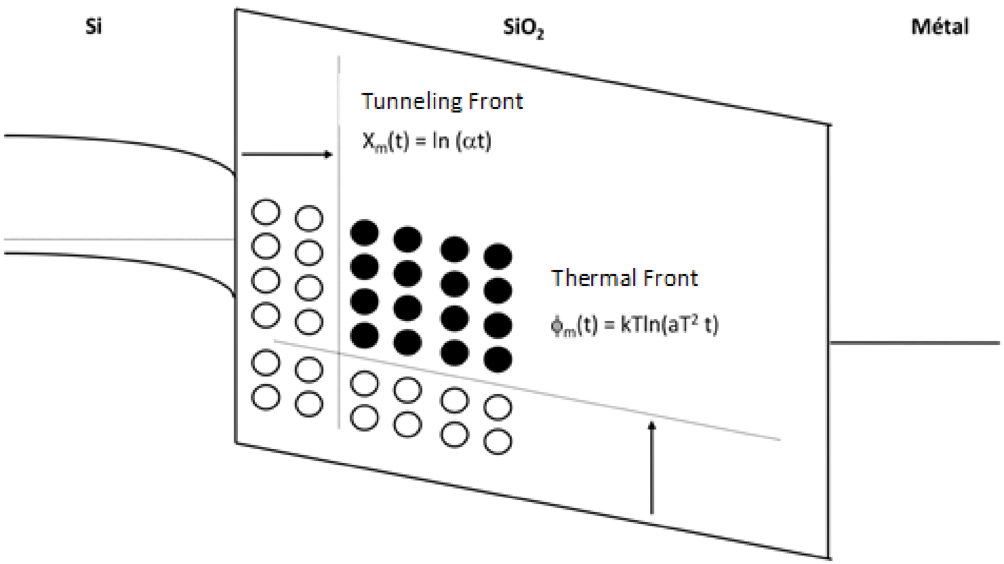
Annealing of N_{ot} and N_{it}



(After P. J. McWhorter IEEE TNS 1990)

Annealing (compensation) of N_{ot} is a long term process dependent on temp and E field

- Tunneling of e^- from Si substrate
- Thermal emission of e^- from SiO_2 valence band

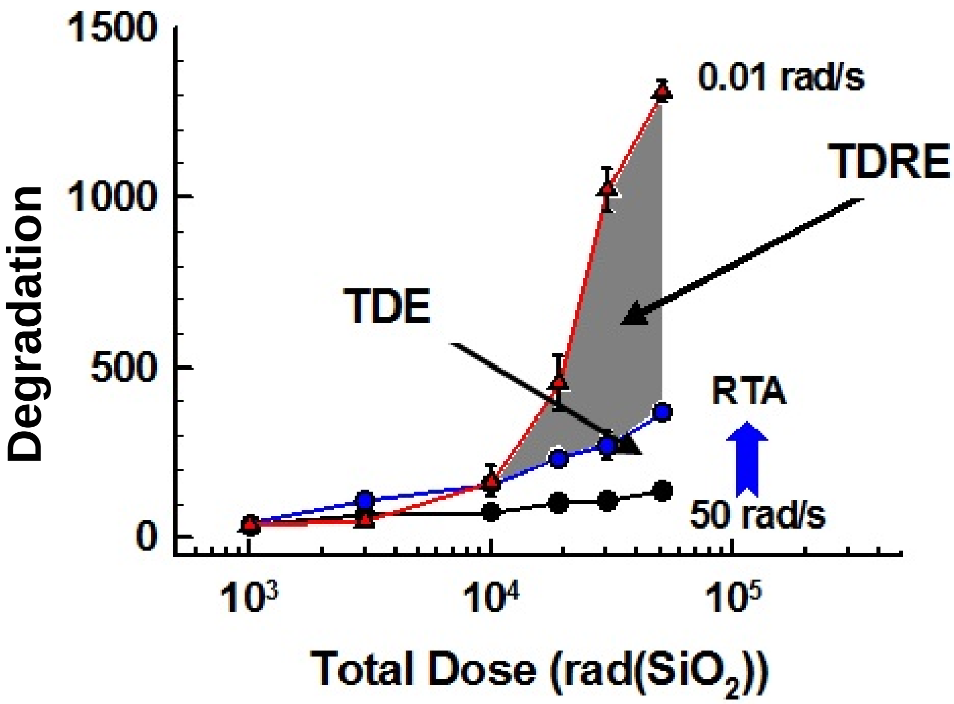
Spatial and energy distribution of N_{ot} affect the rate at which charge neutralization occurs

N_{it} buildup occurs on timeframe much slower than N_{ot}

N_{it} do not anneal at room temp, only at higher temperature

TDE & TDRE

TDE = Time Dependent Effect
TDRE = True Dose Rate Effect



LDR = 0.01 rad/s
HDR = 50 rad/s
RTA= Room temp anneal

Example: @50krad

t_{LDR} = 33 days
t_{HDR} = 15 min
t_{RTA} = 33 days + 15 min

$$t_{HDR} + t_{RTA} = t_{LDR}$$

TDE and TDRE are evaluated for a fixed dose level

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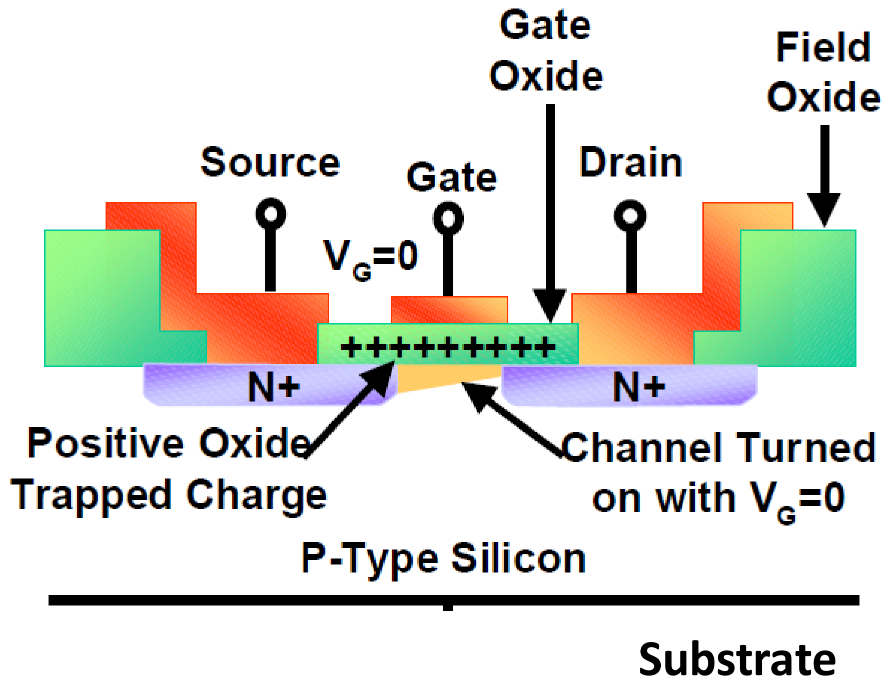
TID Effects in Bulk CMOS

MOS transistor

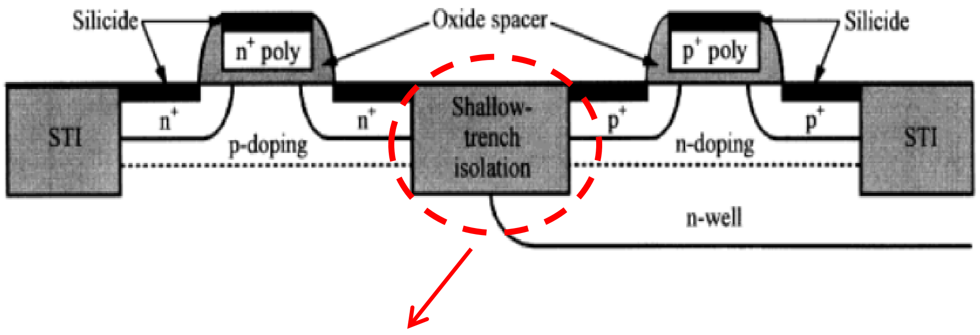


TID defect buildup in CMOS devices can invert the channel interface causing leakage current flow in the OFF state condition (V_{GS} = 0)

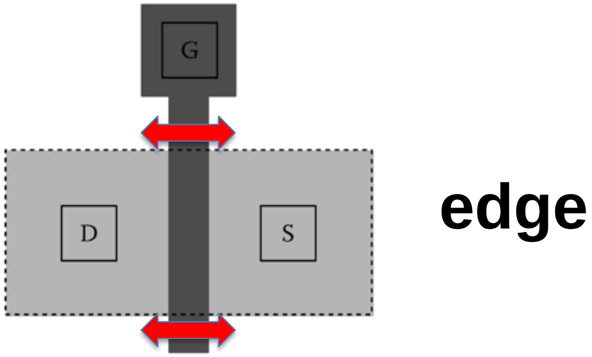
TID induces threshold voltage shift

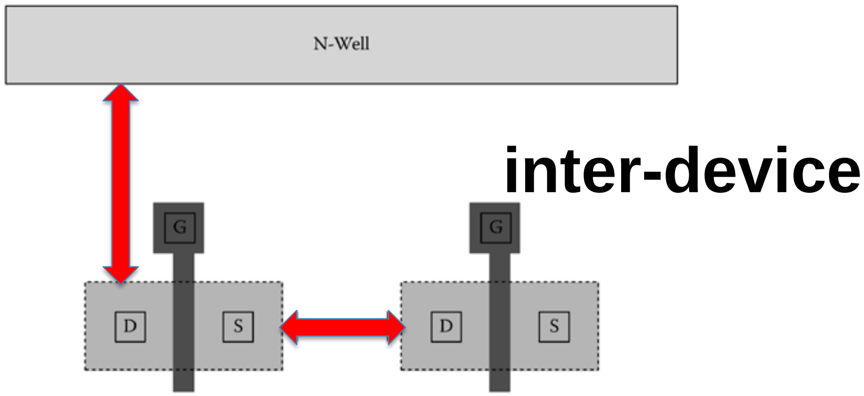
TID Effects in Bulk CMOS

CMOS structure



Field OXide (FOX)
Or Shallow Trench
Isolation (STI) oxides



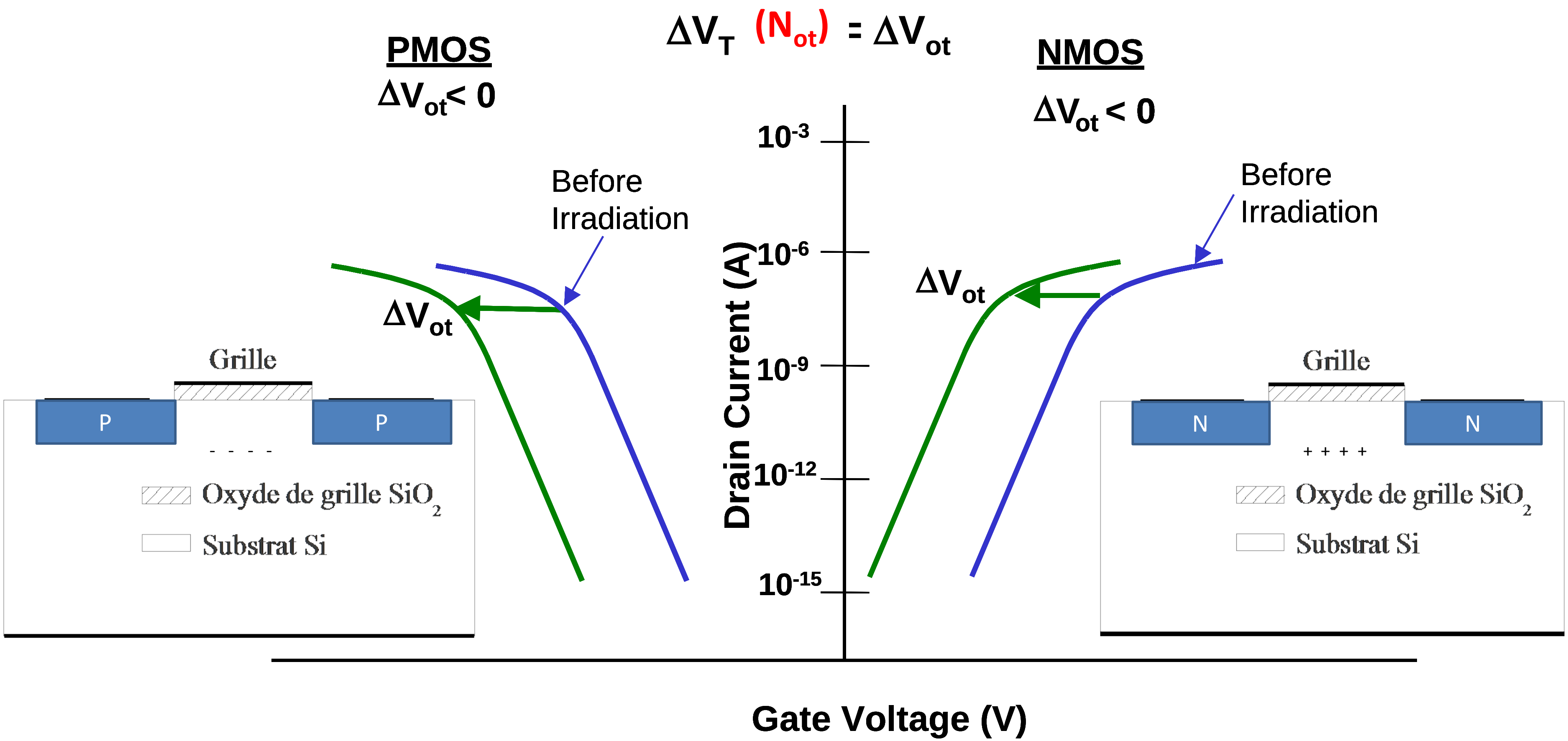


TID defect buildup in CMOS devices can create edge or inter-device leakage paths in bulk integrated circuits

On MOS circuit, TID induces leakage current

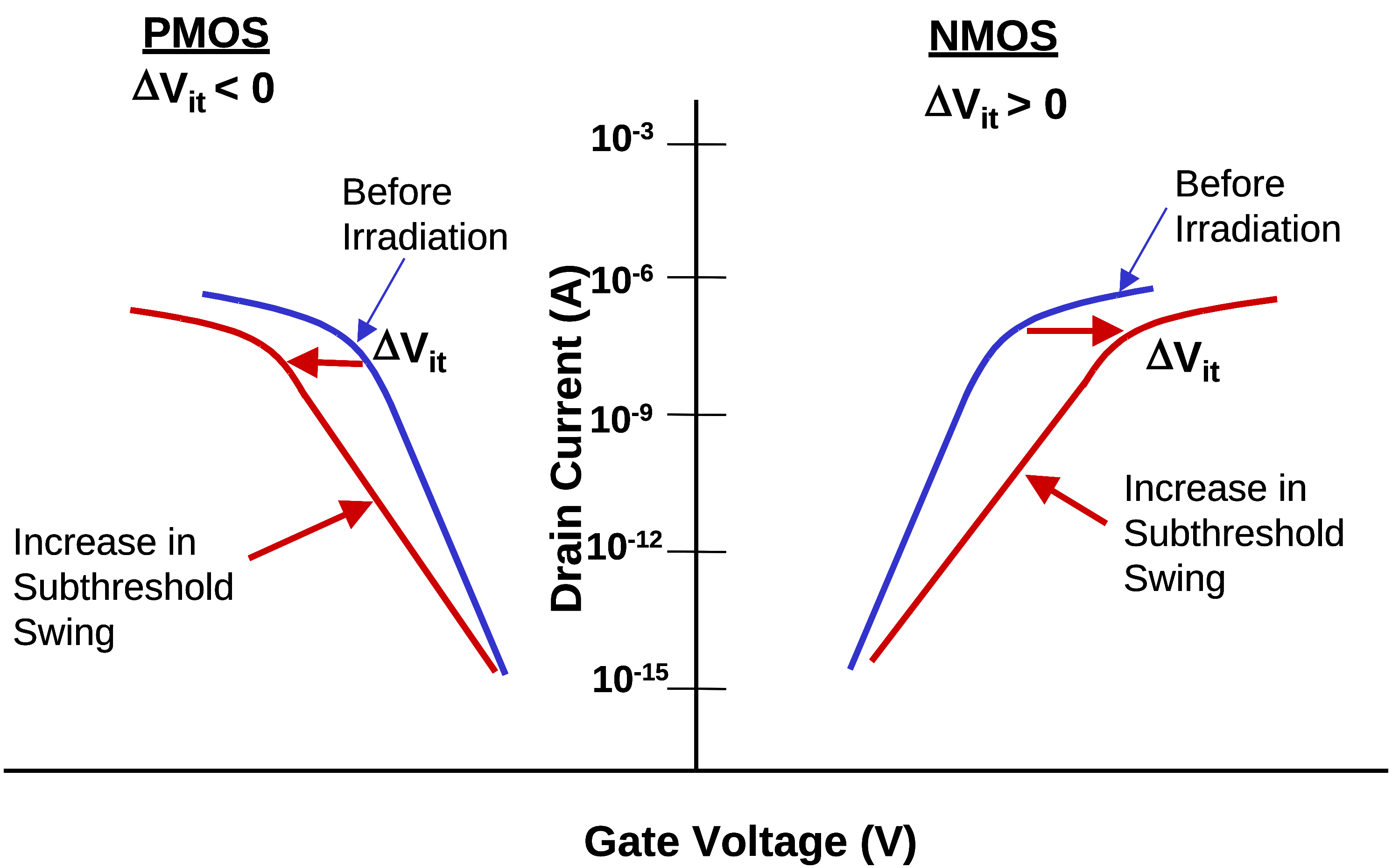
N_{ot} Effects on MOSFET I-V

Trapped holes contribute to net positive charge in the oxide, leading to a parallel, negative shift in MOSFET I-V characteristics



N_{it} Effects on MOSFET I-V

Traps cause increase in sub-threshold swing, threshold voltage shifts, and reduced drive current via mobility degradation



TID and Scaling

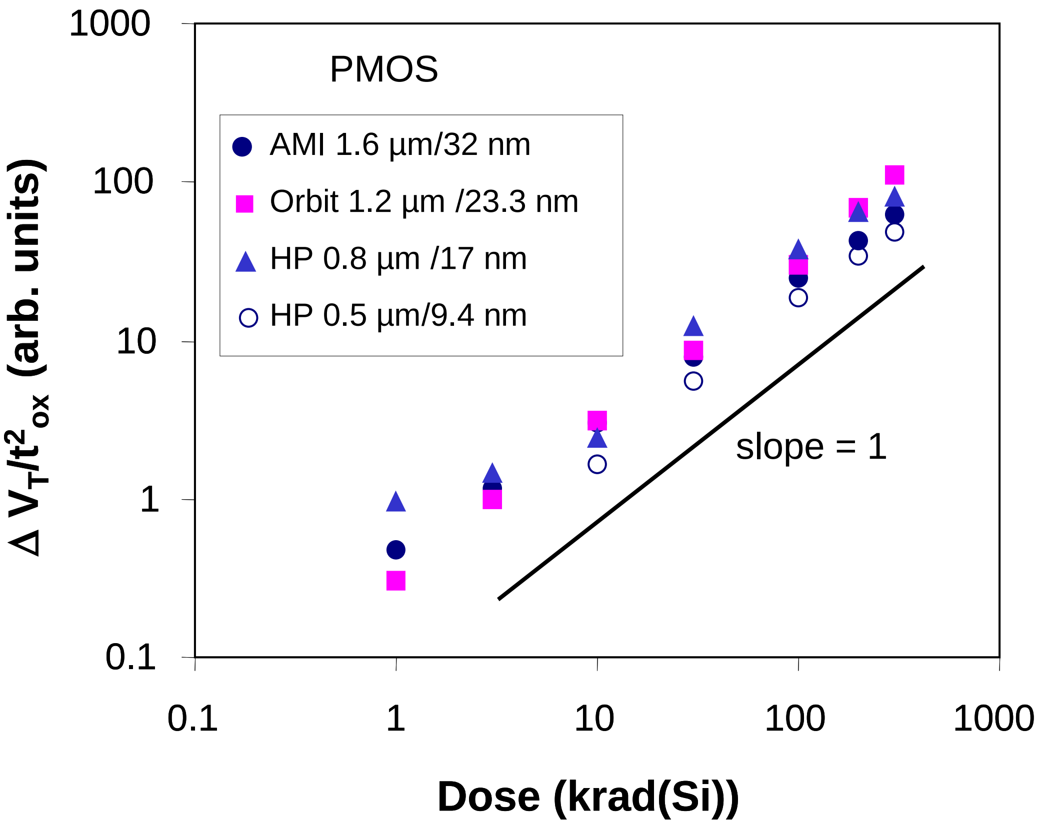
As CMOS has scaled, the device aspect dominating the TID response has changed:

- Gate Oxides
- Shallow Trench Isolation (STI)
- Buried Oxide (SOI)

> 250 nm
180 nm
130 nm
90 nm
65 nm
45 nm
32 nm
22 nm
non-planar

Technology scaling trends for TID are favorable going forward

Dependence on Oxide Thickness



(after Lacoe, IEEE REDW 2001)

$$\Delta V_T = \frac{q\Delta N_{ot} t_{ox}}{\varepsilon_{ox}} - \frac{q\Delta N_{it}\, t_{ox}}{\varepsilon_{ox}}$$

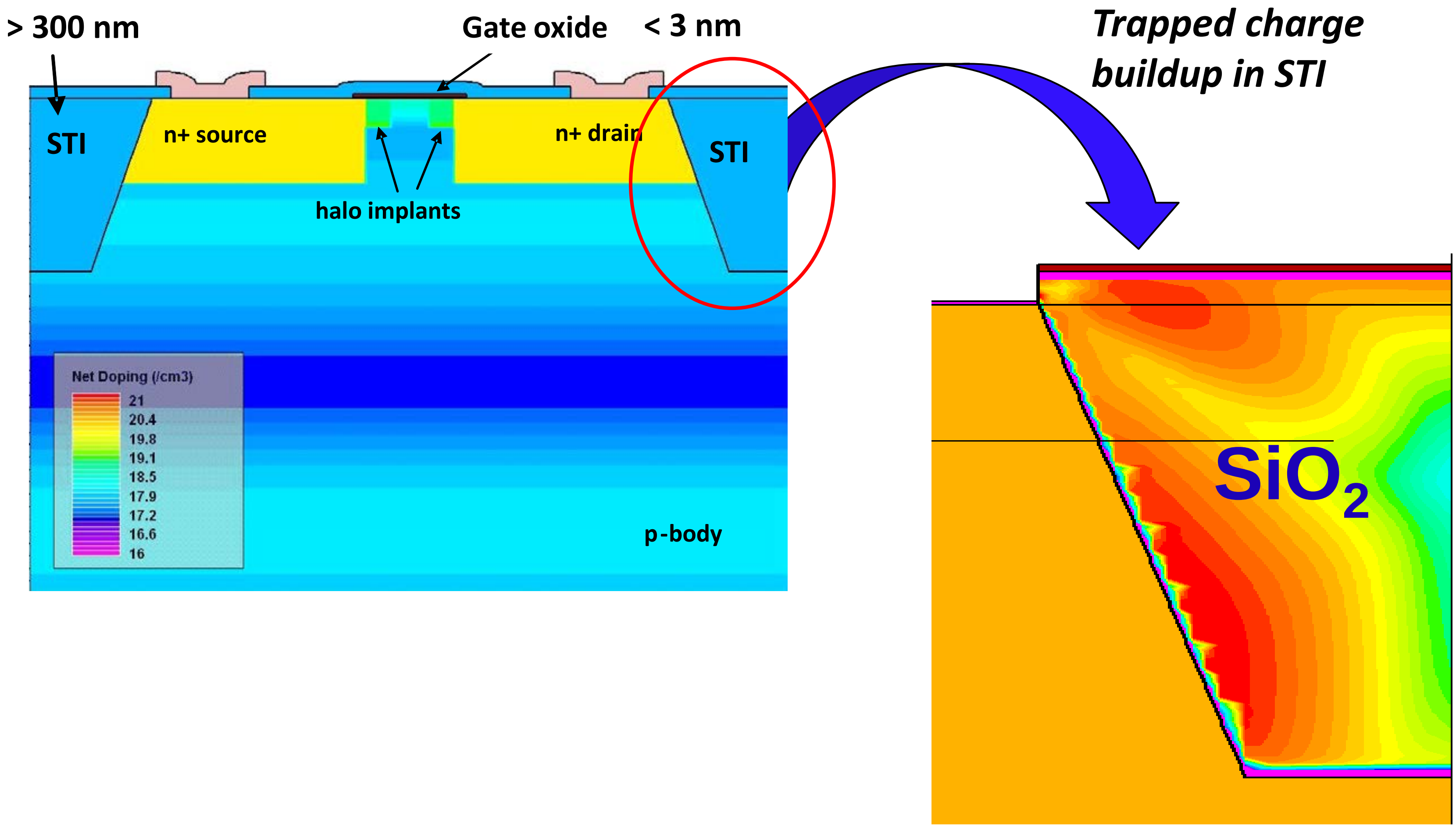
$$\Delta N_{ot} \propto t_{ox} \times \text{Dose}$$

$$\Delta V_T/t_{ox}^2 \propto \text{Dose}$$

TID threat in modern bulk CMOS is defect buildup in thicker field oxides

Primary TID Threat in sub-micron CMOS

TID defect build-up in “thick” isolation oxides (LOCOS or STI) create edge and inter-device leakage parasitics in bulk ICs



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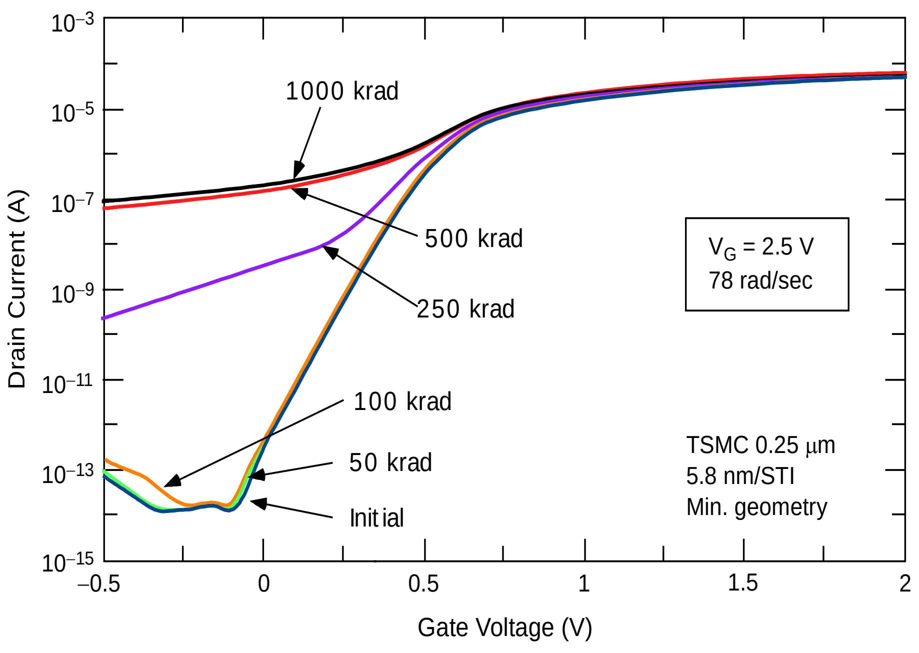
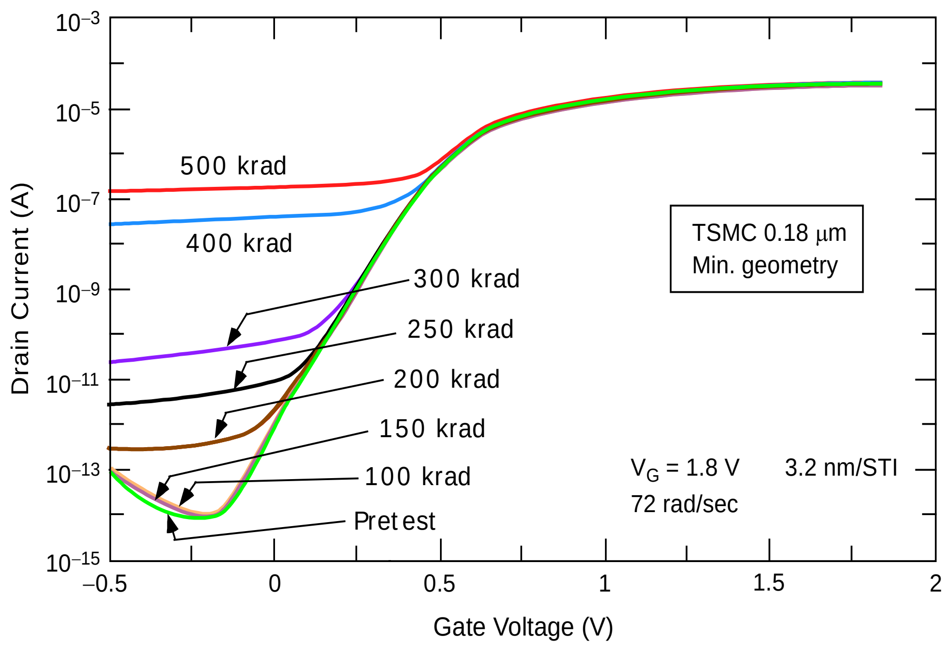
Impact of TID on STI leakage

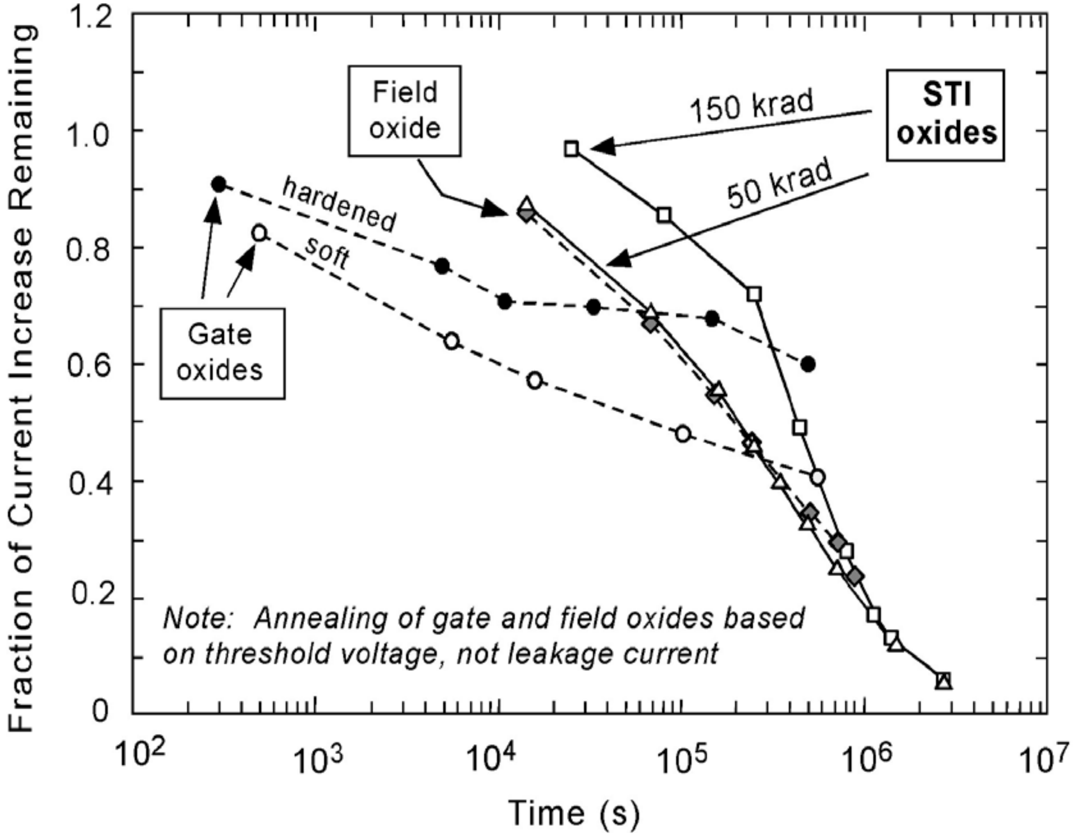




- V_{th} variation cause a left-shift in the logarithmic plot; which is evident for the 0.25 µm process (thicker gate oxide) at lower radiation level

- For both processes a second mechanism comes into play at higher radiation level that is caused by leakage in the field isolation region

Annealing



(after , A. Johnston et al., IEEE 2010)

Annealing processes (tunneling and thermal) are still valid for most advanced CMOS technology

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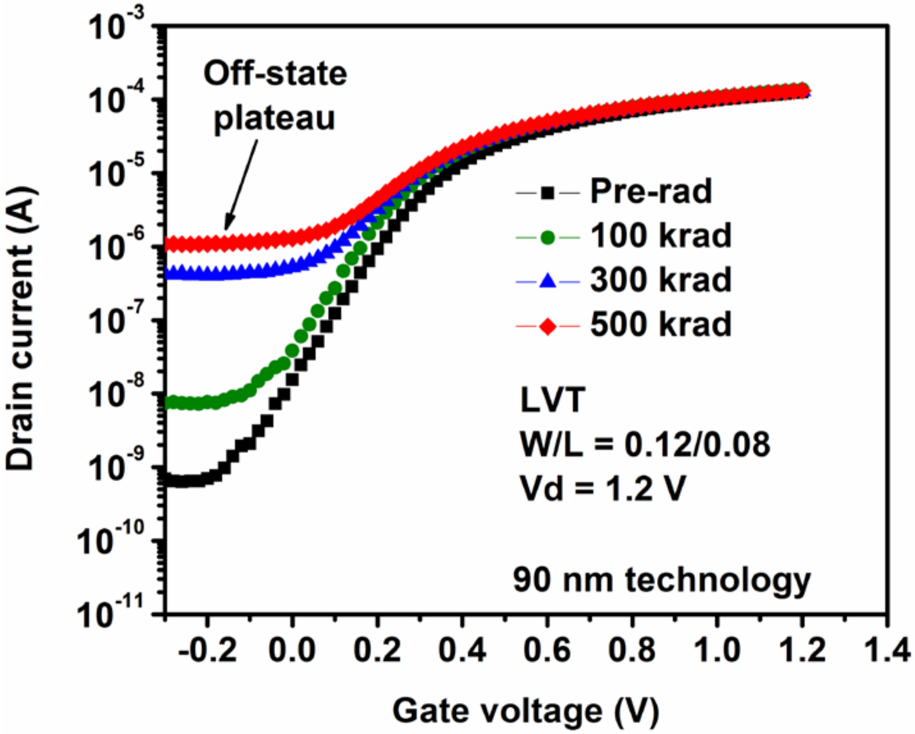
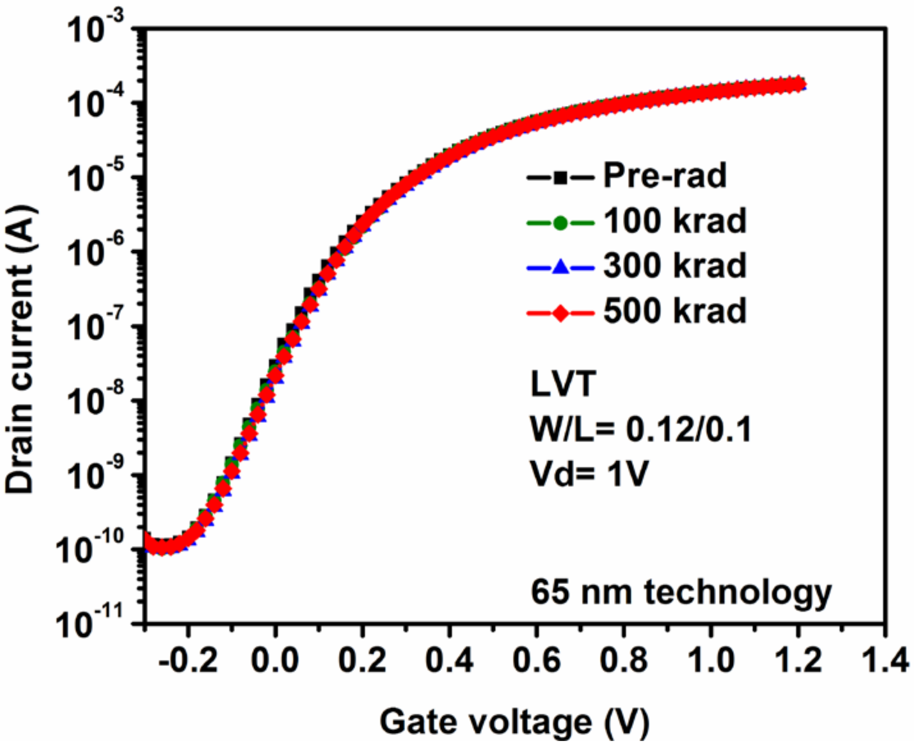
90 nm and beyond

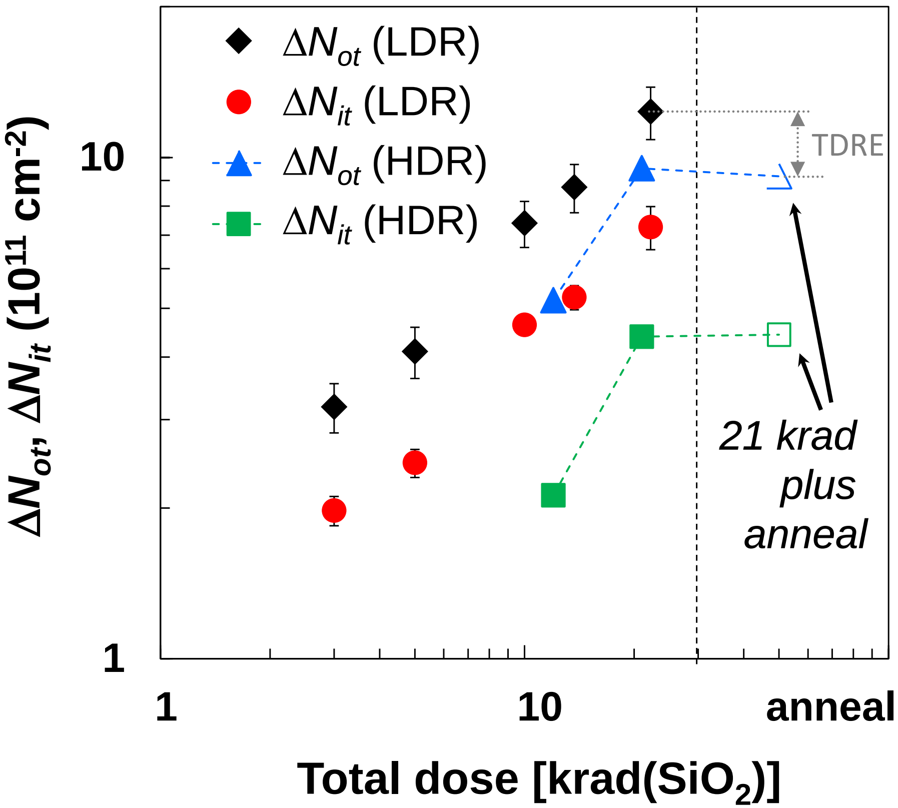




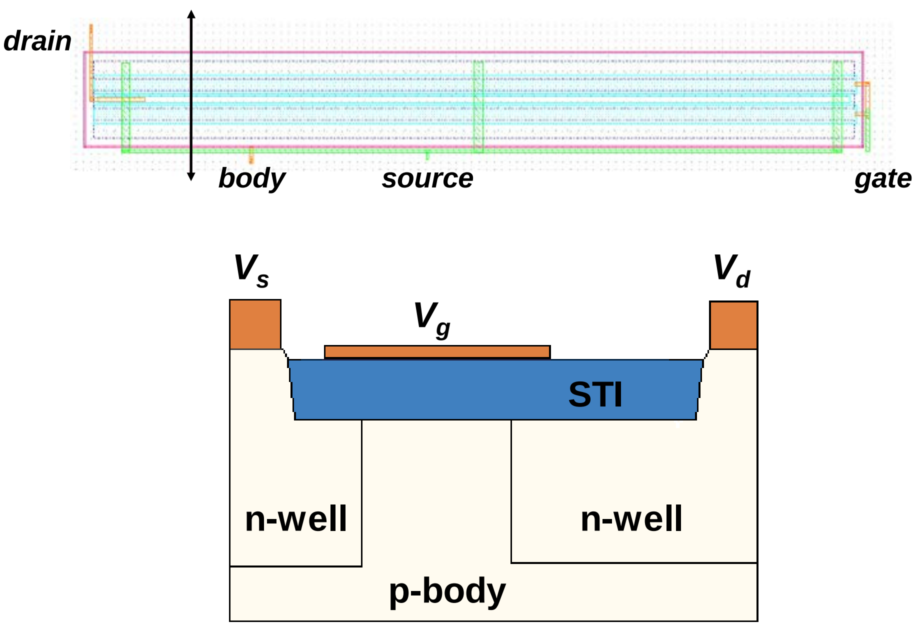
(after N. Rezzack et al., Microelectronics Rel. 2012)

- 90 nm: $I_{Off\text{-}State}$ increases with TID due to charge trapping STI and V_{th} reduction
- 65 nm: $I_{Off\text{-}State}$ current is unchanged with TID due to higher body/channel doping

Dose-Rate Effects 90 nm FOXFETs



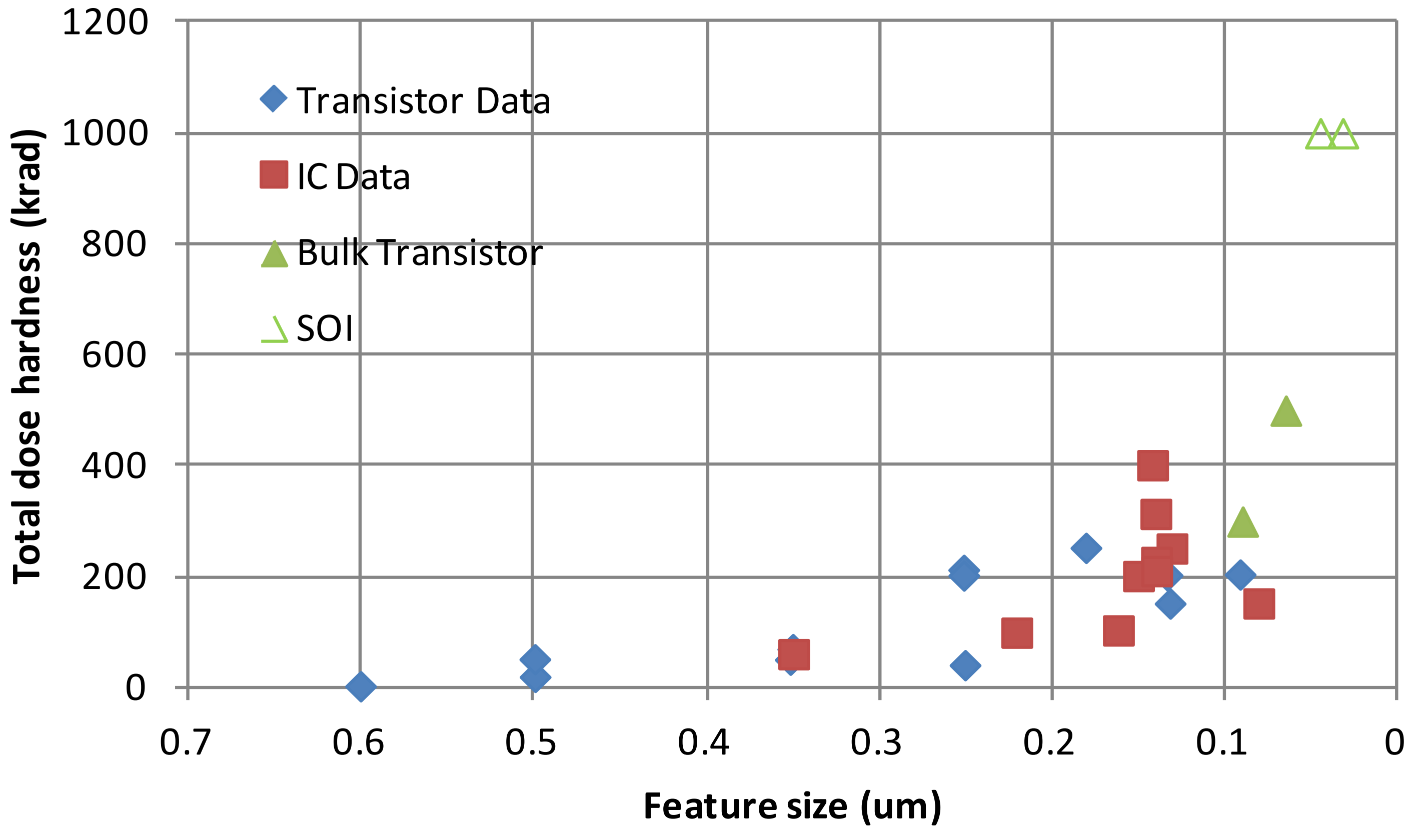
n-well-to-n-well FOXFETs



(After I. S. Esqueda et al, IEEE TNS 2011)

Dose-rate effects in advanced CMOS circuit response may be minimal, but should be considered in cases where STI leakage is a dominant mechanism

Scaling Trends for Digital CMOS technologies



(from P. Dodd et al., IEEE TNS 2010 + some recent data)

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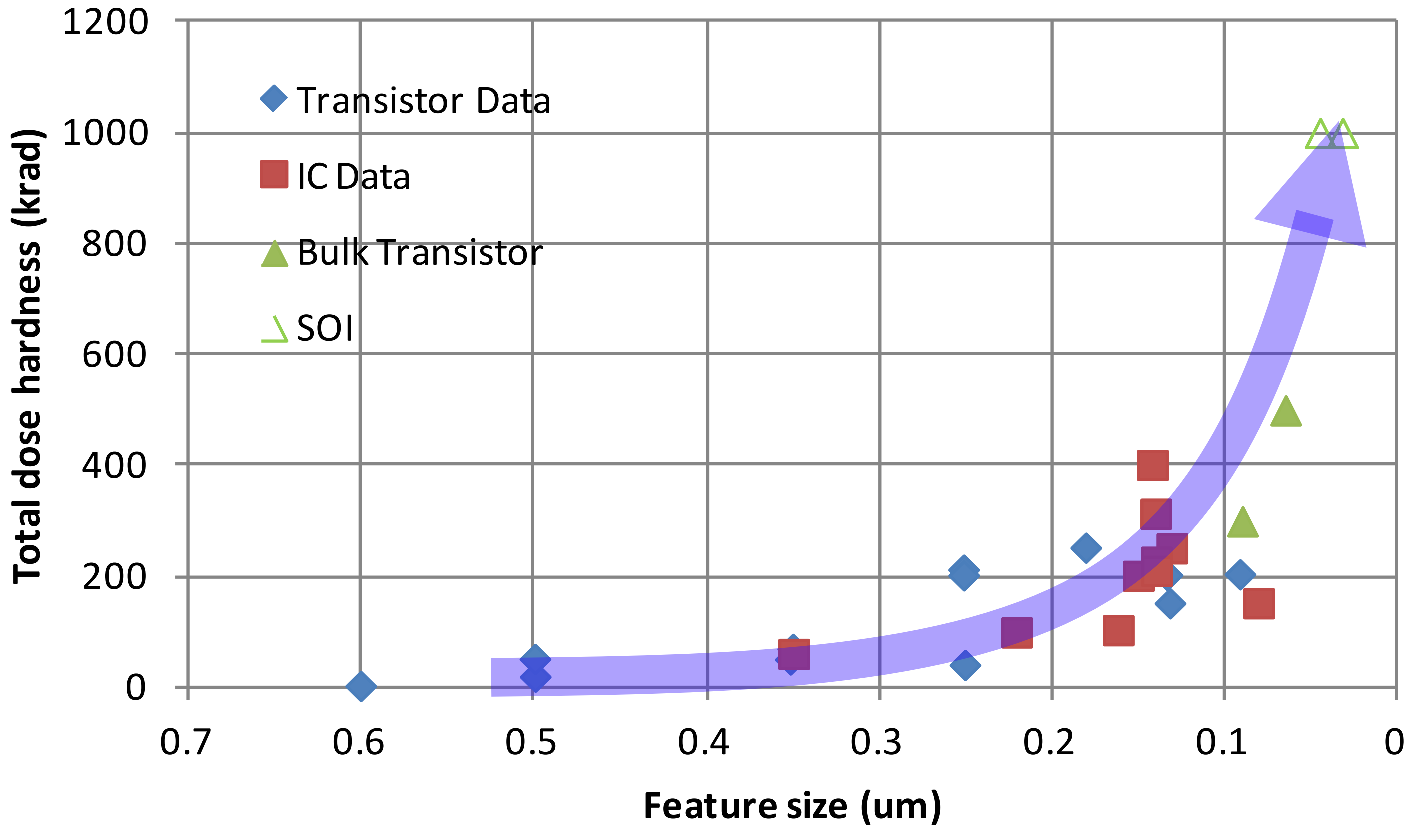

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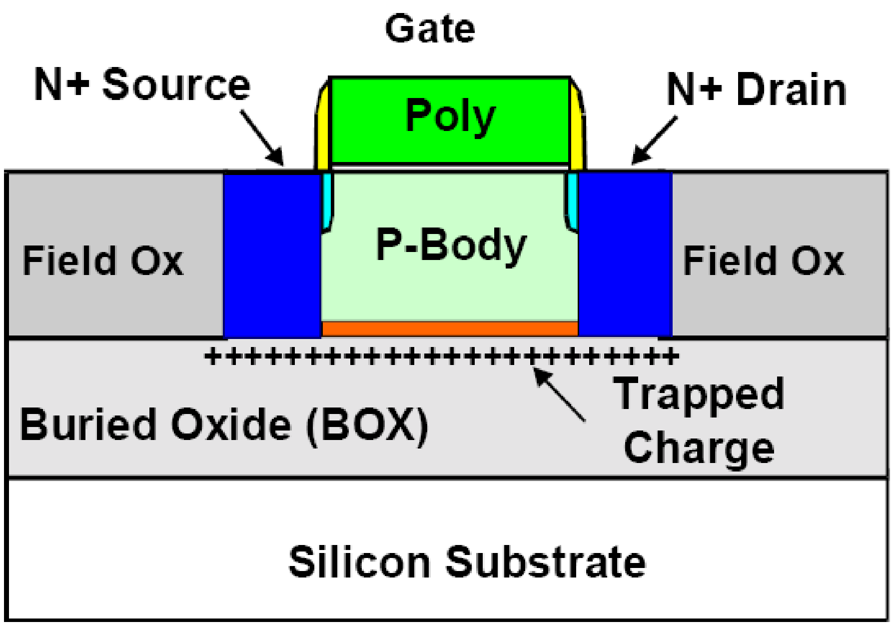
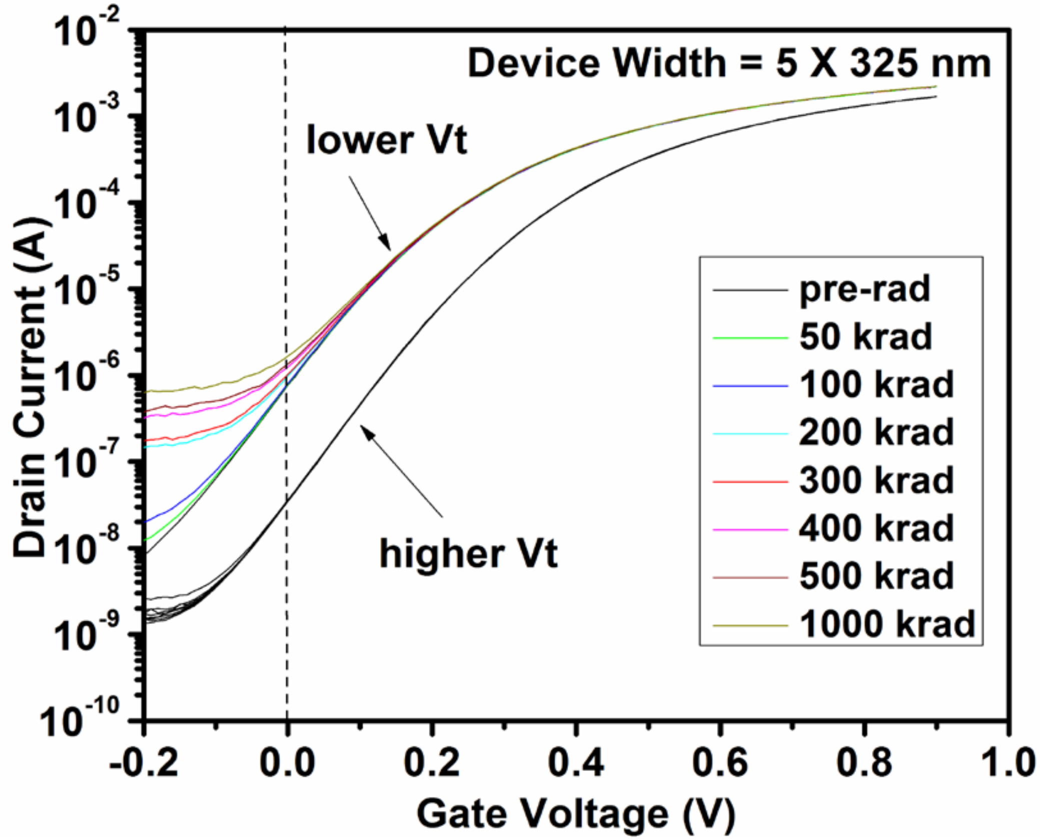
TID Effects in SOI

SOI MOSFET are sensitive to TID due to the presence of the buried oxide layer, where positive charge build-up can take place and lead to:

1. formation of a back-channel leakage path
2. threshold voltage shift due to electrical coupling between the front gate terminal and the back (parasitic) gate terminal



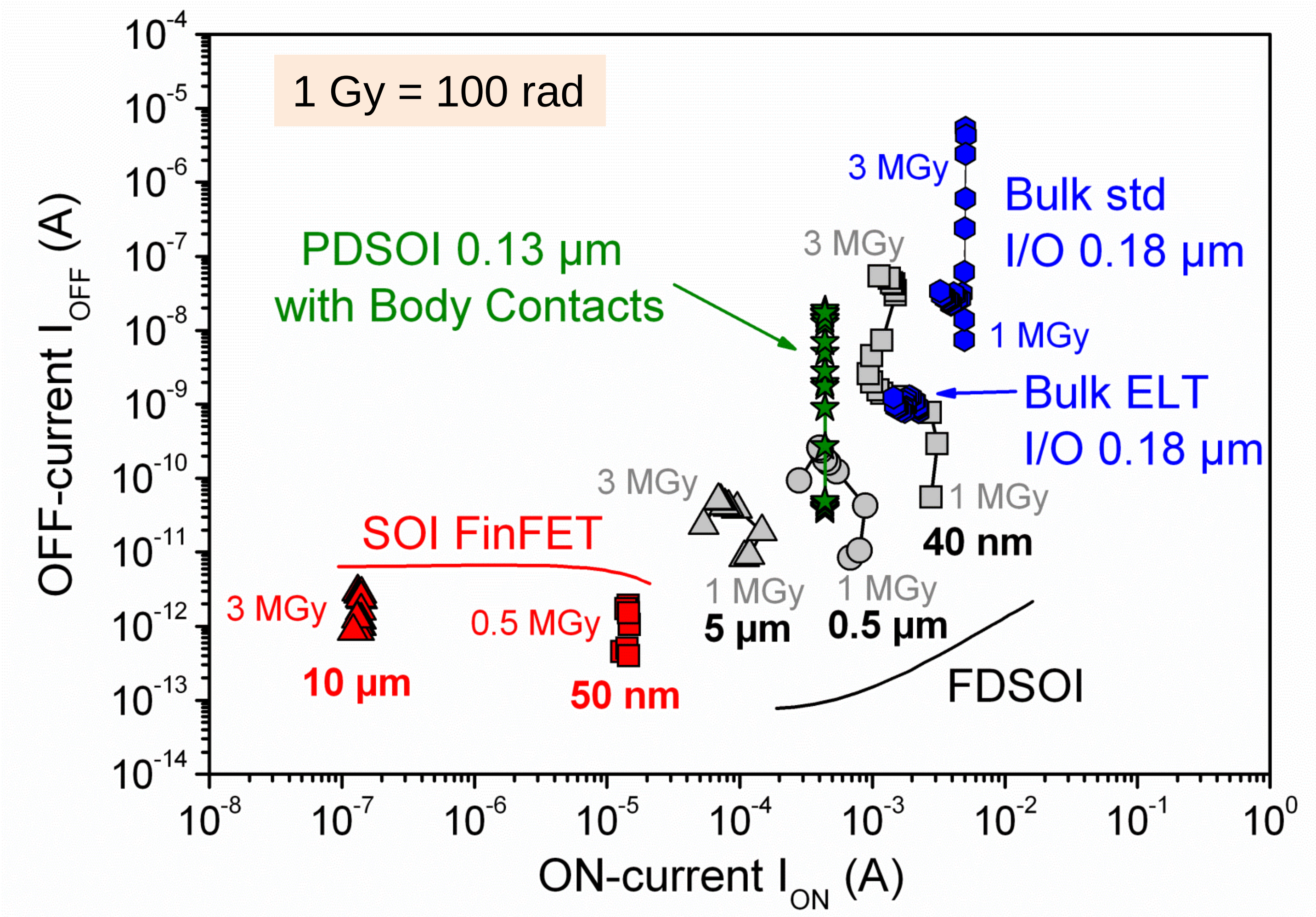
32 nm PDSOI data



(after N. Rezzack et al., IEEE SOI conference 2012)

Only minor sensitivity to TID is observed
Low VT devices show minor increased in Leakage

TID and Advanced Technologies



(after M. Gaillardin et al., IEEE RADECS 2012)

Key points

- Degradation mechanism induced by total dose in MOS transistors involved N_{ot} and N_{it} buildup in its gate oxide
- For CMOS with thinner oxides (< 6 nm), buildup in field oxides normally dominates degradation
- N_{it} negligible for scaled devices with thin gate oxides
- TDEs have to be considered for TID evaluation practices: particularly dose-rate selection and annealing considerations
- Annealing of N_{ot} is a long term process dependent on temperature, applied electric field and spatial distribution of traps
- ELDRS has been observed on few modern CMOS technologies. However, Enhancement Factor (EF) is low
- Moving forward with more advanced technologies, the robustness of technology to total dose effects become exponential

For extreme conditions, i.e. temperature and total dose, many CMOS commercial technologies will cover a wide range of missions

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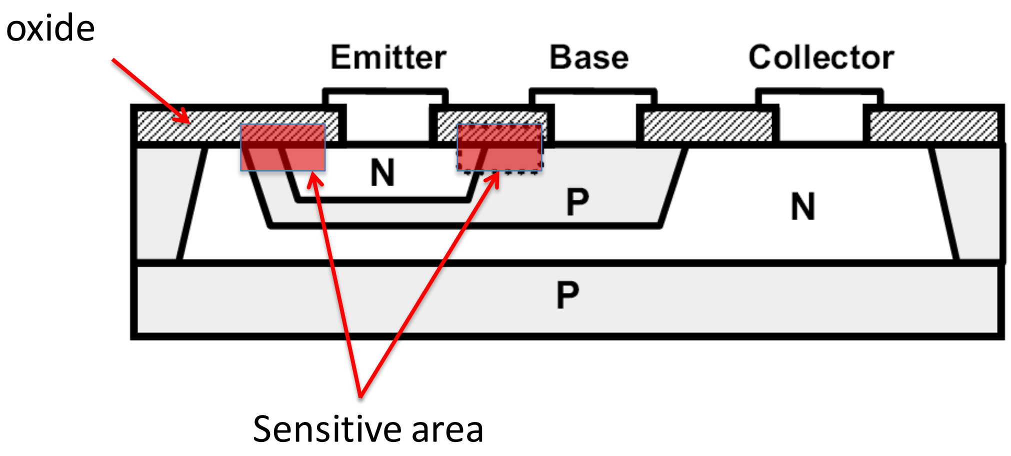
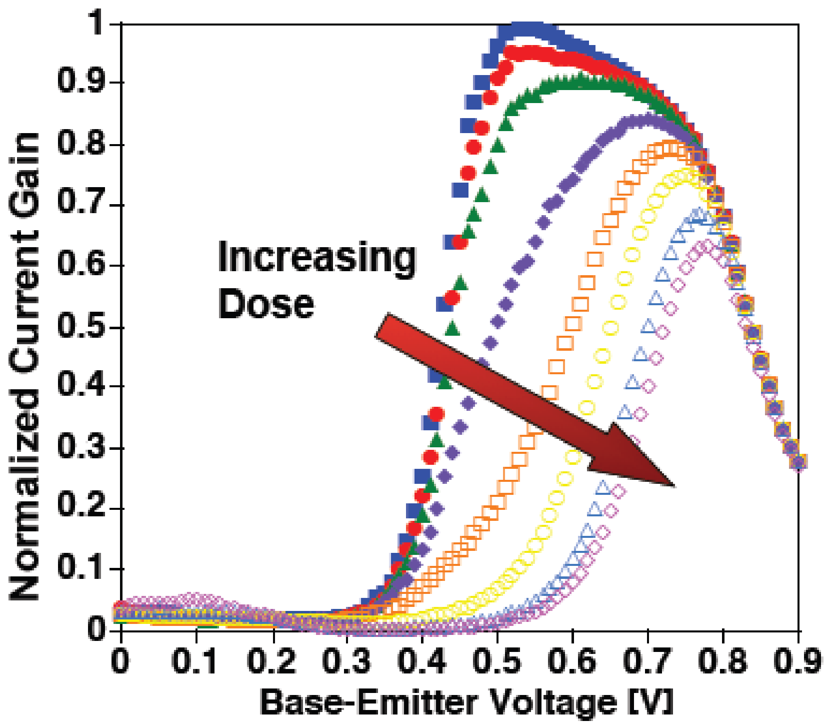
BJT TID Response

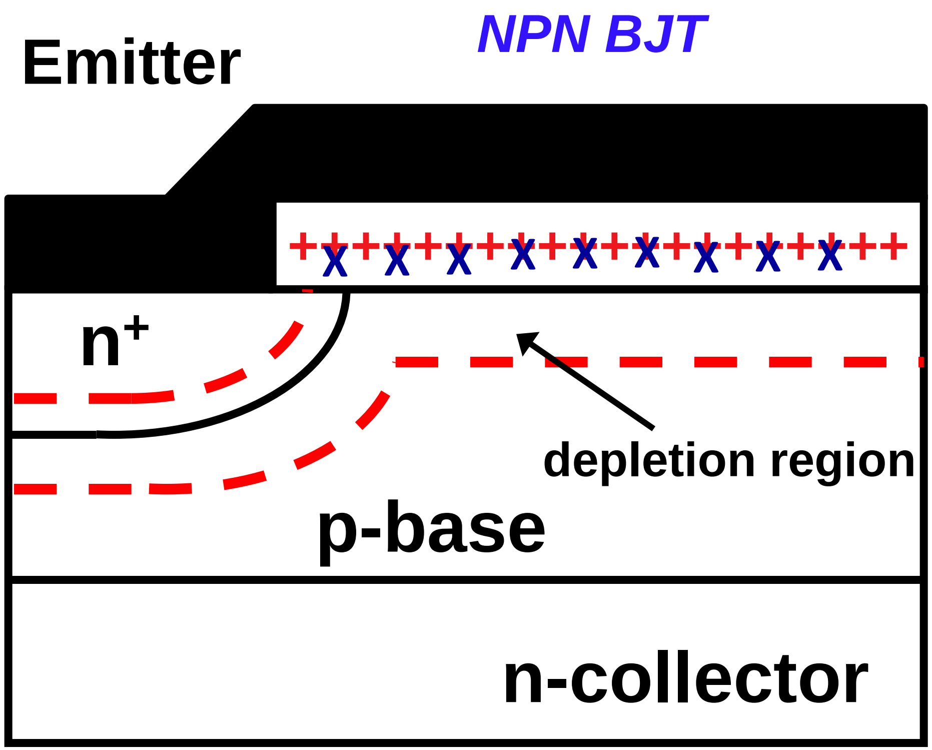


TID effects in bipolar devices are also due to charge trapping in the oxide and creation of interface traps.



In bipolar transistors, TID induces an increase of the base current that can lead to a decrease of the current gain

TID Effects in BJTs



N_{ot} (+) depletes the *p*-type base surface, increasing area of recombination (depletion region)

N_{it} (X) increases surface recombination

In PNP BJTs, base current is primarily a function of N_{it} buildup alone

$$\Delta I_b = q\int_{A(N_{ot})} R_s(N_{it})\,dA$$

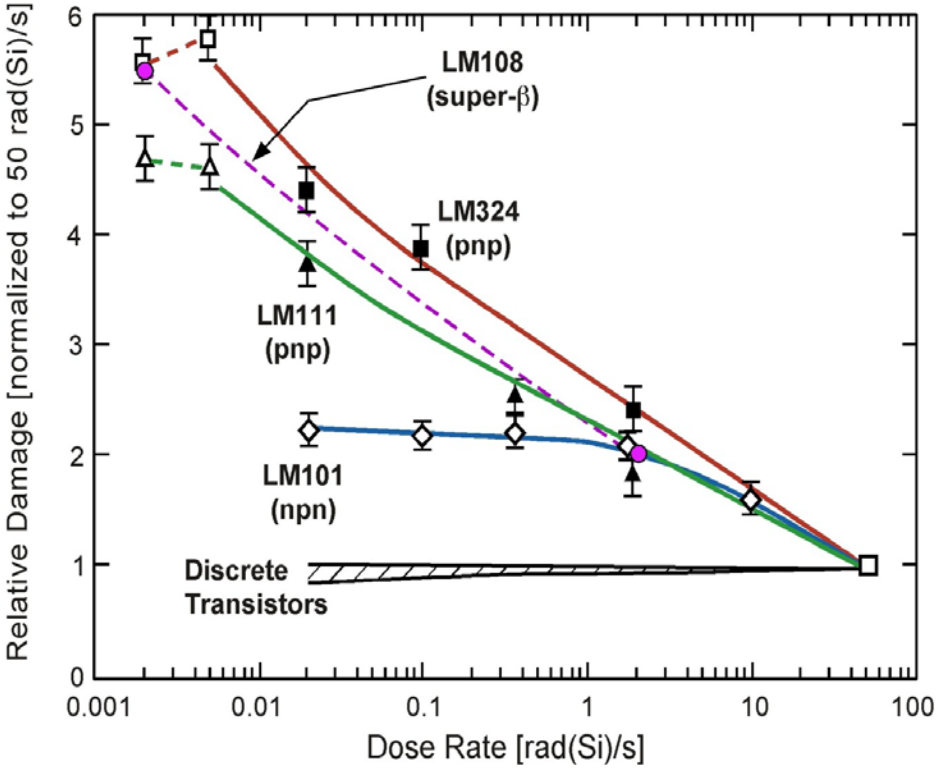
Low Dose Rate
ELDRS

ELDRS = Enhanced Low Dose Rate Sensitivity = more degradation at low dose rate than at high dose rate for some total dose

Damage relative to 50 rad/s as a function of dose rate

Vertical scale is low dose rate enhancement factor (EF)

Circuits with L-pnps have higher EF



(after A. H Johnston et al., IEEE TNS 1994)

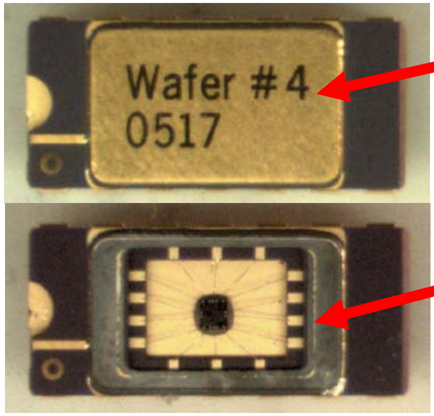
The main issue related to bipolar technologies is ELDRS

Characteristics of ELDRS

- True Dose Rate Effect (TDRE) vs Time Dependent Effect (TDE)
- Bias conditions
- Complex circuit effects
- Effects of post metallization processing
  - Final passivation
  - Pre-irradiation Elevated Temperature Stress (PETS)
  - Molecular hydrogen (H_2)

Source of H_2 in IC Package

- Si interacting with H_2O trapped in package to produce H_2
- H_2 out-gassing from Gold Plated Kovar



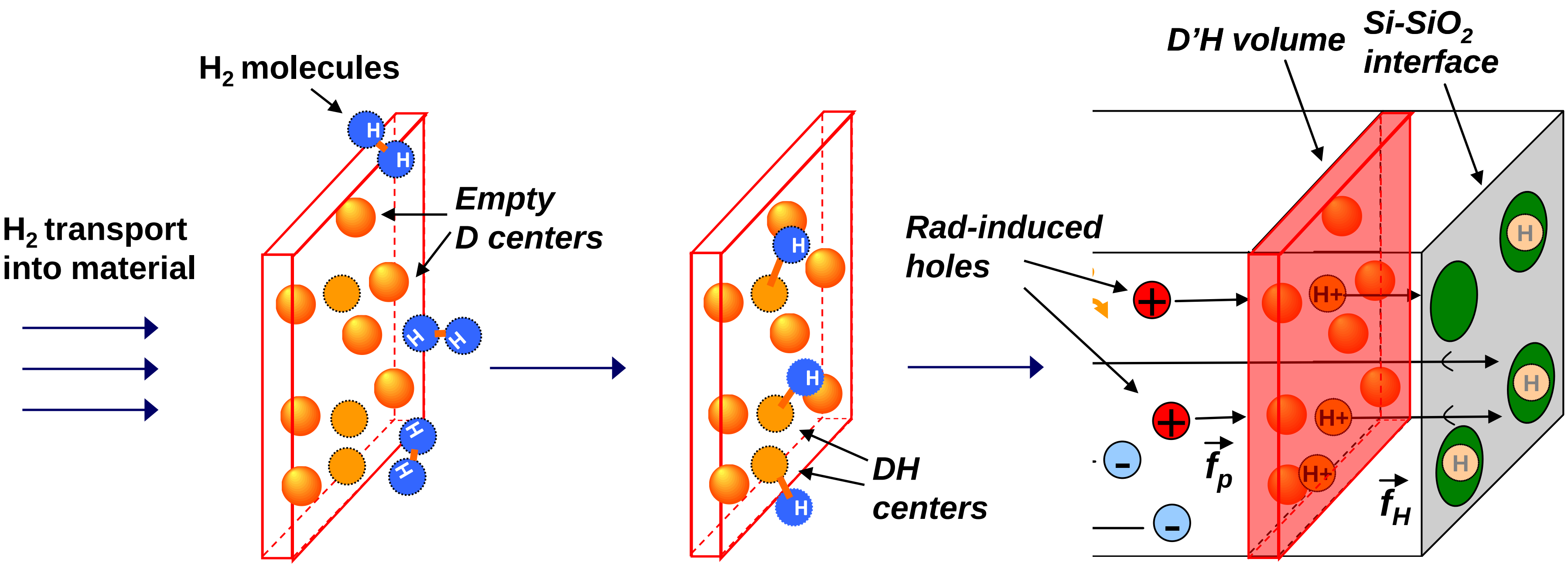
Gold Plated Kovar lid

Gold Plated die substrate

- H_2 is introduced during die attach and by forming gases during packaging processes

Solution to H_2 exists (thermal treatment, getters,…) but no clear guideline or limit as to what level of H_2 might be considered acceptable in sealed packages

Impact of Molecular Hydrogen

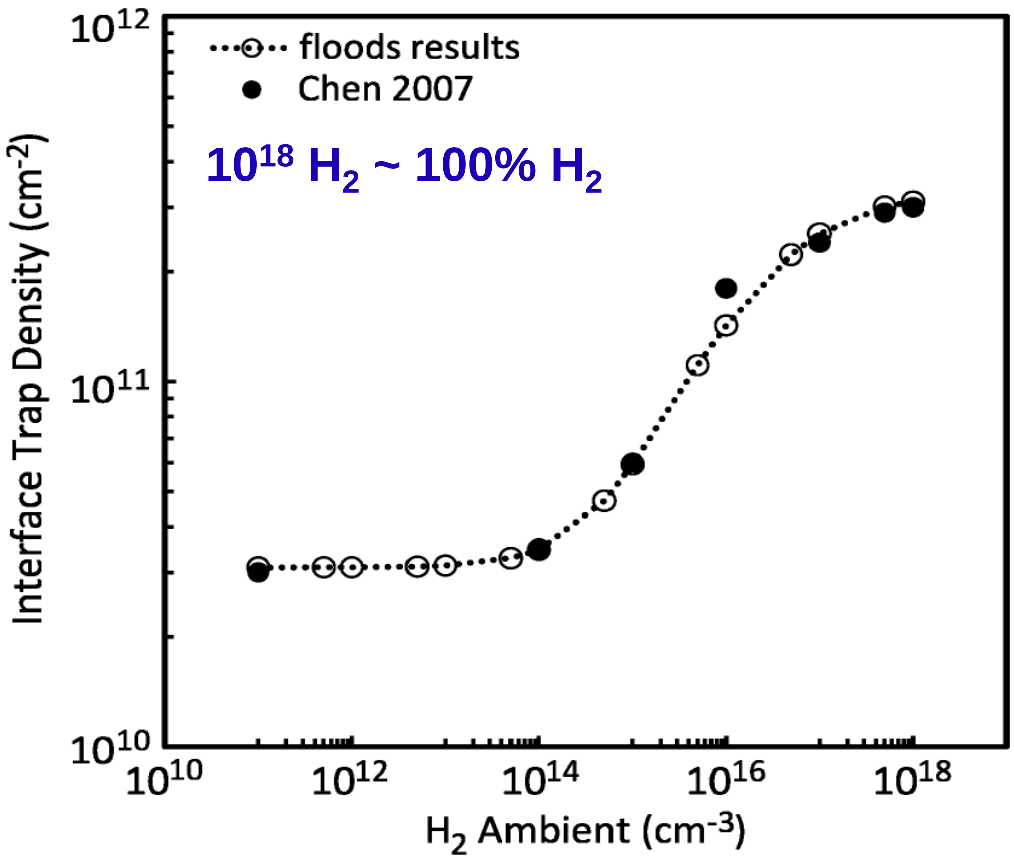


$$H_2 + 2D \rightarrow 2DH$$

$$N_{DH} = \frac{k_1 \left(N_{H_2}\right)^{1/2}}{1 + k_2 \left(N_{H_2}\right)^{1/2}}$$

Molecular hydrogen reacts with empty D centers to generate more DH centers

H_2 Increases N_{it} Degradation



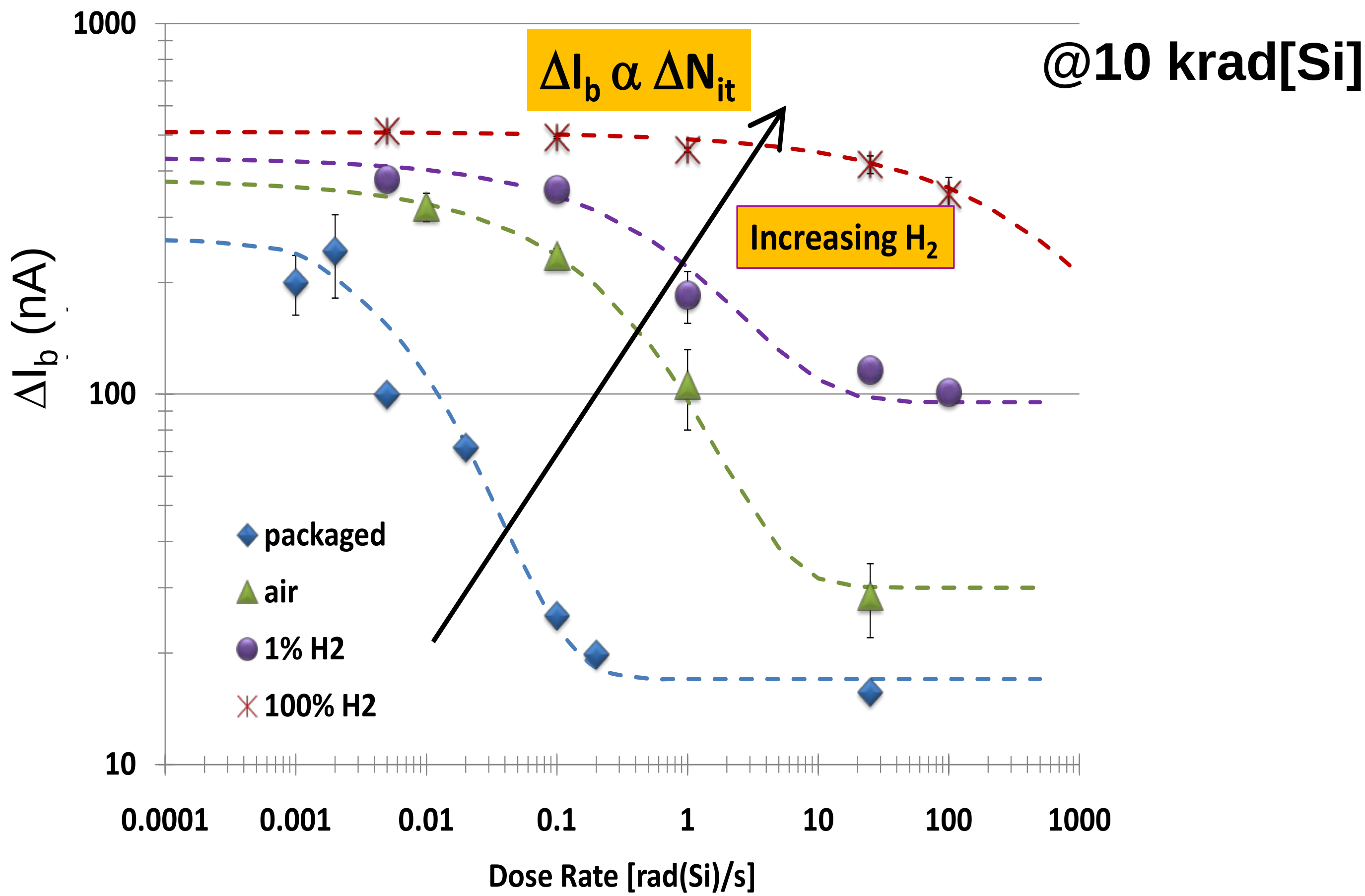
Fit of analytical model describing interface trap formation due to excess H_2

First principles calculations allow describing the complex interplay among defects (with their associated energy levels) in SiO_2

(after Chen et al. IEEE TNS 2007 and Rowsey et al. IEEE TNS 2011)

Externally Applied H_2

NSC LM193; Virgin part, nitride, no H_2 in package; PG, nitride removed, p-glass remained, 0% (in air), 1% &100% (in sealed glass tube)



(after Pease et al. IEEE TNS 2009)

Externally Applied H_2

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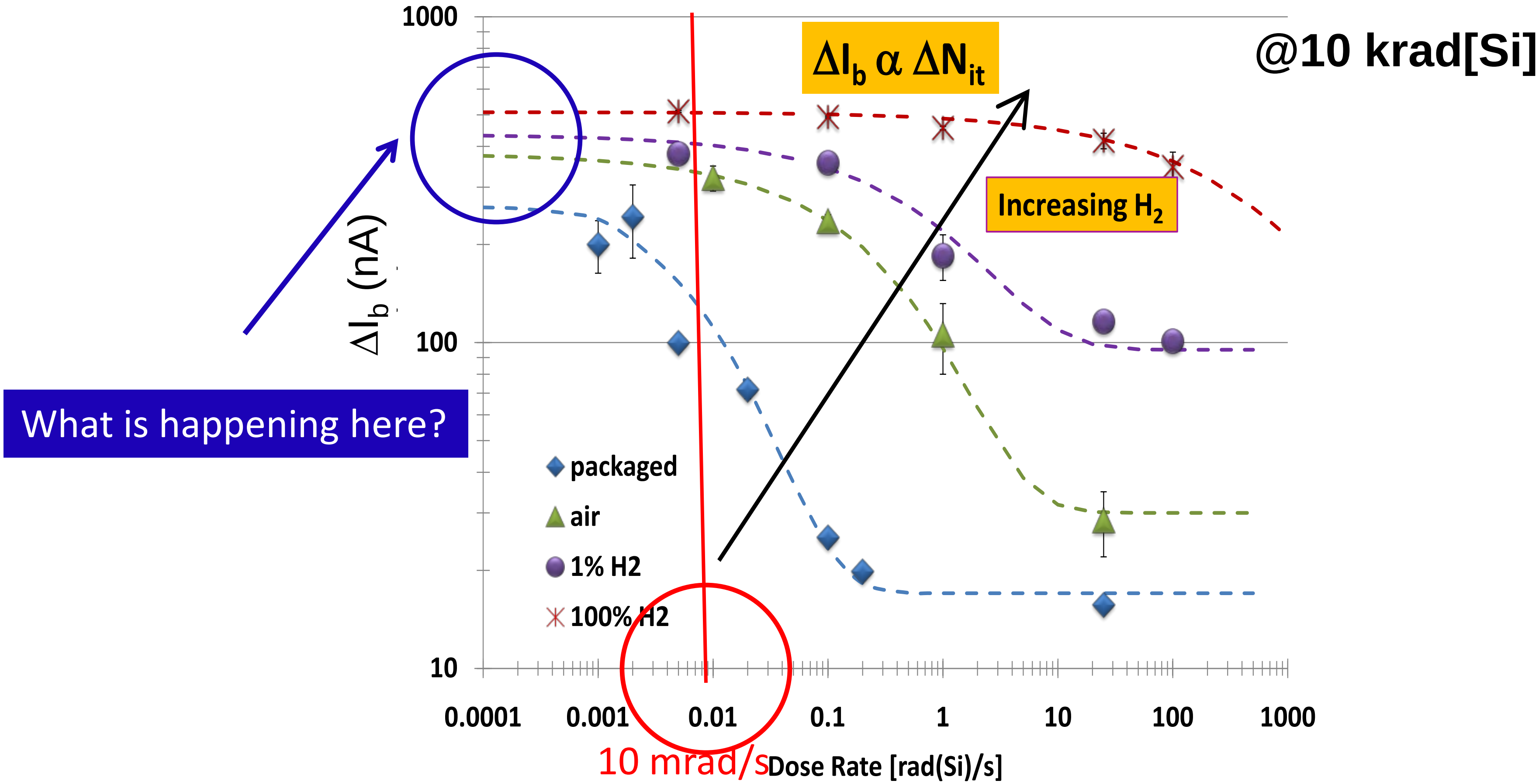
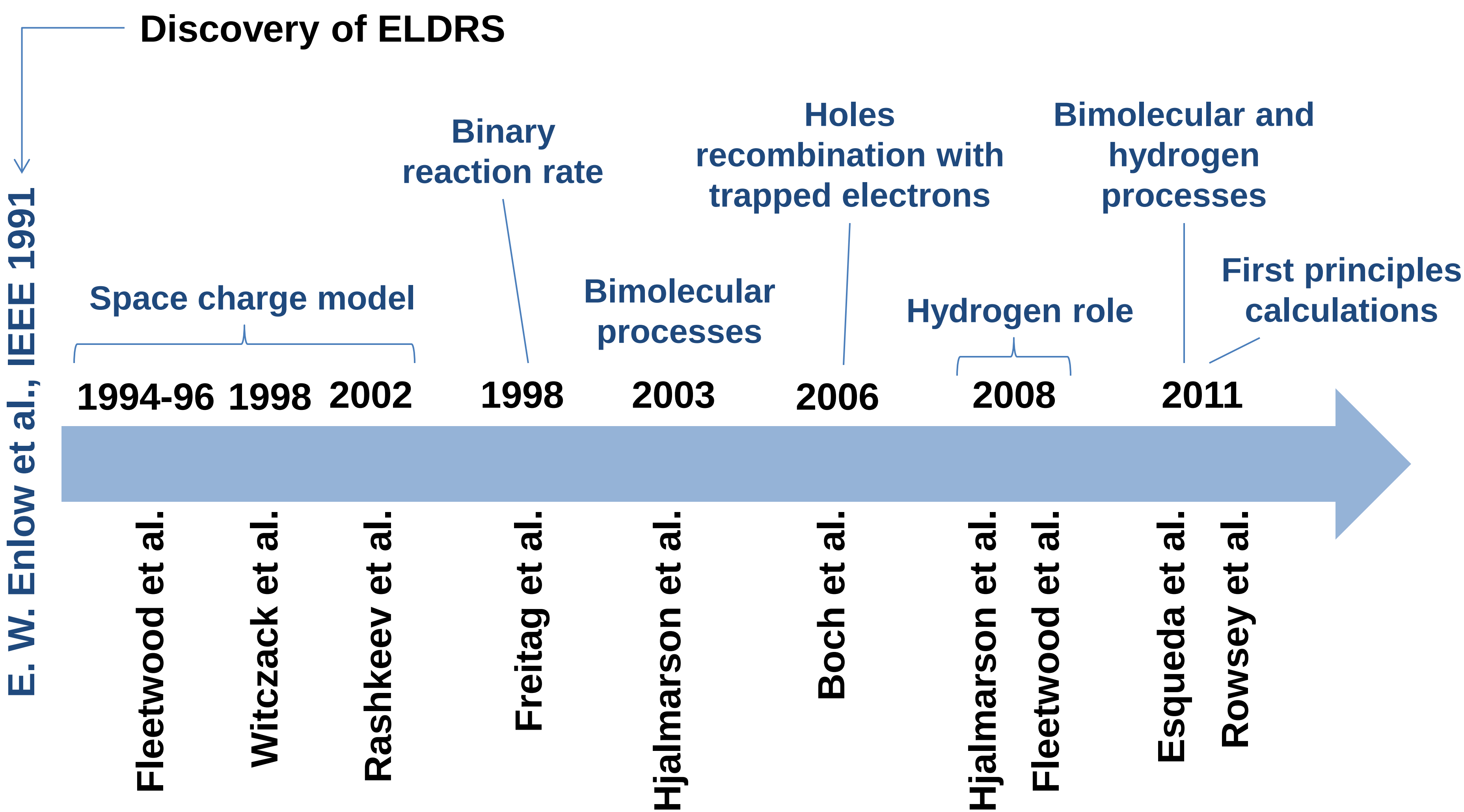


(after Pease et al. IEEE TNS 2009)

ELDRS Models History



Modeling of ELDRS

- Hole trapping:

$$D_A + p \rightarrow D_A^+$$
$$D_A^+ + n \rightarrow D_A$$

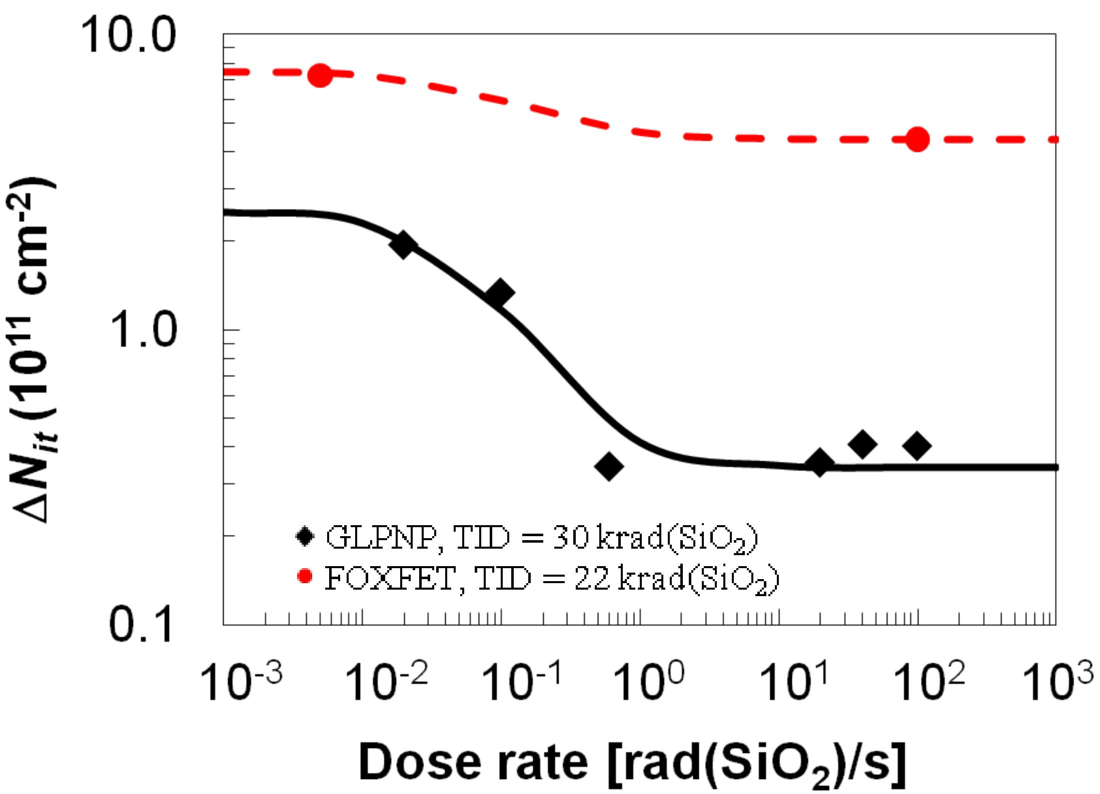
- Proton Release:

$$D_B H + p \rightarrow D_B H^+$$
$$D_B H^+ \rightarrow D_B + H^+$$
$$D_B H^+ + n \rightarrow D_B H$$

- De-passivation:

$$P_b H + H^+ \rightarrow P_b^+ + H_2$$

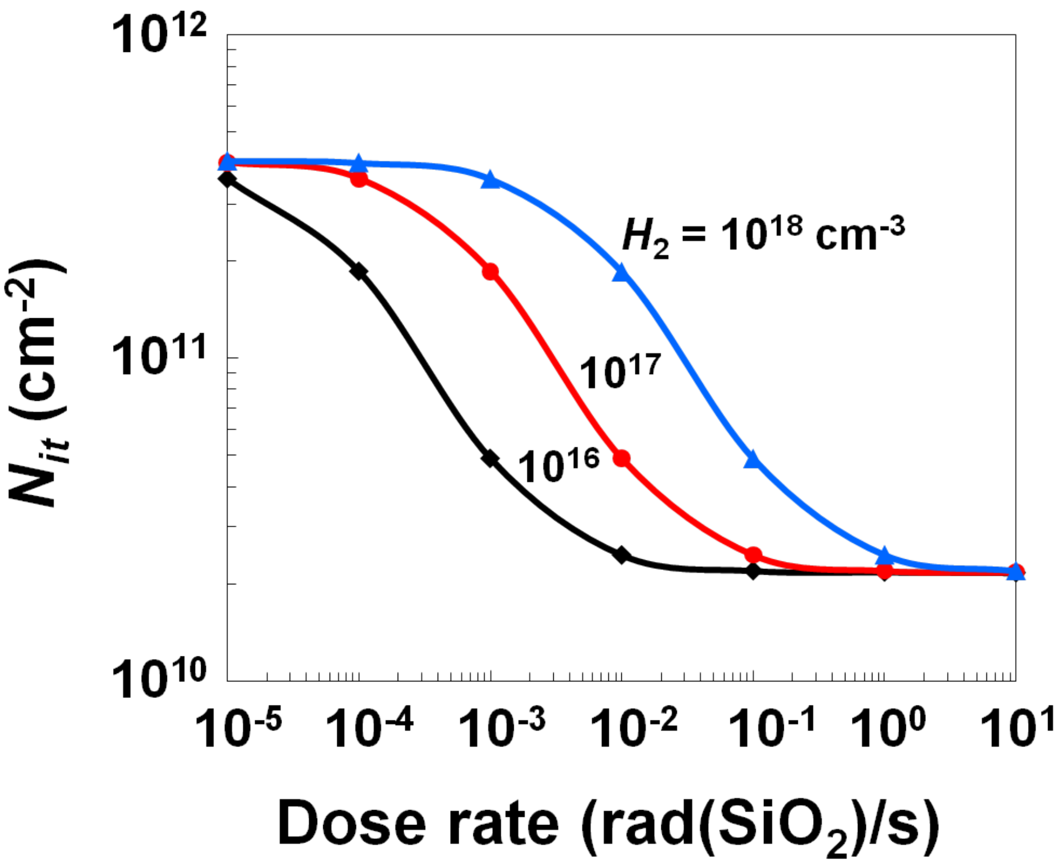
n = electron
p = hole



Competition between reactions in red result in dose rate effects

Hydrogen/ELDRS

- H_2 cracking
  - $D_C + p \rightleftarrows D_C^+$
  - $D_C^+ + H_2 \rightleftarrows D_C H + H^+$
  - $D_C H + p \rightarrow D_C H^+$
  - $D_C H^+ \rightleftarrows D_C + H^+$
  - $D_C^+ + n \rightarrow D_C$

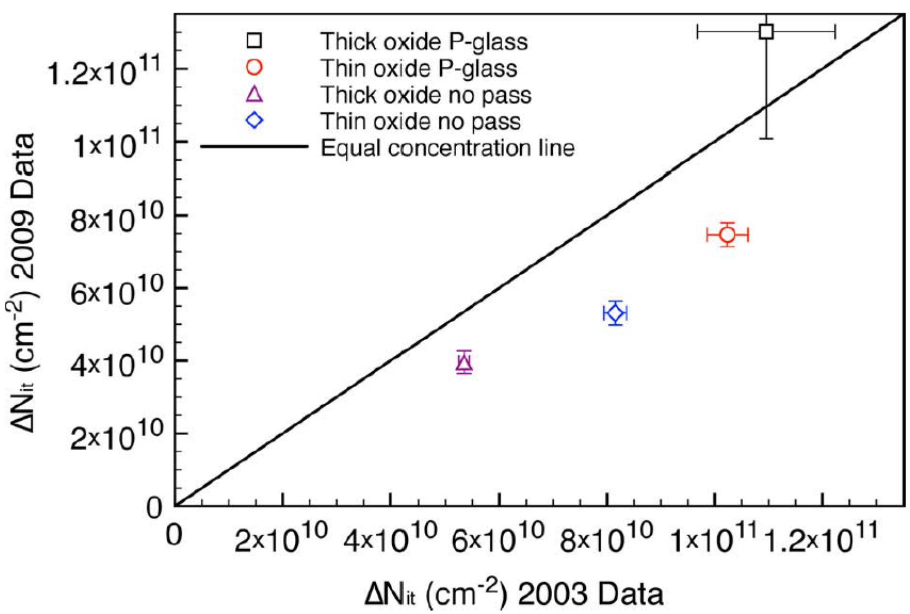


By introducing H_2 cracking, it is possible to describe the effect of H_2 on the buildup of interface traps and on the dose rate response

Aging and Total Ionizing Dose Effects

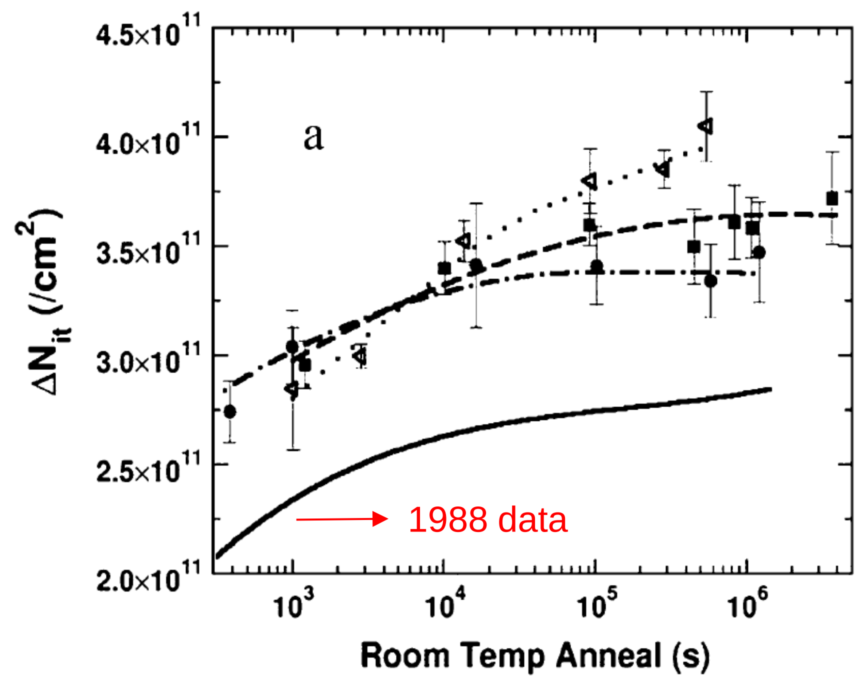
Aging and degradation trends are still unclear – research studies are on-going

LPNP Bipolar



(After D. R. Hughart IEEE TNS 2009)

MOS



(After I. J. Batyrev IEEE TNS 2006

Water, hydrogen diffusion and device properties might affect total dose response

Key Points

- Mechanisms of degradation in bipolar involve N_{ot} and N_{it} formation in SiO_2. Gain degradation is the primary effect; particularly under low bias
- Bipolar are sensitive to ELDRS. The dose rate sensitivity result from the combined effects of space charge and recombination mechanisms
- Oxide thickness, density, and location of hole traps and hole capture cross-sections affect the buildup of fixed charges near the Si-SiO_2 interface
- Experimental and modeling studies indicated that saturation of N_{it} in presence of H_2 vary based on the trapping characteristics and H_2 concentrations in the oxide
- With a minimum amount of hydrogen, between 0.1%–0.5%, the degradation can be significantly enhanced
- Aging might affect the total dose response of electronics

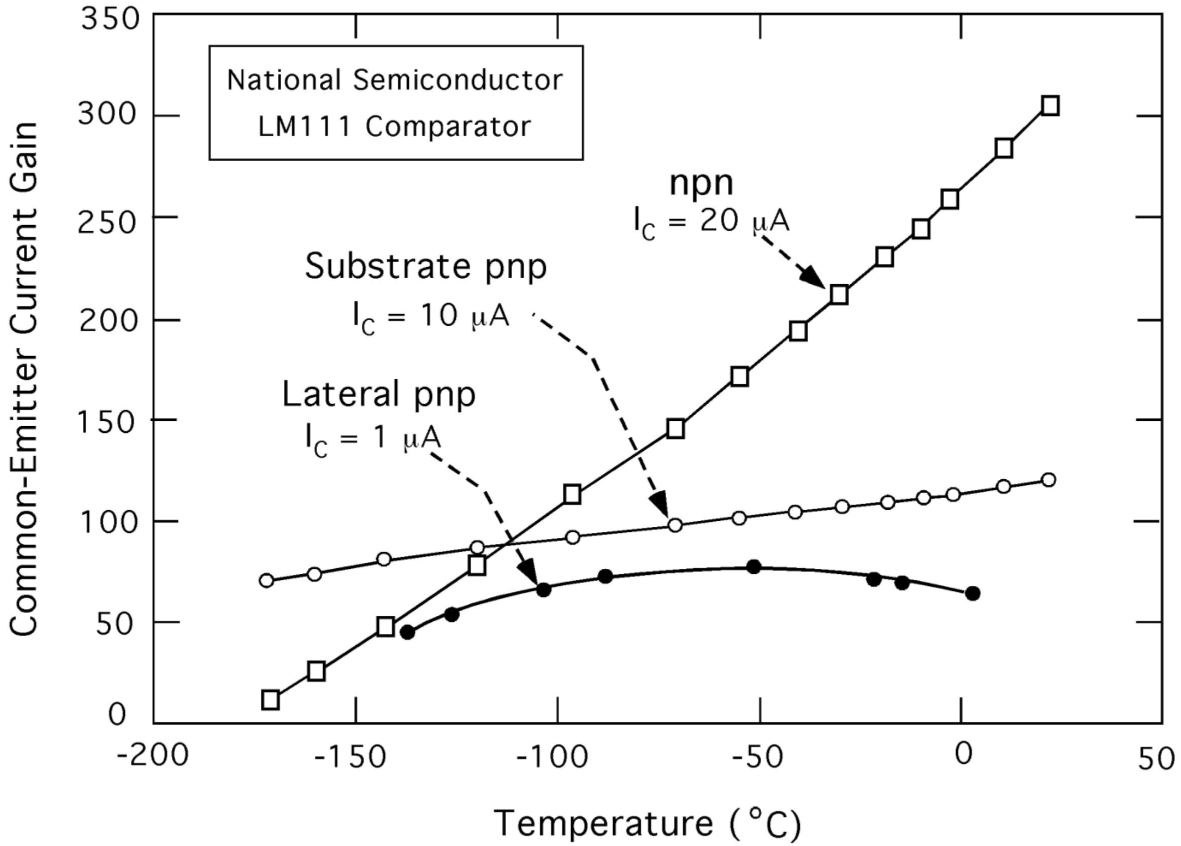
Very few bipolar devices work properly at total dose level beyond 250 krad

Outline

- **Dose and Dose-Rate Effects in Electronics**
  - TID and damage processes in SiO_2
  - Effects in MOS devices
    - Annealing, time dependent and dose rate effects
    - TID and CMOS scaling
  - Effects in Bipolar Devices
    - Update on ELDRS: mechanism and modeling
    - Hydrogen contamination
    - Aging
- **Pushing the limits to extreme conditions**
  - Low temperature to improve TID performance
  - Challenges for high dose environments
  - Radiation hardness assurance

26th Annual EQ Technical Meeting
Clearwater Beach, Florida
November 12-14, 2014

Low Temperature

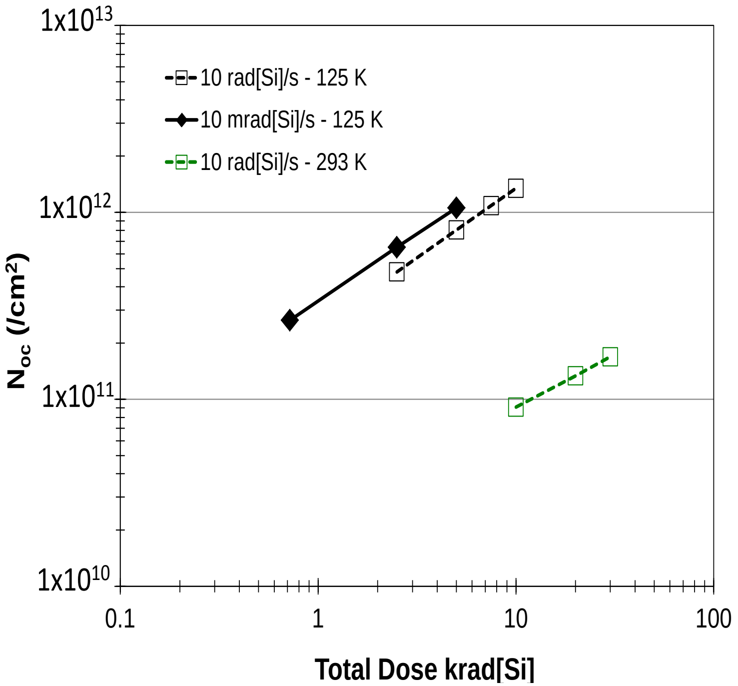


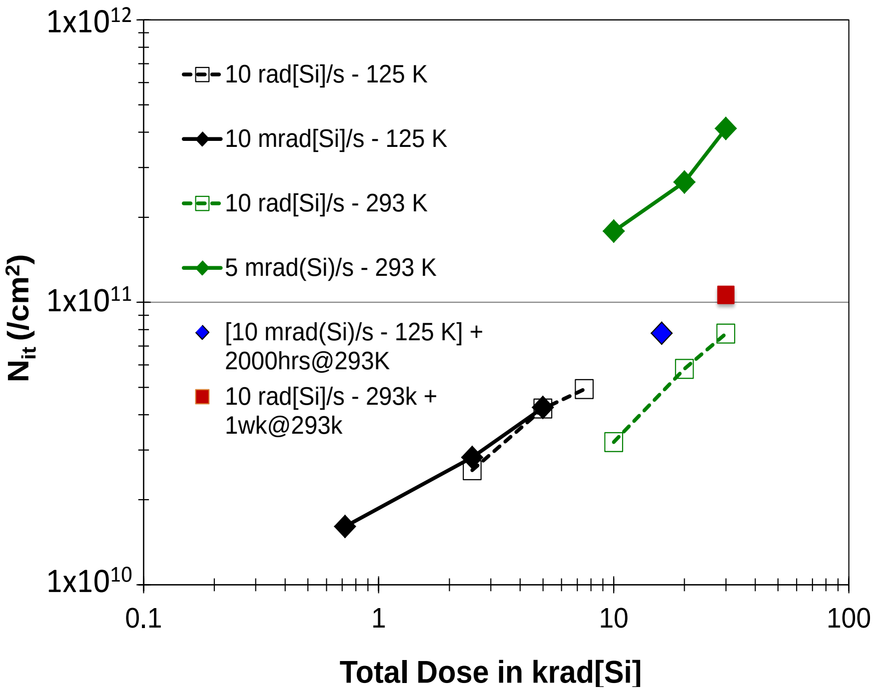
(after A. H. Johnston, IEEE TNS 2012)

Substrate pnp gain decreases only about 30% at low temperature, while the npn gain decreases more than a factor of ten at -160 °C

Mechanism: Impact on N_{ot} & N_{it}

Studies performed on Gated Lateral PNP test structures

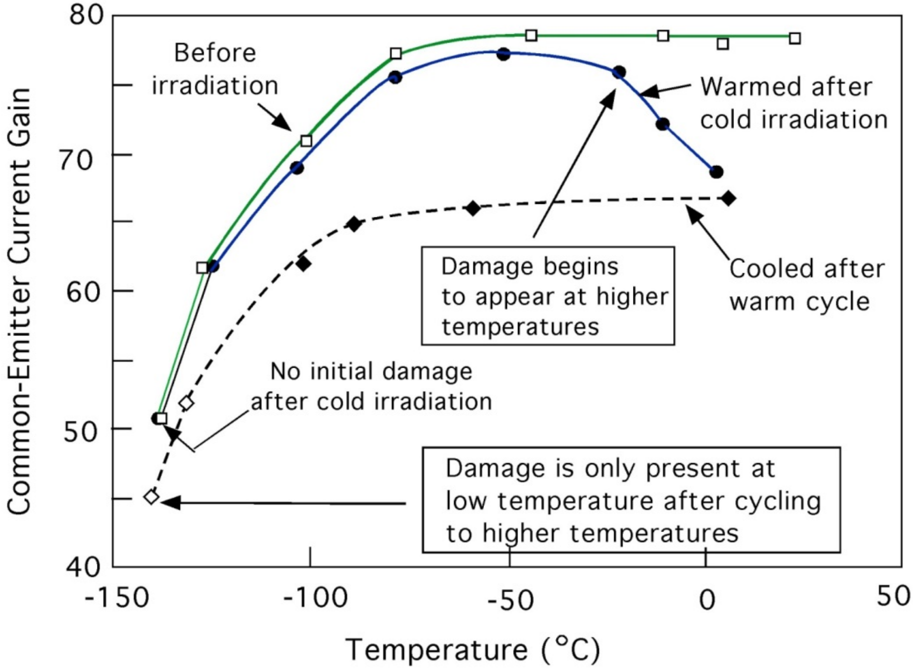


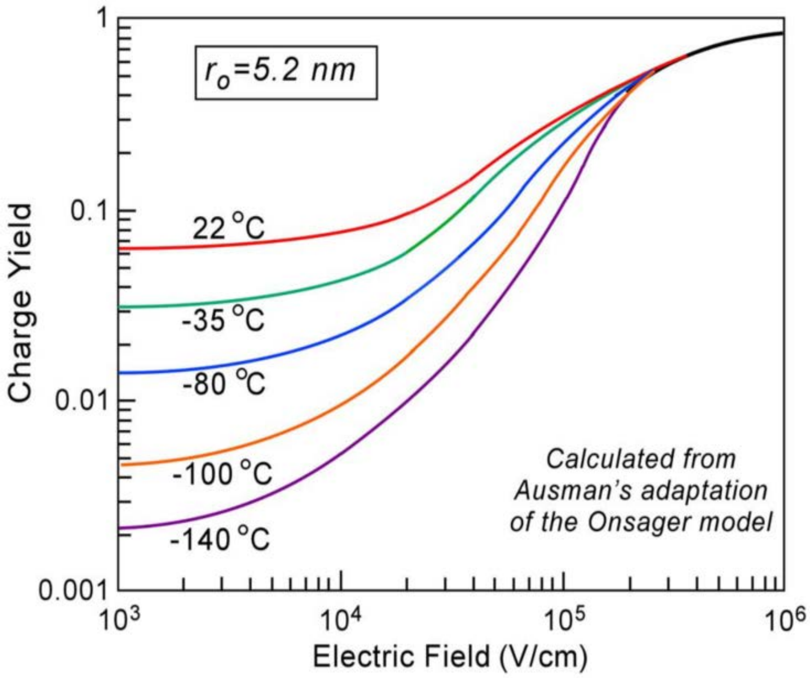


(after Adell et al. IEEE TNS 2012)

- @125K Not buildup is high because hole are “immobile” in SiO_2
- @125K Nit buildup is minimal and EF is reduced

Gain Damage Variation across Temperature





- The holes remains immobile until the part reaches temperatures above -50 °C.
- Damage is only present at low temperature after cycling to higher temperature

Key Points

- Dose rate is often not constant, dose rate selection for qualification is a challenge.
  - Using the lowest dose rate can lead to extremely conservative tests.
- Commercial bipolar electronics can operate at temperatures lower than the mil-spec range.
  - Low temperature performance depends on circuit design.
- The mechanism of degradation at low temperature is controlled by hole transport and mobility; and charge yield is greatly reduced under low field conditions.
- The ELDRS mechanism is greatly suppressed at very low temperature due to the suppression of hole and proton transport.

Many technologies behave properly at low temperature and ELDRS is eliminated

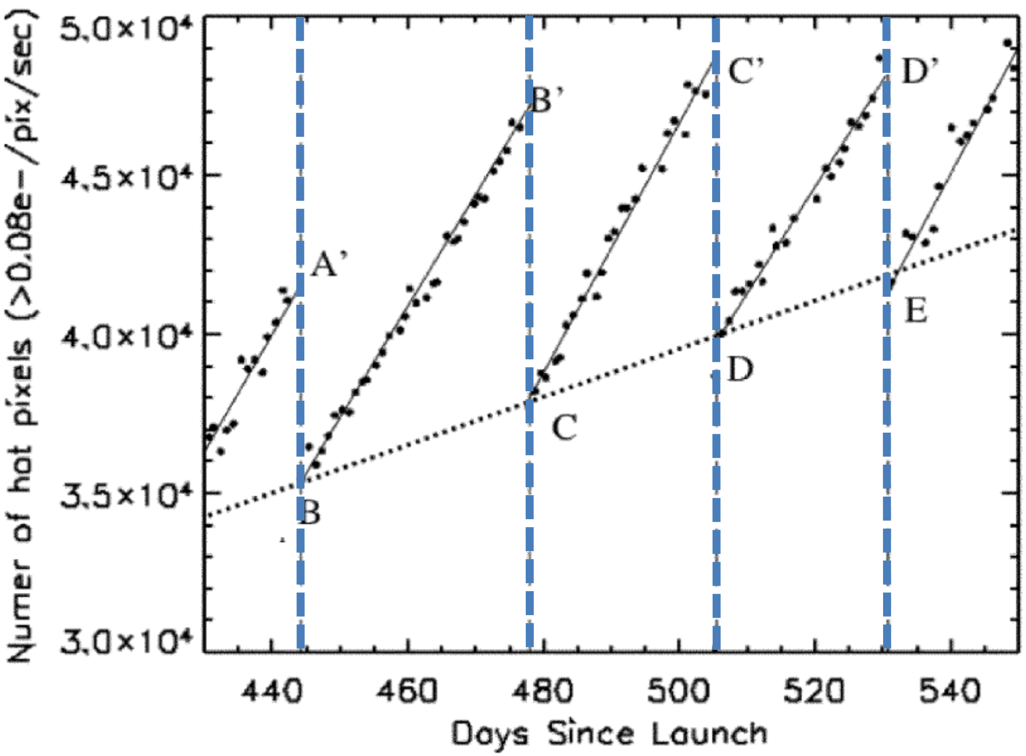
New challenges

1. New solutions must be found for high dose environment since only few devices (particularly bipolar devices) work properly at total dose level beyond 250 krad

2. Radiation Hardness Assurance need to be implemented and the issue of adequate margins need to be taken into account.

Annealing Example

Annealing benefits were demonstrated in the Hubble Space Telescope (HST) in order to anneal hot pixel in CCD.



a monthly anneal to about +20°C for a few hours

(after M. Sirianni et al., IEEE REDW 2007)

All instruments have reported a significant benefit despite the loss of observational time

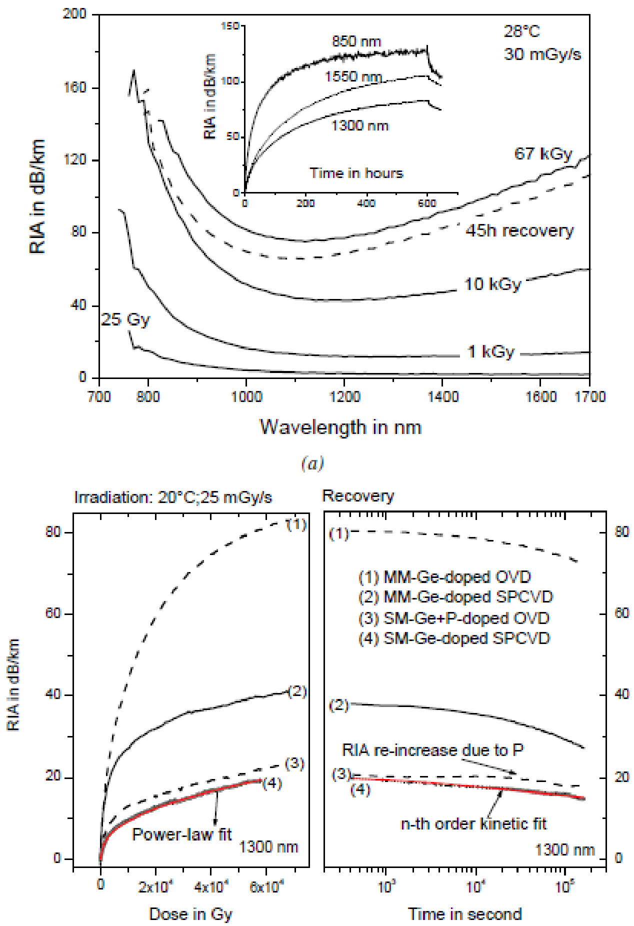
Regeneration for High Dose Missions

Example on Active Pixel Sensor (APS)

(after S. Dhombres et al., NSREC 2014)

When annealing steps are used, lifetime APS can be extended to 1Mrad whereas failure is observed at 180 krad without annealing

Optical Fiber for Nuclear based system



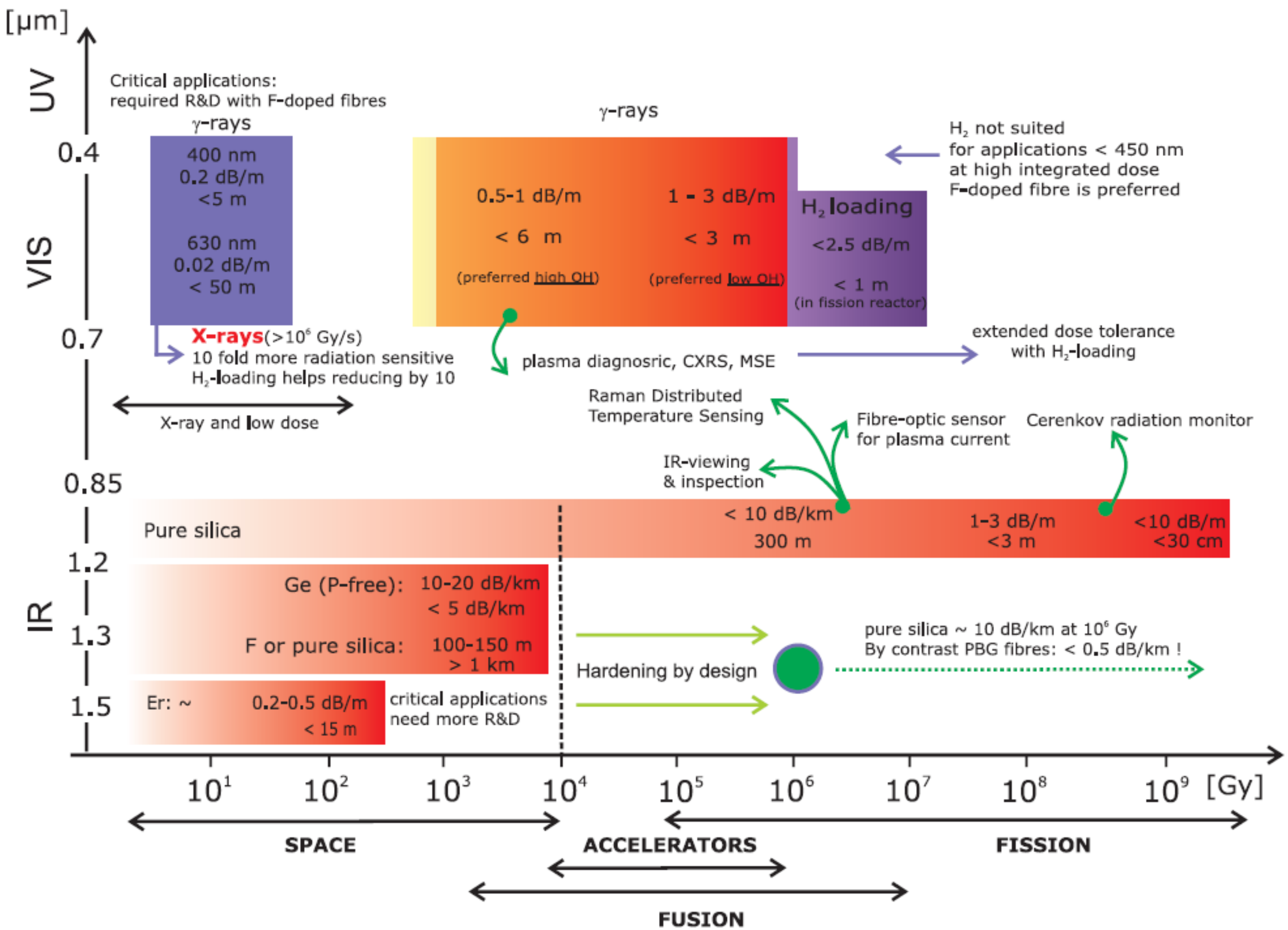
(a)
(b)

- **Attractive:** immunity against electromagnetic interferences, high temp resistance, high sensitivity and accuracy, distributed sensing, compactness, low intrusiveness, passive devices, high bandwidth and multiplexing capabilities
- **Optical Fiber System** remains marginal in applications where radiation is a concern
- **Main effect**: "darkening" of the optical fiber called Radiation Induced Absorption (RIA)
- **Optical Fiber** under radiation is not driven by the sole RIA tolerance but on application requirements (spectral range) and the context of use (temperature, total dose, irradiated length an dose rate)

Radiation hardening of Fibers was demonstrated when using selected wavelength

Photonic technologies are being put on trial by other civil application fields

Optical Fiber for Nuclear based system



Length indicated refers to a 3 dB loss due to RIA.

Data refer to high dose rate conditions (except for space applications) and

30 < T ^{0}C < 150 depending on the application

Radiation sensitivity in Fibers vs. wavelength and total dose

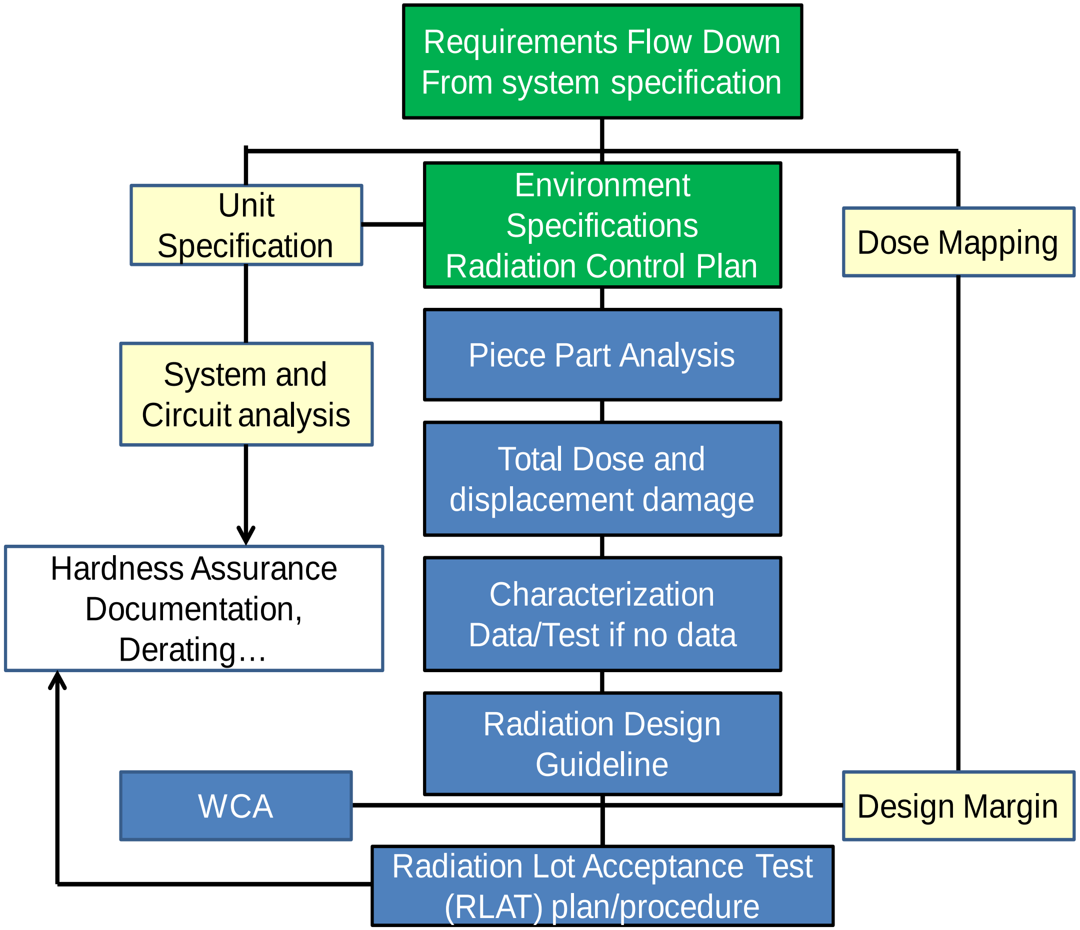
Radiation Hardness Assurance

Space agencies have to guarantee the survivability of electronics

Risk assessment of electronics is an involved process

Spacecraft use a very large number of electronic parts

Evaluation is based on mission requirements



Is there such a thing for Nuclear applications?

Margins?

- Environment
  - Radiation and particle type
  - Local radiation at the part
  - Models
  - Shielding strategy
- Electronic parts
  - Parts availability @300 krad
  - Testing methods – standards not applicable
  - Statistics (99/90) and delta margin?
  - Method other than Worst Case Analysis?
  - Device degradation vs failure definition
- Hidden margin

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- Hidden margin

» But how much margin ?

Any Questions ?

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Backup

Optical Fiber for Nuclear Based System

		WAVELENGTH μm	DOSE MGy	RADIATION CONCERN	Recommendation	Our contribution
SPACE	Data link	1.3/1.5	10 kGy	low	avoid P and cryogenic	
	Gyroscope	1.5	10	high	$<$ 10 m	
HIGH ENERGY PHYSICS	Data link	0.85/1.3/1.5	100 kGy	low	idem as space + L$<$10 m	
	Cerenkov Calorimeter	0.45 or VIS	1	high	need pure silica need RIA compensation	enhanced lifetime using H_2 or F-doped fibres
	Beam monitoring	$<$ 0.85	1-10 kGy	-	-	
FUSION	Data link	0.85-1.5	3	low	avoid digital	use analog and coarse WDM
	In-vessel viewing	VIS or NIR	$<$ 1	high	avoid VIS	IR LIDAR approach at 1 μm
	Plasma spectroscopy	0.4-0.6	10-100 kGy	high	need pure silica	enhanced lifetime with H_2 loading
	IR-Thermography	1-10	15	high	ZrF_4 not suited	Sapphire and/or PCF
	Faraday sensor	1.3-1.5	3	low	L$<$ 50 m	Verdet constant unchanged in pure silica low-birefringence fibres
	Laser diagnostics	0.35	200 Gy /shot	high	need doped silica	F-doped and H_2 fibres required
NUCLEAR	Distributed T°C sensing	1 and 1.3	$>$ 1	low	-	double-ended RAMAN OTDR
	In core sensing	NIR	$>$ GGy	high	minimize silica compaction	interferometry at 1 μm
	Cerenkov	NIR	$>$ GGy	high	need RIA compensation	measured at 1 μm
RADIATION RESISTANT DEVICES						
Fibre Bragg Gratings		1.5	$<$ 10		avoid H_2	use N-doped or femtosecond FBGs
Photonic Crystal Fibres		1.5	$>$ 10		-	ok with hollow-core PBG fibre
Luminescence for high dose monitoring		VIS	$<$ 1		-	enhanced lifetime with H_2 fibres

Table 3.1: Overview of fibre-optic applications in different nuclear facilities and radiation environments.

Applications in different nuclear facilities and radiation environments