SCHOOL OF ENGINEERING
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Effects of moisture on 1/*f* noise and radiation response in MOS devices

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Introduction

Radiation, aging, moisture effects

- 1/*f* noise increases with irradiation exposure
  - Increase in defects responsible for the noise
  - Correlation between pre-rad noise and post-rad ΔV_{ot} [1]-[3]

- Radiation response and reliability can change significantly with aging or moisture exposure
  - Increases in ΔV_{it} and ΔV_{ot} after ~17 years of storage [4]
  - Increase in post-irradiation anneal ΔN_{it} after exposure to humidity at elevated temperature [5]

[1] Fleetwood and Scofield, *Phys. Rev. Lett.*, vol. 64, pp. 579-582, 1990.
[2] Scofield *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 36, pp. 1946-1953, 1989.
[3] Fleetwood *et al.*, *IEEE Trans. Electron Dev.*, vol. 41, pp. 1953-1964, 1994.
[4] Rodgers *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 52, pp. 2642-2648, 2005.
[5] Batyrev *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 53, pp. 3629-3635, 2006.

Introduction: 1/*f* noise in MOS

Noise measurements provide information about defect densities and energy distributions

- 1/*f* noise results from fluctuations in device channel current
- Fluctuations in inversion layer charge density - capture and emission of charge carriers at trap sites at or near Si/SiO_2 interface
- For linear operation, MOS noise is given by [6]:

$$S_{V_d} = \frac{q^2}{C_{ox}^2} \frac{V_d^2}{(V_g - V_t)^{\beta}} \frac{k_B T D_t(E_f)}{LW \ln(\tau_1/\tau_0)} \frac{1}{f^{\alpha}}$$

- α - frequency dependence
  - For uniform $D_t(E_f)$, $\alpha = 1$
- β - gate-voltage dependence, $S_{Vd} \sim (V_g - V_t)^{-\beta}$
- For $D_t(E_f)$
  - Uniform: $\beta = 2$
  - Increasing toward E_V: $\beta < 2$
  - Increasing toward midgap: $\beta > 2$

[6] J. H. Scofield and D. M. Fleetwood, *IEEE Trans. Nucl. Sci.*, vol. 38, pp. 1567-1577, 1991.

Experimental Detail

Devices and experimental setup

- Fabricated in 1984, packaged in 1987 at Sandia National Labs
  - 2, 3, 4 µm x 16 µm (*L* x *W*) nMOS and pMOS transistors
  - t_{ox} = 26 nm, 32 nm, 37 nm, 68 nm
  - with and without high temperature N_2 post-oxidation anneals

- Highly accelerated stress tests (HAST) used to introduce high concentrations of hydrogen into device oxide layers

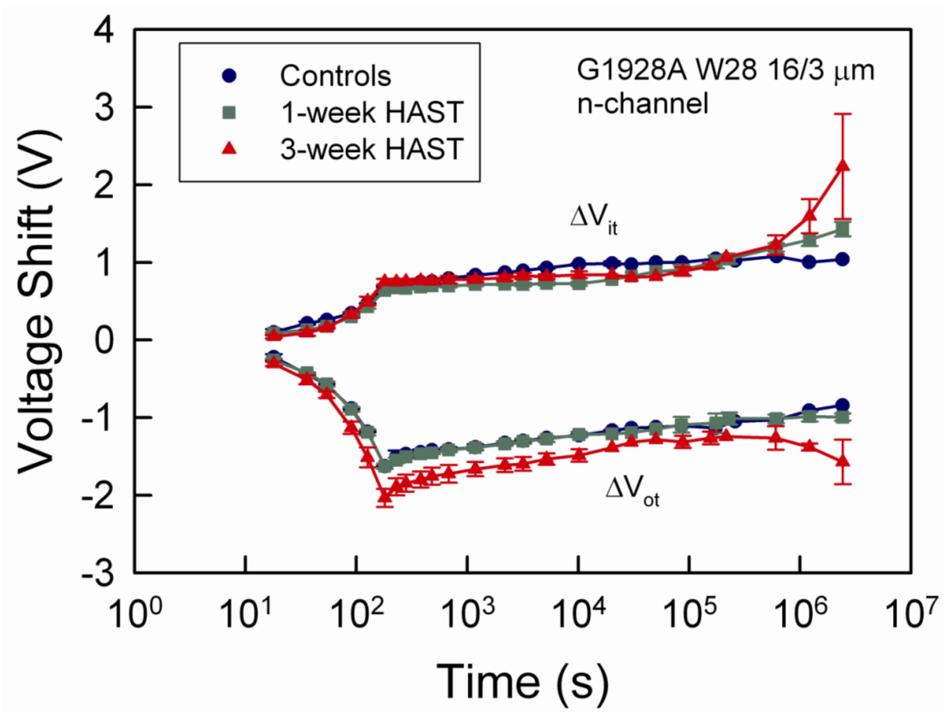
- Exposed to 85% relative humidity at 130 °C for times of one week up to three weeks
  - Control devices remained hermetically sealed during exposure (or were not exposed at all); all pins were grounded

- Threshold voltage and noise measurements made before and after moisture exposure, and during irradiation experiments

Results

I-V - nMOS

➢ **HAST exposure leads to increased radiation-induced charge trapping for nMOS transistors, especially during post-irradiation annealing**



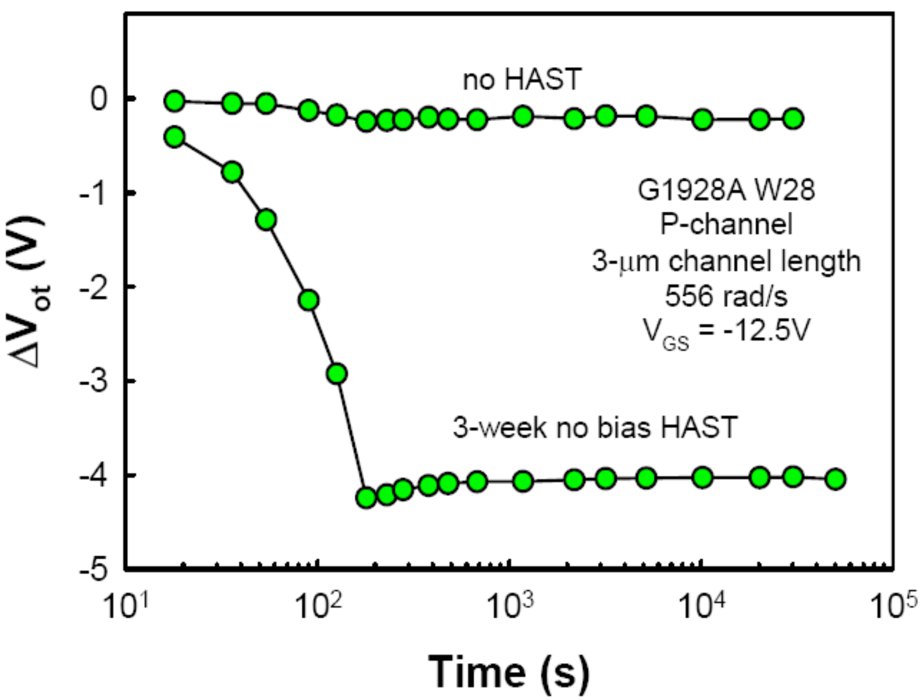
- 100 krad(SiO_2) total dose
- Rad/anneal bias - V_{gs} = 12.5 V
- t_{ox} = 68 nm
- Larger increase in ΔV_{it} after ~ 10^5 s for HAST exposed devices than control device
- Increase in ΔV_{ot} after ~ 10^5 s for 3- week HAST exposed device
- Results consistent with aging studies previously done on these type devices [7]

[7] Schwank *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 55, pp. 3206-3215, 2008.

Results

I-V - pMOS

➢ **HAST exposed pMOS transistors exhibit much larger increases in radiation-induced charge than nMOS transistors**



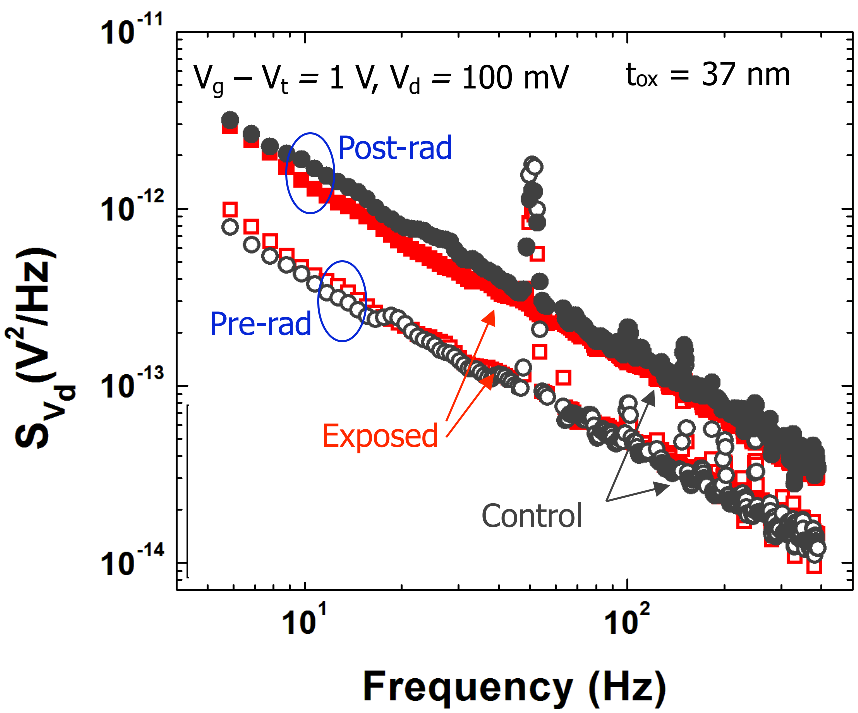
- 100 krad(SiO_2) total dose
- Rad/anneal bias - V_{gs} = -12.5 V
- t_{ox} = 68 nm
- 3-week HAST exposed device experienced much larger increase in ΔV_{ot} than control device
- Similar effects also observed in other devices with thinner oxides, and in parasitic field oxides

[7] Schwank *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 55, pp. 3206-3215, 2008.

Results

1/*f* noise – nMOS

➢ **Moisture exposure has little effect on nMOS noise**



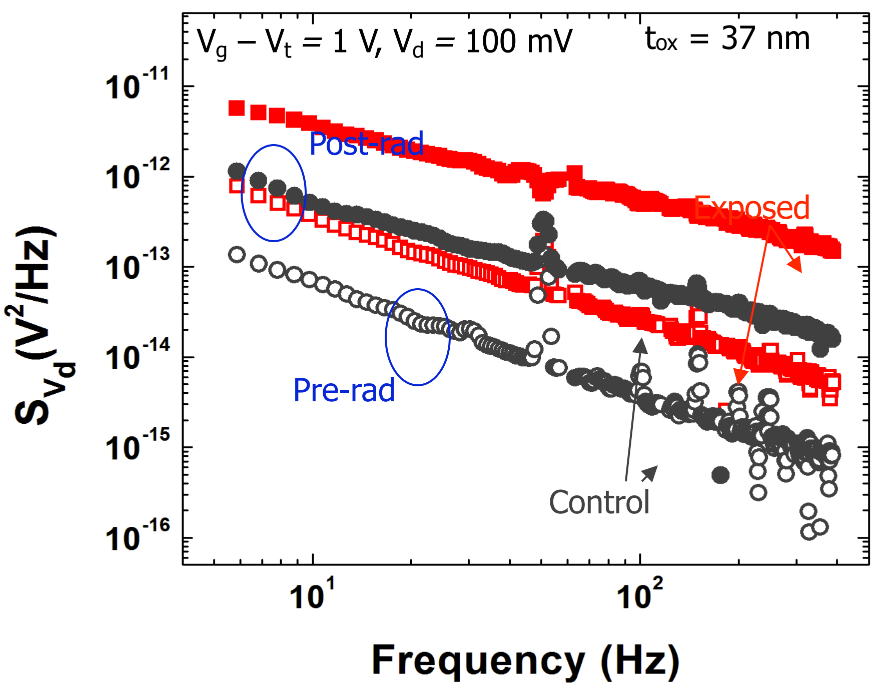
- 500 krad(SiO_2) total dose
- +6 V gate bias, other pins grounded

- Small difference between moisture-exposed and control nMOS noise
- $\alpha \approx 1$ for both devices – relatively uniform $D_t(E_f)$

Results

1/*f* noise - pMOS

➢ **pMOS noise increases considerably with moisture exposure**

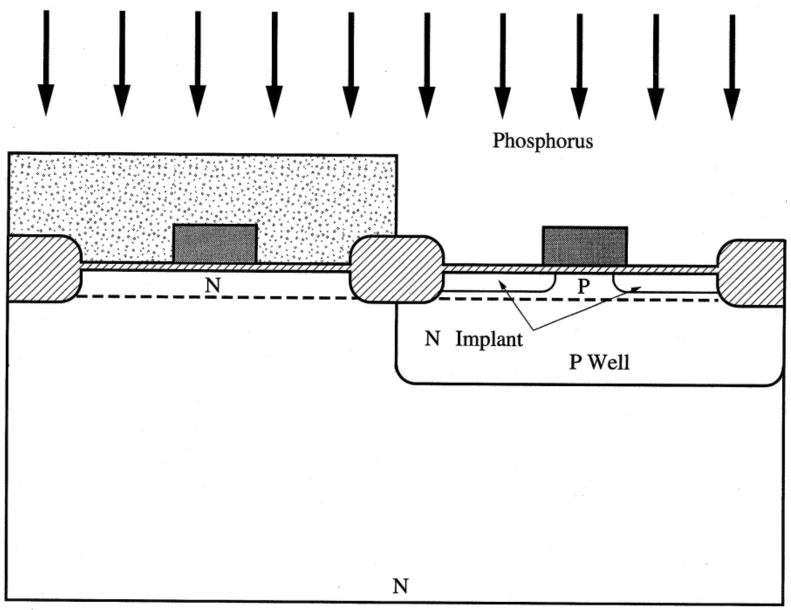


- 500 krad(SiO_2) total dose
- +6 V gate bias, other pins grounded
- Moisture-exposed pMOS noise much greater than control pMOS noise
- Change in frequency dependence with irradiation
  - Pre-rad $\alpha > 1$
  - Post-rad $\alpha \approx 1$ – more uniform $D_t(E_f)$
- S_{Vd} correlated to density of O-vacancies [8]
  - HAST exposure resulted in an increase in O-vacancies in pMOS devices

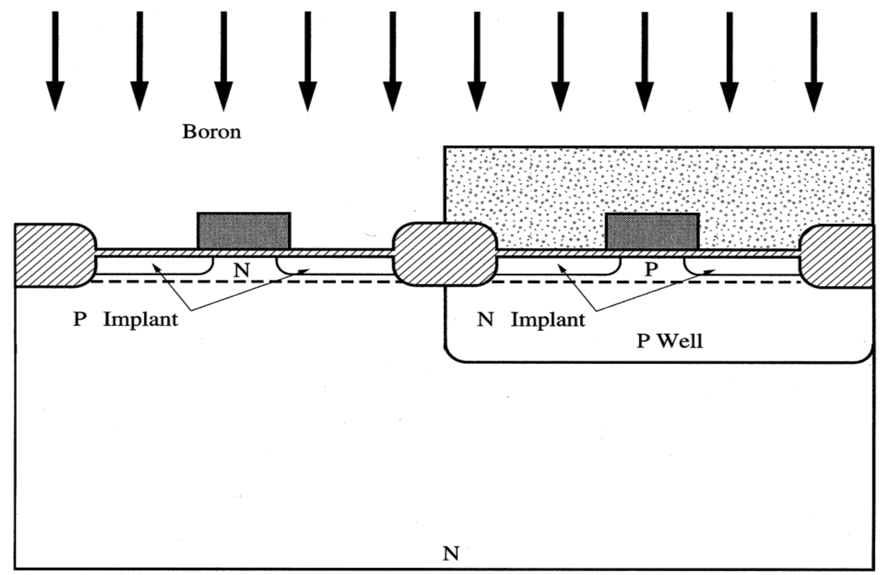
[8] Fleetwood *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 2674-2683, 2002.

Differences in nMOS/pMOS response to moisture exposure

- Phosphorus/boron atoms present in field oxide regions surrounding gate oxide in nMOS/pMOS devices due to source/drain implant steps



NMOS



PMOS

Different nMOS/pMOS response to moisture exposure

- Studies report that boron can accelerate water penetration in doped oxides (compared to undoped SiO_2) [9], [10]
  - Boron increases the number of molecular water absorption sites without strongly interacting with water, allowing diffusion into the film
- Phosphorus can suppress water penetration [9], [10]
  - Phosphorus reduces the number of molecular water absorption sites and reacts with water to prevent penetration deep into the film
- Water diffusion results in enhanced defect creation in pMOS gate oxides
- Time dependence consistent with experimental results [11]

[9] M. Yoshimaru *et al.,* J. Electrochem. Soc. 143,3032 (1996).

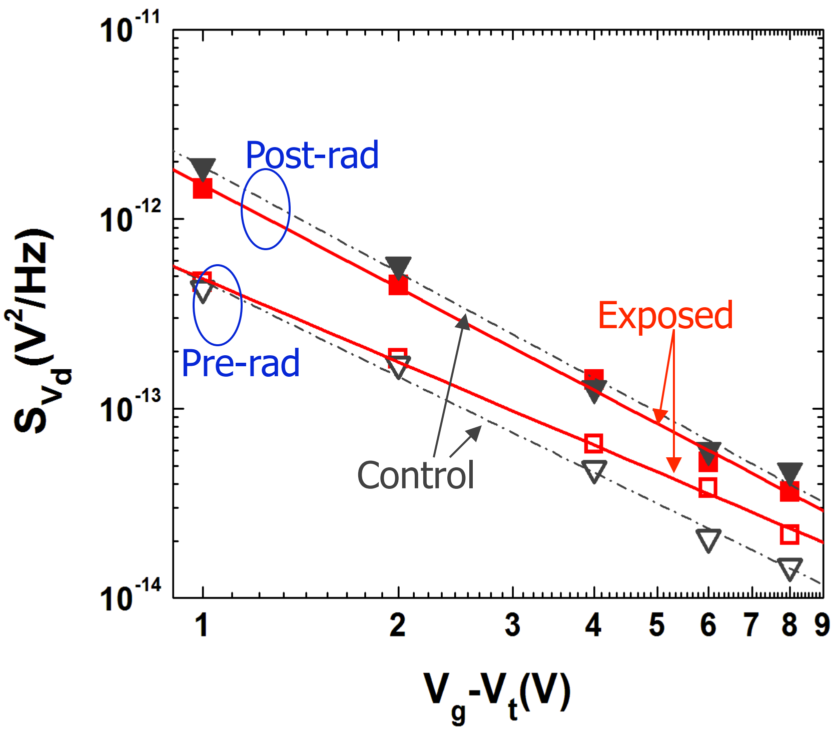
[10] A. G. Thorsness *et al.,* J. Electrochem. Soc. 150,F219 (2003).

[11] For details, please see: D. M. Fleetwood, S. A. Francis, A. Dasgupta, X. J. Zhou, R. D. Schrimpf, M. R. Shaneyfelt, and J. R. Schwank, "Moisture effects on the 1/*f* noise of MOS devices," Transactions of the 215th ECS Meeting, Vol. 19(2), Silicon Nitride, Silicon Dioxide, and Emerging Dielectrics 10, edited by R. Ekwal Sah, J. Zhang, J. Deen, J. Yota, and A. Toriumi, San Francisco, CA, May 24-29, pp. 363-377 (2009).

Results

1/*f* noise – nMOS

➢ **Radiation exposure has small effect on nMOS 1/*f* noise gate-voltage dependence**

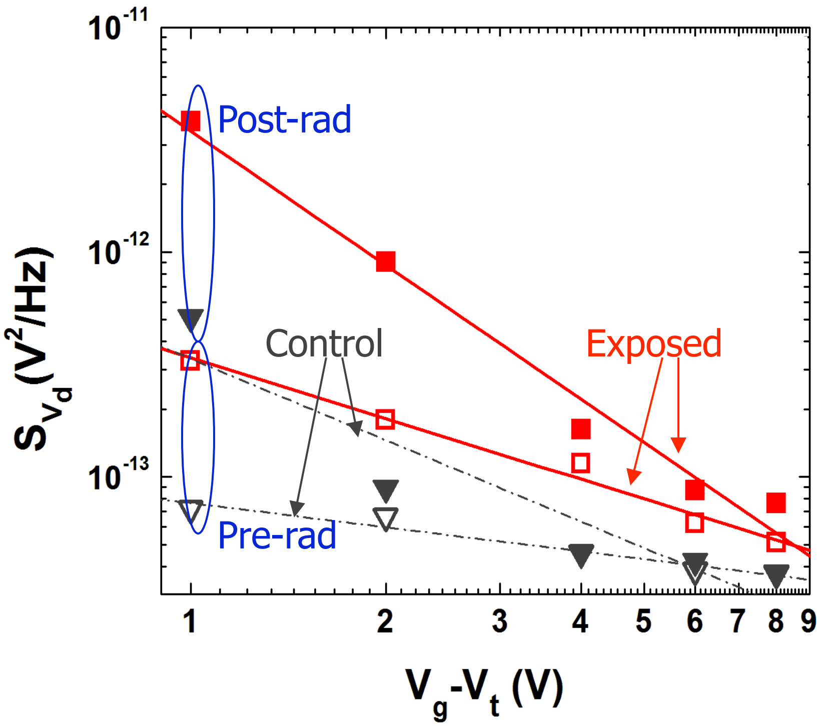


- $S_{Vd} \sim (V_g - V_t)^{-\beta}$
- Small changes in gate-voltage dependence with irradiation
- Control
  - Pre-rad β = 1.7
  - Post-rad β = 1.9
- Exposed
  - Pre-rad β = 1.5
  - Post-rad β = 1.8
- More uniform $D_t(E_f)$ after irradiation

Results

1/*f* noise – pMOS

➢ **pMOS 1/*f* noise gate-voltage dependence changes significantly with irradiation**



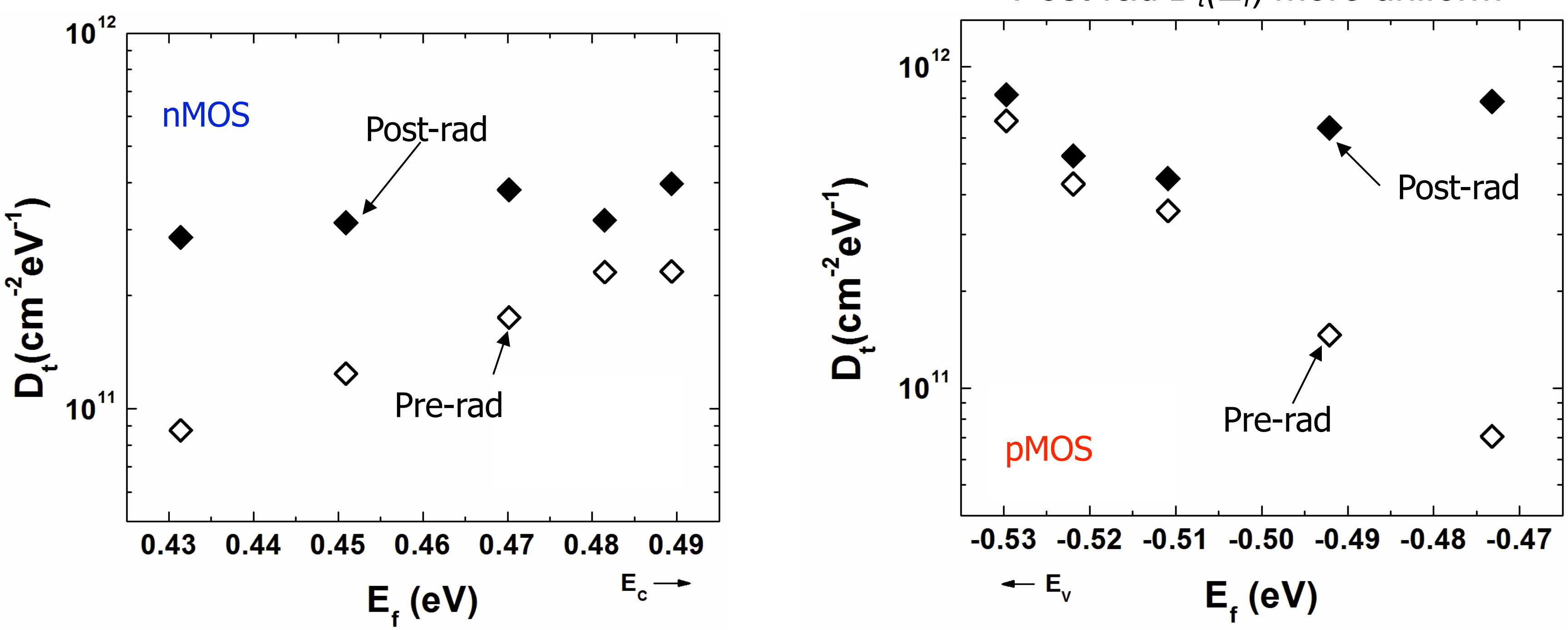
- Control
  - Pre-rad $\beta = 0.4$
  - Post-rad $\beta = 1.2$
- Exposed
  - Pre-rad $\beta = 0.9$
  - Post-rad $\beta = 2.0$
- Large change in gate-voltage dependence with irradiation – change in $D_t(E_f)$ with irradiation

Results

1/*f* noise – nMOS vs. pMOS

➢ **Different trap energy distributions underlie observed differences in frequency, gate-voltage dependences**

- nMOS – small variation in $D_t(E_f)$ with energy
- pMOS – pre-rad $D_t(E_f)$ increasing toward E_V
- Post-rad $D_t(E_f)$ more uniform

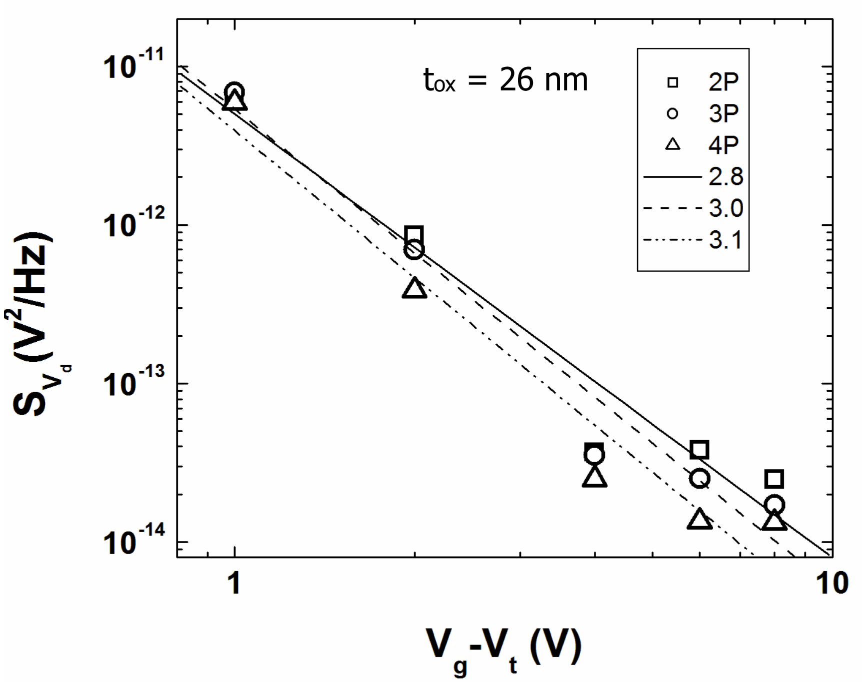


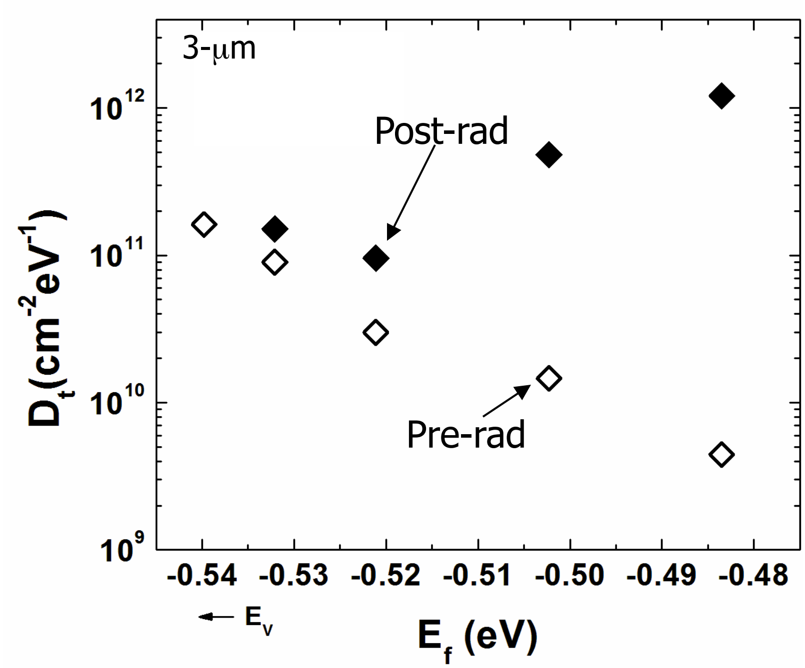
Results

1/*f* noise – pMOS

➢**Some moisture-exposed transistors exhibited extremely large changes in gate-voltage dependence after irradiation**

- β >> 2 for 2, 3, 4 μm –channel length transistors, post-irradiation (pre-rad, β << 2)
- Pre-rad $D_t(E_f)$ increasing toward E_V
- Post-rad $D_t(E_f)$ increasing toward midgap





Conclusions

- Moisture exposure can significantly affect MOS oxide trap charge and interface trap buildup during irradiation and annealing; effects more significant for pMOS transistors than for nMOS.
- Enhanced defect generation leads to significant increases in 1/f noise.
- Gate-voltage and frequency dependences of 1/*f* noise can change significantly with irradiation, revealing information about defect densities and energy distributions.