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Early-Stage Mechanisms in Time-Dependent Dielectric Breakdown in the Si/SiO_2 System

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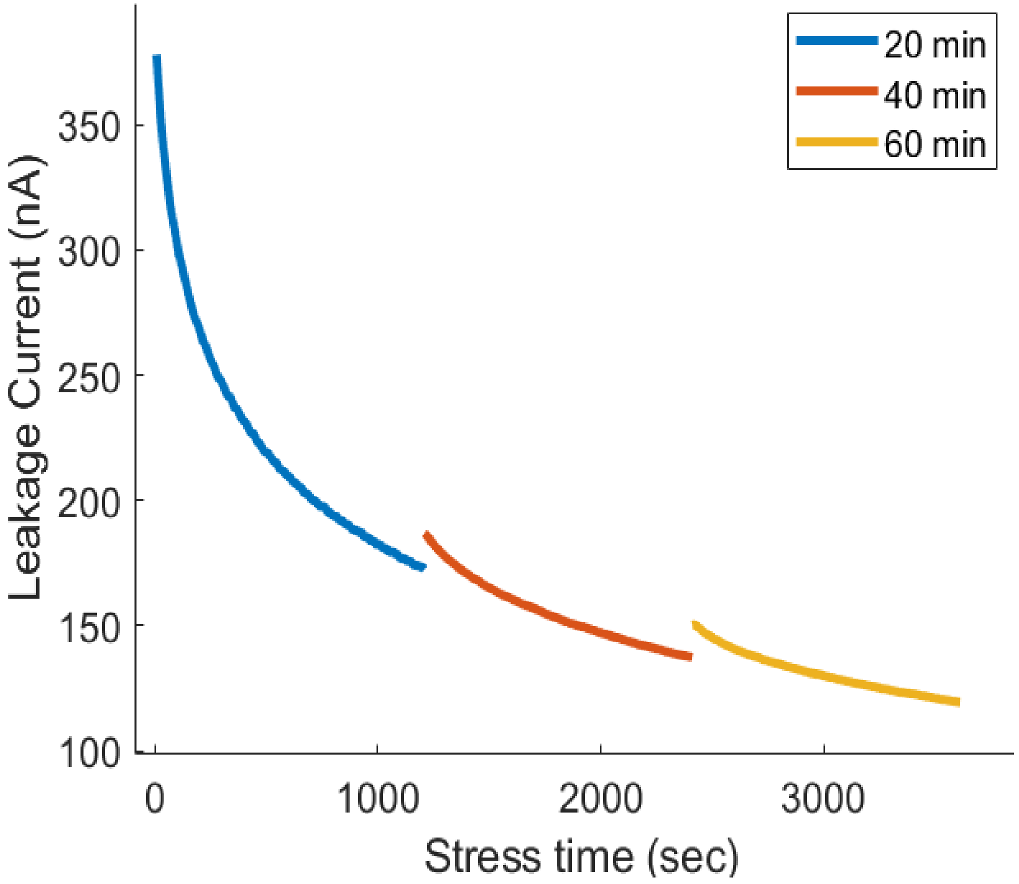
Presentation Breakdown

- Introduction to electrically detected magnetic resonance (EDMR).
- Investigating the defects involved in spin-dependent recombination (SDR) in high-field stressed Si/SiO_2 MOSFETs.
- Investigating the build-up of defects involved in spin-dependent trap-assisted tunneling (SDTAT) in high-field stressed Si/SiO_2 MOSFETs.
- Using near-zero-field magnetoresistance (NZFMR) to observe changes in interface chemistry through-out the lifetimes of high-field stressed devices.

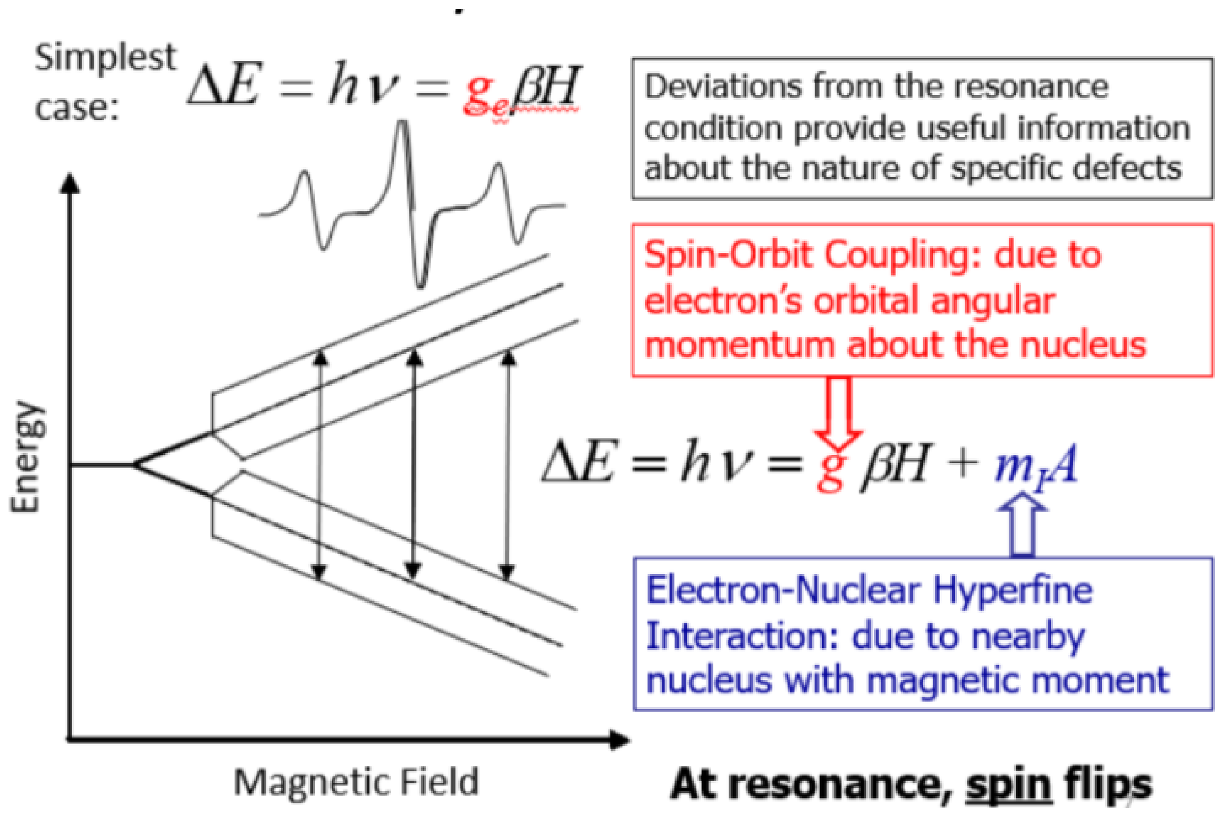
Time Dependent Dielectric Breakdown (TDDB)

- TDDB is one of the most important reliability problems in solid-state electronics.
- Device structures can be aged through high constant voltage stressing.
- This stressing results in a change in both the stress-induced leakage current (SILC) and changes in Fowler-Nordheim tunneling.



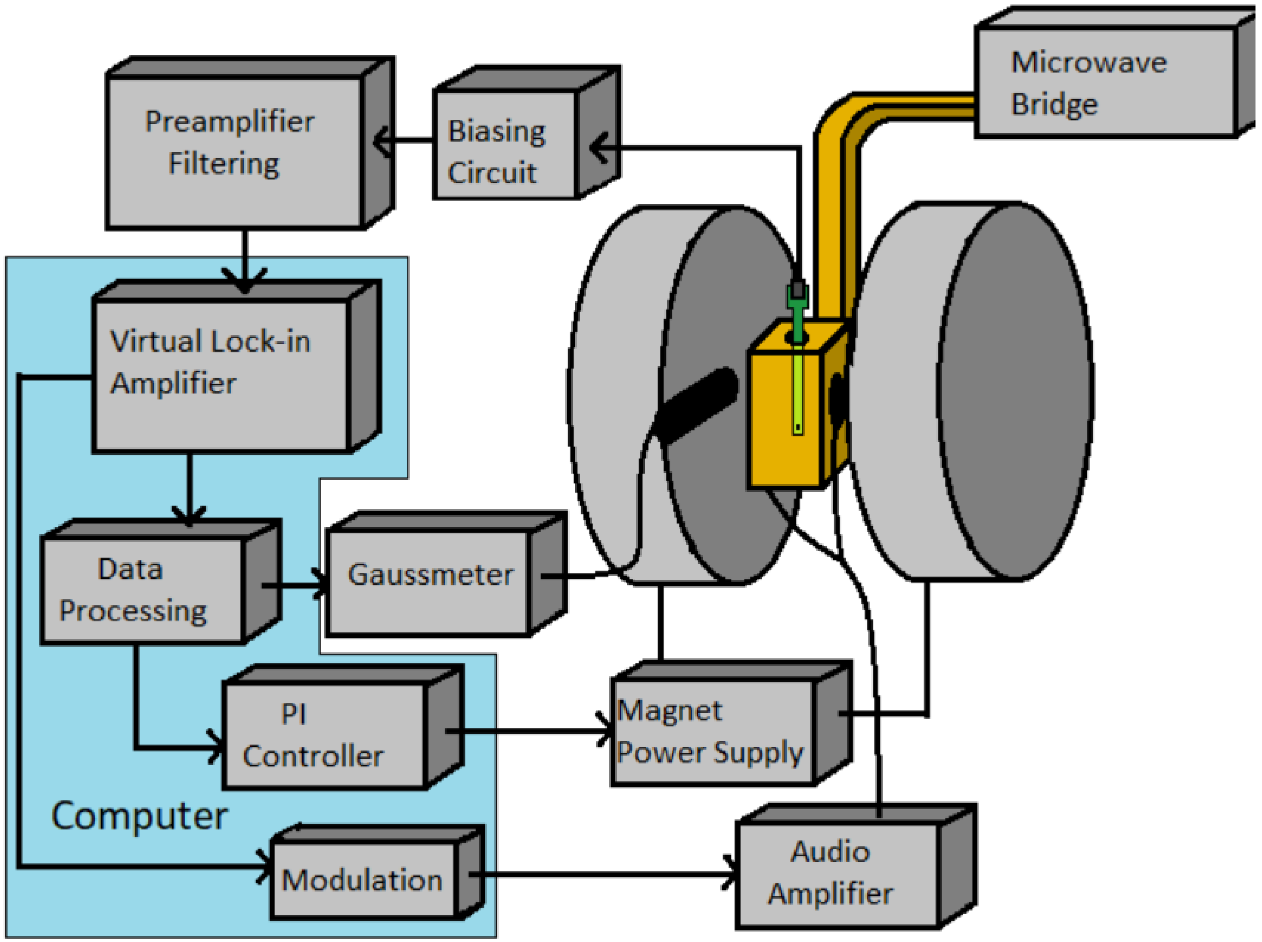
Overview of Magnetic Resonance

- Energy levels of paramagnetic defect sites are split by a magnetic field.
- By applying a microwave radiation of frequency v and a slowly-changing H to a sample, one can "flip" defect electrons.



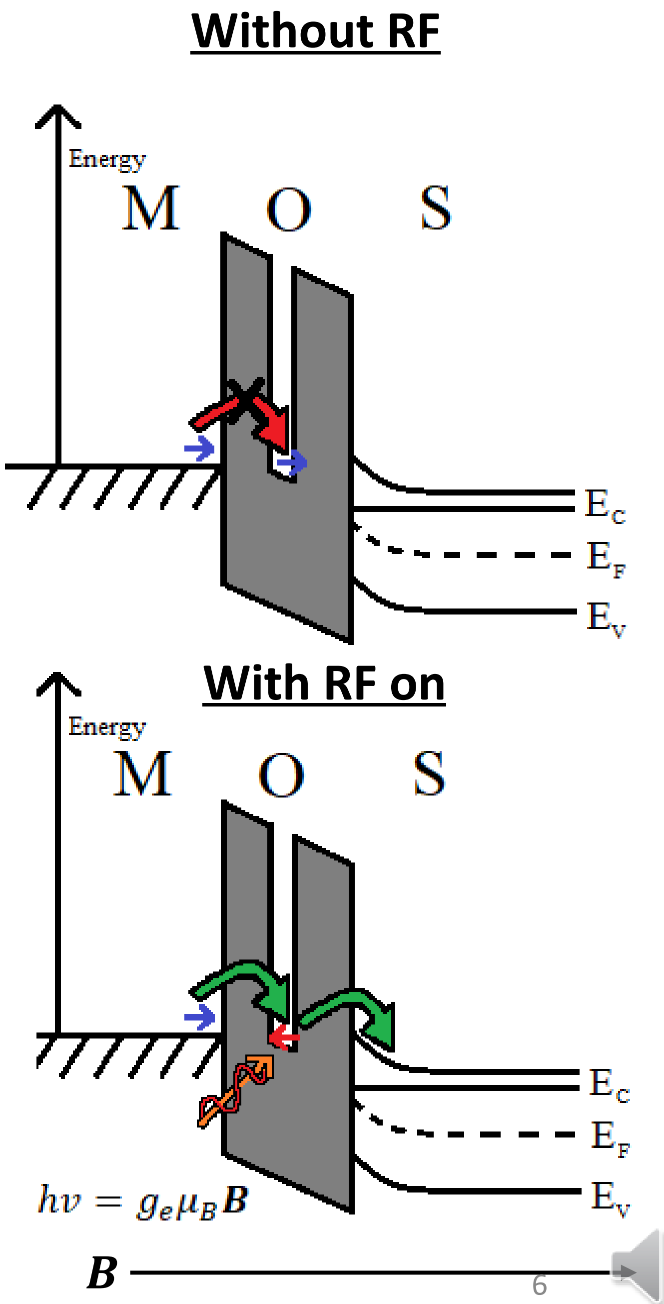
Electrically Detected Magnetic Resonance (EDMR)

- Classical EPR is not sensitive enough to study traps in practical MOSFETs (sensitivity $\cong 10^{10}$ defects).
- EDMR sensitivity is about 10^7 times greater than EPR [1].
- This sensitivity boost makes EDMR an incredibly powerful analytical tool for analyzing the chemical nature of paramagnetic defects in technologically meaningful devices.



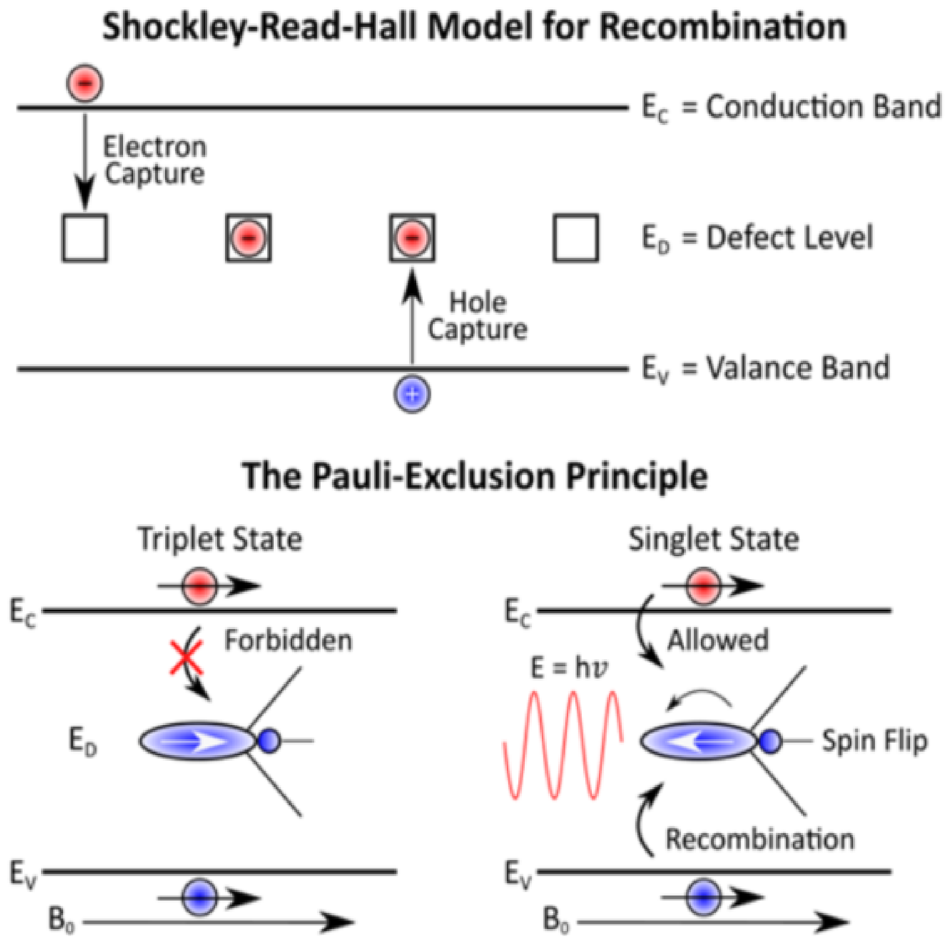
Spin-Dependent Trap Assisted Tunneling (SDTAT)

- Operates on the principles of variable range hopping.
  - Trap to trap tunneling events conserve momentum; they are a function of both energy and tunneling distance.
- RF induced resonance events can "flip" the spins of oxide defects, allowing forbidden tunneling transitions to occur.

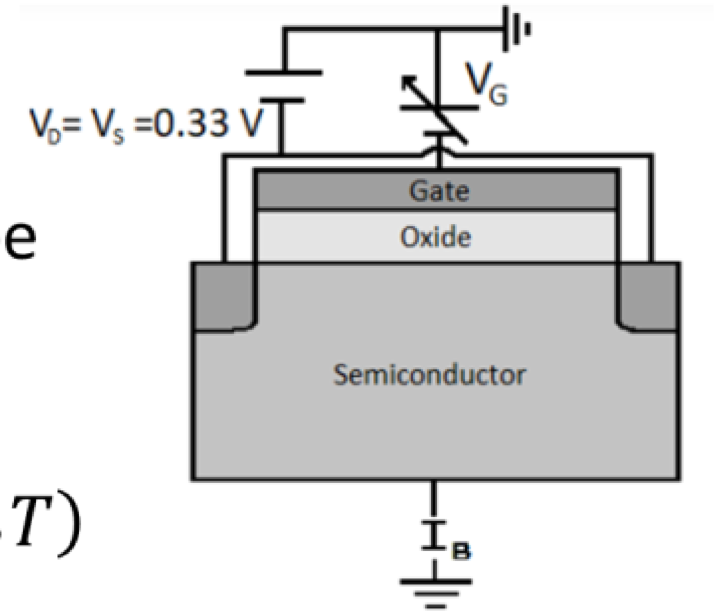


EDMR via Spin-Dependent Recombination (SDR)

- Shockley-Read-Hall Model for Recombination.
- Pauli Exclusion Principle forbids capture if conduction electron/deep level electron have the same spin quantum number.
- Magnetic resonance “flips” the defect electron spin, allowing previously forbidden capture and recombination.
- This increases the recombination current at resonance.



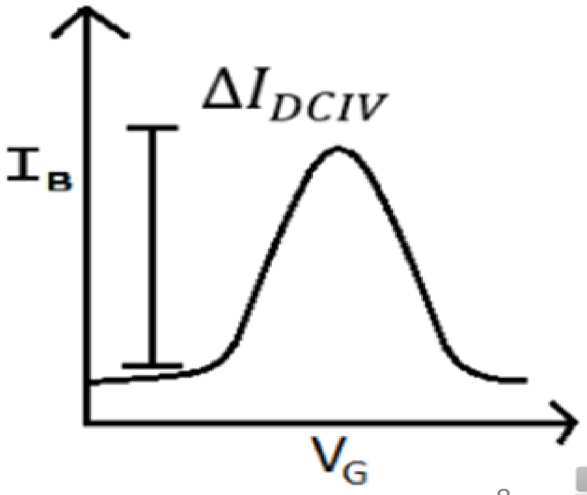
Gated Diode (dc I-V) EDMR



- Developed by Grove and Fitzgerald [2], dc I-V can be used to calculate interface densities using the equation:

$$\Delta I_{DCIV} = \frac{1}{2} q_0 n_i \sigma v_{th} D_{it} A q_0 |V_e| \exp(q_0 |V_e| 2 \mathrm{k}_B T)$$

- The dc I-V peak voltage is the biasing condition for EDMR.

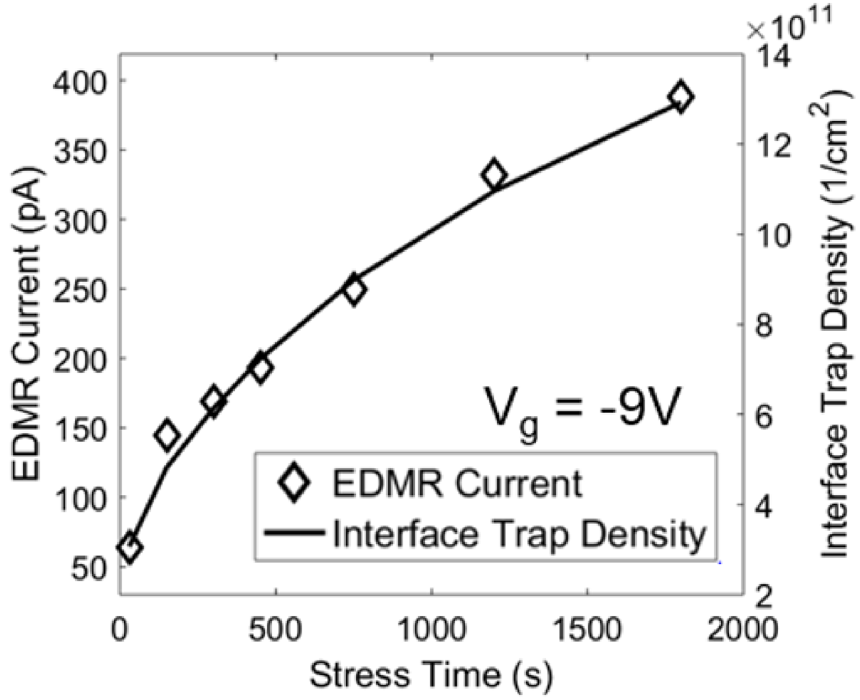


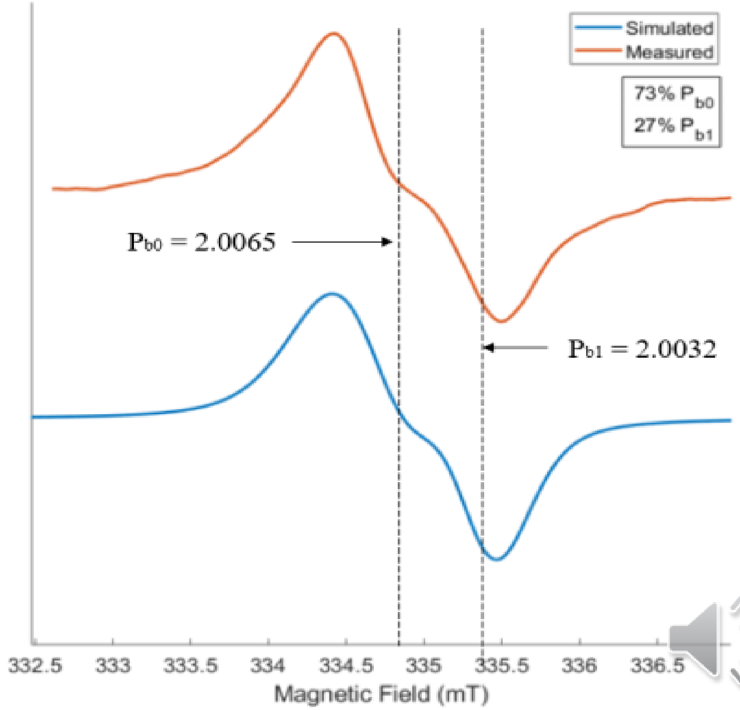
Experimental

- Identical 1.89×10^{-5} cm^2 Si/SiO_2 total gate area nMOSFETS with 7.5 nm thick oxides.
- MOS structures consisting of 126 devices, all with 15 by 1 μm channel dimensions.
- During EDMR, dc I-V source/drain biases used were -0.33 V.
- High-field stressing was done at a constant gate bias of -9 V for various lengths of time.
- All EDMR measurements were done with the magnetic field perpendicular to the (100) interface plane.

High-field Stressed Si/SiO_2 SDR

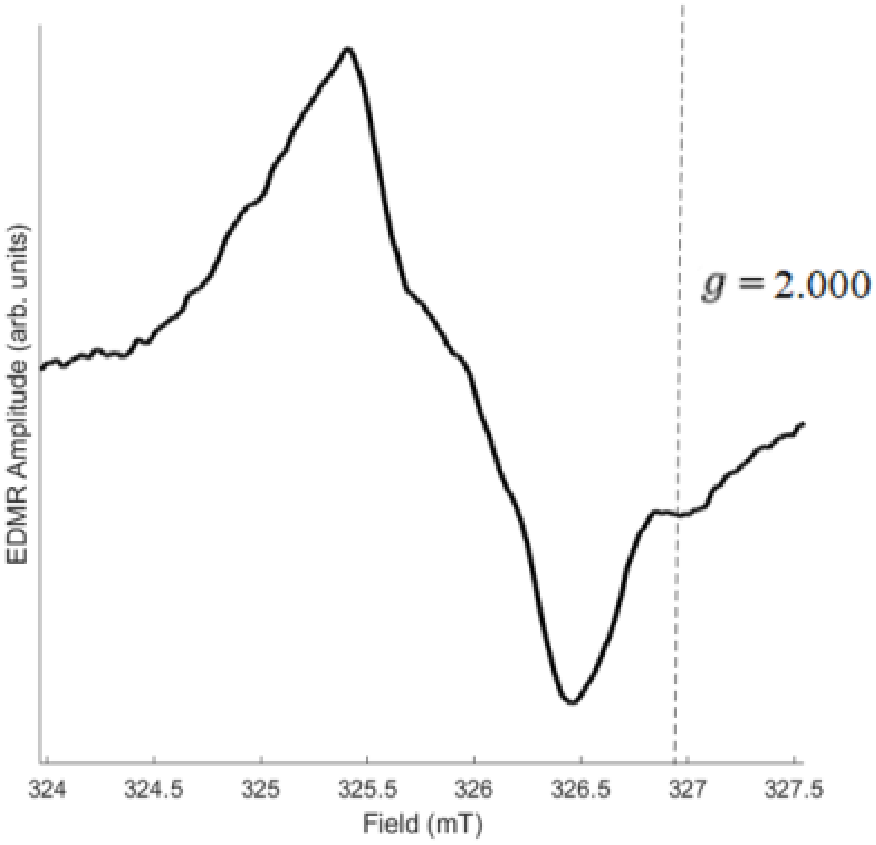
- Interface defect density and EDMR current are compared below throughout the lifetime of several devices subjected to different levels of **negative** gate stressing.
- Good agreement is found in all cases; likely can be extended to longer time scales.
- Simulations via EasySpin [3] clearly show that the defects generated are dominated by the P_{b0} and P_{b1} centers.





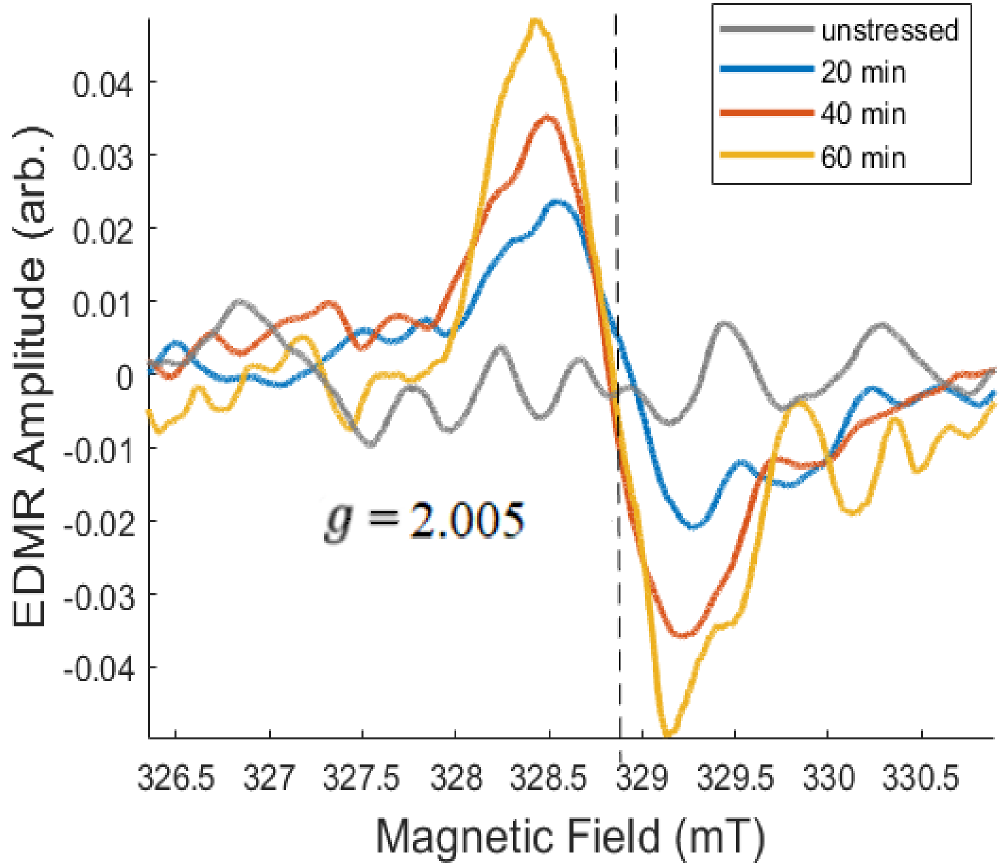
Low-Temperature SDR

- Along with the P_{b0} and P_{b1}, there is an additional feature that forms at $g = 2.000$ with high-field stressing.
- This g-value corresponds to an E' center, which is most likely made visible due to a change in the temperature-dependent spin-relaxation time of the oxide defect at 200 K.



SDTAT Results on High-Field Stressed MOSFETs

- Signal of SDTAT response increases with high-field stressing time.
- Dominant features were the P_{b0} ($g = 2.0065$) and P_{b1} ($g = 2.0032$) center.
- The EDMR results are in close correspondence with the increase in D_{it} measured via dc I-V.
- The lack of E' defects in the SDTAT spectra suggest a rate-limiting step.



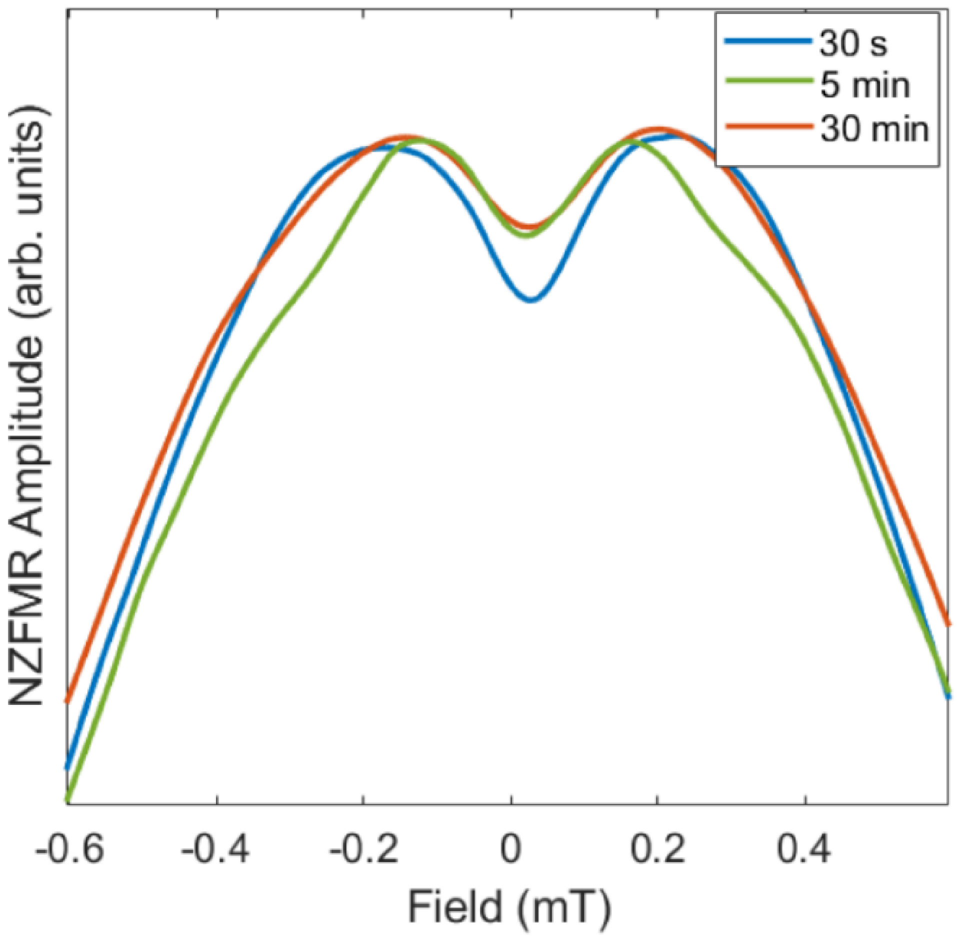
	Unstressed	20 min	40 min	60 min
Mid-gap D_{it} (10^{11} cm^{-2} eV)	.117	10.934	14.826	18.188

Near-Zero-Field Magnetoresistance (NZFMR)

- Can detect both SDTAT and SDR without an RF microwave source.
  - No B_1 is necessary; great potential for analyzing “packaged” devices.
- NZFMR utilizes the mixing of states at near-zero fields due to local magnetic field interactions.
- The theoretical NZFMR response can be modeled via the Stochastic Quantum Liouville Equation (SLE), a theory developed by Flatté and Harmon [4] and advanced for use in MOS devices by Frantz, Harmon, and Flatté [5].

NZMFR via SDR

- Changes in line shape are critical in the analysis of NZFMR spectra.
- These changes can only be due to two factors: kinetics and hyperfine interactions.
- For a constant V_f, the recombination kinetics must be constant.
- Only magnetic nuclei in the system are ^{29}Si nuclei (4.7%) and H (100%).
- The results demonstrate that hydrogen must be redistributed throughout high-field stressing.



Conclusions

- We provide evidence and chemical identification of both interface (P_{b0} and P_{b1}) traps and oxide (E') defects generated in Si/SiO_2 MOSFETs during the early to middle stages of TDDB.
- We find that the dominant defect in the SDTAT spectrum in these high-field stressed MOSFETs are the P_{b0} and P_{b1} defects.
- We show that the interface-to-oxide tunneling event is the rate-limiting step in Si/SiO_2 in the earlier stages of TDDB.

References

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