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ECE695: Reliability Physics of Nano-Transistors

Lecture 19: Spin-Dependent Recombination and Electrically Detected Magnetic Resonance

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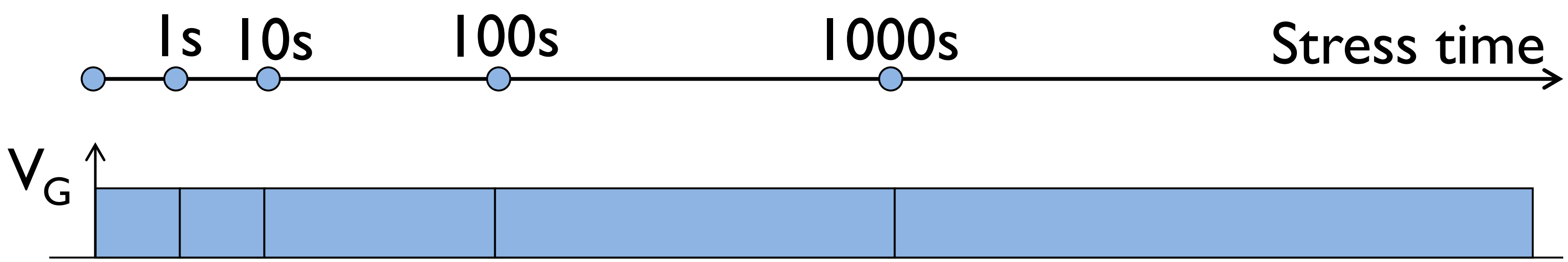
Outline

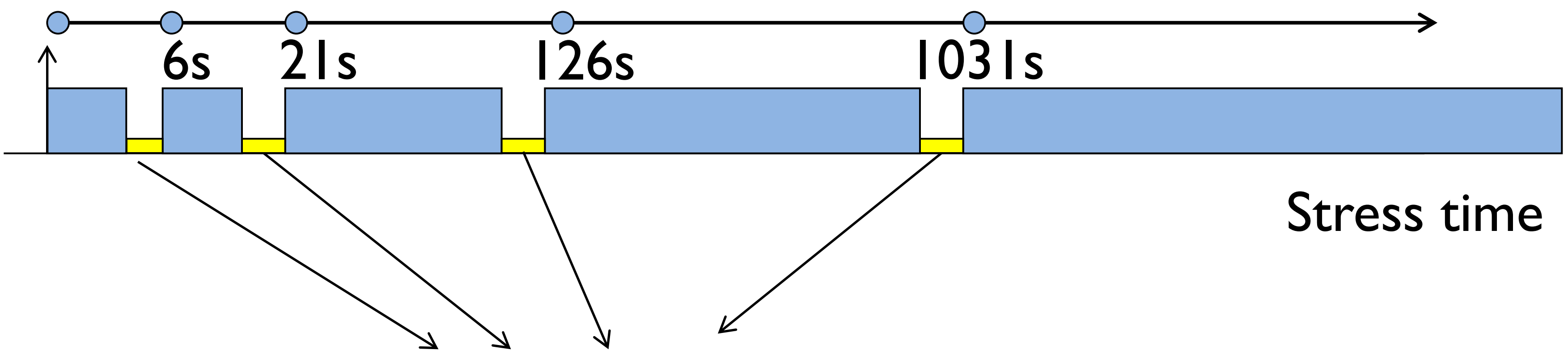
1. Importance of measuring interface damage
2. Electronic Spin Resonance (A quick review)
3. Spin Dependent Recombination
4. Electrically detected spin-resonance and noise-spectroscopy
5. Comparing the approaches
6. Conclusions

Measurement is a complex process

We periodically stop the stress and measure defects …

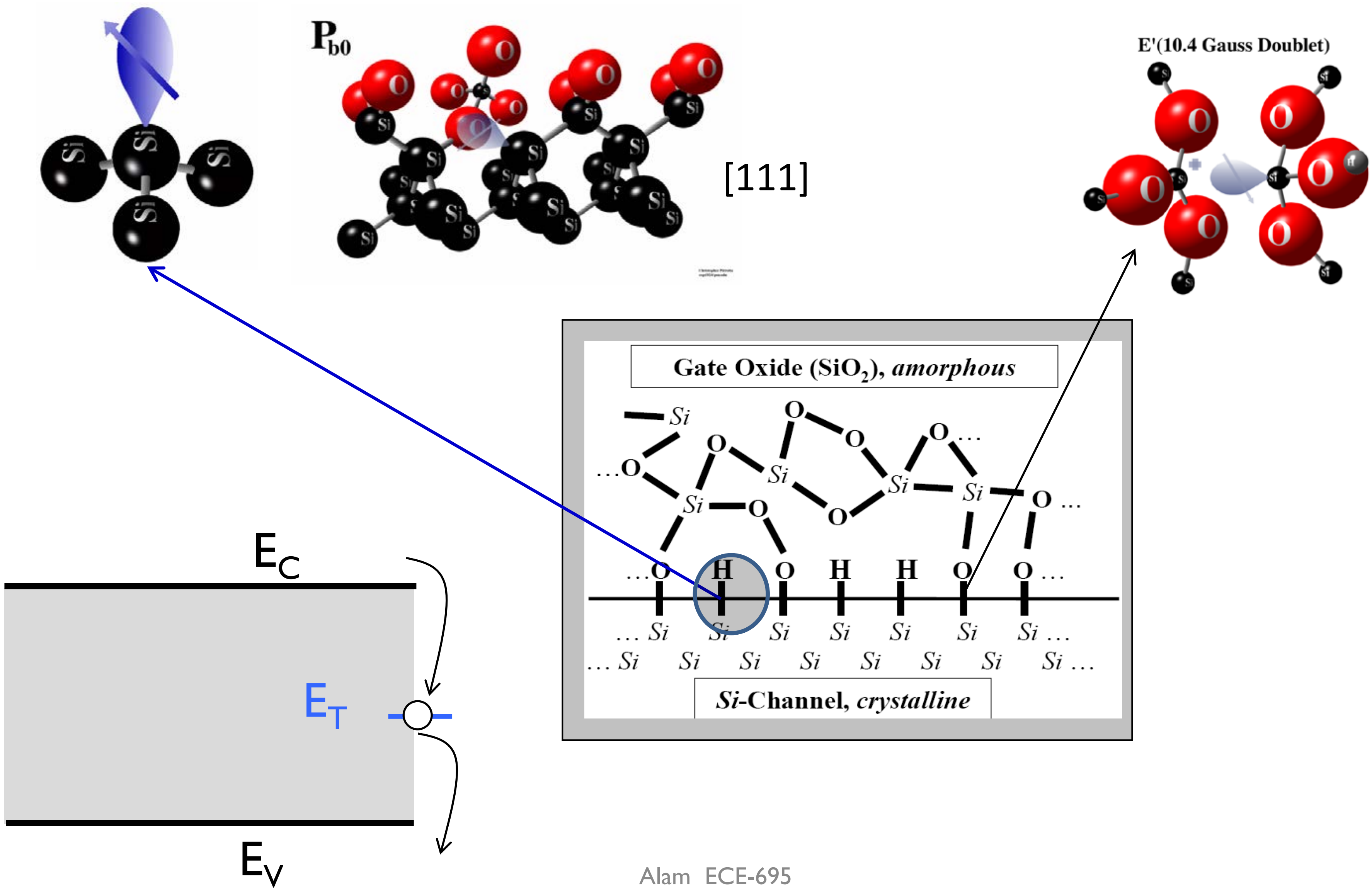


The measurements are often complex and interpretation of data depends on our interpretation of measurement

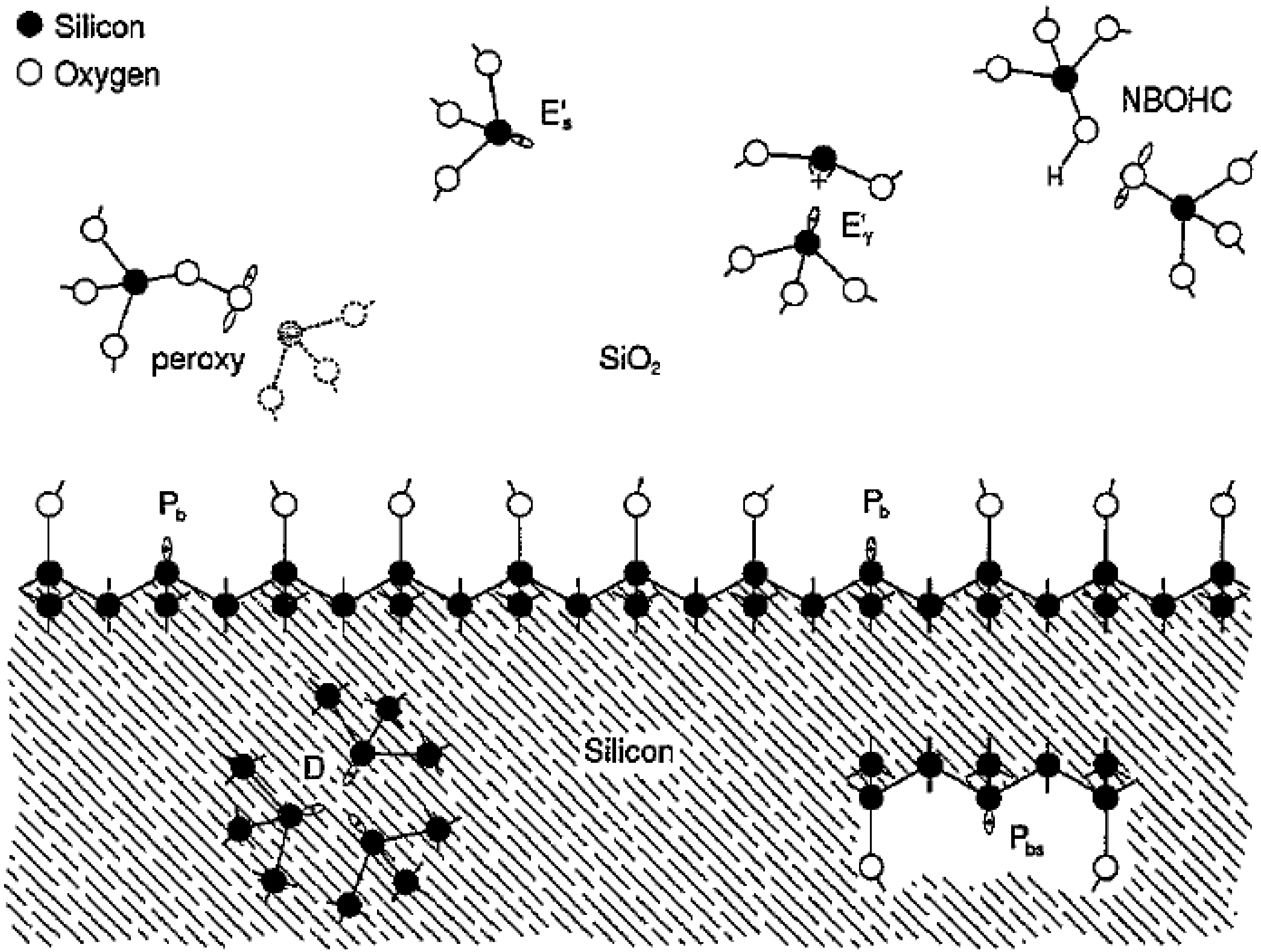


C-V, SILC, DCIV, CP, SDR, Idlin methods, …..

Review and background



Different types of ESR-visible defects



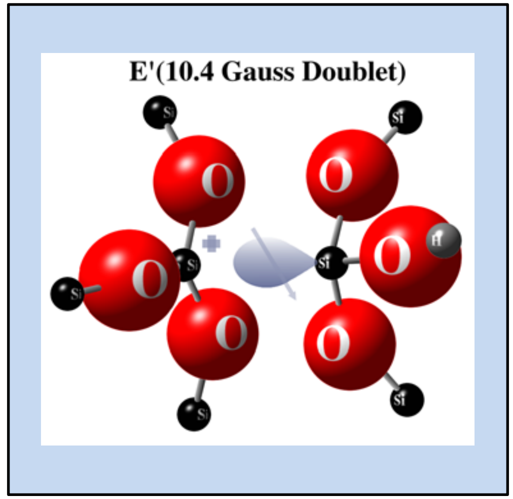
Nonbridging oxygen hole center

Helms and Poindexter, 1994.

ESR: a 'microscope' for defects

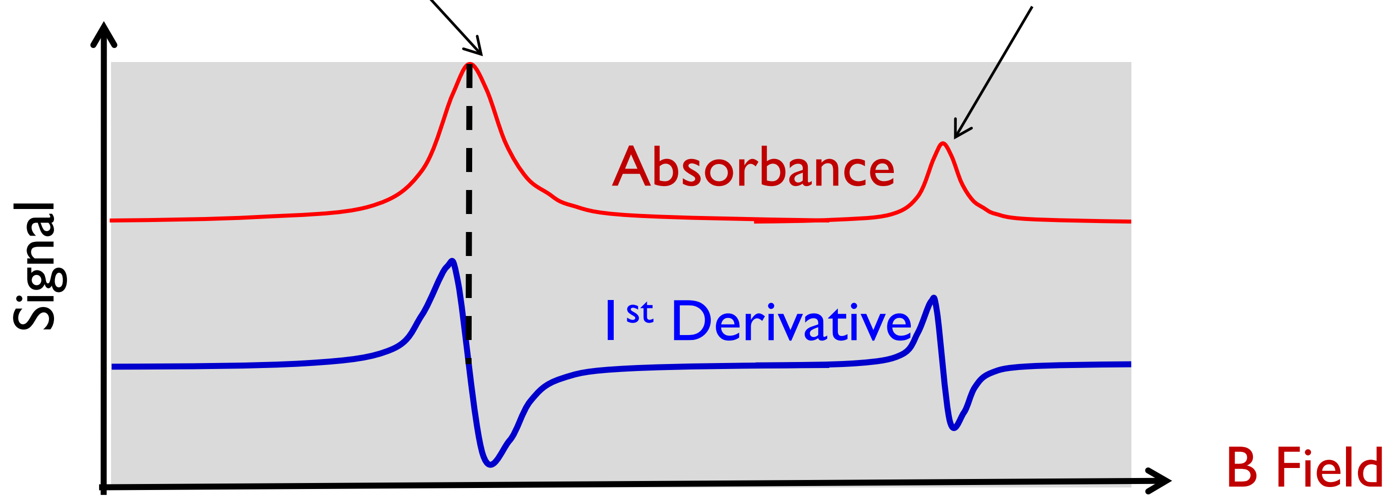
10 GHz Microwave

Variable B-field

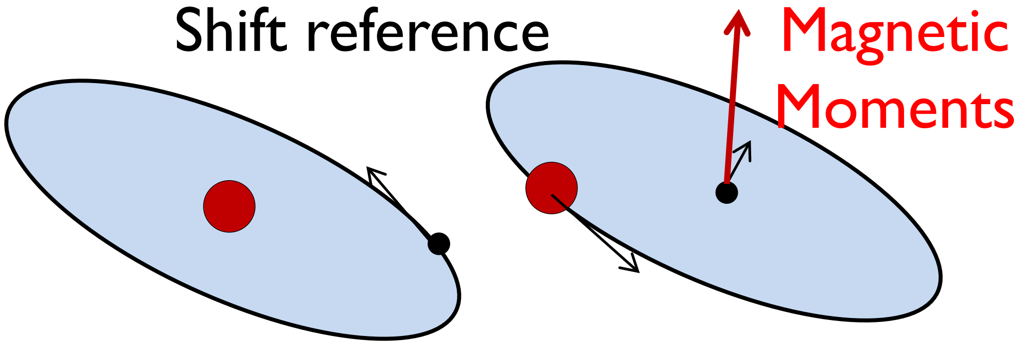


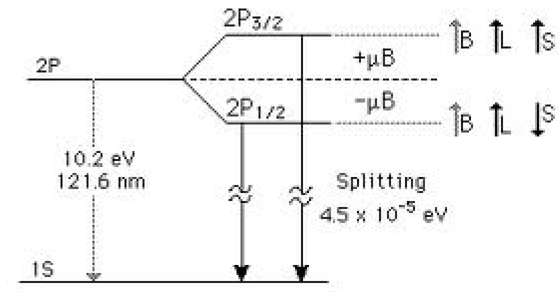
Absorption spectra

Defect 1 $h\nu = g_e \mu_B B_0$ Defect 2

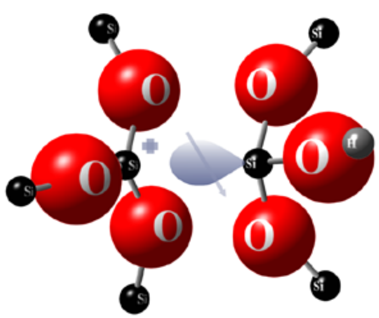


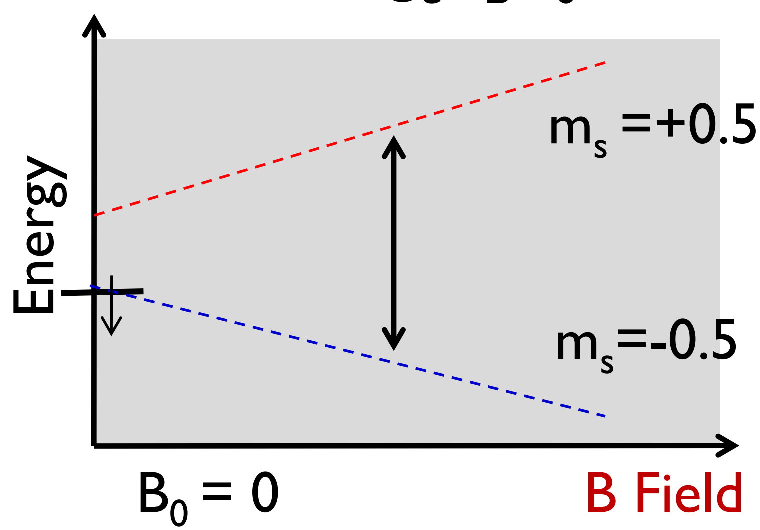
Hyperfine interaction & paramagnetic resonance





$$\Delta E = g_e \mu_B B_0$$



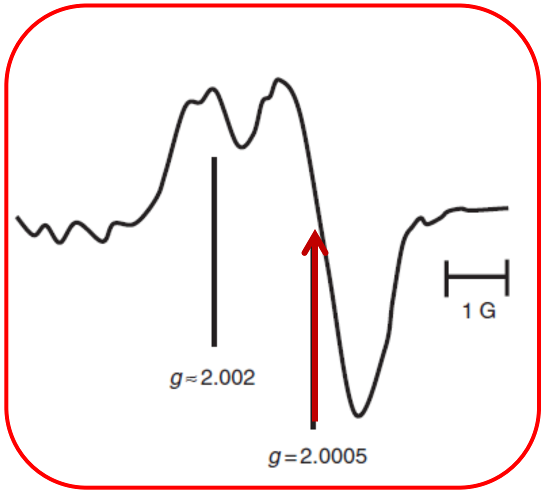


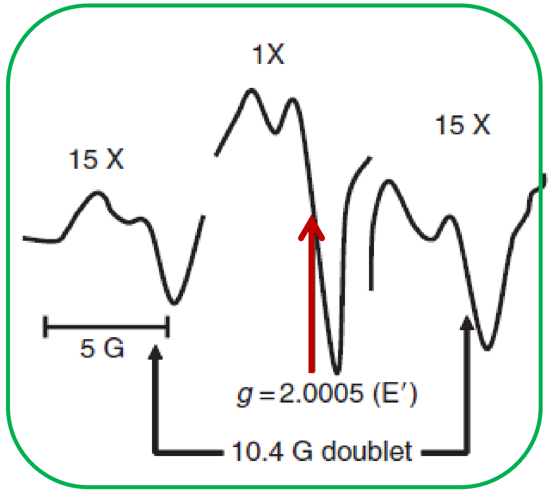
B-value suggests local environment

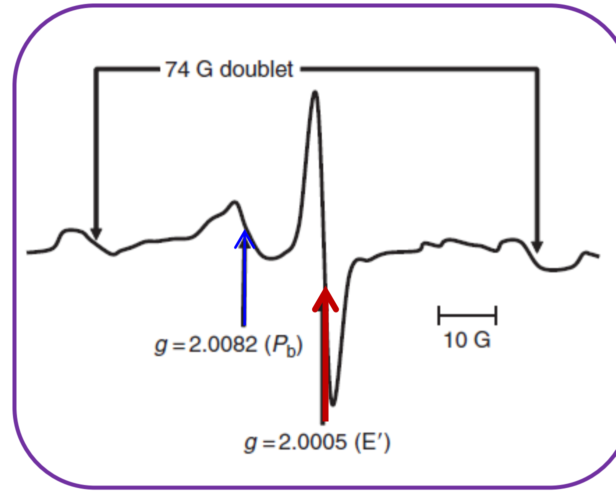
easyspin.org

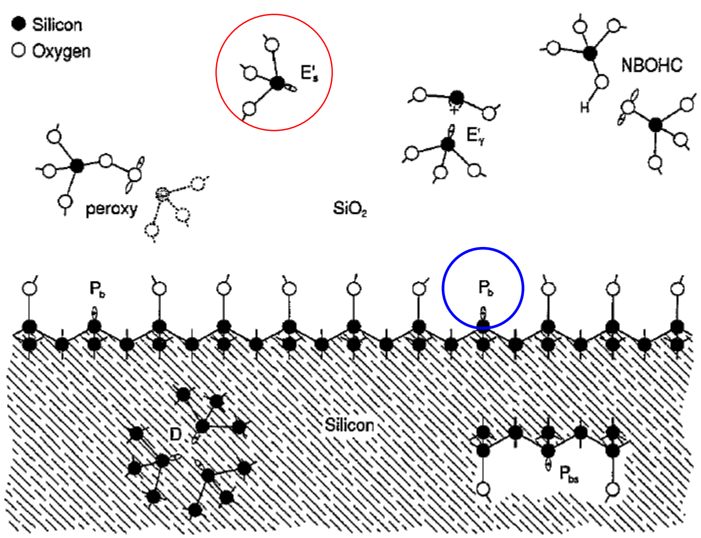
} m_I ; m_s = 1/2

ESR signature of different defects

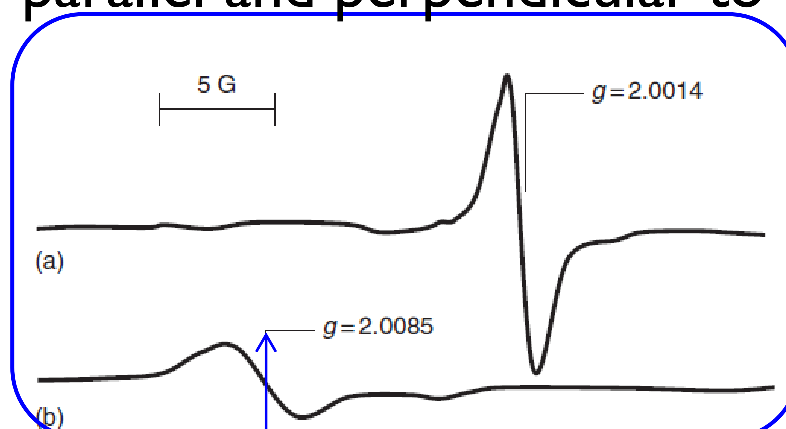








Pb parallel and perpendicular to <111>



P. M. Lenahan, 2004.

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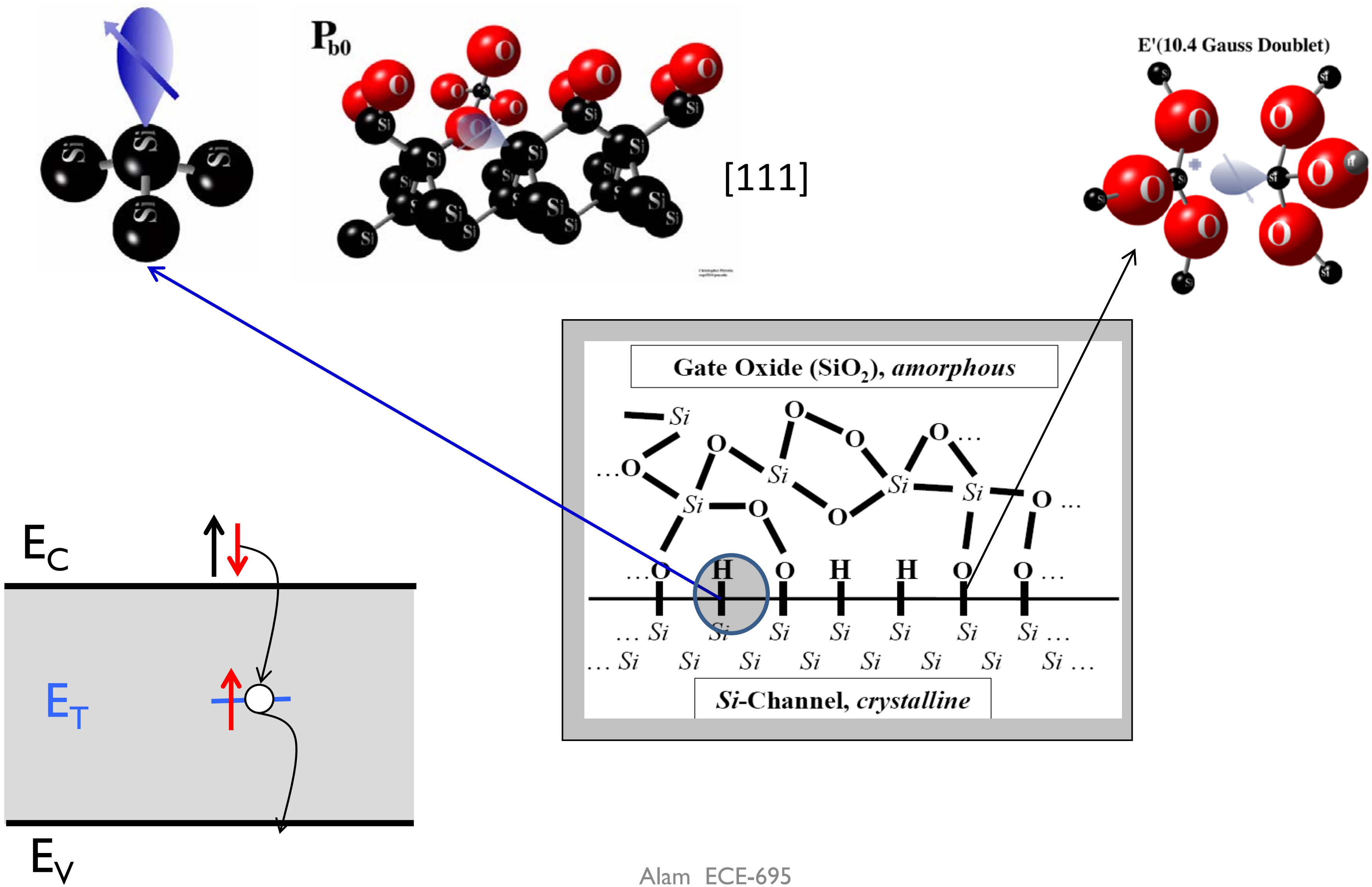
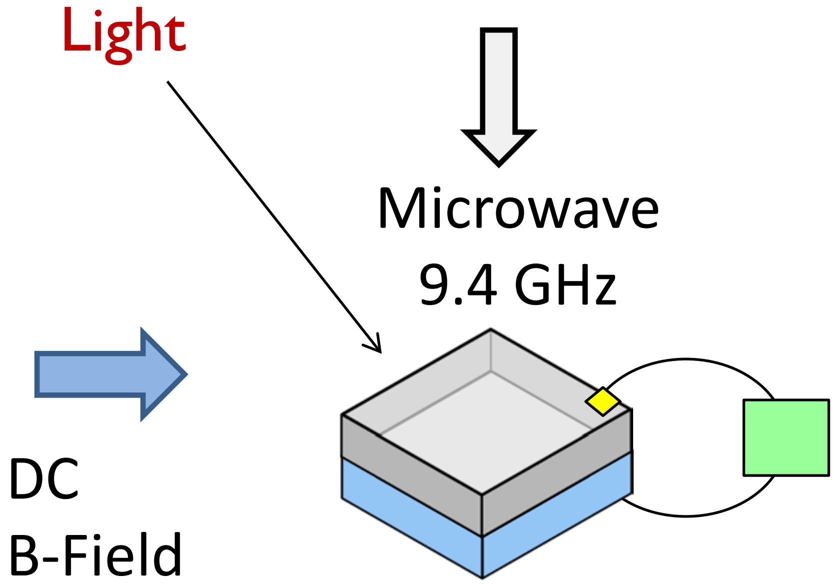
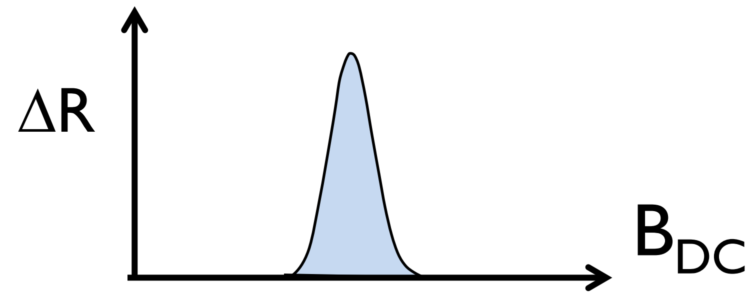
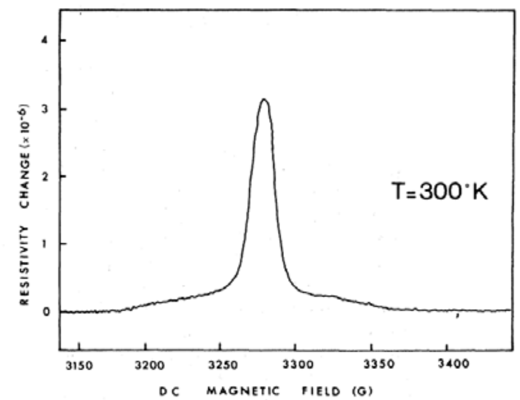
Spin dependent recombination



Basics of a SDR measurement







$$\frac{d(\Delta n)}{dt} = G - \frac{\Delta n}{\tau(B)} = 0$$

$$\tau(B) \equiv \left(\sigma N_{IT} \upsilon\right)^{-1}$$

$$\Delta n(B) = G \times \tau(B)$$

$$\Delta J = J - J_0 = q\Delta n(B)\upsilon$$

$$= qG\upsilon \times \tau(B)$$

Singlet vs. Triplet States: How to make lifetime B dependent

$$s(s+1)=\sqrt{2}$$

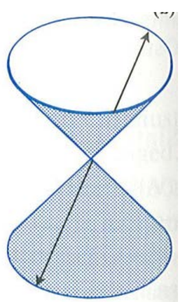
T_1^{+1}

T_1^{0}

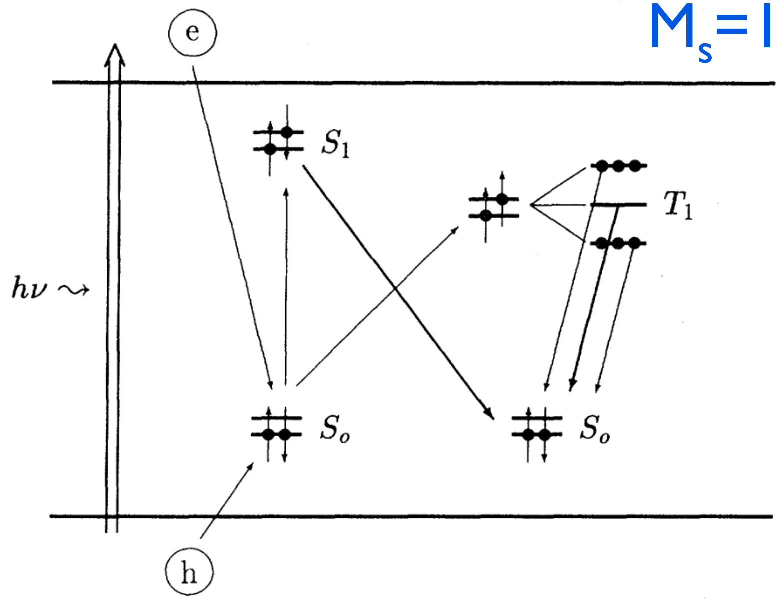
T_1^{-1}

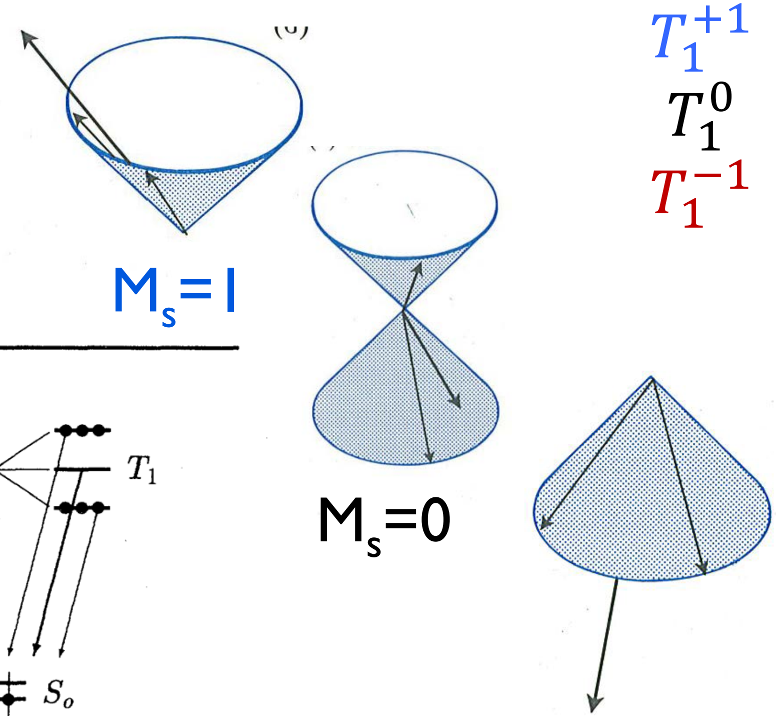
$$\omega_L \propto \frac{\mu_B B_0}{\hbar}$$

$$s(s+1)=\sqrt{3}/2$$



S=0, M_s=0





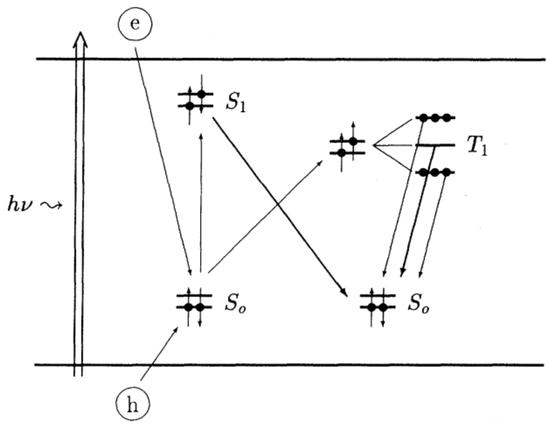
M_s=1

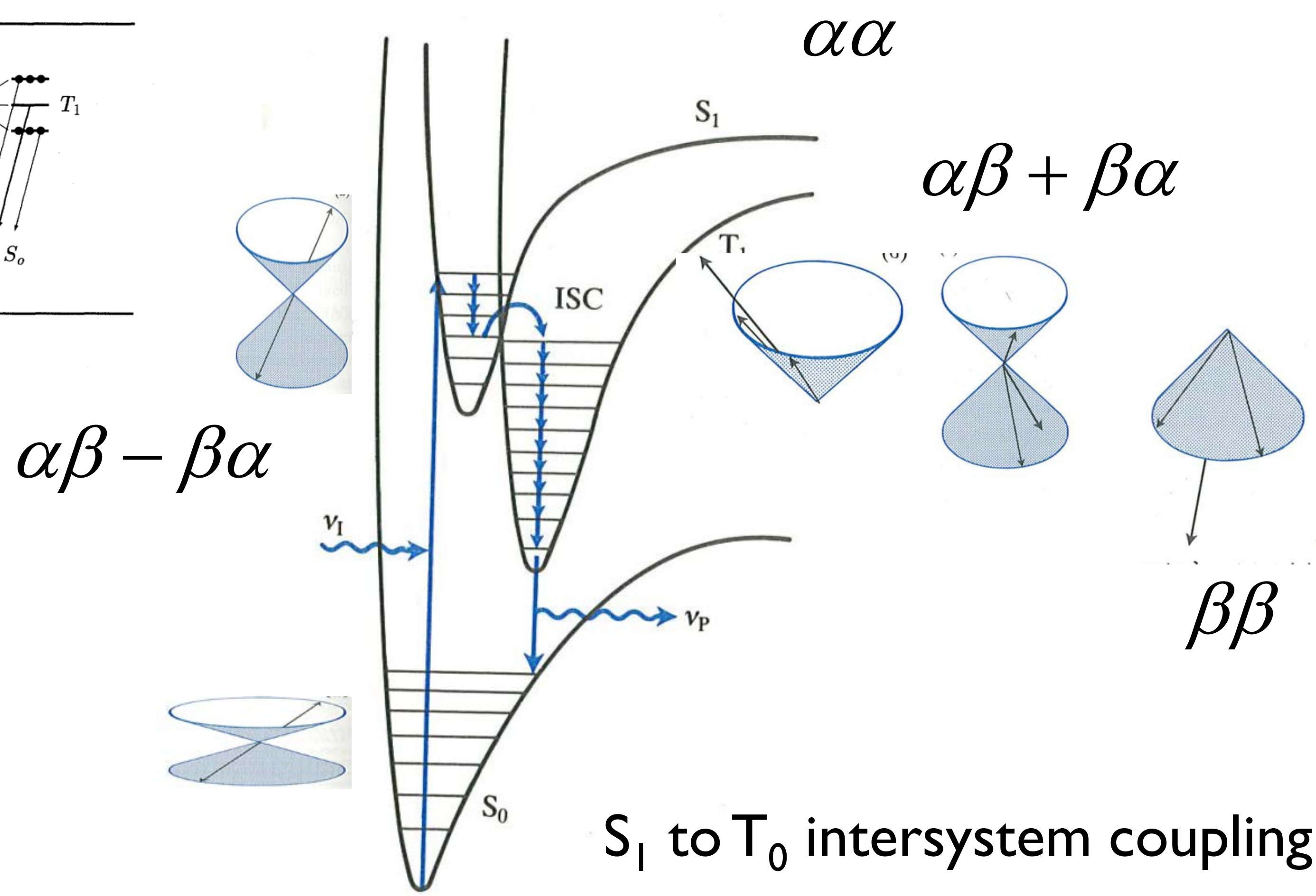
M_s=0

M_s=-1

S=1

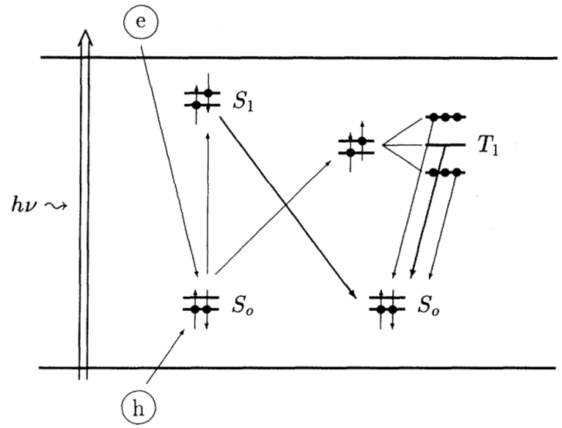
Another perspective of spin relaxation





S_1 to T_0 intersystem coupling

Rules of spin relaxation



T_1^{+1}

T_1^{0}

T_1^{-1}

B_{DC}

1. S_0 to S_1 transition is allowed both ways.

2. S_1 to T_1^0 transition through intersystem coupling (note $\Delta S_Z = 0$)

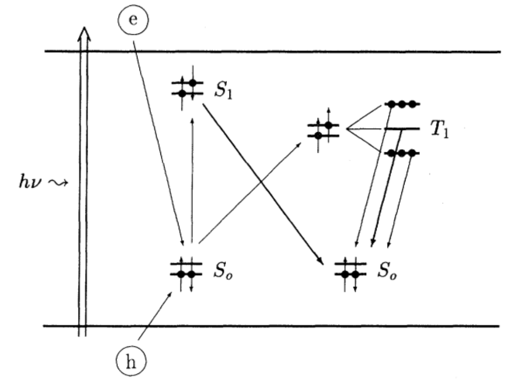
3. Selection rule allows transition with $\Delta S_Z = \pm 1$. Therefore, T_1^{+1} couples to T_1^0, and T_1^0 couples to both T_1^{+1} and T_1^{-1}, but T_1^{+1} does not couple to T_1^{-1}.

3. Coupling between T_1^{+1} and S_0 is similar to that of T_1^{-1} to S_0, but T_1^0 to S_0 is different.

4. The splitting between T_1^{+1} and T_1^0 is different from that of T_1^{-1} and T_1^0. The field couples to only one group. And this restores equilibrium among the states.

Derivation of the key result

Trap-assisted Direct



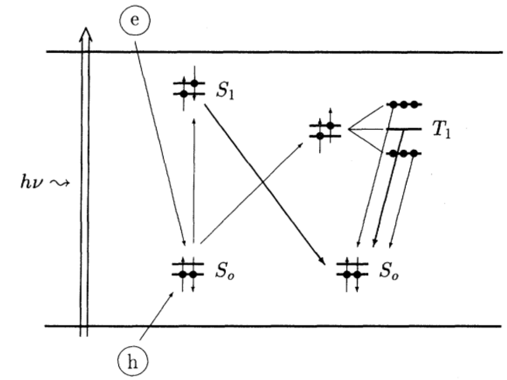
$$\frac{dn_e}{dt} = G - \sigma n_e n_{S_0} - R n_e$$

$$\frac{dn^+}{dt} = \frac{\sigma n_e n_{S_0}}{3} - n^+ R - (n^+ - n^0)W - (n^+ - n^0)B$$

$$\frac{dn^0}{dt} = \frac{\sigma n_e n_{S_0}}{3} - n^0 R_0 - (n^0 - n^+)W - (n^0 - n^-)W - (n^0 - n^+)B$$

$$\frac{dn^-}{dt} = \frac{\sigma n_e n_{S_0}}{3} - n^- R - n^- R - (n^- - n^0)W$$

Derivation … continued



$$\frac{dn^{+}}{dt} = \frac{dn^{0}}{dt} = \frac{dn^{-}}{dt} = 0$$

$$n_T = n^0 + n^+ + n^- = \frac{\sigma n_e n_{S_0}}{3} F(\mathrm{B})$$

$$f(\mathrm{B}) = \frac{(R+W)(2R_0 + R + 9W) + B(R_0 + 5R + 9W)}{(R+W)(RR_0 + 2RW + R_0 W) + B(RR_0 + 2RW + R_0 W + R^2)}$$

$$G = \frac{\sigma n_e n_D}{1 + \frac{1}{3}\sigma n_e n_D F(B)} + R n_e$$

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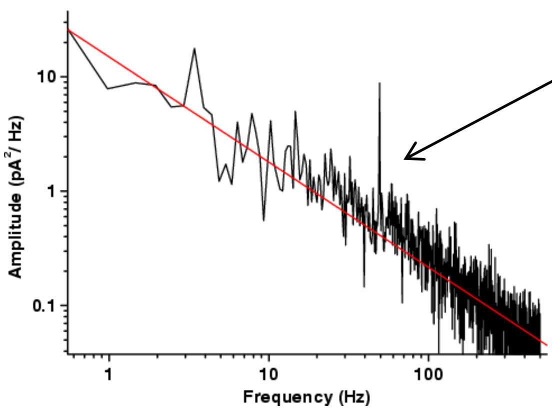
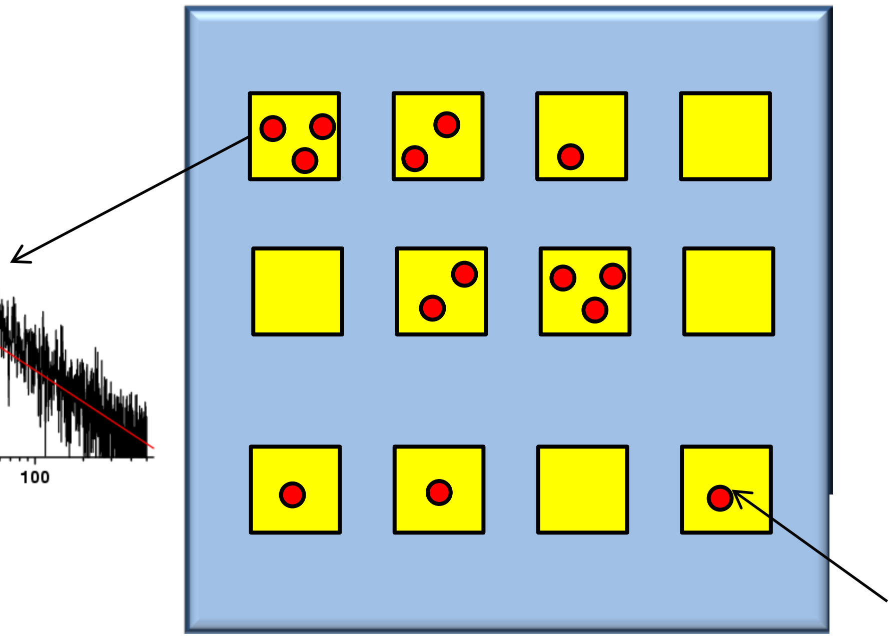
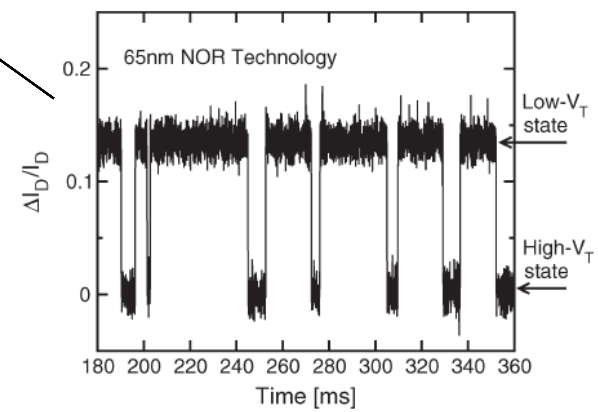
Recall: Statistics of trapping

$$10^{17}\,\text{cm}^{-3}\times 2\text{nm}\times 100\text{nm}\times 100\text{nm} = 2 \text{ traps/device}$$

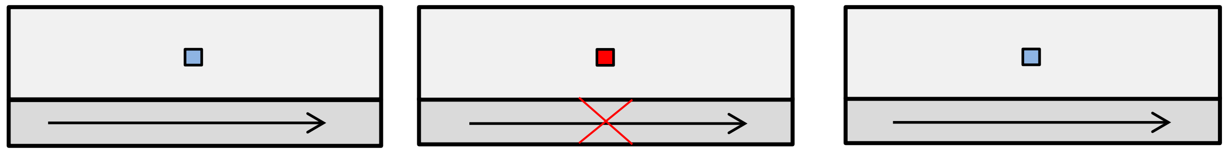




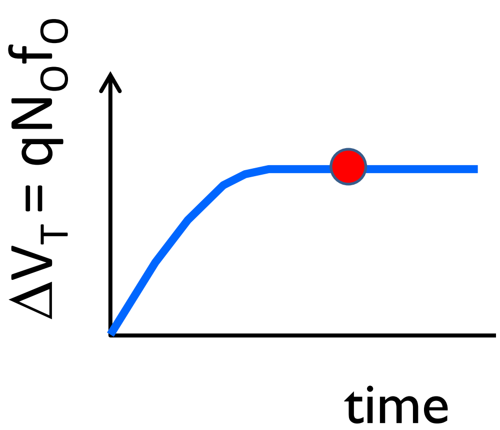
$$P_n = \frac{N^n e^{-N}}{n!}$$

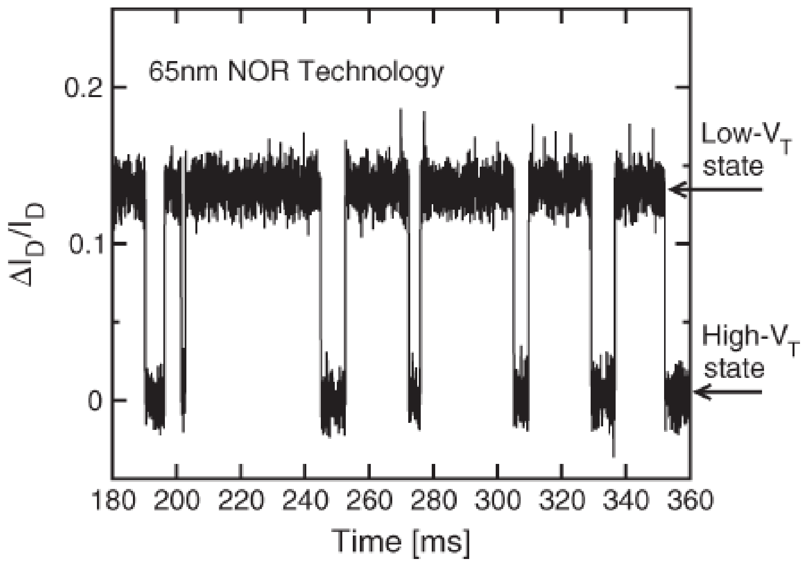


Fluctuation in single trap occupation



Sodini, IEDM, 200

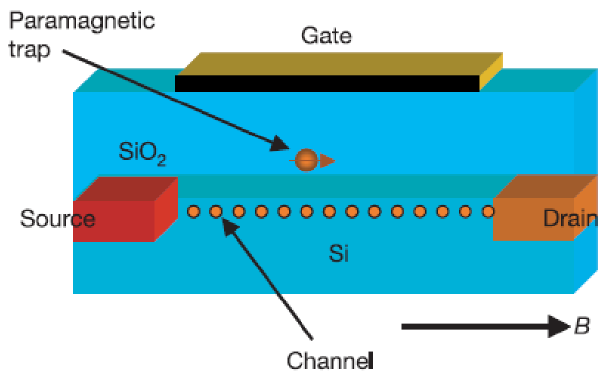




$$S(\omega) = \frac{1}{T \to \infty}\left\langle \left|F(\omega)\right|^2 \right\rangle = \left[\frac{N_0{}^2 \tau_c}{1+\left(\tau_c \omega\right)^2} \right]$$

Electrically detected spin resonance of a single trap in a MOSFET

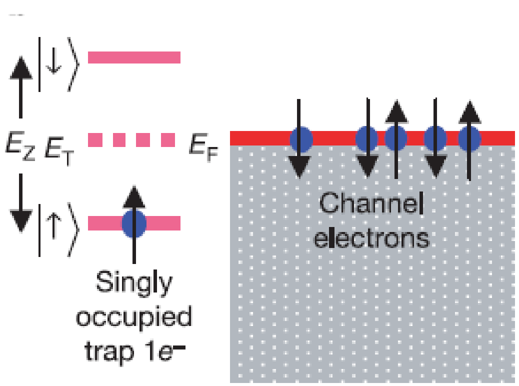
Ref. Xiao, Nature, 430, 435, 2004.



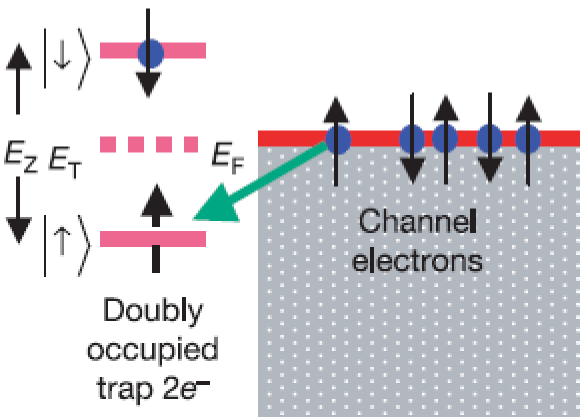
Paramagnetic Trap with single electron

$$E_z = g\mu_0 B_0$$

Singly occupied

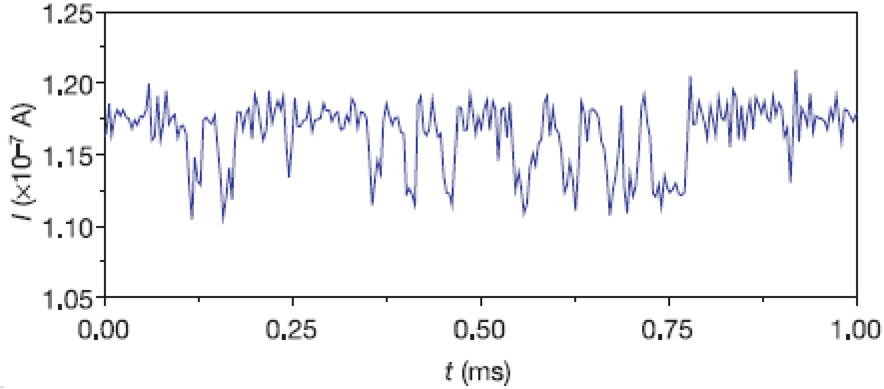


Doubly occupied

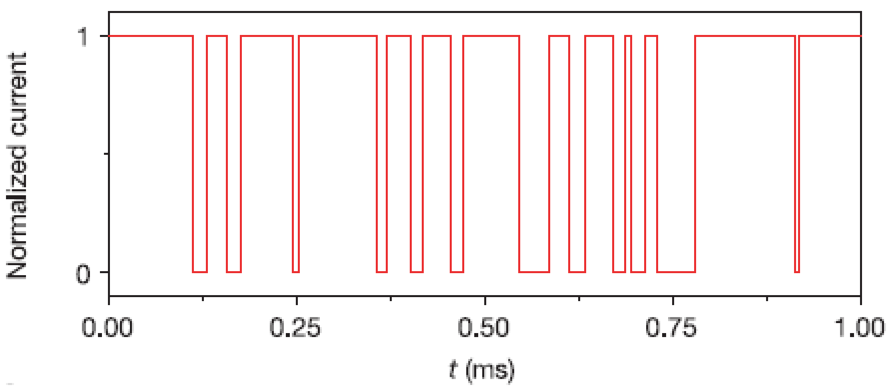


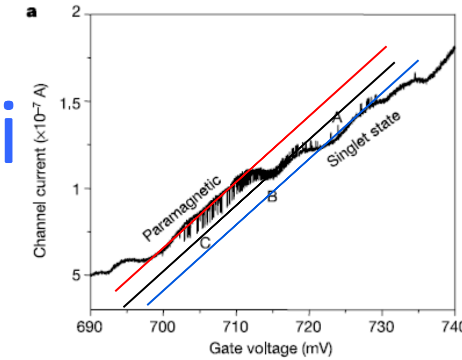
Energy level splitting of a si

1. Original data (E_T~E_F)

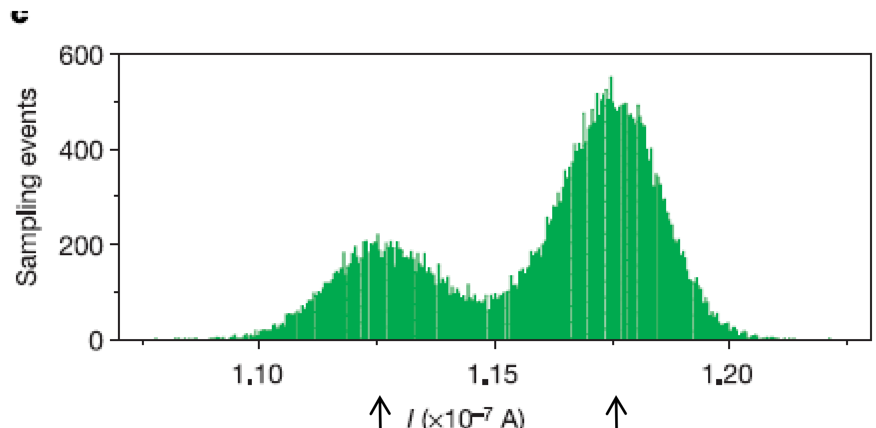


2. Cleaned data (E_T~E_F)





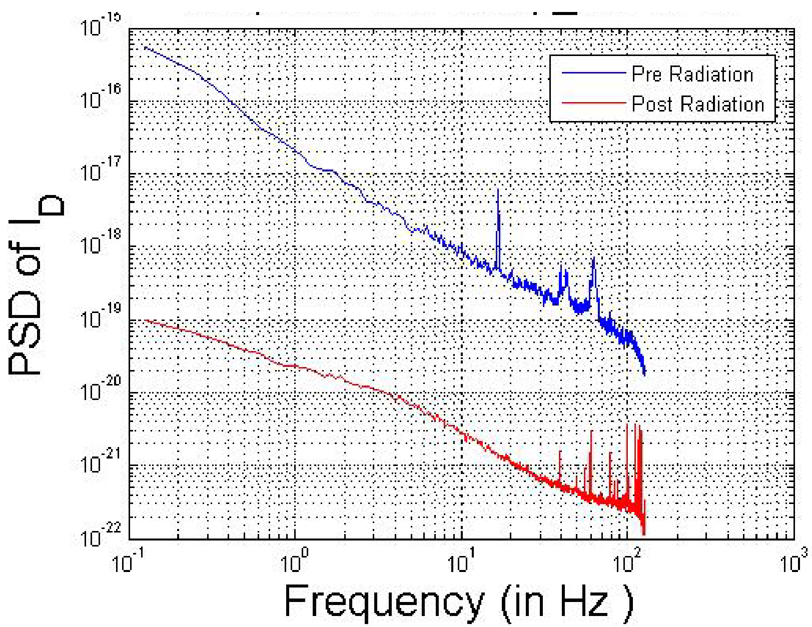
2. Statistical Distribution

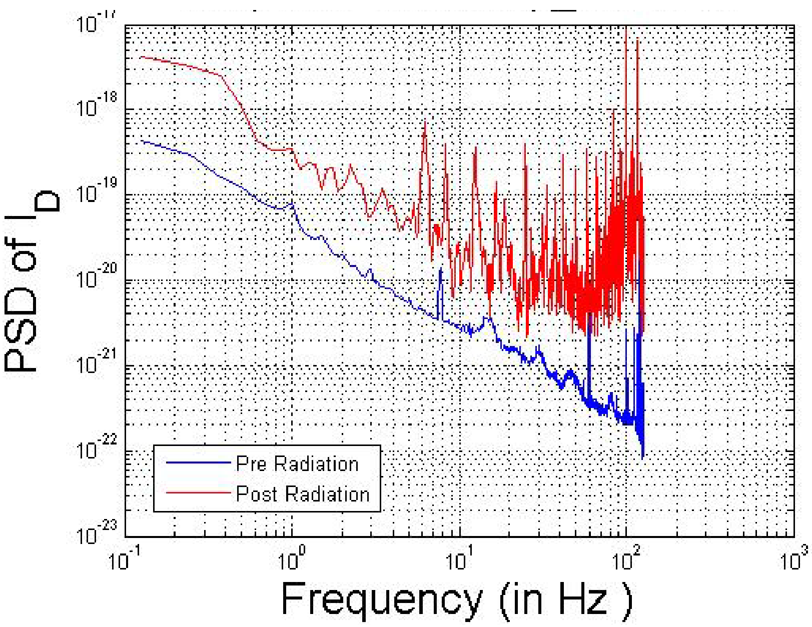


Doubly occupied

Singly occupied

Noise as a characterization tool





Overall, noise can be a sensitive monitor of shallow traps

Conclusions

- ESR has long been a powerful tool for chemists and physicists, SDR has a long history as well.

- The modern synthesis of SDR and ESR in the form of EDSR has become a powerful tool.

- The approach is sensitive, the key challenge is complexity of setup. Cannot be used for routine characterization of wafer.

- A combination of analytical tools allow fundamental understanding of a given reliability problem. Once this goal is achieved, classical tools are often more convenient.

References

- *I followed the derivation of L.S. Vlasenko et al. Electron Paramagnetic Resonance vs. spin-dependent recombination: Excited triplet states of structural defects in irradiated silicon, PRB, 52(2), 1995. p. 1144. The original work was done by D. Lepine, Spin-Dependent recombination on silicon surface, PRB, 6(2), 1972. p. 436.The first correct formulation is due to* 4D. Kaplan, I. Solomon, and N. Mott, J. Phys. Lett. **39**, 51 ~1978 – although they emphasized direct e-h recombination, not the trap-assisted generalization we discussed.
- *C. Boehme and K. Lips – Theory of time-domain measurement of spin-dependent recombination with pulse electrically detected magnetic resonance", PRB, 68, 245105, 2003 provides a more sophisticated quantum mechanical treatment of the problem.*
- *The EDMR (electrically detected magnetic resonance) technique has become sophisticated enough to detect single spin– see, L. Martin, "A scheme for electrical detection of single-electron spin resonance", PRL, 018301, 2003. T. Wimbauer et al., Defects in planar silicon p-n junctions studied with electrically detected magnetic resonance. APL, 76(16), 2280, 2000. M. Xiao et al., "Electrical Dectection of the spin resonance of a single electron in a silicon field-effect transistor, Nature, p. 435, 2004.*
- *K. Hung et al., Random Telegraph Noise in Deep-Submicrometer MOSFETs, 11(2), p. 90, 1990..* B. Gross and Charles G. Sodini. 1/f noise in MOSFETs with ultrathin gate dielectrics.

  In IEDM Technical Digest, pages 881{884, 1992.

Self-Test Questions

Q1. If a signal disappears from ESR because of negative-U configuration, can it be detected by SDR or EDSR methods?

Q2. What is the relationship between Gauss and Tesla as units of magnetic field?

Q3. Was the original SDR method for bulk or interface traps?

Q4: What is the relationship between RTN noise spectra and EDSR spectra? At what point will they be substantially different?

Q5. For single spin, we have 2 states. at the ground level. For two spins, we have 4 states (singlet and triplet).How many spin states do you expect for a 3-spin system?

Q6. What are the advantages and disadvantages of spin-based detection?

Q7. What is the difference between hyperfine interaction and hyper-polarizibility?

Q8. If ESR experiments are used for NBTI degradation, what type of time exponent would you expect? What about HCI degradation ?