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

Gate Oxide ($\text{SiO}_2$), amorphous

$\text{Si}$ $\text{Si}$ $\text{Si}$ $\text{Si}$ $\text{Si}$ $\text{Si}$ $\text{Si}$ $\text{Si}$ $\text{Si}$

Si-Channel, crystalline

$P_{b0}$
Different types of ESR-visible defects

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

Absorbance

1st Derivative

B Field
Hyperfine interaction & paramagnetic resonance

\[ \Delta E = g_e \mu_B B_0 \]

B-value suggests local environment

easyspin.org
ESR signature of different defects

Pb parallel and perpendicular to \(<1\bar{1}1>\)

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Spin dependent recombination

Gate Oxide (SiO₂), amorphous

Si-Channel, crystalline

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Basics of a SDR measurement

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

\[
\Delta n(B) = G \times \tau(B)
\]

\[
\Delta J = J - J_0 = q \Delta n(B) \nu
\]

\[
= q G \nu \times \tau(B)
\]
Singlet vs. Triplet States: How to make lifetime $B$ dependent

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

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

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

$S=0, M_s=0$

$T_0^1$

$T_1^0$

$T_1^{-1}$

$S=1$

$M_s=1$

$M_s=0$

$M_s=-1$
Another perspective of spin relaxation

$\alpha \alpha$

$\alpha \beta + \beta \alpha$

$\alpha \beta - \beta \alpha$

$S_1$ to $T_0$ intersystem coupling
Rules of spin relaxation

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 $T_1^{-1}$.
4. 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.
5. 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

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

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

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

\[
\frac{dn^-}{dt} = \frac{\sigma n_e n_{S_0}}{3} - n^- R - n^- R - (n^- - n^0)W
\]
Derivation ... continued

\[ \frac{dn^+}{dt} = \frac{dn^0}{dt} = \frac{dn^-}{dt} = 0 \]

\[ n_T = n^0 + n^+ + n^- = \frac{\sigma n_e n_s}{3} F(B) \]

\[ f(B) = \frac{(R + W)(2R_0 + R + 9W) + B(R_0 + 5R + 9W)}{(R + W)(RR_0 + 2RW + R_0W) + B(RR_0 + 2RW + R_0W + R^2)} \]

\[ G = \frac{\sigma n_e n_D}{1 + \frac{1}{3} \sigma n_e n_D F(B)} + Rn_e \]
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Recall: Statistics of trapping

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

$$P_n = \frac{N^n e^{-N}}{n!}$$
Fluctuation in single trap occupation

\[ \Delta V_T = qN_0 f_0 \]

\[ S(\omega) = \frac{1}{T \to \infty} \left\langle \left| F(\omega) \right|^2 \right\rangle = \left[ \frac{N_0^2 \tau_c}{1 + \left( \frac{\tau_c \omega}{2} \right)^2} \right] \]
Electrically detected spin resonance of a single trap in a MOSFET


Paramagnetic Trap with single electron

\[ E_z = g \mu_B B_0 \]

Singly occupied

Doubly occupied

Singly occupied trap 1e⁻

Doubly occupied trap 2e⁻
Energy level splitting of a single trap

1. Original data ($E_T \sim E_F$)

2. Cleaned data ($E_T \sim E_F$)

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


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?