Recent Electrically Detected Magnetic Resonance Results: Effects of Barium and Nitrogen on Interface Defects; Disappearing E’ Centers

Patrick Lenahan and James Ashton, Penn State University, University Park, PA 16802
Aivars J. Lelis, United States Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783, USA
Daniel J. Lichtenwalner, Wolfspeed, a Cree Company, 3028 E. Cornwallis Rd, Research Triangle Park, NC 27709, USA
Mark A. Anders, National Institute of Standards and Technology (NIST), 100 Bureau Drive, Gaithersburg, MD 20899
Arthur H. Edwards, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland
Air Force Base, New Mexico, 87117-5776
Peter A. Schultz, Sandia National Laboratories, Albuquerque, NM 87185-1322 USA
Renee M. Van Ginhoven, Directed Energy Directorate, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico, 87117-5776
Introduction I

- Electrically detected magnetic resonance (EDMR) via spin dependent recombination (SDR) via bipolar amplification effect (BAE) and spin dependent charge pumping (SDCP)
- (New) spin dependent electron nuclear double resonance (EDENDOR)
- Theory help from Arthur Edwards, Renee Van Ginhoven and Peter Schultz
Introduction II

• The effects of NO introduced nitrogen on near-interface defects

• The disappearance of E’ centers

• The effects of barium on near-interface defects
Electron Paramagnetic Resonance (EPR)

**Simplest Case:**
\[ \Delta E = h\nu = g_e \beta H \]

Deviations from the resonance condition provide useful information about the nature of specific defects.

- **Spin-Orbit Coupling:** due to electron’s orbital angular momentum about the nucleus
  \[ \Delta E = h\nu = g\beta H + m_I A \]

- **Electron-Nuclear Hyperfine Interaction:** due to nearby nucleus with magnetic moment
Spin-Orbit Coupling & Hyperfine Interactions

\[ \Delta E = h\nu = g\beta H + m_I A \]

Effectively, nuclear moment field averaged over wave function.
Electrically Detected Magnetic Resonance (EDMR)

• EPR limitations:
  • Sensitivity $10^{10}$ total defects
  • Sensitive to ALL paramagnetic defects in the sample

We want to identify defects in devices like transistors

We want to know how specific defects affect device performance

• EDMR
  • Sensitivity of 1000 defects or better
  • Only sensitive to electrically active defects within device under study
EDMR Measurement Techniques: SDR & SDCP

Spin Dependent Recombination

- Electron Capture
- Hole Capture
- $E_C = \text{Conduction Band Edge}$
- $E_D = \text{Defect Level}$
- $E_V = \text{Valence Band Edge}$

Large Magnetic Field

$h\nu = g\beta H$

Under Resonance Condition (simplest case)

This is a forbidden transition

This is an allowed transition

Spin Dependent Charge Pumping

$V_{TH}$ $V_H$ $t_H$

$V_{FB}$ $V_L$ $t_L$

$\Delta V_G$

$E_C$ $E_F$ $E_V$

SiC $SiO_2$

SiC $SiO_2$

$n^+$ recombination

$I_{CP}$

This is a forbidden transition

This is an allowed transition
Bipolar Amplification Effect (BAE)

This is a spin dependent recombination (SDR) EDMR measurement. It is sensitive to only levels around the middle of the band gap.
Variable Frequency EDMR

- $g$ broadening scales with frequency
- Hyperfine broadening is (nearly) frequency independent
- If line width is dominated by $g$, it will be proportional to frequency

\[
H_{\perp} - H_{\parallel} \approx \nu \left[ \frac{1}{g_{\perp}} - \frac{1}{g_{\parallel}} \right] \frac{h}{\mu_B}
\]

\[
\approx \nu \left[ \frac{g_{\perp} - g_{\parallel}}{g_{\perp} g_{\parallel}} \right] \frac{h}{\mu_B} \frac{1}{\nu}
\]

\[
\Delta H \approx \nu [\Delta g] \frac{h}{4\mu_B}
\]

\[
\frac{4\mu_B}{\hbar \nu} \Delta H = \Delta g
\]
Effects of NO Anneal on 4H-SiC MOSFET EDMR (Earlier results)

NO anneals consistently result in a very large decrease in the EDMR response due to near interface silicon vacancies on the SiC side and hydrogen complexed E’ centers on the oxide side.
The Effects of NO Annealing on BAE EDMR

NO anneals broaden the BAE EDMR response slightly. BAE is sensitive to defects around the middle of the bandgap.
The Effects of NO Annealing on SDCP EDMR

NO anneals broaden the SDCP response dramatically. The SDCP is sensitive to defect levels in more than 80% of the SiC bandgap.
Nitrogen Decoration of Silicon Vacancy Defects

Theoretical work by Edwards, Schultz, and Van Ginhoven show that the second nearest neighbor nitrogen would broaden silicon vacancy EDMR spectra by about 1.5 G. Their work also shows that the nearby nitrogen would lower the 0/- level by about half an eV. These results are consistent with and explain the differences in SDCP and BAE measurements on NO annealing of 4H-SiC MOSFETs.
The Effects of Nearby Nitrogen on Calculated Energy Levels and Hyperfine Interactions

Calculated nitrogen energy level change, about 0.5 eV

Calculated nitrogen hyperfine broadening 1-2 G
Disappearing E’ Centers:
We are unable to detect hydrogen complexed E’ centers in new 4H-SiC MOSFETs

E’ centers almost certainty play a role in bias temperature instabilities (Lelis et al.)
Electrically Detected Electron Nuclear Double Resonance in a Wafer Probing Station
ENDOR Response

\[ I = \frac{1}{2} \]
\[ S = \frac{1}{2} \]

ENDOR Response

\[ v_n = \frac{g_n \beta_n H}{h} \]

\[ g_n \] is known for all nuclei

Easily identify the nuclei responsible for the hyperfine interactions
Electron-Nuclear Double Resonance (ENDOR) Example

Energy Level Diagram

\[ \mathbf{S} = \frac{1}{2} \text{ (Electron Spin)} \]
\[ \mathbf{I} = \frac{1}{2} \text{ (Nuclear Spin)} \]

\[ \alpha_e, \beta_e = \text{Electron Spin Wavefunctions} \]
\[ \alpha_n, \beta_n = \text{Nuclear Spin Wavefunctions} \]

\[ W_n, W_e = \text{Nuclear and Electronic spin relaxation rates} \]

- Pump the Nuclear-Spin Flip to Increase the EPR/EDMR Response
- Identify the local nearby magnetic nuclei

Electron-Nuclear Double Resonance (ENDOR)

Energy Levels for:
\[ \mathcal{H} = g \beta H \cdot S - g_n \beta_n H \cdot I + hA S \cdot I \]

- \( S \) is the electron spin operator
- \( g_n \) is the dimensionless nuclear g-factor
- \( \beta_n \) is the nuclear magneton
- \( A \) is the isotropic hyperfine coupling, given in terms of Hz
- \( I \) is the nuclear spin operator
EDENDOR of SiC n-MOSFET Source-Body Junction
Due to Silicon Atoms
Expected Average $\nu_n = 2.73 \text{ MHz}$
Ultra-Low Field/Zero Field SDR: Spin Dicke Effect

The effect is observed when $B_0 \approx B_1$. This is shown in the red curve as the side bumps near the zero field response. These measurements have potential to evaluate hyperfine interactions.
Zero Field SDCP in 4H-SiC MOSFETs

The zero field SDCP (ZFSDCP) response does not require an applied oscillating RF or microwave magnetic field.

The ZFSDCP may have much of the analytical power of EDMR.

Singlet-triplet mixing vs. singlet-triplet transformation.
Summary

• SDCP/BAE comparison suggests that high concentrations of nitrogen near Si vacancy centers alter the EDMR spectrum and lower the energy levels

• DFT calculations provide a consistent explanation for SDCP/BAE differences in NO and without NO annealed SiC MOSFETs

• We do not observe hydrogen complexed E’ centers in new 4H-SiC MOSFETs. In earlier devices, these centers were almost invariably present

• Three new spin based techniques: EDENDOR, Spin Dicke, and ZFSDCP all have potential for 4H-SiC MOSFET studies