Nanosecond Risetime Pulse Characterization of SiC p+n Junction Diode Breakdown and Switching Properties

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Outline

Pulse testing reveals very important SiC device behaviors not observed by conventional DC and RF testing.

Reverse bias diode pulse testing
   Stable and unstable SiC reverse breakdown.

Forward bias diode pulse testing
   Rectifier reverse recovery switching transients.
   Perimeter-governed device minority carrier lifetimes.

These behaviors directly impact SiC power device performance & reliability.
Bias pulse is formed by discharge of semirigid coax when Hg switch is momentarily triggered.
A Tale of Two Diodes
(Part 1: DC Testing)
Epitaxial Small-Area 4H-SiC p+n Diodes

Wafer A*

\[ V_{\text{DC BKDN}} = 140 \text{ V} \]

* NASA Lewis Run #1841
  J. Appl. Phys. 80, p. 1219

Wafer B**

\[ V_{\text{DC BKDN}} = 142 \text{ V} \]

** NASA Lewis Run #1905
  IEEE EDL 18, p. 96
A Tale of Two Diodes
(Part 2: Reverse Bias Pulse Testing)

Experiment: Subject devices to single-shot reverse-bias pulses of increasing amplitude until catastrophic breakdown failure occurs.

Wafer A
($V_{DC\text{ BKDN}} = 140$ V)

(b) Shot #2
Input Pulse Amplitude = 83 V

Voltage (V)
Current (A)

Time (ns)

Wafer B
($V_{DC\text{ BKDN}} = 142$ V)

Shot #2
Input Pulse Amplitude = 116 V

Voltage (V)
Current (A)

Time (ns)
A Tale of Two Diodes

(Part 2: Reverse Bias Pulse Testing)

Wafer A
(V$_{DC\, BKDN}$ = 140 V)

- Catastrophic Device Failure, Device Physically Destroyed!

Wafer B
(V$_{DC\, BKDN}$ = 142 V)

Pulse Breakdown Discussion

Behavior of devices on Wafer A is unacceptable for many power applications.
• Extremely high reliability, immunity to “glitches” required for most aerospace applications.

Differences between “unstable” Wafer A and “stable” Wafer B:
• Single epi-growth (Wafer B) vs. two-step epi growth (Wafer A).
• SIMS revealed excess Al, N near Wafer A junction not present in Wafer B.
• n-substrate (Wafer B) vs. p-substrate (Wafer A).

Exact physical mechanism still uncertain.
• Bulk failure mechanism - no evidence of surface breakdown.

Positive temperature coefficient breakdown observed only on very small-area \( A < 1 \times 10^{-4} \text{ cm}^2 \) Wafer B devices.
• Elementary (1c) screw dislocations affecting breakdown???
PN Diode Reverse Recovery*

Idealized Test Circuit

Diode Reverse Recovery Current Transient

Minority carrier (hole) lifetime $\tau_p$ related to storage time $t_s$ by:

$$t_s = \tau_p \left\{ \text{erf}^{-1} \left[ 1 + \frac{1}{|I_R|/|I_F|} \right] \right\}^2$$

Reverse Recovery Current Transients
Device Area = 8.1 x 10^{-3} \text{ cm}^2, R_s = 200 \ \Omega

I_F \text{ varied for approximately fixed } I_R

\begin{align*}
V_R &= 30 \text{ V} \\
I_F(t=0^-) &= 0.2 \text{ A} \quad 0.3 \text{ A} \quad 0.4 \text{ A} \quad 0.5 \text{ A} \quad 0.6 \text{ A} \quad 0.7 \text{ A}
\end{align*}

$t_s$ increases as $I_F$ increases.

$I_R \text{ varied for fixed } I_F$

\begin{align*}
I_F(t=0^-) &= 0.65 \text{ A}
\end{align*}

$V_R = 30 \text{ V}$

$V_R = 40 \text{ V}$

$t_s$ decreases as $I_R$ increases.
Storage Time ($t_s$) Dependence on $I_R/I_F$

Experimentally measured storage time behavior follows predicted physical theory.

Effective minority carrier lifetime for this device is 300 ns ($A = 8.1 \times 10^{-3} \text{ cm}^2$)

$$t_s = \tau_p \left\{ \text{erf}^{-1} \left[ 1 + \frac{1}{I_R/I_F} \right] \right\}^2$$

where $\tau_p = 300$ ns
Effective minority carrier lifetime decrease with decreasing area suggests presence of significant perimeter surface recombination effects.
p⁺n Diode Effective Lifetime

Device Hole Recombination = \( R_{\text{Eff.}} A = R_{\text{Bulk}} A + R_{\text{Perim.}} P \)

\[ \frac{\Delta p_n}{\tau_{p \text{ Eff.}}} A \approx \frac{\Delta p_n}{\tau_{p \text{ Bulk}}} A + S_{p \text{ Perim.}} \frac{\Delta p_n P}{A} \]

\[ \frac{1}{\tau_{p \text{ Eff.}}} \approx \frac{1}{\tau_{p \text{ Bulk}}} + S_{p \text{ Perim.}} \left( \frac{P}{A} \right) \]

\[ y = b + mx \]

\( \tau_{p \text{ Eff.}} = \tau_p \) extracted from reverse recovery switching measurement \( t_s \) vs. \( I_R/I_F \) data.

Can estimate \( \tau_{p \text{ Bulk}} \) and \( S_{p \text{ Perim.}} \) from linear plot of \( 1/\tau_{p \text{ Eff.}} \) vs. \( P/A \).
The bulk minority carrier lifetime inherent to this SiC epilayer is much longer than the average lifetime measured on a small-area device. This is due to large perimeter surface recombination.

\[
\frac{1}{\tau_{p \text{ Eff.}}} \approx \frac{1}{\tau_{p \text{ Bulk}}} + s_{p \text{ Perim.}} \left( \frac{P}{A} \right)
\]

\[
y = b + mx
\]

\[
\tau_{p \text{ Bulk}} \approx 0.7 \, \mu s
\]

(4H-SiC, \( N_D = 2 - 4 \times 10^{16} \, \text{cm}^{-3} \))
Storage Times at Constant Current Density

Indicates bulk Auger recombination insignificant compared to perimeter-governed SRH recombination.
Discussion

This work demonstrates by example that perimeter surface recombination can significantly impact SiC bipolar device electrical characteristics via reduced effective minority carrier lifetimes.

• Possible contributing factor to experimental observations of:
  - Low current gains (< 20) in SiC BJT’s produced to date.
  - SiC pn diode current densities below theoretical predictions.
  - Fast switching response of SiC pn diodes and thyristors.

• Greater impact on smaller (IC) devices than larger (power) devices.

• Lifetime reduction likely to be exacerbated by “multi-finger” or “multi-cell” geometries that increase effective perimeter-to-area ratio.

Development and optimization of appropriate SiC surface passivation and junction termination technologies could reduce or eliminate lifetime-limiting role of surface recombination in SiC bipolar devices.
Discussion (cont.)

- Potential impact on n- or p-type 4H- and 6H-SiC at all doping densities (？).

Figure from Janzen & Kordina, ICSCRM-95 p. 657.

- Effect present in ion implanted or heavily compensated SiC junctions?
Summary

Pulse testing reveals very important device behaviors not observed by conventional DC and RF testing.

Observed behaviors directly impact SiC power device
  • reliability
  • switching speed
  • current (density) rating

Pulse testing should play an important role in SiC power device development and qualification.