Perimeter Governed Minority Carrier Lifetimes in 4H-SiC p^+n Diodes Measured by Reverse Recovery Switching Transient Analysis

Philip G. Neudeck

NASA Lewis Research Center
Cleveland, OH

39th Electronic Materials Conference
Fort Collins, CO
June 25-27, 1997

Acknowledgments

NASA Lewis

David Larkin
J. Anthony Powell
Luann Keys
Andrew Trunek
John Heisler
Bruce Viergutz
Gene Schwarze
Jan Niedra
W. Dan Williams

Army Research Laboratory

Chris Fazi

SiC Bipolar Technology

Silicon carbide bipolar devices could prove useful in some applications.

- Bipolar power devices: PN & PiN rectifiers, thyristors, IGBT's, etc.
- BJT based high temperature instrumentation & control IC's.

Problem: Short SiC minority carrier lifetimes limit device performance.

Reported lifetimes measured in devices **well below** 1 µs.

- Increased bipolar power device specific ON resistances.

- Reduced minority carrier injection conductivity.

- Low BJT current gains.

- "Best" SiC BJT gain of only 15 (5 ns effective lifetime) [1].

\+ Fast diode & thyristor switching speeds.

[1] Y. Yang et. al. in Silicon Carbide & Related Materials 1995, IOP Publishing, p. 809.

Measurement of Lifetimes in SiC

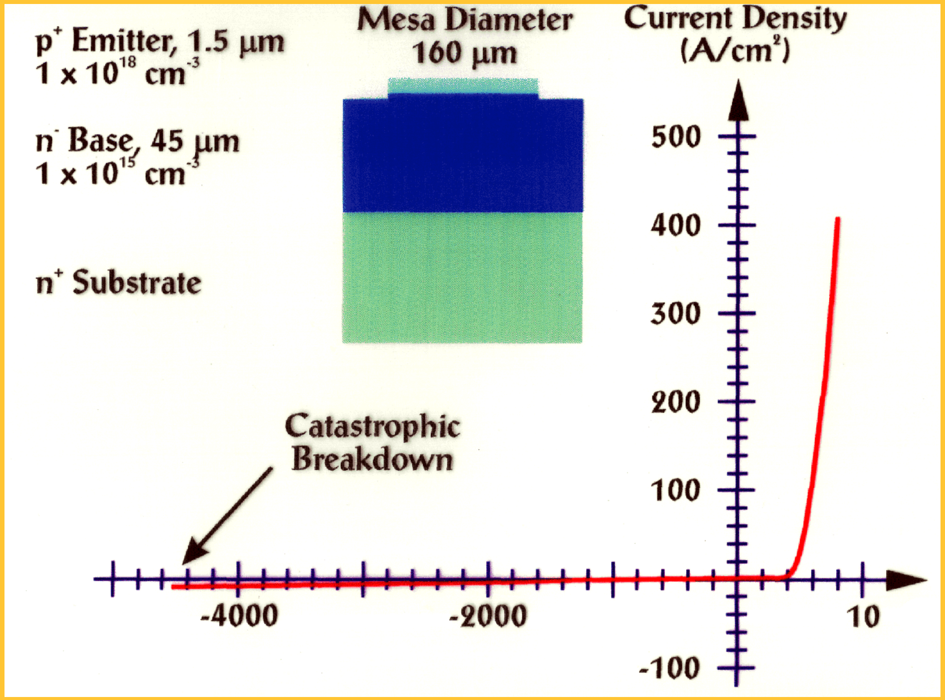
While valid comparisons are somewhat problematic, the majority of experimental SiC bipolar device results do not appear to be consistent with SiC minority carrier lifetimes obtained by optical measurement of SiC starting material prior to device fabrication.

Photoluminescence decay consistently measures longer lifetimes (often more than an order of magnitude longer) than effective lifetimes extracted from electrical measurements of comparably-doped SiC bipolar devices.

Need to better understand physical mechanisms so that improved bipolar electrical device performance can be realized.

O. Kordina et. al., Appl. Phys. Lett. 67, 1561 (1995).

0.43 µs minority carrier lifetime of n- layer measured by PL decay.



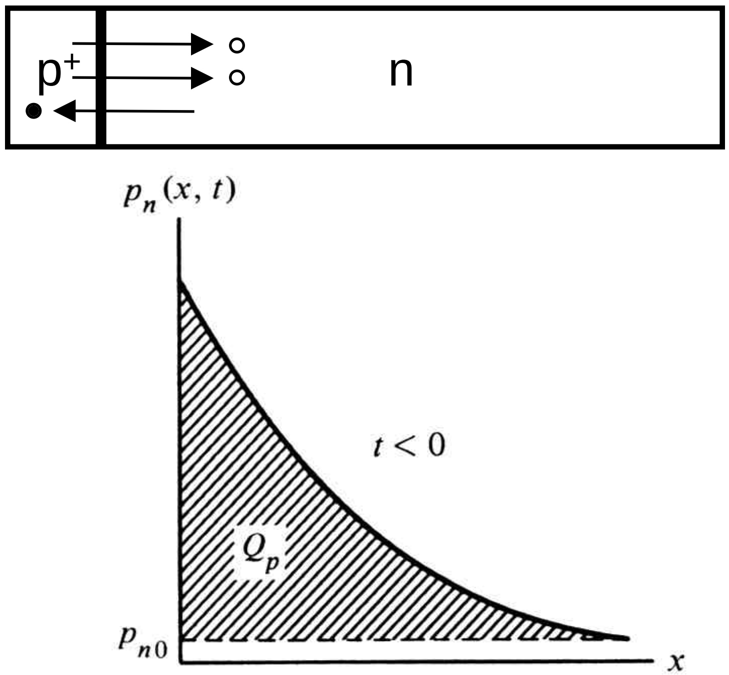
"A forward voltage drop of 6 V was typically obtained at 100 A/cm^2."

"Simulations, however, predict a forward drop of approximately 3.6 V at 100 A/cm^2 for a device with these material properties. This discrepancy between the simulated and measured values is at present unclear."

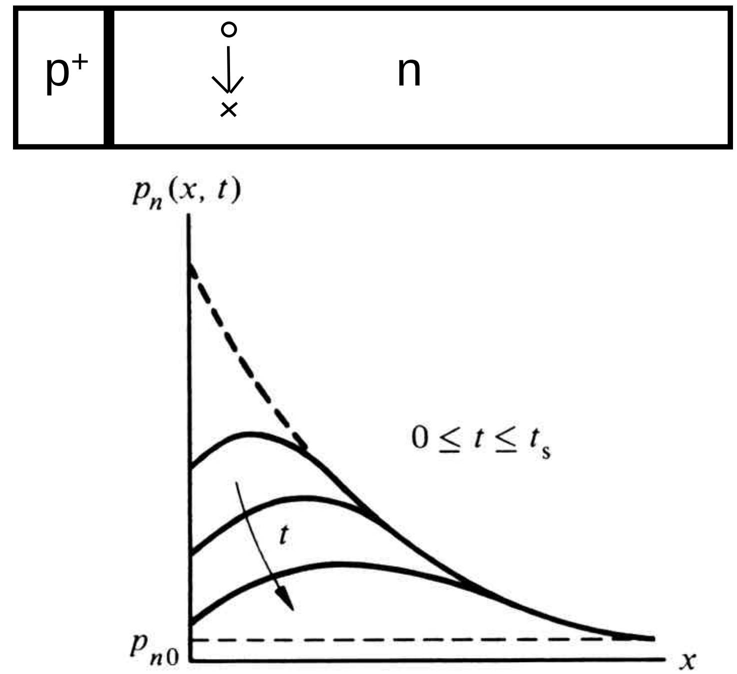
PN Diode Reverse Recovery

Facilitates measurement of diode switching and effective minority carrier lifetime.

Forward bias ($t \le 0^-$)



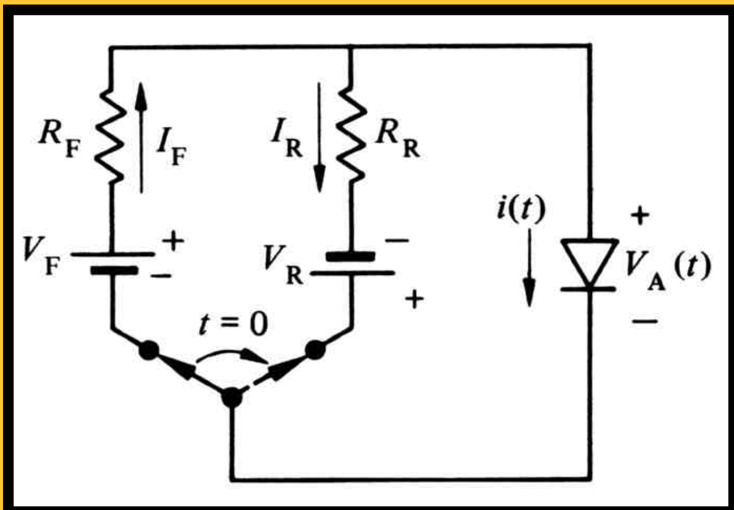
Switch to reverse bias at t = 0



Excess minority carriers must recombine when pn diode switched from forward to reverse bias at t = 0.

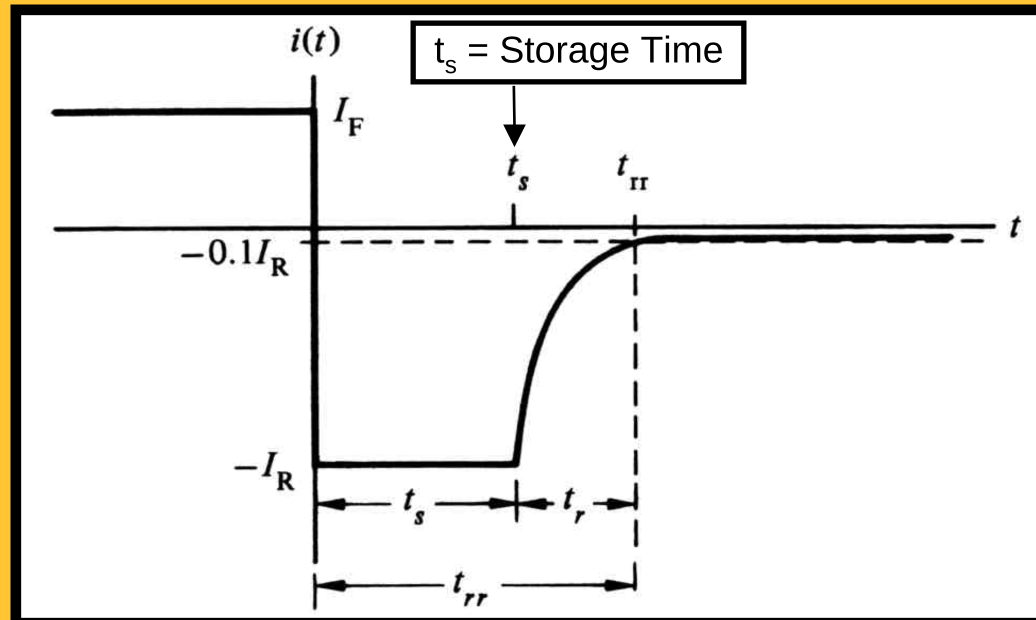
PN Diode Reverse Recovery*

Idealized Test Circuit



(zero inductance)

Diode Reverse Recovery Current Transient



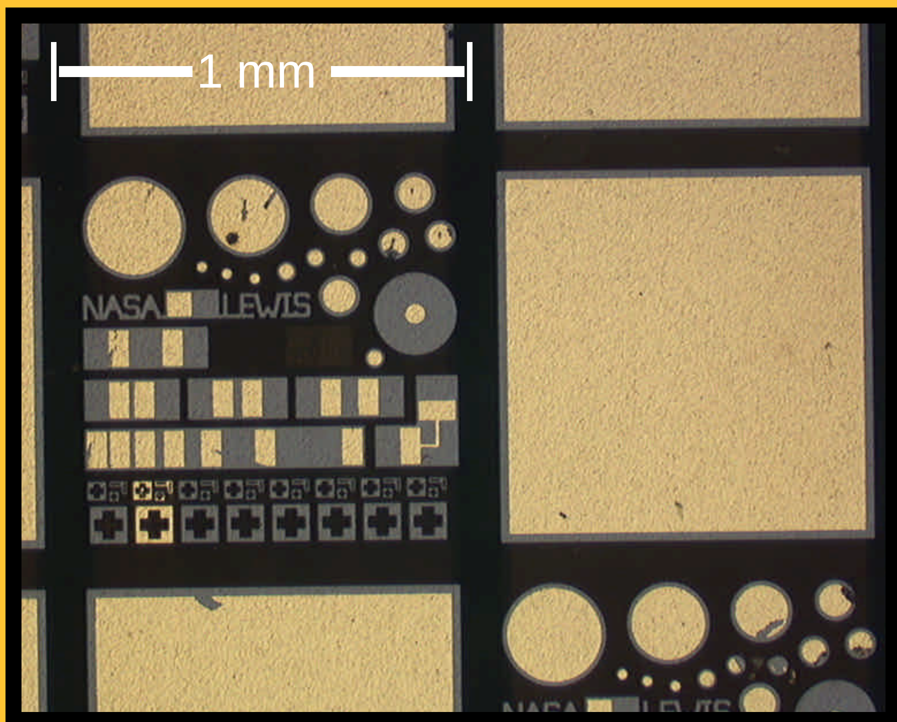
Minority carrier (hole) lifetime τ_p related to storage time t_s by:

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

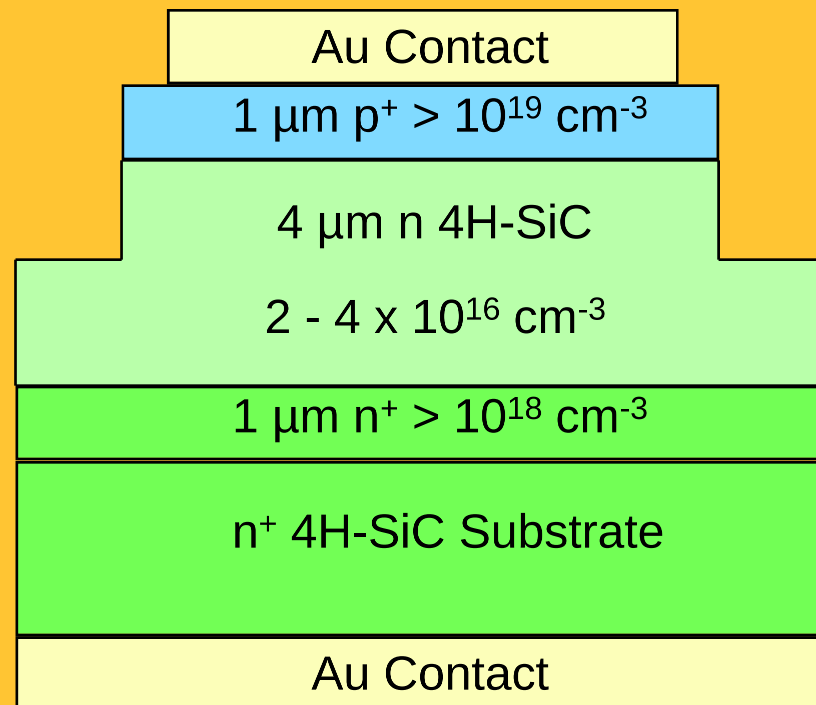
* G. Neudeck, The PN Junction Diode, 2nd Ed., Addison-Wesley Publishing, p. 111.

NASA Lewis 4H-SiC p^+n Diodes

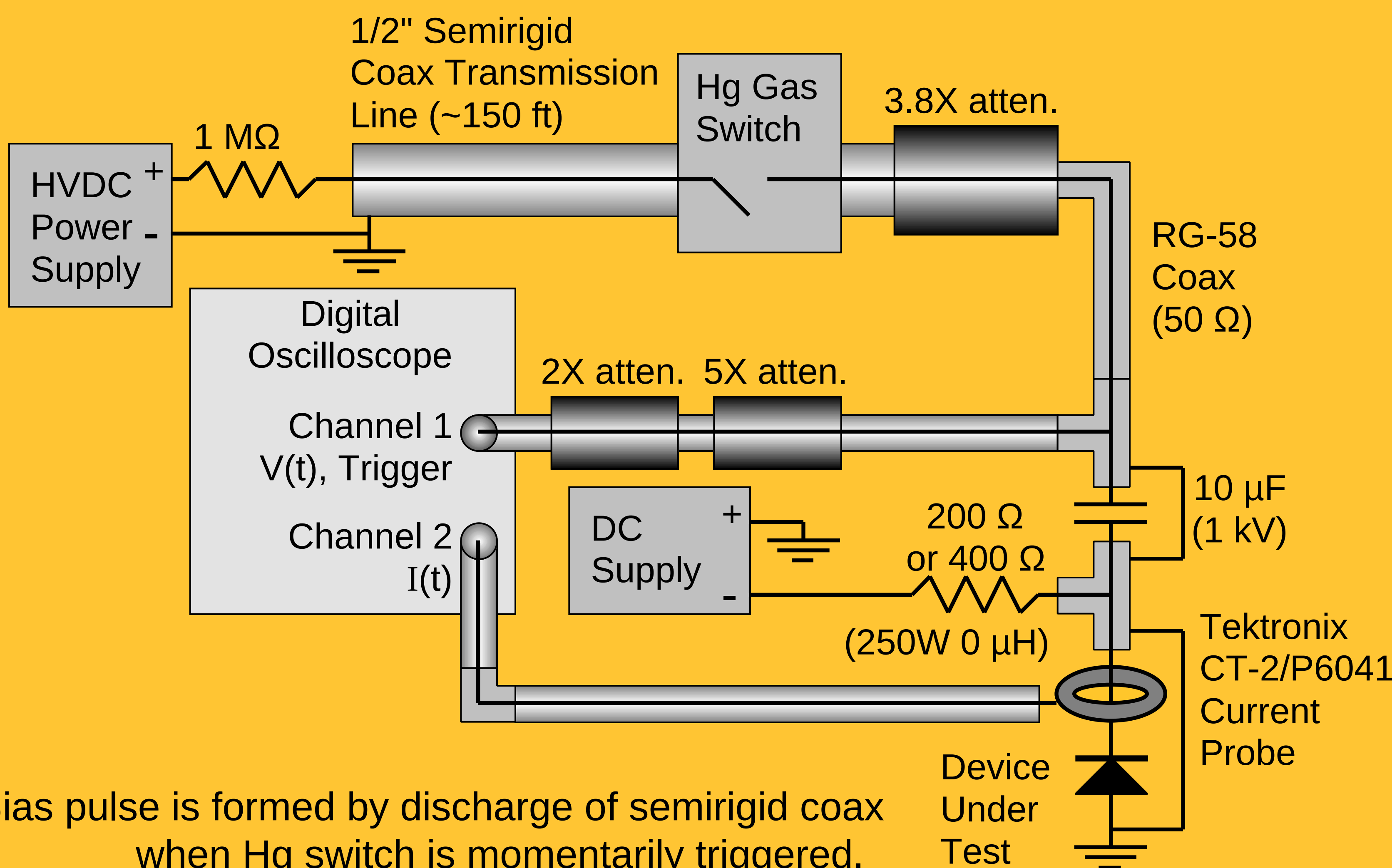
Diode Array Before Packaging



Device Cross-Section



Reverse Recovery Test Circuit

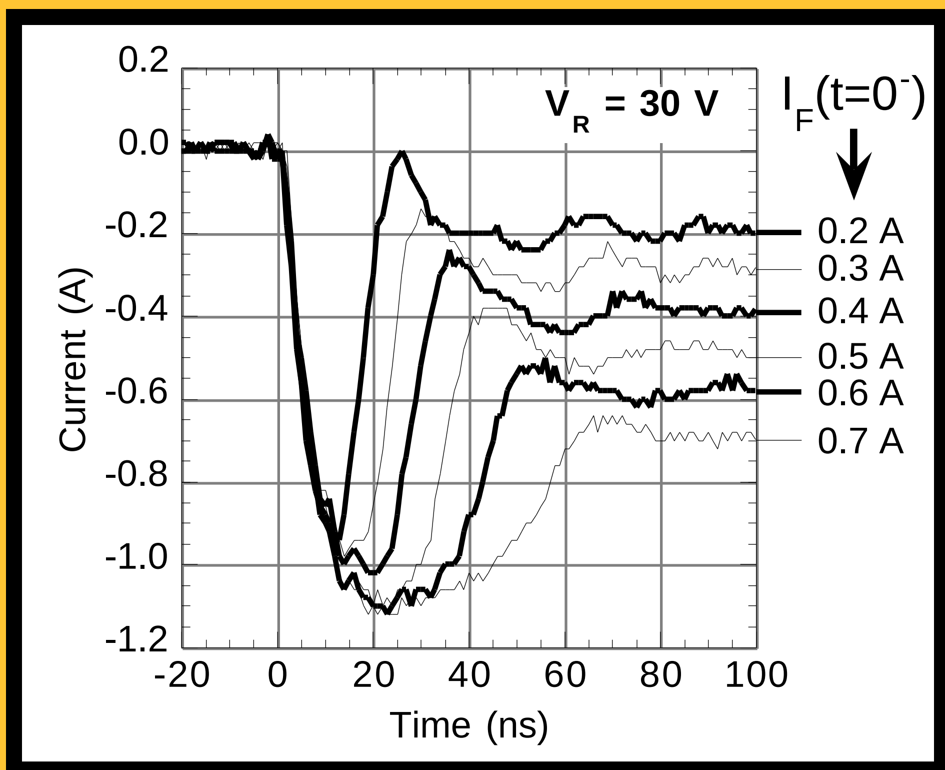


Bias pulse is formed by discharge of semirigid coax when Hg switch is momentarily triggered.

Reverse Recovery Current Transients

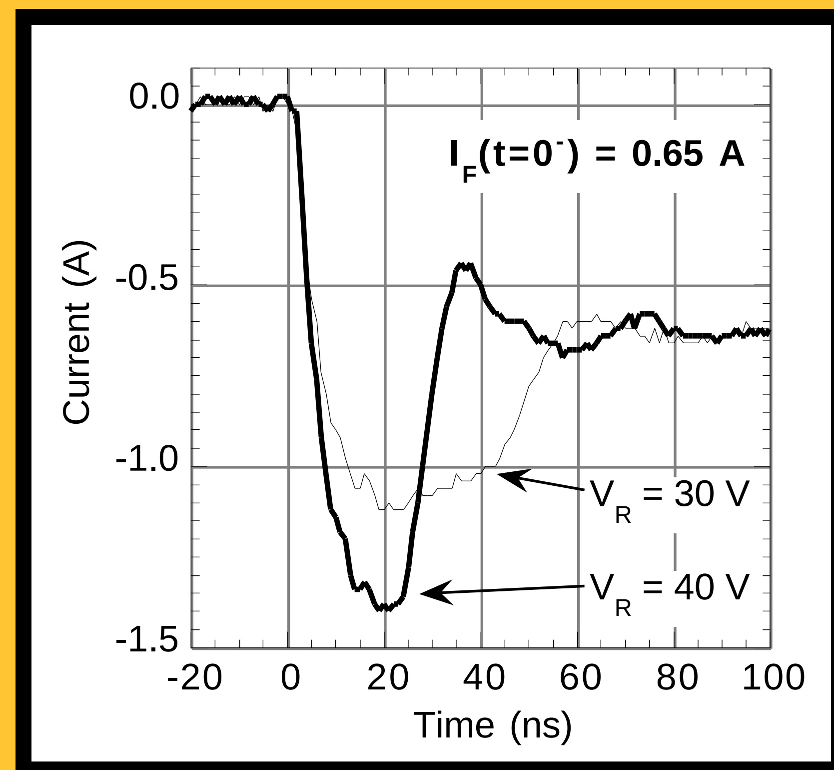
Device Area = 8.1 x 10^{-3} cm^2, Rs = 200 Ω

I_F varied for approximately fixed I_R



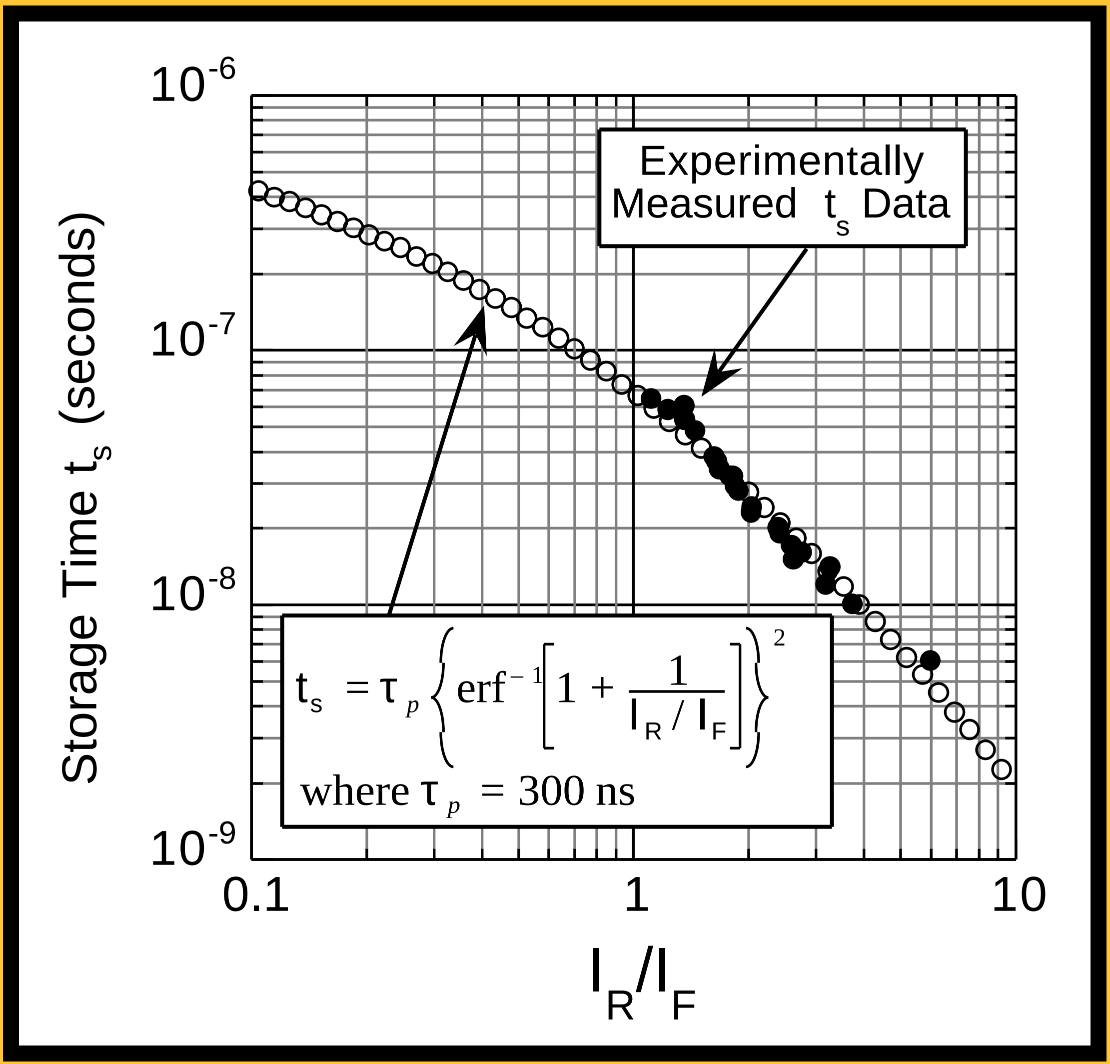
t_s increases as I_F increases.

I_R varied for fixed I_F



t_s decreases as I_R increases.

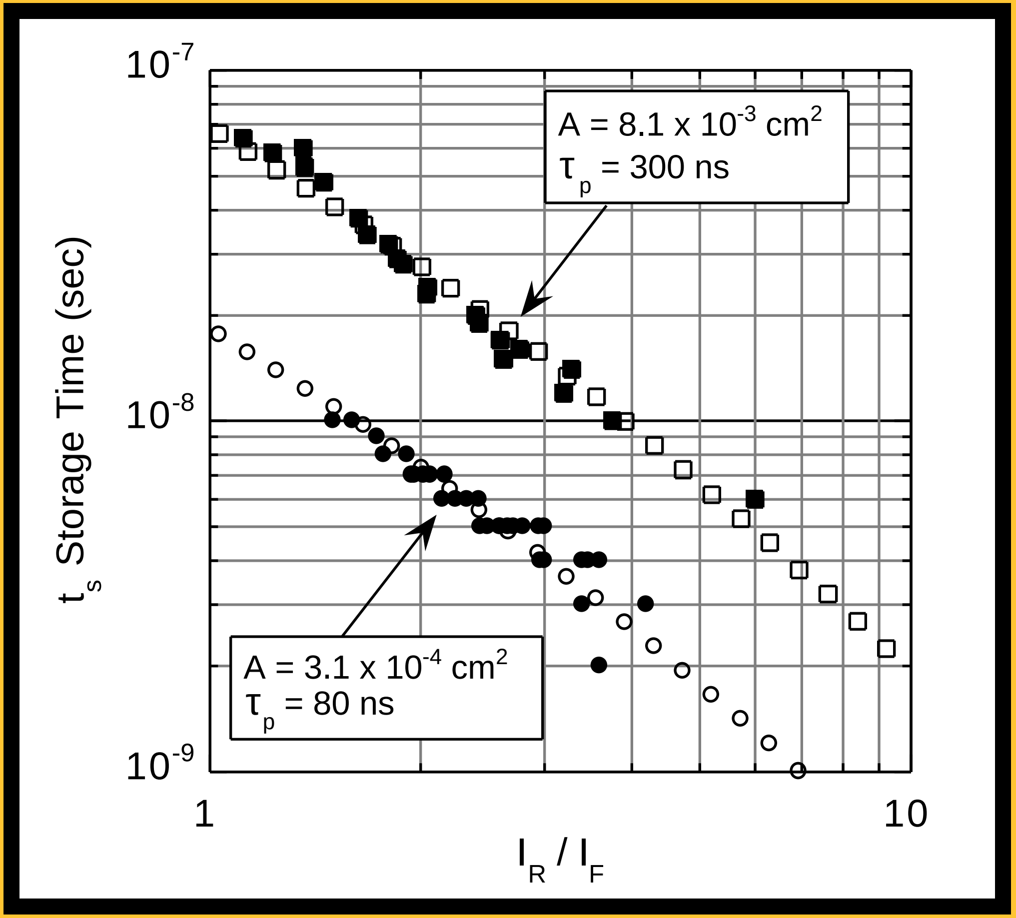
Storage Time (t_s) Dependence on I_R/I_F



Experimentally measured storage time behavior follows predicted physical theory.

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

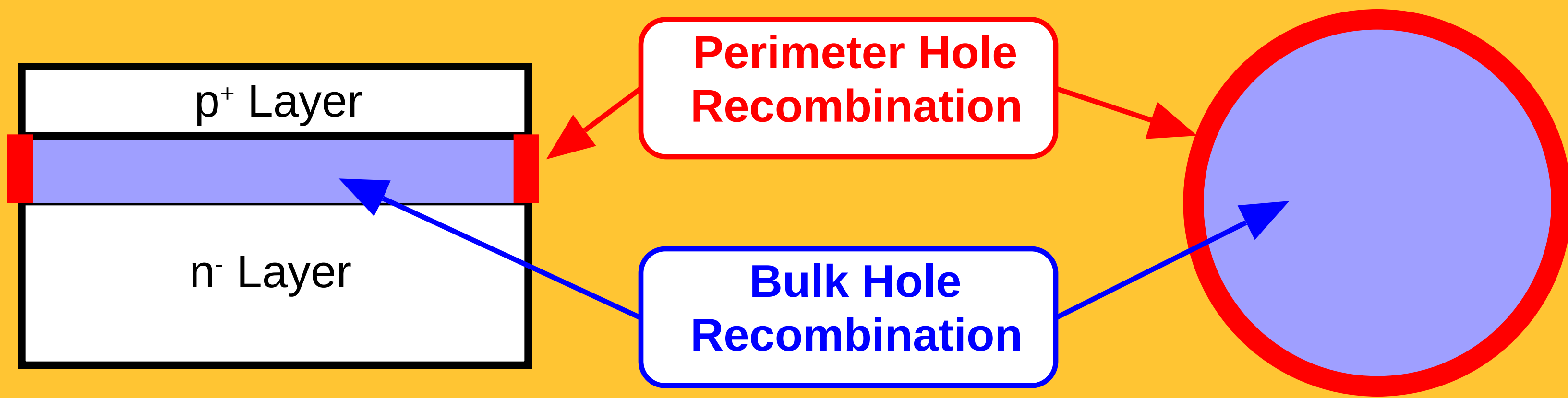
Storage Times (t_s) of Larger vs. Smaller Devices



Effective minority carrier lifetime decrease with decreasing area suggests presence of significant perimeter surface recombination effects.

p^+n Diode Effective Lifetime

Side View of Diode | Top View of Diode



Device Hole Recombination = $R_{Eff.}A = R_{Bulk}A + R_{Perim.}P$

$$\frac{\Delta p_n}{\tau_{p\,Eff.}} A \approx \frac{\Delta p_n}{\tau_{p\,Bulk}} A + s_{p\,Perim.} \Delta p_n P$$

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

$$y = b + mx$$

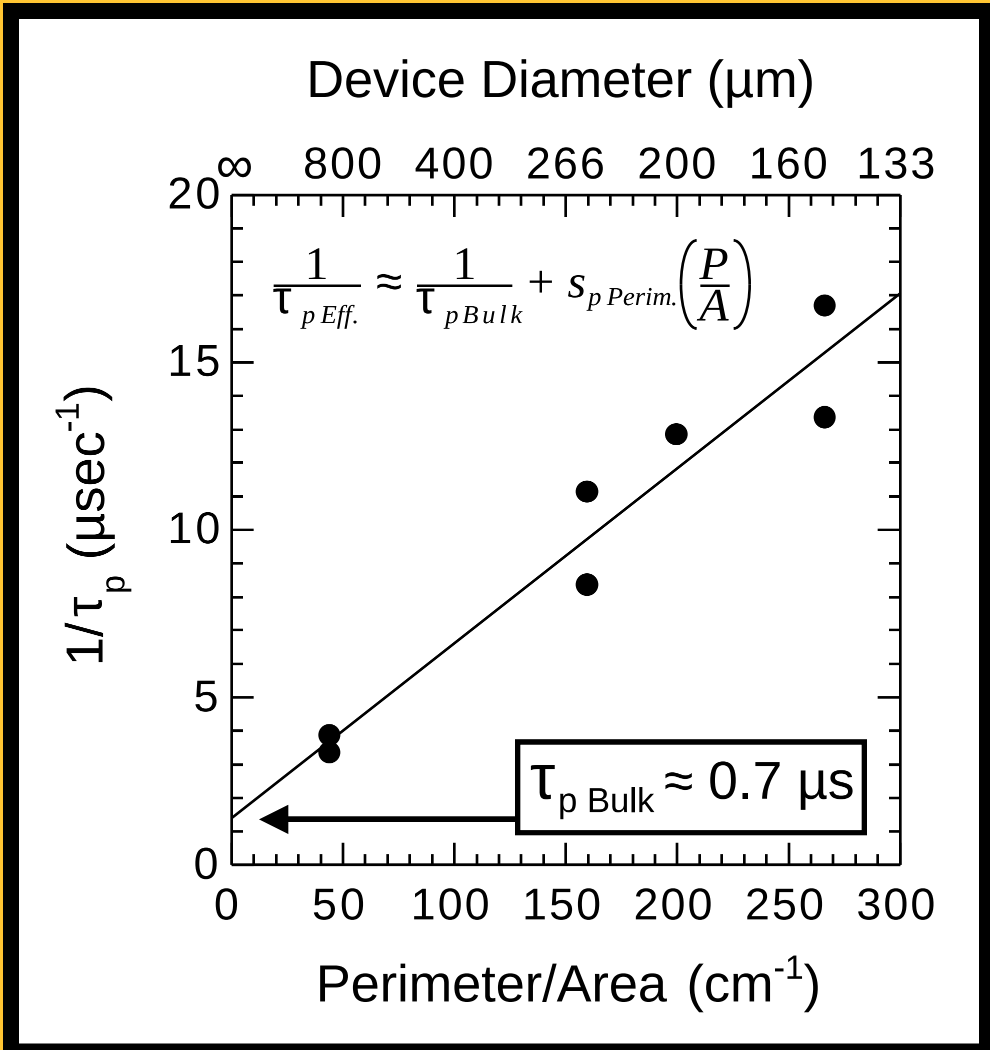
$\tau_{p\,Eff.} = \tau_p$ extracted from reverse recovery switching measurement t_s vs. I_R/I_F data.

Can estimate $\tau_{p\,Bulk}$ and $s_{p\,Perim.}$ from linear plot of $1/\tau_{p\,Eff.}$ vs. P/A.

National Aeronautics and
Space Administration
Lewis Research Center

INSTRUMENTATION & CONTROL TECHNOLOGY DIVISION

Bulk Minority Carrier Lifetime Extraction



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

$$y = b + mx$$

$\tau_{p\,Bulk} \approx 0.7\ \mu s$

(4H-SiC, $N_D = 2 - 4 \times 10^{16}\ cm^{-3}$)

The bulk minority carrier lifetime inherent to this SiC epilayer is greater than 2X longer than the apparent lifetime measured on any individual small-area device, due to the effects of large perimeter surface recombination.

Discussion

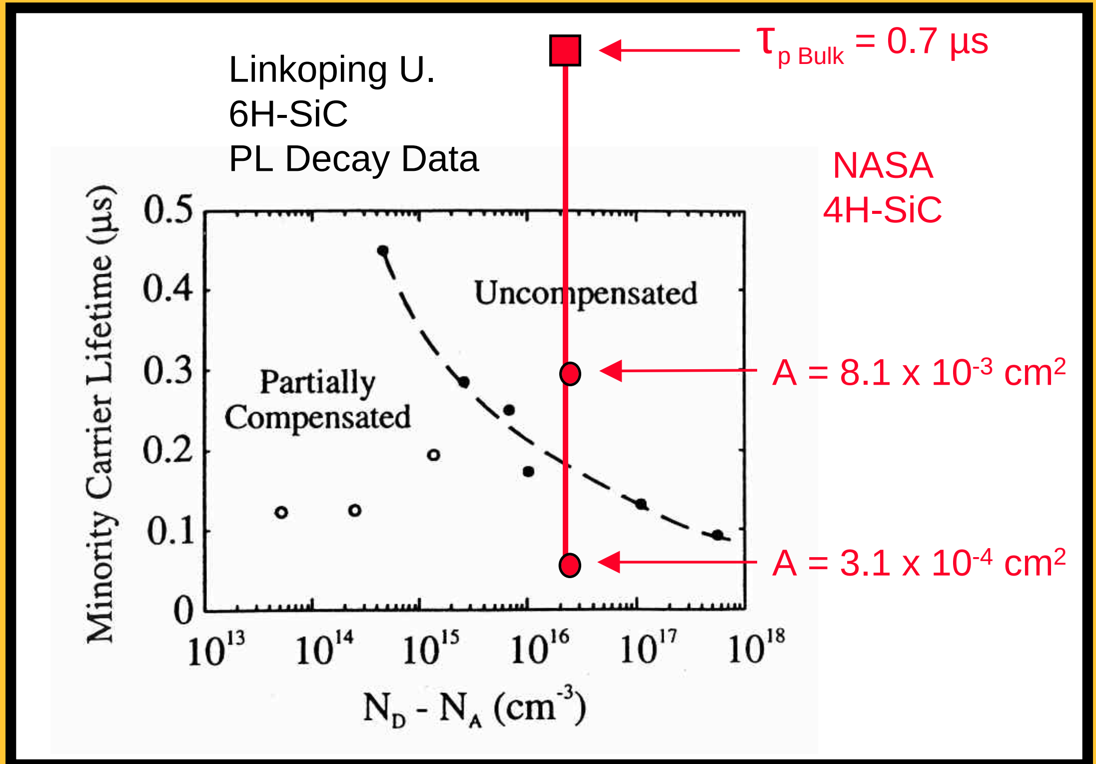
This work demonstrates by example that perimeter surface recombination can significantly impact SiC bipolar device electrical characteristics via reduced effective minority carrier lifetimes.

- 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.

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?

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.