Highly Reliable Positive Temperature Coefficient of Breakdown in 4H-SiC PN Junction Rectifiers

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Breakdown Behavior of SiC

Can highly reliable positive temperature coefficient behavior be obtained in SiC?

6H-SiC work has indicated negative temperature coefficient behavior below 475 °C.

Not much published on breakdown properties of 4H-SiC junctions.

Potential Factors Impacting Measured SiC Breakdown Properties

A. Material Quality Issues (Solvable with Technology Development)

1) Crystal Defects (Micropipes, Screw Dislocations, Inclusions)

2) Contaminants, Deep Levels

B. Inherent Material Property Issues

1) Band Structure (Bandgap, Carrier Transport Properties)

2) Incomplete Ionization of Dopants (Carrier Freeze-out)

C. Measurement Techniques

During conventional I-V measurements, junction heating can cause $T_{Ambient} \neq T_{Junction}$.

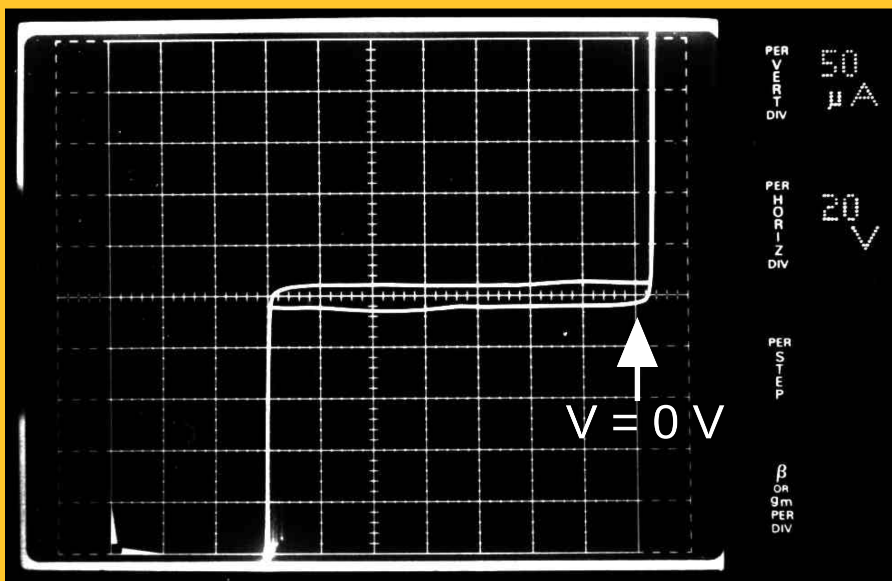
Observing time evolution of device current and voltage as device self-heats during breakdown bias pulse is more accurate test of breakdown behavior.

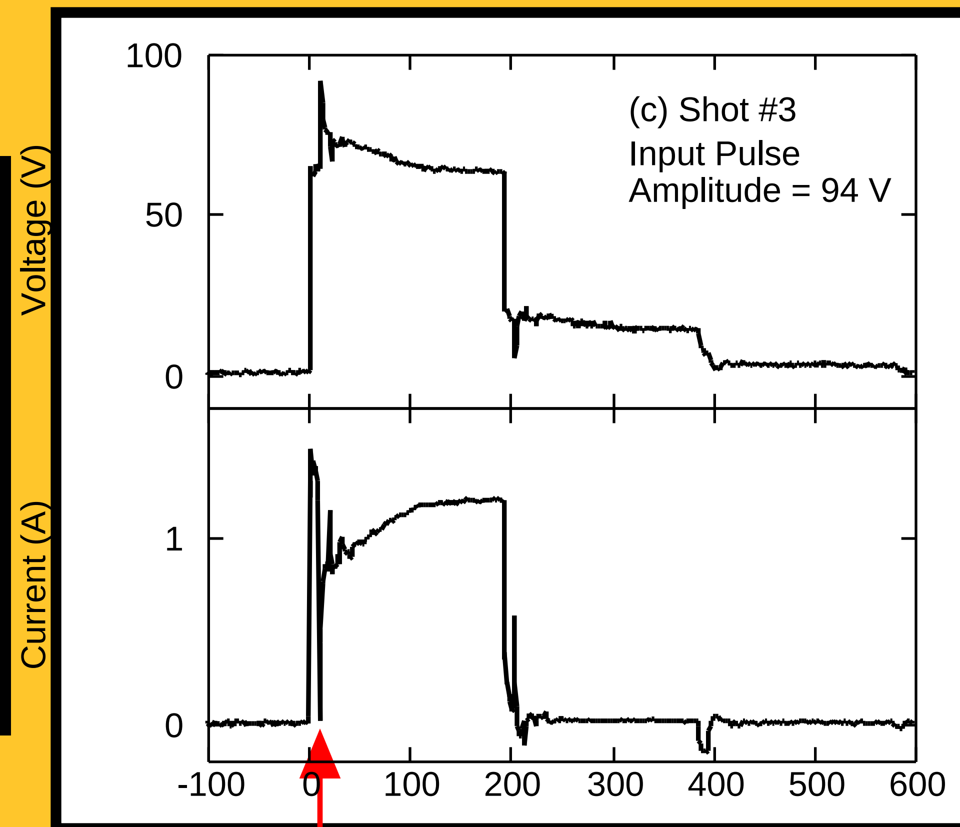
D. Device Geometry (Doping profile, edge termination, etc.)

Unstable Breakdown in 4H-SiC PN Rectifier

Device Area = 1.96×10^{-5} cm^2

$N_D = 2 \times 10^{17}$ cm^{-3} $T_{Ambient} = 24$ °C



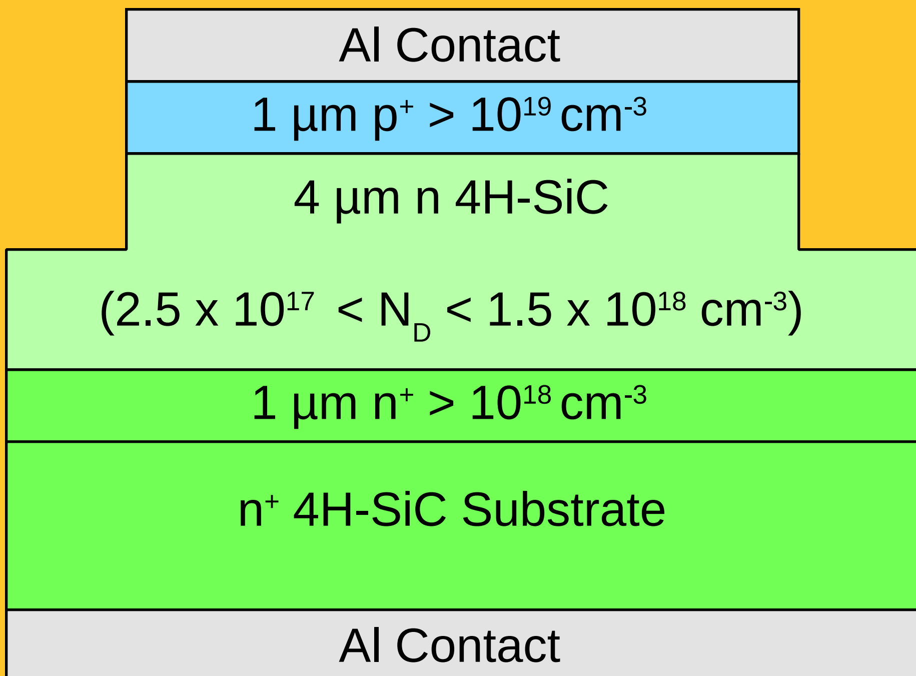


Catastrophic diode failure (t < 20 ns)

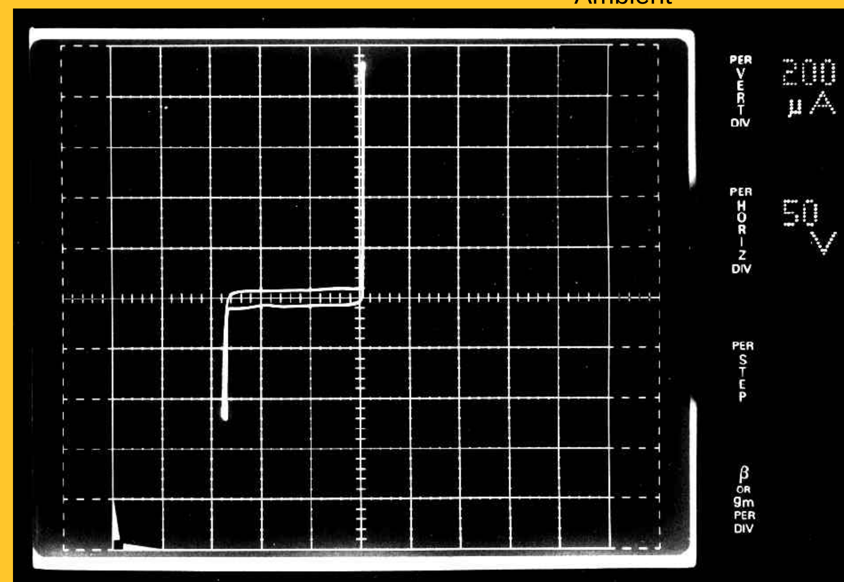
P. Neudeck, C. Fazi, & J. Parsons, Trans. 3rd International High Temperature Electronics Conference, Albuquerque NM, June 11-13, 1996.

Diode fails at pulse amplitude that is less than 70% of curve-tracer ascertained DC breakdown voltage!!!

4H-SiC p^+n Junction Diodes

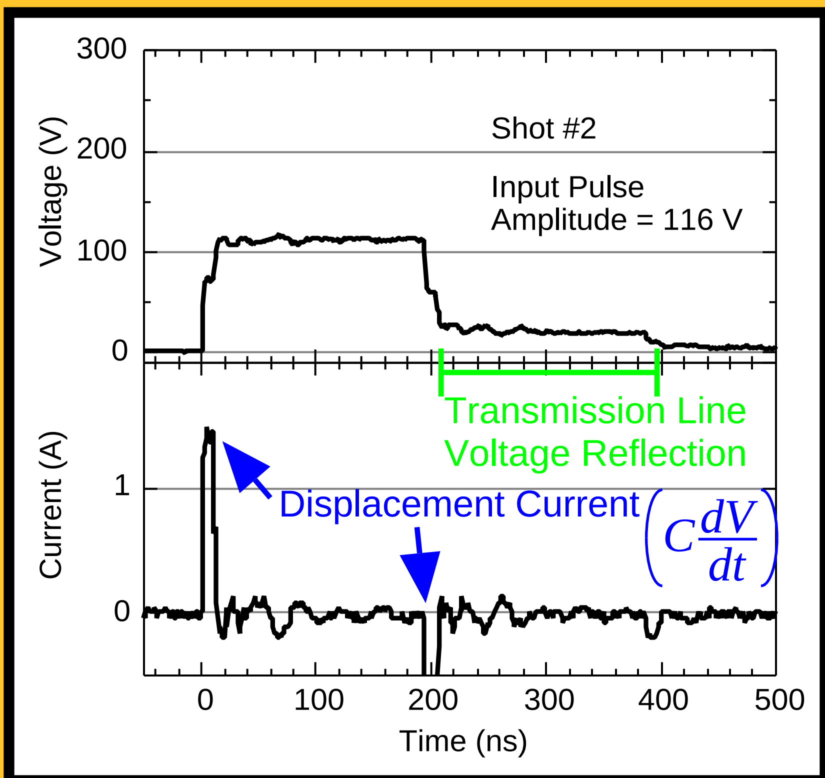


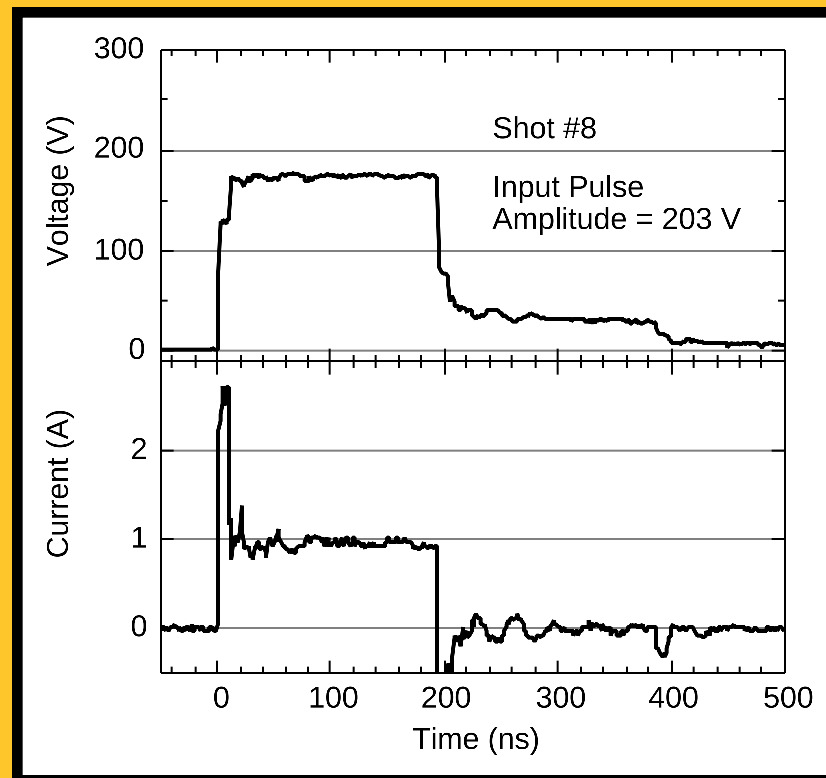
NASA Sample 1904-5
$N_{CV} = 4.3 \times 10^{17}$ cm^{-3}
75 µm diameter device, $T_{Ambient} = 24$ °C



Pulse Testing of NASA Lewis 4H-SiC p⁺n Rectifier 1905-4

(V_{BKDN} 135 VDC, 75 µm diameter device, $T_{Ambient}$ = 24 °C)





As expected, no conduction current flows because pulse amplitude is less than 135 V DC-measured breakdown voltage.

As pulse amplitude exceeds 135 V DC knee voltage, measurable conduction current flows.

Diode voltage "clamps" below input pulse voltage.

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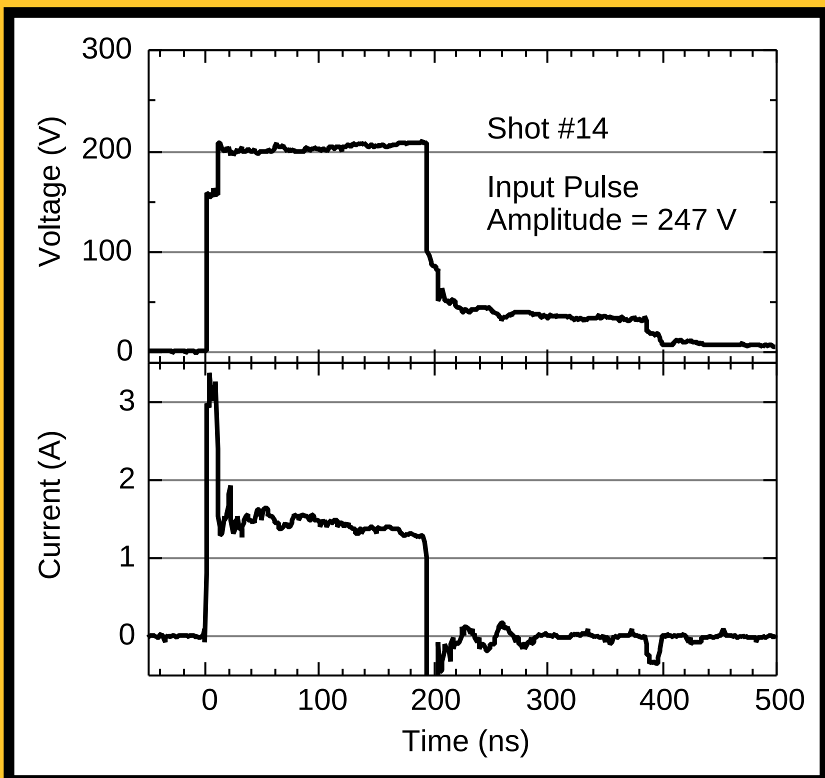
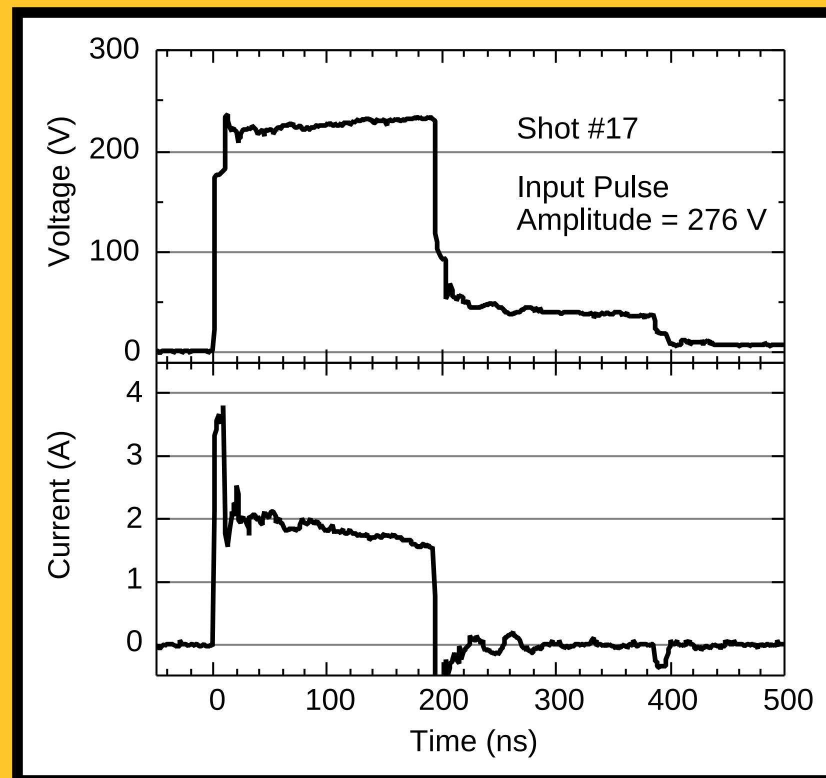
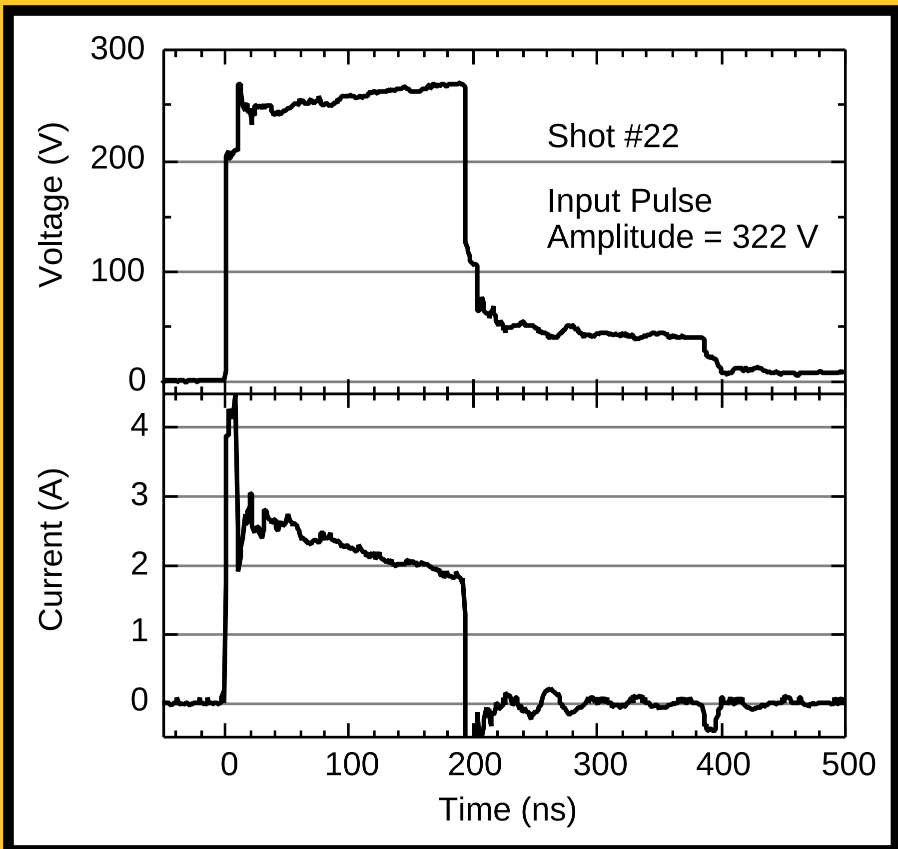
Pulse Testing of NASA Lewis 4H-SiC p$^+$n Rectifier 1905-4 (V_{BKDN} 135 VDC, 75 µm diameter device, $T_{Ambient}$ = 24 °C)





As pulse amplitude is increased, diode begins to exhibit definitive positive temperature coefficient behavior.

Pulse Testing of NASA Lewis 4H-SiC p$^+$n Rectifier 1905-4
(V_{BKDN} 135 VDC, 75 µm diameter device, $T_{Ambient}$ = 24 °C)



Clear positive temperature coefficient behavior (current drops, voltage increases as junction self-heats).

Peak current of ~ 2.5 A corresponds to peak current density of 56,560 A/cm^2.

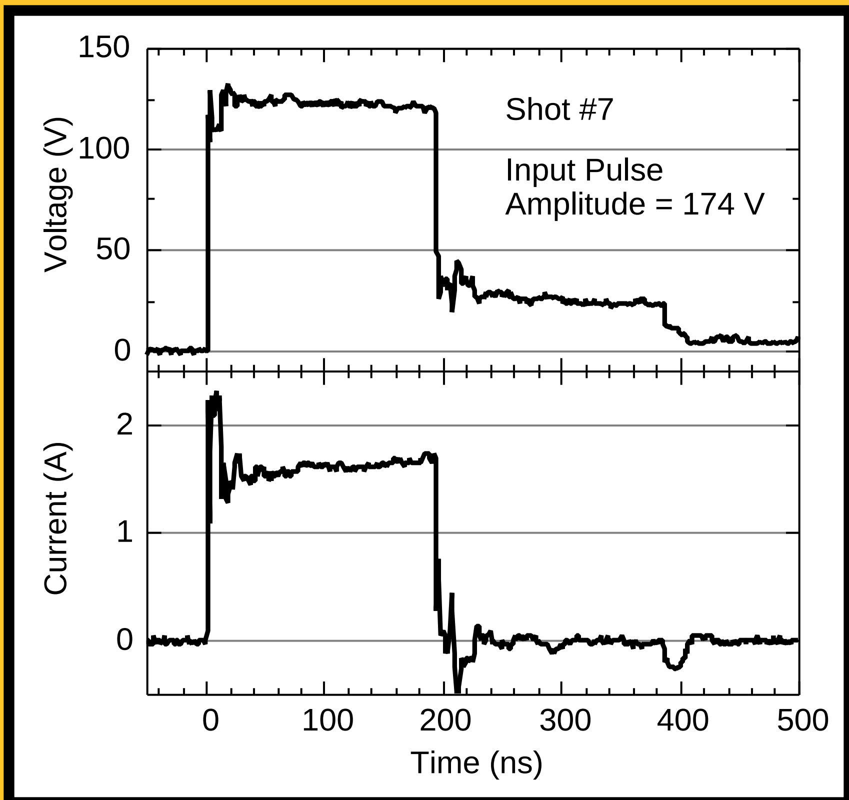
Contact metallization failure prevented further testing after this pulse.

Low-current I-V measurements following pulse testing showed no degradation in junction rectifying characteristics.

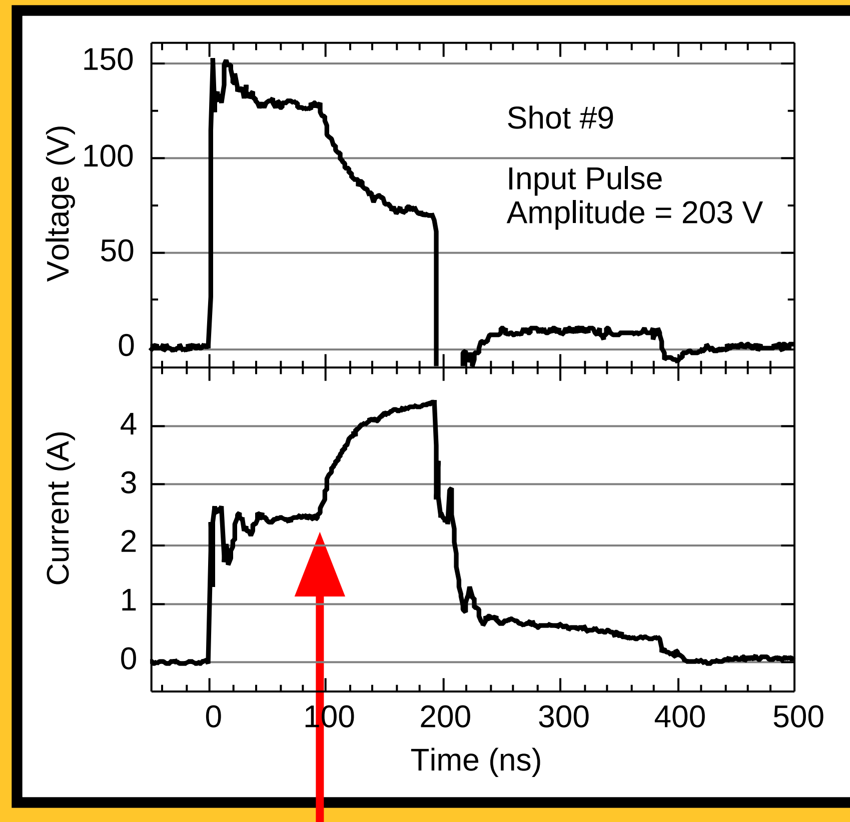
Junction seems to exhibit "conditional stability" in that the device self-heats during first ~ 50 ns before definitive positive temperature coefficient behavior is observed for the rest of the pulse.

Pulse Testing of NASA Lewis 4H-SiC p^+n Rectifier 1905-4

(V_{BKDN} 80 VDC, **250 µm diameter device**, $T_{Ambient}$ = 24 °C)



Negative Temperature Coefficient Behavior



Catastrophic Diode Failure (t = 100 ns)

Unable to observe positive temperature coefficient behavior on devices larger than 10^{-4} cm^2.

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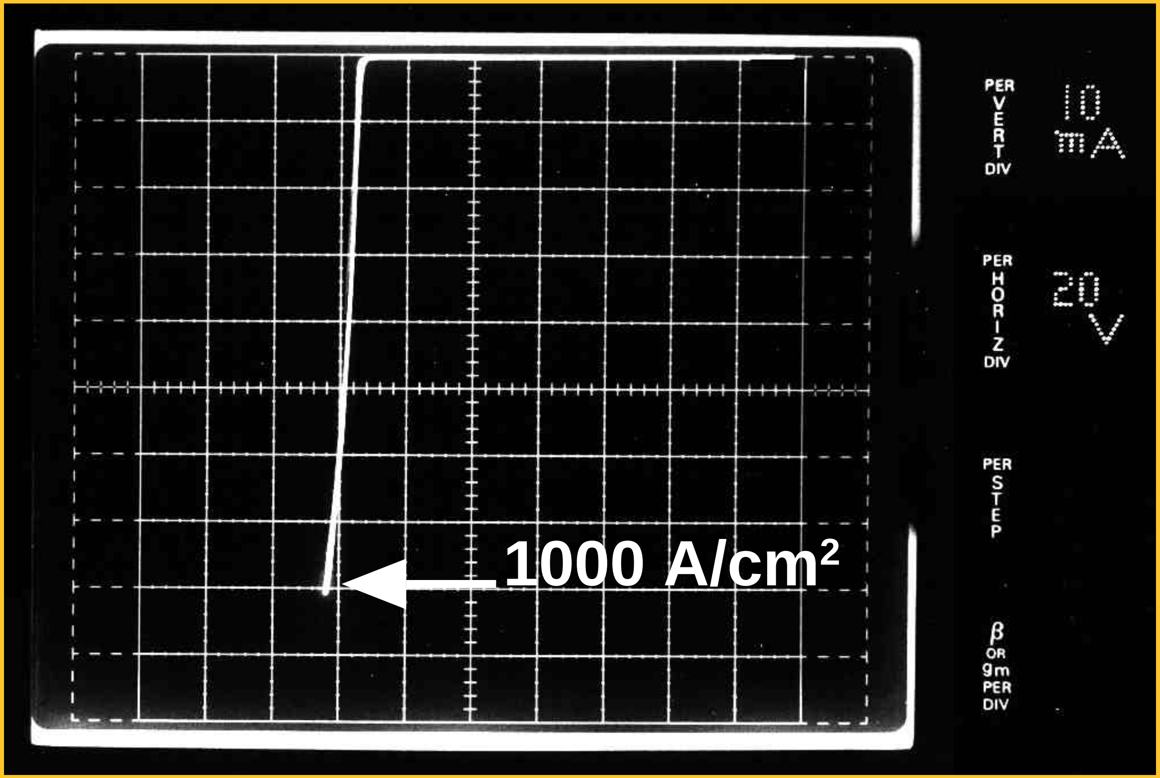
Reverse I-V of PTC 4H-SiC Diode

Area = 7.85 x 10^{-5} cm^2, T_A = 24 °C



Summary & Conclusion

- Stable reverse breakdown properties necessary for highly reliable power devices.

  Positive Temperature Coefficient (PTC) of breakdown voltage (exhibited in silicon power devices) is an important requirement for high reliability.

- Small-area 4H-SiC $p^{+}n$ junction rectifiers tested in this work exhibited PTC behavior.

  Observed J_{BKDN} > 50,000 A/cm^2 under 200 ns bias pulse,
  J_{BKDN} > 1000 A/cm^2 under half-wave.

  "Conditionally stable" device self-heats to definitive PTC without damage.

- Optimization of device design and crystal growth should lead to further improvements in SiC rectifier breakdown properties.

- A GREAT DEAL MORE EXPERIMENTAL BREAKDOWN DATA FROM HIGH-QUALITY DEVICES IS NEEDED to quantitatively ascertain the SiC breakdown behavior picture as a function of doping, temperature, deep-levels, device geometry, etc.