Solid State Discharge Switch Replacements

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Outline

• Overview of Solidtron’s Enabling Technology
  – Pulse discharge targeted designs

• Solidtron Performance
  – Hyper-fast discharge capabilities
  – High action capabilities

• Solid State Discharge Switch Replacements
  – Motivation
  – Approach
  – Performance
  – Experimental results

• Summary

• Questions
Super-GTO Vs. GTO

SGTO is an IC foundry-fabricated GTO mated with Silicon Power’s proprietary low inductance ThinPak package.

Fabricated in 3.3cm² die in 6 inch silicon at very high yield, repeatability and uniformity!

SGTO Advantages:

- Cell structure 3000 x denser
- Upper transistor >100x improved
- Forward drop greatly reduced
- Three times lower turn-off switching loss
- Turn-on improved by 2 orders of magnitude
Solidtron Vs. Super-GTO

Solidtron follows SGTO strategy, focusing on pulse discharge versus turn-off applications.

Solidtron Advantages

- Emitter area maximized
- Internal metal interconnect density improved
- Upper transistor gain further improved
- Increased cathode bonding pad area

8 inch starting material and improved manufacturing process further improving yield while driving cost down.
Solidtron: The Enabling Technology

GTO Versus Solidtron, Fundamental Differences

- Higher cell density improves current uniformity, drastically improving $\frac{di}{dt}$ capability
- Upper base doping profile improved for higher gain
- Metal interconnects improved, increased upper transistor gain and electrode bonding area

Traditional thyristor design revisited, capturing IC house capability
**1600V Solidtron Product line:**
- Simple gating schemes (low power, easy isolation)
- Unmatched $\frac{di}{dt}$ capability (>200kA/$\mu$s observed)
- Easily implemented in series/parallel configurations
- Efficient bidirectional current capability

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-on delay</td>
<td>&lt;90 ns</td>
</tr>
<tr>
<td>Jitter</td>
<td>&lt;100 ps</td>
</tr>
<tr>
<td>Fall time</td>
<td>&lt;40 ns</td>
</tr>
<tr>
<td>$\frac{di}{dt}$</td>
<td>&gt;200kA/$\mu$s</td>
</tr>
</tbody>
</table>

Anode Current $I_{pk}$ 160ns ½ period

Capacitor Voltage (Ch2 Max Ref only)

170ns ½ cycle ring down – Yellow = Anode Current, Cyan = Capacitor Voltage
Solid state discharge switch offers:

- Rugged yet simple gate trigger
- Repeatable fabrication and performance
- Bidirectional current flow capability
- Very high MTBF, minimizing down time

Hyper-Fast 1600V Solidtron Discrete products

Available in:
- TO-247
- TO-264
- Custom SMT packages
Solidtron Performance: Ultra-Fast

4000V Solidtron Product line:
• Maintains simple gating schemes
• $\frac{di}{dt}$ capability >100kA/$\mu$s
• Bidirectional current capability
• **Offers more compact HV Solid State Discharge Switches (fewer series levels)**

Single 0.9”x0.6” chip (2cm$^2$ active area), 6.5kV* die pulse discharge test:
• 4kV
• 45kA $I_{pk}$
• Bidirectional current flow
• $\frac{di}{dt} = 105$kA/$\mu$s

*6.5kV BV, 4kV rating
Solidtron Performance: High Action

6.5kV High Action Solidtron Performance

Single 0.9”x0.6” chip (2cm² active area), 6.5kV die pulse discharge test:
- >20kA peak capability
- 20.8V forward drop
- 1mΩ effective on-resistance
- \( I^2t \) capability > 10kA²s

Measured \( \frac{di}{dt} \) capability to 100kA/μs
Solid State Discharge Switches

**Motivation**

- Compliance with RoHS
- Eliminate conditioning requirements
- Eliminate requisite heaters
- Simplify gating
  - Requires 24V, <<1W supply and a ground referenced TTL trigger signal
- Improve efficiency
  - In both energy transfer and off-state conditions
- Improve turn-on delay and jitter
- Increase usable lifetime
  - No terminal erosion
- Eliminate liquid cooling requirements
- Increase mechanical installation flexibility
- Improved performance over competitor’s solid state switch replacements
- Smaller volume of competitor’s solid state switch replacements
  - No large clamps
  - Much smaller heat sinks
Motivation

- Short voltage withstand time
- Complicated gating sequence required

**Grid 1 - Pulsed**
- Unloaded grid 1 drive pulse voltage: 300 V, 1000 µs
- Grid 1 pulse duration: 2.0 ms
- Rate of rise of grid 1 pulse (see note 5): 1.0 kV/µs
- Peak inverse grid 1 voltage: 450 V
- Loaded grid 1 bias voltage: see note 8
- Peak grid 1 drive current: 0.3 A, 1.0 A

**Grid 1 - DC Primed (See note 6)**
- DC grid 1 unloaded priming voltage: 75 V, 150 V
- DC grid 1 priming current: 50 mA

**Cathode**
- Heater voltage: 6.3 ± 5% V
- Heating time: 5.0 min

**Reservoir**
- Heater voltage (see note 1): 6.3 ± 5% V
- Heating time: 5.0 min

E2V CX1180 Thyatron
25kV peak
1kA max
Motivation

Excelitas HY53 Hydrogen Thyatron

Absolute Ratings
(Minimum)(Non-Simultaneous)

- $e_{py}$, Peak Forward Anode Voltage (Notes 1, 2 & 3) .......... 40 kV
- $i_{bo}$, Peak Forward Anode Current (Notes 4, 5 & 6) .......... 10,000 A
- $i_{ox}$, Peak Reverse Anode Current (Note 7) .......... 0.1 Ib
- $e_{py}$, Peak Reverse Anode Voltage (Note 8) .......... 25 kV
- $e_{py}$, Min., Minimum Anode Supply Voltage .......... 3500 V DC
- $t_p$, Anode Current Pulse Duration, (Note 5) .......... 10 μsec.
- $I_{an}$, Average Anode Current .......... 8 A dc
- $I_{p}$, RMS Average Current (Note 9) .......... 47.5 A ac
- $P_a$, Anode Dissipation Factor (V x A x pps) (Note 10) .......... 160 x 10^4
- $t_r$, Maximum Anode Current Rise Rate .......... 1 x 10^4 a/sec

A Typical Operating Conditions (Note 11)
(Simultaneous)

- $e_{py}$, Peak Forward Voltage .......... 35 kV
- $i_{bo}$, Peak Forward Anode Current .......... 5000 A
- $t_p$, Anode Current Pulse Duration .......... 2.0 μsec.
- $F_r$, Pulse Repetition Rate .......... 500 Hz
- $I_{an}$, Average anode current .......... 0.66 A dc
- $I_{p}$, RMS Average Current .......... 90 A ac
- $P_a$, Anode Dissipation Factor (V x A x pps) .......... 77 x 10^4
- $t_r$, Maximum Anode Current Rise Rate .......... 1 x 10^4 a/sec
Motivation

**NL-8900 Ignitron**

**Mechanical:**
- Envelope: Stainless Steel
- Anode Material: Stainless Steel
- Mounting Position: Axis Vertical, Anode Up
- Net Weight: 24 lb (10.9 kg)
- Diameter: 7.25" (18.4 cm)
- Seated Height (Nominal): 10.75" (27.3 cm)

**Ignitor Ratings:**
- Voltage:
  - Open Circuit (Ignitor +): MIN 1000 V, MAX 35000 V
  - Inverse (Ignitor -): MIN 5 V
- Current, Short Circuit: 500 A
- Length of Firing Pulse, 1/2 Sine Wave: 5 to 10 µs

**Thermal:**
- Type of Cooling: Liquid
- Inlet Water Temperature (MIN): 10 °C
- Inlet Water Temperature (MAX): 30 °C
- Water Flow (At MAX Current): 3.0 GPM
- Cathode Temperature (MAX): 35 °C
- Anode Header Temperature (MAX): 55 °C
- Ambient Temperature: 10 to 30 °C
- Anode to Cathode Temperature: (Note 1)
Motivation

RK2M High Pressure Spark Gap

SSDS may consume more volume however, can provide virtually infinite events with discharges up to 35kA with 8/20μs waveform

**PRODUCT SPECIFICATIONS**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Maximum Value</th>
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<tbody>
<tr>
<td>DC breakdown voltage range (SBV)</td>
<td>kV</td>
<td>0.5...5</td>
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<tr>
<td>Impulse ratio (8/20 μs waveshape)</td>
<td>-</td>
<td>&lt;1.5</td>
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<tr>
<td>Breakdown voltage tolerance within the lifetime</td>
<td>%</td>
<td>&lt;15</td>
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<tr>
<td><strong>Peak current (8/20 μs)</strong> (Note3,4)</td>
<td>kA</td>
<td>5</td>
</tr>
<tr>
<td>Charge transfer, single discharge (8/20 μs)</td>
<td>Coulomb</td>
<td>4</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>Hz</td>
<td>100</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>MΩ</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Operating temperatures</td>
<td>°C</td>
<td>-80...+200</td>
</tr>
<tr>
<td>Net weight</td>
<td>g</td>
<td>20</td>
</tr>
</tbody>
</table>

**NOTES**

1) Each overvoltage gap is manufactured with a specific static (or DC) breakdown voltage (SBV). This voltage can be set anywhere within the available min-max range. The SBV is specified by the addition of a dash number to the part number, giving the SBV in kilovolts.

2) Impulse ratio is measured at dynamic breakdown voltage with rise rate of 15 kV/μs = 3 max @ 1.0 kV, less than 1.5 @ > 10.0 kV dc. The dynamic breakdown voltage is a function of the rate of rise of the applied voltage (dv/dt). In general, it will be higher for higher dv/dt.

3) Current pulse waveform - damped sinusoidal with the second half-wave amplitude not more than 60 % of the first half-wave.

4) The tube can be operated with peak currents up to 10 kA, however limiting the peak current can increase spark gap life.

**OUTLINE**

(All dimensions are in millimeters)

36 x 34 x 12 mm
### ABB Solid State Thyatron Replacements:

<table>
<thead>
<tr>
<th>Part Number</th>
<th>VDRM V</th>
<th>VRRM V</th>
<th>I-Pulse kA</th>
<th>Device</th>
<th>Type</th>
<th>Gate Driver</th>
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<tbody>
<tr>
<td>Asymmetric Blocking</td>
<td>4500</td>
<td>18</td>
<td>80</td>
<td>Discharge switch</td>
<td>Repetitive</td>
<td>None</td>
</tr>
<tr>
<td>P5TH 30J4501</td>
<td>4500</td>
<td>18</td>
<td>110</td>
<td>Discharge Switch</td>
<td>Repetitive</td>
<td>None</td>
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<tr>
<td>5SPY 36L4503</td>
<td>4500</td>
<td>18</td>
<td>150</td>
<td>Discharge Switch</td>
<td>Repetitive</td>
<td>Integrated</td>
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<tr>
<td>5SPY 36L4506</td>
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<td>18</td>
<td>150</td>
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<td>Integrated</td>
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<tr>
<td>Multiwafer Components</td>
<td>13.500</td>
<td>60</td>
<td></td>
<td>Crowbar Diode</td>
<td>Non-repetitive</td>
<td></td>
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ABB: “Due to having higher reliability and lower maintenance costs, ABB’s optimized semiconductor components, mostly as complete assemblies, are increasingly being used to replace thyratrons and ignitrons.”
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However, due to having relatively low di/dt capability, \( \leq 40\text{kA/\mu s} \), they can be used in only a few thyatron applications.

Remember (1) 4kV, 2cm\(^2\) Solidtron demonstrates 100kA/\(\mu s\)!!!
Solid State Ignitron Replacement

Despite smaller volume and weight, Solidtron Thyatron replacements offer (over other solid state and gas tubes):

- Integrated isolated gate drive requiring negligible power
- High reliability and lifetime
- \( \gg> 80\text{kA}/\mu\text{s} \) di/dt capability
- Bidirectional current capability
- An order of magnitude improvement in switch losses

*LSS-Light Silicon Sandwich*
- Silicon Power’s earliest iteration of small volume thyristors
Solid State Discharge Switches

Target Applications

- Plasma Gasification
  - waste gasification,
  - coal gasification,
  - Hydrogen production
  - Synthesized Fuel Production

- Plasma Water/Air Purification Systems
  - Cleaning of fracking water
  - Purifying in/out water for pharmaceutical manufacturing
  - Purifying in/out water for food processing
  - Airplane cabin conditioning
  - Industrial air pollution

- Lasers Systems
  - Ablation
  - Spectroscopy
  - Lithography
  - Micromachining

- Klystron Triggers
  - Satellite Communications
  - UHF Transmitters

- Linear Accelerators
  - Radiotherapy for cancer treatment
  - Radiosurgery...
  - Scientific...
  - Nuclear Fusion Reactors

- Crowbar Circuits
  - Protection of sensitive electronics...server farms, digital broadcast equipment, the Cloud...etc.

- Radar Modulators
  - Military...Army, USN, USCG, USMC, USAF
  - Commercial...Airports, Weather, Maritime

- Marx Generators
  - Lightning simulation
  - Utilities HV insulation testing

  _The List goes on..._
**Disruptive Design**

**Solidtron designed specifically for Solid State Discharge Switches**
- low cost discrete package
- Easily Paralleled or connected/gated in series
- Easily cooled with Off-The-Shelf Heatsink (Max dissipation only 29W/level)
- *No more large presspack clamps and heatsinks !!!*

![Graph showing predicted performance with different models and parameters](image)

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PPC 2017 Brighton, UK  18-22 June, 2017
Hyper-Fast Solid State Thyatron Replacement

40kV SSTR-1 (Twin Stack) Vs. e2v CX2282

- Initial TO-247 version demonstrated 365k pulses
  - 3kA, 300ns square wave
- Similar 20kV and 60kV derivatives planned to complete the product offering
- Greatly improved power dissipation in off-state (snubber resistors much higher in value)
- TO-264 version offers **36x** increase in action
Solid State Thyatron Replacement

Prototype Thyatron Replacement Switch using 
**Hyper-Fast 1600V Solidtron**

- $\frac{di}{dt}$ capability is >200kA/μSec
- Fiber Optically Triggered
- Small size - 9” Tall, 3.75” Base diameter
- Voltage capability of 40kV

- Yellow - 4.3kA Peak Current w/average $\frac{di}{dt}$ of ~60kA/μSec (Circuit Limited)
- Run at 100 Pulses Per Second without cooling

Anode Current
Capacitor Voltage (Ch2 Max Ref only)

50nSec rise time
Peak I >4kA
Rep Rate = 100PPS
Solid State Discharge Switch

4kV High Action Solidtron

Gen1 24kV Bi-directional Switch Assembly Pulsing 200kA
Replaced NL-8900 Ignitrons in Magnetic Pulse Welding System

- Yellow - Demonstrates 200kA Ringing Waveform (169kA Peak reverse)
- Magenta – Voltage across a single level – ~2500V to Vf
- Cyan – 1 of 12 legs – worse case current imbalance (perfect 16.6kA)

- 8 levels of 6 parallel modules
- 192 chips operating in concert, 96 high action Solidtron and 96 S-diodes
- 4 of these units were paralleled for 800kA
- More than 10,000 operational events recorded

12kV (4 level) model shown (13.25” x 10.5” x 4”)

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Solid State Ignitron Replacement

**Myth: Solid State Switches Are Too Big**

Solid State Switch replacement requires roughly 10x volume for same maximum ratings.

- **12kV model shown**
  - (13.25” x 10.5” x 4”)
  - *Effective Volume: 557in³*

- **555in³/12kV, 1,700in³/36kV**

- NL8900 ratings:
  - 35kV, 300kA
  - (Ø 7.25” x 10.75”)
  - *Effective Volume: 141in³*

- Failed after 200 events
- Demonstrated > 10,000 events

- **141in³/35kV**
Solid State Ignitron Replacement

Fact: Solid State Switches Are NOT Too Big

12kV model shown
(13.25” x 10.5” x 4”)
Effective Volume: 557in³

2 series levels used
1,110in³

NL8900 failed after 200 events
Solid State Switch demonstrated 10,000; predicted to
• Halving Ignitron current/voltage increases life by 10x
  o 4 units predicted to survive 20,000 events

Effective Volume:
2,250in³
(100% larger)

20,000 ignitron events Predicted
3,000,000 SSD events Predicted
Solid State Discharge Switch

6.5kV High Action Solidtron
Pulse Switch Assembly

Testing of Gen1 80kA unit at US Army Research Lab (ARL)

- Superior Current Sharing (Cathode 1-Cathode 2)
- Excellent Voltage Balance (Across 4 levels)
- Synchronized and repeatable 32 Chip turn-on

80 kA Unit #016 in ARL PFN

200 Pulse Discharges

~10in³ (163cm³)
Solid State Discharge Switch

Pulse Switch Assembly (PSA):
- Simple isolated current transformer gating
- Coaxial current delivery for very low inductance
- 10kV DC continuous operation
- Only 375μΩ resistance with a diode knee of 3.63V!

![PSA Current vs. Forward Drop](image)

PSA:
- $R = 375\mu\Omega$
- $V_D = 3.63V$

Modules:
- $R = 125\mu\Omega$ [1]
- $V_D = 1.21V$

[1] includes ~ 26 μΩ parasitics
Summary

• RoHS compliance
• Power density myth dispelled
• Unparalleled solid state $\frac{di}{dt}$ capabilities
  – Hyper-fast demonstrated 200kA/μs
  – High action, ultra-fast demonstrated 100kA/μs
• $f(i(t))$ capability, determined by experimental and/or sim data exceeds most if not all commercially available gas or solid state thyatrons available
• Designed with modular, scalable sub-assemblies
  – Enables fitment for most thyatron or ignitron applications