Ultra-Fast, High Reliability Solid State Thyratron, Ignitron and Thyristor Replacement*

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Abstract

Silicon Power has developed ultra-fast, high reliability Solid State Thyratron and Ignitron Replacements (SSTIR) which also displace conventional SCRs and GTOs. The switches, based on our 2nd Generation Si and SiC SGTOs [1], exhibit turn-on delays <100ns, have di/dt capabilities in excess of 100kA/μs, operate for over 10,000 hours and are capable of handling reverse current.

In addition to these performance benefits, our SSTIRs have a simple low voltage, low power gating scheme and require no external support systems (e.g. heaters, grid controls).

I. INTRODUCTION

The necessity to control large currents at very high voltages (several kA and tens of kV) has kept Thyratron and Ignitron technology relevant for close to a century. The drawbacks to these technologies, their low lifetime (as short as hundreds of hours), large, complicated, costly support systems and poor efficiency has led the drive to develop a high performance, high reliability replacement.

Silicon Power's answer is a solid state thyristor technology which replaces the gas plasma in Thyratrons and Ignitrons with the electron-hole plasma of a thyristor. While thyristors have been displacing Thyratrons since the 1960s, their capability limited the replacements to mostly low and medium-power applications. Silicon Power's semiconductor and packaging technologies surpass the capability of legacy thyristors and provide the long sought high-power, high reliability Thyratron and Ignitron solid state replacement.

II. ENABLING TECHNOLOGY

The fundamental building block of the SSTIR is Silicon Power's Super GTO (SGTO). The SGTO comprises legacy thyristor performance, enhanced with the precise repeatability enabled by IC house technology. SGTOs, fabricated in an IC house improves cell density by three orders of magnitude compared to press-pack thyristors, improving: current uniformity, specific on-state resistance and di/dt capability, see Figure 1 [1].

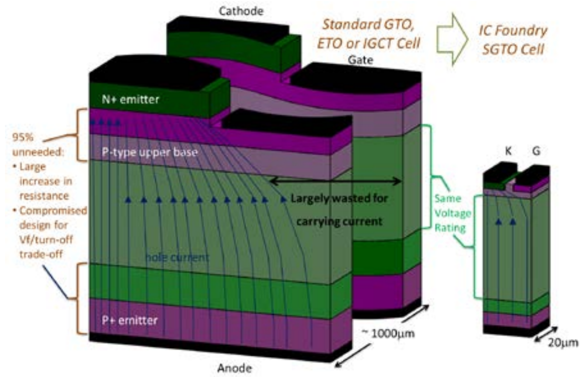

Figure 1. Schematic cross-sections of legacy press pack thyristor (left) compared to the SGTO (right)

The implanted charge and diffusion depths are controlled so accurately that the optimal doses and depths can be targeted and achieved with near 100% repeatability, further reducing switching speed and conduction losses. Finally, IC fabrication of SGTOs yields a planar voltage termination, improving yield and simultaneously lowering leakage current by factors close to 1,000.

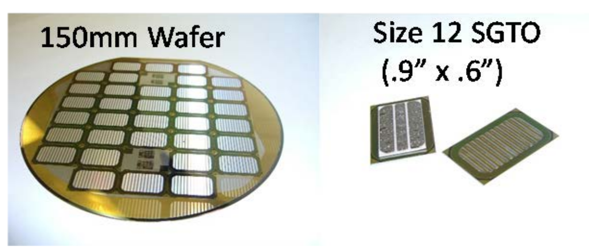

Figure 2. Left, 150mm IC fabricated SGTO wafer. Right, single 2cm^2 active area SGTOs with and without a thinPak lid

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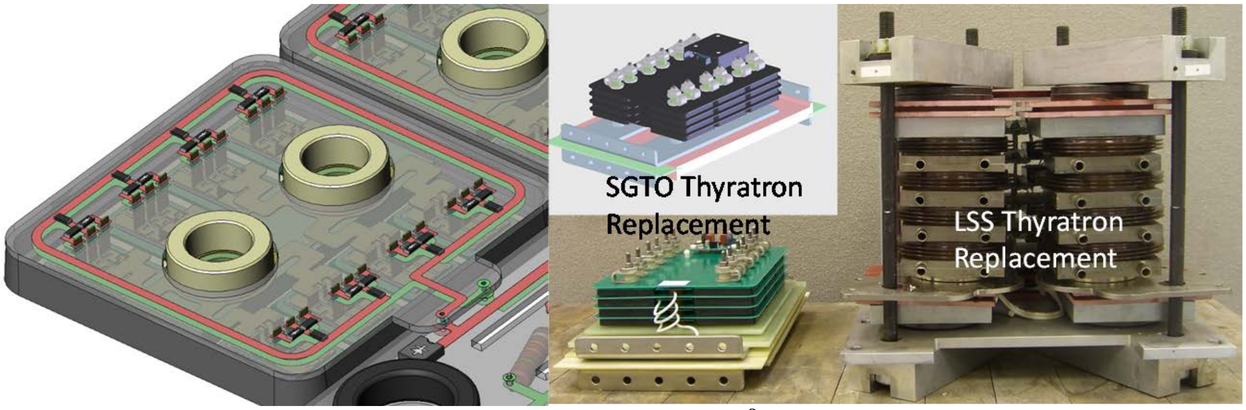

Figure 3. Left, single pulse switch module (PSM) consisting of 16cm^2 of active area. Center, Pulse Switch Assembly (PSA) using 4 series levels of 6 parallel PSMs (192 SGTOs). This PSA (whose volume is less than 1 gallon) discharged 500kA at 10kV. Right, Equivalent legacy press pack thyristor replacement. Note the large, heavy clamps and the water cooled heat sinks, necessary due to the lower performance compared to an SGTO.

Currently, we fabricate our SGTOs in a 150mm IC foundry, with up to 400 die per wafer, a 34 die wafer is shown in Figure 2. Because there are several chips per wafer, defects in the starting material do not cause the loss of an entire wafer. To further improve fabrication yield, the mask is designed to alignment rules several generations older than the IC foundry's, virtually eliminating loss due to lithography.

To aid in the displacement of legacy thyristors, Silicon Power has developed a packaging scheme emulating the straight forward stacking of series press pack thyristors to achieve higher voltages, however, we have eliminated the need for a heavy high pressure clamp system. This packaging scheme provides a modular, scalable system allowing quick turnarounds of systems to meet specific applications as, shown in Figure 3.

III. PERFORMANCE AND RELIABILITY

A. First Generation SSTIR

Silicon Power has demonstrated exceptional di/dt and action capability of our 2nd generation SGTO. One 6.5kV 2cm^2 active area device has successfully discharged greater than 20kA with an I^2t over 20kA^{2}s, exhibiting an effective 1mΩ resistance [1]. At this time, this design has shown di/dt capability exceeding 80kA/µs. These devices are the foundation of our first generation SSTIR.

The first Ignitron replacement targeted was the NL-8900. Our first generation SSTIR achieved 20kV, bidirectional 200kA discharges in a magnetic welding system. The modular scalability of the constituent PSAs was verified with 10,000 discharge events of 800kA using 4-Gen 1 SSTIRs in parallel without failure (the NL-8900 Thyratron failed after only 200 such events). The ability of our SSTIR design to distribute the load current uniformly is a key contribution to the exceptional lifetime of our switch. The outcome of the SSTIR yields assurance of the reliability to scale a system in arrangements of series and/or parallel PSMs/PSAs to accommodate any voltage and current needed. Figure 4 depicts the exceptional uniformity of both ¼ of the SSTIR current being shared through one PSA, as well as ideal current distribution through 1/12th of the PSA's constituent legs.

Figure 4. Yellow: 200kA underdamped discharge (169kV Peak reverse). Magenta: Voltage across SSTIR (test circuit used 2500V, note the maximum performance is achieved at voltages > 12kV). Cyan: current through 1 of the 12 current paths, 16.6kA peak demonstrats ideal current distribution.

B. Second Generation Ultra-Fast SSTIR

Silicon Power is now leveraging the unmatched di/dt capability of our discrete 1600V SGTO devices for the second generation of SSTIRs. The second generation SSTIR maintains the simple gating, high reliability, bidirectional current flow and modular design of its predecessor, while enabling higher di/dt capability,

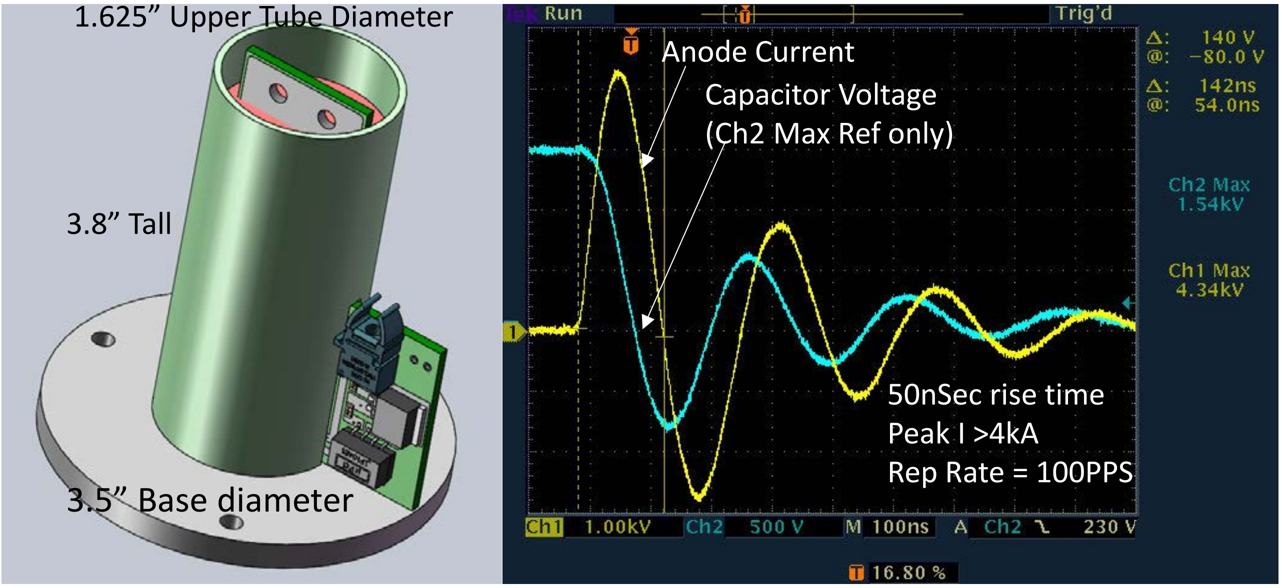

Figure 5. Prototype small Ultra-Fast SSTIR, rated for 10kV and 4kA discharge at 100 pulses per second. 50ns to peak current of 4.3kA, 2.8kA of reverse current.

shorter pulse widths and even faster turnaround of prototype designs.

Our existing discrete SGTOs have already been demonstrated in low power discharge applications with first ½ pulse widths as short as 100ns. The low losses enable operation without active cooling. Silicon Power offers several triggering options, running directly off existing Thyratron trigger supplies (although consuming a small fraction of the power needed by the Thyratron) or adapting the SSTIR for customer specific triggering, for example a fiber optic triggered gate, as shown in Figure 5.

Optimization of the 1600V SGTO design is leading the way for Silicon Power to offer SSTIRs that will displace many commonly used Thyratrons. Among changes internal to the SGTO, the chip is designed to maximize the capability of a standard, low cost TO-264 package, adding compatibility with inexpensive commercial off the shelf heat sinks. We have predicted the frequency capability of our 2nd generation SSTIR using only one of our optimized SGTO as a function of the peak current of a 1μs ½ pulse width discharge (500ns to I_{peak}). Figure 6 depicts this performance against common Thyratrons manufactured by E2v, L3 and Excelitas. Like the 1st generation SSTIRs, series and parallel strings of these

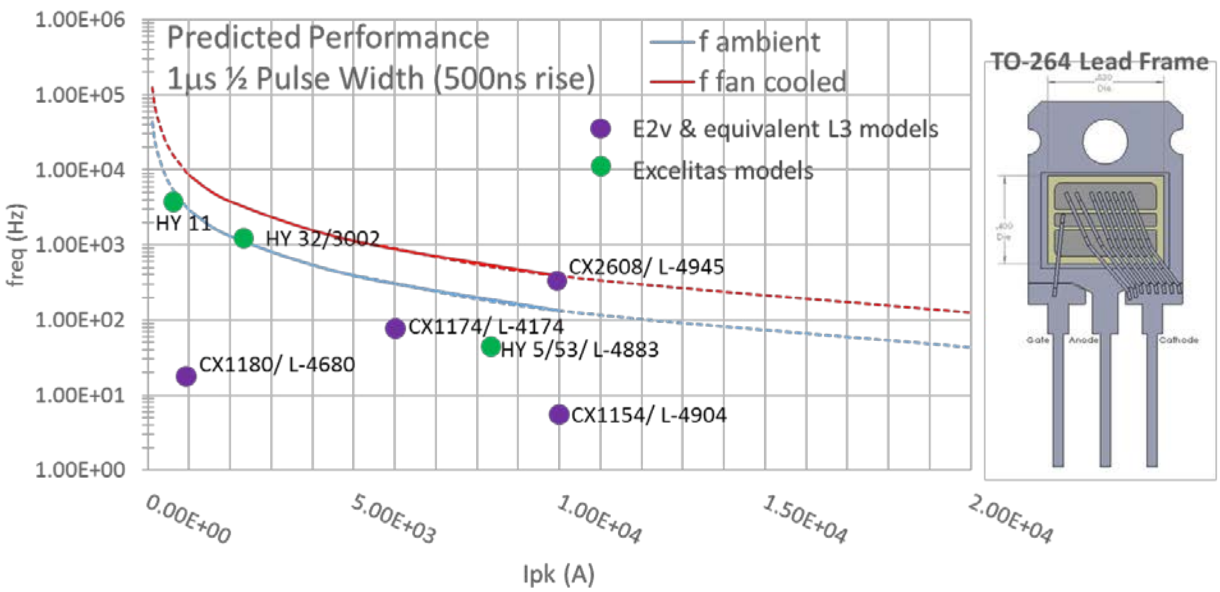

Figure 6. Projected performance of one optimized SGTO against commonly available Thyratrons and a schematic representation of the optimized SGTO in a standard TO-264 package.

devices are easily arranged to replace most, if not all, Thyratrons.

Just as the 1st generation SSTIR outlasted conventional Thyratrons, we project the 2nd generation SSTIR to exceed the lifetime of Thyratrons by at least three orders of magnitude.

Silicon Power has been actively researching the use of our SGTOs in current limiters. The strategy we have employed uses several switches to conduct the nominal load current. When a fault is detected (by increased magnitude or di/dt of the expected load current), auxiliary switches are used to discharge a capacitor through the main switch in a way that opposes the main current flow.

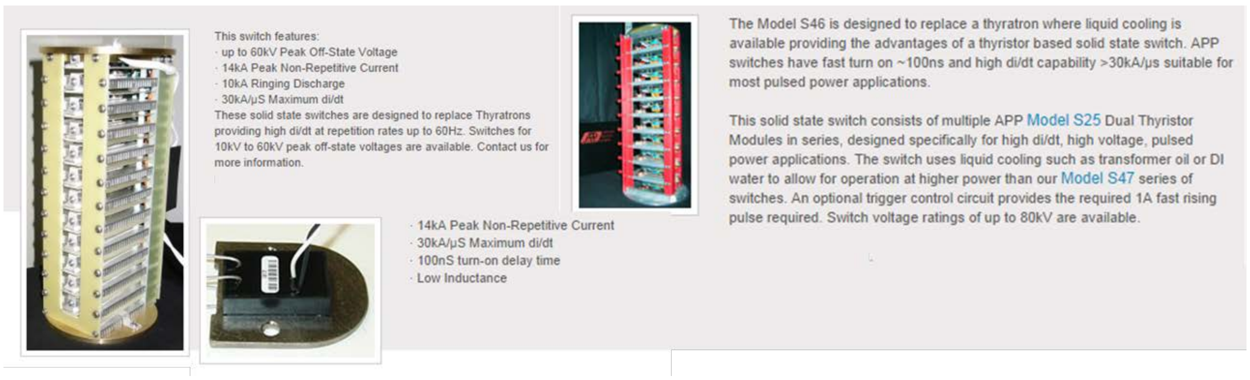

Figure 7. Examples of Applied Pulse Power Solid State Thyratron Designs

IV. APPLICATION EXAMPLES

A. Existing Thyratron Replacements

Silicon Power has recently acquired Applied Pulse Power, who offers an array of Solid State Thyratron Replacements. Their designs have been used in medical applications, radar modulators, Marx generators and more. Using a modular approach, they too have demonstrated switches capable of 60kV and 14kA of non-repetitive current. Their designs offer both liquid and passive cooling, Figure 7 depicts specifics of 2 of their designs.

With this acquisition, Silicon Power has begun to integrate our unique packaging and device designs to increase the performance, efficiency, reliability and volume manufacturability of their current lineup. The experience of Silicon Power combined with Applied Pulse Power is blazing the trail leading to the obsolescence of gas Thyratrons and Ignitrons.

B. SSTIR as Opening Switch

The above details several advantages gained with Silicon Power's SSTIR as a closing switch. However, we have also utilized the high di/dt and action capability of the SSTIR to demonstrate compact, reliable and low loss opening switches.

The very low on-state losses of the SGTO make it an ideal candidate for high current steady state applications, such as HVDC and AC current limiters/breakers. Also, with magnetic fields capable of storing 100,000 times the energy density of electric fields, finding a low loss switch capable of breaking current is attractive for energy storage applications, and high di/dt applications such as rail guns.

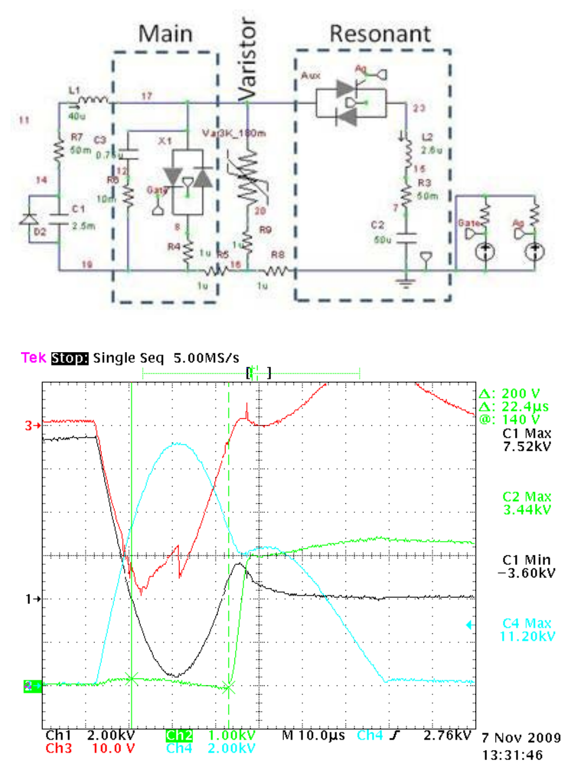

Figure 8. Top, schematic diagram of SSTIR implemented for an opening switch. Main section conducts normal current flow, resonant section contains LC resonant circuit and discharge SSTIR. The varistor shown clamps the inductive voltage developed by the load. Bottom, experimental data of 8cm^2 of SGTO turning 7.5kA of current off using just one 2cm^2 SGTO to supply the resonant current.

The design for opening switches uses an LC resonant circuit that provides enough reverse current through the main switch, so that it can commutate with only minor gate assistance. This setup increases the maximum controllable current of the main switch to a level restricted only by the energy stored in the commutating resonant capacitor, see Figure 8. Amazingly, this topology is able to break the main current in just 20μs!

This scheme is well suited for the compliment of a MARX generator, known as XRAM [2]. XRAM stores magnetic energy in a series of inductors. When the system demands transfer of energy, the current of all series inductors is transferred to the load, providing a linear multiplication of the stored current to be delivered.

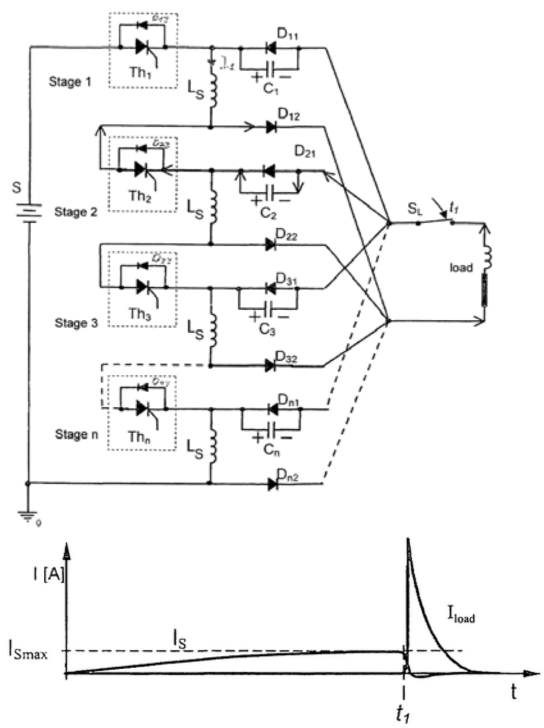

Figure 9. Top, schematic of XRAM generator. Bottom, representation of storage current and load current

Figure 9 shows a general schematic of an XRAM system. Current is stored in a series of inductive stages, each with its own switch and resonant circuit. At time t_1 the load switch is closed, transferring the current stored in each stage to the load. This amplifies the load current while simultaneously commutating the current through each stage's thyristor (in our case it would be an SGTO assembly) where they can safely turn off and await the next cycle.

V. CONCLUSION

Silicon Power has developed a transformative technology with its 2nd generation SGTO. The use of such switches in SSTIR provides a viable, long lasting replacement for both Thyratrons and Ignitrons. Transferring the outstanding performance of SGTOs into an ultra-fast version closes the gap where, until now, solid state solutions were not available to replace all Thyratron and Ignitron applications.

The modular and scalable packaging scheme developed can be tailored to fit any required Voltage and Current levels. In addition, Silicon Power has developed layout schemes to reduce parasitic inductance associated with the relatively large distance current must flow through the gas switch, thus improving maximum obtainable di/dt.

The enhanced performance of our SGTO compared to legacy thyristors enables a practical solution for current breakers, limiters and magnetic energy storage systems.

VI. REFERENCES

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