Design and Reliability of a High Voltage, high Current Solid State Switch for Magnetic Forming Applications

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Abstract

The presentation will give information about the long term reliability of semiconductor components which are used in high current, high di/dt discharge switches as they are used in systems for electro-magnetic forming. Prototype equipment for laboratory use has shown the capability of the switches and equipment to fulfil the requirements requested by the end-users. This however is not enough to be used in the industrial production lines under continuous and repetitive heavy load conditions. Because of the relative high life-time expectations of the durable equipment used for magnetic forming in the automotive industry the life-time of the semiconductor switches, the inductive loads and the capacitor banks are becoming an issue. The presentation will only describe the semiconductor reliability A prototype system for 21 kVdc and pulse current of 210 kA was designed and built in the year 2005 by Siemens for the Fraunhofer Institute in Chemnitz, Germany. The semiconductor switch was supplied by ABB Switzerland Ltd. For this experimental machine only low repetition rates of one shot per several minutes and a limited expected life-time of approx. 15.000 – 20.000 shots was acceptable for the experimental work. The requirement from the automotive industry however is at least one shot per 15 seconds and an operational life-time of ≥ 2 Mio shot at the mentioned power level. During the last year ABB has done extensive tests to evaluate the behaviour of the semiconductor components used in high current solid state switches under the specific application conditions for production processes. In the presentation the test results of high current semiconductor devices are described for 250.000 shots and 1 Mio shots, and recommendations for reliable solid state switch designs are given.

1 Introduction

Semiconductor devices have made dramatic progress in power handling during the last decade. The today's technology and production capabilities make it possible to produce devices with high blocking voltage combined with very high current handling. Depending on the design and the device structure also very high current rise rates in the range of up to several tenths' of kA/µs are possible. Especially for single pulse or medium pulse repetition rates semiconductor devices are getting more and more competitive to conventional technologies like Thyratrons, Ignitrons, Spark-Gaps and Mechanical Switches. The main advantages are the reliability, lifetime and almost no maintenance of the semiconductor switches if the characterization is done right. Main advantages like longer life-time, environmental friendly (no mercury etc.) and flexible mounting position are compensating the higher initial cost of a solid state design. The type of semiconductor used and the rating of the device are extremely important for a reliable operation and need an in-depth know-how of the application and the switching device. ABB has developed over the years a specific range of semiconductor devices and adapted standard products which can fulfil the requirements for pulsed applications. Based on the 21 KV / 210 kA switch assembly, supplied for an experimental system, which was described at the ICHSF 2006 [1] further reliability tests were done to evaluate the behaviour of the semiconductor devices under the given application conditions. This paper will show some of the results of tests.

2 Device Technology

Semiconductor devices for pulsed applications can be divided in Turn-On and Turn-Off devices. Turn-On devices are Thyristors structures and in the group of Turn-Off devices we find the GTO's (Gate-Turn-Off Thyristor), IGCT's (Integrated Gate Controlled Thyristor) and IGBT's (Insulated Gate Bipolar Transistor). For high energy short pulse discharge applications, like high speed forming, mostly thyristor technology is used. The table below gives a short overview of the different possibilities.

Device Type	Max. Forward Blocking Voltage	Max. Peak Pulse Current Capability	di/dt	Switch-On	Switch-On/Off
Thyristor	≤ 8500 V	120 kA	1.5 kA/µs	Yes	No
GTO-Like Thyristor	4500 V	150 kA	50 kA/µs	Yes	No
Integrated GTO-Like Thyristor	4500 V	150 kA	50 kA/µs	Yes	No
GTO	4500 V	4 kA	3 kA/µs	4 kA	4 kA
IGCT	≤ 6000 V	4 kA	2 kA/µs	4 kA	4 kA
IGBT (Wire bonded module)	≤ 6500 V	1 kA	5 kA/µs	1 kA	1 kA
IGBT (Press Pack Module)	4500 V	2 kA	5 kA/µs	2 kA	2 kA

Table 1. Overview of different semiconductor device technologies.

For High Speed forming the use of capacitor discharge switching is very common because high energy has to be switched into a load in a very short time. The capacitor can be discharged completely, and means that devices with high switch-on capability were selected. The devices used for the reliability test were Integrated GTO-like Thyristors which are used in the 21 kV / 210 kA discharge switch. The driver unit is integrated with the device and the freewheeling diode is monolithic integrated on the same silicon wafer as the switching part to minimize induction.

2.1 GTO-like Devices

Thyristor (SCR) technology is a well proven solution which is used for high current, relative long pulses and low current rise rates in capacitor discharge applications. Standard commercial of-the-shelf devices can be used as long current rise rates stay clearly below

700 A/µs. Depending on the application, the pulse current, current rise-time, pulse length and pulse repetition rate, different wafer designs can be selected to fulfil the requirements. Figure 1 shows a variety of Ø 51 mm thyristor wafers with different capabilities. Most of the designs are available in different diameters for different current capabilities. Blocking voltages can be from 1800V till up to 8500V per device for the thyristor designs and up to 6000V for the highly interdigitated designs (GTO-like structure). For higher voltage, devices are stacked in series connection.

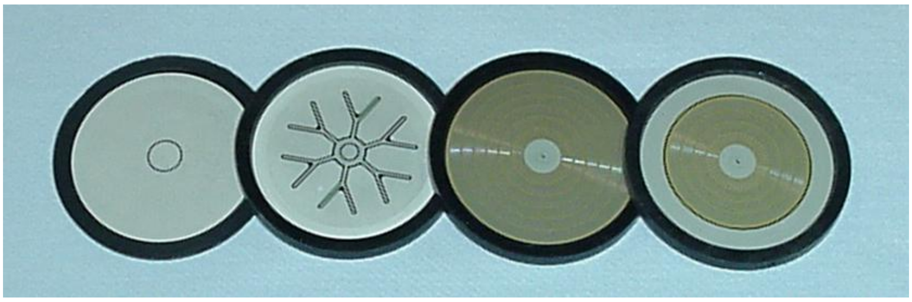


Figure 1. *Si-Wafers Ø51 mm for di/dt < 0.1kA/ms, 1kA/ms, 18kA/ms and 15kA/ms.*
The right one is with a monolithic integrated freewheeling diode.

The two wafers on the right side of the picture are representing the GTO-like wafer structure, of which the right one is the reverse conducting version with monolithic integrated diode. These GTO-Like structures use a lot of small thyristor segments on one silicon wafer, and have a very high di/dt and fast switch-on capability.

2.2 Device design

In the year 2005 a reverse conducting solid state switch was designed and supplied for 21 kV / 210 kA and up to 400 kA under short circuit conditions. Devices used were of the GTO-like technology, reverse conducting and using 3 parallel devices with 91 mm wafer size, ABB P/N 5SPR 26L4506. Fig, 2 shows the semiconductor part built-up.

Figure 2. Low Inductive Housing, GTO-Like wafer and Complete Device

The semiconductor part is combined with a driver unit which is powered by a closed loop current source power supply and optical triggered. This construction enables easy series connection as the isolation voltage of the closed loop high voltage cable is the isolation between the device levels in the switch. This technology is possible for voltages up to 40 kVdc. Fig. 3 shows the complete switching device with integrated driver unit.

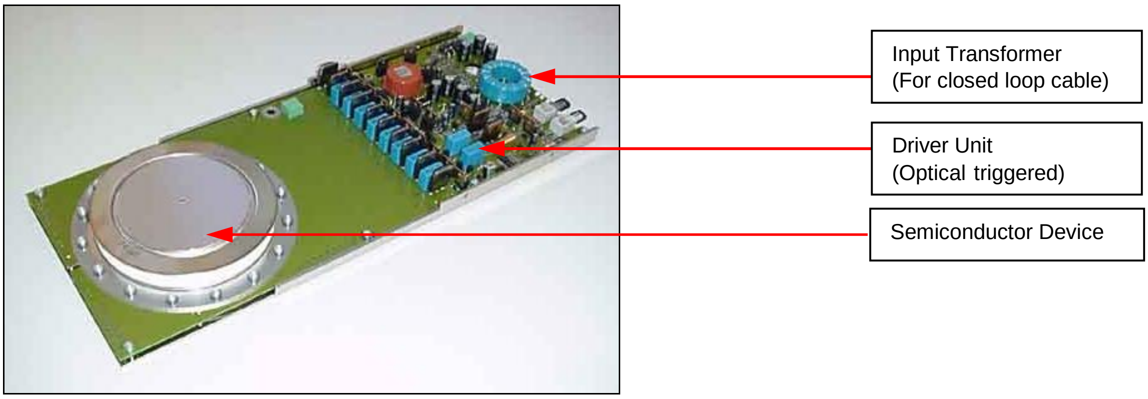


Figure 3. *Discharge Device p/n: 5SPR 26L4506, Vdrm=4500V complete with driver unit.*

Because of the required current capability, devices with 4500V blocking voltage are used. Higher blocking voltages will reduce the current capability.

3. Switch Assembly

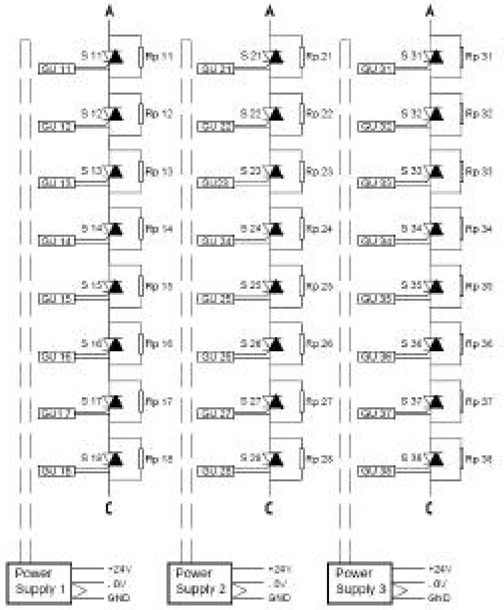
3.1 Reverse Conducting Discharge Switch 210 kA / 21 kVdc / 100 µs

Table 2 shows the basic specification of the complete switch assembly for the 100 kJ discharge system [2], using reverse conducting devices.

Parameter	Normal Condition	Short Circuit Condition
Max. Charge Voltage	21 kV	21 kV
Peak Pulse Current Forward	210 kA	420 kA
Peak Pulse Current Reverse	90 kA	150 kA
Current Rise Rate (di/dt)	3 kA/µs	9 kA/µs
Pulse Duration	100 µs	50 µs
Pulse Form	Damped Sine Wave	Damped Sine Wave
Pulse Rep. Rate	1 Shot / Min.	1 Shot / 10 mins
Lifetime	20.000 Shots	1.000 Shots

Table 2. *Specification for Reverse Conducting 210 kA / 21 kV switch assembly.*

To reach the required life-time of 20.000 shots it was calculated that three (Np=3) devices in parallel and eight (Ns=8) devices in series connection have to be used to share the current and voltage. The switch was built-up with three independent stack assemblies each having 8 devices in series connection. The current per device is therefore limited to about 70 kA under normal conditions and 140 kA under short circuit conditions. The last one should happen only maximum 1000 times. Fig. 4 shows the circuit diagram of the switch assembly with 3 stacks in parallel, each stack has its own power supply and one light distribution box will fire each stack independent or all 3 stacks simultaneously.



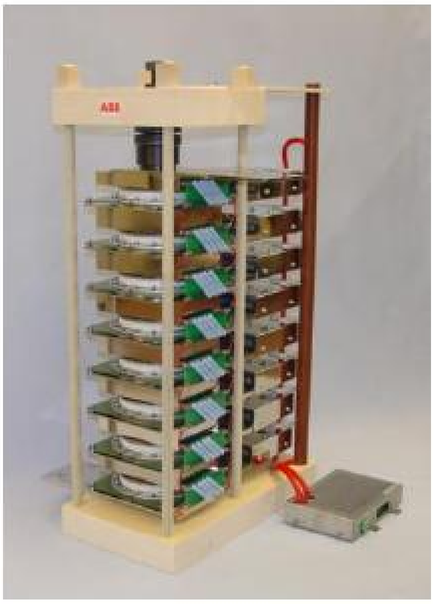


Figure 4: *Circuit diagram 21 kV switch*

Figure 5: *Picture of <u>one</u> stack assembly*

Because of reverse conducting devices are used and no switch-off is required no snubber circuit is needed. Only voltage sharing resistors are connected over each device level. Three independent stacks were used in parallel to avoid hard parallel connection of 3 devices. This configuration allows also the use of one single stack if less power is required. Every stack can handle the 70 kA nominal and the 140 kA short circuit condition. The driver units are optical triggered from a light distribution box and this box can be selected to fire 1, 2 or all 3 stacks simultaneously or sequential. The figures below show measurements on one of the stack assemblies.

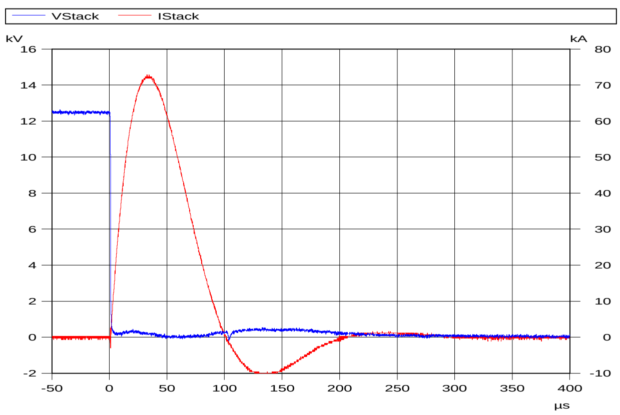


Figure 6: *Single Stack Pulse Test*

4. Reliability

4.1 Reliability of devices

Compared to Ignitrons and Spark Gaps, solid state switches have very good life times, but have not infinite life. For a semiconductor device the design and the production processes are most important. Quality- and Process management in the Waferfab are of vital importance. The life-time of a semiconductor is in the application mostly limited by mechanical stress or cosmic ray. Mechanical stress is caused by temperature steps in the silicon due to current pulses. The temperature of the silicon can increase more than 100°C within some micro seconds and the larger these temperature steps are the shorter life-time is expected. Therefore it is important to avoid large temperature steps if long life and high reliability is required. To accomplish this high reliability systems will have more or larger size devices which means often higher costs. Important is also the influence of cosmic ray [3] on the silicon wafer. To reach an acceptable FIT rate (1 FIT is 1 failure in 10^{-9}h) per device of ≤100 it has to made sure that the DC voltage on the device is maximum 65% of the device blocking capability. This means that a device with Vdrm=4500V should not be charged with higher DC voltage as 2900Vdc. In case of higher DC voltage the device will have a reduced life-time. The semiconductor manufacturer can calculate the expected life-time of devices if the application conditions are known in detail. The experimental system was designed for 20.000 shots with a repetition rate of 1 shot per minute but a production line in the industry will need ≥ 2 Mio shots with a repetition rate of one shot every 15 seconds. Therefore ABB has made calculations and several tests to verify the difference.

5. Tests

5.1 Test Conditions

The test was performed with an application oriented damped sine wave of 100 µs duration and I-peak = 70 kA for the first test, later for the second and third test with I-peak = 31 kA.

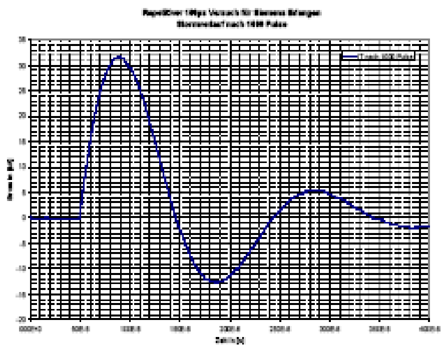


Figure 7: *Damped Sine wave 100µs*

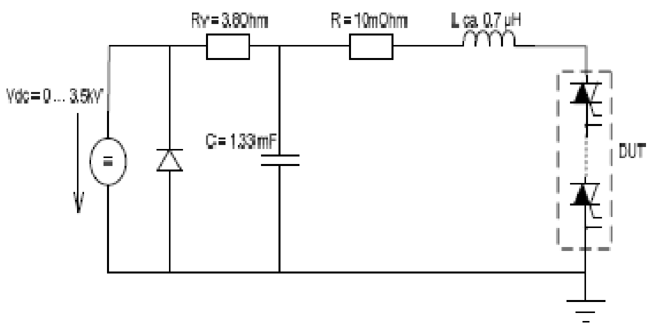


Figure 8: *Test circuit*

The test was done with two series connected reverse conducting devices 5SPR 26L4506. Vdc 5.6kV (2.8kVdc per device level) Peak pulse current for the first 20.000 shots was

70kA, later reduced to 31 kA for 250.000 and 1 Mio shots. All devices survived these tests and finally the wear-off at wafer level was analysed.

Test No.	Devices	Date	Vdc charge	I-pulse	t-pulse	Rep. Rate	Shots
1	5SPR 26L4506	27.04.2007	2.8 kV	70 kA	100µs	1 shot / 6 sec	20260
2	5SPR 26L4506	20.06.2007	2.8 kV	31 kA	100µs	1 shot / 6 sec	252600
3	5SPR 26L4506	26.08.2007	2.8 kV	31 kA	100µs	1 shot / 6 sec	1040000

Table 3: *Overview of tested devices and shots*

The test was done with a pulse repetition rate of 1 shot per 6 seconds, which is 2.5 times more as the specified one shot per 15 seconds. Still the devices did not need active cooling and could be cooled with convection air. Investigations were done, optically at cathode and anode side, with IR camera and Electron microscope REM/EXD.

5.2 Test No. 1 - Device Test 20.000 shots @ 70 kA

After the test the devices were still functioning but leakage current was increasing at a level of 2.8kV and higher. Changes were found at the cathode contact fingers and some molten craters on the aluminium metallisation on the anode side of the wafer. These changes are indicating that the end-of life for the wafer is very near.


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Figure 9: *Anode side of wafer with partly melted aluminium contact layer. The middle picture is enlarged 45x, right picture 440x*

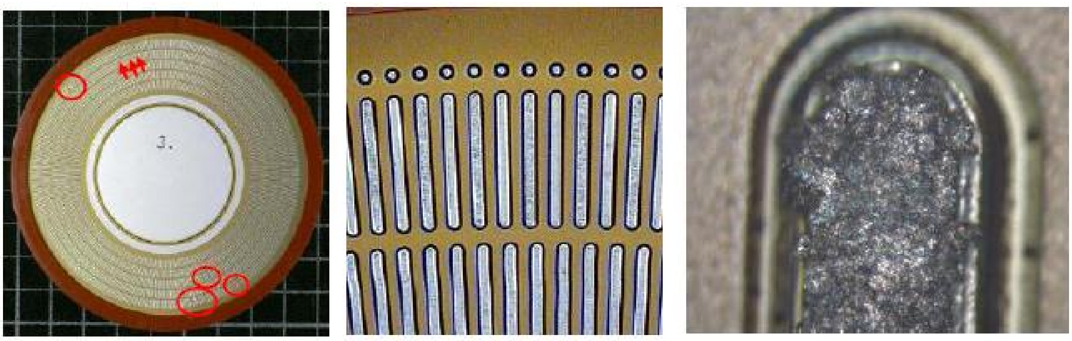

Figure 10: *Cathode side of wafer, middle picture shows contact finger arrangement, right picture shows burned contact finger with almost an cathode-anode short*

5.2 Test No. 2 - Device Test 250.000 shots @ 31 kA

Four additional devices were used for the second test run, but with current reduced to 31 kA at the same pulse width of 100 µs. After 250.000 shots two of the devices were taken out of the switch assembly and dismantled for inspection of the wafer. Both devices were still functioning and the leakage current at 2.8 kVdc was not increased. Very small changes were found at the cathode contact fingers and some melting spots on the aluminium metallisation equally spread over the silicon wafer. The results shows that the damage to the wafers was visible but clearly less as in test No.1, after the device had seen 12x more shots. With the remaining 2 devices the test was continued, see results under test No.3.

Figure 11: *Anode side of wafer shows uncritical small spots in aluminium contact layer.*

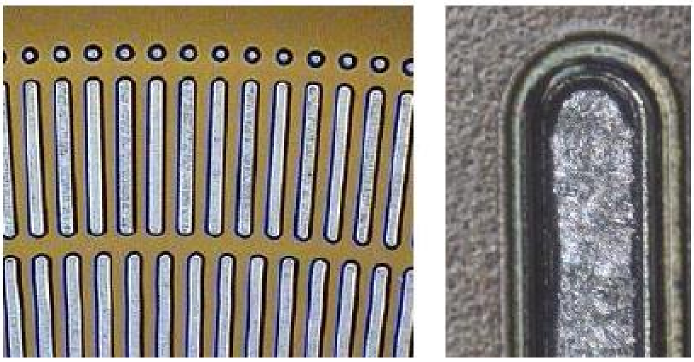

Figure 12: Cathode side, contact fingers show very little wear-off.

5.3 Test No. 3 - Device Test 1.040.000 shots @ 31 kA

Test No.2 was continued with the two remaining devices till a total of more than 1 Mio shots had been performed under the same condition. After 1.04 Mio shots the test was stopped and the wafers analysed. Both devices were still functioning and the leakage current at 2.8 kVdc had not increased. Changes were found at the contact fingers and melting spots on the aluminium metallisation of the wafer. There was no damage, only wear-off which is not critical compared to the result of test No. 1. The small spots on the anode side are dense but not deep in the aluminium layer. It is expected that about 40 – 50% of the life-time was consumed. This will result that a device failure under the given condition of 31 kA @ 100 µs pulse width is not expected before 2.5 Mio shots, which is more than 50x the result of the original experimental design. It has to be mentioned that the tests were done on a limited quantity of random selected devices.

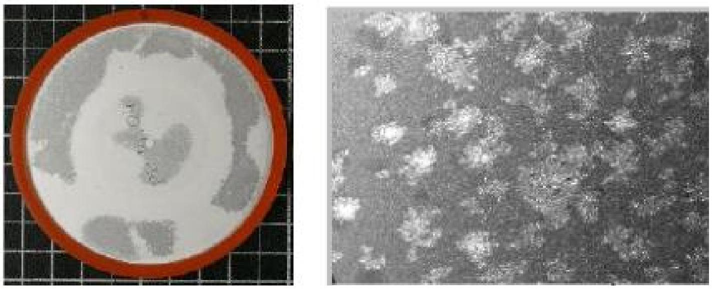
(Enlarged 220x)

Figure 13: Anode side of wafer with small molten spots on the aluminium contact layer.

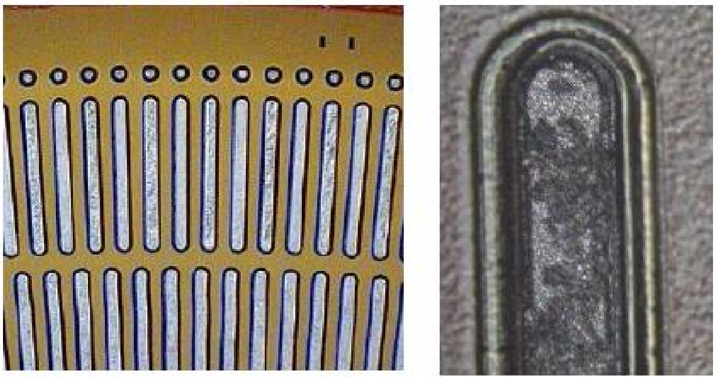

Figure 12: Cathode side, contact fingers show very little wear-off and some burned spots, which are uncritical.

6. Conclusion

It can be concluded that the devices used for the experimental 100kJ / 21kV / 210kA discharge system are a reliable solution as enough silicon area is used. For industrial use the life-time has to be increased substantially. The test result with the 200kA switch using Np=3 devices (70kA per device) compared to a 210kA switch using Np=6 devices (31kA per device) shows that by almost doubling of the silicon area, an increase in life-time by a factor of 50 can be reached. This also means that a 50x higher reliability will double the cost of the semiconductor switch assembly. The test was performed to give the end-user proven results for industrial applications. Based on the results, it can be stated that the reliability of proper designed solid state switches is clearly superior to ignitrons and spark gaps. Despite the initial higher costs, the solid state design offers much higher reliability, longer life-time and lower operation costs. ABB is striving to further improve the performance, the reliability and reduce the cost for this type of solid state switches.

References

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[3] ABB Switzerland Ltd Application Note 5SYA 2046 "Cosmic Ray on IGCT"