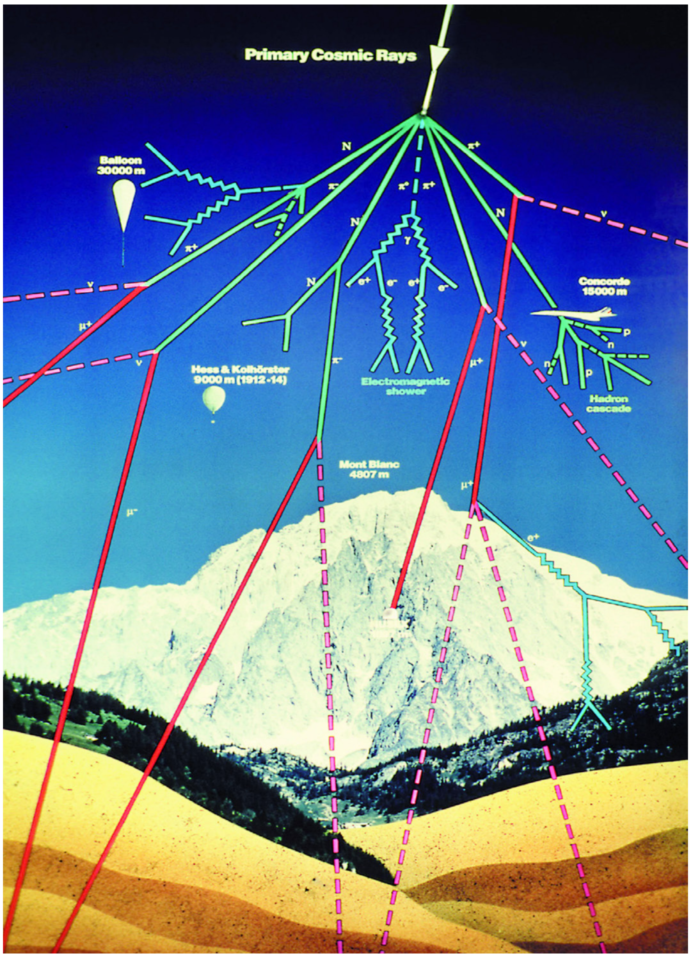
Application note 5SYA 2046-03

Failure rates of IGCTs due to cosmic rays

In the early 1990's a new failure mode for high current, high voltage semiconductor devices was discovered. The failure mode was of considerable practical significance and caused a series of equipment malfunctions in the field.

This failure mode affects all kind of devices like diodes, thyristors, GTOs, IGCTs, IGBTs, etc. It consists of a localised breakdown in the bulk of the devices and is not related to junction termination instabilities. The location of the breakdown spot on the wafer is random. The onset of the breakdown occurs without a precursor within a few nanoseconds and there is no sign of early failures or wear out. The failure rate is, thus, constant in time but strongly dependent on the applied voltage and shows a small dependence on temperature.



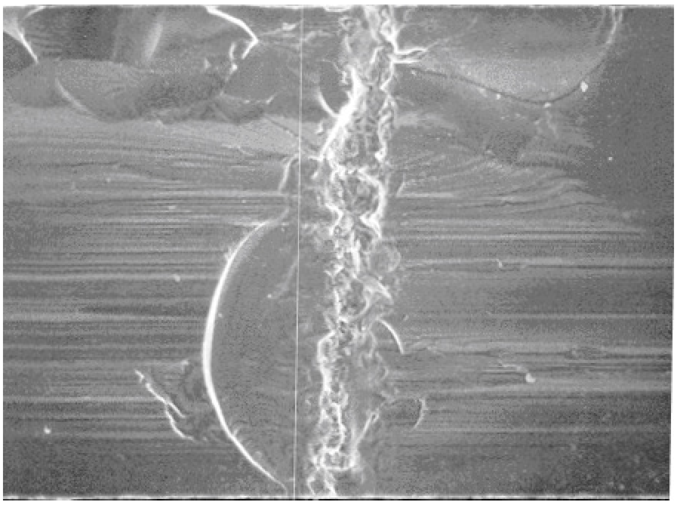
Contents

1 Introduction

Experiments in a German salt mine 140 m below ground did not show any of these failures, while experiments on the Jungfraujoch (3480 m above sea level) in the Swiss Alps yielded a much higher failure rate than in laboratories close to sea level. Furthermore, irradiation with heavy energetic particles creates the same failure patterns. All together it was concluded that “cosmic rays” are the root cause of this kind of failure and this conclusion is now supported by a vast number of experiments done all around the world.

Primary cosmic rays are high-energy particles, mostly protons, that are found in space and that penetrate our atmosphere. They come from all directions and have a wide energy range of incident particles. Most of these cosmic rays originate from supernovae. Originally the Austrian physicist Viktor Hess (Nobel Prize 1936) discovered cosmic rays because of the ionization they produce in our atmosphere. In fact, a primary cosmic ray particle usually does not reach the surface of the earth directly but collides with an atmospheric particle (see front page). There it generates a variety of other energy-rich particles, which later collide with other atmospheric particles. The process of a cosmic ray particle colliding with atmospheric particles and disintegrating into smaller pions, muons, neutrons, and the like, is called a cosmic-ray shower. Most of the generated particles are harmless for semiconductor devices but some, mostly neutrons, may be lethal. Occasionally cosmic ray related events are observed, which do not lead to any perceivable damage but in general, the device is doomed even if fast fuses are used.

Today, ABB’s high current, high voltage semiconductors are designed such that the failure rate due to cosmic rays is reduced to an “acceptable” level. Nevertheless, cosmic ray induced failures have to be taken into account for every power electronic circuit. In particular, semiconductors for applications with a high utilisation of the device’s blocking capability and for equipment operating at high altitudes have to be assessed carefully. This application note is intended to provide a basis on which the power electronics designer can estimate failure rates, adjust parameters such as DC-link voltages or simply select the right semiconductor device for a particular application.



A molten channel through a silicon device created by a charge avalanche triggered by incident cosmic rays during blocking.

2 Modelling the failure rates

In order to provide the user with a simple failure rate calculation tool, a mathematical model (Eq. 1) was developed that covers the three most important influences: blocking voltage, junction temperature, and altitude. The failure rate model consists of three multiplicands:

① the dependence on the DC-voltage (VDC in volts, VDC > C1) at nominal conditions, i.e. 25 °C and sea level

② the dependence on the temperature (T_{vj} in degrees Celsius), term equals unity if T_{vj} equals 25 °C

③ the dependence on the altitude (h in meters above sea level), term equals unity if h equals 0, i.e. sea level.

$$\lambda(V_{DC},T_{vj},h) = \underbrace{C_3 \cdot \exp\left(\frac{C_2}{C_1 - V_{DC}}\right)}_{①} \cdot \underbrace{\exp\left(\frac{25 - T_{vj}}{47.6}\right)}_{②} \cdot \underbrace{\exp\left(\frac{1-\left(1-\frac{h}{44300}\right)^{5.26}}{0.143}\right)}_{③} \qquad \text{Eq. 1}$$

The multiplicands ② and ③ equal unity at nominal conditions (25 °C and sea level, respectively). Thus, the formula can be simplified for certain cases. If for example a converter operates only at sea level, multiplicand ③ can be neglected. The formula is only valid for DC blocking conditions. Varying blocking voltages, blocking duty cycles or overvoltage spikes due to switching operations should be addressed as described in paragraph 4.

Please note:

- The model delivers failure rates in FIT, i.e. number of failures within 10^9 element hours.
- The formula is only valid if the DC-link voltage VDC is larger than the parameter C_1 because the formula has a pole at C_1. For VDC values below C_1 the failure rate is regarded as zero.
- The failure rate model describes only failures that are due to cosmic rays. The model does not cover failures due to other root causes

2.1 Voltage dependence

The formula for the voltage dependence (multiplicand ①) is a pure fit to measured data at DC-voltage. The formula has no physical background but fits the data almost perfectly.

The model’s parameters C_1, C_2, and C_3 are, therefore, characteristic values of the individual devices and can be looked up in the table in section 3. The parameters have also no physical meaning.

2.2 Temperature dependence

The formula for the temperature dependence (multiplicand ②) is again a fit to measured data. However, experiments indicate that the failure rates decrease exponentially with temperature and that this dependence is practically independent of the device type. Therefore, the formula does not require any device specific parameters.

2.3 Altitude dependence

The formula for the altitude dependence (multiplicand ③) assumes a screening of cosmic rays by the atmosphere and is, thus, based on the barometric formula. This implies that all devices are affected the same way, so again the formula does not contain any device specific parameters.

3 Failure rates of the individual IGCT types

The following table gives the device-specific parameters for the individual IGCT types. The cosmic ray induced failure rate of the integrated gate unit part is not accounted for, but is assumed to be less dominant for typical applications. The cosmic ray measure-

Product	C_1 [V]	C_2 [V]	C_3 [FIT]
5SHX 08F4510	2650	5500	4.22E+06
5SHX 14H4510	2650	5500	7.66E+06
5SHX 26L4520 5SHY 35L452x 5SHY 40L4511 5SHY 55L4500	2650	5500	1.39E+07
5SHX 06F6010	2900	8700	1.27E+07
5SHX 10H6010	2900	8700	2.31E+07
5SHX 19L6020 5SHY 50L5500	2900	8700	4.21E+07
5SHY 42L6500	3100	16800	8.52E+07

ments were done with the smallest (corresponding to the D-housing) device type on wafer level. The model parameters were afterwards fitted to the measured failure rates scaled to the device area of the respective larger IGCT. All values are typical values and may vary considerably.

Section 3.1 gives two examples of how to calculate the failure rate by using the formula and sections 3.2 and 3.3 show some selected graphs for each product listed above together with the underlying measurements.

3.1 Calculation examples

Assume a 4.5 kV IGCT in L-package (5SHY 35L4520) operated at a DC-link voltage of 3400 V, a temperature of 0 °C and at sea level. Because the altitude is at its nominal value the last multiplicand can be ignored. Together with the parameters from the table above, the failure rate formula now reads:
Eq.2

$$\lambda(3400V,0°C,0m) \;=\; 1.39\cdot 10^{7}\,FIT\cdot \exp\left(\frac{5500}{2650-3400}\right)\;\cdot\;\exp\left(\frac{25-0}{47.6}\right)\;\approx\; 15400FIT$$

15400 FIT means 15400 failures within 10^9 element hours or an MTTF of $1/\lambda$ = 65000 h, i.e. 7.4 y. Assuming a converter output stage with six IGCTs, the MTTF reduces to 1.2 y and this is usually not regarded as sufficient reliability. Obviously, the targeted DC-link voltage is too high.
Assume again a 4.5 kV IGCT in L-package (5SHY 35L4520) that is operated now at a DC-link voltage of 2800 V, a temperature of 25 °C and at an altitude of 6000 m. Because the temperature is at its nominal condition the multiplicand ② can be ignored. Together with the parameters from the table above the failure rate formula now reads:

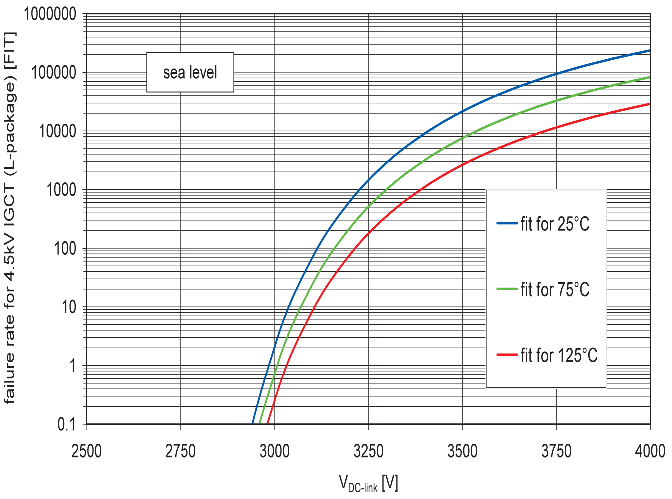
Eq. 3

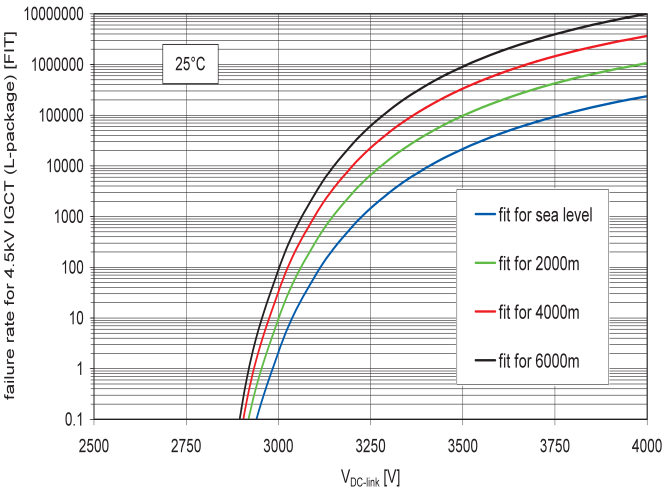
$$\lambda(2900V,25°C,6000m) \;=\; 1.39\cdot 10^{7}\,FIT\cdot \exp\left(\frac{5500}{2650-2900}\right)\;\cdot\;\exp\left(\frac{1-\left(1-\frac{6000}{44300}\right)^{5,26}}{0.143}\right)\;\approx\; 0.16FIT$$

In this example the MTTF is $6.1\cdot 10^9$ h or 700000 y. Even if the circuit contains a number of devices the overall reliability will not be affected by cosmic ray induced failures. Nevertheless, due to the statistical nature of the effect there might be cosmic ray failures in the field. Furthermore, the assumption of a constant DC-voltage is not realistic for typical applications. A variation of the DC-voltage due to e.g. input voltage variations or specific operations modes (breaking operation) is to be expected. Even more important is the repetitive over voltage the device has to withstand during switching. Dealing with this area is explained in more detail in section 4.

3.2 Graphs for 5SHX 26L4520, 5SHY 35L452x, 5SHY 40L4511 and 5SHY 55L4500

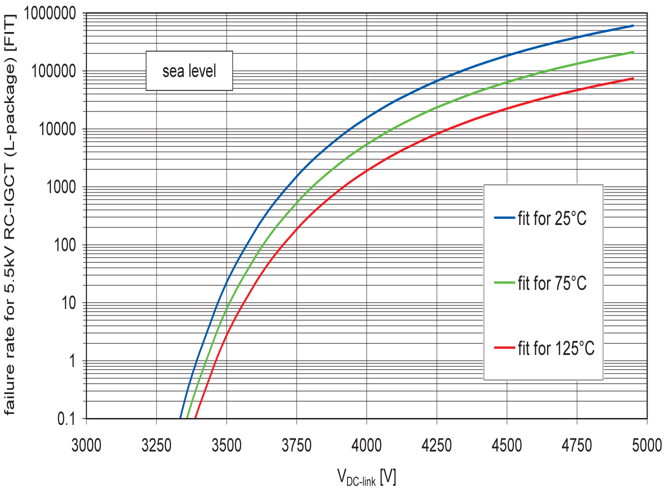
Relevant test report: LB PTS 05-013 and LB PTS 07-048

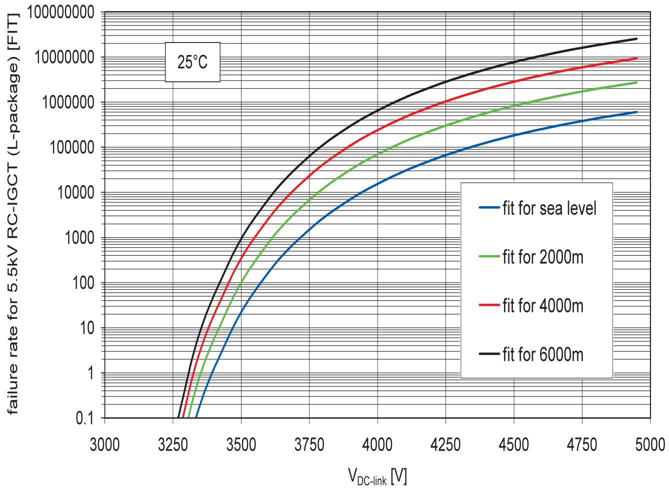




3.3 Graphs for 5SHX 19L6020 and 5SHY 50L5500

Relevant test report: LB PTS 04-043 and TR PTS 10-168





4 Varying voltages

The model assumes a DC-voltage. However, in most cases the applied voltage is not constant at all due to overvoltage spikes during switching or varying DC-voltage during operation. Here a more sophisticated approach is necessary. In fact, the correct value would be obtained by integrating the failure rate over the voltage distribution. Of course, this could be done numerically using the failure rate formula. However, due to the exponential voltage dependence of the failure rate it is usually sufficient to consider only the highest voltages and the voltages to which it is mainly exposed. Assume for example a converter that operates at a DC-link voltage of 2800 V. Due to switching over-voltages the device is exposed 0.3 % of the time to a voltage of 3500 V (mainly defined by the clamp design). The converter is equipped with 4.5 kV IGCT in L-package (5SHY 35L4520) and operates at 60 °C and sea level. If one of the IGCT conducts 50 % of the time (during conduction cosmic ray failures are impossible due to the very low voltage) the formula for this device reads:

$$\begin{aligned}&49.7\%\cdot\lambda(2800V,60°C)+0.3\%\cdot\lambda(3500V,60°C) \approx\\&49.7\%\cdot 0FIT+0.3\%\cdot 10300FIT \approx 0FIT+31FIT \approx 31FIT\end{aligned}\qquad \text{Eq. 4}$$

This means, that the failure rate due to cosmic ray is mainly determined by the switching overvoltage.

5 Revision history

Version	Change	Authors
02		Nando Kaminski, Thomas Stiasny
03		Björn Backlund, Tobias Wikström

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Note

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