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Cosmic Ray Testing at FHNW

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1 Summary

Cosmic ray robustness is an important aspect of high power semiconductors. FHNW offers turn key cosmic ray tests complete from pretests of the devices to reporting after the tests.

One important point in cosmic ray testing is the timeline, which is quite long when compared with other tests in the industry. It can take up to almost a year to get the first results (see section 3 for details).

This report explains the background of cosmic rays (origin, how to read the results) as well as the test methodology employed at the FHNW.

2 Background

2.1 Origins / Make up of Cosmic Rays

Cosmic rays are high-energy particles originating from outer space which collide with atoms in Earth's atmosphere, generating secondary particles. It is these secondary particles which can affect semiconductors. Most important are the high energy (> 10 MeV) neutrons which make up 60-80 % of the particles reaching the surface. There are around 13 high energy neutrons per square cm per hour at sea level. The atmosphere attenuates the cosmic rays, thus the flux increases with the height above sea level.

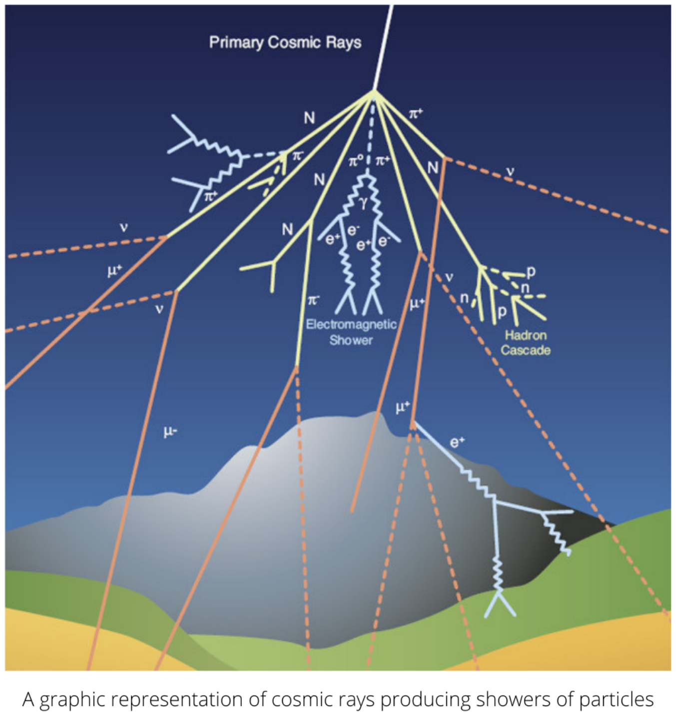

Figure 1: Schematic view of a "cosmic shower"[1]

[1]Source: https://spectrum.ieee.org/cosmic-ray-failures-of-power-semiconductor-devices

2.2 Effects on Semiconductors

Most of the high energy neutrons will simply pass through the semiconductors without any interaction. But when they do interact with an atom in the device where the electric field is high enough, a "streamer" can form. This streamer leads to a local breakdown in the device, thus shorting it. It is thus important to design a device such, that there are no areas which develop a high electric field already at a low voltage. Ideally the field is homogenous in the whole device and the full device gets sensitive to cosmic rays at the same time.

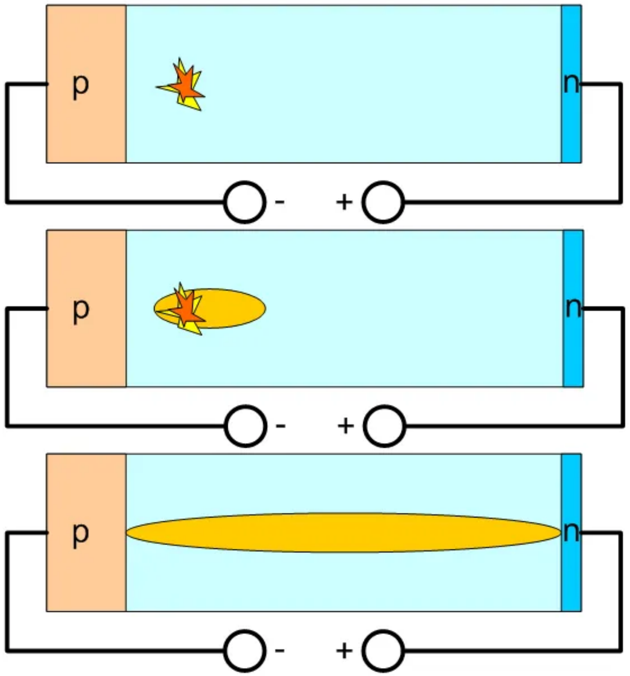

Figure 2: Schematic view of a streamer forming[1]

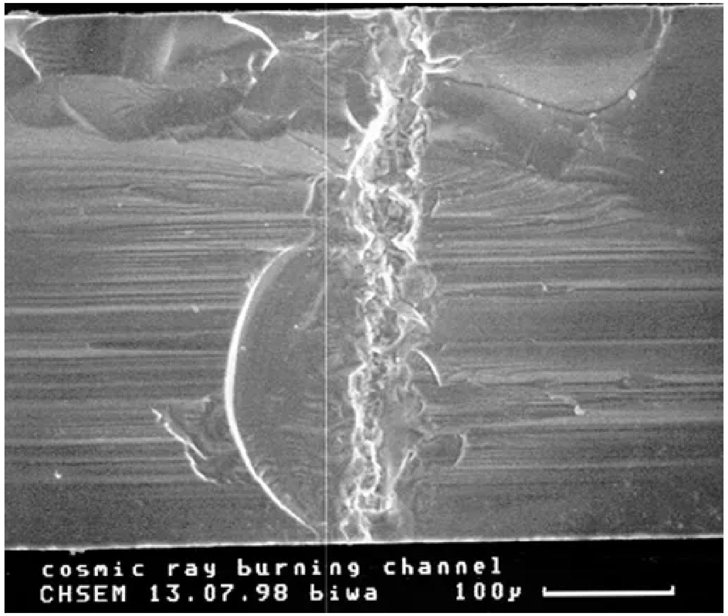

Figure 3: Molten channel from a streamer(picture taken with scanning electron microscope)[1]

In an inverter the channel formed by the streamer will lead to a catastrophic failure of the device. In testing however the power into the failure is limited, thus we can still look into the device to see the failure.

The picture above shows such a molten channel from a failure in a cosmic ray test.

[1] Image Source: https://spectrum.ieee.org/cosmic-ray-failures-of-power-semiconductor-dev

2.3 How to read cosmic graphs

The result of a cosmic ray test is a graph as shown in Figure 4. It shows the "Failures in time"-rate (FIT-rate) vs the applied voltage. The FIT-Rate is how many devices are expected to fail within 1 billion device hours. The device hours is the sum of all operational hours of all devices. Let's take an example of a locomotive-fleet with 100 locomotives, each locomotive housing 50 IGBT modules. In one year we would have 50 * 100 * 24 * 365 device hours or 44 million h (assuming the locomotives are operational around the clock). In this case we would expected one device in the locomotive fleet to fail per year if our FIT-rate was 22 (1e9 / 44e6). It is important to note that the FIT-rate of different failure mechanisms (of which cosmic ray is one) have to be added up. In other words the cosmic ray failures are in addition to other failures from other sources.

Let's look into the graph itself: Typically devices are unaffected by cosmic rays as long as the field in the device is low enough. This is reflected in the graph by the flat line at low voltages. Although we do report a low failure rate of 0.02 FIT in fact there where no failures in the test. For making the data more readable however, one failure is assumed, as otherwise the FIT-rate would be zero. With the assumption of one failure the FIT-rate now reflects the tested time-frame which also reflects the accuracy. (The 0.02 FIT means we tested not 1 but 50 billion device hours).

Above a certain voltage the device gets sensitive to cosmic rays and the FIT-rate increases dramatically. Usually the 1 FIT-rate is what is taken as the characteristic value (which is 900 V for the example on the right). In a good design the FIT-rate picks up late but very fast, which is to say the FIT-rate ramps from 0.02 to > 10 FIT in only a few Volts.

The example shown in figure 4 would be good to be used in DC link voltages up to 800 V at sea level.

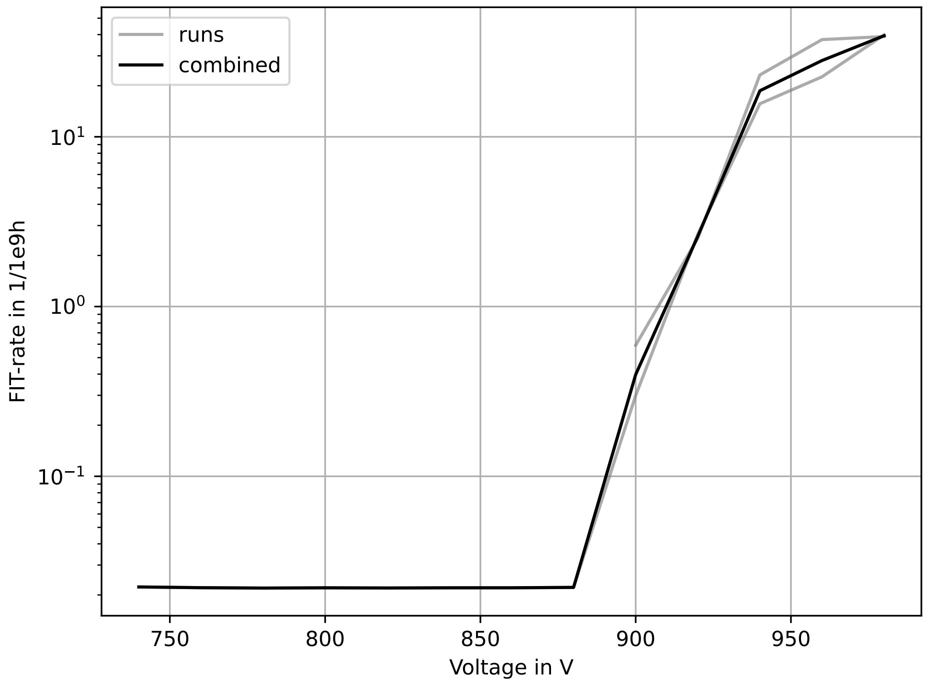

Figure 4: Example cosmic ray graph

3 Service Offering

FHNW offers the following:

- Assembly of DUTs (device under test) for discrete devices (i.e. TO-247)
- Pretest of assembled DUTs
- Beam-time reservation
- Actual test at beam line
- post processing and reporting of data
- upon request: additional pretests are possible

The customer is expected to supply:

- The devices to be tested
- Testing conditions / voltage levels (we can advise, but the final say is with the customer)
- Support with assembly if bare dies are to be tested

3.1 Timeline

A typical cosmic ray test works like this: DUT "Pipe-cleaner": If a DUT is used for the first time, a pipe-cleaner should be made. For this samples are assembled and then assessed for their blocking capability. Sometimes the soldering and bonding processes have to be adapted because it's now on a PCB and not on a DCB-Substrate.
DUT Assembly: Once the process for assembling DUTs is tested, the assembly of the actual DUTs can commence.
DUT Pretest: The assembled DUTs are tested for their blocking capability. If they block less then expected they should not be used for the cosmic test as this could lead to wrong results.
Beam-line lead time: Beam-lines have a varying lead-time. Sometimes just weeks but it can also be months if they are down for maintenance. This is only done after we are sure the DUTs work to prevent replanning in case the DUTs have to be remade.
Cosmic Tests: The DUTs are taken to the beam-line and tested. Preliminary results will be available the next day.
Reporting: The data collected during the test is checked for consistency and some corrections are made.
Decay time: After the DUTs have been subjected to the particle beam they become radioactive. Depending on the amount of heavy elements (Copper, Iron) in the DUTs it takes up to a few months for the DUTs to be ready to ship back.

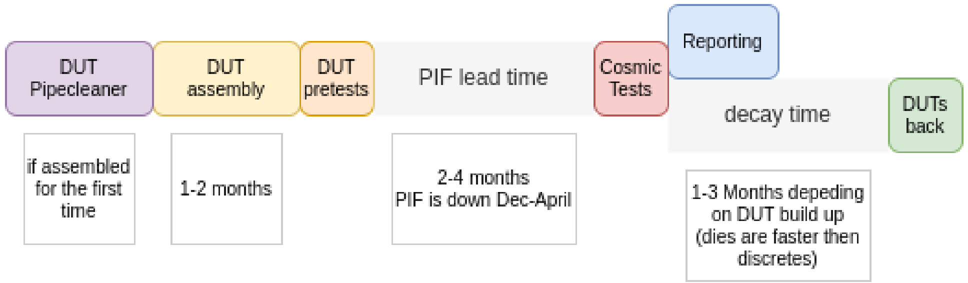

Figure 5: Typical cosmic timeline

3.2 What needs to be defined

- Number of devices to be tested (i.e. for chip-set that would be an IGBT and a Diode)
- Goal of the test: Product qualification or research. Can also be depending on results: i.e. if split A is ok, skip split B and use split A for qualification.

- Number of runs to be done per device (usually 2 for a qualification)
- Voltage levels to be tested (i.e. start at 740 V with 20 V steps)
- In case of dependency: What is your goal? (i.e. <1 FIT at 800 V)
- Bare die or discrete device?
- Protons or Neutrons (Protons are standard, Neutrons should only be used if there is a good reason as the test will be more expensive)

4 Testing Methodology

4.1 Pre-measurement

To ensure proper functionality of the DUTs every device is tested up to the specified blocking voltage and held there for 120 seconds. This is to make sure there are no weak devices which would artificially increase the FIT-rate.

4.2 Test at beam-line

At the beam-line the samples are again pretested with 500 V (independent of device blocking voltage) to make sure there is no damage from transportation. After the pretest the first actual test voltage is applied then the beam turned on. This starts the cosmic ray test as the devices are now subject to a particle beam while blocking at high voltage. Since the goal of the test is to collect the FIT-rate at different voltages, we have to ramp up the voltage stepwise during the test. The next voltage is taken when either

- enough particles have passed (testing longer won't give any new information)
- enough devices have failed (testing longer would not leave enough devices for the next voltage)

The tests starts out with up to 48 DUTs which will gradually fail during the course of the test.

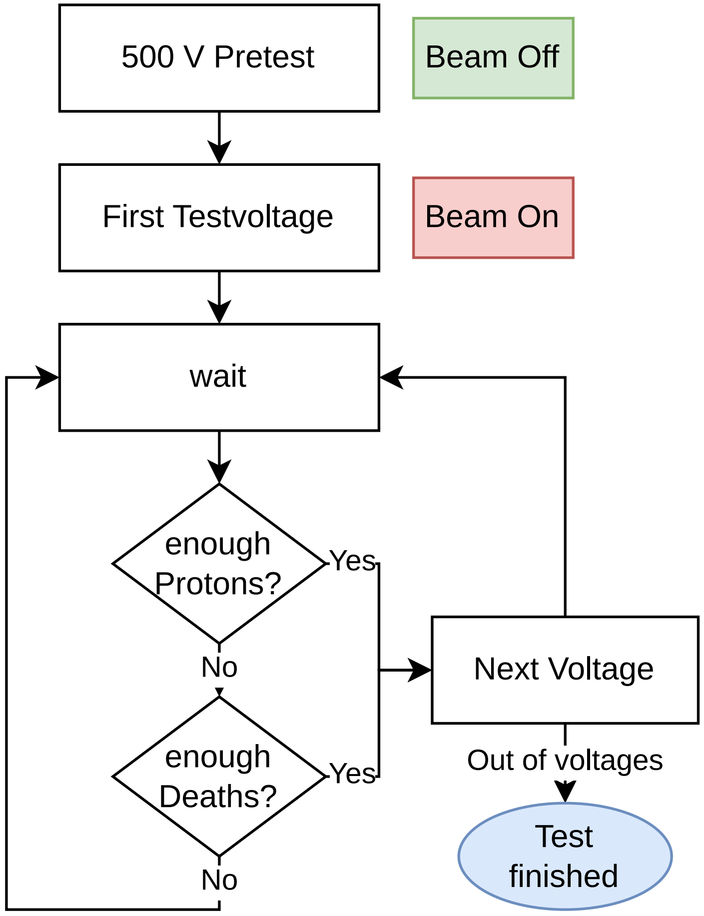

Figure 6: Cosmic test process at beam line

4.3 Data evaluation and reporting

Initial results are already available from the test at the beam-line. While these results are not far off there are some aspects which influence the results and are not available during the test itself.

Those are

- Not all devices might fail. A not failed device has to be assumed to be not connected at all. Thus the number of devices in the test has to be lowered. This will slightly increase the FIT-rate.
- The measurement of the proton flux has a small offset. This offset is evaluated during the 500 V pretest. Correcting the flux offset will lower the total protons passed and thus simulated lifetime also leading to a slight increase in FIT-rate
- There might be false positives, where one channel turned off not because the device failed but the of some interference from another channel failing. These failures are discarded and thus the FIT-rate will slightly decrease.

With all those correction the final FIT-rate can be plotted. It should be noted that these corrections are usually not significantly impacting the results.

5 Technical Specifications

5.1 Device Under Test

Currently there are two ready made PCBs for the following DUTs:

- TO-247
- Bare dies up to 17x17 mm (example shown right)

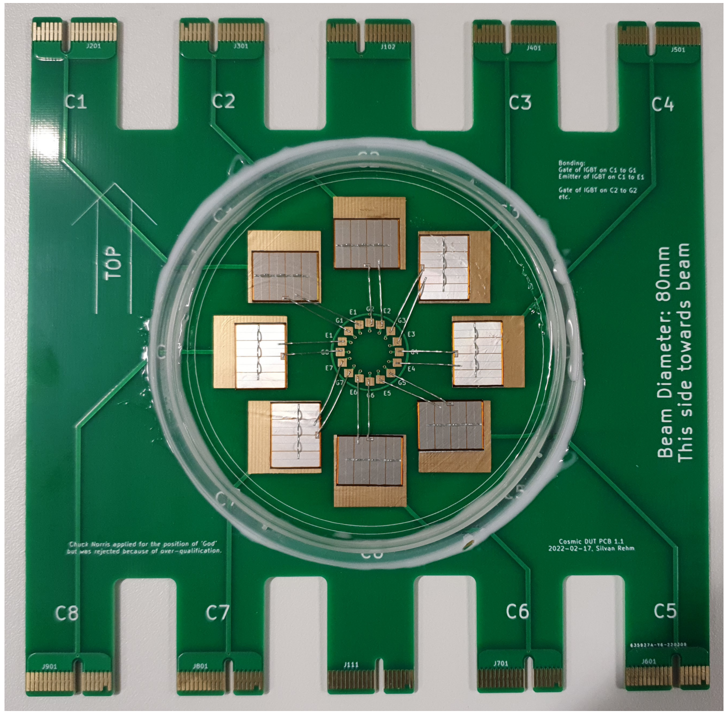

Figure 7: DUT assembled with bare dies

Other DUTs will require a special PCB to be made. FHNW does offer this service.

Considerations for other DUTs:

Per PCB there are maximum 8 devices and a maximum of 6 PCBs can be tested together. It is of course possible to fit fewer bigger devices on the PCB or leave out PCBs if the devices are to thick.

- max height for using 6 PCBs: 40 mm
- max beam area : circular with 80 mm diameter

5.2 Test System

The following are starting parameters. If necessary they can be adjusted (i.e. for a leaky device)

- maximum leakage current: 75 μA
- maximum tested voltage: 1700 V (higher voltages are currently under development)

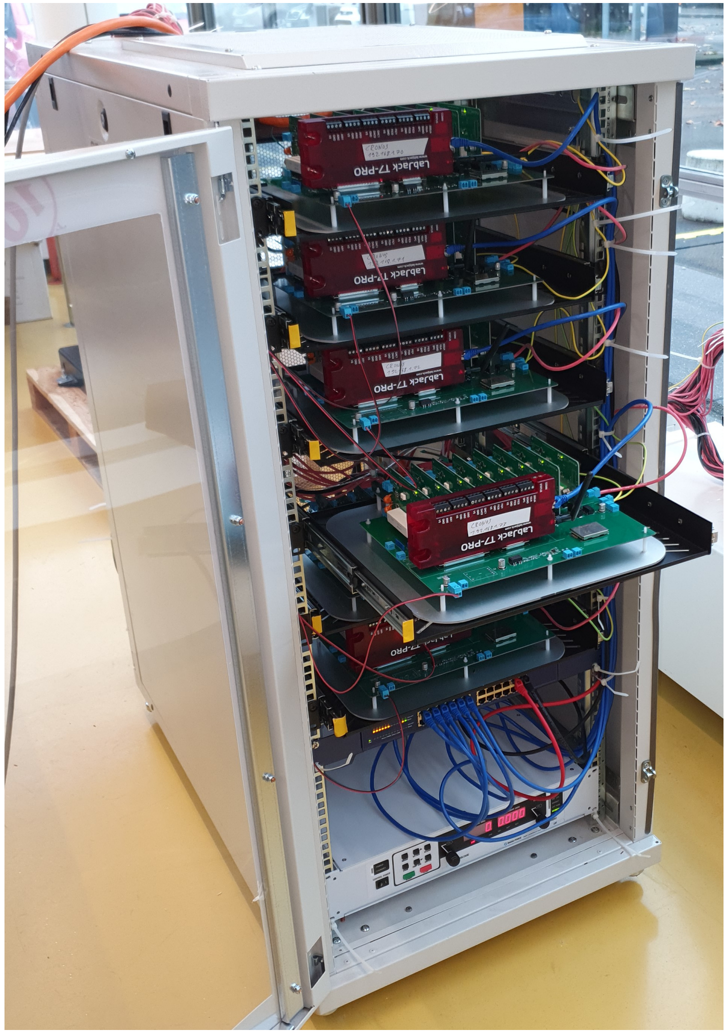

Figure 8: Test System

5.3 Beam Lines

We currently offer test at two beam-lines. If you require a specific beam-line, please contact us.

Protons, default (PSI, Villigen, Switzerland)

Protons are the default way of testing cosmic ray as they are close by and offer short test time with only around 120 seconds for simulating the required 1 billion device hours. Various comparisons showed that the results are the same as with Neutrons.[1]

- Energy: 230 MeV
- Test time per voltage: 120 s

Neutrons (Chip IR, Oxford, UK)

If necessary Neutrons can be used to test cosmic ray robustness. However, it should be noted that this is a significantly bigger effort then using Protons. Not only is the testing time over 20x longer also the whole test system has to be shipped to Oxford.

- Energy: atmospheric spectrum
- Test time per voltage: approx 1h

[1] Soelkner, G. Ensuring the reliability of power electronic devices with regard to terrestrial cosmic radiation. Microelectron. Reliab. 2016, 58, 39–50

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