

Encapsulation of Power Modules for Extreme Environment Electronics

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Abstract

It has been demonstrated that wideband gap devices fabricated from SiC, or GaN grown on SiC, can operate over a much wider temperature range than traditional silicon or GaAs devices. However, most of the packaging technology in use to today was developed for silicon or GaAs devices and much of this technology is fundamentally limited in its temperature range. For example encapsulation and housing materials often have maximum service temperatures of 200°C. Therefore, new technologies are needed to enable the wide spread use of these new devices at elevated temperatures. In particular, the identification or development of suitable gels and housing materials for power electronic modules operating at high temperature is a critical issue. These power modules operate with very high internal voltages, and gels and polymeric housings have traditionally been used to prevent arcing within the packages.

This paper seeks to address one of these fundamental issues, which is the dielectric breakdown strength associated with the encapsulating gels and housing materials under extreme environmental conditions. Several potential materials were selected and long term reliability data on a number of encapsulation gels and housing materials that are suitable for operation of these devices in excess of 180°C is provided. Baseline electric breakdown data measured at high temperature as well as data on aged samples has been collected.

Keywords: *Encapsulants, Housings, GaN, SiC, Extreme Environments*

1. Introduction

Wide Band Gap (WBG) semiconductor materials, principally SiC and GaN can operate continuously at extreme temperatures. As a result, these Wideband gap semiconductors are being considered for fabrication of power devices used in high temperature applications [1-2]. The reliable operation of most power electronic modules that are being fabricated today is limited to the temperatures around 150°C due to the intrinsic limitations of the Si power devices. Likewise the bulk of packaging technology in use today is vulnerable to extreme temperatures and therefore not useful in high power applications where the junction temperatures may exceed 200°C. For example, many of the dielectric gels commonly used to encapsulate the power electronics to prevent electric discharging at the active portion of the device fail due to dielectric breakdown when used at these temperatures.

This same reasoning can be applied to the power module housings. These housings are a barrier

between the power electronics inside the module and the external world, it not only prevents dielectric breakdown of the module due to high power applications but also protects the microelectronics from contamination and physical damage. The electrical insulating properties of many of the housings materials in use today degrade with time and temperature. Therefore the dielectric property of the housing materials is of prime concern.

This paper focuses on identifying and testing of the dielectric strengths of potential high temperature dielectric gels for encapsulation of power module and housing materials that can be used with operating junction temperatures greater than 180°C.

2. Identification of Candidate Materials

Encapsulating Gels:

Encapsulating gels are soft dielectrics which have properties that provide electrical and mechanical protection of the internal circuitry.

Table 1: Properties of Selected Encapsulating Gels.

Product	Maximum Operating Temperature (°C)	Mix Ratio	Dielectric Strength (V/mil)	Resistivity (Ohm-cm)	Cure Cycle	Uncured Viscosity (cps)	Hardness
TSE 3051 GE-Silicone	200	1:1	370	1E+14	2hours@ 125°C	700	8.5mm [†]
Dow Corning 3-4190	180	1:1	560	1.5E+15	40mins@ 150°C	2200	A:24 [‡]
GEL 8100 Nusil	240	2:3	500	1E+15	2hours@ 105°C	525	9mm [†]
Dow Corning 3-4680	260	1:1	480	1E+14	40mins@ 150°C	2000	2-4mm [‡]

[†]: ASTM D 1403, 1/4 cone penetration measurement [3]

[‡]: ASTM D 2240 Shore A hardness [4]

Some of the desired properties of these gels are high temperature stability to 200°C and beyond depending on the application, electrical insulation to prevent electric discharge and arcing inside the module, and sealing capability. Although silicones have a high CTE, the very low elasticity modulus (E) of these gels allows encapsulation of wire bonds and power devices without exerting excessive strain on them during periods of thermal shock of cycling [5]. Several materials that have potential to operate at 200°C and beyond were considered and compared. The properties of all the considered materials are given in the above table.

After a close examination of all the key properties GEL8100, 3-4680 and 3-4190 have been selected for further testing of their dielectric strength as a function of time and temperature.

Housing materials:

In order to form a proper interface between the internal electronics and the external surroundings of the power module, the module housing has to meet mechanical, electrical and thermal requirements [6-8]. It is desirable for the housing materials to have very high dielectric

strengths to protect external surroundings from the high voltages inside the power module. It is also desirable for these materials to have a relatively high tensile strength in order to provide strong mechanical support to the module and its external connections. The properties of all the considered materials are shown in the table 2 shown below.

After close examination of the possible housing materials, Torlon 5030 and 4203 as well as Ryton PPS filled and unfilled polymers have been selected for further testing.

3. Experimental Approach

High Voltage Testing:

A Teflon fixture has been designed for the evaluation of the dielectric breakdown strength of the encapsulating gels and housing materials. Each test sample was placed inside this fixture before applying any test voltages to it. Since Teflon has a very high dielectric strength, it prevents electric discharging around the edges of the sample under test. The bottom part of the Teflon fixture has a small recess inside which the test sample is placed. Metal screws were

Table 2: Properties of Selected Housing Materials.

Product	Nominal Tensile Strength (Kpsi)	Coefficient of Thermal Expansion (ppm/°C)	Heat Deflection Temperature (°C)	Max. Service Temperature (°C)	Thermal Conductivity (W/m-K)	Dielectric Strength (V/mil)
Ryton-PPS	13	52.1	254	232	0.302	385
Torlon 4203L	27	30.6	278	260	0.259	580
Torlon 5030	29.7	16.2	282	254	0.360	840

used to tighten both the parts of Teflon fixture after the sample has been placed inside it so that the sample can be held tightly in position.

A high precision adjustment screw (AJS8 0.5H from Newport Solutions) was threaded into the upper part of the Teflon fixture and this metal screw serve as a high voltage electrode. The electrode being hemispherical at its tip with a diameter that is less than half the length of the test sample ensured that partial discharging did not take place at the corners. High temperature and high voltage rated cables were used to connect the electrical terminals of the source supply to the electrodes in the Teflon fixture. This entire assembly was placed on a metal tray inside an oven. Figure 1 & 2 show the setup and the design of Teflon fixture.

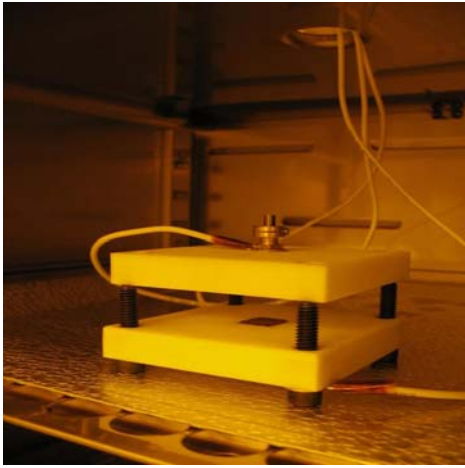


Figure 1: Teflon fixture inside which the samples are placed for Dielectric Breakdown testing. The two halves have been separated to show the electrode structures.

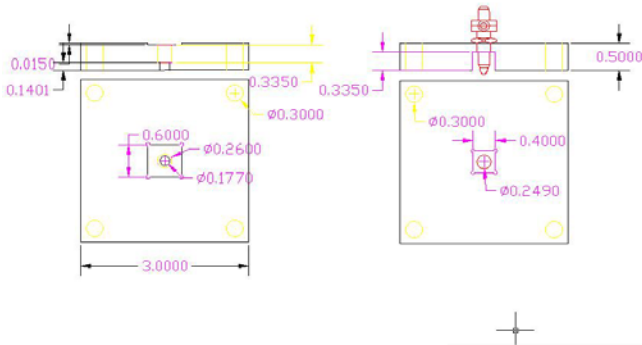


Figure 2: Design of the Teflon fixture featuring the top and bottom parts & the electrode configuration.



Figure 3: Mold structure with a copper substrate sample placed inside prior to dispensing the encapsulating gel.

Encapsulating Gel Samples:

The measured value of the breakdown strength is a strong function of the thickness of the sample that is being tested. It is therefore necessary to control the variance in the thickness of the gel samples. The encapsulating gels are usually a mixture of two parts: Part A and Part B. Both the parts are free flowing individual components, which are mixed in finite proportions and later cured according to their respective cure schedules. Once mixed the gels have a certain working time before which they should be cured. After they are cured they polymerize and turn into soft gel like materials.

Since these gels are very soft and transparent, it is very difficult to determine the thickness and control the variance in the gels down to the order of a mil. Therefore, the gel samples were made under very controlled conditions taking into consideration all the possible factors such as volume of the gel dispensed, variance in the mold structures, and variance in the dispensing equipment

In order to control the volume of the mold inside which samples are made, a separate mold structure was made out of brass tubing (as shown in Figure 3) that is 0.5 inch in diameter. This tubing was cut into a cylindrical ring like structures with an approximate height of 0.5 inch.

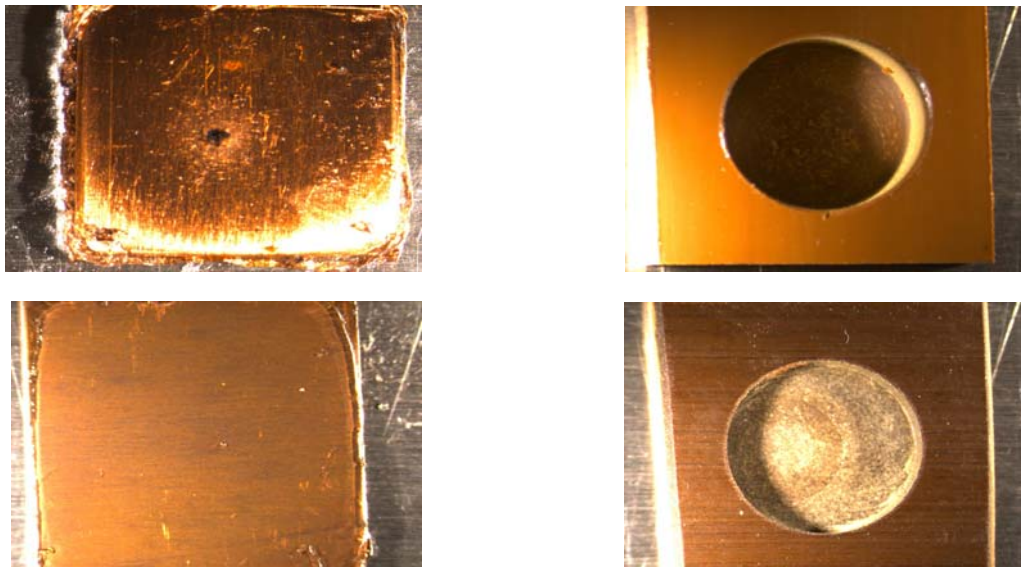


Figure 4: Breakdown samples of encapsulants (left) and housing materials (right).

The inner radius of all the cylindrical rings which are cut from the brass tubing was measured, and sixteen rings which have almost identical inner radius were chosen and glued to a copper sheet that was 4" x 4" in size. Gels were dispensed and cured inside these ring like structures. Sixteen samples were made in a single batch process by using these molds.

In order to determine the exact quantity of the gel that was required to deposit a ten mil thick gel on the copper samples; 21 mil thick copper sheets which were 0.5"X0.45" in dimension were placed inside these rings with a 12 mil thick wire on top of each copper sheet, different volumes of gel were later dispensed inside each mold and cured, this approach deposited gels of different thicknesses on top of each copper sample. The thickness of the gel on each sample was approximated by probing the top surface of the gel and comparing it with the surface of a 12 mil thick wire on top of copper sheet under a high resolution microscope. After several repeated attempts it was found that dispensing 36 μ l of the gel inside these rings produced a cured gel with an approximate thickness of 10mils on top of 21mil thick copper sheets that were 0.5"X0.45" in dimension. It was very important to dispense this material very accurately in quantities of 36 μ l of gel per sample with repeatability.

In order to accurately control the volume of the gel that is being dispensed, a 10 μ l Biohit pipette

with a precision of 0.01 μ l was used to dispense the gel into the mold so that desired volume of gel is always dispensed without introducing significant variance in the resulting gel samples.

Housing Samples:

Three housing materials with high dielectric strengths were chosen for testing. Since these materials are only available in certain minimum thicknesses, and the resulting required voltages would have been very high, these samples were machined into thinner geometries. The dielectric strength of Torlon 5030 is 840V/mil and if the thinnest available sample of Torlon 5030 (80mil thick sheet) was selected a voltage as high as 70KV would have been required. In contrast the Ryton glass filled PPS was readily available as 15 mil thick sheets so samples were cut directly from a sheet into samples that were 0.5"X0.5" in dimension.

Sample Size Estimation and Randomization:

After setting all the above process parameters by considering all the significant process variables, a preliminary test was performed on a few test samples. Statistical analysis was performed on this preliminary test data in order to determine the process variance and the sample size. It was calculated from the statistical analysis that at least 8 samples of each gel would be required at each data point for a confidence level of 95% [9-11]. Therefore 10 samples of each gel have been categorized into two groups for further testing;

therefore 160 samples were required for testing the performance of one gel. For the housing materials it was found that 6 samples were required per data point, and with the samples being classified into two groups, required 120 samples for testing each housing material.

The samples were categorized into two groups for further testing. The samples prepared in batches are distributed randomly between both the groups and the data points so that the process error in the samples was uniformly distributed among both the groups and also among all the data points of each group. Samples were made in batch process and the samples from each batch were randomized based on Latin Square Randomization (LSR) model and were distributed to each group.

Sample preparation:

Three gels namely Nusil Gel 8100, Dow Corning Gel 3-4190 and 3-4680 were chosen for testing their dielectric breakdown strengths. Each gel has their respective cure schedule and mix ratios. One hundred and sixty samples were required per each gel and 16 samples can be made in each batch process. Copper sheets 0.5"X0.45" in dimension were cleaned with 100% Isopropyl alcohol. Each copper sheet was labeled with a number and code on its back denoting the sample number and the type of gel dispensed on it. The mold structure was cleaned thoroughly with 100% alcohol and then rinsed with distilled water, and the labeled copper conductors were placed inside the mold. Meanwhile the gels were mixed in their prescribed proportions: Part A: B mix ratios for the gels are as follows Gel 8100 2:3, Dow Corning 3-4190 and 3-4680 1:1 respectively. After mixing the gels in their prescribed proportion, the mixture was thoroughly stirred for 5 minutes using a magnetic stirrer in order to ensure proper mixing of both the parts of the gel. With the help of a 10µl Biohit Pipette, a 36µl volume of the mixed gel was dispensed in each molded ring over the top of the copper conductors already placed within the molds. This dispensing process was performed in such a way that the variance in the volume of gel being dispensed for each sample was negligible. Later the samples were cured inside an oven according

to the proper cure schedule for each gel. Those cures schedules were: 100°C for 120 minutes in case of Nusil Gel8100, 150°C for 5 minutes for Dow Corning 3-4680 and 150°C for 15 minutes for 3-4190. After cure the samples were randomized according to an LSR model and were distributed for further treatments.

The housing materials were prepared by machining the raw plastic materials into the form of cubes, which are 0.5"X0.5" in size. The Torlon samples were milled down to 15 mils in their thickness at the center with a diameter of 0.3", while this was unnecessary for the Ryton samples. After machining, the samples were cleaned with isopropyl alcohol, rinsed with DI water, and labeled. The labeled samples were then randomized according to an LSR model before they were distributed for further treatments.

Accelerated Aging:

To assess the effect of exposure of samples to high temperature for long durations, the samples were subject to high temperature storage (HTS). A portion of the samples for each gel were set aside as control set and were not exposed to any treatment, while the rest of the samples were tested with HTS. During this test the samples were treated in the presence of air and no measures were taken to prevent oxidation. Eighty samples from each gel were subjected to HTS to assess the effect of exposure of the encapsulating gels to high temperature for long duration of time. HTS was carried out at 180°C in a Yamato DKN 400 forced convection oven. Three thermocouples were used to monitor the temperature of the samples during the HTS. This test was conducted in ten steps of 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 hours. After each step, eight samples were tested for the dielectric breakdown at a temperature of 180°C.

4. Results

The recorded dielectric breakdown values of the gel samples are plotted as a function of temperature for the control set of samples and as a function of soaking period for the remaining high temperature storage set. From the graphs

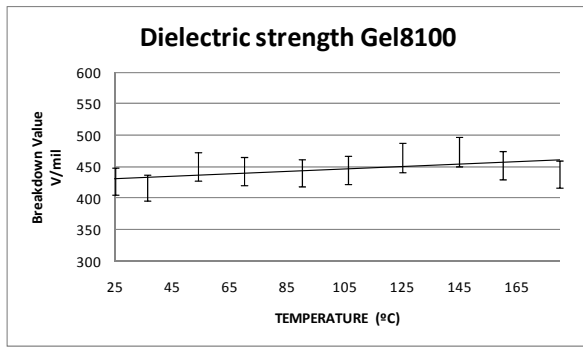


Figure 5: Average Breakdown strength of Nusil Gel 8100 encapsulating gel plotted as a function of temperature.

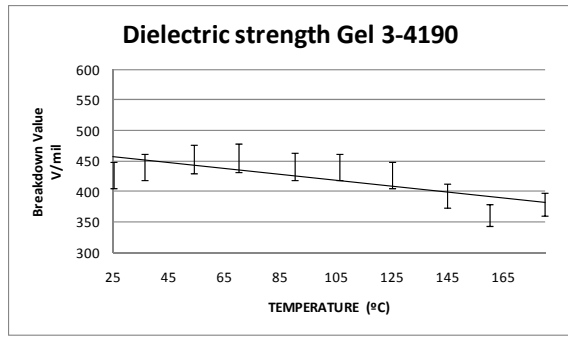


Figure 6: Average Breakdown strength of Dow Corning Gel 3-4190 encapsulating gel plotted as a function of temperature.

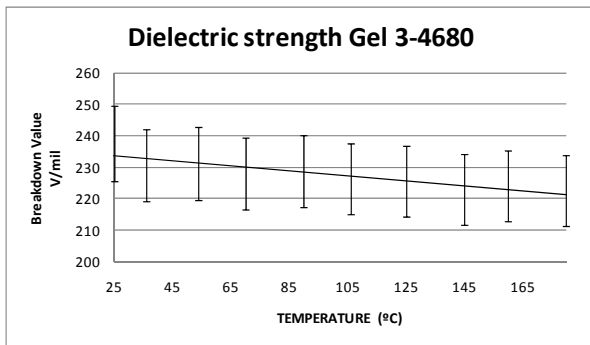


Figure 7: Average Breakdown strength of Dow Corning Gel 3-4680 encapsulating gel plotted as a function of temperature.

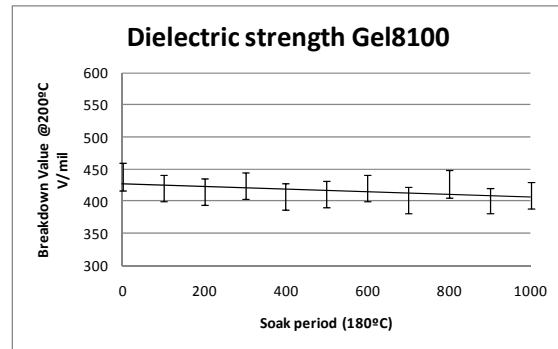


Figure 8: Average Breakdown strength of High Temperature Storage samples of Gel 8100.

listed in figures 5-7 we can see that there is no statistical significant variation in the breakdown values of the samples of the three gels as a function of temperature. From figures 8-10 we can also observe that the encapsulating gels are functioning equally well at high temperatures even after 1000 hours of high temperature storage. While a change in the data is observed it is not statistically significant, and no visible change occurs in the gels in terms of their physical appearance or viscosity.

For housing materials the recorded leakage currents are plotted as a function of temperature for the control set and as a function of soaking period for high temperature storage set. From figure 11 it can be seen clearly that the Ryton glass-filled PPS samples failed beyond 100°C as their leakage current exceeded 1 μ A, whereas the samples of Torlon 5030 and Torlon 4203 remain unaltered as seen in figures 12 & 13 with only a minor change in the leakage currents in these samples even at high temperatures.

5. Conclusions

The three gels studied in this work Nusil Gel 8100, Dow Corning 3-4190 and Dow Corning 3-4680 all exhibited no statistically significant change in their dielectric properties as a function of hours exposed to high temperatures. These materials also exhibit no statistically significant change in their breakdown strength as a function of temperature up to 180 °C. As a result, these materials have potential for use in SiC based power modules operating with junction temperatures up to 180 °C.

Two of the three housing materials Torlon 5030 and Torlon 4203 show no statistically significant changes in their electrical properties as a function of hours stored at high temperature. While the leakage current through these materials increases slightly with increasing temperature this effect is minor and should not be a barrier to their use in high temperature power modules.

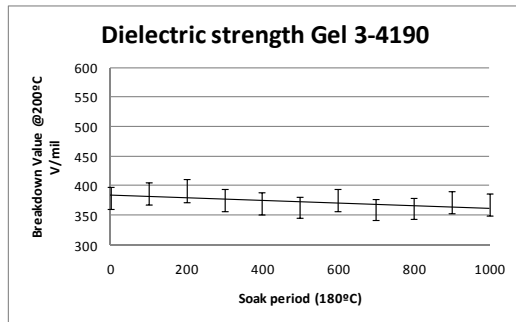


Figure 9: Average Breakdown strength of High Temperature Storage samples of Gel 3-4190.

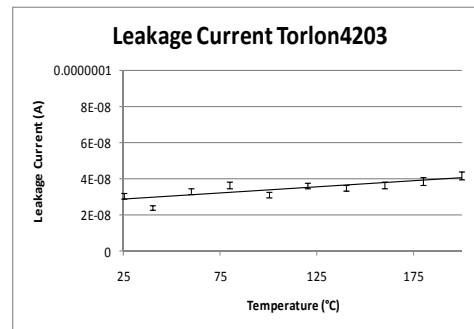


Figure 13: Leakage current of Torlon4203 samples measured as a function of temperature.

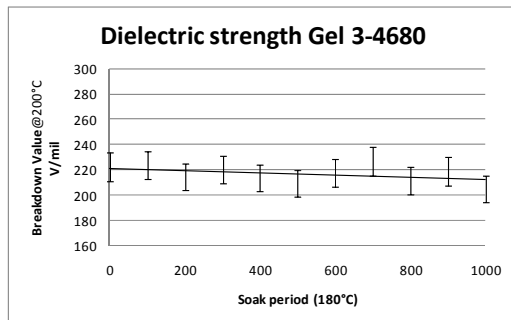


Figure 10: Average Breakdown strength of High Temperature Storage samples of Gel 3-4680.

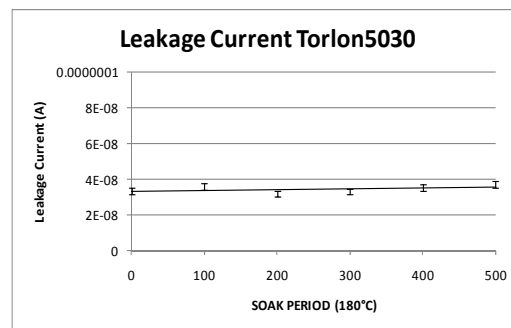


Figure 14: Leakage current of High Temperature Storage Torlon 5030 samples.

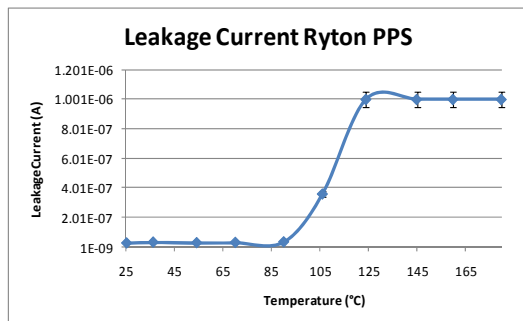


Figure 11: Leakage current of Ryton PPS samples measured as a function of temperature.

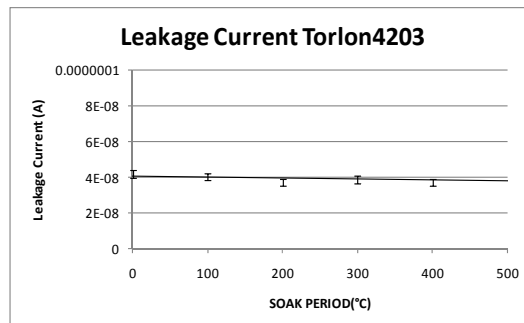


Figure 15: Leakage current of High Temperature Storage Torlon 4203 samples.

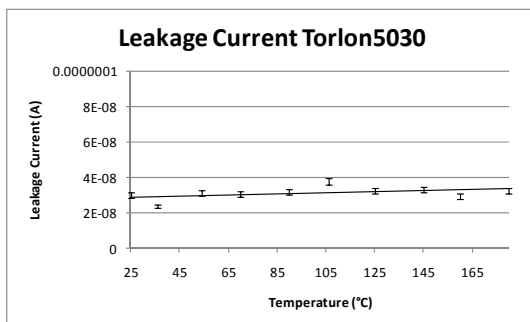


Figure 12: Leakage current of Torlon 5030 samples measured as a function of temperature.

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7. References

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