# High Frequency TDDB of Reinforced Isolation Dielectric Systems

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This paper was presented at the 2020 IEEE International Reliability Physics Symposium (IRPS). 2020 IRPS was a virtual conference which took place in May 2020. This is the final, published version of the reviewed and accepted article. It is available in the proceedings of the 2020 IRPS.

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***Abstract*— Reinforced isolation provides protection of equipment and operators that interact with high voltage domains. Standards that define it have evolved over time from those that require only partial discharge to confirm reliability at the high voltage operating conditions, to those that also require a time dependent dielectric breakdown model (TDDB) for verifying reliable working voltage. In this paper we assess the impact of AC frequency, waveform, and rise and fall times on lifetime, which are important parameters that are not included in the current standards.**

***Index Terms*-- frequency, isolation, reinforced, TDDB**

## I. INTRODUCTION

Reinforced Isolation devices are used to provide safety for equipment and operators against high voltage (HV) operation or transient events. Several techniques are used to achieve reinforced isolation, including optical, inductive and capacitive communication across the isolation barrier, which may be comprised of SiO2, polyimide, or a polyimide/silicone epoxy combination. Reliability modeling is important for determining the working lifetime of HV isolation products that experience continuous HV stress (e.g., 400 to 1500Vpeak) with high frequencies (e.g., 10 kHz to 100 kHz) and high dV/dt (e.g., up to 300 V/nanosecond).

Several standards exist to establish the isolation level of an electronic device [1]. Some of the early standards for optical isolation devices, such as IEC 60747-5-5, require only partial discharge testing to confirm reliable operation. Partial discharge (PD) occurs inside an insulation system when voids or interface delamination exists with sufficiently large volume to support a discharge during HV AC stress. PD over time degrades the insulator and leads to failure. PD can be observed during standard 60 Hz HV AC testing and units with observable PD are generally screened out.

The more recent HV isolation component standard VDE 0884-11 released in 2017 adds to the aforementioned PD testing requirements a TDDB requirement in which lifetime projection models are specified to assess the reliability at the given working voltage.

This work begins to assess the questions of: 1) Is TDDB necessary to confirm reliability of optical isolation devices at the rated working voltage? 2) Are current methods for screening PD effective for ensuring reliability at higher frequencies and higher dV/dt transitions typical of modern pulse-width-modulation and half bridge rectifier systems?

## II. DEVICE, STRESS PROCEEDURE, DATA

The first experiment stressed optical isolation devices using TDDB with 60 Hz AC sine wave stress. The devices under test are rated for working voltages up to 1140 Vpeak (or 806 Vrms) sine wave, and are routinely tested for PD at 1.5 kVrms 60 Hz AC sine wave. The devices incorporate an 80 μm minimum thickness polyimide film attached to the LED die and to the photodiode die with silicone epoxy.

Sample populations of the optical isolation devices were tested for PD using an HT-9464 PD tester. The PD test results are shown in figure 1, which is a plot of the fraction of units for which PD was observed as a function of the applied 60 Hz AC sine wave voltage. The onset voltage for PD was 2.1 kVrms and the observation of PD increases for higher voltages.

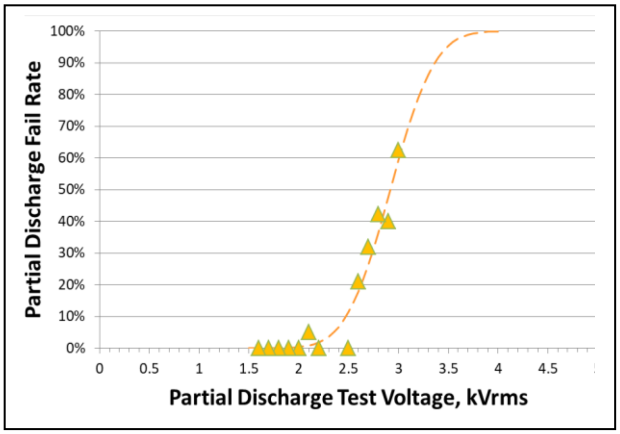

Figure 1. Partial discharge observation rate. Test conditions: Method-B1 per IEC 60747-5 with Vini 1 sec = 7.2 kVrms, Vpd 1 sec varied as the abscissa of this graph with the PD fail criterion > 5 pC.

TDDB was tested at 5 voltages as shown in figure 2, using an AR7715 high voltage 60Hz sine wave tester. The data is consistent with a common TDDB model:

$$\text{Time-to-Fail} = A * \exp(-\gamma * V)$$

where $\gamma$ is the voltage acceleration factor, which is 2.2x10-3 Vrms$^{-1}$ in this fit. Projection of the data shows shorter than expected lifetime at the rated working voltage. Lifetime may improve for stress voltages below the onset of PD. However, TDDB testing is too long to be practical at lower voltages.

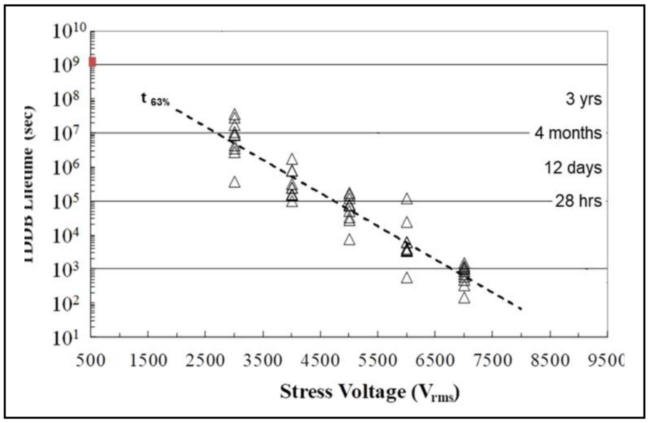

Figure 2. TDDB of optical isolation device. Stress voltage is 60 Hz sine wave continuous waveform. Fail criterion is leakage >100 uA. Lifetimes are shown for 10 units tested at each voltage.

Insulator lifetime due to PD induced wear out has been shown to be inversely proportional to the number of cycles [2]. So, a HV amplifier (Trek 20/20) was used to test TDDB of the same type of optical isolation devices at higher AC sine wave frequencies. Results are shown in figure 3. The measured lifetimes reduce as the inverse of the frequency as expected.

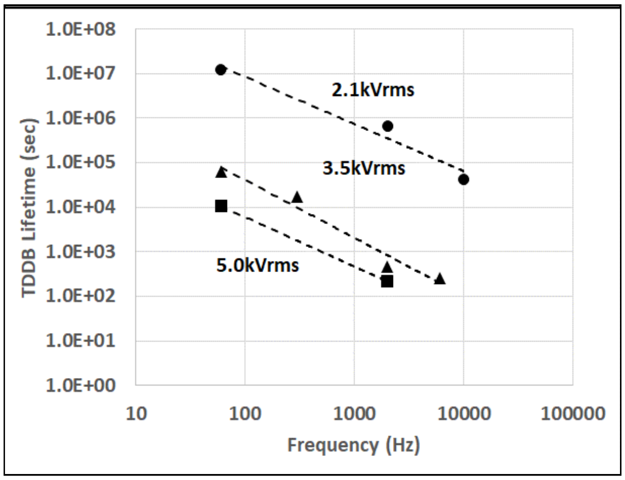

Figure 3. AC sine wave TDDB of an optical isolation device as a function of frequency.

In the second set of experiments, we stressed inductive isolation devices that use ~30 μm polyimide insulation, applied by liquid spin-on coating and subsequent curing which is not prone to voids and the resultant PD. Units were TDDB stressed at higher frequency sine wave or square wave AC voltages. Figure 4 shows TDDB with 300 Hz bipolar square wave where only the rise/fall time was changed. The rise times for square wave conditions are the times from V10% to V90%. Fig. 4 shows that the TDDB lifetimes degrade at shorter rise/fall times (or higher dV/dt) and are nearly linearly proportional to the rise/fall time.

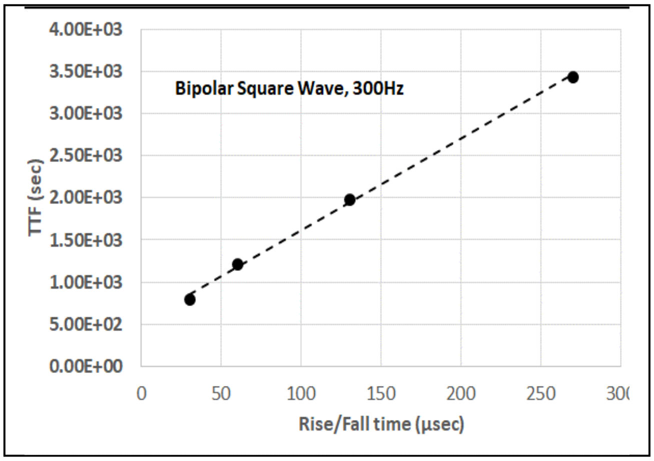

Figure 4. Bipolar square wave AC voltage TDDB for an inductive isolation device using polyimide as a function of rise and fall time at 5 kVpeak.

Lifetimes from sine wave TDDB of the polyimide insulation also degrade at shorter rise/fall times (or higher dV/dt). Sine wave TDDB of different frequencies and stress voltages ranging from 2 kVpeak to 7 kVpeak are shown in figure 5 together with the square wave TDDB data from Fig.4. The lifetimes under sine wave stress match the lifetimes under square wave stress for the same rise and fall times, as shown in figure 5. For this analysis, the rise times for sine wave conditions were calculated as the equivalent rise time of a square wave with the same slope at V=0.

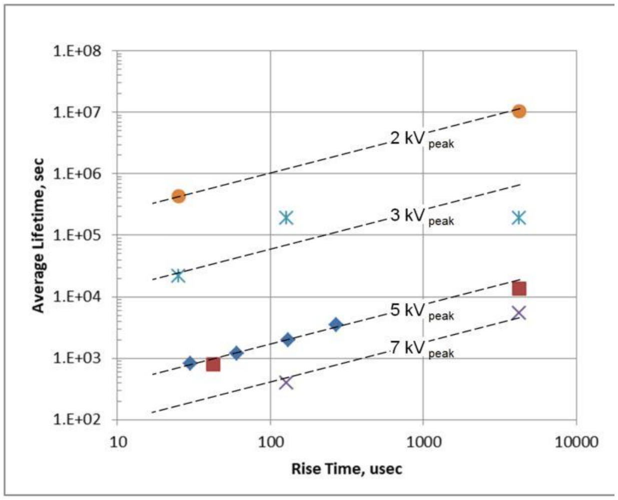

Figure 5. AC voltage TDDB for an inductive isolation device using polyimide as a function of rise and fall time. All data is sine wave, except the blue diamonds which are bipolar square wave 300 Hz as in Fig. 4.

In the third set of experiments, TDDB of polyimide insulators was tested as a function of exposure to $H_2O$ from the ambient. Figure 6 shows Weibull distributions for three sample populations of isolation devices with a 25 μm polyimide insulator. All samples were received with unknown moisture condition. One sample population was tested on units as received. A second population was tested immediately after a 48 hour bake at 150C to reduce moisture in the sample. And a third population was tested after a 48 hour 150C bake followed by 168 hours in a “water box” with 100% humidity air at 25C. TDDB was tested using an AR7715 60Hz sine wave tester at 5kVrms and 25C, with a failure criterion of >100µA. Results show about 2 orders of magnitude degradation in lifetime comparing polyimide isolation devices which are saturated with $H_2O$ compared to devices which have been baked to remove most of the $H_2O$.

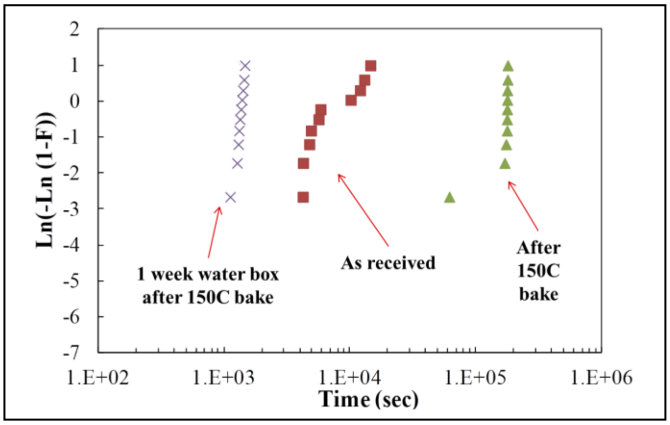

Figure 6. TDDB Weibull distributions for a high voltage isolation device using 25µm polyimide insulator. Sample populations with three different preconditions were tested. TDDB stress is 5kVrms 60Hz continuous sine wave. Test temperature is 25C. Fail criterion is leakage >100µA.

Finally, we also tested a capacitive isolation device which uses $SiO_2$ insulator between the capacitor plates. The $SiO_2$ was applied by Plasma Enhanced Chemical Vapor Deposition (PECVD) and is built up to a total thickness of 10 µm using 3 layers with Chemical Mechanical Polish (CMP) of each layer. No PD was observable on 240 units up to 5 $kV_{rms}$, which is the limit of the test setup. Results for bipolar square wave AC TDDB using a Trek 20/20 HV amplifier are shown in figure 7. Lifetimes exhibit only a weak dependence on frequency.

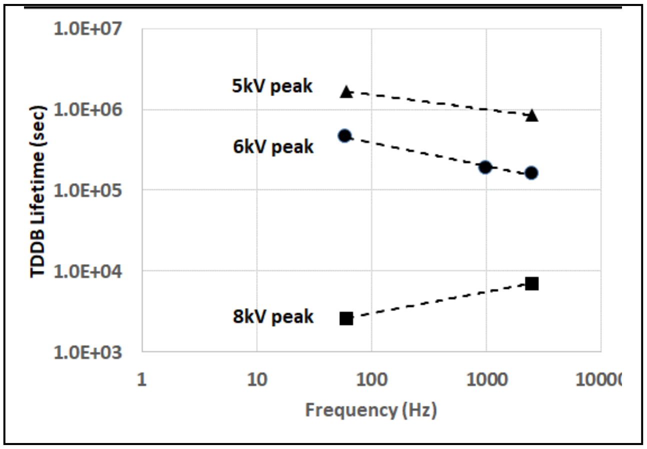

Figure 7. Bipolar square wave AC TDDB for a capacitve isolation device using 10 µm SiO2 dielectric as a function of frequency. Rise time = 30 µsec.

## III. DISCUSSION OF THE ROLE OF PARTIAL DISCHARGE

PD is a localized avalanche (ionization) that occurs in voids in the insulation system, as illustrated in figure 8 [3]. It is caused by a local field enhancement in the void due to the applied electric field as well as to the field from the surface charges that have been left by previous PD activity. The avalanche is first initiated by electrons from field emission or from photo ionization due to cosmic/radioactive radiations. Subsequent avalanche is supported by surface electrons de-trapped by the alternating applied field. During HV AC stress, these electrons bombard the void surface and cause electrical trees that coalesce over time and eventually lead to the breakdown of the insulation material.

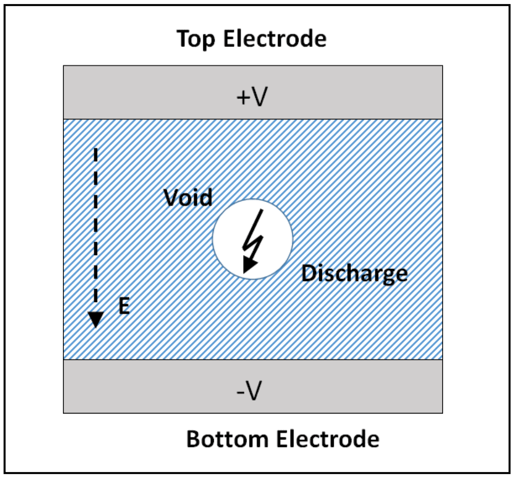

Figure 8. Illustration of partial discharge which can occur in internal voids within an insulator.

The physical failure mechanism of insulator wear out due to partial discharge is indicated in the X-Ray image in figure 9 of a void in a sample which had partial discharge at time-0.

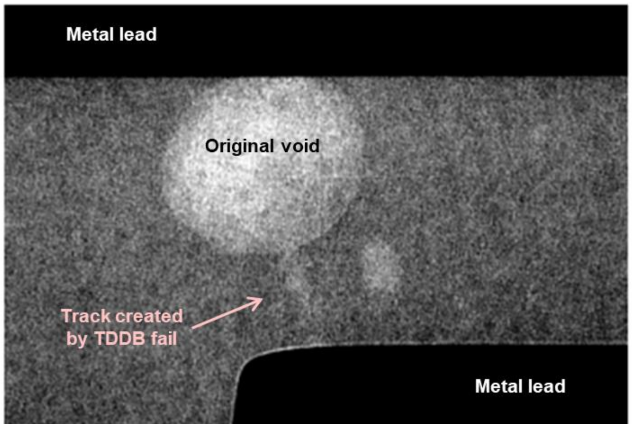

Figure 9. X-Ray image of an internal void which failed during TDDB testing due to partial discharge. Notice the track extending from the void down to metal inside the insulator. This sample was selected for TDDB testing because partial discharge was observed at time-0.

This sample was selected for TDDB testing because partial discharge was observed at time-0. The TDDB failure mechanism can be seen as a track through the insulator created by the repeated erosion of the insulator by each partial discharge event. The track dimension is expected to grow incrementally with each partial discharge event until the track is large enough to reach the electrode and cause the TDDB failure. Therefore the insulator lifetime under PD would be proportional to the inverse of the number of cycles of PD events, and thus inversely proportional to the frequency as shown in figure 3.

The occurrence of PD events is affected by the structure and the process of building the isolation device. For example, internal interfaces within the insulator provide more opportunities for voids to be formed or to remain in the insulator after processing is completed. The onset voltage of PD events depends on the size, shape and orientation of the void relative to the metal electrodes within the insulator. Larger voids or elongated voids which are oriented parallel to the applied electric field will be more prone to create PD events. And the magnitude of the PD event increases with higher dV/dt of the rise and fall times of the applied AC stress [2].

Partial discharge has been recognized as a risk for isolation products. Standards for high voltage isolation products require 100% screening to remove units with observable PD. However, the PD screening technique is limited, because it is tested only at 50 or 60Hz sine wave and because the test time is short, typically only 1 second in length. Also, the voltage amplitude of the PD test is specified by the standards as a multiplication factor of the maximum working voltage for the device. However, a recent paper demonstrated that PD screening may need to use higher voltage amplitude than the standard multiplication factor in order to remove PD induced failures from TDDB for various types of voids that can occur in the insulator [4].

## IV. DISCUSSION OF TDDB OF POLYIMIDE

Many authors have reported effects of $H_2O$ absorption on the physical and electrical properties of polyimide. The quantity of $H_2O$ absorbed can be observed by weight gain measurements on the order of a fraction of a percent weight gain for polyimide films exposed to moist air environments [5]. Larger space charge formation is observed in polyimide under parallel plate bias as a function of elongated exposure to water, and the authors explain this result as due to easier charge transfer from the electrode into the sample due to a lower potential barrier after water absorption [6]. Lower potential barrier may explain the degraded TDDB lifetimes observed after $H_2O$ absorption into the polyimide insulator.

The strong effects of moisture on polyimide TDDB lead to a complex understanding. Activation energy of TDDB is challenging to assess since the samples dry out at higher temperature. The observed dependence on rise and fall times during square wave TDDB may be a function of $H_2O$ absorption into the polyimide insulator.

Space charge accumulation has an important role in dielectric breakdown of polyimide films [7]. The effect of space charge is to reduce the breakdown voltage for waveforms with higher dV/dt switching.

## V. CONCLUSIONS

Accelerated TDDB is difficult for isolation devices that exhibit partial discharge during TDDB testing. Lifetime projections from higher voltages at which PD occurs to lower voltages that are below the onset of PD may be inaccurate. Accelerated TDDB of isolation devices that have partial discharge during TDDB depends strongly on frequency. Lifetimes are proportional to the inverse of the frequency. This can be understood because there is about one partial discharge event for each transition to high voltage. Per Wang, et al [2], lifetimes due to PD fail mode are reduced for square wave voltage stresses as the rise/fall time reduces.

TDDB of polyimide insulators is strongly dependent on the rise and fall times of the applied stress waveform as well as the moisture content of the samples. Lifetimes drop by more than an order of magnitude as rise/fall times are reduced from 4000 to 30 microseconds or as sine wave frequency increases from 60 to 2000 Hz. And lifetimes are two orders of magnitude lower after samples are exposed to moisture compared to samples that are baked dry. Space charge accumulation in polyimide films is a major failure mechanism [6,7] which can explain the strong lifetime degradation of polyimide with high moisture absorption and with high dV/dt switching conditions.

The relative insensitivity of $SiO_2$ insulator TDDB to frequency suggests a significantly different wear out mechanism than for polyimide. Space charge accumulation is not a significant mechanism in $SiO_2$ insulator dielectric breakdown. And the $SiO_2$ isolation devices tested do not exhibit partial discharge, because these $SiO_2$ insulators were created using multiple layers of PECVD thin film deposition with CMP polishing between layers which effectively eliminate voids in the dielectric.

This report shows the need for further TDDB characterization to better understand these important effects. Lifetime at high frequency and high dV/dt rise/fall times are important for pulse width modulated motor drives and half bridge power converters, especially in modern systems using SiC and GaN high voltage power devices.

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