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High-Voltage Atmospheric Breakdown Across Intervening Rutile Dielectrics

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Abstract

This report documents work conducted in FY13 on electrical discharge experiments performed to develop predictive computational models of the fundamental processes of surface breakdown in the vicinity of high-permittivity material interfaces. Further, experiments were conducted to determine if free carrier electrons could be excited into the conduction band thus lowering the effective breakdown voltage when UV photons (4.66 eV) from a high energy pulsed laser were incident on the rutile sample. This report documents the numerical approach, the experimental setup, and summarizes the data and simulations. Lastly, it describes the path forward and challenges that must be overcome in order to improve future experiments for characterizing the breakdown behavior for rutile.

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CONTENTS

Contents

Acknowledgments.....	4
Contents	5
Figures.....	5
Nomenclature.....	6
1. Introduction.....	7
2. Numerical Approach	7
3. Experimental Setup	8
3.1 High-Voltage Test Setup.....	8
3.2 Rutile Samples	9
3.3 Imaging Diagnostics	9
3.4 UV Laser Interface.....	9
4. Results	10
4.1 Rutile Cylinder Translation.....	10
4.2 UV Irradiation of Rutile with Applied Voltage	15
4.3 Experiments with Delrin and Nylon	16
5. Summary and Conclusions	18
References.....	19
Distribution	20

FIGURES

Figure 1: Experimental setup for generating and imaging electrical discharge.....	8
Figure 2: Schematic of the UV laser interface optics. A 266 nm (4.66 eV) was expanded using a 4x beam expander and focused onto a sample within the high-voltage electrode gap. Spot size was controlled by translating the focusing lens. Beam energy was set at the laser controller	10
Figure 3: Results from rutile sample displaced 0mm and experimental time taken from the start of current: a) Voltage and current measurements with ICCD synchronization; b) ICCD image with labeled features. T is timing relative to current start, tf is frame time. The electrode is 0.5mm above the rutile sample. Breakdown voltage was 13.5 kV.....	11
Figure 4: EIGER electric field simulation of the experimental geometry shown in Figure 2. Higher field strengths are indicated in air by lighter shading.	12
Figure 5: ICCD of discharge path rutile sample displaced 6mm from axis. The lower part of the image is the edge of the cathode. Breakdown voltage was 12.5kV.....	13

Figure 6: Electric field simulation of the experimental geometry shown in Figure 5. Higher field strengths are indicated in air by lighter shading.	13
Figure 7: ICCD of discharge path rutile sample displaced 14mm from axis. The lower part of the image is the edge of the cathode. Breakdown voltage was 19kV.....	14
Figure 8: Electric field simulation of the experimental geometry shown in Figure 7. Higher field strengths are indicated in air by lighter shading.	14
Figure 9: Graph showing the change in breakdown voltage as sample displacement increases. Experimentally measured breakdown threshold of empty 10.5mm gap is indicated.	15
Figure 10: a) Composite image of UV laser on the rutile sample inducing plasma at the surface indicated by the yellow circle. The plasma emission is very low compared to the reference image: b) image of the plasma emission alone. Peak voltage at the sample was 12 kV.	16
Figure 11: Second configuration for testing the effects of UV radiation on the rutile sample.....	16
Figure 12: Machined samples compared to rutile samples. From left to right: Delrin, Nylon, new rutile, used rutile.	17
Figure 13: Composite image from the ICCD showing reduced breakdown voltage in the presence of: a) a Delrin sample at $d = 13.75\text{mm}$ and 19kV peak voltage and b) a nylon sample at $d = 12.75\text{mm}$ and 19kV peak voltage.	17

NOMENCLATURE

CVT	Current Viewing Transformer
DDG	Digital Delay Generator
DOE	Department of Energy
EIGER	Electromagnetic Interactions GenERalized
ϵ_r	Relative permittivity
ICCD	Intensified Charge-Coupled Device
LAC	Lightning Arrestor Connector
SNL	Sandia National Laboratories
UV	Ultraviolet Light

1. INTRODUCTION

Sensitive electrical systems may be subject to strong transient currents from lightning strikes, switching feedback, or shorting due to component failure. Surge arresters of many forms rely on dielectric surface flashover to safely redirect these electrical spikes to ground. It was observed that the presence of a high-permittivity material between two electrodes significantly reduces the breakdown threshold of the gap and the standard deviation of breakdown levels [1]. However, the physical mechanisms involved with this process are not well characterized. Recent work has quantified the effects of certain gas compositions, electrode geometries, and humidity on the surface flashover phenomenon of low-permittivity materials [2][3].

This report presents experimental and modeling results of electrical breakdown in the presence of intervening dielectrics. The materials considered were a sintered TiO_2 material known as rutile, Delrin, and nylon. Rutile is a unique semi-conducting material with strong bandgap absorption in the ultraviolet and relative permittivity ϵ_r near 100 depending on the manufacturing process. The majority of the experiments presented here utilize the highly non-uniform electric field produced by a cone-to-plane electrode geometry with a rutile cylinder resting on the planar electrode. Additionally, experiments were conducted using a high energy pulsed UV (4.66 eV) laser incident on one side of the rutile samples to determine if electrons pumped into the conduction band would facilitate arc formation. And lastly, Rutile ($\epsilon_r \sim 100$), Delrin ($\epsilon_r = 3.7$), and nylon ($\epsilon_r = 2.5$) samples were compared in an off-center geometry. Significant reductions of breakdown threshold were measured for each material in comparable configurations.

2. NUMERICAL APPROACH

The simulations described here used the EIGER code [4], which solves for electromagnetic or electrostatic fields using boundary element methods. In this case EIGER solves for the electrostatic field for a particular configuration of electrodes at different potentials. The electric field solution is calculated for a voltage difference of 1 volt between the electrodes. The electric field is linear in the voltage differences and can be evaluated for other voltage differences through simple scaling. To find the breakdown threshold, we vary the electrode voltage through scaling and integrate the primary ionization coefficient (α) along a field line until the Townsend breakdown threshold [5] is exceeded just as the integration path touches the anode. This threshold is dependent on the secondary electron emission coefficient (γ). For the model used here, α depends on the magnitude of the electric field, the type of gas through which the breakdown occurs, and the gas pressure. Values for parameters appearing in the functions for α and γ are derived from fits to experimental data for different gases [6]. This approach has been applied to a number of test cases (including the pin and ground plane electrode configuration) and compared to both analytical results and experimental data with good agreement [6].

3. EXPERIMENTAL SETUP

3.1 High-Voltage Test Setup

The experimental setup used for this work is shown schematically in Figure 1. The pulsed electrical driver of this system was a positive polarity surge test generator (HiLo PG 24-2500) with a surge current rise/fall time of 8/20 μ s and +25kV peak surge voltage. The voltage pulses were transmitted through a high-voltage coaxial transmission cable to the test fixture (not shown). The test fixture was designed to support the current and voltage probes while allowing fine x-y-z translation of the electrodes. The ground of the transmission cable was separated and connected to six return-current cables arranged coaxially and attached to the cathode of the system.

The center conductor of the transmission cable passed through a calibrated Pearson current loop (CVT) to measure current delivered to the electrode gap. A Tektronix high-voltage probe was also fielded between the conductors of the transmission cable at the test fixture.

The Al anode used was conical with 82° full angle and a 0.5mm radius tip. The Al ground plane, upon which the rutile samples rested during experiments, was 50mm in diameter. The voltage delivered to the test stand was gradually increased over several attempts to ensure breakdown occurred near the peak of voltage pulse. This minimized the effect of the time rate of voltage increase in order to better compare with the EIGER electrostatic simulations.

Figure 1: Experimental setup for generating and imaging electrical discharge.

3.2 Rutile Samples

The rutile samples were prepared by spray coating a TiO_2 powder with a solution of polyvinyl alcohol (binder), polyethylene glycol (plasticizer), and oleic acid (lubricant). The powder mixture was then air dried, deagglomerated using a mortar and pestle and then passed through a sieve. This powder was uniaxially dry pressed at 3000psi into 5cm diameter x 2 cm thick discs and then cold isostatically pressed at 30000psi. The discs were then oven dried at 270C and slow sintered for two hours at 1350C (static air and ambient pressure). The sintered discs were then machined into 1cm diameter 1cm long cylinders. The samples were then thermally annealed in flowing air at 1000C for 6 hours.

Thermally annealing these samples allows oxygen molecules to fill vacancies within the TiO_2 crystalline structure that would otherwise act as electron traps [7]. This process also acts to heal subsurface damage caused during the sample machining and ensures optimal surface uniformity. Rutile produced using this procedure has a relative permittivity of approximately 100. A new sample was used for each experiment and the electrode was positioned over the midpoint of the cylinder axis.

3.3 Imaging Diagnostics

Imaging dielectric surface breakdown requires nanosecond gating and high signal gain to capture transient behavior. A fast-gated intensified charged coupled device (ICCD) with cathode sensitivity above 10% between 300nm and 750nm and an image size of 25mm x 25mm (1024x1024 pixels) was used for these experiments (Andor iStar 334T). All images shown were produced by combining a reference image (50ms exposure, external lighting) with an experimental image (10ns exposure, self-illuminated).

Image formation was achieved using an f/2.8-4 macro zoom lens (Nikon AF Zoom-Nikkor 24-85mm) at close range or an f/5-6.3 ultra-telephoto lens (Tamron SP AF200-500mm A08) fielded farther from the discharge. Spatial image resolution was 50-100 μm . The high-voltage system and the imaging system were triggered externally from a digital delay generator (DDG).

3.4 UV Laser Interface

The laser used was an Nd:YAG operating in the fourth harmonic to produce 266nm radiation (New Wave Research - Tempest). The energy measured after the steering optics was 45mJ with 5ns pulse width. Experiments utilizing the UV laser were configured with a 10.5mm electrode gap with the rutile sample placed either with the cylinder axis centered below the upper

electrode, as shown in Figure 2, or with the flat end surface centered below the upper electrode. The voltage delivered to the test stand was set to 12 kV, corresponding to a value just below the self-break threshold of this configuration $13.5 \pm 1.5\text{kV}$. The system was synchronized such that the UV pulse would arrive at the rutile sample at the peak of the voltage pulse. Also, the final focusing lens could be translated axially in order to vary the spot size at the rutile sample.

Figure 2: Schematic of the UV laser interface optics. A 266 nm (4.66 eV) was expanded using a 4x beam expander and focused onto a sample within the high-voltage electrode gap. Spot size was controlled by translating the focusing lens. Beam energy was set at the laser controller.

4. RESULTS

4.1 Rutile Cylinder Translation

This series of experiments explores the effect of a 1cm diameter, 1cm long rutile cylinder on the breakdown voltage of a 10.5mm electrode gap at various positions. The electrodes remained in a fixed coaxial position while the sample was translated between $d = 0\text{mm}$ (directly below the electrode) and $d = 14\text{mm}$.

The results taken during a discharge where the sample was directly below the anode at $d = 0\text{mm}$ are shown in Figure 3 Frame a). The voltage delivered by the pulse generator rose to 13.5kV prior to breakdown (solid line). As the voltage dropped, the current increased (dashed line). This time is taken as the experimental $t = 0\text{s}$. The black square indicates the timing of the ICCD image 3.5 μs after current start.

The ICCD image, shown in Figure 3 Frame b), shows the discharge path across the right side of the cylinder. The plasma channel carried 6kA at the time of this image and appears as a 4mm wide emission zone that terminates to ground through an air path, leaving the lower surface of the sample undamaged.

Figure 3: Results from rutile sample displaced 0mm and experimental time taken from the start of current: a) Voltage and current measurements with ICCD synchronization; b) ICCD image with labeled features: 't' is timing relative to current start, t_f is frame time. The electrode is 0.5mm above the 10mm rutile sample. Breakdown voltage was 13.5 kV.

The electrostatic simulation of the experimental geometry, shown in Figure 4, shows the effect of the rutile sample on the electric field structure. The arrows indicate the direction of the field lines, while the shading indicates field strength. The field structure is highly nonuniform with strong field enhancement near the anode indicated by the lighter shading (all simulations use the same scale). The field lines enter the sample at a near orthogonal angle due to the high relative permittivity of rutile.

Figure 4: EIGER electric field simulation of the experimental geometry shown in Figure 2. Higher field strengths are indicated in air by lighter shading.

Comparing the experimentally observed discharge path with the simulated electric field produced, it is clear that the discharge path does not correlate with the electric field lines, but instead traverses the field lines as the arc tracks the surface of the sample. EIGER computed an unrealistic calculated voltage breakdown (65kV) due to the extremely low tangential component of the electric field at the sample surface and the high concentration of field between the cone tip and the rutile cylinder surface.

The image from a $d = 6\text{mm}$ experiment is shown in Figure 5 with the complementary simulation shown in Figure 6. Three distinct breakdown regions became clear as the sample was displaced farther from axis: air breakdown from the sample to the anode, surface breakdown along the rutile sample, and air breakdown from the ground plane to the sample. The discharge threshold of this configuration was 12.5kV.

Comparing the experimentally observed discharge path to the simulated electric field shows that the air breakdown occurred along field lines and there was reduced field enhancement near the anode due to the increased distance to the sample. The near-normal field lines at the surface again produced an unrealistic breakdown prediction of 86kV.

Figure 5: ICCD of discharge path rutilite sample displaced 6mm from axis. The lower part of the image is the edge of the cathode. Breakdown voltage was 12.5kV.

Figure 6: Electric field simulation of the experimental geometry shown in Figure 5. Higher field strengths are indicated in air by lighter shading.

The arc formation attached to the rutile sample for all positions until displacement was increased to 14mm. The experimental image is shown in Figure 7 with complementary simulation in Figure 8. The plasma channel formed along the electric field line directly between the ground plane and the anode. The breakdown voltage for this shot was not recorded due to a technical failure. However, the maximum voltage delivered was 19kV. The EIGER simulated breakdown of this configuration was 14kV.

Figure 7: ICCD image of discharge path near rutile sample displaced 14mm from axis. The lower part of the image is the edge of the cathode. Breakdown voltage was 19kV.

Figure 8: Electric field simulation of the experimental geometry shown in Figure 7. Higher field strengths are indicated in air by lighter shading.

The voltage breakdown values of all displacements tested are shown in Figure 9. The error bar estimate of $\pm 1.5 \text{ kV}$ was established through a five-shot series at $d = 0 \text{ mm}$. The range of measured breakdown voltages was 11kV to 19kV between $d = 0 \text{ mm}$ and $d = 14 \text{ mm}$. In comparison, the empty gap breakdown for this geometry was experimentally determined to be 34kV (17kV for 5.25mm gap due to maximum voltage limitations). Therefore, the presence of the intervening rutile dielectric reduced the breakdown threshold of this electrode configuration by 67% to 44%. Remarkably, this breakdown reduction persisted as the sample was displaced 14mm from axis and the discharge formed directly between the electrodes. The physical

mechanism for this observation is not understood, but it is hypothesized that the rutile sample acts as an electron source due absorption of UV radiation from coronal plasma formation near the conical electrode. This secondary electron emission could aid in the formation of an electron avalanche without necessarily interacting directly with the arc itself.

Figure 9: Graph showing the change in breakdown voltage as sample displacement increases. Experimentally measured breakdown threshold of empty 10.5mm gap is indicated.

4.2 UV Irradiation of Rutile with Applied Voltage

The series of experiments using the laser-rutile configuration, shown in Figure 2 and described in Section 3.4, were conducted with 45mJ of energy and spot sizes varying from ~1 cm to a spot size approaching the diffraction limit of ~6 μm . This yields an energy density ranging from 0.053J/cm² to 1485J/cm² and a peak flux density range of 0.01 GW/cm² to 300 GW/cm².

Figure 10 depicts the results of focusing the maximum flux density, 300GW/cm², onto the rutile sample at the peak of a 12kV test: dim surface plasma was generated on the sample, but no arc channel was formed. The result was the same for the minimum flux density. The synchronization for this test was verified by triggering an empty gap at higher voltages.

The sample was repositioned so that a flat face of the rutile cylinder was located directly beneath the anode and the laser was aligned to illuminate the center of the face as depicted in Figure 11. This configuration minimizes the direct discharge path length along the face of the rutile cylinder. A breakdown could not be induced for both the highest and lowest flux densities tested.

Figure 10: a) Composite image of UV laser on the rutilite sample inducing plasma at the surface indicated by the yellow circle. The plasma emission is very low compared to the reference image: b) image of the plasma emission alone. Peak voltage at the sample was 12 kV.

Figure 11: Second configuration for testing the effects of UV radiation on the rutilite sample.

4.3 Experiments with Delrin and Nylon

The last set of experiments was designed to further investigate the effect of relative permittivity ϵ_r on the voltage hold off of the electrode gap. Identical 1cm long, 1cm diameter samples of Delrin ($\epsilon_r = 3.7$) and nylon ($\epsilon_r = 3.5$) were produced to compare with rutilite ($\epsilon_r \sim 100$) and are shown in Figure 12. Each sample was oriented 14mm off-axis to match the configuration shown in Figure 7 and Figure 8. The surge voltage was set to 19kV and the sample was moved 0.25mm per attempt until breakdown was induced.

Breakdown occurred for the Delrin sample at $d = 13.75\text{mm}$ and for the nylon sample at 12.75mm. In both cases, the arc channel formed directly between the electrodes as shown in Figure 13.

Figure 12: Machined samples compared to rutile samples. From left to right: Delrin, Nylon, new rutile, used rutile.

Figure 13: Composite image from the ICCD showing reduced breakdown voltage in the presence of: a) a Delrin sample at $d = 13.75\text{mm}$ and 19kV peak voltage and b) a nylon sample at $d = 12.75\text{mm}$ and 19kV peak voltage.

5. SUMMARY AND CONCLUSIONS

A gated imaging system, UV laser, and electrical diagnostics were utilized during a series of electrical discharge experiments to gain insight into gap breakdown in the presence of a high-permittivity rutile cylinder with a 10mm diameter. The breakdown plasma channel attached to the sample where the cylinder axis was within 14mm of the electrical axis. At the final sample displacement of 14mm, the discharge formed directly between electrodes. Remarkably, the breakdown range for these shots only varied from 11kV to 19kV, whereas the breakdown threshold of the empty electrodes was found to be 34kV. These results indicate that the rutile sample reduced the hold off voltage of the electrodes by 44% - 67% without altering the discharge path or directly interacting with the arc.

EIGER was used to perform numerical simulations of the experimental geometry considering the dielectric properties of the rutile sample and the gas composition of the air. Poor agreement between simulations and experimental results indicate that breakdown in the presence of a rutile surface involve more than the effects of the high permittivity on the electrostatic field. UV radiation produced by coronal plasma at the anode surface was identified as a potential factor contributing to the reduced breakdown threshold of the off-axis rutile experiments. To test this hypothesis, another set of experiments were performed with an additional flux of UV radiation incident on the sample during peak voltage (variable up to $300\text{GW}/\text{cm}^2$). The pulse voltage was set at the maximum value as to not exceed the self-break threshold. However, experiments with this additional UV radiation did not induce arc channel formation at any flux density up to $300\text{GW}/\text{cm}^2$.

The last set of experiments was designed to further investigate the effect of relative permittivity ϵ_r on the voltage hold off of the electrode gap. Identical 10mm long, 10mm diameter samples of Delrin ($\epsilon_r = 3.7$) and nylon ($\epsilon_r = 3.5$) were produced to compare with rutile ($\epsilon_r \sim 100$). Each sample was oriented 14mm off-axis to match the configuration of the final rutile experiment. The surge voltage was set to 19kV and the sample was moved 0.25mm per attempt until breakdown was induced. However, the breakdown threshold of these two low-permittivity materials was reduced similarly to the rutile experiments. The role of high-permittivity materials in surge arrestors and the role of UV flux on surface breakdown should be investigated further.

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