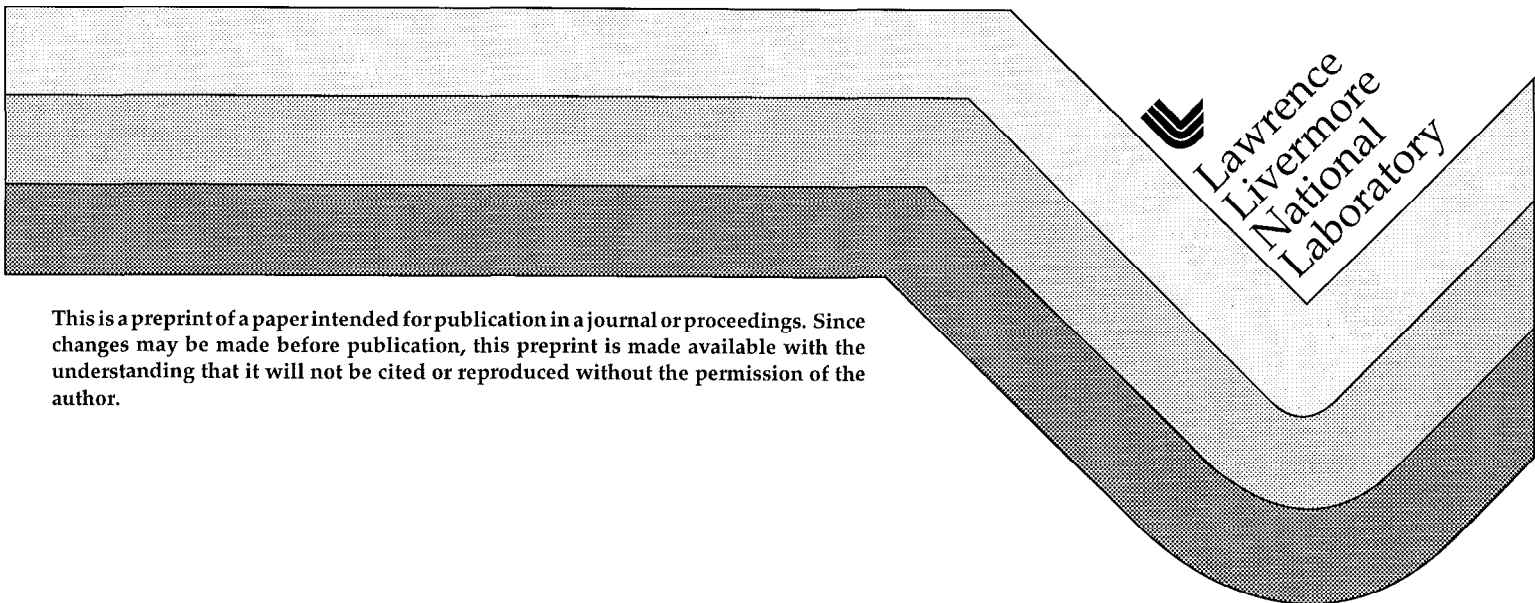# Multilayer Ultra High Gradient Insulator Technology

S. E. Sampayan
P. A. Vitello
M. L. Krogh
J. M. Elizondo

Lawrence Livermore National Laboratory

MULTILAYER ULTRA-HIGH GRADIENT INSULATOR TECHNOLOGY

S. E. Sampayan, P. A Vitello, Lawrence Livermore National Laboratory, P.O Box 808,
Livermore, CA 94551, USA, M. L. Krogh and J. M. Elizondo,
AlliedSignal, FM&T, P. O. Box 419159, Kansas City, MO 64141, USA

Abstract - We are investigating a novel insulator concept which involves the use of alternating layers of conductors and insulators with periods less than 1 mm. These structures perform many times better (about 1.5 to 4 times higher breakdown electric field) than conventional insulators in long pulse, short pulse, and alternating polarity applications. We present our ongoing studies investigating the degradation of the breakdown electric field resulting from surface roughness, the effect of gas pressure, and the performance of the insulator structure under bi-polar stress. Further, we present our initial modeling studies.

1. INTRODUCTION

A high gradient insulator consists of a series of very thin (<1 mm) stacked laminations interleaved with conductive planes. This insulator technology was originally conceived and disclosed by Eoin Gray in the early 1980's [1] and follows from experimental observations that the threshold electric field for surface flashover increases with deceased insulator length [2, 3]. The concept laid dormant until the mid-to-late 1980's, when this technology was pursued and successfully showed substantial increases in the breakdown threshold over conventional, single substrate insulators [4]. In more recent work, we pursued verification of the technology and showed an increase of 1.5 to 4.0 times that over conventional insulator technology [5] In later studies, we explored the properties of these structures in the context of switching applications, investigating their behavior under high fluence photon bombardment [6].

2. EXPERIMENTS

Small sample testing (approximately 2.5 cm diameter by 0.5 cm thick) was performed in a turbo-molecular pumped, stainless-steel chamber at approximately 10^{-6} T. High voltage was developed with a 10 J "mini-Marx". The Marx developed a pulsed voltage of approximately 1 to 10 μs (base-to-base) and up to 250 kV amplitude across the sample. Diagnostics consisted of an electric field sensor and a current viewing resistor. Failure of the insulator was determined by a prompt increase in Marx current and a prompt collapse in the voltage across the sample.

Samples were fabricated by interleaving layers of 0.25 mm fused silica. The interleaved metallic layers were formed by depositing gold on each planar insulator surface by a sputtering technique and then bonding the stacked layers by heating while applying pressure. Bond strength between the gold layer and substrate using this technique was measured to exceed 10 kpsi. To perform the breakdown experiments, the structure was slightly compressed between highly polished bare aluminum electrodes which establish the electric field for the tests.

To obtain a particular data set, the insulators were subjected to several low voltage conditioning pulses. The voltage was then increased a small amount incrementally until breakdown occurred. Voltage was then reduced for several shots and then incrementally increased again until a constant value was achieved. In these experiments, however, we generally observed that these insulators did not condition. Once a breakdown occurred at a particular field, reducing the voltage slightly and increasing it again did not cause an increase in breakdown field To produce a given data set we would apply up to 150-200 shots to a given structure and would attempt to determine if any damage to the structure occurred which significantly altered the breakdown characteristics At these applied energies, we generally did not observe any degradation. These data were then reduced to reliability plots by determining the total number of successful shots over the total number of applied shots. In these data we define the electric field as the applied voltage divided by the total insulator length. We define reliability at a given electric field as the total number of successful shots over the total number of shots.

Using this method, we observed flashover of the small samples at approximately 175 kV/cm for these fused silica substrates (Fig. 1). The effect of pulse width from 1-10 μs on this breakdown threshold was well within the statistical nature of our data. The trend in conventional insulator technology (Fig 2) for 0° insulators indicates a breakdown threshold of approximately 50 kV/cm. Thus, there was a net increase in the performance with these insulators over conventional technology of approximately 3.5.

We are also studying various effects which can adversely affect these new structures. For instance, to ensure concentricity, a finish grinding operation was performed on the outside diameter. This process is a time consuming second operation and an alternate

on the multilayer high gradient structures. Similar results are obtained for bi-polar pulses (Figure 6). This result leads us to conclude that this lamination technique scales the performance of thin insulators to the entire structure with each layer acting independently.
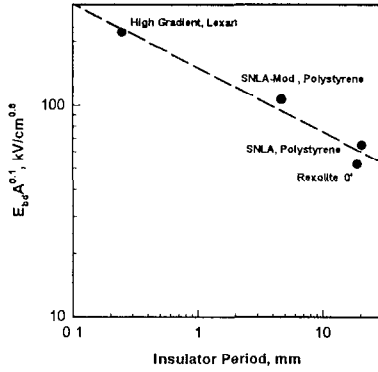

Fig. 6   The effect of period length scaling under bipolar stress [8]

3. MODELING

Voltage breakdown for insulators surrounded by vacuum is believed to take place along the insulator surface and not within the insulator or exterior to the insulator in the vacuum. Breakdown occurs on the time scale of nanoseconds, making this a difficult process to study experimentally. The basic physical processes involved are poorly understood Present theories of surface breakdown are mainly descriptive, and are not suited for the purpose of designing insulators. Due to the computationally intensive nature of a self-consistently model of surface breakdown, few attempts have been made to model the complete process.

The two most widely accepted published models for surface breakdown focus on the initial process occurring either just below or just above the insulator surface [9, 10] These models focus respectively on solid state physics phenomena, and the propagation and emission of electrons through the vacuum just exterior to the insulator surface. Both models lead to surface heating, and evaporation of gas from the insulator. This evaporated gas is the medium where ultimately the voltage breakdown occurs along very localized "streamer" channels. Pressures in the evaporated gas close to the insulator surface where the discharges form can reach a significant fraction of atmospheric pressure. The surface breakdown is likely to be closely related to high pressure voltage breakdown processes [11].

We have compared processes involved in surface voltage breakdown with other well understood voltage breakdown phenomena at high pressure. Our conclu-

sion is that an accurate theoretical model of surface breakdown must also include the long time scale evolution of the streamer discharge though the evaporated gas. Further, the tip of a propagating streamer is known to produce intense high energy radiation emission which we believe can lead to photo-conduction in the insulator. As conduction in the insulator will strongly modify the voltage which drives the streamer discharge, accurate coupling of the streamer to the insulator must also be included. Thus, our modeling approach is that the surface breakdown couples competing processes inside and external to the dielectric surface, and that a detailed, self-consistent model must be built to accurately study this process

Our baseline code is INDUCT95 [12] This code is a plasma discharge code that has been applied to plasma reactors, flat panel plasma display discharges, streamer discharges and other problems involving complex systems. It solves the standard time dependent fluid equations of the form

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot n_i \mathbf{v}_i + \sum_{j=1}^{N_c} R_{ij} \qquad (1)$$

and:

$$\frac{\partial n_i \mathbf{v}_i}{\partial t} = -\nabla \left(n_i \mathbf{v}_i \mathbf{v}_i \right) + \frac{q_i n_i \mathbf{E}}{m_i} - \frac{1}{m_i} \nabla n_i k T_i - \sum_{j=1}^{N_N} n_i \mathbf{v}_i v_{ij} \quad (2)$$

for the ions, where R_i is the source term for the changes in the ion densities. And for the electrons

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot \Gamma_e + \sum_{j=1}^{N_c} R_{ej} \qquad (3)$$

with the energy balance equation.

$$\frac{\partial W_e}{\partial t} = -\nabla \cdot \mathbf{Q} - e \Gamma_e \cdot \mathbf{E} - P_{inelastic} \qquad (4)$$

where Γ_e is the electron flux and $P_{inelastic}$ is the energy loss rate due to inelastic collisions

Preliminary examples of results are shown in Figures 7 and 8 This simulation was performed with the updated version of INDUCT95/HYBRID and uses a Monte-Carlo treatment of electrons and a fluid treatment of ions to follow the discharge development. Several geometry configurations and surface materials were investigated. The standard configuration studied had an electrode separation of 1 mm with an applied voltage of 50 kV/cm An insulator with a dielectric constant, ε_r=15 was placed between the electrodes The dielectric was considered to either have a flat surface (Figure 7) or a step discontinuity (Figure 8) halfway between the electrodes. Electrons were launched with random initial direction from the cathode triple point until they either struck the insulator or the anode. Upon striking the insulator, electrons generated secondary electrons.

The secondary emission yield is a strong function of incident electron energy Secondary yield profiles were

fabrication means was pursued To simplify fabrication, we attempted an ultrasonic machining process. Although it was possible to fabricate the part in a single operation, the surface was left slightly rougher. Comparison of the breakdown characteristics of these samples showed significantly more scatter and on average a slightly decreased breakdown threshold of approximately 25% (Fig 3)
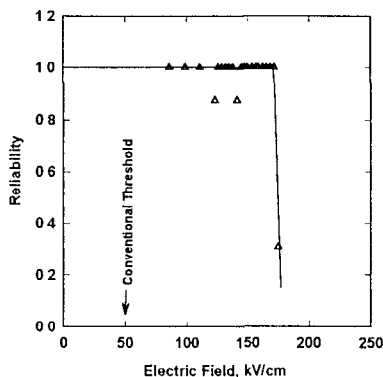

Fig 1   Pulsed surface breakdown reliability ground fused silica high gradient insulator
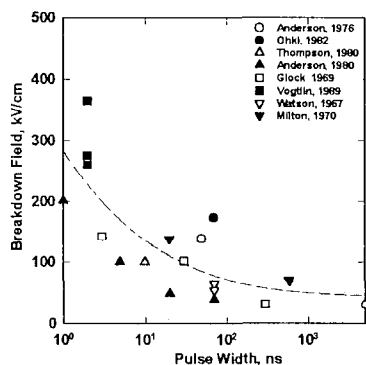

Fig 2.   Pulsed surface breakdown electric field as a function of pulse width for single substrate, straight wall insulators

The structures were also subjected to increased pressures to determine susceptibility to breakdown (Fig. 4). In these data, using the previously described procedure, a fixed reliability was established at the various pressures All data was then normalized to a mean breakdown electric field. Susceptibility to breakdown stays relatively constant up until about the 10^{-3} T range, at which point, the field at which breakdown occurs decreases rapidly. Also shown are data from previous work by Smith [7]. From this comparison, it appears that these new structures show a lower breakdown electric field threshold than these previous data.
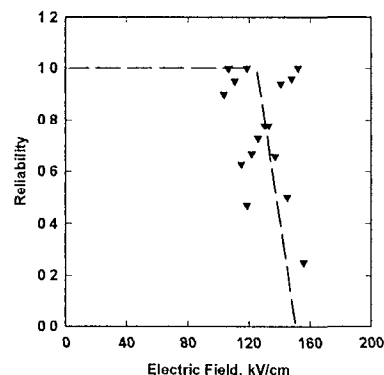

Fig 3   Pulsed surface breakdown reliability roughened fused silica high gradient insulator
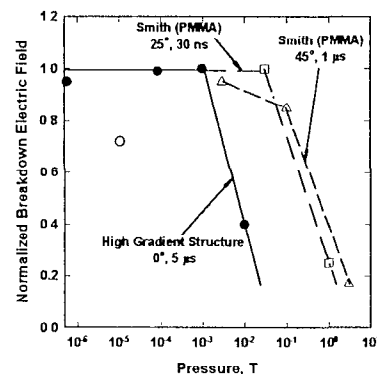

Fig. 4   Effect of gas pressure on the performance of high gradient insulators
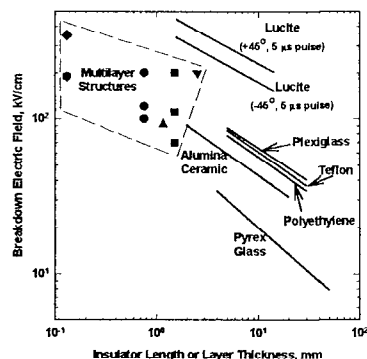

Fig. 5   The effect of insulator length scaling (conventional insulators, [3]) compared to individual layer thickness (multilayer insulators) on the surface breakdown electric field.

Our data for varied layer thickness and materials were compared to classical insulator length scaling (Figure 5). The trend is generally equivalent when the scale length is defined as the individual lamination thickness

modeled for Al_2O_3 and Cr_2O_3 The secondary yield for Al_2O_3 has a maximum of 2 42 while the Cr_2O_3 peaked at 0.98. A yield greater than unity implies that the electron impact can lead to a positive surface charge on the insulator as more than one electron will be emitted. Simulation results showed strong positive surface charging for Al_2O_3 and weak negative surface charging for Cr_2O_3 for the flat dielectric case (Figure 7). Regions of positive surface charge on the insulator attract electrons emitted from the triple point and electrons emitted by secondary emission. This attraction leads to enhanced scattering onto the insulator surface which results in avalanche. For Cr_2O_3, the negative surface charge repelled electrons from the triple point, reducing scattering and no avalanche was obtained. As would be expected, the insulator geometry was found to strongly influence surface charging A step dielectric geometry was also modeled for Al_2O_3. Strong negative surface charging developed along the step due to high energy electron impact (the secondary emission yield drops below unity at high energy). This negative charge repelled electrons upwards away from the insulator surface, inhibiting the avalanche growth for this geometry.
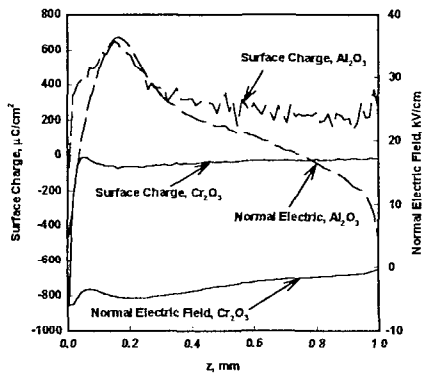

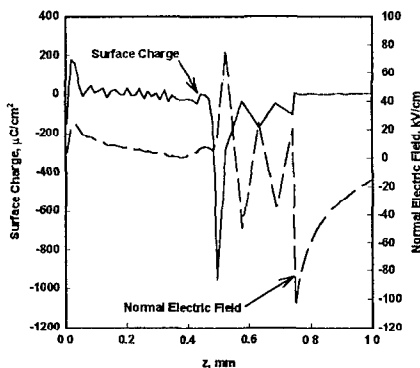Fig. 7. INDUCT result for two secondary emission coefficients, straight insulator.

Fig. 8 INDUCT result for a straight insulator with an outward step discontinuity at z=0.5 mm.

4. SUMMARY

We are continuing development of a new high gradient insulator technology. The insulator consists of finely spaced metal electrodes interleaved with the insulator substrate. We observe up to a factor of 4 improvement over conventional straight wall (0°) insulators We have also tested the susceptibility of these insulators to breakdown under various conditions: surface roughness resulting from different fabrication techniques and the effect of gas pressure. Further, we are developing the necessary design tools to model and scale the behavior of the high gradient insulator. From our study of present models, we conclude that an accurate theoretical model of surface breakdown must also treat photo-ionization during the long time scale evolution of the streamer discharge through the evaporated gas. That is, the tip of a propagating streamer is known to produce intense high energy radiation emission which we believe can lead to photo-conduction in the insulator As conduction in the insulator will strongly modify the voltage which drives the streamer discharge, accurate coupling of the streamer to the insulator were included. We showed initial calculations that were performed

REFERENCES

a) Work performed under the auspices of the US Dept of Energy by LLNL under contract W-7405-ENG-48

[1] Private communication, Eoin Gray

[2] O Milton, IEEE Trans. Electr Insul, vol EI-7, 1972, pp 9-15

[3] A. S Pillai and R. Hackam, J Appl Phys, vol 53(4), pp 2983-2987

[4] J Elizondo and A Rodriguez, in Proceedings of 1992 15th International Symposium on Discharges and Electrical Insulation in Vacuum (Vde-Verlag Gmbh, Berlin, 1992), pp.198-202

[5] S. Sampayan, et al, in Proceedings of the 1995 Particle Accelerator Conference (IEEE, New York, NY, 1995), pp.1269-1271.

[6] S Sampayan, et al, in Proceedings of the 1995 Particle Accelerator Conference (IEEE, New York, NY, 995), pp 2123-2125.

[7] I. D Smith, "Pulsed Breakdown of Insulator Surfaces in Poor Vacuum," unpublished AWRE report, Aldermaston, United Kingdom

[8] R. A. Anderson and W. K Tucker, J.Appl.Phys, vol 58, pp 3346-3349 (1985)

[9] A. Watson, J. Appl. Phys, vol 38, p. 2019 (1967).

[10] G Blaise, J Appl Phys, vol. 77, 2916 (1995)

[11] E.W. Gray, J. Appl Phys., vol 58, 132-141(1985)

[12] P. A. Vitello, et.al., UCRL-MA120465, March 24, 1995