Research Journal of Engineering Sciences ISSN 2278 – 9472
Vol. **2(12),** 1-8, December **(2013)** *Res. J. Engineering Sci.*

AC Breakdown behavior at Sub-millimeter Air Gaps

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Available online at: www.isca.in, www.isca.me
Received 4th June 2013, revised 15th December 2013, accepted 26th December 2013

Abstract

Breakdown of air gaps of few millimeters have been studied under AC voltage, 50 Hz by using different electrode configurations. Different electrode configuration (using commercially available thin razor blades, needle- plane, 2 hemispheres) have been studied in the gap regimes of 100 µm to 1 mm. The present work aims at verifying the values of breakdown voltages for 1mm gap for blade electrode. Efforts will be made to reduce the gap as accurately as possible and study the breakdown behavior. In the present work, optical flats are used to ensure parallelism or planarity by placing the blade electrodes in horizontal manner, so that investigation can be conducted with one-dimensional planar electrodes. Observations were carried out with the help of magnifying glass. The effect of electrode material was also studied by changing one of the electrode material while conducting experiments with needle plane setup and observed results are extensively studied and reported. Such an approach is expected to prove helpful in explanation of breakdown voltages and the current inception voltages which may arise in micro electromechanical systems (MEMS) in the course of their operation and lots of other related fields

Keyword: Electric breakdown, partial discharge, microelectrodes, electric field.

Introduction

Recently various material processing techniques have been actively developed in order to produce micro machines and/or micro robots used for medical instruments, sensors, inspection/repair of piping on nuclear power plant or chemical process plants, and so on. The silicon based micro-parts have been almost produced by means of a photolithography which is frequently used in fabrication of semiconductor ICs. On the other hand, the metal based parts have been shaped by LIGA process and/or focused ion beam (FIB) process. These precise processes are based on the material removing technique; photo-chemical reaction, laser ablation and ion beam sputtering.

In the earlier work, Asokan et. al[1], mechanical support structures were used for making series and parallel combination of blade electrodes and observation were reported by FEM plots and comments were made by giving evidences through field intensity factor plots (β) Vs Gap distance. Endeavors have been made on similar lines to conduct study with different electrode geometry with different materials of different electrical conductivity (namely, aluminum, zinc, copper and stainless steel).

Previously Study has been made for needle plane gap configuration by Slade and Taylor[2] for the gap regimes ranging between 0.2 µm to 40 µm and the departure from Paschen's curve was reported

Present Work: The miniaturization of electrical components is rapidly advancing day by day. This miniaturization includes higher conductor densities leading to smaller conductor spacing in connectors, switches, and micro electromechanical systems (MEMS). In these components the spacing between the electrical conductors is routinely dropping to as size as minimum as possible.

This miniaturization increases the possibilities for integration of high voltage systems with other micro devices and provides opportunities to reduce the size of many high voltage systems. For e.g. micro switches, electrode configurations to hold off with large hold off capabilities in air at atmospheric pressure[3].

However, a micro-joining technique, which includes welding and solid state bonding, will be surely required to produce or assemble more complex structure of the micro-parts. In order to carry out micro-welding successfully, heat power must be precisely controlled and concentrated on the microscopic area.

For analyzing and appreciating such processes, it is inevitable and strongly required to posses the extensive knowledge of the breakdown behavior for the smaller regimes (sub millimeter/micro levels). This range of air gaps has been chosen for the study since, as per the authors' survey, relatively less information is available in this context. To bridge this gap, we conducted extensive analysis of AC breakdown behavior at 50 Hz frequency over sub millimeter air gaps for different electrode configurations with different material compositions.

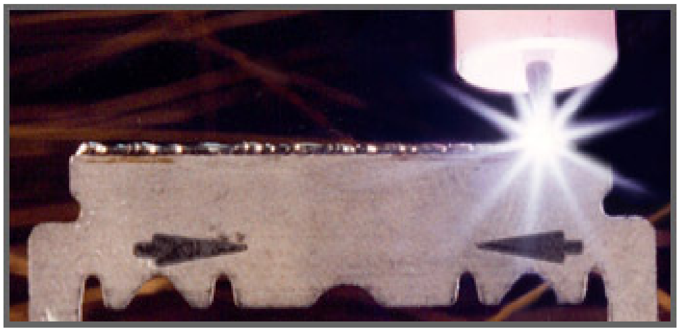

Figure-1
Fine-Line Micro welding being done on the edge of razor blade

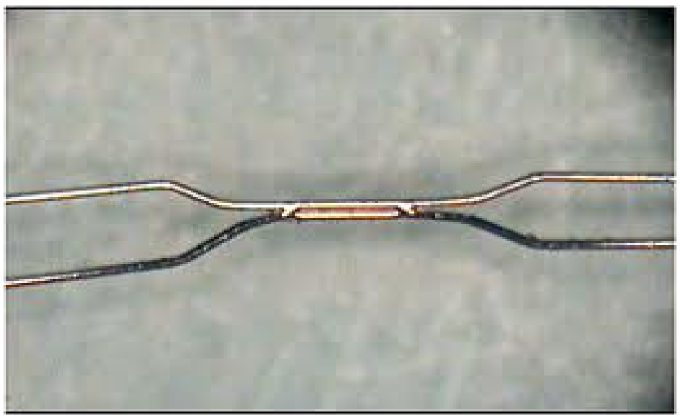

Figure-2
Example of micro-welding done on .0025 inch 304 stainless wires

Methodology

Experimental Setup: The test kit operates from single phase mains supply. The circuit comprises of the following: i. 1. Auto transformer 0-2A, 230V, 50Hz. ii. 2. Step up transformer 230V / 60,000V ac. iii. 3. Control panel.

Main supply is connected to the auto transformer through a fuse and switch. Output of the auto variable transformer feeds the primary winding of the H.V. step up transformer through a push button actuated relay. Midpoint of the H.V. transformer is solidly earthed. The set is complete with an oil test cup, made of high impact transparent, acrylic sheet and 2.5mm “GO”, “NOGO” gauge.

The circuit is provided with the following safety interlock:

Zero start interlock: Zero start interlock is provided on the auto – variable transformer so that the HV can be switched “ON” only if the auto variable transformer knob is held in zero position.

Door Interlock: Door interlock is provided at the top cover so that HV can be switched ‘ON when the top covers is closed.

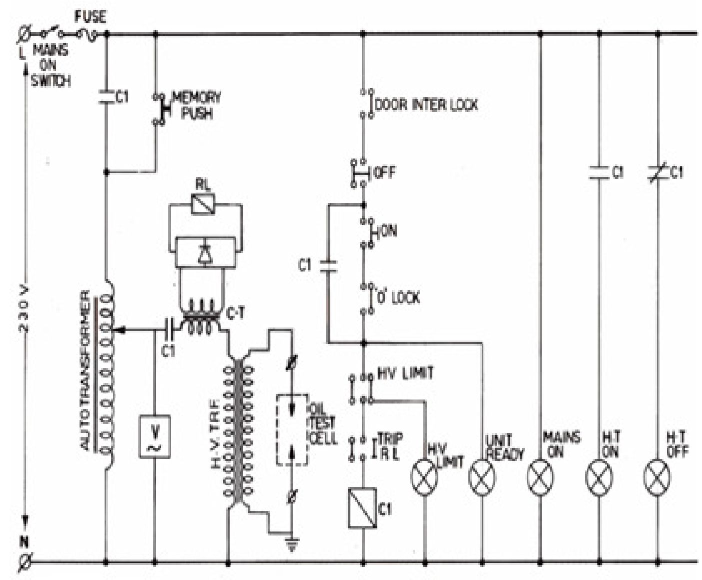

Figure-3
Circuit Diagram of the Step-down transformer for BDV Analysis

Figure-4
Front panel of Step down Transformer

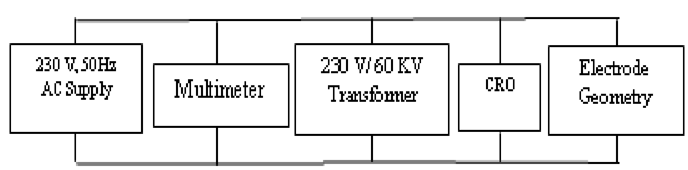

Figure-5
Block Diagram of overall experimental setup

But the major problem was that, the HV calibrated analog voltmeter didn’t have any divisions between 0-10kV. The range 0-10kV was supposed to be of main interest. Since the breakdown voltage for air gaps at sub-millimeter range usually comes in the range of 0-4kV. In order to check out this problem, a digital multimeter (model no. MS 8201) with an AC voltage measuring range of 0-750V AC was used across the primary winding itself and another multimeter of same make was connected across secondary. The zero error of the analog HV calibrated voltmeter was found to be 0.53V.

Taking the readings from both the digital multimeters, a calibration curve was plotted for the range of 0-0.5kV.

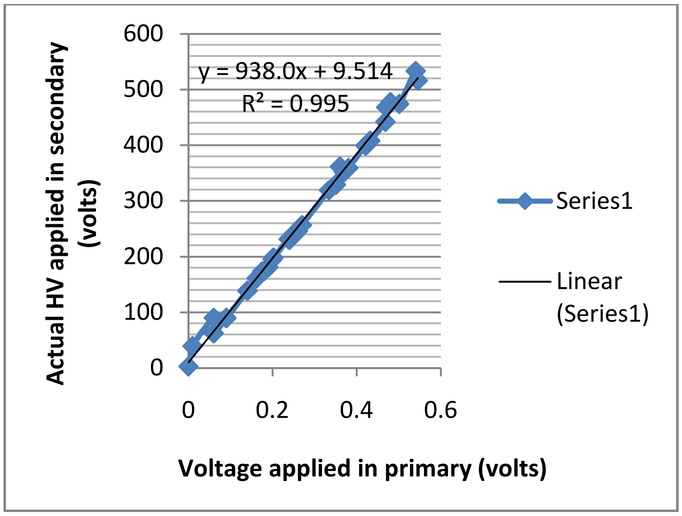

Figure-6
The graph hence obtained was used to determine the actual BDV from the reading recorded from the multimeter

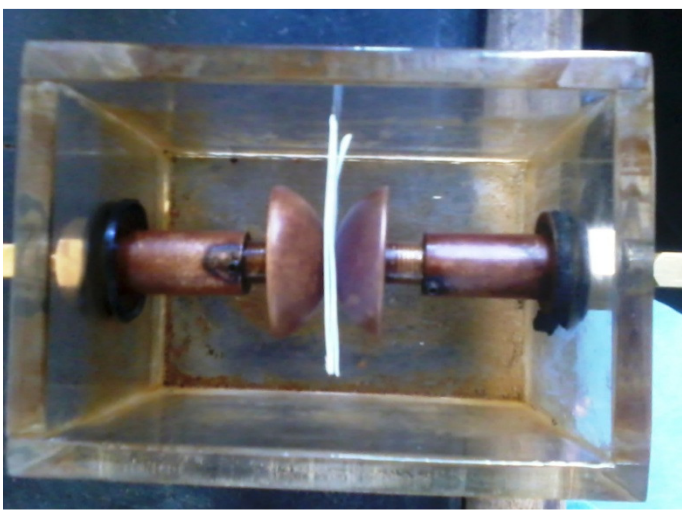

Figure-7
Space between the 2 hemispherical electrodes being setup by spacer method using "GO", "NOGO" principle using GSM bond paper of std. thickness 0.1 mm

The capacitance for such electrode configuration was found negligible when tested in a Desauty's Bridge arrangement and digital multimeter. The capacitance values hence found out were found even lesser than 0.1 nf which can be suitably neglected and hence can be suitably assumed that there won't be any phase difference between the conduction current and displacement current while breakdown.

Results and Discussion

Hemispherical Electrodes Configuration

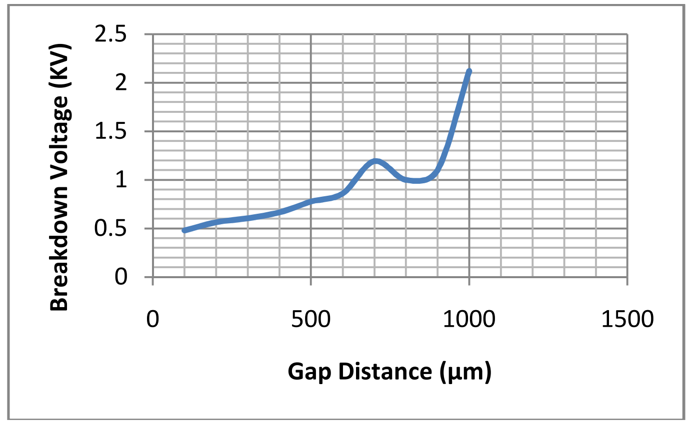

Figure-8
The graph showed an abrupt increase at the gap distance of 0.7 mm. The electric potential distribution pattern was observed using ANSYS 12.1 software as follows:-

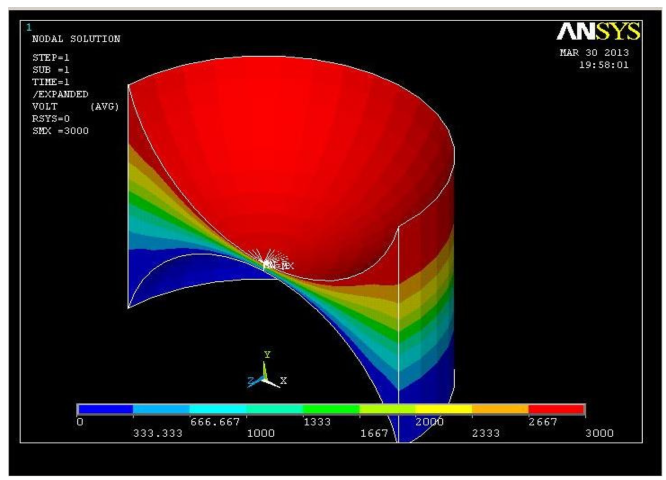

Figure-9
FEM plot showing electric potential distribution pattern

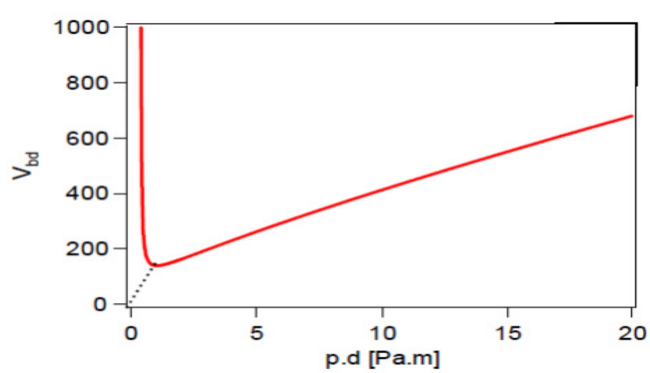

Figure-10
Paschen's Curve showing pdmin in air at atmospheric pressure

As per Paschen's curve pdmin for air at atmospheric conditions corresponds to a gap distance of 7.5 µm and since the study is carried out for gap distances ranging from 100 µm to 1000 µm the observed BDV plots for every configuration is an increasing curve.

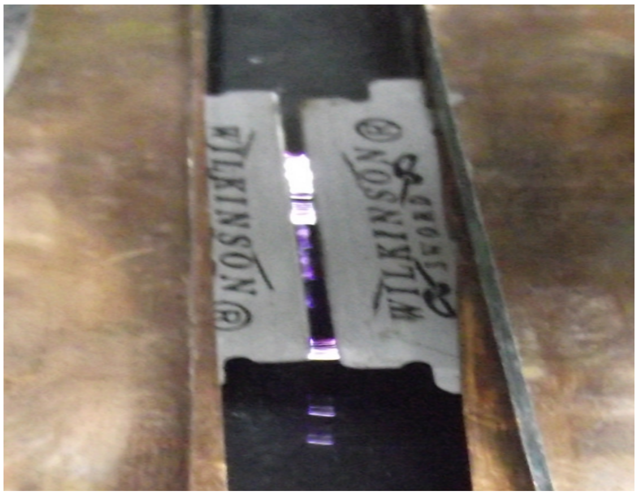

Figure-11
Electrical discharge occurring at razor blades, used as electrodes for carrying out one dimensional breakdown analysis

Chromium coated stainless steel blade electrodes (high aspect ratio: 20 µm edge thickness and 33 mm length) were arranged upon two optically flat glass plates which are given electrical connection by means of copper foils (thickness 0.05 mm) and sandwiched with one more pair of such flats, as shown in the figure above.

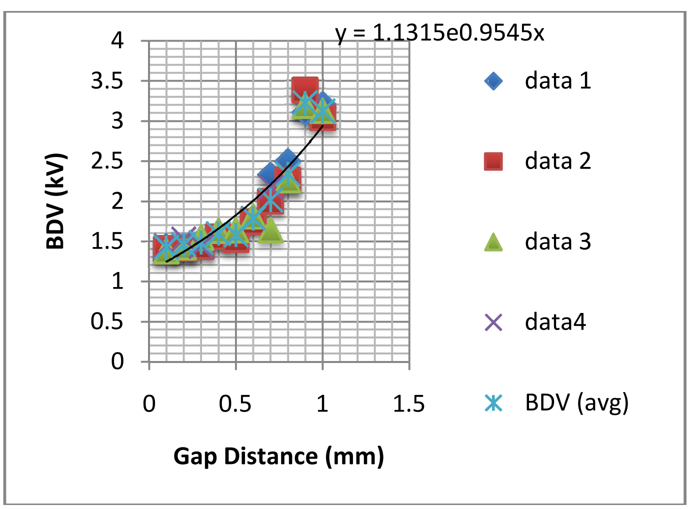

Figure-12
BDV plot obtained for blade electrode configuration

The alignment of such blade electrodes were ensured by sandwiching them using optical flats and touching both of them with their edges which are as thin as 20 µm. If the blade electrodes touch each other with a uniform linear contact it is ensured that they are aligned perfectly.

For setting gap distance between such electrodes again the spacer method with go-no-go principle was adopted and the readings of breakdown voltage Vs gap distance were tabulated as shown by the graph above, in this gap regime too, the peaks and scatter were observed within a gap range of (0.7mm to 1mm).

The FEM analysis for electric potential distribution for such electrode configuration depicts:-

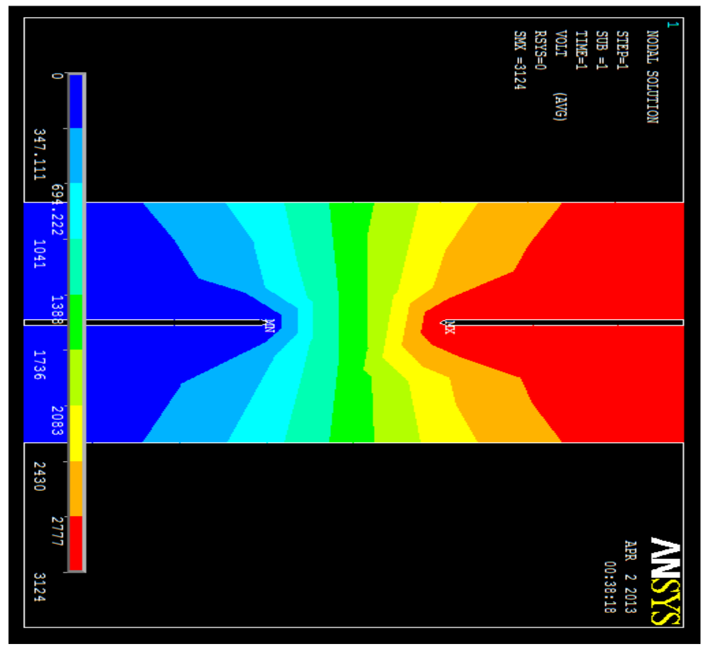

Figure-13
Cross- sectional View of the FEM plot for blade electrodes

Needle Plane Configuration: In order to appreciate the breakdown behavior at fully non-uniform electrode configuration, we choose our next setup as needle-plane electrodes.

The needle used were nickel plated with dimensions: Length=26 mm, Needle diameter=0.55 mm, Tip diameter=20 µm

For measuring the tip diameter of the needle electrode, we used travelling microscope which had the least count for measurement as 0.01 mm.

The anode materials were changed one by one as already stated from stainless steel, zinc, copper to aluminum. For setting gap distance in such configuration, screw gauge type arrangement was used where 1 mm on a linear scale is divided into 10 divisions on a rotating scale.

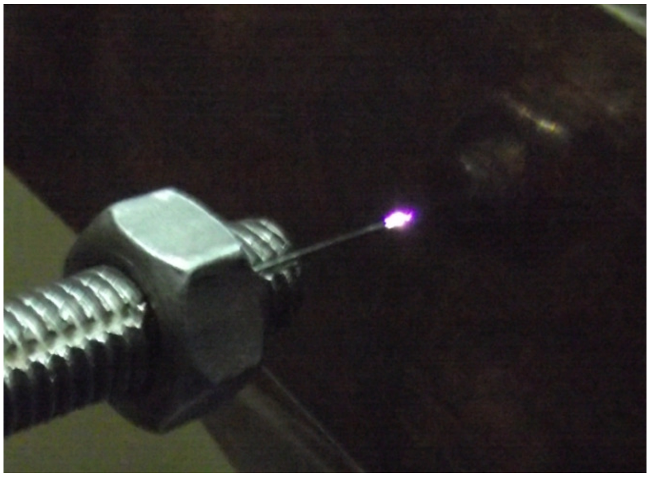

Figure-14
Electrical discharge taking place in needle plane configuration

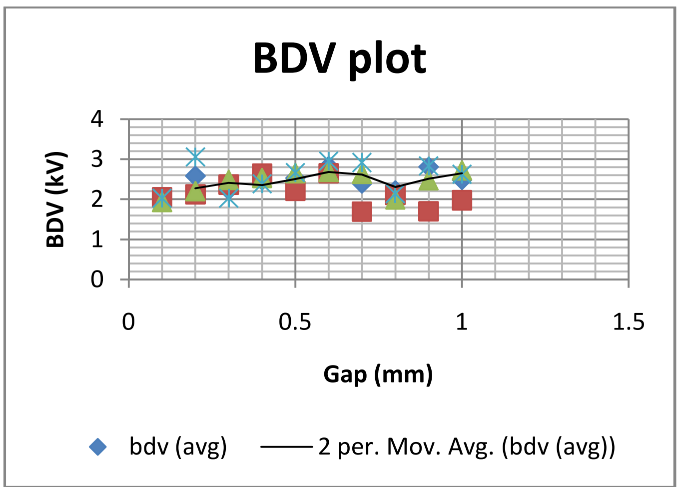

Figure-15
Breakdown voltage Vs Gap Distance plot for needle and Copper Electrode Combination

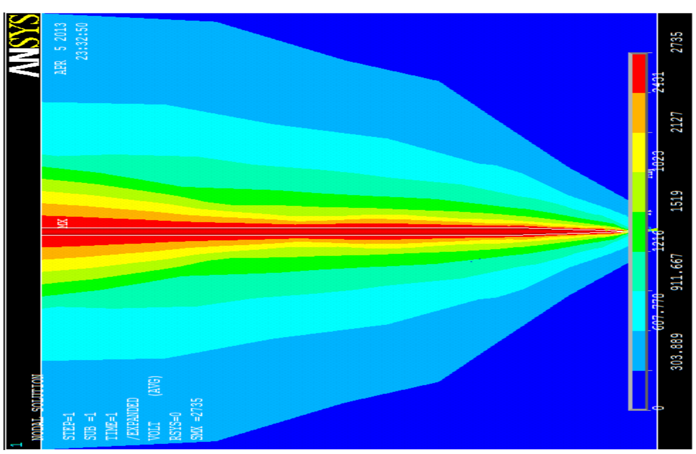

Figure-16
FEM Plot for needle plane setup showing electric potential distribution

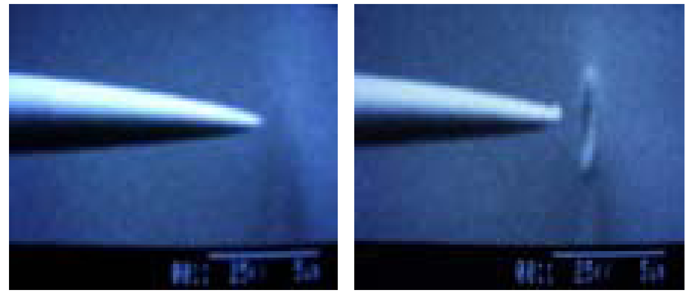

Figure-17
Magnified View of Needle Plane combination, before and after indentation

The indentations formed on the metal plates were as follows:-

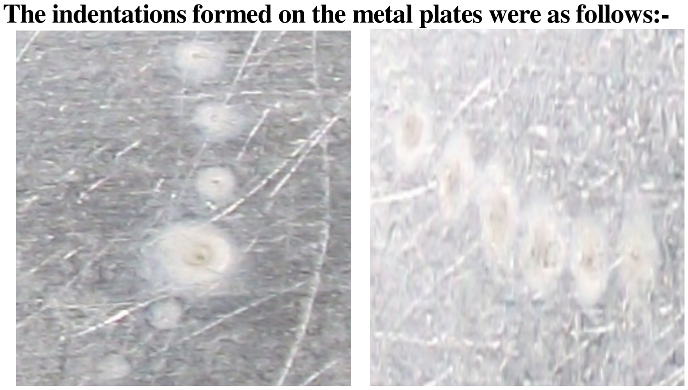

Figure-18
Indents made on Aluminum Plate

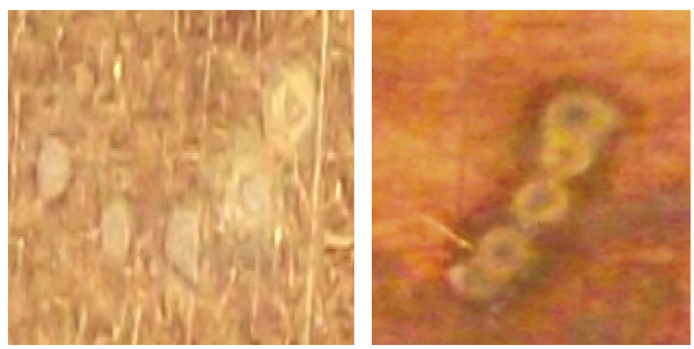

Figure-19
Indents made on Copper Plate

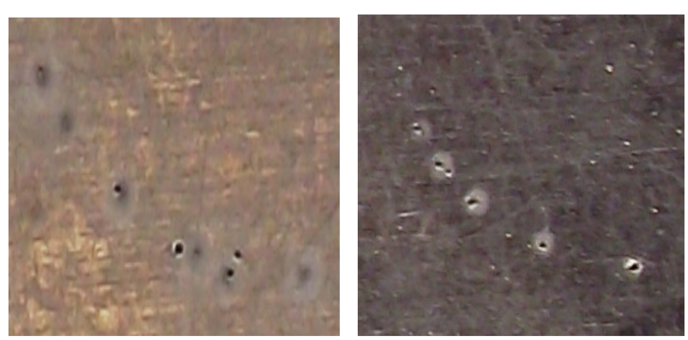

Figure-20
Indents made on Zinc Plate

Discussions: Since the mean free path of the electrons in air at atmospheric pressure is about 0.5 µm, electrons from the cathode will have very few collisions before reaching the anode at small contact gaps (<4 µm). The presence of air in these small contact gaps will thus have only a small effect on the breakdown process.

However in a needle-plane configuration the "air column" undergoing breakdown is very thin which involve very few air molecules in the column for breakdown. Hence breakdown behavior in this configuration matches with vacuum breakdown results.

The dependence of breakdown voltage upon the area of the electrode as observed previously for plane electrodes in Schumann et. Al[4] was even verified and observed by our obtained results.

Moreover the breakdown strength (kV/mm) was found almost independent upon the electrode geometry considered for the study.

Hence it is confirmed from the study that irrespective of the electrode configuration taken for study, the variation of the breakdown strength with gap distance remains same.

The BDV plot for all the setups in a combined form when plotted for comparison was observed as below:

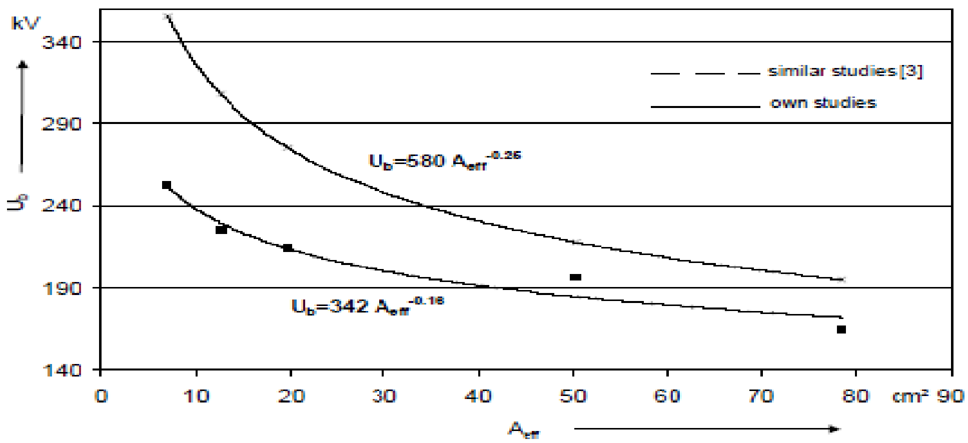

Figure-21
Breakdown voltage dependency on the effective area under constant surface conditions and constant gap distance (s=10mm) courtesy: Schumann et. al[11]

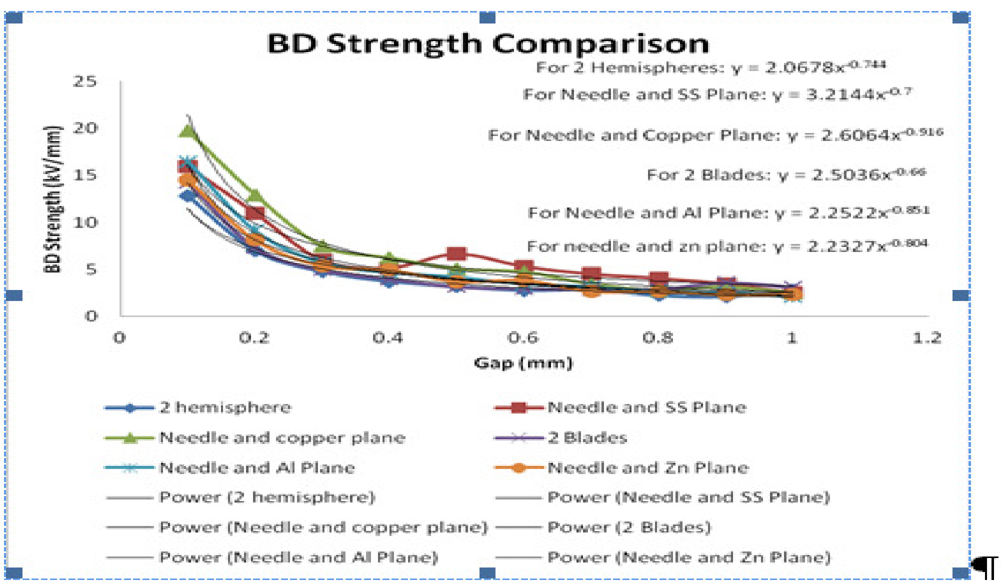

Figure-22
Breakdown strength plot for different electrode geometry

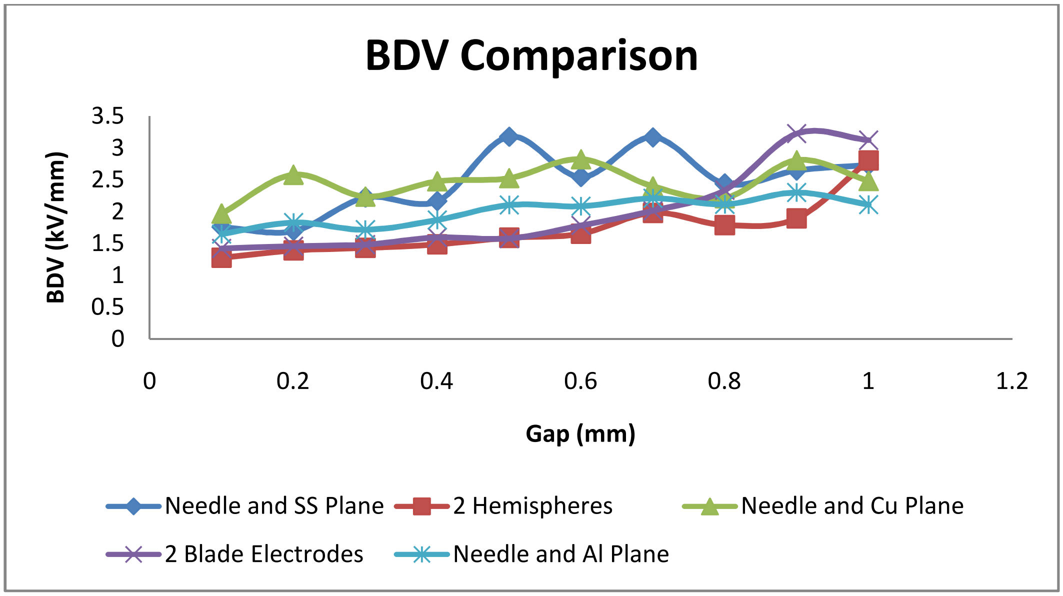

Figure-23
Combined BDV plot for all the electrode combinations

The observed graph clearly depicts the dependence of breakdown voltage on the surface area of the electrode which takes part in conduction process during breakdown since the lowest BDV pattern was observed for the hemispherical electrodes which had the greatest surface area taking part in breakdown followed by 2 blade arrangement followed by the needle plane arrangement.

When the pattern is observed only for the needle plane setup with different electrode material, it can be clearly noticed that the BDV is even dependent upon the material properties such as melting point, binding energy, work function of the metal electrodes etc.

The most exciting result was this dependence since the earlier works namely: Dhariwal et. al.[5], Townsend et. Al[6] etc. suggested that the breakdown voltage depends on the electrode material properties only under vacuum conditions since there is no influence of the surrounding medium on the breakdown process. But when the breakdown takes place in an air column which is thin as a cylindrical column with diameter of 20 µm (the tip diameter of the needle), under atmospheric pressure, the breakdown voltage still depends on the electrode material properties.

Conclusion

The research and development undertaken for such an extensive analysis endowed us great knowledge and experience. The experiments done for different electrode geometry for different material combinations were the most time consuming and challenging task. Learning ANSYS for FEM analysis proved very helpful and interesting. Measuring the pre- discharge currents for these many setups and carrying out break down analysis for different frequencies for such variety have been categorized for the future work. The future scope of this effort can also be assumed as the measurement of other related phenomena taking place simultaneously with the electrical discharge like liberation of ozone gas whose quantity can be measured as a function of time and electrode material properties, such phenomena can be also exploited for metal sheet cutting with a degree of precision of few micrometers etc.

References

1. Asokan T., Balachandra T. C., Electrical Discharge Behaviour At Micro-Gaps, IEEE Transactions on Di-electrics and Electrical Insulation, **18(6), (2011)**
2. Paul G. Slade and Erik D. Taylor, Electrical Breakdown in atmospheric air Between Closely Spaced (0.2µm-40µm) Electrical Contacts ", *IEEE Transactions on Components and packaging Technologies*, **25(3), (2002)**
3. Strong F., Skinner J., Dentinger P. and Tien N., Electrical breakdown across micro scale gaps in MEMS structure, Proc. of SPIE, 6111 **(2006)**
4. Schumann U., Budde M. and Kurrat M., Influence of Shield Capacity on the Breakdown Voltage of Vacuum Tubes, XXIst International Symposium on Discharges and Electrical Insulation Vacuum, Yalta, Ukraine, **(2004)**
5. Torres J.M. and Dhariwal R.S., Electrical field breakdown at micrometer separations, *Nanotechnology,* **10,** 02-107, **(1999)**
6. Townsend J., Electricity in Gasses, Oxford University Press, **(1915)**

7. Rakshit Tirumala, A Mathematical Model For The Departments From Paschen's Law At Micro meter Gaps Using Ion Enhanced Field Emission, Ionization and Ion Transport Final Project Paper, May 5, 2010 Notre Dame, IN USA

8. R.H, Fowler, F.R.S. and L. Nordheim, Electrical Emission in Intense Electric Field, Proceedings of the Royal Society of London Series A, Containing Paper of a Mathematical and Physics Character, **(1928)**

9. German L., Electrical breakdown between close electrodes in air, Journal of Applied Physics, **30(1),** 46-51 **(1959)**

10. Lee R.T., Chung H.H. and Chiou Y.C., Arc erosion behavior of silver contacts in a single arc discharge across a static gap," *Proc. Inst. Elect. Eng.,* **148(1),** 8-14 **(2001)**

11. Moyad A. Ahmad, Influence of ground electrode area on breakdown current in RF capacitively coupled plasma", *Iraq Journal of Physics,* **10(17),** 90-97 **(2012)**

12. Balachandra T.C. and Nagabhushana G.R., Anode Hotspot Temperature Estimation in Vacuum Gaps under 50 Hz Alternating Excitations, *IEEE transactions on Electrical Insulation,* **28(3), (1993)**

13. BoyleW.S., Kisluik P., Departure from Paschen's Law law of Breakdown in gases, *The Physical Review,* **97,** 255-259 **(1995)**

14. Go D.B., Pohlman D.A., A mathematical model of the modified Paschen's Curve for breakdown in microscale gaps, *Journal of Applied physics- in press* **(2010)**