Electrical Discharge Characteristics of 1-D Plane Micro-electrodes

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Abstract— ***Breakdown characteristics of electrodes with high aspect ratio, possessing 20μm tip thickness and 15mm length, referred as 1-D plane electrode are studied with air gaps ranging from 50μm to 25mm under DC, 50Hz AC and high frequency (5kHz). Electrostatic finite element modeling (FEM) is performed to understand the electric field magnitude and distribution. An exponential increase in the breakdown strength with air gaps below 1mm is observed. Interestingly, 50μm air gap display about 17kV/mm, an indication that micro-gaps behave similar to that of vacuum gap. The FEM analysis support that the actual / applied E-field ratio reduces rapidly at air gaps below 1mm. A critical analysis of the E-field ratio and experimental results observed with micro- gaps, i.e., below 1mm, suggests that the breakdown is dictated by factors other than E-field. The observed characteristics are discussed in terms of limited ionization across the micro-gap.***

I. Introduction

Electrical discharge characteristics of micro-cavities or gaps are of great interest as it is applicable to several miniaturized technologies. The breakdown characteristics of conventional macro-gaps are influenced by several factors such as electrode configuration, gap and environment. However, the influence of these parameters is yet to be understood in micro-gaps. A few investigations reported on the micro-gap using cylindrical or spherical electrode configuration [1-5] have revealed that the breakdown characteristics of micro-gaps deviate from Paschen law. Similarly, the breakdown characteristics of multiple micro-gaps in series formed by depositing thin electrodes on semiconductor substrate are reported [6]. Note that the breakdown in this configuration is attributed to surface flashover or breakdown along the semiconductor surface. The present work is aimed at understanding the dynamic breakdown characteristics of air in micro-gaps formed by well-defined micro-tip electrodes.

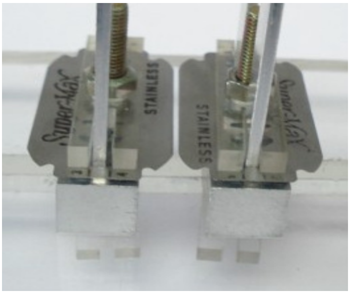
II. Experimental Procedure

Chromium coated razor blades with tip thickness of 20μm and 15mm length are chosen for the present work. The blade electrodes are arranged in parallel using a fixture as shown in Fig. 1a. The desired air gap is attained accurately and subjected to breakdown tests under 50Hz AC, DC and high frequency (5kHz). The current and voltage waveforms are recorded by using oscilloscope. Each data presented in this paper corresponds to an average of at least 4 data points. 3D FEM model of the electrode configurations at different gaps are studied using ANSYS. The electric field distribution across the air gap obtained through FEM and the experimental results are compared.

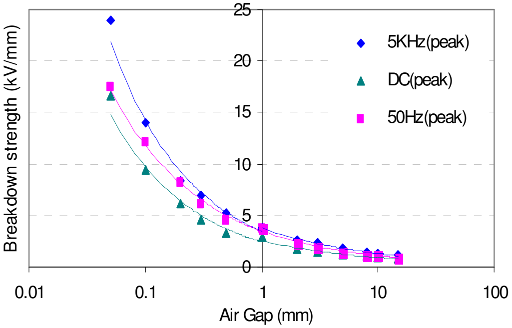
III. Results and Discussion

A. *Micro-gap breakdown characteristics*

The breakdown strength, observed under DC, 50Hz AC and high frequency (5kHz), as a function of air gap are compared in Fig. 1b. The breakdown strength in all cases decreases exponentially with an increase in the air gap. Note that the typical breakdown strength (3kV/mm) of conventional parallel plane electrode configuration is observed in the 1D electrode around 1mm gap (Fig. 1b). An exponential increase in the breakdown strength is observed with a reduction in the gap below 1mm. The observation of higher breakdown strength >10kV/mm for gaps below 100μm suggests that the micro-gaps formed by 1D electrodes exhibit vacuum gap like behavior. The electrostatic 3D FEM model of the 1D electrode configuration, shown in Fig. 2a, evidences that the field concentrates sharply near the tip. The e-field ratio (actual / applied) estimated from FEM model is shown as a function of gap in Fig. 2b. Note that the e-field ratio decreases rapidly as the gap is reduced. The ratio of 1,an indication of uniform field, is observed below 100μm. These results suggest that the micro-tip electrodes exhibit uniform field as the magnitude of micro-gap reduces below 100μm. However, the e-field ratio closer to 1 does not justify the increased breakdown strength of micro-gaps above 3kV/mm. Fig.3 shows the current and voltage waveforms observed at breakdown of different gaps under DC field. Two current peaks (i) during breakdown or associated with voltage collapse (at

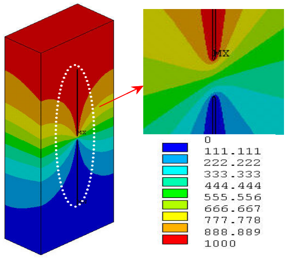


(a)

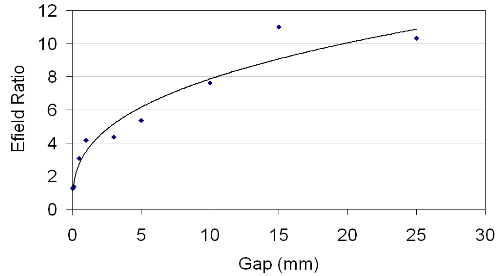


(b)

Fig. 1 (a) Electrode arrangement and (b) Breakdown characteristics of 1-D electrode



(a)



(b)

Fig. 2 (a) Potential plot and (b) E-field ratio Vs gap of 1-D electrode

about 5ms) and (ii) opposite polarity around 30ms are observed. Though the voltage collapses within 1ms, the first peak current is seen around 5ms. During this period, significant oscillations of voltage and current are seen. The extent of pulse-like oscillation is higher at lower gap compared to larger gap as evidenced in Fig. 3. Note that the magnitude of these oscillatory current and voltage is about 4 times higher than that of the main signal. These oscillations may be attributed to the system inductance. It is also possible

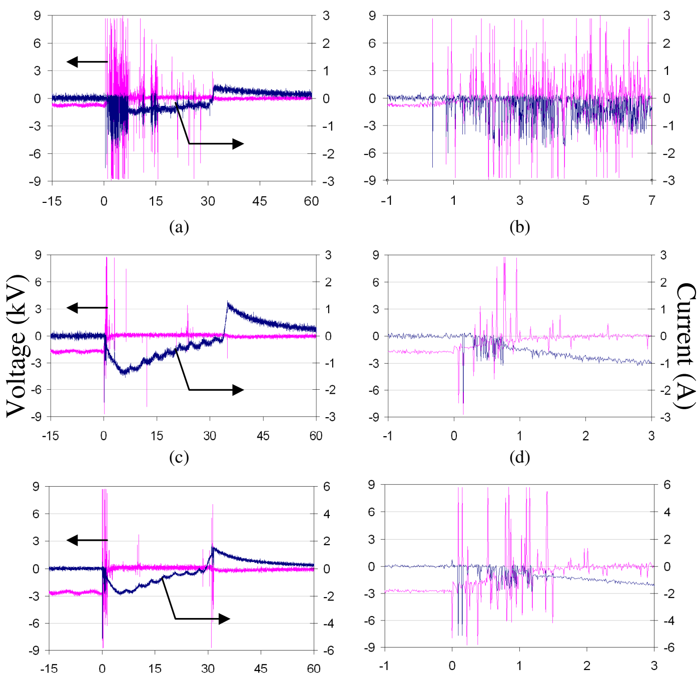


Fig. 3 DC breakdown waveforms of 1-D electrodes; (a), (c) & (e) correspond to 50, 500 and 1000 µm gap. (b), (d) & (f) is the expanded waveform of the initial stage of breakdown respectively.

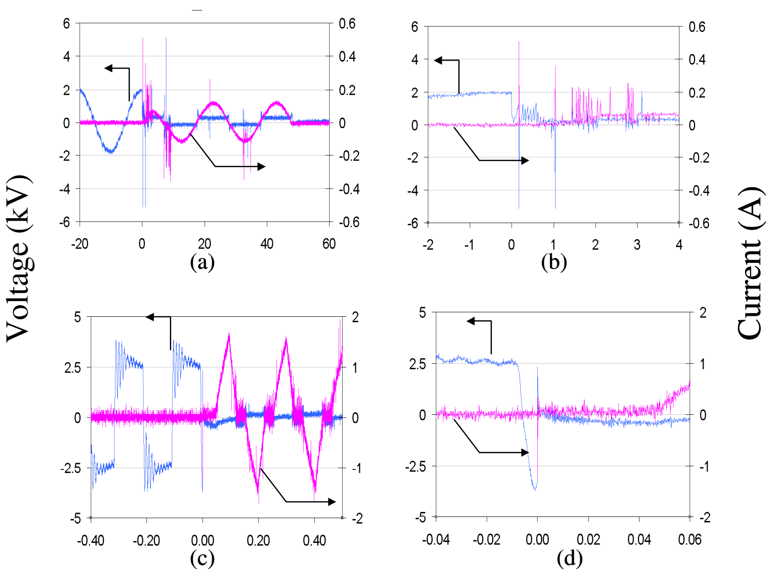
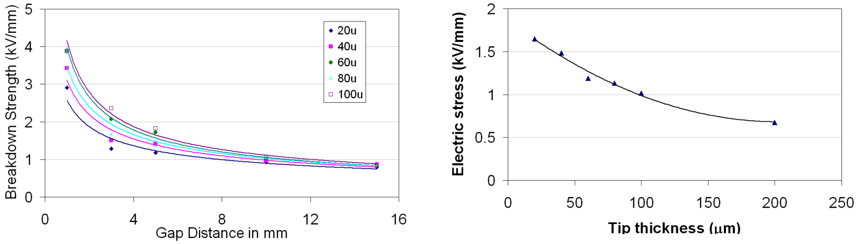


Fig. 4 Breakdown characteristics of 1-D electrodes at 1mm gap with (a) & (b) 50 Hz AC and (c) & (d) 5 kHz. (X-axis in milliseconds)

that the longer oscillation time with alternate polarity reversal may be attributed to the limited ionization across the gap which may not be adequate enough to cause breakdown faster as normally observed in the macro-gaps. It is hypothesized that the positive charge built around the negative electrode may compensate the negative polarity and modify the same to positive. It may therefore be stated that the pulse like voltage oscillations may be attributed to the combination of system inductance and charge alignment near the electrode vicinity. The dissipation of these charges is believed to be slow and hence the observed delay in the recovery of the micro-gap. Fig. 4 shows the waveforms observed at 1mm gap under 50Hz and 5kHz. As can be seen, the breakdown waveforms under these fields are found to exhibit similar trend to that observed under DC near the inception stage of breakdown. Note that about 5% of the peak applied voltage is observed after the breakdown along with the current oscillation till the gap recovers in both cases. In the case of DC, the recovery time observed in micro gaps is longer compared to that of observed under macro-gap breakdown.

B. Electrode tip effect

As stated earlier, one of the major variables that influence the breakdown characteristics of macro-gap is the radius of curvature or thickness of the electrode. In order to understand the role of the same in micro-gaps, the desired electrode tip thickness is obtained by sandwiching multiple blades. FEM analysis was performed on the multi-blades as done for single blade. Fig. 5a shows the comparison of breakdown strength of different multiple sandwiched blades thickness as a function of gap. As expected the breakdown voltage increase with an increase in the tip diameter. The effect is less pronounced at larger gaps compared to the smaller gaps. FEM analysis shows reduction in the peak electric stress with increase in tip diameter, which supports the observed trend in experimental results.



(a) (b)

Fig. 5 Effect of tip thickness on breakdown strength as a function of gap (a) Experimental results and (b) Peak E-field from FEM for various tip thickness for the gap of 5mm

IV. CONCLUSION

The breakdown characteristics of 1-D microelectrodes are studied experimentally as well as analytically for gaps ranging from 50 μm to 25mm. The breakdown characteristics of micro-gaps are found to be distinctly different from that of conventional macro-gaps. Higher breakdown strength observed in micro-gaps is attributed to a combination of uniform E-field and limited field emission and ionization across the gap that causes charge accumulation and polarity reversal of electrodes.

REFERENCES

[1] L. H. Germer, "Electrical breakdown between close electrodes in air," *Journal of Applied Physics*, vol. 30, pp. 46-51, Jan .1959.

[2] R. S. Dhariwal, J. M. Torres and M. P. Y. Desmulliez, "Electric field breakdown at micrometer separations in air and nitrogen at atmospheric pressure," *IEE Proc. Sci. Meas. Technol.*, vol. 147, pp. 261-265, Sep. 2000.

[3] J. M. Torres and R. S. Dhariwal, "Electric field breakdown at micrometer separations in air and vacuum," *Proceedings of Microsystem Technologies*, vol 6, pp. 6–10, 1999.

[4] Wallash, A., Levit, L., "Electrical breakdown and ESD phenomena for devices with nanometer-to-micron gaps," *Proc. Of SPIE*, vol. 4980, pp. 87-96, 2003.

[5] Paul G. Slade and Erik D. Taylor, "Electrical breakdown in atmospheric air between closely spaced (0.2 μm-40 μm) electrical contacts," IEEE Trans. Components and Packaging Technologies, vol 25, pp. 390-396, Sep. 2002.

[6] Fabian W. Strong, Jack L. Skinner, A. Alec Talin, Paul M. Dentinger and Norman C. Tien, "Electrical breakdown response for multiple-gap MEMS structures," IEEE 44th Annual International Reliability Physics Symposium, pp.421-426, 2006.