Influence of pressure on *V-t* characteristics across micrometer-scale surface gap

H. Iwabuchi[1], S. Matsuoka[1] A. Kumada[1], K. Hidaka[1]

[1]*The University of Tokyo, Faculty of Electrical Engineering and Information Systems, 7-3-1 Hongo, Tokyo, Japan*

With the miniaturization of MEMS (micro electromechanical systems) devices, the insulation width and the separation between electrodes in such devices have been accordingly reduced. Consequently, electrical breakdown phenomenon across micrometer-scale gap is of great practical interest for insulation designing of miniaturized devices. In this paper, *V-t* characteristics across micrometer-scale surface gap were measured changing the gap width, polarity of applied voltage, and the gas pressure. In atmospheric air, the *V-t* characteristics were almost flat. On the other hand, in lower-pressure air, the breakdown voltage increases especially under the positive voltage application. The results can be explained by the collision of electrons; In low-pressure air, the collision between electrons and neutral particles hardly occurs across micron gaps, therefore, the discharge path can increase for generating positive ions. Under the positive voltage application in lower pressure, the source of initial electron can be distant from high voltage electrode.

1. Introduction

In recent years, development of semiconductor manufacturing technology is accelerating the miniaturization of MEMS (micro electro-mechanical systems) devices. The application of these MEMS device has been widely increased. For example, electrostatic actuation with low power consumption and simple design has been developed as an efficient method based on MEMS technology. For efficient operation of these actuators, a large force between micro gaps is required. Because the force is proportional to the square of the electric field strength, the most convenient method to raise the force can be attained by making the gap smaller which means narrowing the electrodes' separation. By narrowing the insulator thickness, these devices are exposed to high risk of breakdown which causes serious damage [1][2][3]. Therefore, it is necessary to investigate the insulation strength of micro-meter scale gaps which are contained in such devices.

The authors have measured the breakdown and the pre-breakdown characteristics across micrometer-scale surface gaps [4][5]. In this paper, *V-t* characteristics across micrometer-scale gap were measured changing the gap width, polarity of applied voltage, and the gas pressure. The discharge process across micrometer-scale gap was investigated.

2. Experimental setup

2.1. Micrometer-scale surface gap fabricated on oxidized silicon wafer

A pair of metal electrode was fabricated on SiO_2 insulation layer by using MEMS technology as shown in Figure 1. The gap between electrodes was set at 1-50 μm. oxidized silicon wafer was consisted of 525-μm thick silicon and 2-μm thick silicon dioxide. On top layer, aluminum electrodes of 100 nm thick were fabricated. The curvature on the tip of electrode was approximately 200 nm. In this study, Si layer was grounded when the voltage was applied.

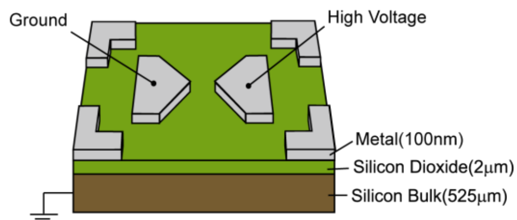

Figure 1. Micrometer-scale surface gap

2.2. Measurement circuit

The measurement circuit used in this study is shown in Figure 2. In order to apply the impulse voltage, the high speed transistor switch (BEHLKE Power Electronics GmbH, HTS41) was utilized in RC circuit to control charge and discharge of capacitor. This switch can be controlled by TTL signal to set the on and off time. The capacitor was assigned to 1 nF and current limiting resistance was set at 2 kΩ to prevent an extra damage of the sample.

The discharge current was measured by current transformer (Tektronix, CT1, 25 kHz to 1 GHz).

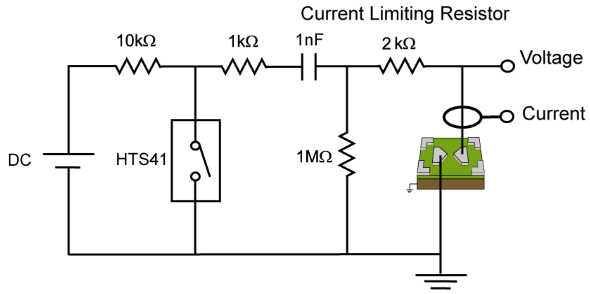

Figure 2. Measurement circuit

2.3. Electric field intensity across micrometer-scale surface gap

The electric field intensity in the vicinity of micrometer-scale surface gap was calculated based on finite element method using COMSOL Multiphysics Ver. 4.3b.

The electric field intensity on the high-voltage electrode and the grounded electrode under the application of 500 V is shown in Figure 3. The electric field intensity on the high voltage electrode is approximately 10^9 V/m, which was independent from the gap width. On the other hand, the electric field intensity on the grounded electrode is strongly dependent on gap width: the electric field intensity on the grounded electrode was under 10^6 V/m across 50- μm gap.

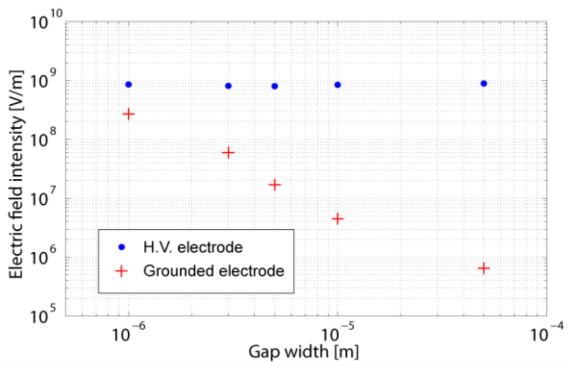

Figure 3. Electric field intensity on the high voltage electrode and the grounded electrode

2.4. Determining of breakdown

Typical voltage and current waveform when the discharge occurs are shown in Figure 4. The displacement current flows when the impulse voltage is applied. In Figure 4, when the voltage application time reached 9.5 us, the applied voltage is sharply dropped to 50V. The estimation of breakdown was determined by the drop of voltage and the light emission in this study.

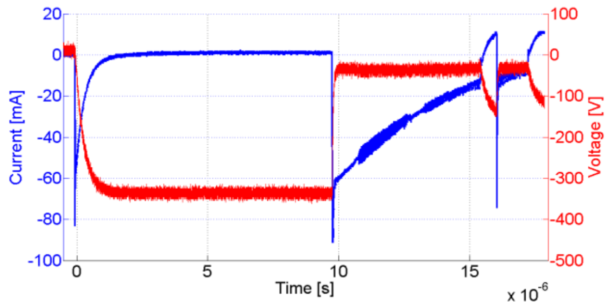

Figure 4. Typical voltage and current waveform when the discharge occurs

3. Experimental results

3.1. *V-t* characteristics under the circumstances of atmospheric air

Figures 5-7 show the *V-t* characteristics under the circumstances of atmospheric air. The result shows that the breakdown voltage under positive voltage application is approximately 1.2 times higher than the one under the negative voltage application. It can be explained by the source of initial electrons. Under negative voltage application, the initial electrons are emitted from cathode surface by electric field emission subjected to Fowler-Nordheim equation. On the other hand, under negative voltage application, the initial electrons are emitted from insulator surface in the vicinity of anode.

V-t characteristics under the circumstances of atmospheric air are almost flat in both case of negative and positive voltage application. The result shows that the breakdown voltage is mainly determined by the electric field intensity on the source of initial electrons. It coincides well with the result that breakdown voltage across micrometer-scale gap is independent of gap width; the electric field intensity on the cathode is independent of gap width shown in Figure 3.

3.2. *V-t* characteristics under the circumstance of lower-pressure air

Figures 8-10 show the *V-t* characteristics under the circumstances of lower pressure air. The result shows that the breakdown voltage under positive voltage application is approximately 1.2 times higher than the one under the negative voltage application.

The result shows the same tendency to the one shown in 3.1. It can be explained by the source of initial electrons: the source of initial electrons is independent of gas pressure. In lower-pressure air, the breakdown voltage increases especially in $t < 1\mu s$ under the positive voltage application. The breakdown voltage under the negative voltage application less increases than the one under the negative voltage application. In $t > 1\mu s$, the *V-t* characteristics are almost flat.

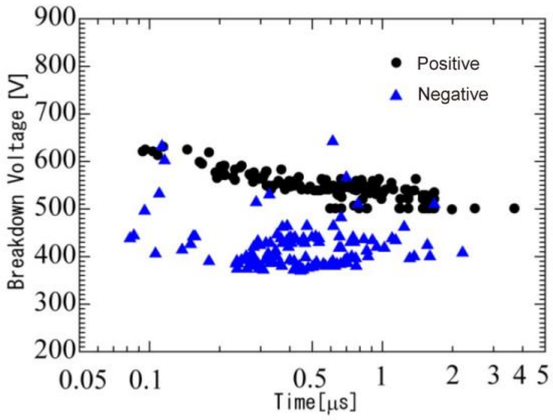

Figure 5. *V-t* characteristics across 30-μm gap in 100-kPa air

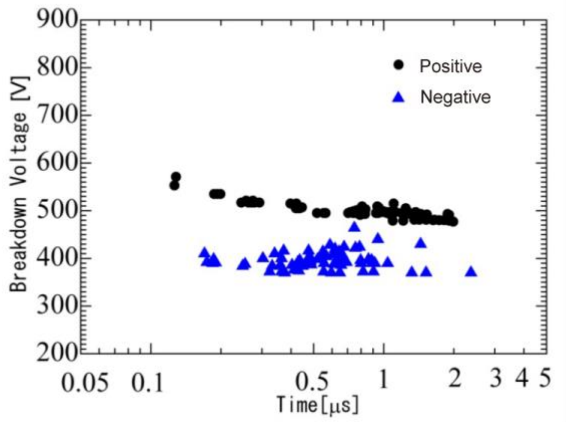

Figure 6. *V-t* characteristics across 10-μm gap in 100-kPa air

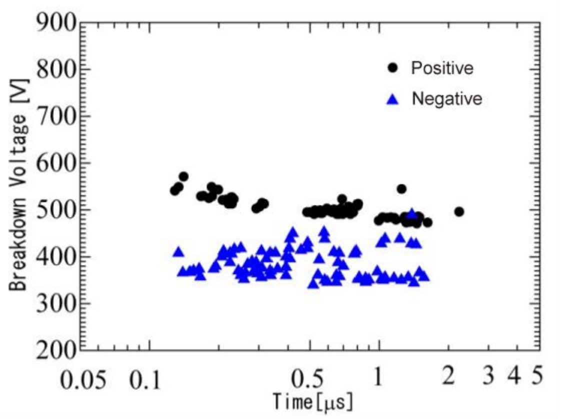

Figure 7. *V-t* characteristics across 3-μm gap in 100-kPa air

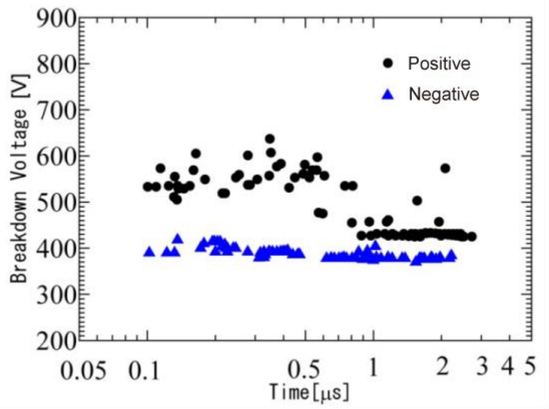

Figure 8. *V-t* characteristics across 10-μm gap in 30-kPa air

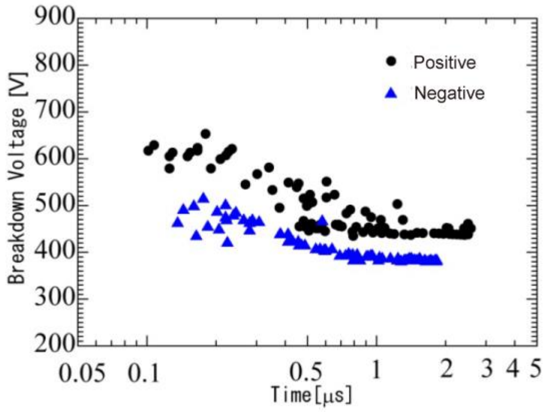

Figure 9. *V-t* characteristics across 3-μm gap in 10-kPa air

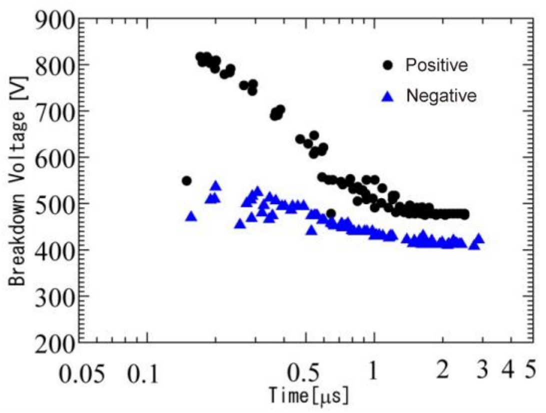

Figure 10. *V-t* characteristics across 3-μm gap in 1-kPa air

4. Discussion

Under the circumstances of lower-pressure air, the breakdown voltage increases in $t < 1\mu s$. In low-pressure air, the collision between electrons and neutral particles hardly occurs across micron gaps, therefore, the discharge path can increase for generating positive ions. Under the positive voltage application in lower pressure, the source of initial electron can be distant from high voltage electrode and extremely high voltage is necessary for breakdown. Under the negative voltage application in lower-pressure air, the source of initial electrons is the surface of the cathode and the electric field intensity is substantially higher than the one on the insulator surface shown in Figure 3. Consequently, the breakdown voltage under the negative voltage application less increases in $t < 1\mu s$.

5. Summary

V-t characteristics of micrometer-scale surface gap were measured changing gap width, polarity of applied voltage, and gas pressure. In atmospheric air, *V-t* characteristics were almost flat and the breakdown voltage is independent of gap width. The results show that the breakdown voltage is determined by the electric field intensity on the source of initial electron. The breakdown voltage under the positive voltage application is approximately 1.2 times as high as the one under the negative voltage application. The source of initial electron under the positive voltage application can be estimated to the insulator surface in the vicinity of anode.

In lower-pressure air, the breakdown voltage increases especially in $t < 1\mu s$ under the positive voltage application. The result can be explained by the collision of electrons. In low-pressure air, the collision between electrons and neutral particles hardly occurs across micron gaps, therefore, the discharge path can increase for generating positive ions. Under the positive voltage application in lower pressure, the source of initial electron can be distant from high voltage electrode.

6. References

[1] P. Slade and E. Taylor, “Electrical breakdown in atmospheric air between closely spaced (0.2 um–40 um) electrical contacts”, Proc. of 47th IEEE Holm Conference on Electrical Contacts, pp.245-250, 2001

[2] J. M. Torres, R. S. Dhariwal: “Electric field breakdown at micrometer separations in air and vacuum”, Microsystem Technologies, vol.6, No.1, pp.6-10, 1999.

[3] T. Ono, D. Sim and M. Esashi, “Micro-discharge and electric breakdown in a microgap”, J. Micromechan. Microeng., **10**, pp.445–451, 2000

[4] F. Rezaeifar et al., “*V-t* Characteristic of Electrical Discharge across Micro Gap in Atmospheric Pressure Air”, 15th Asian Conference on Electrical Discharge, November 2010, China.

[5] H. Iwabuchi et al., "Pre-breakdown Phenomenon in Micrometer-scale Gap", 31st ICPIG, July 2013, Spain