POLARITY EFFECT ON BREAKDOWN PHENOMENON ACROSS MICROMETER-SCALE SURFACE GAP IN ATMOSPHERIC AIR

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ABSTRACT

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, breakdown and pre-breakdown phenomena under impulse voltage application across micro-meter scale gaps fabricated on SO wafers were observed. Prior to the breakdown, it was observed that current pulse flew. Changing the electrode configuration and the application voltage polarity, charge quantity, current pulse waveform, and sparkover voltage are measured. The discharge process across micrometer-scale gap was also investigated.

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 separation, 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 aluminium surface gaps [4][5]. In this paper, the breakdown and the pre-breakdown phenomena in a micrometer-scale surface gap with tungsten and titanium electrodes are experimentally investigated changing the electrode configuration and the voltage polarity. The discharge process across micrometer-scale gap is investigated.

2. EXPERIMENTAL SETUP

A pair of metal electrode was fabricated on SiO_2 insulation layer by using MEMS technology as shown in Fig. 1. The gap between electrodes were set at 1, 3, 5, 10, 50 μm. SO wafer was consisted of 525-μm thick silicon and 2-μm thick silicon dioxide. On top layer, tungsten or titanium electrodes of 100 nm thickness 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.

The measurement circuit used in this study is shown in Fig. 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 a current transformer (Tektronix, CT1, 25 kHz to 1 GHz).

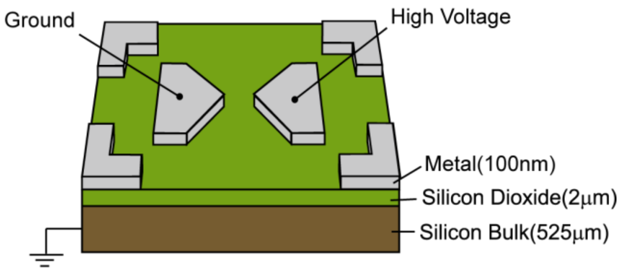


Fig. 1 Micrometer-scale surface gap

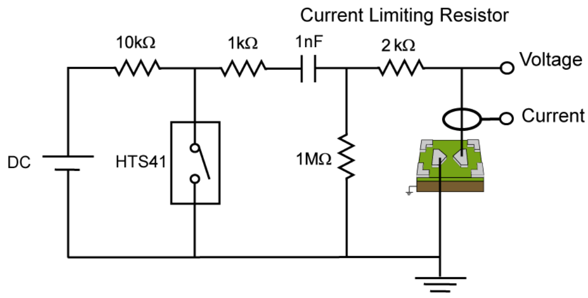


Fig. 2 Measurement circuit

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

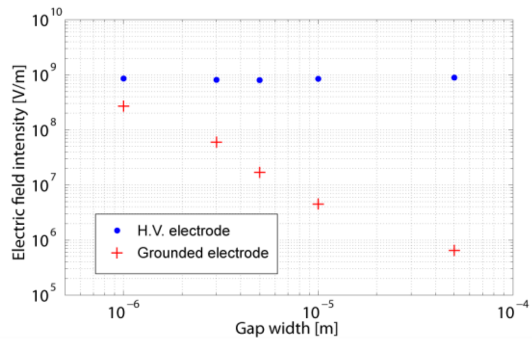


Fig. 3 Electric field intensity on the high voltage electrode and the grounded electrode

3. BREAKDOWN CHARACTERISTICS ACROSS MICROMETER-SCALE SURFACE GAP

Typical voltage and current waveforms under the impulse voltage application are shown in Figs. 4 and 5. Fig. 4 was obtained under the positive voltage application and Fig. 5 was obtained under the negative one. A pulsed pre-breakdown current is recognized to superimpose on the displacement current shown in the figures with red circles. The amount of charge emitted by pre-breakdown phenomenon was calculated by the integration of the current waveform and turned out to be more than 10^{-11} C, which indicates that electron avalanche occurs in 1-μm gap.

Fig. 6 shows the relationship between the gap width and the instantaneous voltage at the occurrence of breakdown under the impulse voltage application. The results show that the breakdown voltage under positive voltage application is approximately 1.5 times as high as the one under the negative voltage application. The result can be explained by the source of initial electrons. Under the negative voltage application, the initial electrons can be emitted from the cathode electrode surface.

On the other hand, under the positive voltage application, the electric field intensity on the cathode is strongly dependent on the gap width shown in Fig. 3 and it is substantially small to trigger field emission across the gap over 3 μm. Therefore, under the positive voltage application, the initial electrons can be emitted from the vicinity of the anode, where the electric field intensity is relatively high.

The light emission from the electrodes at the discharge occurrence was observed by an ICCD camera (Andor, INSTASPECV). Fig. 7 shows the light emission across 50-μm gap under the positive voltage application, and Fig. 8 shows the one across 1 μm gap. Both figures were obtained with tungsten electrodes. In both electrode configurations, light was emitted from the edge of the anode and emitted from the cathode locally. The melted region on the cathode after the breakdown may correspond to the weakest region on the cathode: the electric field was concentrated on that region because of the small projections. Under the negative voltage application, the result shows the same tendency to the one under the positive voltage application. The result indicates that the discharge path was formed from the small projection on the cathode to the anode edge, which is independent from the polarity of the applied voltage.

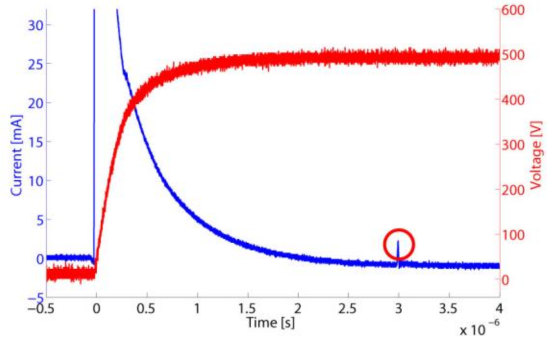


Fig. 4   Typical voltage and current waveforms under positive impulse voltage application

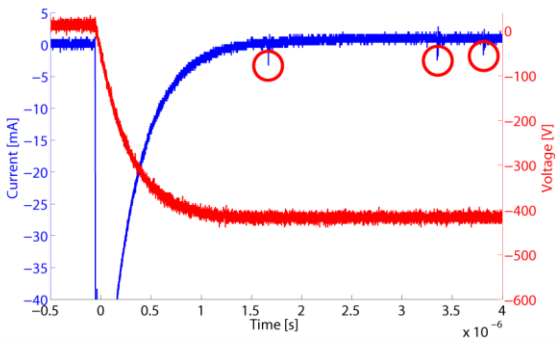


Fig. 5   Typical voltage and current waveforms under negative impulse voltage application

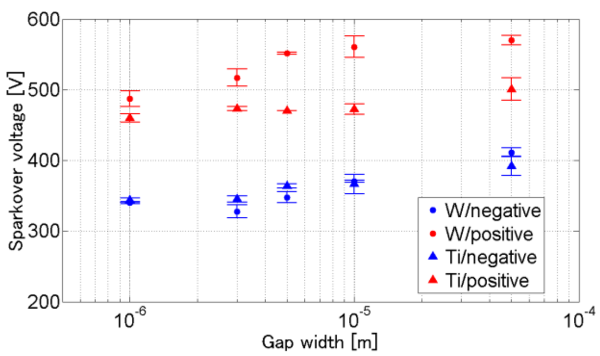
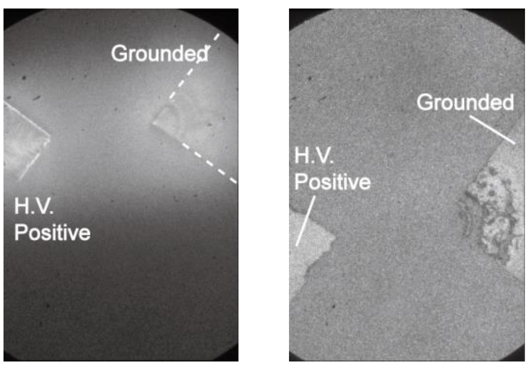
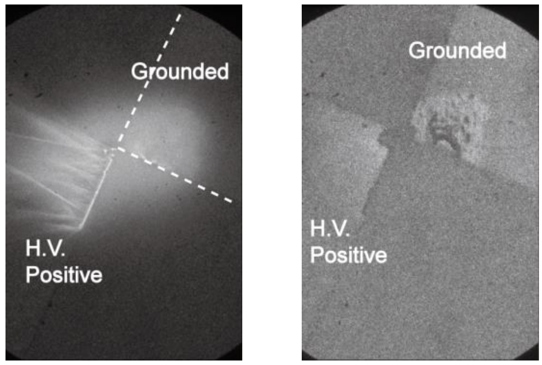


Fig. 6   Relationship between the gap width and the instantaneous voltage at the occurrence of breakdown



(a) *(b)*

Fig. 7   Picture of electrodes with 50-μm gap under the positive voltage application (a) in the breakdown (b) after the breakdown



(a) *(b)*

Fig. 8   Picture of electrodes with 1-μm gap under the positive voltage application (a) in the breakdown (b) after the breakdown

5. REAKDOWN PROCESS ACROSS MICROMETER-SCALE SURFACE GAP

In this section, the breakdown process across micrometer-scale surface gaps is discussed. In both materials of electrode, the breakdown voltage shows the same tendency shown in Fig. 6. Therefore, the material of electrode can have little effect on the breakdown process.

Under the negative voltage application, the source of initial electrons can be the cathode. As the electric field intensity on the cathode is over 10^8 V/m as shown in Fig. 3, the electric field emission can occur from the small projection on the cathode. The breakdown process under the negative voltage application is shown in Fig. 9. The electrons emitted from the small projections on the cathode can collide to the SiO_2 surface and multiplied. The SiO_2 surface is charged with positive. The electric field intensity on the cathode is strengthened by the positive charges on the SiO_2 surface. Therefore the electric field emission from the cathode is sustained and the discharge path is formed from the cathode small projection to the anode edge. In this process, a lot of metal vapors can be emitted from the electrode and the gas pressure in the micrometer-scale gap was multiplied in the vicinity of the electrode. The pre-breakdown current can occur by the local electron avalanche on the vicinity of the electrode.

Under the positive voltage application, the cathode is grounded and the electric field intensity on the cathode is under 10^6 V/m especially across the gap over 10 μm. In this case, the electric field emission hardly occurs from the electrode. The source of initial electrons can be the SiO_2 surface on the vicinity of the anode because the breakdown voltage under the positive voltage application was approximately 1.5 times as high as the one under the negative voltage application as shown in Figs. 5 and 6. The breakdown process under the positive voltage application is shown in Fig. 10. The electrons emitted from in the vicinity of the anode can collide to the anode edge and large amount of metal vapor is emitted. With the generation and the diffusion of the metal vapor, the vapor density for whole gap gradually increases. In such situation the electric field intensity on the cathode increased with the space charges in the gap. Therefore, the electric field emission from the cathode small projection is induced and the discharge path is formed from the cathode small projection to the anode edge. In this process, a lot of metal vapors can be also emitted from the electrode and the gas pressure in the micrometer-scale gap was multiplied in the vicinity of the electrode. The pre-breakdown can occur by the electron avalanche in the metal vapor.

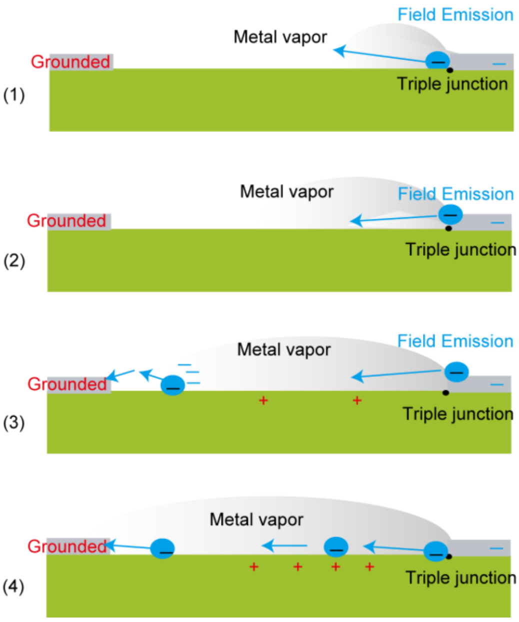


Fig. 9 Breakdown process across micrometer-scale surface gap under the negative voltage application

6. SUMMARY

The pre-breakdown and the breakdown process across micrometer-scale surface gap fabricated with tungsten and titanium electrodes were observed and the breakdown process across the gap was proposed. Under the negative voltage application, the source of initial electrons can be on the cathode, on the other hand, that is in the vicinity of the SiO_2 surface under the positive voltage application. The discharge path was formed from the anode edge to the cathode small projection. Metal vapor can play an important role to the pre-breakdown phenomena.

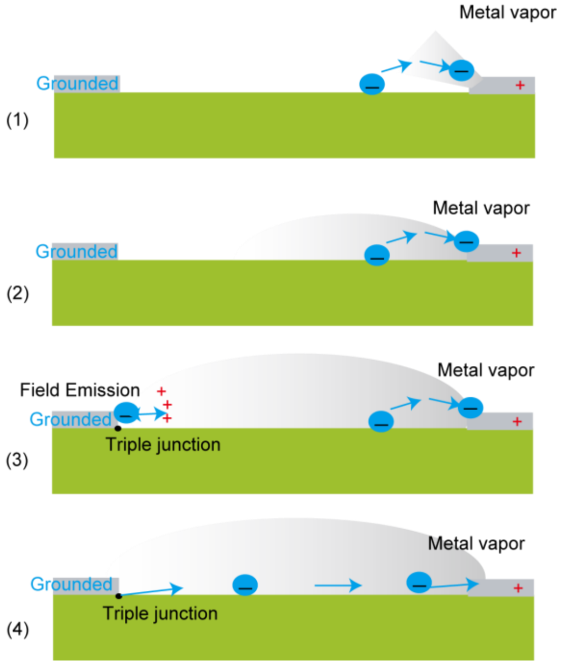


Fig. 10 Breakdown process across micrometer-scale surface gap under the positive voltage application

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