IMAGING OF MICRO-DISCHARGE IN A MICRO-GAP OF ELECTROSTATIC ACTUATOR

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ABSTRACT

Weak light emission caused an ionization process of gases in the micro gap of an electrostatic actuator under a high electric field can be imaged using a high sensitive CCD camera, even if the electric field strength is below the breakdown threshold. The observation of the ionization process give an information about a space charge distribution in gases. It is found that irregular instability and the inhomogeneous distribution of electric field develop micro-discharges. The micro-discharge evaporates an electrode material, results in increasing the pressure in the gap, finally grows up to the breakdown. This effect is seemed to be remarkable, especially in narrow gaps. Furthermore, the electric breakdown threshed depends on the electrode material. Silicon-to-silicon gap configuration shows a higher breakdown threshold as well as the prebreakdown threshold in comparison with silicon-to-metal gap. It suggests that γ_i effect plays an important role in this process.

INTRODUCTION

Electrostatic actuation is an efficient method because of the simplicity and the low power consumption for MEMS devices. Many kinds of micro-actuators based on electrostatic principle have been developed. In these actuators, a large force, a large stored energy and a long stroke is required. As we have seen, the force is proportional to the square of the field strength. Therefore, most easy method to raise the force can be achieved in making the small gap. The force is limited by a maximum electrostatic field strength which is restricted by the electric field of breakdown. The electric field breakdown sometimes causes serious damage to an actuator. The breakdown voltage (flash-over voltage) of uniform electric field between plane electrodes in air can be estimated from Paschen's low which is expressed as a function of a pressure and a gap. It is believed that, with a small gap spacing below several micrometer in air, fewer ionizable molecules lead to higher breakdown voltage from Paschen's low. However some papers reported that the breakdown threshold differs from estimated values from Paschen's low when gaps are below 3~5μm even for smooth electrode [1,2].

The breakdown in gases is generally due to the cooperation of two processes, the ionization of gas molecules by electron collision and a secondary process that ions generated by electron collision flow into the cathode surface result in electron emission from cathode surface (γ_i effects: γ_i the yield of electrons per ion incident on the cathode). Mechanism of breakdown process in smaller electrodes gap has been proposed [3], field emission current from the cathode produce a small number of ions, the space-charge field of these ions increase the field emission, that lead to a low voltage breakdown.

In this study, we observed weak photon emission from micro gap during the gas ionization and recombination processes to get an information about breakdown process and provide a monitoring technique for electrical erosion of devices during the operation.

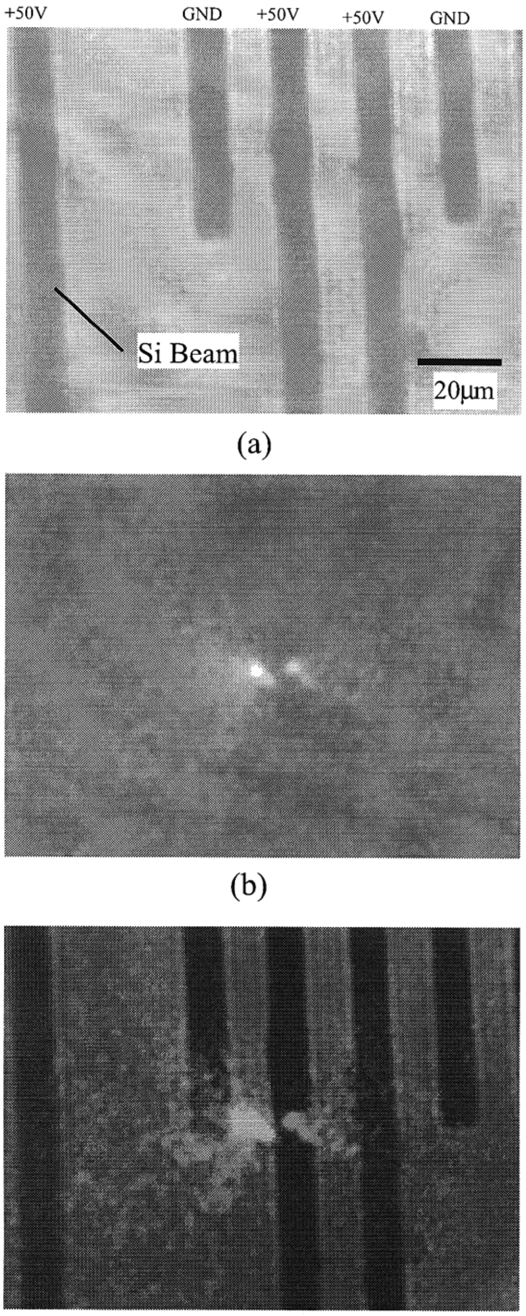
EXPERIMENTS AND DISCUSSIONS

Observation of micro-discharge in a micro gap

To visualize the ionization process, we use an extremely high sensitive CCD-camera (Photon counting type, HAMAMATU Photonics co.,VIM) which has a sensitivity in the wavelength range of 300-900nm. The weak photon images are taken using the camera under a microscope by counting and integrating the photon signal for a few minutes.

It is found that very weak photons are emitted from the micro gap via a localized ionization phenomenon even if electric field strength is lower than that expected threshold for break down.

Figure 1(a) shows the photograph of a part of an electrostatic actuator which consists of free standing silicon beams. The gap between the beams, the width and the thickness of beams is 10μm, 8μm and 15μm, respectively. The high aspect ratio structures are fabricated by ICP-RIE [4]. Thin Cr-Au film (about 5nm thick Cr, 10 nm thick Au) is formed on the vertical wall of the Si beams, and on it thin silicon dioxide film is formed by sputtering. Figure 1(b) shows the light emission image in the gap spacing between neighboring beams, which is measured by the CCD camera



(a)

(b)

(c)

Fig.1. Imaging of Micro-discharge on silicon microbeam. (a) Photograph of the structure which is consist of free - standing silicon beams. (b) Photon image when a voltage of 50V applied between neighboring beams.

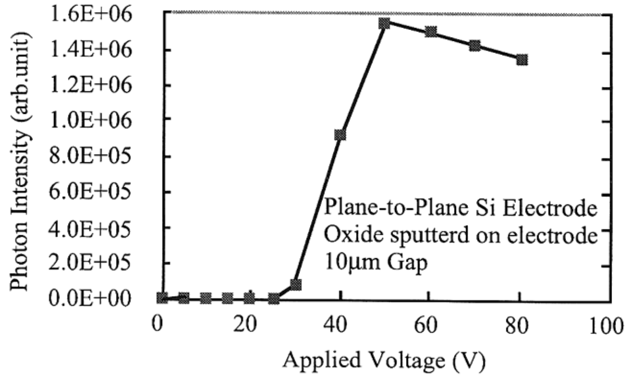


Fig.2. The light emission intensity plotted against the applied voltage.

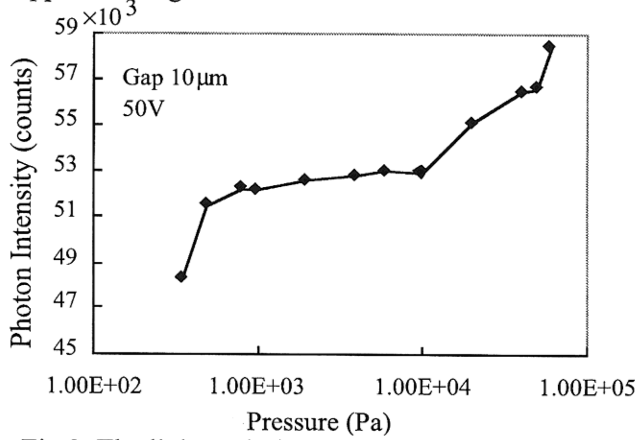


Fig.3. The light emission intensity plotted against the pressure.

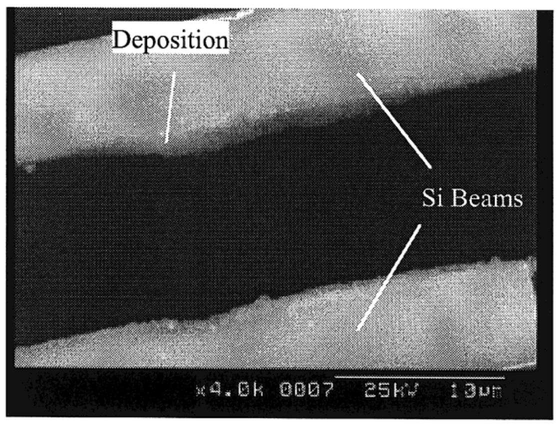


Fig.4. After discharging for about 24 hour, it can be seen deposition on the anode. Micro-discharge evaporates materials on electrodes.

in applying a voltage of 50V via a resistance of 10kΩ in air. Where images are obtained by integrating the photon signal for 1 min. The emission image is superimposed on the photograph of the structure in Fig.1(c). The photon intensity of one bright spot is plotted as a function of an applied voltage as shown in Fig.2. The light emission can be observed above a threshold voltage of about 30V below the estimated breakdown voltage, i.e., that value is about 360V. The threshold voltage is sufficient for ionization of gases. The light emission area at a low electric field has a tendency to localize and occasionally appears at the corner of the beams on which electric field will be concentrating. The pressure dependence of the emission intensity is measured in a vacuum chamber, which shows that the intensity decreases with decreasing the pressure as shown in Fig.3. This result suggests that the emission is caused from ionization of gases.

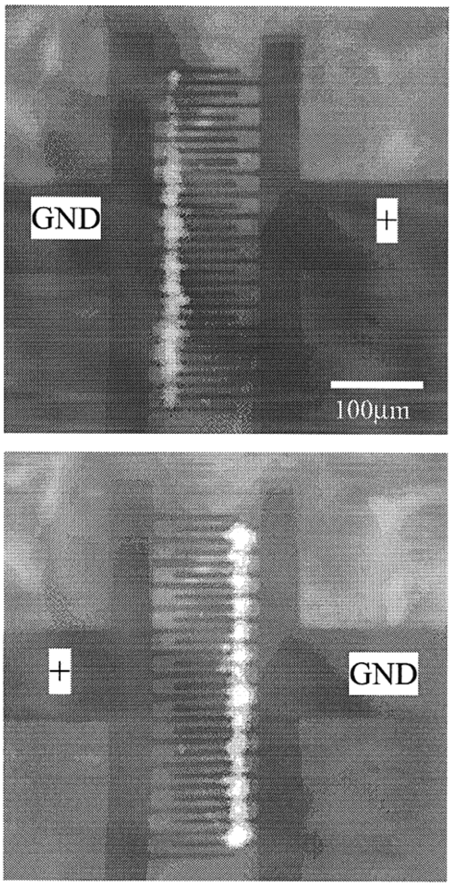


Fig.5 Micro discharge in a gap of comb actuator. When reverse voltage is applied between the electrodes, the micro-discharges occur at the another side of needles. It shows the micro-discharges has a tendency to appear mainly at the tip of the anode needles.

Figure 5 shows light emission images for a fixed silicon comb actuator of which minimum gap spacing is 7μm, and electrode height is 30μm. It shows that the very weak photons are emitted from the gap, almost near the anode. The images are obtained under a condition that the applied voltage is 200V in air, photon counting time is 10min. When reverse voltage is applied, the light emitted area is changed nearby another sides of the tips of beams. As described later, after sometimes breakdown process, the breakdown voltage reaches up to 320V of which value almost corresponds to estimated value from the Paschen's low.

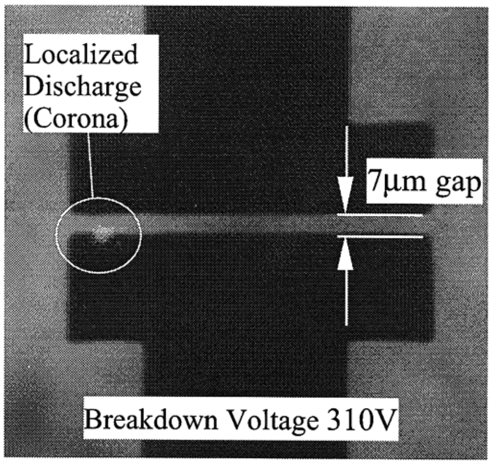
Although several types of discharges are known, it is possible to roughly classify two groups of the form. One of them is a breakdown bridged by spark between electrodes as an ionization process spreads over the electrodes gap, another is a partial breakdown referred to as corona discharge. Generally, the partial breakdown (corona discharge) occurs near the electrode if the electric field is extremely inhomogeneous, such as in a needle to-plane gap geometry. By increasing the electrostatic field of the gap, growth of the corona will leads to breakdown.

In our experiments, it is seemed that the light emission coming from localized area will be caused by ionization process of corona type micro-discharge below the breakdown threshold. The micro-discharges mostly appear in the vicinity of the anode, sometimes in the vicinity of the cathode. The reason of inhomogeneous discharge and the low onset voltage of micro-discharge may come from built in charge stored on the silicon dioxide surface of the beams. As discussed later, more higher onset voltage of a micro-discharge is observed in clean Si electrodes.

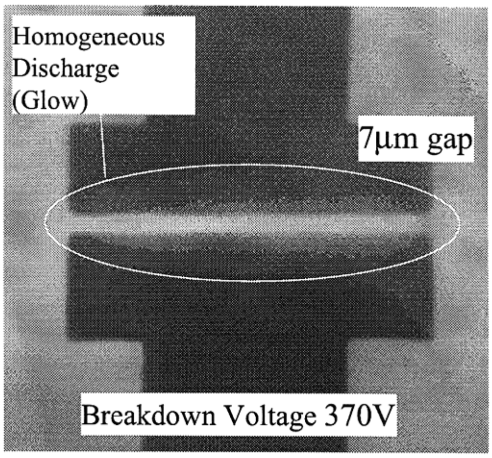
As shown in Fig.4, after discharge for 24 hours some deposition can be seen on the anode electrode near the discharge. The fact suggests that the micro-discharge evaporates or sputters the electrode material. It will increase the pressure between the gap.

Lowering of breakdown voltage by effect of micro-discharge

We investigate an influence of the micro-discharge



(a)



(b)

Fig.6. (a) Micro-discharge in plane-to-plane gap. Highly localized lower the breakdown voltage. (b) In contrast, homogeneous grow discharge appears when the breakdown voltage increase by conditioning effect.

against the onset voltage of a breakdown. As mentioned above, inhomogeneous electric field causes a localized micro-discharge. However, the micro discharge can be frequently observed on a plane-to-plane gap geometry in our experiments. Bright emission spot appears on several electrodes gap, also dark spot appears in the others. In some electrodes gaps, only one discharge spot is observed, and in the other some cases, several spots are observed. Figure 6(a) shows discharge image on which localized discharge spot can be seen at the gap of a plane-to-plane electrode structure in applying a voltage of 280V via the resistance of 10kΩ. Where the electrodes are made by silicon, and the gap, the height and the width of the electrode are 7μm, 30μm and 50μm, respectively. The breakdown voltage is determined by measuring the breakdown current. When breakdown current reaches to 1mA with increasing the voltage slowly, we regard the point as the breakdown voltage. In this procedure, the breakdown current is restricted up to maximum value of 1mA using a limiter circuit. It is found that, after few times breakdown, the breakdown voltage increases from 310V (first breakdown) to about 370V (after few times breakdown). Generally, this phenomenon is called as conditioning effect. As shown in Fig.6(b), after few times breakdown, relatively dark and homogeneous light emission is observed on the broad area of the gap instead of the disappearance of the bright spot. Same behaviors can be observed on the other electrode gap. From these results, it is considered that the micro-discharge causes a lowering of the breakdown voltage. Repeating the breakdown change the condition of electrode surface. It is found that, after few hours, the onset voltage of the breakdown dicreases again. Thin oxide of silicon surface possibly influences the onset voltage.

It should be noted that discharge current is very small, it is difficult to measure the correct discharge current in our system, the value is about 1pA against the light emission intensity of 25000 counts/min.

Micro-discharge of Silicon-Metal Electrodes

Breakdown in case of silicon-to-metal electrodes configuration is investigated. A thin Cr-Au film with the thickness of about 5nm (Cr) and 100nm (Au) is deposited on the vertical wall of the silicon electrode together with on the top-surface by oblique evaporation. The breakdown voltage and the prebreakdown light emission from the gap on an unmovable comb actuator are measured before and after metal film deposition. The gap between the comb-fingers is about 5μm. Light emission intensity of most bright spot is plotted as a function of applied voltage in Fig.7, and breakdown points are indicating in the same figure. More bright and highly localized discharge spots appear on metal deposited electrodes in comparison with

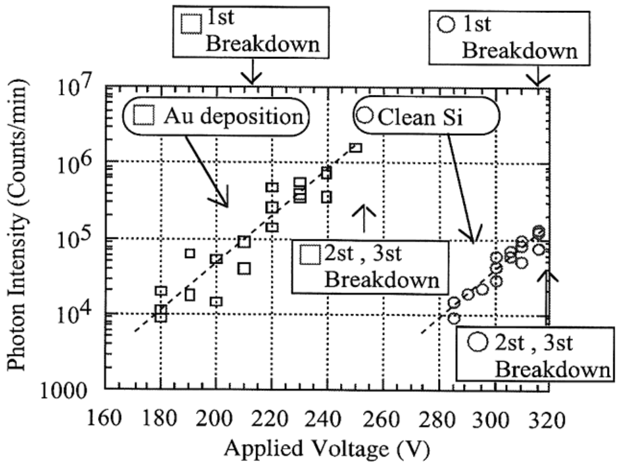
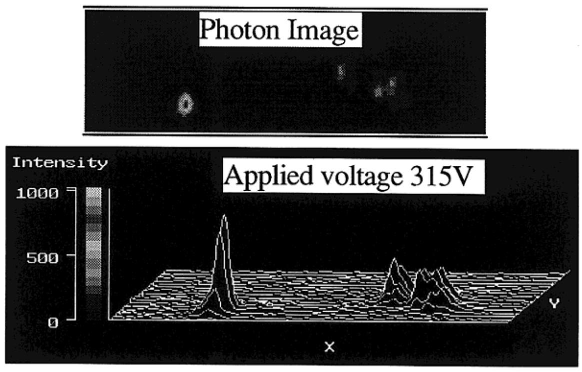
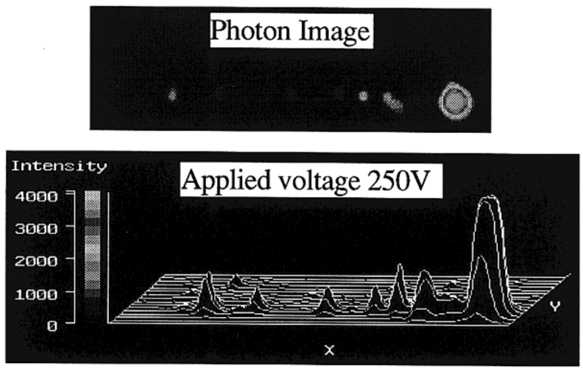


Fig.7. Relationship between prebreak-down light emission intensity versus applied voltage.



(a) Comb-actuator (Clean Silicon)



(b) Comb-actuator (after Cr-Au deposition)

Fig.8. Micro-discharge distribution (a) silicon-to-silicon electrodes. (b) silicon-to-metal electrode. Highly localized micro discharges appear on silicon-to-metal electrode.

that on clean silicon electrodes gap, as shown in Fig.8, both images are taken beneath the breakdown voltage. The onset voltage of the localized discharge for the metal deposited electrodes is about 100V smaller than that for the non-deposited electrodes. Furthermore, the breakdown voltage decreases from 320V to 255V. The breakdown voltage for the silicon-to-silicon electrodes is comparable to that estimated from Paschen's low (about 330V). These results suggest that the breakdown and prebreakdown light emission strongly depend on the electrode material. In the narrow gap configuration, the breakdown is expected to be under the influence of the electrode surface effect of ionization process: 'γ_i effect'.

2μm gap plane-to-plane silicon electrodes

According to Paschen's low, it is expected that, with a small gap spacing below about 5μm in air, fewer ionizable molecules lead to higher breakdown voltage from Paschen's low. The breakdown behaviors on plane-to-plane silicon electrodes with 2μm gap and 5μm gap have been studied. Figure 9 shows the SEM image of the fabricated test structure. The light emission intensity from gaps is plotted as a function of applied voltage as shown in Fig.10, and the breakdown points are indicating in the same figure. The 2μm gap structure shows higher breakdown voltage (380-390V) and onset voltage of the light emission than these of 5μm gap. This tendency agrees qualitatively with Paschen's low. The micro-discharges shows very unstable and irregular behavior below the applied voltage of 330V, always moving in the gap, sometimes bright and sometimes dark, and sometimes periodically fluctuating. Figure 11 shows the selected frames of light emission distribution in the gap with applying the voltage of 330V. (Concerning 5μm gap electrodes, the emission spot seems to be stable in comparison with that on the 2μm gap electrodes.) When increasing the applied voltage above 330V, the localized discharge (corona discharge) develops to a kind of glow discharge where light emission appears on relatively broad area over the gap.

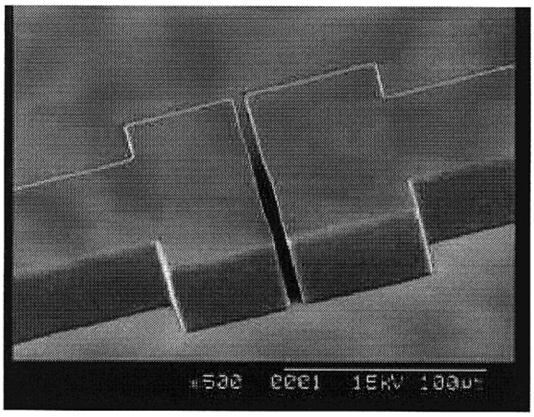


Fig.9. SEM image of fabricated silicon electrodes having a narrow gap.

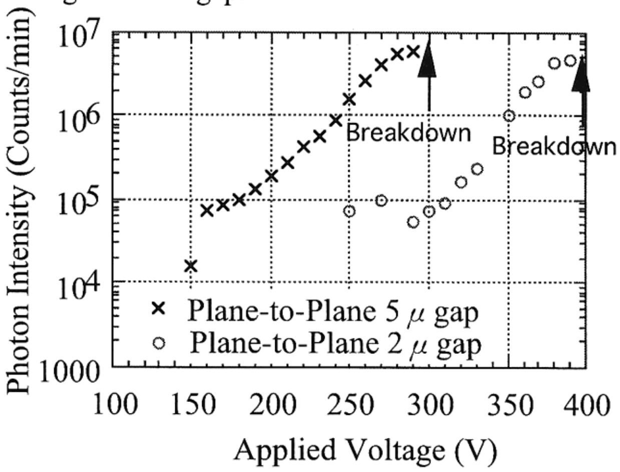


Fig.10. Relationship of light emission intensity of the micro-discharge versus applied voltage in cases of plane-to-plane 2μm and 5μm gap.

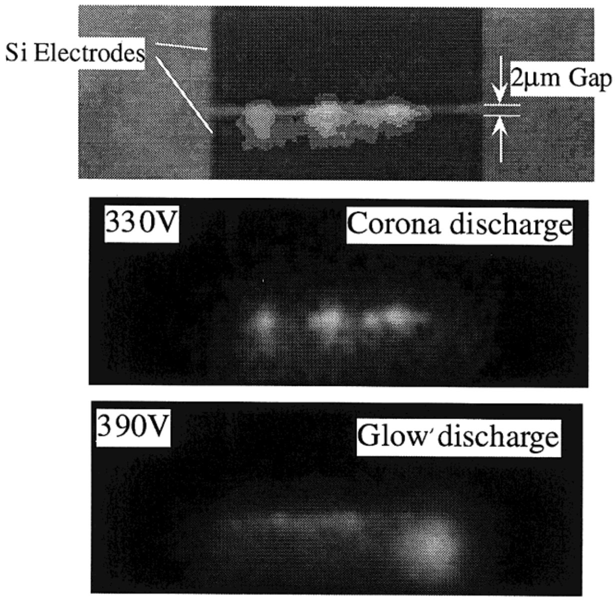


Fig.11. Irregular and instable micro-discharge (330V) appeared in 2um gap develop to in stable glow discharge(390V).

Electrostatic micro-diaphragm pump

Flashes of sparked discharge at 2μm gap of electrostatic actuator for diaphragm pump can be observed through silicon diaphragm. Figure 12 shows the capacitive structure [5] which is consists of thin p+ silicon diaphragm with the thickness of 10μm, opposite Cr-Pt electrode with a thickness of about 100nm on a glass substrate. When applying a voltage of 150V between Cr-Pt electrode and silicon diaphragm, the gap changes from 5.5μm to 2.0μm. The static deflection is confirmed by an optical displacement sensor. On the silicon diaphragm, 2.0μm height SiO_2 stoppers are formed to prevent a contact operation with the opposite electrode. Discharge make it impossible to work the device as it is operated at 150V after 120-130 times On-Off actuation because of electrical erosion of the metal electrode. Note that a current pulses of which maximum height are about few mA are observed. The movement of micro-discharge points can be monitored as an extension of the discharge area during photon counting for 10min as shown in Fig. 13. As a consequence of the micro-discharge, the anode metal electrode is appreciably eroded, leaving on it craters with the size of 2-4μm as shown in Fig. 14. In contrast,

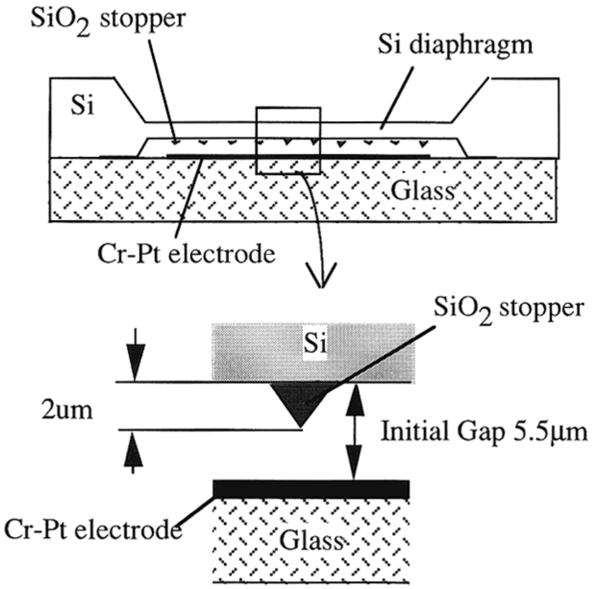


Fig.12. Schematic diagram of electrostatic diaphragm actuator for micro pump.

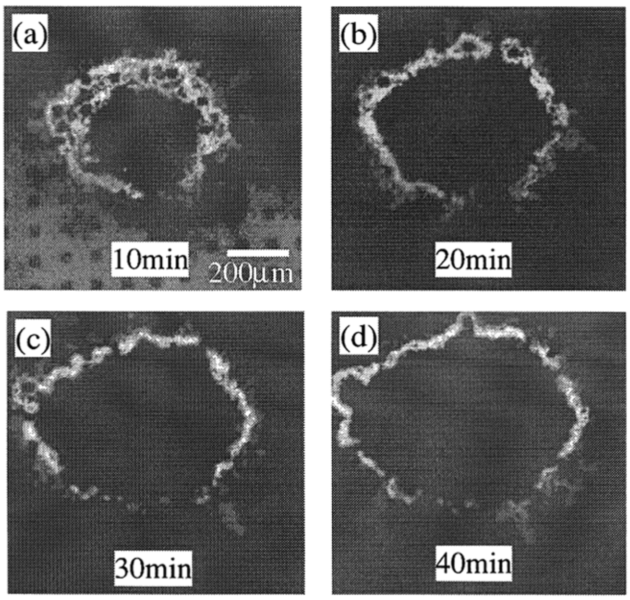
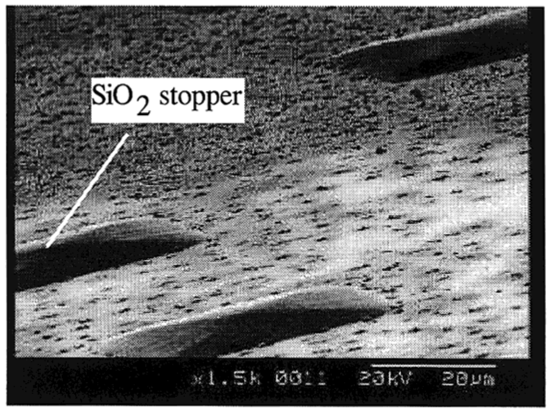


Fig.13. Spark like micro-discharges in the 2μm gap is starting from a points, gradually spreading out to the outside.

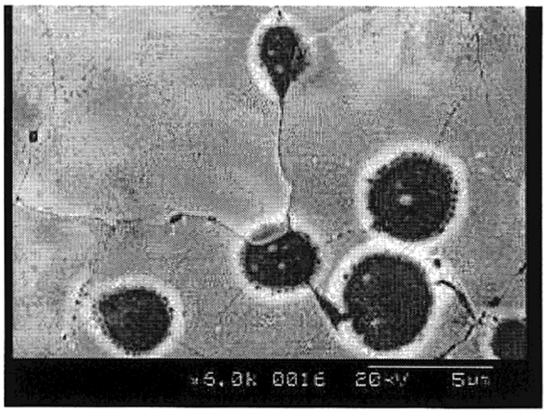
metal deposits on the cathode surface. It is seemed that the arc type discharge vaporizes the metal from the anode by electron bombardment and the heating, results in creasing metal vapor between gap and forming protrusions.

CONCLUSION

It was found that the micro-discharges were caused in micro-gap under a high electric field below the breakdown threshold due to irregularity and inhomogeneity of ionization process. The micro-discharge evaporate electrode material, which probably increase the pressure, consequently lower the breakdown threshold. Departure of breakdown from Paschen's appears especially metal-silicon electrodes configuration in which many strongly localized discharges were observed. In 2μm gap of electrostatic diaphragm actuator which consists of silicon-to-metal electrodes, breakdown occurred at 150V. It suggests that electron emission from the electrode has an influence on the breakdown in the narrow gap.



(a)



(b)

Fig.14 Electrical erosion is caused by a low voltage breakdown (sparked micro-discharge) between 2μm (a) On the cathode depositions appear. (b) On the anode craters appear.

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