Discharging behaviour on insulator surfaces in vacuum: a scanning electron microscopy observation

1997 J. Phys.: Condens. Matter 9 1631

(http://iopscience.iop.org/0953-8984/9/7/024)

J. Phys.: Condens. Matter **9** (1997) 1631–1636. Printed in the UK PII: S0953-8984(97)76197-6

Discharging behaviour on insulator surfaces in vacuum: a scanning electron microscopy observation

H Gong[†][§] and C K Ong[‡]

[†] Department of Materials Science, The National University of Singapore, Singapore 119260
[‡] Department of Physics, The National University of Singapore, Singapore 119260

Received 11 July 1996, in final form 21 October 1996

Abstract. With a scanning electron microscope, charges are implanted locally in solid insulators. Through the control of discharging conditions, various types of surface discharging behaviour are observed. The types of discharging behaviour are reflected by ripple, flooding, circular and shooting-out traces. These new observations of controlled discharging lead to a better understanding of the phenomenon of discharging and insulator breakdown.

Surface flashover or surface breakdown is believed [1–6] to develop in the following five stages:

(1) field establishment due to trapped charge in the insulator;
(2) surface charging due to the diffusion of trapped space charge or from the multiplication of secondary electrons;
(3) subsequent avalanche of the surface discharge;
(4) streamer growth of charges and
(5) finally breakdown as atoms or clusters desorbed from the insulator surface.

Recently, we investigated the nature of stages (1) and (2) using scanning electron microscopy (SEM) [7–11]. It was estimated that the internal field built up in the poly(methyl methacrylate) (PMMA) sample was in the range 2.5–4.8 MV cm^{-1} [11]. Such internal field strength is able to generate electron cascades and hence to destabilize the trapped space charge. In the present work, we attempt to investigate the nature of stages (3) and (4) of the surface flashover using SEM as well. The advantages of using SEM include the ease in selecting discharging conditions, such as the energy, the current of the incident electron probe, and the small and yet controllable area of charge concentration. In the present experiment, we have optimized the SEM conditions to induce surface discharging while the space-charge distribution is under control. This enables us to investigate the discharging behaviour before breakdown occurs.

The JSM-35CF scanning electron microscope is employed in this investigation. In this scanning electron microscope, an optical microscope whose objective lens is movable inside the scanning electron microscope chamber, a Faraday cup, a beam shutter and a liquid-nitrogen baffle are implemented in the original scanning electron microscope instrument. In addition, a picoammeter is connected to the scanning electron microscope; by using this the beam current and the leakage current can be measured. The configuration of such a scanning electron microscope allows us to control the charging and discharging conditions.

[§] E-mail address: masgongh@nus.sg

0953-8984/97/071631+06$19.50

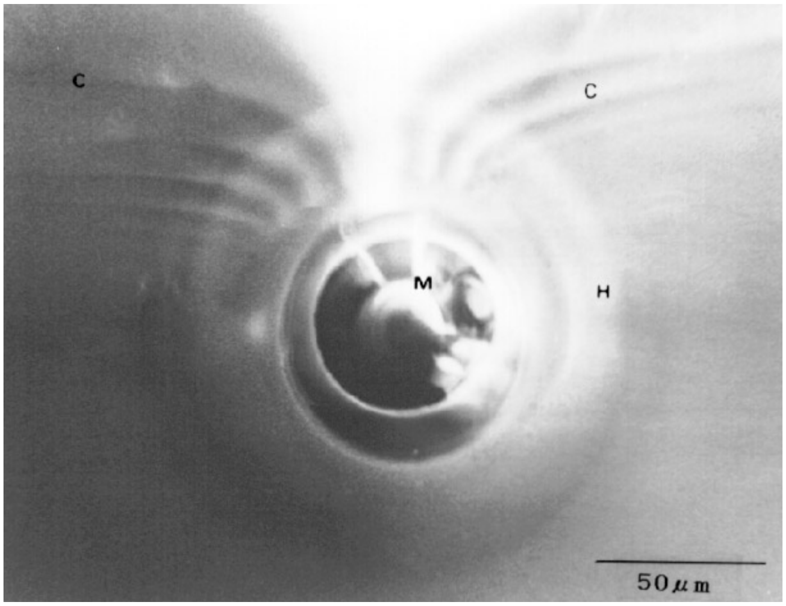

Figure 1. A SEM image showing halo (H) and curved discharging (C) traces on a PMMA surface. The central disc (M) is the mirror image of the scanning electron microscope chamber, and its centre indicates the position of the trapped-charge concentration.

Samples of PMMA of thickness 4 mm and area about 10 mm × 10 mm were investigated. They were carefully cleaned with hexane. After cleaning, each sample was loaded into the scanning electron microscope and kept in vacuum for a few hours before the experiment was performed. In the experiment, a cylindrically focused electron beam (diameter, less than 0.1 μm) of 15–30 keV hits the sample in the static mode. This leads to the implantation or the trapping of electrons locally in the insulator. The charging behaviour is deduced from the mirror image of the scanning electron microscope chamber interior [7]. For discharging to occur, it is necessary to have a perturbing source to excite the trapped electrons. The perturbing factors can be the exposure of the sample to air or the scanning of the sample surface with an electron beam. The former method is complicated by the unpredictable attack and desorption of air on the surface, while the latter allows controlled discharging to occur. In the latter method, a low-energy (1–5 keV) electron beam is scanned across the sample, resulting in the discharging of trapped electrons from the charge implantation area. Our experiments reveal that the behaviour of discharging is related to the energy and quantity of the implanted and scanning electrons, and space-charge distribution. We shall report below a few observations of surface discharging behaviour using the latter perturbing method.

Figure 1 shows a SEM image of the charging and discharging traces of a relatively unstable space-charged PMMA sample (the implantation energy is 20 keV) being scanned by a weak low-energy (1 keV) electron beam. The main features of figure 1 are described below.

(1) A central disc with the features of the scanning electron microscope chamber is the mirror image of the chamber, arising from the space charge trapped in the sample [7].

(2) In addition to the mirror-image disc, discharging traces are found. There are two types of discharging trace in this figure. One is the circular halo and the other is the stream-like curved tracks. The halo indicates that some charged electrons are diffused radially and retrapped in a ring. As we reported earlier [8], the detrapped charges accelerated by the internal field built up by the space charge will form a charge ring at a position when the energy of the excited charge is weak enough and the driving electric field is not strong enough to detrap the charge. The curved tracks observed in the upper left and right of figure 1 are evidence that the discharge process in that part of the sample has not yet formed an avalanche.

(3) The bright region observed in the upper central part of figure 1 is evidence of discharge of the surface charge. As a trapped charge is released, the lattice energy will be converted to local thermal energy and the neighbouring trapped charge will be easier to release. An avalanche of the detrapped electrons is then possible, causing the electrons to rush out to the edge of the sample which acts as an anode established by induced charge. It is seen that the main stream of discharged electrons is directed towards the centre of the upper edge, which has the shortest distance from the trapped charge and thus has a larger electrical field gradient.

(4) We also notice that the discharging traces are generally directed towards the upper edge of the scanning area and these traces are not observed in the lower half of the figure. This is because in our experiment the electron scanning is from the top to the bottom. At the time when the scanning beam reaches the lower half of the sample, the space-charge distribution has been altered such that the internal field established is not strong enough to drive charges out of the potential well and thus no discharging occurs.

Two conclusions can be drawn from this experiment. Firstly, that the discharge phenomenon is observed in the upper half of the sample before the scanning electron beam touches the central space charge suggests that the discharging is initiated from the surface charging rather than from the central space-charge distribution. Secondly, it is found that, once these traces are formed, the image will remain the same even if the same beam scanning is performed many times. This indicates that it is still possible to have a metastable equilibrium state of the space-charge distribution during the discharge stage before breakdown occurs.

The sample used in the second experiment has been charged by electron irradiation to build up the internal field which is lower than the critical value to detrap a charge. The implantation energy is 15 keV, and the sample is subjected to a scanning with a higher-energy electron beam (up to 3 keV). Figure 2 shows an image of the traces of such discharging behaviour and is a typical image of streamer growth of charges (stage (4) in the flashover processes). We observe that, on the right-hand side of the trapped charge, electrons flood out of the trapped-charge region, just like water bursting out from a dam and spreading in an open field. On the left-hand side of the trapped region, we see ripples, but they do not extend very far into the left-hand side. The ripples end on the right-hand side. It should be mentioned that flooding and ripples can appear on any side of the image. The places where they occur appear to be random. In the case of a stable space-charge distribution, the internal field built up by the space charge is not strong enough to detrap a trapped charge or to accelerate the charge to a run-away velocity. At a random position of the sample, where more charges are to be released, the diffusing barrier becomes lower as a result of the release of lattice energy, and an easy diffusion channel is formed. The flooding traces reveal that the detrapped electrons behave like fluid being transmitted with a low velocity. The appearance of ripples suggests that the detrapped electrons are of low

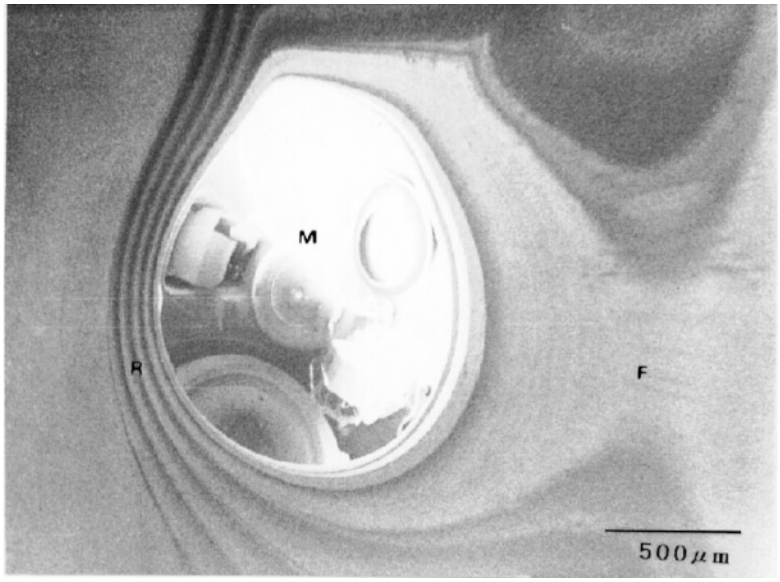

Figure 2. Flooding (F) and ripple (R) discharging traces from the trapped-charge region on a PMMA surface. The disc (M) is the mirror image of the scanning electron microscope chamber, and its centre indicates the position of the trapped-charge concentration.

energy and transmitted in the form of a wave in the sample, similar to water surface wave transmission.

Figures 1 and 2 show cases of slow or weak discharging. For a heavy charge implantation (the implantation energy is 30 keV) and a multiple discharging process using an electron beam (up to 5 keV) scanning around the trapped-charge region, we observed the discharging behaviour shown in figure 3. In the upper right corner of figure 3 lies the mirror image of the scanning electron microscope chamber which indicates the location of the implanted space charge. The image of the chamber is badly distorted with traces of charges radiating out from the implanted charge. More importantly, figure 3 shows jet-like traces in addition to a wide band of diffused electrons from the trapped-charge region. The appearance of the jet-like flashover indicates the higher energy of the discharged electrons and the lower resistance that it encountered during transmitting in comparison with the cases in figures 1 and 2. It is also interesting to observe that the parts of the jet-like traces closer to the implanted charge become fainter after a few electron-beam (1 keV) scans (which is why the continuous discharging line from the trapped-charge region is not recorded), while the parts farther away from the implantation charge are still very clear.

The observation of jet-like traces and the faintness of the traces closer to the implanted charge in figure 3 suggest that flashover is more likely to occur on the sample surface, while the slow discharging in figures 1 and 2 are more likely to occur beneath the surface layer. The reasons are as follows. Discharged electrons travelling on the sample surface, unlike those travelling inside the insulator, encounter a very low resistance so that the discharging traces are straight. In addition, the most generally accepted electron cascade model suggests that discharged electrons hop on the surface, and the impact of these electrons upon the insulator produces additional electrons by secondary emission [4]. Some of these secondary electrons again strike the surface, producing tertiary electrons. Continuation of this process

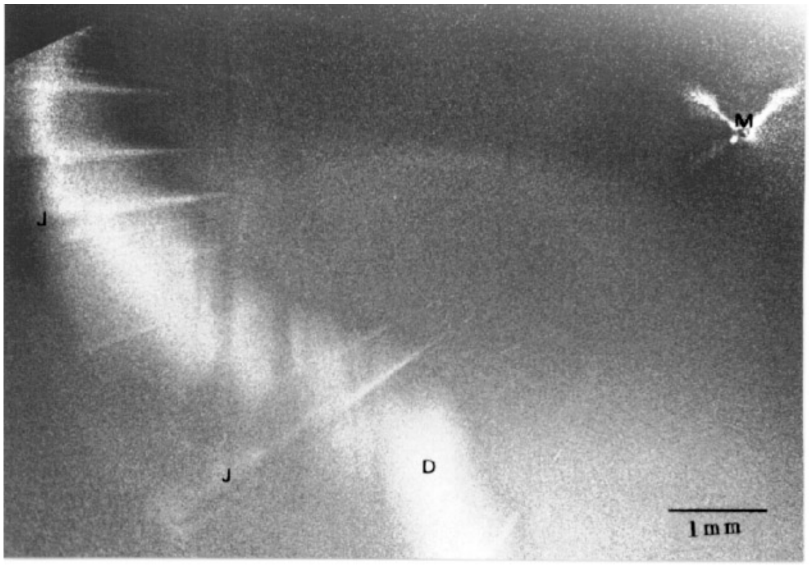

Figure 3. Jet-like (J) discharging traces and diffused electrons (D) from the trapped charge (M) lying in the upper right corner in this SEM image.

results in a secondary-electron emission avalanche (SEEA) [4]. When a SEEA occurs, one should observe an increasing secondary-electron intensity of a trace farther away from the implanted charge. These are just what we observed in figure 3. Following the SEEA theory, the appearance of curved discharge traces and ripple in figures 1 and 2 cannot be interpreted. Such observations can only be interpreted by the transportation of discharged electrons inside the insulator, where they collide with atoms, electrons and phonons so that their travelling speed is low and thus curved traces and ripple appear.

The experimental observations described above suggest that surface flashover can be investigated under controlled discharging conditions. Our controlled discharging results reveal that discharged electrons travel on or beneath the insulator surface, depending on the trapping and detrapping conditions and the speed of the discharged electrons. The experiments for slow discharging show that diffusion of charge occurs even when the perturbing electron beam is away from the trapped-charge region, and discharging charges are travelling inside the surface. The space-charge region remains relatively stable. For the case of fast discharging, the cascade of diffusion charges originates from the surface charge and the space-charge region. The diffusing charge appears to travel along the surface of the sample, and the space-charge region is collapsing.

References

[1] Le Gressus C, Valin F, Henriot M, Gautier M, Duraud J P, Sudarshan T S, Bommakanti R G and Blaise G 1991 *J. Appl. Phys.* **69** 6325
[2] Niemeyer L 1995 *IEEE Trans. Electr. Insul.* **2** 510
[3] Watson P K, Schmidlin F W and Ladonna R V 1992 *IEEE Trans Electr. Insul.* **27** 680
[4] Miller H C 1993 *IEEE Trans. Electr. Insul.* **28** 512
[5] Sparks M, Mills D L, Warren R, Holstein T, Maradudin A A, Sham L J, Loh E and King D F 1981 *Phys. Rev.* B **24** 3519
[6] Grzybowski S, Thompson J E and Kuffel E 1983 *IEEE Trans. Electr. Insul.* **18** 301

[7] Gong H, Le Gressus C, Oh K H, Ding X Z, Ong C K and Tan B T G 1993 *J. Appl. Phys.* **74** 1944
[8] Gong H, Ong C K, Chen H, Le Gressus C and Blaise G 1995 *Appl. Phys. Lett.* **67** 2243
[9] Gong H, Chooi K M and Ong C K 1994 *J. Appl. Phys.* **76** 2412
[10] Gong H and Ong C K 1994 *J. Appl. Phys.* **75** 449
[11] Chen H, Gong H and Ong C K 1995 *J. Phys.: Condens. Matter* **7** 1129