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PAPER

In-vacuum surface flashover of SiN, AlN, and etched SiO_2 thin films at micrometre scales

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Abstract

We investigate the surface flashover voltage threshold for SiO_2, SiN, and AlN thin films over micrometre scale lengths. Furthermore, we test the effects of different etching chemistries on SiO_2 layers. We find that there is little significant difference between untreated SiO_2 samples and those that have been etched with hydrogen fluoride or Transene AlPad Etch 639. SiN and AlN samples performed significantly better than all SiO_2 samples giving a 45% increase in surface flashover voltage at a distance of 5 μm with the difference increasing with electrode spacing.

Understanding and being able to predict voltage discharge in a vacuum is crucial in many areas of technology. There are three general mechanisms in a vacuum that can cause an uncontrolled and unintended voltage discharge. These are: vacuum breakdown in which field emission of charge carriers causes a direct flashover to a nearby electrode [1], bulk breakdown in which the electric field inside an insulator becomes strong enough to transition it into a conductor [2], and finally surface flashover in which charge is carried over the surface of an insulator between two electrodes. Surface flashover seems to be a weak point in vacuum insulation with bulk and vacuum flashover voltage thresholds usually being much higher than that of the surface threshold. Vacuum isolation using dielectrics is used in many areas of electronics and technology [3], including pulsed power devices [4], vacuum MEMS fabricated RF/microwave circuits [5], and microfabricated ion and atom trapping microchips [6]. Moreover, in the fast growing field of ion trapping technology the application of high RF and DC voltages to MEMS fabricated chips is extremely common. The surface flashover threshold over micrometre scale lengths of dielectrics places an upper limit on the achievable trapping depth and secular frequency [7] for many microfabricated ion traps. Higher trap depths increase the ion lifetime [8, 9] and higher radial secular frequencies reduce the Kerr coupling between the axial and radial modes during a qubit gate, which is a source of infidelity for quantum gates [10]. In this case, surface flashover can cause damage as shown in figure 1 where surface flashover has occurred between two neighbouring electrodes which are separated by 10 μm of SiO_2 rendering the device inoperable. As increasing the dielectric distance comes with challenges, finding material with a better surface flashover threshold can significantly improve microfabricated ion traps and other devices. Furthermore, many of the early experiments that empirically influenced theoretical models of surface flashover investigated millimetre scale gaps, with little data on micrometre scale stacks that are present in ion trap devices. Therefore, it is important to understand the surface flashover limitations of materials that could be used in ion trapping devices and the effects of common etching processes over micrometre scales.

While there is no consensus on the exact cause of surface flashover, it is agreed that an electron emission occurs either through field emission or thermal field emission. After this, the mechanism by which charge carriers travel along the surface of an insulator is debated with the most prevalent theory being that of the secondary electron emission avalanche (SEEA) [11]. In this mechanism, we assume a percentage of the emitted electrons will strike the insulator which has positive charges deposited on

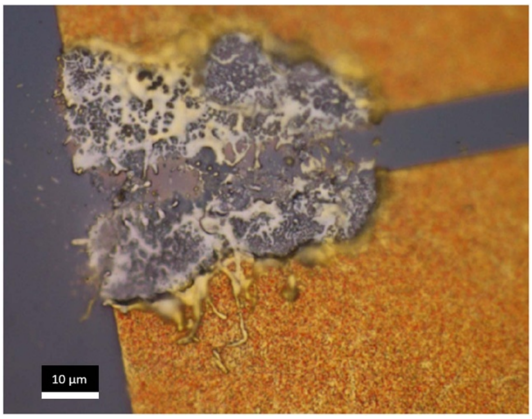

Figure 1. Sample damage after surface flashover. Damage is seen on the corners of the electrodes where the electric field is concentrated.

its surface producing additional electrons by secondary emission. Some of these secondary electrons will strike the insulator again creating a tertiary emission, and so forth. Additionally, the electron collision stimulates gas desorption from the insulator surface. As the desorbed gas reaches a certain pressure, high energy electrons in the electric field collide with gas molecules and cause collision ionisation [12]. This creates a plasma extending across the anode–cathode gap further aiding flashover. Anderson and Brainard provide a detailed explanation of this theory along with experimental data [13]. Pillai and Hackam [14] have found that the relationship between the DC voltage at which surface flashover occurs (V_f) and anode–cathode distance (D) is given as

$$V_\mathrm{f} = \sqrt{\frac{M_\mathrm{cr} E_1 v_0 e D}{2\epsilon_0 \gamma v_\mathrm{e} \tan(\theta)}}. \tag{1}$$

e and ϵ_0 in equation (1) denote the charge of an electron and the permittivity of free space respectively. Other material dependent parameters include the amount of desorbed gas per unit area at the point of flashover M_cr, velocity of desorbed gas molecules v_0, and γ the desorption probability of gas molecules. There is also dependence on the angle of impact θ of electrons colliding with the insulator, and the average electron drift velocity in the desorbed gas v_e which is related to the electron impact energy E_i by [14] $v_\mathrm{e} = 5.94 \times 10^5 \sqrt{E_\mathrm{i}}\ \mathrm{ms}^{-1}$. In Pillai's work [14], it is found that the surface charge density was correlated to the impact energy of electrons when striking the insulator surface, and indicates that the impact energy for sustained SEEA saturates near the lower critical energy E_1. The $V \sim \sqrt{D}$ relationship has been widely reported with some expanding on the theoretical model [15–17].

Electron stimulated desorption from dielectric surfaces has been studied in previous literature [18]. However, reported desorption yields span several orders of magnitude [13, 14] with their dependence on surface chemistry and roughness and other factors not fully understood As there is little widely available data regarding the parameters M_cr, E_1, v_0, and γ, and their dependence on surface condition for different materials, we will group these together with v_e and θ as a fitting parameter τ, defining it as

$$\tau = \frac{M_\mathrm{cr} E_1 v_0}{\gamma v_\mathrm{e} \tan(\theta)}. \tag{2}$$

Previous literature has taken the same approach when studying the surface breakdown in different materials [19]. From theory we expect the surface flashover threshold voltage and distance to flashover to scale as $V_\mathrm{f} \propto \sqrt{D}$. However, the data for flashover over small distances on the micrometre scale is sparse with previous literature also indicating a dependence on the surface roughness and cleanliness of the insulator [16, 20, 21].

Sterling *et al* [19] report a small reduction in surface flashover voltage when depositing the dielectric on a conductive layer compared to depositing the dielectric on another dielectric as this affects the electric field. In this work we have only carried out experiments where we have deposited the dielectric on another dielectric, meaning there may be a small deviation if the dielectric would be deposited on a conductor. Further, Sterling *et al* [19] reports a 5% difference between DC and RF surface flashover thresholds, a difference that was not statistically significant given the rest of the data.

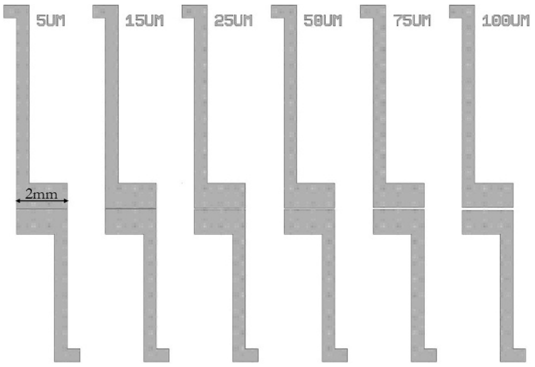

Figure 2. Electrode structure of surface flashover test chips. The distances to flashover are 5, 15, 25, 50, 75, and 100 μm.

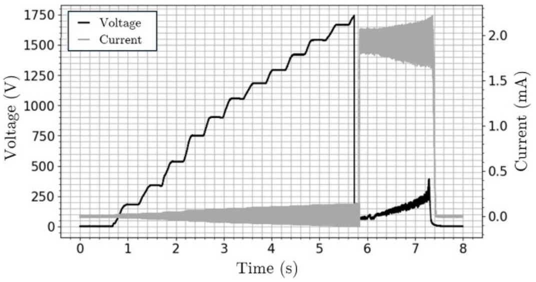

Figure 3. Raw IV data collected from a sample under test. The voltage is increased until surface flashover is detected by a spike in measured current. Surface flashover occurs above approximately 1.5 kV.

Consequently, we choose only to test DC flashover, as the experimental apparatus allows for more accurate DC measurements.

To compare the surface flashover threshold for SiN, AlN, SiO_2, and the effects of etching chemistry, we fabricate a test chip on a fused silica wafer. SiN, AlN, and SiO_2 are chosen for testing as they are commonly used materials in MEMS fabrication and can be easily integrated into ion trap designs. Fused silica is used instead of a semiconductive wafer to avoid bulk breakdown down to the substrate. A 0.5 μm thick test film is then deposited. SiO_2 and SiN samples were deposited via PECVD and AlN samples were deposited via sputtering. Next, a 0.5 μm thick Au electrode is deposited via e-beam evaporation and patterned through lift off lithography. Lift off lithography was chosen so as not to affect the surface chemistry or topology of the test film with an etching process. To test the effect of commonly used etching chemistry on the flashover voltage threshold, some SiO_2 samples were exposed for 5 s in a buffered hydrogen fluoride solution, or Transene AlPad Etch 639 (a common etchant used to etch SiO_2 which does not affect Al pads). 5 s is chosen to provide a minimal etch of the material to maintain the flashover distance while changing the surface chemistry and topography using the etching solution. The anode–cathode electrode distance D varies from 5 to 100 μm on a chip as shown in figure 2. Each gap has a length of 2 mm.

The test chips are mounted on a PCB in a vacuum chamber at a pressure of $\approx 1 \times 10^{-6}$ mbar. A variable DC power supply was used to apply a voltage to the electrodes with the current and voltage being monitored with two digital multimeters that are triggered together and are capable of 1M samples per second recording frequency (Keithley DAQ6510). The voltage applied to the chip was then increased from 0 until surface flashover occurred. With this current and voltage monitoring we are able to spot instantaneous flashovers through a spike in current and match the timestamp to the voltage that was applied at the time of flashover. A sample of data is shown in figure 3 where surface flashover occurs at above 1.5 kV. This method was validated by filming the test and spotting the visible flash and roughly matching it to the time recorded by the multimeter.

Damage caused by surface flashover on the samples is shown in figure 1. Flashes usually occur at the edges of the electrodes which is where we expect the electric field to be concentrated. Results of the experiment are shown in figure 4. The data were fitted to the equation (1) using `scipy.optimize.curve_fit` in *Python 3.13.5*. The table in the legend gives the values for the fitting parameter τ and goodness-of-fit metric R^2. The AlN and SiN samples show significantly higher surface

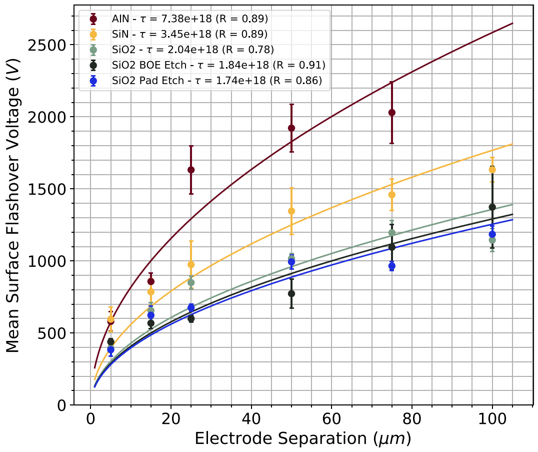

Figure 4. Surface flashover as function of electrode separation for different dielectrics (SiO_2, SiN, AlN) response from samples. The measurement data is fitted to equation (1) using a non-linear least squares regression method. The units of τ are in V m^{-2}. Data for AlN above 100 μm was not recorded as the applied voltage caused breakdown of the mounting PCB before breakdown of the device under test.

breakdown thresholds compared to SiO_2 samples. Secondly, etching chemistry seemed to have a very limited effect on surface flashover. From the data we can see over a small gap of 5 μm, on the length scales found in ion trap microchips, there is a significant increase of around 200 V in surface flashover threshold when comparing SiN and AlN samples to SiO_2. Furthermore, AlN is shown to be the most resilient to surface flashover with the surface flashover threshold exceeding 2 kV at 75 μm. For 100 μm on AlN flashovers occurred on the mounting PCB and therefore no data were for this gap recorded. We believe however that that does not impact the finding in this paper.

In conclusion we investigate the surface flashover voltage threshold of SiN, AlN, SiO_2 along with looking into the effect of different etching chemistries. We focus on micrometre scale lengths and materials used in MEMS devices that could be used in vacuum. Most of previous literature in this area focussed on millimetre to centimetre electrode spacings, with only Sterling *et al* [19]. work investigating micrometre scale surface flashover. We assumed too that the same relationship still holds at this scale. However, the goodness-of-fit metric R^2 between 0.78 and 0.91 might indicate that the relationship does not hold, but further research is required to investigate this. It was found that exposing SiO_2 samples to buffered hydrogen fluoride and Transene AlPad Etch 639 had little significant effect on surface flashover voltage threshold. However, surface characterisation before and after etching was not carried out. Further research would benefit from atomic force microscopy and x-ray photo-electron spectroscopy measurements of the surface to determine whether there is a critical point at which specific surface conditions have an effect on breakdown threshold. SiN and AlN samples performed much better than SiO_2 samples with the difference in performance increasing with anode–cathode distance. AlN samples performed best with the highest breakdown voltage at over 2 kV, however, at smaller anode–cathode gaps the difference between SiN and AlN is negligible. In the context of MEMS fabrication of ion traps where gap sizes between electrodes and ground can vary between 3 to 20 μm, voltages over 150 V are regularly applied. The surface flashover threshold can be increased by hundreds of voltages by switching from commonly used SiO_2 to AlN or SiN for dielectric insulation. As the achieved trap depth is proportional to the peak RF voltage squared [8], an increase of 45% at a distance of 5 μm translates to a $\approx$ 110% increase in trap depth, potentially leading to longer ion lifetimes and increased robustness of microfabricated ion trap devices.

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Data availability statement

The data that support the findings of this study are openly available in the supplementary information.

Supplementary data 1 available at https://doi.org/10.1088/2633-4356/ae57f6/data1.

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