Differentiation of roughness and surface defect impact on dielectric strength of polymeric thin films

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Abstract: Increasing the dielectric strength of polymer films has been a key theme as it is directly responsible for increasing energy density of relevant components such as film capacitors and insulation tapes. Dielectric films with higher roughness and surface defects are subject to the formation of an air gap at the interface between dielectric film and metallised polymer electrodes, which results in inaccurate dielectric strength. The air gap due to roughness was found to result in dielectric strength of 25% higher than that using depositing metal on dielectric films (integral electrode). The integral electrode method is proven to be a better way to test the genuine dielectric strength of thin and rough dielectric films. Surface defects, on the other hand, were revealed to cause lowering of dielectric strength because of their contribution to the localised electric field and charge injection. The detrimental effect of surface defects can be suppressed by submerging the film in oil or coating the film with an oxide layer.

1 Introduction

As one of the most critical properties for a dielectric, a higher dielectric strength represents a better quality of an insulator and is highly desirable for such applications as electrical power systems, power electronics, capacitors, cables etc. Traditionally, the short-time method for dielectric breakdown voltage is defined according to ASTM D3755-14 Standard (under direct voltage) and ASTM D149 Standard (under alternating voltage of commercial power frequencies) [1]. Either a ball–plane test fixture or parallel metal pucks are used for breakdown voltage that are applied across specimens of thickness mostly higher than 0.8 mm. As thinner dielectric materials are being developed, these methods are still used, but subject to limitation in showing genuine dielectric strength due to smaller active test areas and the increased contribution of film surfaces [2, 3]. In fact, polymer films possess three types of issues (wrinkles, roughness and defects) that complicate the measurement of dielectric strength. To minimise the area effect and the mechanical force effect for thin films, metallised polymer films were used as popular electrodes in the last decade [4–10]. The popularly used metallised polymer film electrode is metallised polypropylene (PP) or high-temperature polytetrafluoroethylene (PTFE) with metal facing the test samples with an active area of >2 cm² [11]. When a voltage is applied, the layers are drawn together by electrostatic force, creating close contact. This method has now been extended to films even thinner than 10 μm; however, the surface features such as roughness and defects have not been well-classified. The difference in their impact on the dielectric strength of dielectric thin films is not well-understood. Future’s more electric power applications require higher-voltage stress, thinner dielectric, higher working temperature for a dielectric material [12, 13]. The contribution of film thickness variability, surface defects (e.g. contaminants, pits, dimples etc.) becomes more important with decreasing film thickness. It is a valid concern simply applying metallised polymer electrodes to a dielectric film sample without considering the effect of surface roughness and defects before obtaining a genuine dielectric strength. Fig. 1 shows the schematic contact configuration and a rough surface image of a metallised polymer electrode. Obviously, the electrode surface has quite high roughness (average roughness $Sa=0.166$ μm and peak-valley roughness $Sz=1.528$ μm). Even after an attractive force exerted by an electric field brings electrode and dielectric sample closer, the rough surface from both parties still leaves air gaps in between. This is similar to a metal puck electrode being well-polished down to an average roughness of 0.2 μm [14]. Films with smaller roughness are preferred to be made as a metallised polymer electrode. Indeed, the metallised polymer technology was already used in a metallised film capacitor to enable self-healing characteristics and graceful failure [15, 16]. It makes more sense to leverage a similar method of depositing the metal onto the dielectric film for characterising dielectric films. However, the genuine dielectric strength test is made more complicated when both roughness and surface defect co-exist. Research so far have not shown a clear picture of how roughness influences the dielectric strength of polymer films thinner than ~6 μm. Moreover, they also failed to differentiate the impact of roughness and surface defects [17, 18]. Polarisation–electric-field relationship has also been commonly used as a method in various publications to determine the dielectric strength and energy density of a polymer film [19–23]. However, the test results are not reflecting the impact of surface roughness because of small active electrode areas in the tests. It can be said that the entire dielectric community has not really understood the difference in the effect of roughness and surface defects on dielectric strength. This communication will reveal the different responses of dielectric strength associated with roughness and surface defects, justify the reliable metallised film method for the characterisation of polymer films thinner than ~6 μm, and also

![Fig. 1. Schematic contact configuration and a rough surface image of a metallised polymer electrode](image-url)
Table 1  Roughness of common dielectric films  

| Polymer | Thickness, µm | Sa, µm | Sz, µm |
|---------|---------------|--------|--------|
| PI-30HN | 7.5           | 0.0198 | 0.784  |
| PEI     | 4             | 0.02   | 0.78   |
| PPS     | 8             | 0.0278 | 0.5351 |
| HCPP    | 4.8           | 0.0366 | 0.7753 |
| PPR (hazy) | 5         | 0.0468 | 1.5308 |
| PEN     | 5             | 0.060  | 0.650  |
| PTFE-1  | 4             | 0.0594 | 0.621  |
| PTFE-2  | 6             | 0.142  | 1.371  |

HCPP (high crystalline PP)  
PPR (hazy surface PP)
the ground electrode, and thus exhibits similar climbing trend in the capacitance change. The two-side metallised dielectric film samples exhibit the highest capacitance implying the maximum contact areas. These results prove that the proximity in electrode–dielectric film is critical and the roughness-caused air gap does contribute to the additional voltage withstanding capability. Integrated electrode can show the genuine dielectric strength of dielectric films. The metallised dielectric area may be utilised on one side or both sides of the dielectric films to exclude air-gap contribution, which is confirmed by capacitance measurements.

Surface defects results in lower dielectric strength, which is exhibited by performing tests in the air in comparison with test in the oil. The lowered dielectric strength issue was believed to be related to the localised field stress and plasma injection at the defects. The inorganic coating can be a good path to increase the dielectric strength and high-energy density of polymer films.

4 Conclusions

Decreasing film thickness faces challenges of increased surface roughness and defects. The use of conventional metallised polymer electrodes has the limitation for revealing the genuine dielectric strength of dielectric films because of the air gaps or uneven interfaces between the rough dielectric film and the metallised polymer electrodes. The fake higher dielectric strength can be avoided by depositing metal electrodes onto the active areas of dielectric films. The metallised dielectric area may be utilised on one side or both sides of the dielectric films to exclude air-gap contribution, which is confirmed by capacitance measurements.

6 References

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