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Original Article

Dielectric breakdown toughness from filament induced dielectric breakdown in borosilicate glass

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ABSTRACT

The dielectric breakdown strength of borosilicate glass was measured as a function of the length of a conducting filament in order to determine the critical energy release for the growth of a breakdown channel. The concept is similar to the experimental determination of the toughness in fracture mechanics and based on a Griffith type model for the electrical energy release rate in dielectric materials with space charge limited conductivity. By Focused-Ion-Beam-milling and Pt-deposition, up to 100 µm long conductive channels were fabricated in 163 µm thick borosilicate glass substrates. The dielectric breakdown strength of substrates with filaments longer than 30 µm could be very well described by a $\frac{1}{\sqrt{filament\ length}}$ -dependence predicted by the model Schneider, 2013. With these results for the first time a critical energy release rate for dielectric breakdown was determined being 6.30 ± 0.95 mJ/m.

1. Introduction

Even though dielectric breakdown is a limiting factor for the reliability of electronic devices and components [2,3,4] and despite almost 100 years of research there is no commonly accepted understanding of this phenomenon. There is a great deal of effort being made to improve electrical performance in semiconductor electronics and batteries, but only a few research groups are concerned with the mechanism of dielectric breakdown itself. It seems to be clear that like for the mechanical strength and reliability it has to be distinguished between intrinsic and extrinsic failure mechanism [5]. Applying density function perturbation theory calculations (DFPT) it was shown that von Hippels avalanche model is able to predict the intrinsic breakdown for covalently bonded and ionic materials [6]. For the extrinsic breakdown the existing experimental results are more controversial. In this investigation we favour theoretical models based on the idea of a filamentary breakdown [1,5,7]. In such a model small conducting filaments of length a underneath the electrode in an electrical insulator of thickness d and a dielectric constant ε are assumed. These might be grain boundaries, chemical inhomogeneities with locally increased conductivities or injected charges. Under the application of the external homogeneous electric field E these tiny filaments lead to an electric field enhancement at the filament tip – similar to the mechanical stress field singularity in fracture mechanics, which triggers the dielectric breakdown (Fig. 1). In analogy to fracture mechanics it could be shown that this concept enables the formulation of an energy release rate G_{bd}, which is the released electric field energy per filament extension [1].

$$G_{bd} = \frac{\pi}{8}\varepsilon\varepsilon_0 a d E^2 \tag{1}$$

ε_0 is the permittivity of free space. Dielectric breakdown occurs, when the energy release rate reaches a critical value which is G_c.

$$G_{bd} = G_c \tag{2}$$

Eq. (2) can be solved for the corresponding applied electric field at dielectric breakdown E_{bd} [1]:

$$E_{bd} = \frac{1}{c}\sqrt{\frac{6}{5\pi}}\sqrt{\frac{G_c}{\varepsilon\varepsilon_0}}\frac{1}{\sqrt{d}}\frac{1}{\sqrt{a}} \tag{3}$$

with $c \cong \sqrt{0.15}$. It has been shown in several publications that the extrinsic breakdown strength E_{bd} is proportional to $1/\sqrt{d}$ [5,8,9,10]. In addition, more recently it was shown that also the proportionality to $1/\sqrt{\varepsilon}$ holds for bulk ceramics and polymers [11]. These experimental results support the physical concept of this breakdown model.

Although the temperature dependent breakdown data from Hoshina et al. [12] up to 100 °C are best fitted by the Griffith-type energy release rate model when compared to an intrinsic and thermal breakdown model. A necessity for the result given in Eq. (1) is, that space charge limited conduction (SCLC) prevails in the electrically insulating material [11,13]. This could be shown for several ceramics and is a decisive difference to other breakdown models [11,14].

In this investigation we apply this theoretical concept to determine

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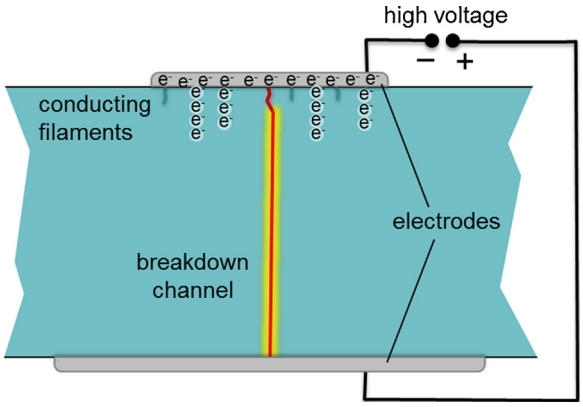

Fig. 1. Schematic illustration of the dielectric breakdown initiated by conducting filaments.

the dielectric breakdown energy release rate G_c experimentally introducing well-defined artificial conducting channels of length a and radius of curvature r_0 at the filament tip.

2. Material and methods

2.1. Material

To our knowledge there are no dielectric breakdown studies with artificially prepared conducting filaments similar to fracture toughness measurements with artificially introduced and sharpened notches [15,16,17]. Consequently the critical length of a filament as a function of the applied electric field is not known yet. The only hint we could use was our own publication [5] where we used the transition between extrinsic and intrinsic dielectric breakdown strength to estimate the size of the natural filaments of the order of some microns for ceramics. In order to avoid as much as possible natural defects such as cracks or grain boundaries as well as anisotropic material properties an amorphous glass was chosen as model material. The reason we did not use single crystals as in previous experiments [5,18] is related to the fact that we observed preferential breakdown channel directions in the single crystals along certain crystal directions.

Commercially available borosilicate cover glasses were used. A summary of the physical characteristics can be found in Table 1.

Before every measurement the samples were cleaned with ethanol and dried at 60 °C for half an hour. For conduction measurements until breakdown and breakdown tests, in addition, electrodes with conductive silver paint were applied, which is described in the following section in more detail.

2.2. Conductivity measurements

Electrical conductivity measurements were performed to determine whether the dielectric breakdown takes place in the space charge limited conduction (SCLC) regime. To cover a wide voltage range the conductivity measurements were divided in two parts. Conduction measurements up to 1 kV were performed in air with a more sensitive device and high voltage conduction measurements until dielectric breakdown were conducted in silicon oil to avoid partial discharge and flash over. All measurements were carried out at room temperature.

Table 1
Main characteristics of the used cover glass (No.1, LabSolute, Germany) at T = 293 K [19].

Material	Borosilicate glass 3.3, Th. Geyer
Composition	80.6 % SiO2, 13.0 % B2O3, 4.0 % Na2O & K2O, 2.4 % Al2O3
Nominal thickness	163 ± 7 µm*
Dimension	24 × 32 mm
Density	2.23 g/cm³
Permittivity	4*
Loss factor tan δ	0.016*
Thermal conductivity	1.2 W·m-1·K-1
Young modulus	64 GPa

* own measurement.

2.2.1. Conductivity measurements up to 1 kV

For these measurements a high-voltage meter Agilent 4339B was used. It can provide dc voltages up to 1 kV and detects currents from 60 fA to 500 µA. The measurement setup, consisting of three electrodes, is placed in a shielded resistivity cell (Agilent 16008B). With these three electrodes, namely a high-voltage (HV)-electrode with 18 mm and a ring-electrode with 22 mm diameter on same potential and the measuring-electrode with a dimension of 110 × 110 mm on opposite potential, the volume current through the sample was detected. With the ring electrode it is ensured that no surface current is detected. The voltage was applied stepwise to the samples and kept constant for 120 s, meanwhile the current was detected every 400 ms. From 1 V to 10 V the voltage was increased in 5 V-steps, from 10 V to 100 V in 10 V-steps and 100 V to 1 kV in 100 V-steps. For each voltage level, the mean current was determined from the last two-thirds of the values recorded during the measurement as done in previous work by Neusel [11].

2.2.2. Conductivity measurements until dielectric breakdown

For the conduction measurement until breakdown a combined setup consisting of high-voltage generator and a picoampere meter was used. The high-voltage generator with voltages up 70 kV ER75P4 (Glassman high voltage, Inc., UK) was linked up with a picoampere meter M1501 P (Sefelec S.A.S., France), which can detect currents from 200 pA to 2 µA. Conductive silver paint was used to provide good electric contact between the high voltage source and the substrate. The applied electrodes had different sizes to minimize field enhancements at the edges. The electrode on the ground side had a radius of R_1 = 5 mm and the electrode, which was connected to the positive high voltage, had a radius of R_2 = 9 mm (see Fig. 2b). They were dried at 60 °C for 1 h to evaporate the solvent. For the measurement the samples were clamped between a steel-made Rogowski-like profile and a brass-made pin-electrode (see Fig. 2a).

The voltage was increased in 1 kV-steps and after a stabilization time of 20 s kept constant for 5 s for the current detection. The current signal was detected every 150 ms and as for the 1 kV conductivity measurements, the mean current for each voltage level was calculated from the last two-thirds of the collected data points. The voltage was raised until it collapsed and the device changed to the current controlled mode with a current of 2 µA, indicating dielectric breakdown.

2.3. FIB-preparation

Conductive filaments of certain depth into the glass substrates were introduced using a Focused Ion Beam (FIB) instrument (FEI FIB Strata 205 single beam). It is equipped with a gallium liquid metal ion source (Ga-LMIS) for imaging and sample modification via material deposition. With two different gas injection systems (GIS) the deposition of a conductor (Pt) and an insulator (SiO_2) is possible. The acceleration voltage for the Ga^+-ions can be adjusted between 5 and 30 kV and the ion beam current can be set stepwise between 1 pA up to 20 nA maximum. The highest possible spatial resolution is approx. 7 nm. Before the samples could be inserted into the vacuum chamber of the FIB, they were cleaned with ethanol and the surface was sputtered with gold to obviate charging effects. Per sample one defined channel was milled in the middle of the rectangular substrate. For the different sized channels, pre-experiments had been conducted to determine the parameters to obtain filaments in the desired depth and shape. For this purpose, a certain circular area and depth were set in the program of the FIB and