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Size-dependence of the dielectric breakdown strength from nano- to millimeter scale

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ABSTRACT

Dielectric breakdown decisively determines the reliability of nano- to centimeter sized electronic devices and components. Nevertheless, a systematic investigation of this phenomenon over the relevant lengths scales and materials classes is still missing. Here, the thickness and permittivity-dependence of the dielectric breakdown strength of insulating crystalline and polymer materials from the millimeter down to the nanometer scale is investigated. While the dependence of breakdown strength on permittivity was found to be thickness-independent for materials in the nm–mm range, the magnitude of the breakdown strength was found to change from a thickness-independent, intrinsic regime, to a thickness-dependent, extrinsic regime. The transition-thickness is interpreted as the characteristic length of a breakdown-initiating conducting filament. The results are in agreement with a model, where the dielectric breakdown strength is defined in terms of breakdown toughness and length of a conducting filament.

1. Introduction

Since about 90 years the phenomenon of dielectric breakdown is investigated theoretically and experimentally. Dielectric breakdown is a limiting factor for the reliability of nano- to millimeter or centimeter-sized electronic devices and components (O'Dwyer, 1958; Nafría et al., 1996; Dissado and Fothergill, 1992). First theories to describe the mechanism of dielectric breakdown as an electron avalanche were developed by von Hippel (1931a, b, 1932), Fröhlich (1939) and O'Dwyer (1967). Within the same time the idea of a thermal breakdown mechanism came up (e.g. Fock, 1927; Moon, 1931; Wagner, 1948). These two basic breakdown models were later on refined for specific applications like thin films by e.g. Klein and Gafni (1966) and enhanced by e.g. O'Dwyer (1982) or Budenstein (1980). Stark and Garton (1955) developed an electromechanical breakdown model for thermoplastic polymers which later on was modified by Fothergill (1991) to a filamentary electromechanical breakdown model. The filamentary electromechanical breakdown model as well as the electro-fracture mechanics model of Zeller and Schneider (1984) based on concepts of fracture mechanics. The analogy between fracture mechanics and dielectric breakdown was also taken into account for models developed by e.g. McMeeking (1986), Suo (1993), Vojta and Clarke (1998), Fu et al. (2000), Wang and Zhang (2001), Zhang and Gao (2004), Beom and Kim (2008), Lin et al. (2009) and Schneider (2013). Whereas electron avalanche breakdown models are appropriate for thin films, gate oxides and other submicron-sized electronic devices, continuum theoretical models are necessary for macroscopic high voltage components like for example X-ray tubes, spark plugs, high-voltage cables or switches. Recently Sun et al. (2012,

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2013) showed convincingly that density function perturbation theory calculations (DFPT) based on von Hippels avalanche model are able to predict the intrinsic breakdown for covalently bonded and ionic materials.

Given the fact that the phenomenon of dielectric breakdown covers the lengths scale range from centimeter to nanometers, astonishingly there is no comprehensive study investigating its size-dependence over these lengths scales. Typically size-dependent measurements cover thicknesses over one or two orders of magnitude (e.g. Owate and Freer 1988, 1989, 1990, 1991; Malec et al., 2010). But there is no systematic study published, where the dielectric breakdown strength of different ceramic and polymer materials with relative permittivities from approximately 2–2000 over a thickness range from 2 nm to 2 mm are investigated.

The objective of this study is, to determine the size and permittivity-dependence of the breakdown strength of different insulating materials from the millimeter to the nanometer scale, and to identify the transition between a thickness-dependent to a thickness-independent regime. Such a transition region had been shown by Joffé (1927) for glass and mica, but was not systematically investigated for other materials. To achieve this goal, existing data from the literature were collected and added to own measurements in size or permittivity regimes, which were not covered. It will be shown that there exists a transition-thickness from a thickness-independent, termed intrinsic, to a thickness-dependent, termed extrinsic, breakdown regime for the investigated materials. For an application in an electrical component, the knowledge of the transition-thickness enables to decide whether an intrinsic avalanche-type model has to be applied for the theoretical description of the breakdown or whether a macroscopic continuum model is necessary.

Focusing on bulk samples (>1 μm), the experimental data basis is used to check the validity of a recently developed Griffith-type dielectric breakdown model (Schneider, 2013). Existing models, like the avalanche breakdown model, thermal breakdown model or electromechanical breakdown model do not describe the measured thickness-dependence respectively permittivity-dependence. The Griffith-type dielectric breakdown model assumes tiny, electrically conducting filaments at the surface of the samples (Fig. 1a). When a critical electrical energy release rate is reached, the longest of these conducting filaments grows unstably to form the typical breakdown channel (Fig. 1b). This critical energy release rate, named the dielectric breakdown toughness, determines vice versa the dielectric breakdown field, if the conducting filament-length is known. Until now, the length and diameter of these conducting filaments is not known. In this investigation, the transition-thickness between extrinsic to intrinsic breakdown regime will be used, to estimate the initial length of breakdown-initiating conducting filament. As a consequence, the dielectric breakdown toughness can be calculated. This approach is very similar to mechanical brittle fracture, where small cracks are assumed to be present in the material. Upon mechanical loading, the energy release rate for a crack reaches a critical value, which may result in unstable crack growth and fracture of the material. Also in the mechanical case, the transition from a thickness-independent to a thickness-dependent regime is used to estimate the length of the failure-initiating cracks (Gao et al., 2003).

2. Materials and methods

2.1. Ceramic sample preparation

Dielectric breakdown tests were performed on ceramic samples with different thicknesses d and relative permittivities ε_r. Therefor cylindrical polycrystalline Al_2O_3-, TiO_2- and $BaTiO_3$-samples with a diameter of 28 mm were prepared.

All polycrystalline samples were formed using uniaxial- and cold-isostatic dry pressing and sintered in a chamber furnace in air (for more details see Table 1). After sintering the samples were ground plan-parallel to thicknesses in the range of 0.3–2 mm. Sample thicknesses in the range of 0.7–0.24 mm were prepared by cutting grooves of different depth into 0.3 mm thick samples with a precision cutting machine (Exakt Apparatebau GmbH and Co.KG, Germany).

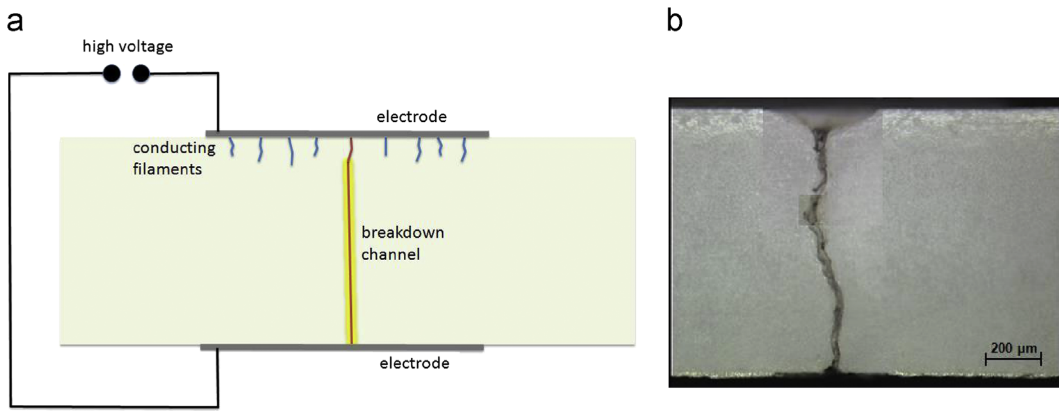

Fig. 1. (a) Schematic picture of the dielectric breakdown initiated by conducting filaments. (b) Light-microscopy image of a cross-section through an Al_2O_3 sample with a breakdown channel.