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Journal of the European Ceramic Society 32 (2012) 1053–1057
www.elsevier.com/locate/jeurceramsoc

Dielectric breakdown of alumina single crystals

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Received 7 September 2011; received in revised form 2 November 2011; accepted 9 November 2011
Available online 16 December 2011

Abstract

The bulk breakdown behaviour of alumina single crystals with two different crystal orientations, $\{1\,1\,\bar{2}\,0\}$-plane (single crystal A) and $\{0\,0\,0\,1\}$-plane (single crystal C), have been studied. Therefore, plan-parallel single crystal samples were electrically loaded until dielectric breakdown was achieved. For each crystal orientation, a characteristic breakdown channel direction through the sample could be defined. In C-oriented crystals the breakdown channel originated parallel to the *c*-axis. For A-oriented crystals, however, the breakdown channel crossed the sample in an oblique direction; the angle between crystal surface and breakdown channel was 60°. Here, the breakdown channel crossed the sample along an A-plane. Although the breakdown channel paths of A and C crystals are different, the observed breakdown strength are identical within the scatter range.

Keywords: Failure analysis; Optical microscopy; Dielectric properties; Single-crystal Al_2O_3; Insulators

1. Introduction

The phenomenon of dielectric breakdown has been investigated since about 1930, by for example von Hippel,[1–3] who studied the mechanism of electric breakdown of alkali halides. Until now, the process causing breakdown in non-conducting materials is not well-understood. For example, ceramic materials which are widely used as insulation materials in industrial applications still exhibit limitations although their dielectric breakdown strength is optimized using empirical methods. The initiation of dielectric breakdown is proposed to be an electronic dominated process[4] and can be described as a sudden destabilisation of charges trapped in the material.[5,6] Defects of the microstructure such as pores, grain boundaries, impurities, crystallographic defects and secondary phases are considered as trapping sites. Therefore, it is generally believed that the resistance against dielectric breakdown is directly connected to microstructure properties.[7–10] In the present study, the focus is on the dielectric breakdown behaviour of alumina single crystals. In order to eliminate microstructural effects, single crystals of two crystal orientations are used. A correlation between crystal orientation and development of the breakdown channel is proposed.

2. Methods

2.1. Material

Dielectric breakdown experiments were performed on commercially available high purity alumina single crystals (Table 1) produced by the Edge-Defined Film-Fed Growth Process.[11] Cylindrical samples with a diameter of 30 mm and thickness of 1.5 mm were cut and subsequently the surfaces of the samples were epitaxial polished on both sides at CrysTec Kristalltechnologie (Berlin, Germany). The two different crystal orientations tested were A-plane and C-plane, parallel to the $\{1\,1\,\bar{2}\,0\}$- and $\{0\,0\,0\,1\}$-plane (Fig. 1), respectively. In this report, samples with a surface parallel to the $\{1\,1\,\bar{2}\,0\}$-plane will be labelled as single crystals A while samples with a surface parallel to the $\{0\,0\,0\,1\}$-plane will be labelled as single crystals C.

2.2. Breakdown test

The breakdown tests were performed in silicone oil at room temperature using rectified ac voltage. For each crystal

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0955-2219/$ – see front matter
doi:10.1016/j.jeurceramsoc.2011.11.013

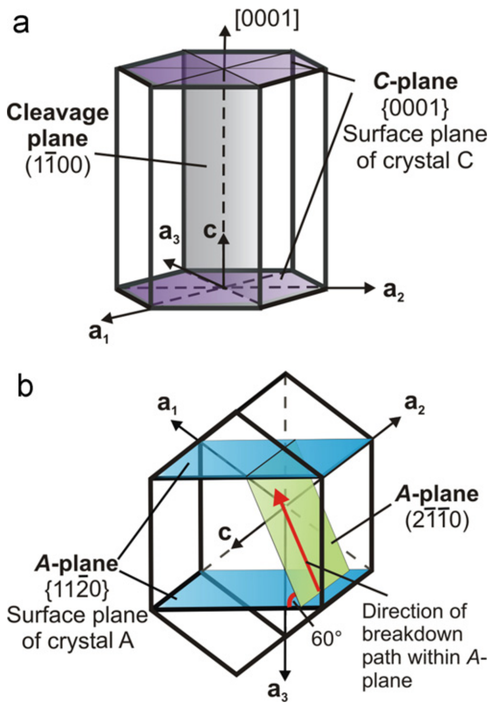

Fig. 1. Schematic picture of surface planes (a) of crystal C and (b) crystal A.

orientation, 11 samples were tested. The high voltage electrode of the measuring cell was a brass-made pin electrode with a rounded tip, enclosed with an unplasticized PVC cylinder to avoid flashover behaviour. The ground-electrode made of stainless steel has a flat surface area for contact with the sample and a rounded edge, similar to a Rogowski profile (Fig. 2). To ensure a good electrical connection between sample and electrodes, a circular shaped layer of conductive silver with a diameter of 10 mm was deposited on the sample surface. The samples with conductive silver electrodes were heated in a drying furnace at 100 °C for 5 h before testing to ensure the evaporation of solvents.

For breakdown, a voltage pulse with a frequency of 50 Hz generated by a function generator (Agilent 33220 A) was amplified from low voltage to high voltage via vacuum tubes, inductors and a transformer coil.

For the breakdown tests, the samples were placed between the electrodes and immersed in silicon oil. The high voltage signal was increased by 0.2 kV/s until the sample underwent breakdown, characterised by a collapsing voltage signal detected with an oscilloscope. In most cases, the dielectric breakdown occurred under emission of light and noise.

Table 1
Impurity content of alumina single crystal measured by optical emission spectrometer and mass-spectrometer.

Element	Content (ppm)	Element	Content (ppm)
Si	10	K	1
S	4	Ca	1
Fe	2	Ti, Y	<1
Na	1	Zr, Cr	<1

Data from CrysTec Kristalltechnologie, Berlin.

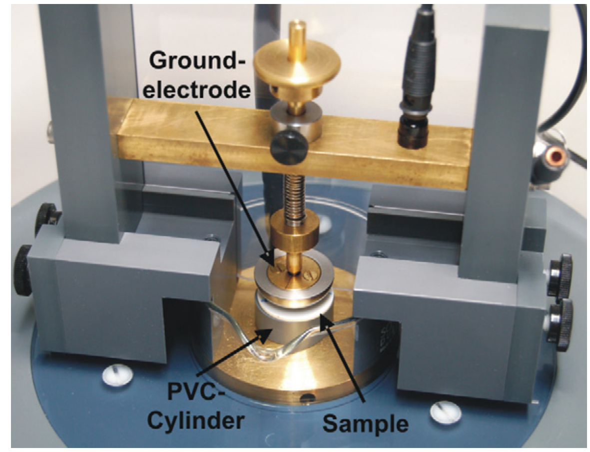

Fig. 2. Measuring cell: the high voltage pin-electrode is enclosed with a PVC cylinder to prevent flashover behaviour between high-voltage electrode and ground-electrode.

3. Results

3.1. Optical observation of breakdown channel

Fig. 3a shows a light microscopy image of the top view of a single crystal C surface ({0 0 0 1}-plane), exhibiting the opening of the breakdown channel beside the conductive

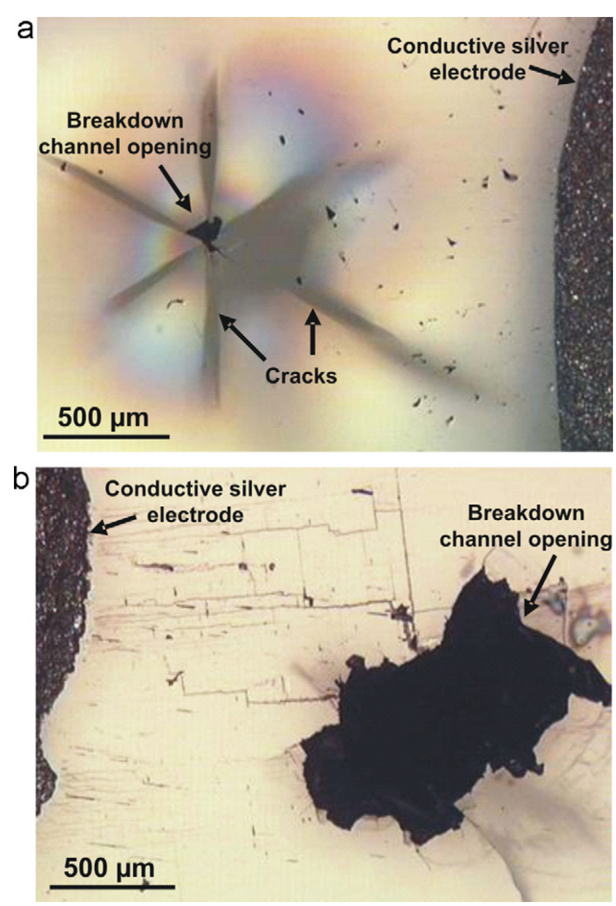

Fig. 3. Optical micrograph with polarisation filter of a characteristic breakdown channel opening (a) of single crystal C and (b) of single crystal A.