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Time-resolved imaging of the electrical breakdown of planar microelectrode gap in atmospheric air

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The aim of this study was to obtain time-resolved images of the electrical breakdown of a planar microelectrode gap along the surface of a glass substrate in atmospheric air. The obtained images revealed details of the events leading to the breakdown. First, a point light emission appeared at the cathode, indicating breakdown initiated by the field emission of electrons from the cathode under extremely high electric fields. Then, a flare-like broad light emission was generated at the anode. Finally, breakdown occurred over the entire gap by the expansion and merger of the two emissions.

1. Introduction

Electrical breakdown or electrostatic discharge (ESD) is a serious problem that has been plaguing the fields of semiconductor manufacturing and microelectromechanical systems (MEMS) for a few decades [1–3]. As predicted by the Moore's law, electronic devices have evolved to become smaller, and their operating electric field strengths have increased considerably. For example, a MEMS actuator and switch require high voltages (typically 20–50 V) in a short gap (typically less than a few micrometers) [2]. Because MEMS structures are integrated in tiny spaces, the high operating voltage may initiate electrical breakdown, causing fatal damage. ESD is generally caused by the contact between the human body and an electronic device. Charges accumulate on the surface of the human body, and when any part of the body touches a device, these charges will discharge. This discharge will generate a very high voltage spike that causes serious damage to the device [3,4]. The electrical discharge or nonthermal plasma generated in a microspace is called the microdischarge or microplasma, and it is expected to find new applications in environmental and medical fields [5,6]. Direct optical observation techniques such as streak imaging or time-resolved imaging of the electrical breakdown are powerful tools that can be used to understand the phenomenon of electrical breakdown.

The electrical breakdown of a microfabricated electrode on an insulating substrate has been studied previously. Several types of electrodes such as interdigitated [7–9], needle–plane [10], needle–needle [11,12], and parallel plane [7,9,13,14] electrodes have also been investigated. These studies mainly reported the voltage–current characteristics, breakdown voltage, and electrode damages caused by the electrical breakdown. On the other hand, optical observation of the microelectrode gap has been carried out by only a few researchers. Ono et al. observed weak light emissions from a microelectrode on the application of a prebreakdown voltage [9]. To visualize very weak light emissions, the signals over a long period were integrated into one image by using a photon-counting charge-coupled device (CCD) camera. To our knowledge, there has been no report so far on the time-resolved images of a planar microelectrode. Therefore, the aim of this study is to obtain time-resolved images of the breakdown of the microelectrodes, especially those of the initiation and development of the breakdown. We believe that such images would help us understand the details of the breakdown process.

2. Experimental method

Planar chromium microelectrodes were fabricated on a glass substrate, using a standard photolithographic process. Three

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different gap lengths—10, 5, and 2 μm—were employed. The thickness of the electrode was 200 nm. The microelectrode gap was created using semicircular electrode tips (tip radius: 25 μm) facing each other, as shown in Fig. 1(a). The electrode was placed on an inverted microscope equipped with an image-intensifying CCD camera (ICCD; C5909-06, Hamamatsu Photonics). A delay pulse generator (DG535, Stanford Research Systems (SRS), Inc.) was used to synchronize the voltage switching, camera recording, and waveform recording using an oscilloscope.

Before the experiments, the glass substrates were placed on a hot plate for heat treatment at 200 °C for 2 h, to remove water molecules adsorbed on their surfaces. The experiments were carried out in atmospheric air at room temperature (approximately 12 °C) and a relative humidity of 40–50%. A positive or negative

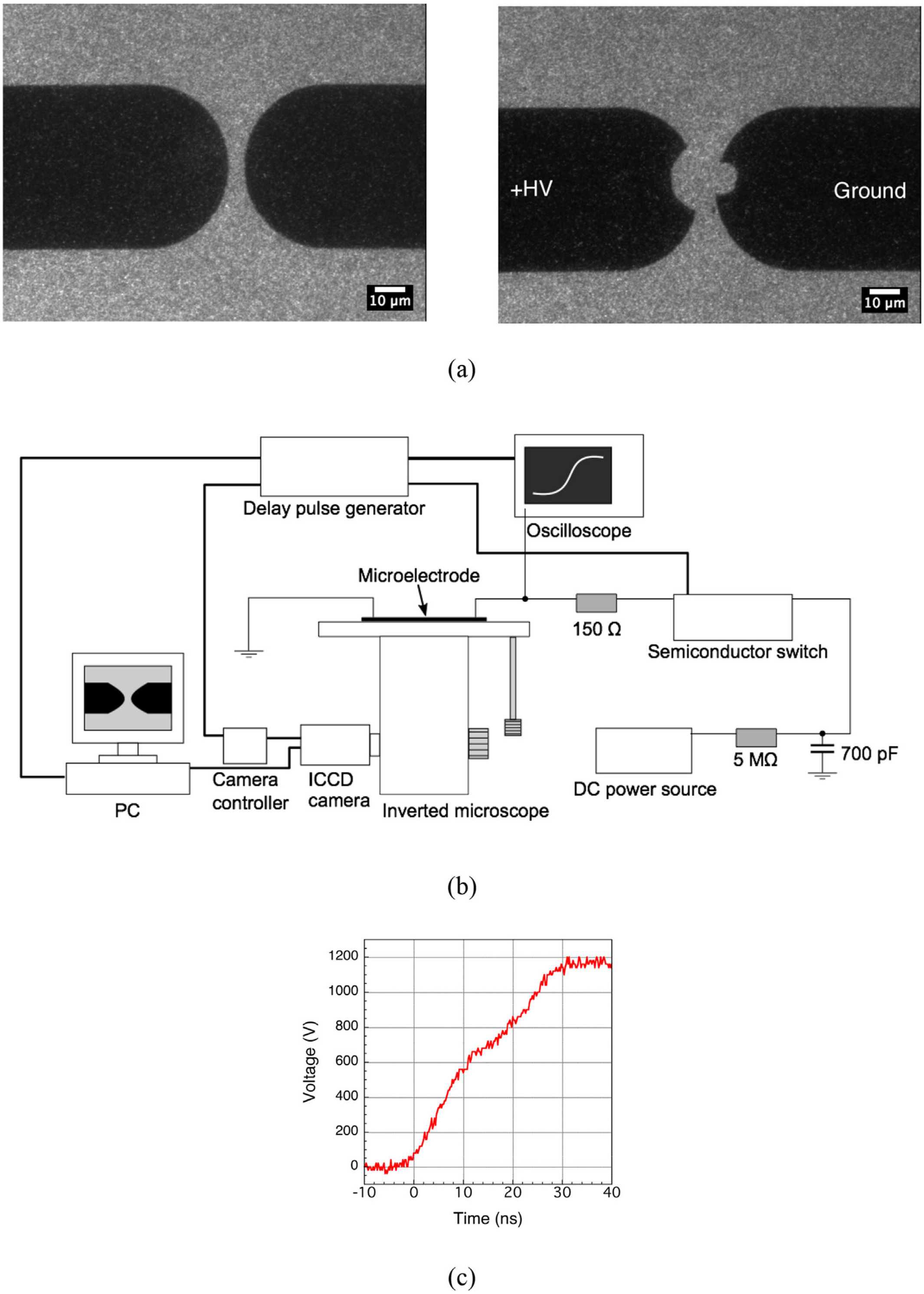

Fig. 1. Experimental setup. (a) Photographs of the microelectrode before (left) and after (right) electrical breakdown. (b) Experimental setup. (c) Typical waveform of the applied voltage (right).