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Schlieren Photography of Current Filaments in Surface-Related Breakdown of Silicon

B. J. Hankla and P. F. Williams

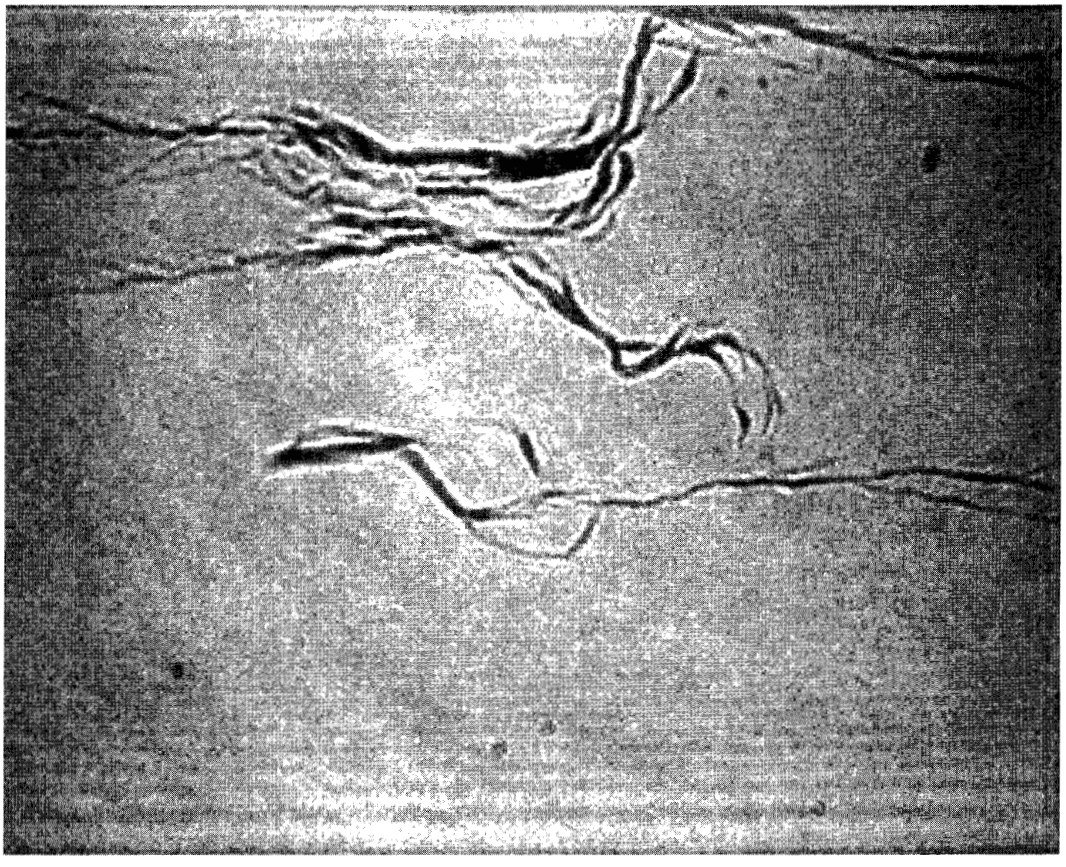

Fig. 1. Schlieren photograph showing filament formation in a p^+–p^-–n^- device. The photo was taken about 70 ns after the onset of breakdown.

***Abstract*— We have used a modified Schlieren technique to photograph current filaments formed inside silicon during the very early stages of surface-related breakdown. We believe that the features we see are due to heating in the filamentary channel. The very rapid formation of these channels suggests that they result from streamer-like phenomena in the bulk silicon.**

A surface-related breakdown process often sets the voltage threshold for semiconductor devices, but the physical basis for the process is not understood. The breakdown occurs in fields well below the dielectric strength of the semiconductor, and is frequently termed "surface flashover" since it is frequently accompanied by weak visible emission. We have been using a Schlieren-like technique [1] to obtain time-resolved images of the events occurring very early in the breakdown process. Filamentary features appear in these images within typically 10–15 ns of the start of the breakdown event, and rapidly evolve into complex structures similar to those seen in the breakdown of atmospheric pressure gases.

The sample for these studies is a rectangular prism of high-purity silicon with dimensions $1 \times 0.8 \times 0.2$ cm. The faces are prepared using a standard chemomechanical polishing process to make low-damage optical-quality surfaces. Phosphorous or boron are diffused into the 0.8×0.2 faces to form n^+ or p^+ regions, and aluminum is evaporated over these surfaces and annealed to provide convenient contact. We have used both n^- and p^- bulk material with carrier density in the 10^{11}–10^{12} cm^{-3} range to make devices. We have investigated all six possible device configurations, but show results only for a p^+–p^-–n^+ device. In low-voltage I–V measurements (up to

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800 V), the device displayed a rectifying characteristic. For voltages below about 100 V in the forward direction, the current was about what is expected based on the measured bulk resistivity, but it increased superlinearly with voltage above this point. This superlinear characteristic is not well understood, but we believe it is due to double injection.

To obtain the images, the sample is mounted between copper electrodes in a vacuum cell, and the cell is evacuated to less than 1×10^{-6} torr. One electrode is connected to a pulse generator producing pulses with about 15-ns risetime, and typically 30-kV magnitude. The other electrode was connected through a 50-Ω resistor to ground. The sample orientation is such that the voltage is applied across the 1-cm dimension of the sample.

To obtain the images, a much-attenuated and spatially filtered 1064-nm beam from a Quanta Ray DCR3 Nd:YAG laser is passed through the 0.2-cm dimension of the sample. The beam is then passed through a second spatial filter consisting of an imaging lens and a 0.2-cm diameter iris placed at its focus. The lens is adjusted to provide an image of the sample on the active surface of a sensitive charge-coupled device (CCD) camera (PAR OMA 4). Optical emission from the sample is discriminated against using a 3-mm thick Schott RG 850 long-wavelength-pass filter. Rays which pass through the sample undeflected pass through the iris and are imaged onto the camera face. Rays deflected due to an inhomogeneous index of refraction in the sample may not pass through the iris, and the corresponding regions will appear darkened in the image. The time resolution of the system is determined by the temporal width of the Nd:YAG laser, and is about 10 ns in this case.

The sensitivity of the technique to index variation is determined by the iris diameter. One cannot freely reduce this diameter, however, because the focal plane of the imaging lens contains the Fourier transform of the object. Reducing the iris diameter reduces, therefore, the spatial resolution of the imaging system. For our setup, our best sensitivity is about $\Delta n_{\min} \approx 0.01$.

Fig. 1 shows a typical photograph obtained from a p^+–p^-–n^+ device about 70 ns after the onset of breakdown. The structures seen are due to variations in the index of refraction in the silicon, caused, we believe, by heating in the current filaments. Using the data of Jellison and Modine [2], we estimate that a temperature variation of about 40°C would be easily visible. Carrier density can also modify the index of refraction. Using a simple Drude model, we estimate that a carrier density of 10^{18} cm^{-3} would produce an index variation of only about 10^{-4}. It is on this basis that we conclude that the structures we see are produced by localized heating.

Although this particular photograph was taken relatively late in the process, the structures first appear about 20 ns after the voltage is applied. The appearance of filamentary structures so early in the breakdown process is surprising, and it raises the question of what physical mechanism is responsible. We believe the most likely explanation to be the formation and propagation of streamer-like phenomena. The existence of streamer-like domains in semiconductors was first proposed by D'yakonov and Kachorovskii [3], and several workers have suggested that they might be responsible for the "lock-on" effect observed in GaAs [4], [5].

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