Reprinted from Journal of Applied Physics, Vol. 39, No. 11, 5077–5082, October 1968

Dielectric Breakdown and Recovery of *X*-Cut Quartz under Shock-Wave Compression*

R. A. Graham and W. J. Halpin
Sandia Laboratory, Albuquerque, New Mexico 87115
(Received 12 October 1967; in final form 2 July 1968)

While a shock wave is traversing a disk of *X*-cut quartz, a piezoelectric current flows in an external circuit connected across the faces of the disk. In this paper measurements of this current are used to study dielectric breakdown and subsequent recovery which occurs in quartz. Quartz specimen disks were impacted at various stress levels in such a way as to produce shock waves that propagated along the *X* axis either in the direction of or opposite to that of the pressure-induced polarization. In the latter case, short-circuit current measurements show that breakdown occurs at a threshold stress greater than 10 and less than 13 kbar. Since the impact experiment produced one-dimensional electrical and mechanical conditions in the specimen disk, it was possible to formulate a mathematical model that permitted solutions for internal electrical fields and resistivity in terms of the measured current. Computations with this model show that the field in the stressed portion of the disk at breakdown is about 7.0×10^5 V/cm, which is an order of magnitude lower than the value observed at atmospheric pressure. Computations with the model also show that recovery from breakdown to essentially infinite values of resistivity occurs during the transit time of the shock wave when the field in the stressed region of the disk is "quenched" to a value of about 1.9×10^5 V/cm. This critical field appears to be the same for all shock stress levels investigated from 13 to 35 kbar. The dependence of the initiation of breakdown on the direction of wave propagation relative to the polarization direction indicates that the shock-wave front furnishes a source of free electrons.

INTRODUCTION

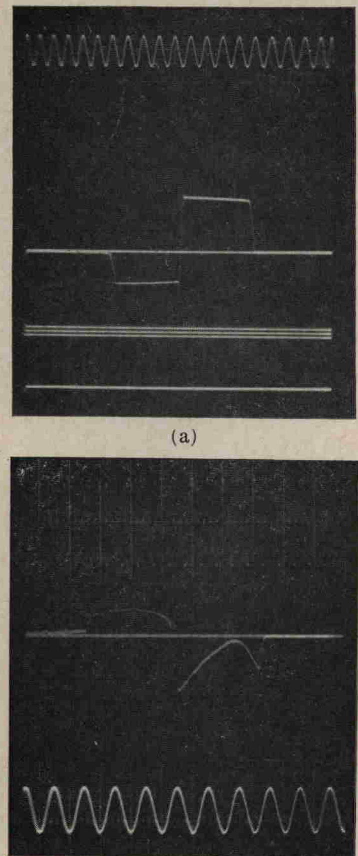
While a shock wave is traversing a piezoelectric disk, the stress-induced piezoelectric polarization produces electric fields which can approach the dielectric breakdown strength of the material at atmospheric pressure. Previously, we reported a detailed investigation of the piezoelectric, dielectric, and mechanical properties of *X*-cut quartz under shock-wave loading from 2 to 50 kbar.[1] We have also reported[2] that dielectric breakdown occurs if the quartz disk is oriented such that the polarization direction is opposite to the shock progagation direction (this is called the $-X$ orientation).[3]

* This work was supported by the U.S. Atomic Energy Commission.

[1] R. A. Graham, F. W. Neilson, and W. B. Benedick, J. Appl. Phys. **36**, 1775 (1965).

[2] R. A. Graham, J. Appl. Phys. **33**, 1755 (1962).

[3] The $-X$ orientation is obtained when the *X*-cut crystal disk is oriented such that the shock wave propagates in a direction opposite to that of the electrical polarization produced, that is, from the $+X$ electrode to the $-X$ electrode. The polarity of the electrodes is determined by placing the disk under compression and noting the direction of current flow through a high-impedance load.



(a)

(b)

FIG. 1. Typical current–time records obtained from (a) $+X$ orientation disks and (b) $-X$ orientation. Time increases from right to left. The records show the current resulting from two wave transits through the disk; the first portion of the pulse corresponds to the propagation of the impact-induced shock wave, and the second portion corresponds to the reflected pulse from the rear of the disk. The analysis is concerned only with the first wave transit. The $+X$ orientation records show no evidence of breakdown while the $-X$ orientation records show a large reduction in current resulting from dielectric breakdown when the shock wave enters the disk. The upper sinusoidal traces in (a) and (b) are 10 MHz timing waves. The lower traces are for current calibration.

Because of the simultaneous combination of stress and high values of electric field that occurs under shock loading, the shock-wave experiment provides a novel opportunity for studying the effect of stress on the dielectric strength, a subject on which there is very little data in the literature.[4]

Measurements of current in an external short circuit connected across the faces of a shock-loaded quartz disk can be used to study this dielectric breakdown behavior. When breakdown occurs, this current is characterized by an initial jump as the shock wave enters the disk, followed by a sharp drop as the high field occurring at this time initiates the breakdown process. Later in time, when the field has been quenched, there is a tendency for the current to recover. Since the previous $-X$ orientation current–time measurements[2] were taken on a specimen whose geometry resulted in three-dimensional electrical and mechanical conditions, it was not possible to obtain a satisfactory mathematical description of the physical processes involved. However, we have now conducted experiments in a one-dimensional guard-ring geometry and observed the short-circuit current during breakdown. For these experiments a mathematical description has been possible, and with it we have performed a quantitative analysis of the experimental data to obtain the transient resistivity–time and resistivity–field behavior accompanying the dielectric breakdown and recovery. It is the object of this paper to report these results.

We will first describe the experiments and the data obtained from them. Following this, a mathematical model for analyzing variable resistivity will be developed. Finally, the model will be applied to the experimental data and the results discussed.

EXPERIMENTAL OBSERVATIONS

The experiment for measuring the short-circuit current from shock-loaded quartz disks has been described previously.[1] Briefly, a projectile faced with a quartz disk is propelled down the barrel of a compressed gas gun to impact on a target that contains the short-circuited specimen disk. The impact of the two disks causes a shock wave to move into the specimen, and the amplitude of the wave is determined by the known mechanical properties of quartz and the projectile velocity, which is accurately measured. The specimen disk has a guard-ring electrode configuration to insure one-dimensional conditions, and special precautions are taken to prevent breakdown along external surfaces. Details of the specimen configuration have been described previously.[1,5] The current is obtained from the voltage drop across a known resistance which is connected across the electroded faces of the specimen.

The current–time record shown in Fig. 1(a) is characteristic of the output of disks having an orientation such that the shock wave propagates from the $-X$ polarity electrode to the $+X$ polarity electrode. No breakdown occurs in this orientation up to a shock stress of at least 30 kbar as evidenced by the approximately constant value of the current. As shown in Fig. 1(b), however, disks oriented such that the shock wave travels from the $+X$ electrode to the $-X$ electrode exhibit current–time records that deviate considerably from constant current.

Experimental current–time data were obtained in the $-X$ orientation for stresses ranging from 8 to 35 kbar. Experiments at 8 and 10 kbar showed no breakdown. The first indication of breakdown in the specimens occurred at 13 kbar. As the input stress was increased above 15 kbar, the breakdown became more pronounced with the current dropping to zero in times

[4] S. Whitehead, *Dielectric Strength of Solids* (Clarendon Press, Oxford, England, 1953).

[5] W. J. Halpin, O. E. Jones, and R. A. Graham in *Symposium on Dynamic Behavior of Materials, ASTM Special Technical Publication No. 336* (American Society for Testing Materials, Philadelphia, 1963).