for stress of approximately 52 kbar. This behavior appears to be a continuation of the trend beginning at 34 kbar. Figures 8 and 9 show two distinct processes occurring. The disruptive breakdown is very pronounced in both figures. The later behavior depends on the stress amplitude with either positive currents or internal conduction occurring for the full transit of the wave.

CHARACTERISTICS OF THE BREAKDOWN PROCESS

Several features of the negative anomaly shown should be summarized. The effect begins at low stress levels in regions considered by us to be macroscopically elastic. The field is definitely shown to be essential to the breakdown since even in the case of substantial positive currents the initial instantaneous negative field is shown to be present. There are distinct stresses and/or fields at which a change in behavior is observed. The first indication of a breakdown occurs at a field more than an order of magnitude lower than the steady-state breakdown field. The breakdown observed is definitely in the quartz itself since the specimens are carefully encapsulated in an epoxy potting compound and identical experiments for +X specimens show smooth waveforms with no evidence of breakdown. The dielectric breakdown nature of the phenomenon is also substantiated by high speed camera observations of the internal luminescence of quartz for high stress impulsive loading reported by Brooks and Neilson.[9]

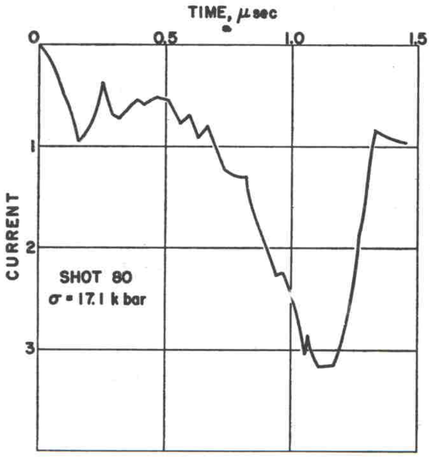

FIG. 6. 17-kbar experimental waveform.

The anomaly is also present for natural quartz. The charge observed for the three experiments performed on natural quartz are identified by the triangles in Fig. 2.

Since the breakdown process begins at such a low electric field, the effect of the transient stress is to lower the electric strength. Under static stress it has been reported[10] that for several materials the electric strength increases with compression until the elastic limit is reached and a sudden decrease in electric strength occurs. Distinct changes in the negative anomaly occur for stresses at which nonlinear mechanical behavior has been observed for quartz. Bridgman performed three linear compressibility experiments on natural quartz.[11–13] In the vicinity of 6 to 8 kbar a change in compressibility was observed. The reported crushing strength for X-cut quartz is 22 kbar.[14] Our +X experiments show a gross discontinuity in the charge-stress relation at 34 kbar. This discontinuity has the appearance of a gross mechanical yield.

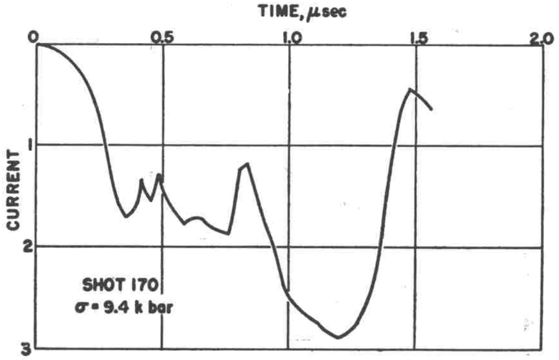

FIG. 7. 9–kbar experimental waveform.

Quartz is known to contain far fewer dislocations than metals and plastic deformation of quartz has not been

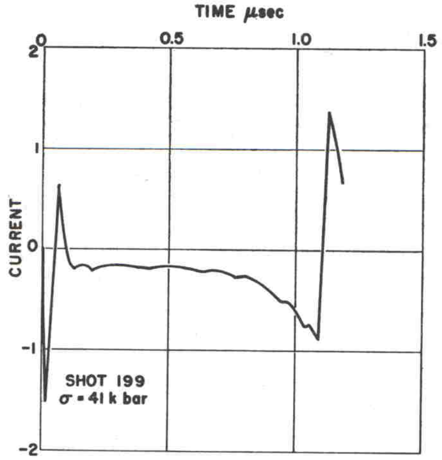

FIG. 8. 41-kbar experimental waveform.

---

[9] W. P. Brooks and F. W. Neilson, Bull. Am. Phys. Soc. **5**, 511 (1960).

[10] S. Whitehead, *Dielectric Breakdown of Solids* (Oxford University Press, Cambridge, England, 1953), p. 108.

[11] P. W. Bridgman, Am. J. Sci. **10**, 483 (1925); also shown in R. B. Sosman, *Properties of Silica, Part II* (Book Department, The Chemical Catalog Company, Inc., New York, 1927), p. 430.

[12] P. W. Bridgman, Am. J. Sci. **15**, 287 (1928).

[13] P. W. Bridgman, Proc. Am. Acad. Arts Sci. **77**, 190 (1949).

[14] R. B. Sosman, *International Critical Tables* (McGraw–Hill Book Company, Inc., New York, 1928), Vol. IV, p. 21.

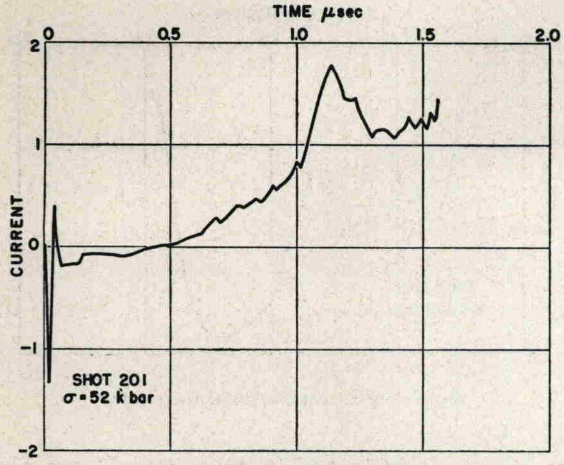

FIG. 9. 52-kbar experimental waveform.

clearly established. Dislocation densities of from 10^2 to 10^3 cm^{-2} have been reported by Hiki[15] for synthetic quartz obtained from the same source as ours.[16]

Since the observed stress for which the dielectric strength changes correlates with mechanical nonlinear stresses, a connection to dislocation motion is suggested. This correlation suggests that the ionization process is a high velocity dislocation motion at the stress wavefront. The observed low stress behavior can be explained if the dislocation motion results in liberated electrons. These experiments are unique in that a slight dislocation motion which might not be observable as plastic deformation can result in profound effects on the electric strength because of the increase in energy due to the high electric field.

Evidence of ionization due to dislocation motion has been shown by Gilman[17] who observed that dislocation motion in LiF results in charge being accumulated on the dislocation. Fischbach and Nowick[18] have reported theoretical and experimental evidence for charge separation due to dislocation motion in NaCl.

SUMMARY

A dielectric breakdown process for −X oriented quartz under transient conditions is observed which may be described as being triggered by stress-induced dislocation motion of various degrees resulting in liberated electrons which are accelerated into the stressed portion of the crystal. For the +X specimens the field direction would keep any liberated electrons at the wavefront, and their influence would only become significant when the charge became large relative to the piezoelectric charge. Once the electrons are accelerated into the stressed crystal with sufficient energy, an electric breakdown process will operate. For low energies, the impaction of the electron produces only partial breakdown, but for high energies an avalanche effect results. Above a stress which is thought to be the mechanical yield, positive currents are observed after the avalanche breakdown.

All the data given in this paper were taken from specimens of one-half inch diameter and one-quarter inch long. Under transient conditions the geometry complicates the later time behavior of the crystal. The times close to impact time, however, are a close approximation to one-dimensional behavior. Although the geometry of the crystal is not expected to alter any of the general features of the negative anomaly a quantitative description of the behavior should be observed on one-dimensional geometry specimens. Experiments on a one-dimensional geometry are planned.

ACKNOWLEDGMENTS

The author is particularly indebted to G. E. Ingram who designed and utilized the electronic circuitry used for this work and whose contributions in all respects are particularly valuable. Dr. G. W. Anderson suggested the over-all nature of the work. Dr. F. W. Neilson is largely responsible for promoting interest in this field and his advice on technical matters is of prime importance. W. D. Ingram is responsible for specimen preparation and mechanical assistance, and Mrs. Diane Martin for the data reduction.

---

[15] Y. Hiki, J. Phys. Soc. Japan **16**, 664 (1961).

[16] Our quartz is Y-bar crystal grown hydrothermally by Sawyer Research Products, Inc.

[17] J. J. Gilman, *Fracture*, edited by B. L. Auerbach, D. K. Felbeck, G. T. Hahn, and D. A. Thomas (John Wiley & Sons, Inc., New York, 1959), p. 209.

[18] D. B. Fischbach and A. S. Nowick, J. Phys. Chem. Solids **5**, 302 (1958).