than $D_1 = D_2$. In the physical sense, a positive value for F at some time t would indicate a net *rate* of loss of volume polarization in region 1 (e.g., a conduction current) while a negative value would indicate a net *rate* of gain. We now make the substitutions from Eqs. (1)–(3) for D_1 in (8) and take a derivative to obtain the differential equation

$$-dD_2/dt = UtF/[Ut+\alpha(l-Ut)] - \alpha l D_2/t[Ut+\alpha(l-Ut)]. \quad (9)$$

By assuming different functions F and certain initial conditions, it is possible to solve (9) for D_2 and then i in an attempt to fit the experimental results. However, since i is already known experimentally, a more direct approach is to obtain F in terms of i. We do this by solving (9) for F, and substituting for D_2 and dD_2/dt from (4) to get

$$F(t) = \left\{\frac{[\alpha(l-Ut)+Ut]}{Ut}\right\}(i/A) - (\alpha l/AUt^2)\int_0^t i(\bar{t})d\bar{t}. \quad (10)$$

There remains, however, the problem of interpreting the meaning of a function F in terms of known physical processes. We do this by relating F to the resisitivity in the stressed region ρ_1 and field E_1 by the expression

$$F = E_1/\rho_1. \quad (11)$$

In this way F represents a conduction current due to a field E_1 impressed on a material of resisitivity ρ_1. From Eqs. (2)–(4), (10), and (11), we can solve for ρ_1 to get

$$\rho_1(t) = t(l-Ut)\int_0^t i(\bar{t})d\bar{t} \bigg/ \left\{\epsilon_1 l \int_0^t i(\bar{t})d\bar{t} - it[\epsilon_2 Ut+\epsilon_1(l-Ut)]\right\}. \quad (12)$$

Similarly, we can solve for E_1 from Eqs. (2)–(4) to get

$$E_1(t) = -[(l-Ut)/Ut\epsilon_2 A]\int_0^t i(\bar{t})d\bar{t}. \quad (13)$$

Using these equations, we can obtain numerical solutions for ρ_1 and E_1 as functions of time by substituting experimentally determined values of current taken from the observed current–time records. This enables the resisitivity to be calculated for each experiment as the field is reduced and recovery from breakdown occurs.

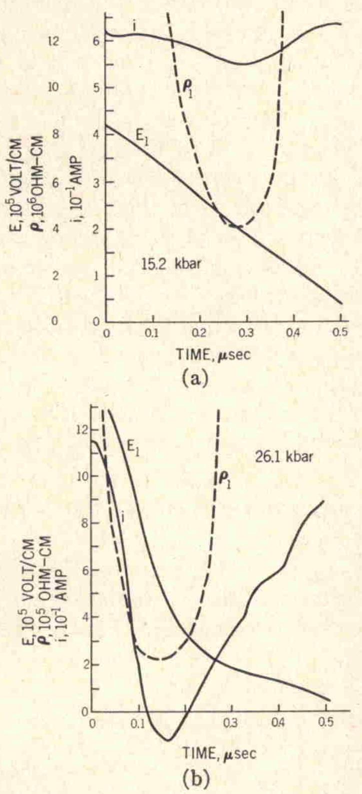

FIG. 5. Typical current–time records for the $-X$ orientation with the resulting calculated resistivity–time and field–time behavior. The current–time records are adjusted to compensate for the short but finite risetime of the current pulse resulting from impact "tilt."

RESULTS AND DISCUSSION

The first indication of breakdown was observed in the $-X$ orientation at a stress of 13 kbar. The maximum field at this stress as computed from Eq. (7) (for $t=0$) is 7.0×10^5 V/cm.[11] This field is almost an order of magnitude smaller than the field required for breakdown at atmospheric pressure.[12]

Resistivity ρ_1 vs time and field E_1 vs time, computed by applying Eqs. (12) and (13) to the current–time pulses obtained at stresses of 15 and 26 kbar, are plotted in Fig. 5. The more rapid reduction of E_1 with time shown in the 26 kbar record should be compared with the linear decrease in time to be expected when resistivity is infinite (and $\alpha=1$) (see Fig. 4). The behavior of ρ_1 is seen to be highly time dependent, thus demonstrating that analysis of the current–pulse data based on the assumption of constant resistivity would be of little value. The main features of the ρ_1 vs time curves are a rapid reduction in resistivity when breakdown occurs, followed by a recovery later in time when the field is "quenched" to some lower value.

Graphs of resistivity ρ_1 vs field E_1 are shown in Fig. 6 for various values of stress from 13 to 36 kbar. Although

[11] For this computation, ϵ_1 is taken as 4.00×10^{-13} F/cm from the atmospheric pressure value of R. Bechmann, Phys. Rev. **110,** 1060 (1958), and the observed 0.3% increase in permittivity with stress reported in Ref. 1. The polarization, P, is also taken from Ref. 1 as 2.78×10^{-7} C/cm^2.

[12] A. Von Hipple and R. J. Maurer, Phys. Rev. **59,** 820 (1941).

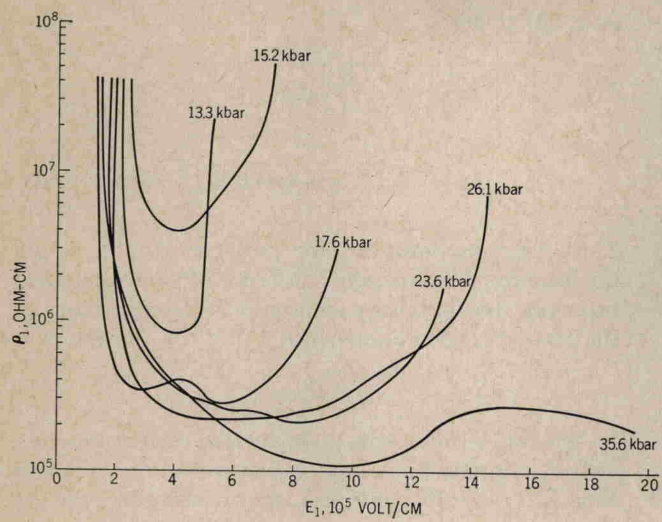

FIG. 6. Resistivity vs field calculated from the observed current–time records. Breakdown occurs at field values to the right of the figure while recovery occurs later in time as the field decreases to values on the left. At all stress levels the resistivity calculated from the observed current–time waveforms is seen to approach an infinite value ($>4\times10^7$ Ω·cm) when the field is reduced to $1.9\pm0.5\times10^5$ V/cm.

each experiment shows behavior of a somewhat different character, there is one distinct feature of the recovery which is common to all experiments. Recovery of essentially infinite values of resistivity ($>4\times10^7$ Ω·cm) occurs over a surprisingly narrow range of fields for all stress levels. Thus, it appears that there is a stress-independent critical field of $1.9\pm0.5\times10^5$ V/cm for the recovery of quartz from dielectric breakdown.

The solutions for ρ_1 at later times after complete recovery give negative values (not shown in the figure) which indicate that a net gain in the rate of electric displacement occurs after recovery becomes well established. This represents the return of previously "shorted" material to a polarized state, which is the expected behavior.

These results describe two phases of the dielectric breakdown phenomena which are: (1) the initiation of the breakdown and (2) the recovery that follows when the electric field is quenched. In shock-loaded *X*-cut quartz, breakdown occurs in the $-X$ orientation, but when the field polarity is reversed, that is, when the quartz is in the $+X$ orientation, breakdown does not occur. Since the field that is present during breakdown is in a direction to accelerate electrons from the shock-wave front into the stressed region of the quartz, it appears that breakdown is initiated from a source of free electrons at the shock-wave front. The presence of free electrons at the front requires shock-induced electronic energy level changes which cannot be accounted for by the magnitude of the strain energy behind the shock wave, although they can easily be accounted for by the motion of dislocations in the wave front. Apparently, the high shear stress in the wave front causes localized dislocation motion, even though the stress behind the wave is considerably less than the Hugoniot elastic limit[13,14] of about 40 kbar.

The phenomenon of a dependence of conduction processes under shock loading on the direction of the stress-induced electric field is not restricted to quartz alone. Recently, for example, Cutchen[15] has shown the effect to occur in ferroelectric ceramics.

The results of the analysis of the recovery process after breakdown in shock-loaded quartz show that the recovery of high-resistivity values occurs when the electric field is quenched to a value of about 1.9×10^5 V/cm. Since this value of field is characteristic of all shock stress levels from 13 to 36 kbar, it appears there is a critical field for recovery which is independent of the stress. The experiments at the various stress levels produced different values of piezoelectric polarization in the quartz specimens so that upon breakdown different values of current were involved. Thus, for the range of currents in the experiment, the critical field for recovery also appears to be independent of the current. Because the critical field determined here does not depend on stress, it may be characteristic of recovery from dielectric breakdown at atmospheric pressure.

ACKNOWLEDGMENT

The authors are pleased to acknowledge the valuable technical assistance of G. E. Ingram and numerous helpful discussions with their Sandia Laboratory colleagues.

[13] Jerry Wackerle, J. Appl. Phys. **33**, 922 (1962).
[14] Richard Fowles, J. Geophys. Res. **72**, 5729 (1967).
[15] J. Thomas Cutchen, J. Appl. Phys. **37**, 4745 (1966).