Piezoeletric Current from x-Cut Quartz Subjected to Short-Duration Shock-Wave Loading*

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When an x-cut quartz disk is subjected to an impulsive load, the piezoelectric current in an external short circuit is ordinarily an accurate time-resolved replica of the stress history at the input electrode. Recently, it has been observed that stress pulses whose durations are less than the shock-wave transit time through the disk sometimes produce anomalous current-vs-time responses. In the present work, x-cut quartz disks are subjected to stress pulses of six different durations and with amplitudes from 9 to 29 kbar. Carefully controlled accurately known pulses are applied to the samples by the impact of projectile-mounted quartz disks of various thicknesses. The piezoelectric current accompanying each stress pulse is continuously monitored as the pulse propagates through the sample disk. It is found that the anomalous current is a consequence of shock-induced conductivity in the region of the quartz disk that has been shock loaded and subsequently unloaded to a lower stress value. The threshold for conductivity is found to depend upon both stress amplitude and pulse duration. The threshold is further determined to be controlled both by a critical unloading stress value and by a critical electric field value. The critical unloading stress value is found to be 11.2 ± 0.7 kbar, and the critical electric field is found to be $(2.8 \pm 0.3) \times 10^5$ V/cm.

I. INTRODUCTION

When an x-cut quartz disk is subjected to shock-wave loading, the piezoelectric polarization produces a current in an external circuit connected between electrodes on the two faces of the disk. In previous papers[1–14] various characteristics of this current have been described for shock loading from 2 to 300 kbar. It has been shown[4,6,10] that in a linear approximation, independent of the wave profile, the short-circuited current $i(t)$ is given by the relation

$$i(t) = (kA/t_0)\,\sigma(t), \qquad 0 < t < t_0, \tag{1}$$

where k is a piezoelectric current coefficient, A the area of the charge-collecting electrode, t_0 the time required for a shock front to traverse the quartz disk at the adiabatic sound speed of 5.72 mm/μsec, and $\sigma(t)$ the stress history at the input electrode. This linear approximation is the basis for a time-resolving quartz stress gauge that has been widely used for stress measurements up to about 25 kbar. The wide use of this "Sandia quartz gauge" as a shock-profile detector is largely a result of its ability to respond accurately to stress pulses of *arbitrary profile* within restricted stress ranges.

Recently, several investigators reported that quartz disks, constructed and used as quartz gauges, *sometimes* exhibited responses that were grossly different from those predicted by Eq. (1), when they were subjected to stress pulses with durations less than the wave transit time t_0 in the gauge. Typical of these "anomalous" responses is that produced by subjecting the gauge to a stress wave with unloading, as shown in Fig. 1. In this record a very large anomalous tail, i.e., large positive excursion in current, occurs 800 nsec after first signal, even though the stress at the input face of the gauge is known to be almost zero at this time. Observation of anomalous responses on unloading raises serious questions as to the applicability of Eq. (1) when stress pulses involving unloading are encountered.[15]

The present paper describes an experimental and theoretical study of the characteristics of x-cut quartz disks employed in the Sandia quartz gauge configuration which have been subjected to short-duration stress pulse loading. As previously reported,[11] the "anomalous tail" is found to be due to a shock-induced conductivity in the region of the disk which experiences stress unloading. The experimental arrangement used to study the piezoelectric response will be presented, followed by a description of the results. These results will then be analyzed with an electrostatic theory. The phenomenological observations will then be used to propose physical mechanisms responsible for shock-induced conductivity of x-cut quartz.

II. EXPERIMENTAL ARRANGEMENT

The experimental configuration used in the present investigation is a modification of the impact configuration developed by the authors, used for the previous piezoelectric response studies of quartz,[12–14] and widely applied to other shock-loading investigations.[13,14,16] Preliminary analysis showed that both stress amplitude and pulse duration were potentially significant variables. Hence, the principal experimental problem was to achieve short-duration stress pulses, with amplitudes which are precisely specified at all times. The techniques for planar impact experiments with long-duration stress pulses are highly developed, but the short-duration loading has not been employed extensively; hence, new methods were developed to achieve the precision and control required.

The impact configuration shown in Fig. 2 is designed to achieve the symmetric impact of a projectile-mounted x-cut quartz disk (called a flier), upon an x-cut quartz disk mounted on the muzzle of a compressed gas gun. The velocity of the projectile is measured at three locations terminating at the impact plane. The gun barrel is evacuated so that gas pressure does not increase between the impacting surfaces.

For this symmetric impact condition, the particle velocity u imparted upon impact into both the flier and sample is exactly

$$u = \tfrac{1}{2} u_0, \tag{2}$$

where u_0 is the velocity of the flier at impact. Thus, the input to the sample is known to the accuracy to which the flier velocity is measured.

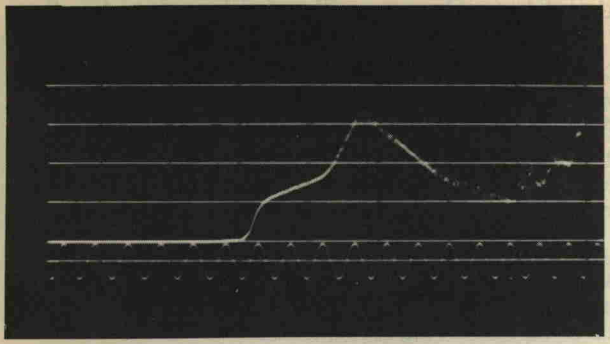

FIG. 1. Current-vs-time response observed from a quartz gauge subjected to a stress pulse propagating through a steel sample. Time increases from left to right; the timing wave has a period of 100 nsec. The maximum stress amplitude is 25 kbar. The shape of the stress pulse is determined by the elastic-plastic response of the steel sample and the unloading of stress late in time. An anomalous increase in current 800 nsec after first signal cannot be accounted for with Eq. (1). This record was obtained by Stanton under conditions as reported in Ref. 15.

The present investigation was accomplished with greatly improved accuracy in the velocity measurement compared to that previously reported.[6] The accuracy of a single velocity measurement, as calculated from the accuracies of the displacement and the time measurements, is ±0.02%. Three measurements of projectile velocity are accomplished on each experiment. The standard deviation of an individual velocity measurement from the mean value of the three velocity measurements on a particular experiment is 0.03%, when all the experiments in this paper are considered as a group. This indicates that the projectile velocity is constant for an interval of travel before impact and that the quoted impact velocities are precise to 0.1%, with 99% confidence limits.

The stress or particle velocity is varied by achieving various flier velocities; the pulse duration is varied by using fliers of different thicknesses which produce pulse durations proportional to their thicknesses. The principal problem is to achieve a precisely aligned impact surface on the thin flier which is accelerated down the gun barrel. The surface of the flier disk which is opposite to the impact face is unsupported and open to the vacuum in order to achieve a precisely specified stress after the stress pulse is reflected from this surface. Flier thicknesses from 0.65 to 2.5 mm were used in the experiments and propelled to velocities up to 0.4 mm/μsec. To prevent cracking due to excessive vibrations as the flier is accelerated down the barrel, the fliers were mounted as detailed in Fig. 2.

The median value of "tilt", i.e., misalignment achieved between impacting surfaces, was 500 μrad for the thin flier experiments. The value is calculated from the observed rise times of the quartz responses assuming that the flier and sample impact surfaces are planar. The thick impactors used in four experiments achieved mean tilt values of 200 μrad.

Excessive peak accelerations are minimized by the long-barrel (27 m) compressed gas gun[17] which allows the use of relatively massive projectiles. It was also found that the use of helium gas as a driver, as opposed to air, reduces deformations to the flier; presumably because lower driving pressures are utilized to achieve the same terminal velocity.

The Sandia quartz gauge configuration is designed to permit measurements from that portion of the shock-loaded quartz disk in which both the mechanical and electrical fields are precisely one dimensional. As shown in Fig. 2, this is accomplished with an electrode configuration consisting of an inner electrode and an outer annular guard-ring electrode. The width of the outer electrode is at least 1.5 times the thickness of the disk. The insulating gap separating the inner and outer electrode is nominally 0.09 mm wide; field perturbations due to the insulating gap are not detectable until the shock front approaches to within a distance equal to the width of the gap.[18] Furthermore, the insulating gap area is less than 3% of the inner electrode area, so that local field perturbations are negligible compared to the total area.

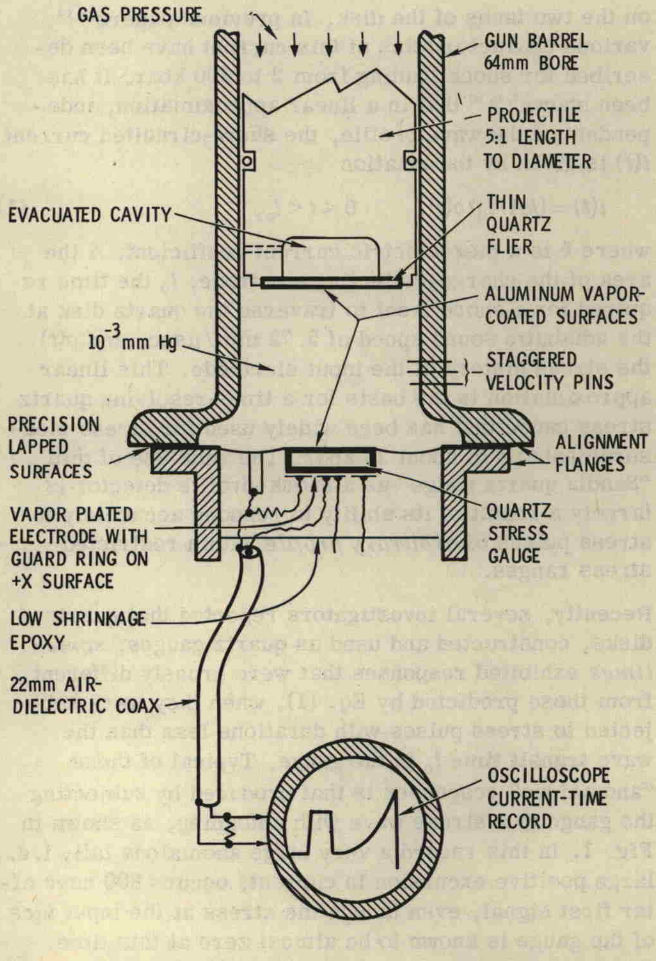

FIG. 2. Experimental configuration used to impart well-defined short-duration shock loading to the samples. Thin x-cut quartz fliers mounted on the projectile are impacted upon x-cut quartz samples to produce an input particle velocity which is known to ±0.1%. Various pulse durations are achieved by fliers of different thicknesses, and various stress amplitudes are achieved by impacts at different velocities.