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ELECTRICAL AND OPTICAL MEASUREMENTS ON FUSED QUARTZ UNDER SHOCK COMPRESSION

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ABSTRACT

The resistivities of specimens of SiO_2 (fused quartz) singly and doubly shocked in the 10 to 45 and 27 to 90 GPa range, respectively, demonstrate a marked decrease from values of $\sim 10\Omega \cdot m$ to $\sim 0.1\Omega \cdot m$ at single shock pressure of ~ 40 and double shock pressure of ~ 74 GPa. The shock-induced polarization profiles also show a sudden change of electrical properties of the material at those pressures. The rapid decrease in resistivity suggests a further transformation to an unknown phase or production of an electron bound level.

INTRODUCTION

The shock-wave equations of state of SiO_2 for various initial forms have been studied over a wide range of dynamic pressure[1-4]. However, other measurements on physical properties of SiO_2 under shock compression are necessary to identify the high pressure and high temperature state because a small change of volume or pressure can not be detected by the EOS experiments. We have performed measurements of electrical resistivity, shock-induced electromotive-force, and shock-induced radiation spectra of fused quartz specimens. The resulting data are discussed in light of our knowledge of the electrical properties of dielectrics and their relation to the previous equation of state studies. The data are also discussed with the recent observation of shock-induced radiation.

EXPERIMENTAL

Both resistivity and shock-induced polarization measurements were carried out in longitudinal geometry by using a charged capacitor method[5]. The disc-shaped specimens were impacted by a copper or tungsten flyer plate at speeds from 1.1 to 3.2 mm/μsec. The impedance match method was used to determine both the initial and reflected shock states in the specimen using the Hugoniot data of McQueen et al.[6] and Wackerle[1], for copper, tungsten, and fused quartz. Both reflected Hugoniot and isentropic states were approximated using the principal Hugoniot curve. Shock temperatures were estimated on the basis of standard thermodynamic formulae.

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Experimental details are described elsewhere[5].

The basic element of apparatus for measureing shock induced radiation of matter was the use of a EG&G Princeton Applied Research optical multichannel analyzer (OMA2). The light from the shock-compressed state via the uncompressed material was focused onto an entrance slit of a spectrometer by a collecting lens system. The incident light was dispersed into spectrum in the region between 400 and 820 nm, and recorded by a sensitive vidicon detector with a silicon diodes target. The gating time was about 300 nsec, which was during shock compression. The experiments were carried out by using 40 mm propellant gun of California Institute of Technology. Details will be described elsewhere.

RESULTS AND DISCUSSION

Resistivity measurements are summarized in Fig. 1. It is clearly seen from Fig. 1 that the resistivity of fused quartz under shock loading gradually decreases with the first shock pressure up to 36 GPa and rapidly decreases by about two orders of magnitude at 36∿40 GPa. Results of the reflected shock-compression state also show that the rapid decrease of resistivity occurs at about 70 GPa.

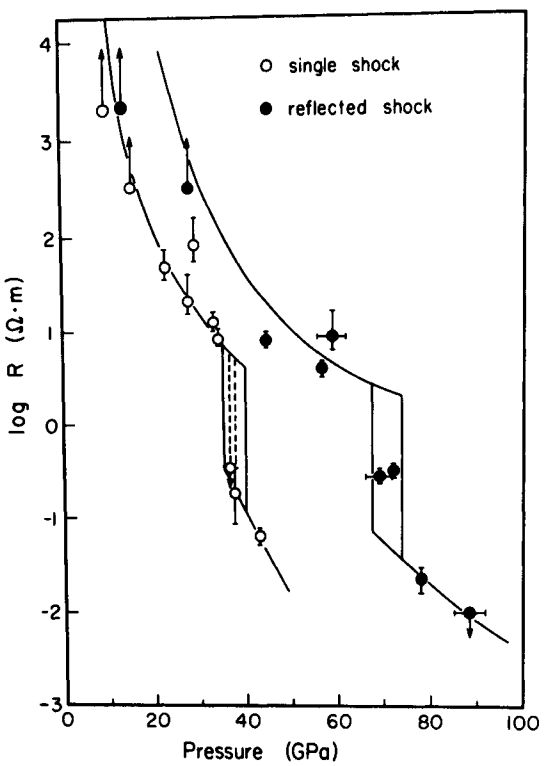

Fig. 1. Logarithm of electrical resistivity (R) as a function of shock pressure for fused quartz.

Polarization signals at pressure below 37.5 GPa were too small and unclear to be recorded. However, at 43 GPa, a positive voltage of about 1V is gradually generated following shock propagation and the sign of the voltage changes upon a reflection of the shock wave. This suggests that changes of the electrical

properties at shock pressures of 36.5 to 37.5 GPa depend on time and that the true transition in the electrical state of fused quartz occurs nearer 40 GPa and 3250K. The polarization signal also suggests that an effective positive charge is produced at the shock front as the conductivity increases.

The resistivity versus reciprocal shock temperature (Fig. 2) clearly demonstrates two regimes of electrical resistivity behavior.

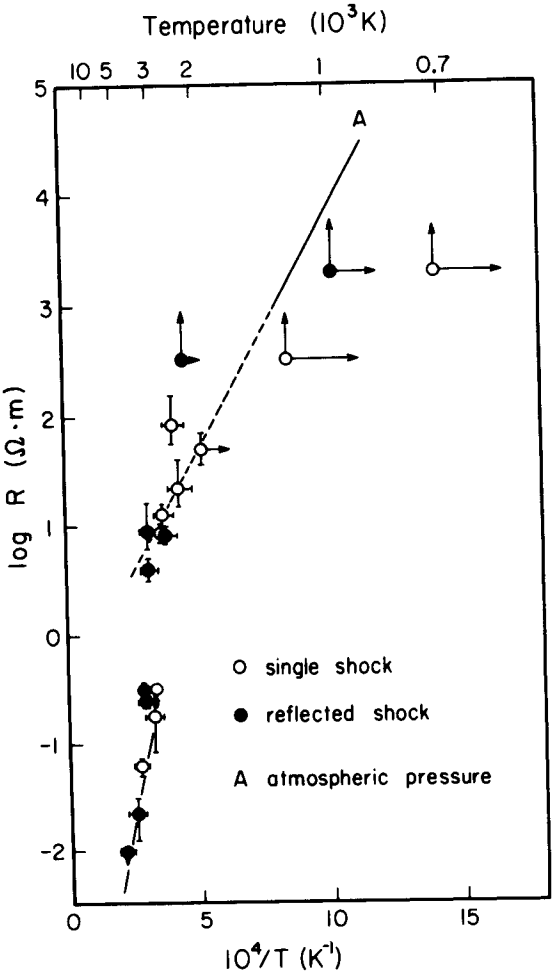

Fig. 2. Logarithm of electrical resistivity (R) as a function of reciprocal shock temperature for fused quartz. Solid line A shows temperature dependence of resistivity for fused quartz (ref. 7).

The temperature dependence of resistivity for fused quartz at atmospheric pressure has been reported[7] and is also shown in Fig. 2. This is approximately represented by the equation, $R = 0.251 \times \exp(0.88\ /kT)$, where R and kT are in Ω·m and eV, respectively. An extrapolation of this line agrees well with shock-wave data with larger resistivity than 1 Ω·m. In the regime over which the high temperature and high pressure data agree, we believe that fused quartz has partially transformed to stishovite. Therefore, we infer no significant difference exists between ionic transport processes in normal fused quartz and the presumed shock-induced high pressure phase, stishovite.

However, at the higher temperature, the activation energy suddenly changes and the resistivity is approximately represented as, $R = 2 \times 10^{-5} \times \exp(2.4 \pm 0.5\ /kT)$. This sudden change of activation energy suggests the occurrence of structural change in

SiO_2 into another high-temperature and high-pressure phase.

However, no appreciable increase of density is observed in the Hugoniot data for fused quartz above ∿40 GPa. Some evidence has been found for the occurrence of phase change of SiO_2 with a similar or slightly higher density than stishovite[8-10]. If a four- or six-coordinated glass still exists under shock conditions because of the reconstructive phase transition to stishovite, glass-transition or crystallization may probably occur at that pressure and temperature. Although a resistivity decrease of about two orders of magnitude occurs on melting in some minerals[11,12], this does not appear to be consistent with the shock temperature measurements for fused and crystalline quartz, which suggest that the onset of melting stishovite under loading occurs at higher pressure and temperature than those for the change in electrical properties[13].

Preliminary observation of shock-induced radiation spectrum within the mixed phase region at 22 GPa shown in Fig. 3 suggest a few broad lines in the spectrum, which are superimposed into lattice-temperature radiation. The strongest emission band appears at 509 nm with half height width of 20 nm, and the second one at 589 nm with 20 nm. These wave lengths correspond to 2.44 and 2.10 eV.

Molecular orbital calculations on the electronic structure of fused or amorphous quartz have been carried out using a variety of cluster-models, and show that the width of valence band and energy gap are of the order of 9 and ∿13 eV, respectively, while the experimental value of the gap is 11 eV[14-16]. The defect electronic states are due to oxygen vacancies and proton interstitials. The latter and Na^+ are the main impurities in commercial fused quartz. They give rise to electron levels in the gap which

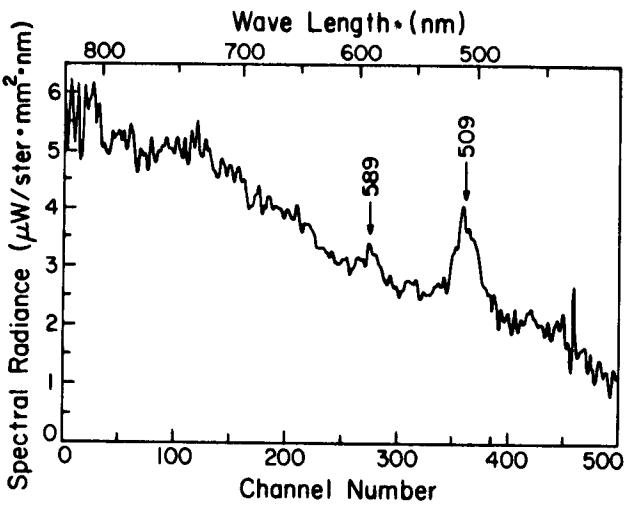

Fig. 3. Shock-induced radiation spectrum of fused quartz at 22 GPa. Collecting time is 300 nsec.

are dependent on the model cluster size[16]. The oxygen vacancy is responsible for some of the ultraviolet absorption bands. If we assume that the electron level of 2.4 ± 0.5 eV in the gap is produced during shock-compression, it should be an acceptor bound level or an electron trap because the polarization result suggests a positive carrier. It is likely that disruptive effects of shock front produce this defect as an electron trap similar to the luminous defects introduced by mechanical damage of semiconductor. It is also likely that activated free-atomic state exists between quartz and stishovite in the mixed phase region. When a change in phase is taking place, such a condition may exist in the high pressure region because of the reconstructive and slow reaction to stishovite. However, to explain the sudden change of the resistivity, the above model needs a sudden change of carrier concentration or increase of the number of traps because the thermal activation of electron increases continuously with temperature.

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