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HIGH PRESSURE HUGONIOT OF SAPPHIRE

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The Hugoniot of sapphire was measured for the first time above 145 GPa, from 80 GPa to 340 GPa in shock-wave experiments using projectiles accelerated by a two stage gas gun. The transit times of the shock waves were measured either optically with a streak camera or through electrical pin contacts. The Hugoniot in this pressure range fits U_S=8.74+0.96 U_p in km/s.

INTRODUCTION

Sapphire is a technologically important material frequently used in high pressure physics. In the form of ruby (Cr-doped sapphire) it indicates pressure in a diamond anvil cell through the pressure shift of its fluorescence. However, at megabar pressures the fluorescent lineshape changes, making its interpretation increasingly difficult[1]. A first-principles calculation of the optical properties of ruby requires its high pressure equation of state (EOS).

In shock-wave physics, sapphire is an important window material because it has a high density (4.0 g/cm^3) relative to other window materials such as LiF (2.64 g/cm^3). This produces higher shock pressures upon impact. Also, its density can be a better impedance match to some samples, minimizing undesired reflected waves. Often in these applications an EOS accurate at multi-megabar pressures is needed. Previously the Hugoniot (shock EOS) of sapphire had not been measured[2] beyond 145 GPa. We have measured the Hugoniot from 80 to 340 GPa in two stage gas gun experiments using optical and electrical pin contact methods.

METHOD

The Hugoniot was determined by measuring the speed of a shock through sapphire created by impact of a disk projectile. The projectile density, Hugoniot and velocity combined with the sapphire shock speed (U_s) using elementary shock relations[3,4] yields the sapphire mass velocity (U_p). The locus of U_s-U_p data constitutes the Hugoniot.

The sample was high quality sapphire of [0001] orientation obtained from either Union Carbide Co. or Crystal Systems Co.[5] Its density averaged ρ=3.989 g/cm^3. Except for a shot using Pt, the projectile was a Ta disk, 1 - 2 mm thick and 24 mm diameter. The projectile was accelerated by a two stage light gas gun up to 7.8 km/s. The transit time of the shock across the sample was determined either optically or by electrical contact pins.

Shorting Pin Technique

Figure 1 shows the target design employing electrical shorting pins to record the shock transit time across a "top-hat" sample. The technique is described in more detail in ref. 4. The bottom and top pin circle diameters were 19.3 and 9.6 mm respectively and the step height was 1.3 mm. The tilt and bowing of the flyer at impact were determined from the distribution of pin arrival times and used in calculating the transit time of the center of the shock surface. If the center pin failed the amount of bowing could not be determined, and this amount could be significant (20 ns out of a transit time of 100 ns for high velocity shots). This critical reliance on a single pin is a disadvantage which motivated us to employ the optical technique described below.

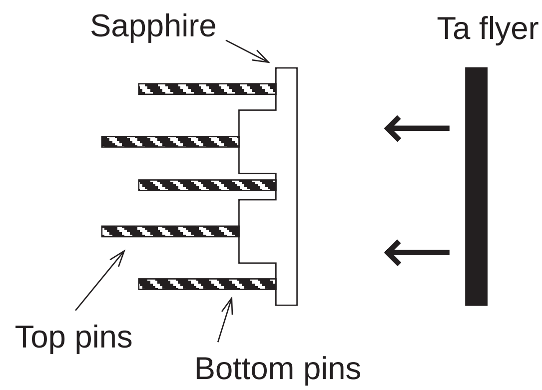

Figure 1. Target design using the electrical pin technique to measure shock speed in a sapphire "tophat". The electrical pins short when they encounter the shock-wave. Six "top" pins and six "bottom" pins encircle a center pin.

Optical Technique

Figure 2 illustrates the target design used with an optical technique similar to that described in ref. 6, but using an indicator fluid. A sapphire (Sp) cylinder 5 mm thick and 18 mm diameter is mounted against a copper baseplate and surrounded by an indicating fluid such as bromoform or benzene. The fluid emits light when shocked. An opaque gold film covering the sapphire blocks light internal to the sapphire. The Sp/Au/fluid and baseplate/fluid surfaces are imaged to the entrance slit of a streak camera. The shock emerging from the baseplate first creates light at the baseplate/fluid interface, then later at the rear of the sample.

Figure 3 shows a digitization of a streak camera record plotting first appearance of light along a line bisecting the target. Light first appears on either side of the sapphire as it breaks out of the baseplate. It appears at the rear

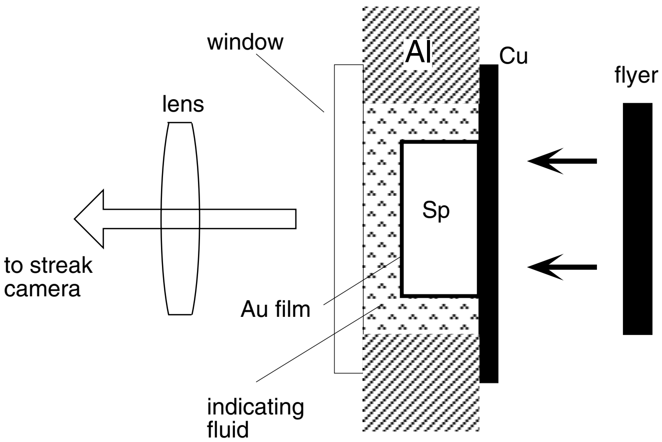

Figure 2. Target design for the streak-camera technique. The indicating fluid emits light when shocked. The lens images the sapphire (Sp) face and the Cu baseplate to the streak camera slit.

face of the sapphire later. The tilted and bowed nature of the shock front due to the projectile distortion is clearly seen, especially in the expanded view Fig. 3b. The release wave propagating inside and from the sapphire sides slows the periphery of the shock front, forming the "bat-ears" shape.

The transit time is found by translating the shoulder points upward until they fit the same parabolic curve defined by the top points inside the bat-ears. The turn-on time of the flash was assumed to be identical for the Cu/fluid and Sp/Au/fluid interfaces. This is reasonable since the calculated pressures developed at the two surfaces are similar.

An advantage of this technique over the electrical pin method is that amount of bowing can be determined with confidence. Secondly, the sample can be approximately twice as thick while still avoiding side release waves, since there is no central hole for the center pin as in the tophat shape. The disadvantage of the technique is that amount of light produced in the flash and the proper exposure to use for the camera for a given impact velocity is not easily calculated and must be discovered empirically.

RESULTS AND DISCUSSION

The U_s-U_p data are plotted in Fig. 4 along with data of ref. 2. A linear best fit through all the data yields the relation U_s=8.74+0.957U_p for 80<P<340 GPa. The error bars for most of our data are smaller than the datum symbols. We have not determined the source of the statistical fluctuations in the data. Since the fluctuations are much greater than our estimated measurement error it is due to either sample-to-sample variations in material properties, or an unknown source of uncertainty in our experiment.

The slope (S) of the U_s-U_p relation is less than unity. This is atypical of most materials, which have slopes[2] 1.2 - 1.7. We don't believe sapphire's low S value is due to its hardness, since although some hard materials[7] have low S (diamond: 1.0, B_4C: 0.67), others don't (TaC:1.27, WC: 1.17). In a counter-example, two soft materials having low S values are calcium (S=0.95) and cesium (S=1.04).

Materials undergoing polymorphic phase transitions under shock can have a depressed U_s which could

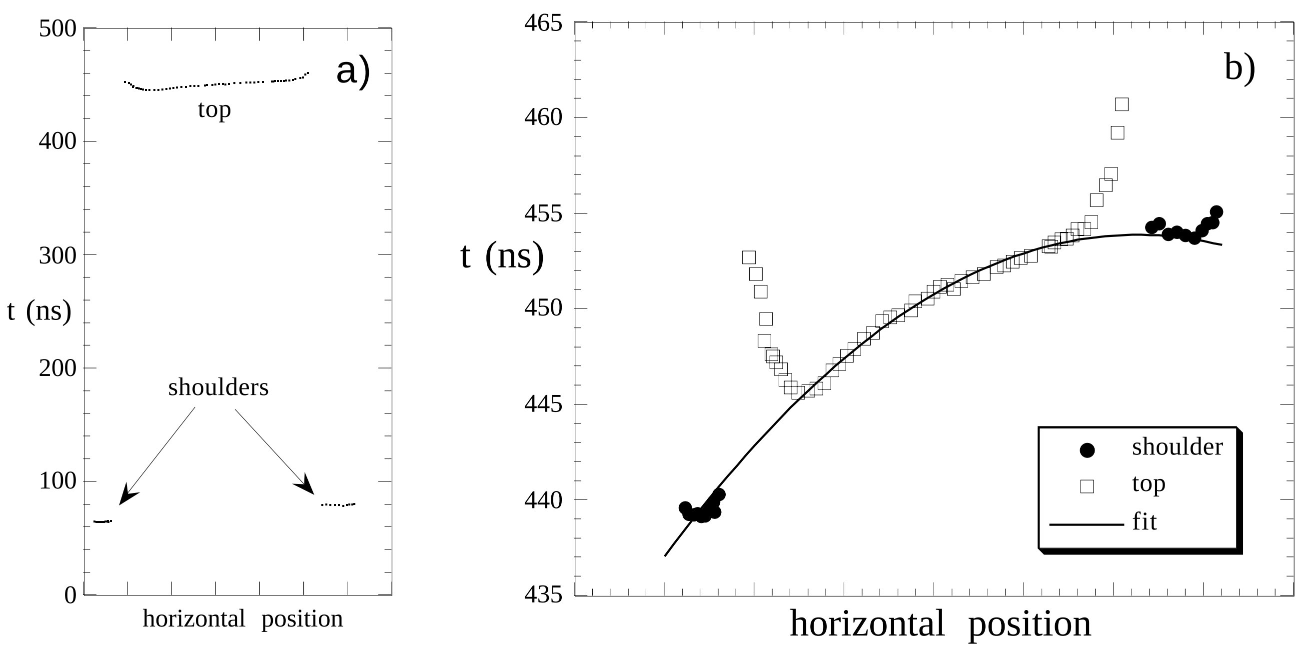

Figure 3. a) Streak camera record plotting time of breakout of shock versus horizontal position across a line bisecting the target. Breakout first occurs from baseplate (shoulders), then from the rear face of the sapphire cylinder. b) Close up of same record, with the shoulder points translated 374 ns upward. The "bat-ears" are due to the side release waves. A parabola is fitted through the top points inside the bat-ears. The bowing and tilt of the shock wave front due to the projectile distortion is clearly seen.

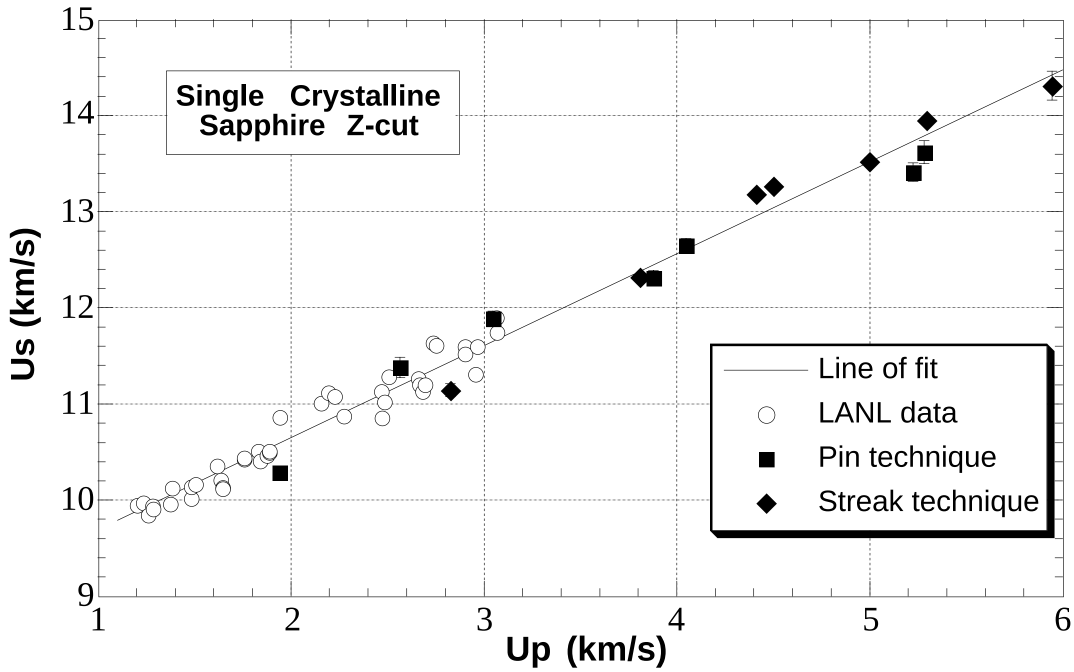

Figure 4. Experimental Hugoniot data (shock speed vs. mass velocity) from this work and ref. 2 (circles, Los Alamos Nat. Lab.). Symbols distinguish the two techniques used, diamonds: electrical pin contacts, squares: streak camera. The line of best fit through all the data is U_S=8.74+0.957U_p. For our data only, most error bars are smaller than the symbols.

manifest a low S for a limited range of pressures. If the transformation is rapid a two-wave profile[8] results with the faster wavefront maintaining a constant U_s for a range of pressures. In this case the transformation nature is easy to notice. If the transformation is sluggish (producing a mixed-phase final state over a broad pressure range), a single wave-front can be produced which has a depressed U_s. This could produce a low S. For sufficiently high pressures when the shocked state is entirely of the final phase, the U_s-U_p behavior should possess a higher and more typical S value.

We are aware of no direct evidence that sapphire is undergoing a phase transition, and we have no higher pressure Hugoniot data to check whether its S value eventually increases, which would support this notion. Since there are no projectile materials significantly denser than Pt, our 340 GPa datum is the highest we can attain in a direct shock with our gas gun.

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