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OPTICAL EXTINCTION OF SAPPHIRE SHOCK-LOADED TO 250 – 260 GPA

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Abstract. Sapphire, a common optical window material used in shock-compression studies, displays significant shock-induced optical emission and extinction. It is desirable to quantify such non-ideal window behavior to enhance the usefulness of sapphire in optical studies of opaque shock-compressed samples, such as metals. At the highest stresses we can achieve with a two-stage gas gun it is technically very difficult to study the optical properties of sapphire without the aid of some opaque backing material, hence one is invariably compelled to deconvolve the optical effects of the opaque surface and the sapphire. In an effort to optimize this deconvolution process, we have constructed sapphire/thin-film/sapphire samples using two basic types of thin films: one optimized to emit copious optical radiation (the hot-film sample), the other designed to yield minimal emission (the cold-film sample). This sample geometry makes it easy to maintain the same steady shock-stress in the sapphire window (255 GPa in our case) while varying the window/film interface temperature. A six-channel time-resolved optical pyrometer is used to measure the emission from the sample assemblies. Two different sapphire crystal orientations were evaluated. We also comment on finite thermal conductivity effects of the thin-film geometry on the interpretation of our data.

INTRODUCTION

Sapphire is an important window material for optical studies of shock-compressed materials [1,2]. Sapphire has an important advantage over the (100) orientation of lithium fluoride (hereafter simply LiF); namely it has a significantly greater shock impedance. On the other hand, the optical transparency of sapphire under shock-compression conditions is not as good as that of LiF [3,4] and so some care does need to be exercised when using sapphire in quantitative optical studies.

Both Urtiew [5] and McQueen and Isaak [6] investigated sapphire as a shock-compression window above 80 GPa. At such high shock stresses one is compelled for technical reasons to use an opaque backing material which is then viewed through the window. Both the backing and the window are shock-compressed and emitting optical radiation and it is very difficult to deconvolve the emission due to the window from that due to the backing.

In this paper we use a novel thin film sample construction to facilitate the deconvolution of the window emission component from that due to the opaque backing. We present preliminary results of an attempt to quantify some aspects of sapphire's non-ideal window behavior for single shock loading of sapphire in the stress range 250 – 260 GPa. This is the upper limit of stress we can achieve in sapphire in a single shock wave at our two-stage light gas gun facility using a tantalum impactor.

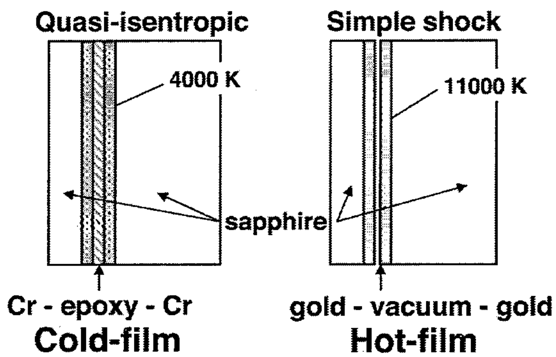

Figure 1. Our two types of samples. The sample on the left is designed to emit relatively less and we call it the "cold-film" sample. The one on the right is designed for copious optical emission and we call it the "hot-film" sample. The impactor generates the shock from the left, the shock wave propagates from left to right, and optical emission is viewed by the pyrometer in the thicker sapphire from the right. All chromium and gold films are 500 nm thick.

EXPERIMENTAL PROCEDURE

The sapphire used was single-crystal synthetic material of typical purity better than 99.996 %. Two window surface orientations were used: (0001) c-plane, and (1,-1,0,2) r-plane orientations. The indices refer to the x-ray (also known as "structural") hexagonal cell [7].

Sample construction is outlined in figure 1. A thinner sapphire of 1.00 mm thickness was always used for the impacted side of the sample, while a thicker sapphire of 3.00 mm was used for the optical observation side. The thin and thick sapphires were always matched in surface orientation within a given sample. That is, each sample contains two sapphires and they were either both r-plane or both c-plane, but not mixed.

The cold-film sample uses chromium, a relatively incompressible metal that therefore shocks to relatively low temperatures. Furthermore, a thin layer of epoxy (on the order of ten microns) is sandwiched between the chromium coatings and causes it to ring-up to the final steady stress (determined by the sapphire), which further keeps down the temperature of the chromium film. The hot-film sample is of gold, with a vacuum gap of about three microns. The higher-than-sapphire shock impedance of gold together with the absence of the low impedance layer of epoxy cause the initial shock in the downstream gold layer to overshoot the final stress. Gold was chosen because its shock temperature under the same conditions is much higher than chromium. Also, gold is not a good reflector for the UV and bluer visible wavelengths so that it should have a large spectral emissivity at these same wavelengths. All these things add up to copious emission from the gold backing of the hot-film sample.

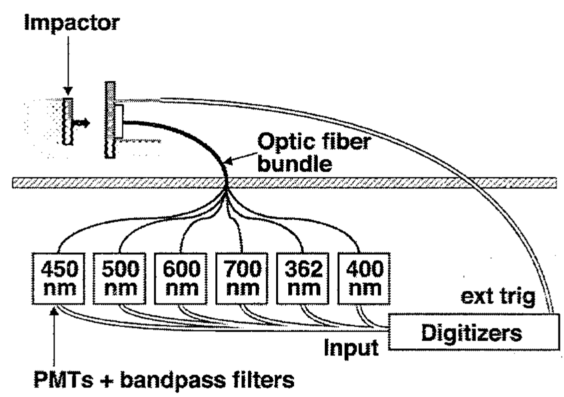

Figure 2. Optical pyrometer used for these experiments.

Shock stress was achieved by using a 1.5 mm tantalum impactor in our two stage light gas gun at Lawrence Livermore National Lab [8]. While we strove to make the sapphire shock stress identical for each experiment, small variations in gun performance produced the finite stress range 250 – 260 GPa. The emission was collected by our six-channel time-resolved optical pyrometer system [9]. A diagram of the collection scheme is shown in fig. 2. The pyrometer was calibrated by a tungsten-halogen lamp standard of spectral irradiance.

An effort was made to keep signal levels at the 100 to 200 mV level, requiring significantly more neutral density filtering for the hot-film samples than for the cold-film samples. To obtain the correct relative intensities between the relevant hot-film and cold-film sample data, the latter were reduced in amplitude by the transmittance of the excess of filters used for the hot-film sample data.

RESULTS

Figure 3 displays idealized data traces.

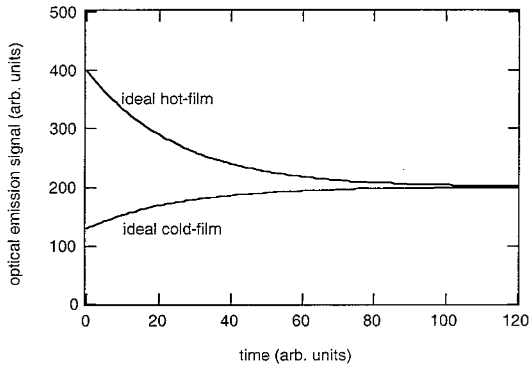

Figure 3. Idealized trace showing film-as-sole-emitter to window-as-sole-emitter transition.

Time zero is the signal immediately after the shock wave has passed through the thin film but has not progressed far into the thicker "viewing" sapphire. The hot-film signal is much greater than the cold-film signal because the film signal is relatively unobstructed by the mostly unshocked, (and thus transparent) sapphire. Eventually the shocked sapphire becomes optically thick enough to be opaque. The pyrometer will only see opaque sapphire at the temperature resulting from the shock loading to 255 GPa. This is represented by the two different sample signals eventually merging to the same result with time. The rate at which the signal makes the transition from film-as-sole-source to sapphire-as-sole-source is determined in both cases by the optical attenuation characteristics of sapphire. The analysis depends also on the spectral emissivity of the film sample. If the backing films are perfect absorbers/emitters (i.e. blackbody) then the transition from film-as-sole-emitter to sapphire-as-sole-emitter is single exponential with the sapphire attenuation coefficient as the exponent. We acknowledge that this assumption is imperfect but in the present analysis we adopted it as an expedient in order to obtain approximate, but reasonable, results.

The pyrometry traces from the hot and cold films for the longest wavelength channel (700 nm center, 36 nm bandwidth) are displayed together for c-plane sapphire in fig. 4.

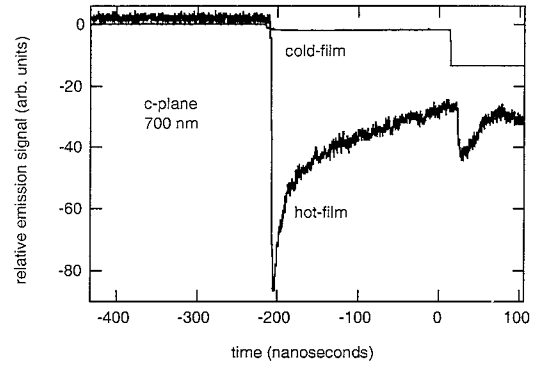

Figure 4. Hot-film and cold-film samples, c-plane sample, 700 nm wavelength. Because these are PMT output the signal is negative. Shock-compression of the thin film occurs at about –200 ns. Shock wave reaches rear sample surface at about +10 ns.

We see that the hot-film sample signal is much more intense than the cold-film sample.

The shortest wavelength (362 nm center, 10 nm bandwidth) c-plane data is shown in fig 5. As with 700 nm, the hot-film sample signal is much more intense than the cold-film sample signal. However, the hot-film sample signal appears to decay more rapidly for 362 nm than for 700 nm.

A very similar set of results is found for the r-plane orientation of the sapphire at both 362 and 700 nm (not displayed).

The analysis of the time rate of change of the signal yields an upper bound to the optical attenuation coefficient (i.e. worst-case scenario attenuation: the material can be more transparent but not less so). This is because the cooling of the hotter film by heat transport into the surrounding sapphire will also give the appearance of a signal that decays with time. Since both the optical and heat transport effect combine together to give the total apparent attenuation coefficients that we measure, we claim that our measurements reported are upper bounds on the optical attenuation. For c-plane sapphire we compute upper bounds to the optical attenuation coefficients of 3.5 cm^{-1} and 9.2 cm^{-1} for 700 and 362 nm respectively. For r-plane sapphire we compute 3.2 and 9.4 cm^{-1} for 700 and 362 nm respectively.

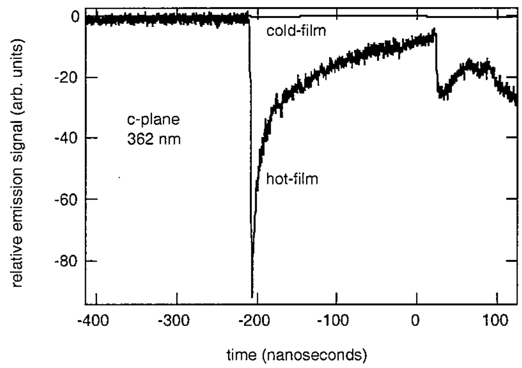

Figure 5. Hot-film and cold-film samples, c-plane sample, bluest wavelength (362 nm).

DISCUSSION

Perhaps the most important result of this work is that the cold-film sample signal level allows us to make a reasonable assessment of the window's emission contribution to the case of the hot-film signal. This is because the window emission contribution to both the cold-film and hot-film signal should be nearly identical. For the case of sapphire between 250 and 260 GPa, we see that the emission from sapphire contributes very little to the overall emission in the hot-film case. This in turn puts a tighter constraint on the arithmetic process of determining a total attenuation coefficient from the hot-film sample data.

We advise the reader that the attenuation coefficient results reported here are most appropriate to the use of sapphire with an optical pyrometer similar to ours. Light scattering contributes to optical attenuation but its impact varies with system design. For example, the results we presented here may not be as appropriate for sapphire as a VISAR window.

There does not seem to be much difference between our r-plane and c-plane result at 255 GPa. Lower stress optical studies showed substantial differences in c-plane versus r-plane optical and mechanical behavior [10,11].

The upper bound for attenuation coefficient does seem to be significantly greater for 362 nm relative to 700 nm. However, thermal relaxation of the emitting films also would cause a qualitatively similar effect.

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REFERENCES

1. W.J. Nellis, M. Ross, and N.C. Holmes, Science, **269**, 1249 (1995).
2. J.D. Bass, B. Svendsen, and T.J. Ahrens, in High-pressure research in Mineral Physics, ed. M.H. Manghnani and Y. Syono, pp 393-402 (Terra, Tokyo, 1987).
3. L.M. Barker and R.E. Hollenbach, J. Appl. Phys. **41**, 4208 (1970).
4. J.L. Wise and L.C. Chhabildas, in Shock Waves in Condensed Matter-1985 (Proceedings of the Fourth APS Topical Conference on Shock Waves in Condensed Matter, Spokane, WA, July 22-25, 1985), edited by Y.M. Gupta (Plenum, New York, 1986), p. 441.
5. P.A. Urtiew, J.Appl. Phys. **45**, 3490 (1974).
6. R.G. McQueen and D.G. Isaak, J. Geophys. Res. **95**, 21753 (1990).
7. M.L. Kronberg, Acta Metallurgica, **5**, 507 (1957).
8. A.H. Jones, W.M. Isbell, and C.J. Maiden, J. Appl. Phys. **37**, 3493 (1966).
9. N.C. Holmes, Rev. Sci. Instrum. **66**, 2615 (1995).
10. J. Hyun, S.M. Sharma, and Y.M. Gupta, J. Appl. Phys. **84**, 1947 (1998).
11. D.E. Hare, D.J. Webb, and N.C. Holmes, in Shock Compression of Condensed Matter-1999, edited by M.D. Furnish, L.C. Chhabildas, and R.S. Hixon (Americal Institute of Physics, New York, 2000), p. 637.