

(1975). From index of refraction measurements on shock-loaded KCl and KBr, Kormer *et al.* (1966) have inferred that the transitions are complete in 10^{-11} s.

Al'tshuler *et al.* observed a reverse transition under unloading at about 1.0 GPa lower pressure than the loading transition. Samara and Chrisman (1971) report for the case of static loading a hysteresis of 500 MPa between loading and unloading.

Pressure-particle velocity states at the impact surface in Hayes' experiments are shown in Fig. 27. Although the transition occurs at the correct pressure, a rapid transformation to a metastable state more energetic than the equilibrium state is indicated in the mixed phase region above the transition. Hayes computed the excess entropy of this state and suggested that it is associated with the nucleation of many small nuclei. Other sources of excess entropy may be production of point defects, large interfacial areas, and internal strains. Podurets and Trunin (1974) have considered effects of interfacial area associated with many small nuclei.

I. III-V and II-VI compounds—CdS, InSb, and BN

Cadmium sulfide and indium antimonide undergo transitions within their elastic compression ranges under shock loading; hence the relative contribution of shear stress is especially large. Boron nitride is of particular interest because shock loading has been found to cause an irreversible transition to a high-pressure phase. Furthermore, in a monumental achievement, x-ray diffraction measurements have been accomplished on the high-pressure phase of BN in the shocked state.

Jones and Graham (1971) summarize the data of Kennedy and Benedick (1966) on CdS and unpublished data of Kennedy and Benedick on InSb (1965). Both of these crystals apparently undergo phase transitions with large, about 20%, volume changes which are consistent with static observations of the wurtzite-to-rock salt structure for CdS (Kabalkina and Troitskaya, 1964) and the zinc blende-to-white tin structure (Hanneman *et al.*, 1964) or an orthorhombic structure for InSb (Kasper and Brandhorst, 1964). Kennedy and Benedick (1966) also reported large decreases in resistance in CdS shock-loaded above the transition in a manner consistent with that observed by Samara and Drickamer (1962) under static loading. (Static high-pressure work on these materials has been reviewed by Rooymans, 1969.)

Under shock loading both transitions are observed at mean pressures and volume compressions significantly less than static values. Hence, even though the volume change between high- and low-pressure phases is about the same as is determined statically, the shock transitions may be strongly influenced by shear. The possibility of a metastable state cannot be ignored.

Although high-pressure phases of shock-compressed solids are rarely recovered after the loading, dense boron nitride is apparently easy to recover since many different groups have recovered dense phases of BN, albeit with somewhat different results. Bundy and Wentorf (1963) reported a direct transformation of hexagonal BN to wurtzite under static loading at 13 GPa at temperatures around 300 K and a preference to form a cubic, zinc blende form at temperatures between 2500

and 4000 K. Frequently, both forms appeared together. Shock wave loading experiments have shown the presence of a transition between 12 and 12.8 GPa (Adadurov *et al.*, 1967; Al'tshuler *et al.*, 1967; Coleburn and Forbes, 1968), in agreement with static loading measurements. Kuleshova (1969) has reported a significant increase in resistance of shock-loaded BN at 13.5 GPa.

Batsanov *et al.* (1965) reported recovery of an unidentified dense form of BN after shock loading. Adadurov *et al.* (1967) recovered wurtzite crystallites after shock loading above 12 GPa. Dulin *et al.* (1969) reported recovery of both wurtzite and diamond structure crystallites with wurtzite predominating under shock loading from 12 to 50 GPa at initial temperatures between 120 and 800 K. Loading pressure did not appear to influence the yield of dense phases; however, increase in initial temperature and reduction of initial density reduced the yield. Coleburn and Forbes (1968) recovered micron-size cubic zinc blende crystallites with traces of wurtzite. Soma *et al.* (1975) have also reported recovering the wurtzite form of BN from shock loading. These observations indicate that although dense phases are always recovered for hexagonal BN shock-loaded above 12 GPa, the yield and structure of the dense phase apparently depends upon details of shock loading and characteristics of the starting material.

With their flash x-ray diffraction apparatus, Johnson and Mitchell (1972) obtained diffraction records for BN in the shocked state at 24.5 GPa, a pressure sufficiently large to produce a single shock in the high-pressure phase. Their records showed a diffraction line corresponding to the 100 line of the wurtzite phase, narrower and more intense than those obtained from recovered samples after shock loading. It was inferred from this that the crystal in its shocked state retains its crystalline form in large measure and that the micron-sized particles found in recovered samples are produced by extensive inelastic deformation and/or microfracturing that follows the initial shock. The single 100 line is not sufficient for complete identification of the high-pressure phase, but the determination that the transition produces large, uniformly oriented crystallites that attain significant sizes in times of a few tens of nanoseconds is a significant result. Ritter (1973) has discussed lattice deformation mechanisms consistent with the observations of Johnson and Mitchell (1972).

J. Quartz

Quartz is a material with properties much admired and widely utilized at atmospheric pressure. Under shock loading, its properties are complex, and for that reason quartz may be the most interesting of materials included in this review. Much of the interest stems from shock loading created in nature by the impact of meteorites on the earth, which creates dense polymorphs of quartz and other perplexing changes in the properties of quartz rocks. High-pressure polymorphs of quartz are possible candidates for earth mantle material and are consequently of considerable interest in geophysics (see the review by Ahrens *et al.*, 1969). Further interest in quartz under shock loading follows from the wide use of quartz gauges in shock loading research.

Crystalline quartz is also of interest because it exhibits the largest purely elastic strain of any solid yet investigated and, when the stress of the HEL is exceeded, quartz exhibits an apparent catastrophic and substantial loss of shear strength, unlike most solids. With these incentives for research, it is not surprising that shock loading investigations of quartz are of relatively long standing and continue to the present. This section considers shock loading investigations of quartz not because they are typical of work on other materials or are comparable to static pressure investigations, but because of the unique behavior of quartz, which in many respects has no counterpart in static high-pressure investigations.

In 1962, Neilson *et al.* described impressive luminosity and piezoelectric effects that indicated unusual mechanical properties in shock-loaded quartz. These observations led Wackerle (1962) to carry out an investigation of the stress–volume behavior of quartz under shock loading from 4 to 70 GPa. Wackerle's classic paper reported a thorough, comprehensive investigation of both fused quartz (vitreous silica) and crystalline quartz which exposed a number of unusual effects. Further investigation of these effects are the source of much of the subsequent work on quartz. Adadurov *et al.* (1962) published a less extensive investigation at the same time as Wackerle. Contemporary work by Fowles (1962) was published at a later date (Fowles, 1967).

Wackerle observed the following effects:

1. In crystalline quartz, HELs varied from 4.5 to 14.5 GPa and depended upon the crystallographic orientation and particulars of the experiment.
2. In crystalline quartz, a substantial reduction of shear strength is observed for stresses immediately above the HEL, unlike the behavior of most solids which are believed to maintain an approximately constant level of shear strength above the HEL.
3. An apparent phase change in crystalline quartz at 14.4 GPa.
4. A mixed phase region in crystalline quartz which extended from 14.4 to 38 GPa (the compressibility in this region was unusually small and the cusp in the R–H curve at 14.4 GPa did not lead to a multiple wave structure).
5. A well-defined high-pressure R–H curve that was common for both fused and crystalline quartz.
6. An anomalous low-stress compressibility for fused quartz (as expected from ultrasonic third-order elastic constant measurements and from earlier static measurements by Bridgman), finally changing to a compressibility that decreases with stress in the normal manner.
7. Recovery of amorphous quartz from crystalline quartz shock loaded to 50 GPa.
8. Recovery of compacted fused quartz from fused quartz shock loaded at 25 GPa, and normal fused quartz from samples loaded at 50 GPa.

Wackerle's stress–volume curve for crystalline quartz, shown in Fig. 28, demonstrates many of these unusual properties.

Discovery of the shock transition at 14.4 GPa and an approximate temperature of 475 K occurred almost si-

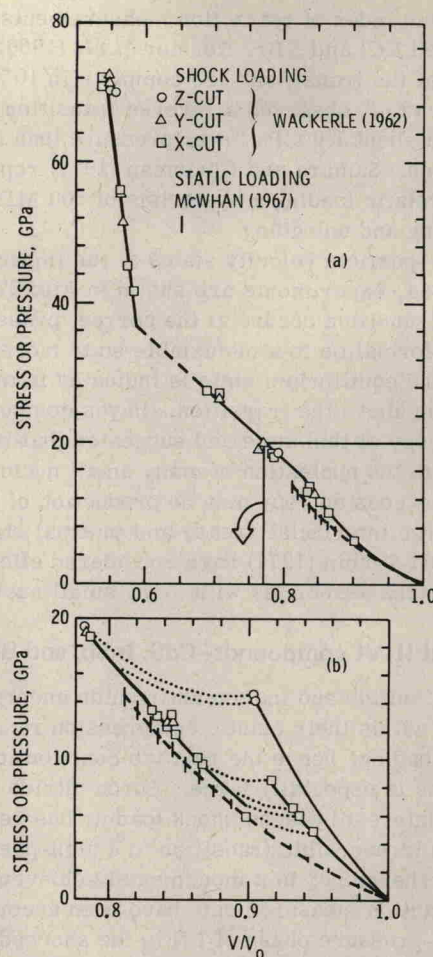


FIG. 28. The stress–volume relation for quartz determined by Wackerle (1962). The upper portion of the figure, a, emphasizes the data above the transition at 14.5 GPa. A mixed phase region extends from 14.5 to 39 GPa. Properties of the high-pressure phase, which has properties similar to stishovite, can be determined from the data above 39 GPa. The lower portion of the figure, b, emphasizes the elastic compressional properties of quartz with unusually large HEL values. For stresses above the HEL the material loses a substantial portion of its shear strength and approaches hydrostatic compressions. This loss of shear strength is apparently associated with heterogeneous melting described in Sec. VI.C.

multaneously with the discovery of a dense polymorph of quartz with a density of about 4.28 Mg/m³ and rutile structure by Stishov and Popova (1961). This dense phase, called stishovite in this country and stipovorite in the Soviet Union, was synthesized at a pressure of about 16 GPa and a temperature of 1473 K. Previously, Coes (1953) had synthesized a hexagonal dense phase of quartz, now known as coesite, at 3.5 GPa and 1023 K.

Wackerle's investigation of the high-pressure phase was extended to 260 GPa by Al'tshuler *et al.* (1965). Ahrens and Rosenberg (1968) obtained loading and unloading data in the mixed phase region. High-pressure investigations by Trunin *et al.* (1971a) extended to 650 GPa, and Trunin *et al.* (1971b) studied porous samples with densities of 1.15, 1.35, 1.55, 1.75, and 2.2 Mg/m³. Except for porous solids, in which temperatures are very high, the high-pressure phase above 38 GPa has properties close to those expected for stishovite. Trunin *et al.* (1971b) found differences in the R–H