Shock Compression of Covalently Bonded Planetary Materials

Boya Li[1], Alex Li[1], Marc Meyers[1], Shiteng Zhao[2], Hye-Sook Park[3], Bruce Remington[3], Christopher Wehrenberg[3], Eduardo Bringa[4]
[1] University of California San Diego, [2] Lawrence Berkeley National Laboratory, [3] Lawrence Livermore National Laboratory, [4] Universidad Nacional de Cuyo

Research Objectives

Olivine and perovskite are the most abundant minerals in Earth's mantle. Laser shock and isentropic compression on the covalently bonded planetary materials in an extreme regime of pressures and strain rates can be used to explore the deformation mechanisms of the interior of Earth. The objective of this study is to explore a new mechanism for deformation of covalently bonded materials under the extreme conditions of shock and quasi-isentropic compression.

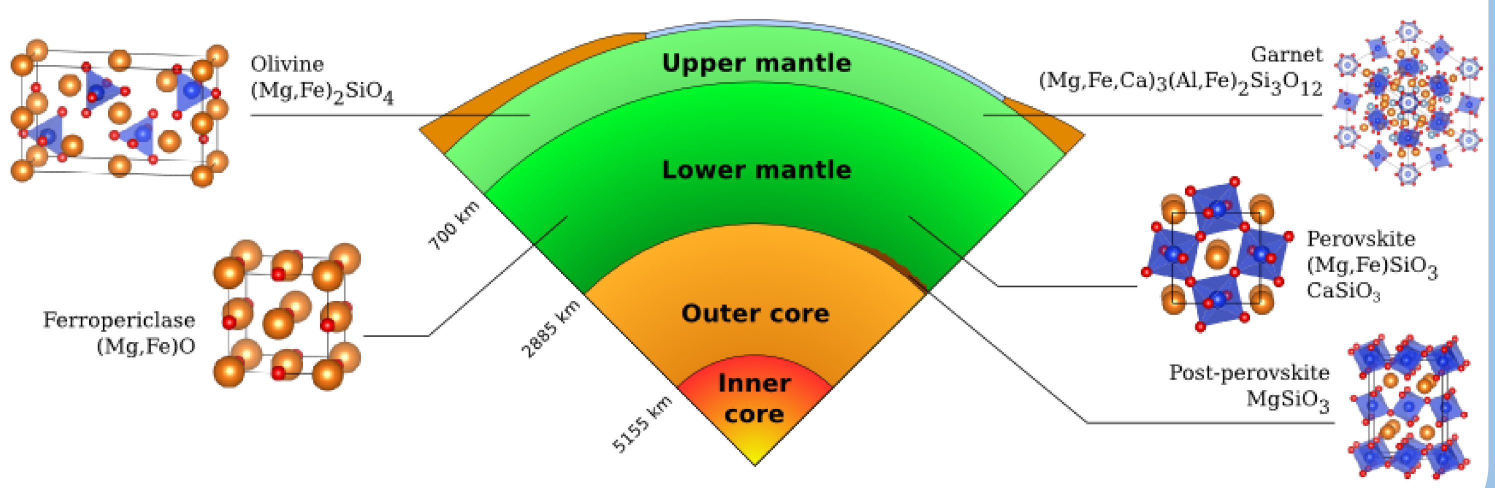

Fig. 1 The structure of Earth's interior, and some examples of minerals found in the mantle [1].

Target Materials

Three important minerals: olivine ($(Mg^{2+}, Fe^{2+})_2SiO_4$), forsterite ($Mg_2SiO_4$), and perovskite ($CaTiO_3$) will be investigated in this research project. Diamond is another typical covalently bonded material that is of interest to this project.

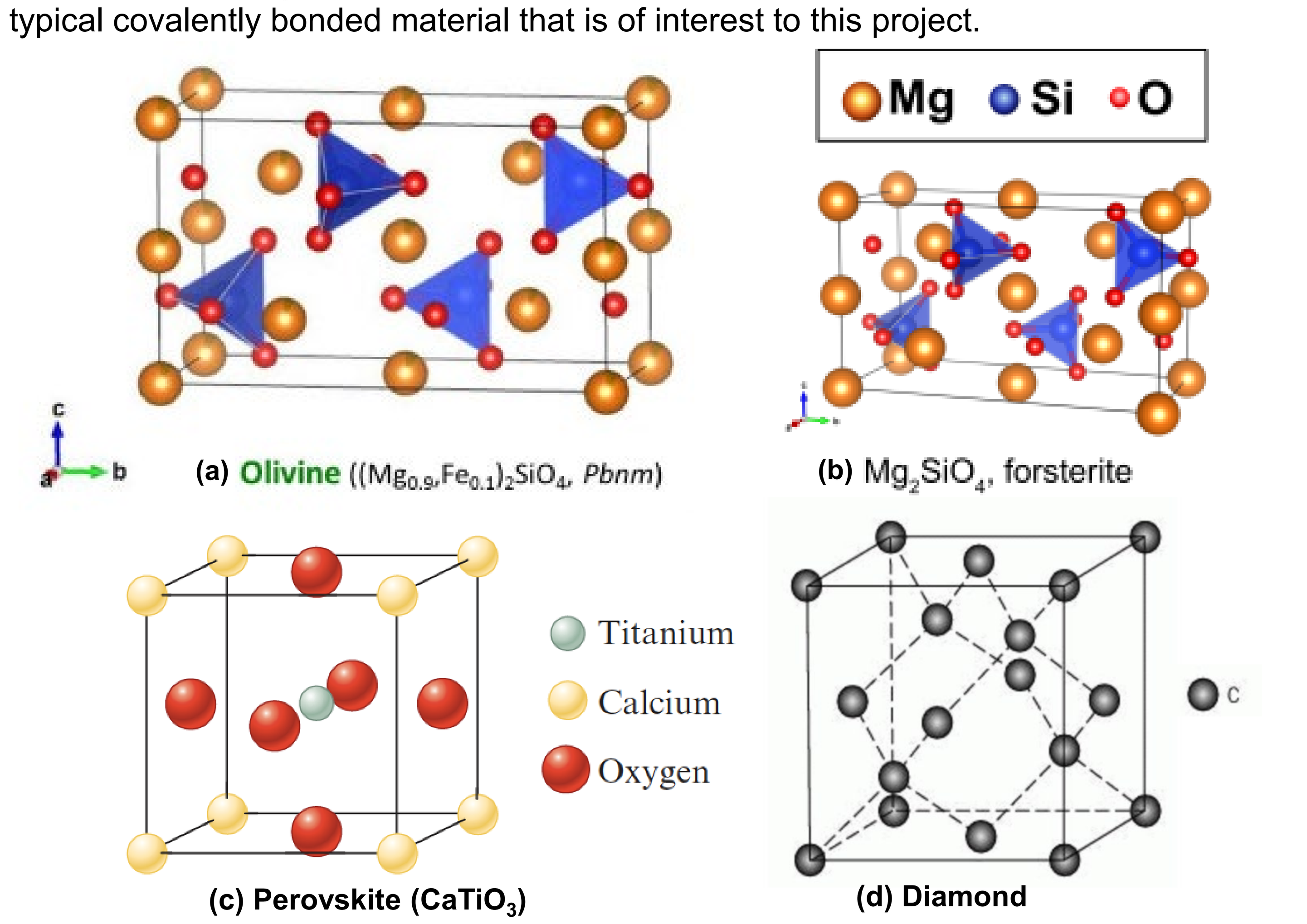

Fig. 2 Planetary materials olivine, forsterite, and perovskite that will be subjected to shock compression at different amplitudes. (a) SiO_4^{4-} tetrahedra (blue) are shown with Mg^{2+}, Fe^{2+} (orange) and O^{2-} (red) atoms. SiO_4^{4-} tetrahedra are isolated in olivine [2].

Deformation Mechanisms

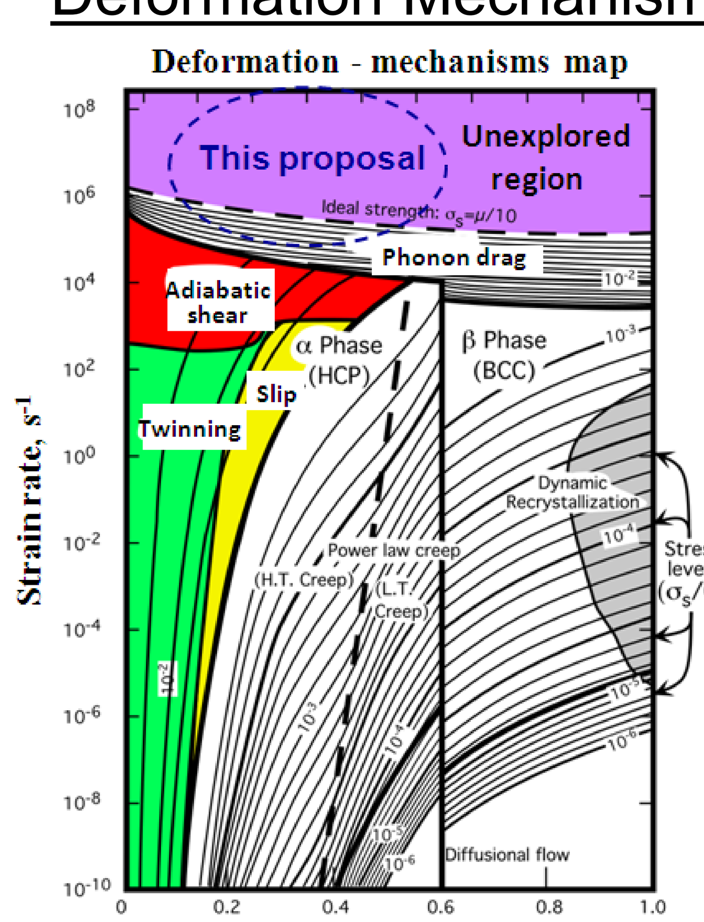

Fig. 3 Strain rate vs. temperature plot showing different regimes of deformation and failure.

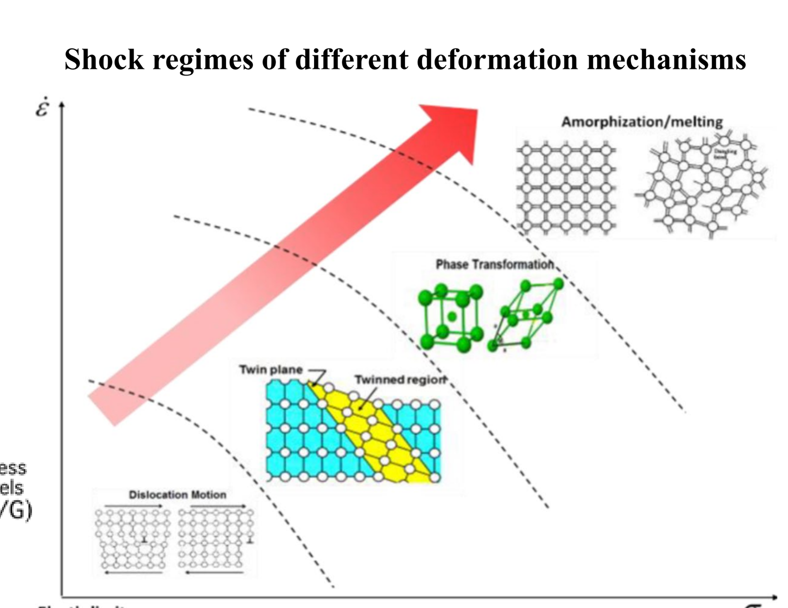

Fig. 4 Strain rate vs stress in shock regime showing different regimes of deformation and failure: as stress increases, strain rate and temperature giving rise to four different shear-driven deformation mechanisms.

Experimental Setup

Omega Laser Facility can generate large amplitude stress pulses with nanosecond duration, sufficient to shock the materials above their phase transition threshold. The target was assembled in a vacuum chamber to prevent oxidation of the target and absorption /scattering of the laser. The high energy density laser was deposited onto a target package which is comprised of a metal foil (~100 µm) and a mineral crystal (3 mm in diameter and 5mm in height) encapsulated in a metal cup to prevent it from shattering under shock compression and release. A 3 mm thick momentum trap was used to trap the shock wave at the rear surface. The close acoustic impedance of the metal to the mineral serves to minimize reflection of shock waves at interfaces/free surfaces, reducing damage and aiding successful recovery.

The metal foil has three functions: (1) as an ablator to transform laser energy into stress pulse; (2) as a heat shield which minimizes the preheating induced by laser irradiation; (3) as a pulse shaper to make the shock pulse on the target surface planar (uniaxial strain condition). The rear (free) surface velocity of the metal foil to the laser shock is characterized by velocity interferometry (VISAR). Separate VISAR experiments were conducted to measure the particle velocity and further infer the shock pressure.

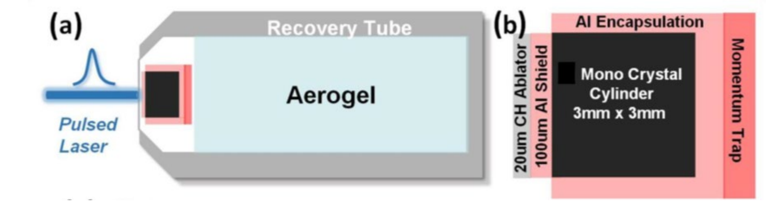

Fig. 5 (a) Experimental assembly for laser shock compression of covalently bonded monocrystals; (b) detail of monocrystal with impedance matched capsule and momentum trap

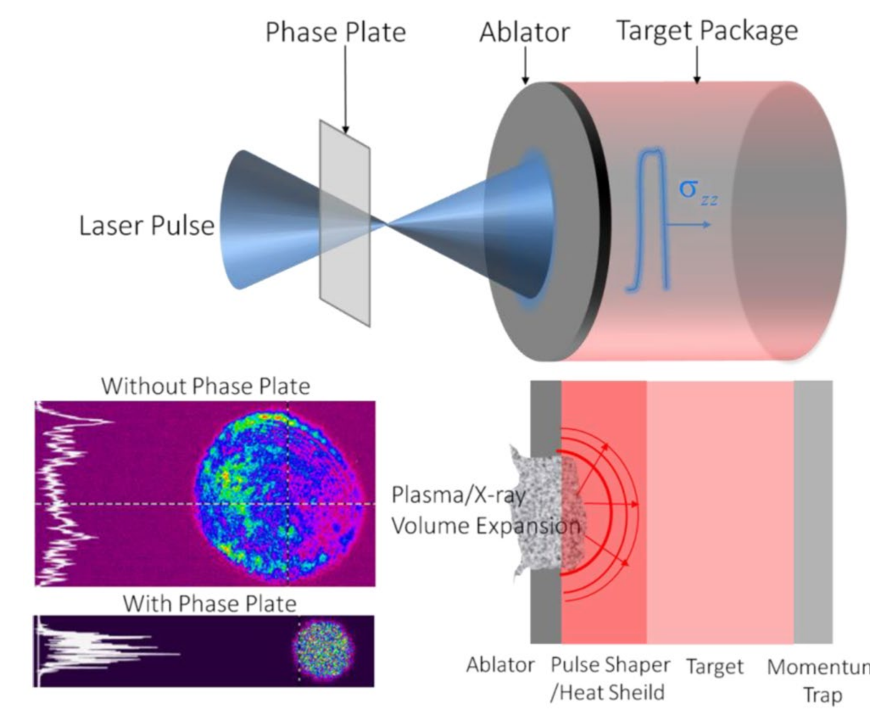

Fig. 6 Isentropic Compression Experiment (ICE) Drive for shock recovery experiments

Previous Results of Covalently Bonded Materials

Four covalently bonded elements (Si, Ge) and compounds (B_4C, SiC) were investigated by our group using the Omega facilities to generate the shock and quasi-isentropic pulses.

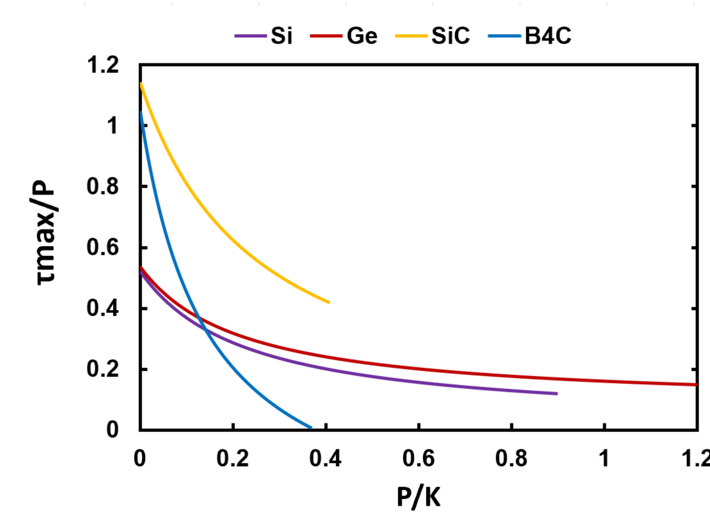

Fig. 7 Shear stress/pressure ratios for four covalently bonded materials studied at Omega.

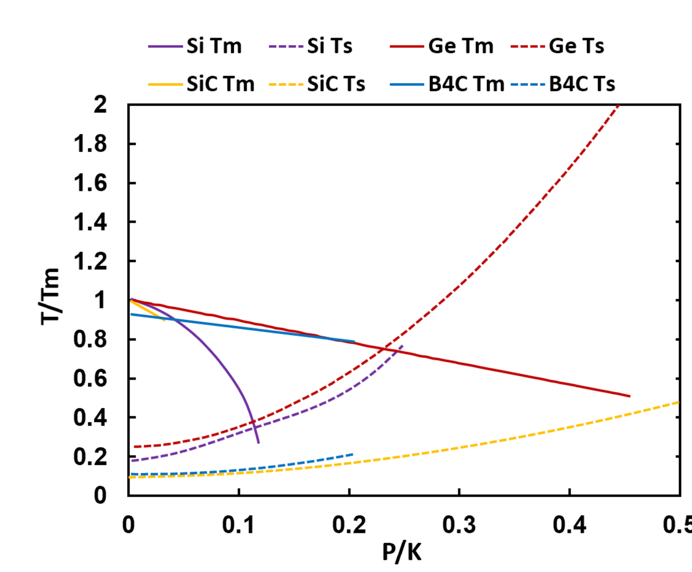

Fig. 8 Shock temperature as a function of pressure and melting point for materials with negative Clapeyron slope.

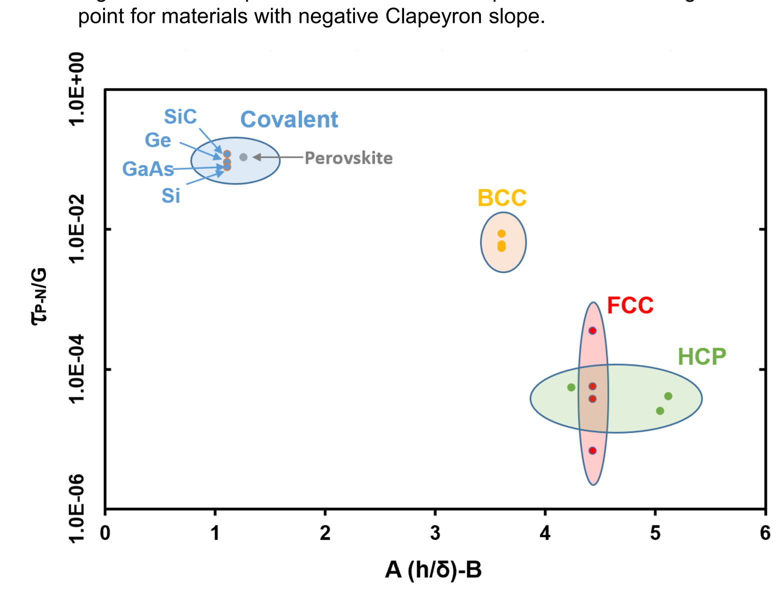

Fig. 9 Peierls-Nabarro stress for metals and covalently bonded materials as a function of structural parameters h (spacing of atomic planes between which dislocations glide) and δ (lattice periodicity in the direction of the dislocation glide); A and B are correction parameters [3].

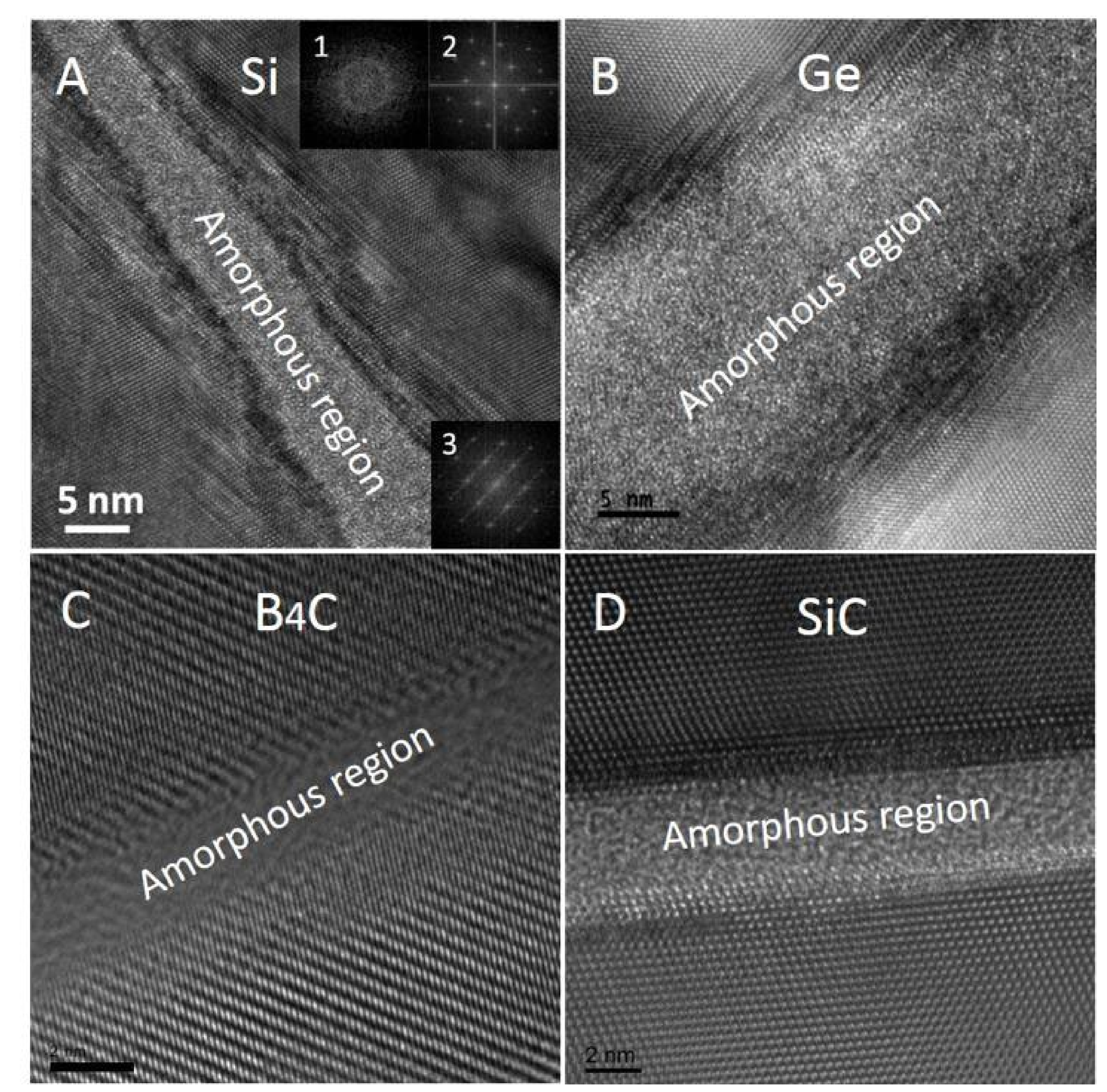

Fig 10. Shock/shear amorphization in (A) Si, (B) Ge, (C) B_4C, and (D) SiC [4].

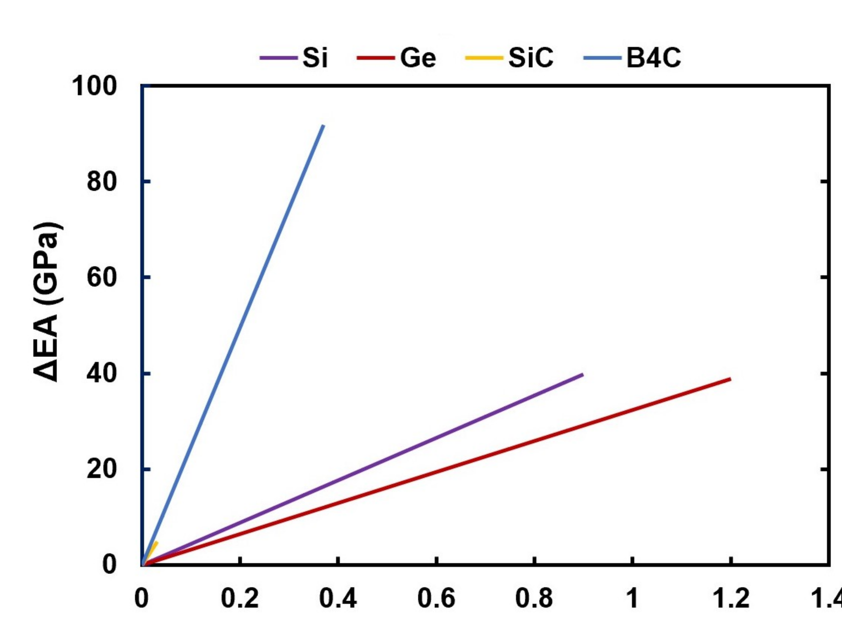

Fig. 11 Energy change of phase transition from crystalline to amorphization with pressure of four covalently bonded materials

Discussion

Both observations and molecular dynamics calculations shown in Figure 12 predict the formation of amorphous bands at angles close to 45° relative to the shock front.

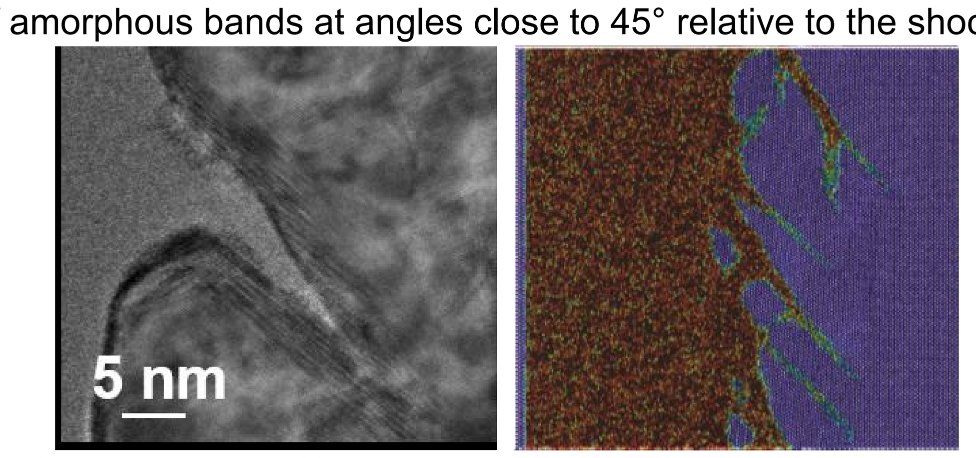

Fig. 12 Experimentally obtained (a) and computationally simulated (MD) amorphization band (b) in silicon [6].

Preliminary Results of Olivine

Preliminary experiments (Zhao et al., unpublished results, 2019) on shock recovered olivine at Omega Laser Facility at low and intermediate pressures showed that olivine deformed by dislocation activities. Figure 13 (a) shows a high density of dislocations generated below the shock surface with a shock compression of 20 GPa. These dislocations generally have a Burgers vector of <100> and tend to group together and exhibit a band-like morphology. At a shock pressure of 40 GPa, planar deformation features are observed shown in Figure 14 (a). This shear band-like feature has a thickness of tens of nanometers. This suggests that the deformation is localized, and we suspect that this dislocation activity forming planar deformation feature is the precursors to solid state amorphization. The experiments were carried out at a shock pressure below the threshold of amorphization. We plan to use a higher shock pressure to trigger amorphization in the following experiments.

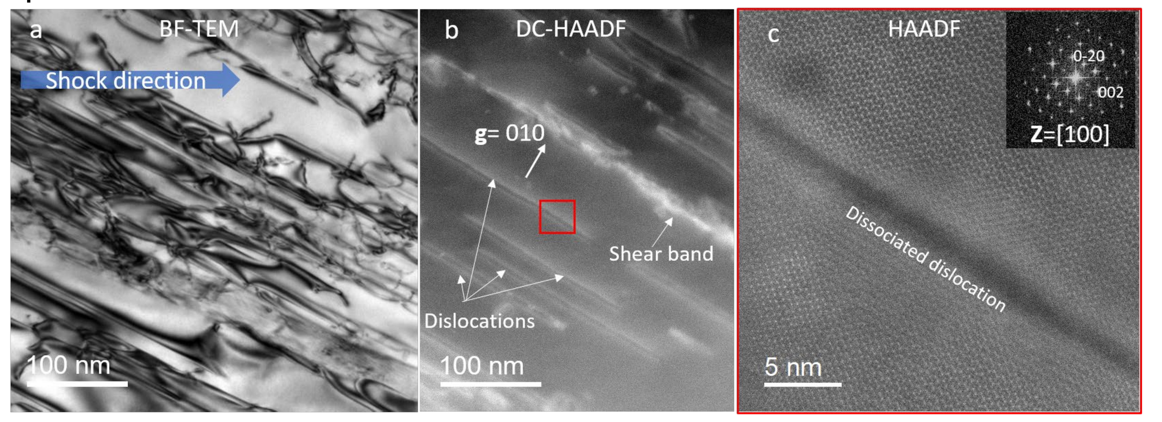

Fig. 13 Post-shock olivine exhibits dislocations under shock pressure of 20 GPa [7].

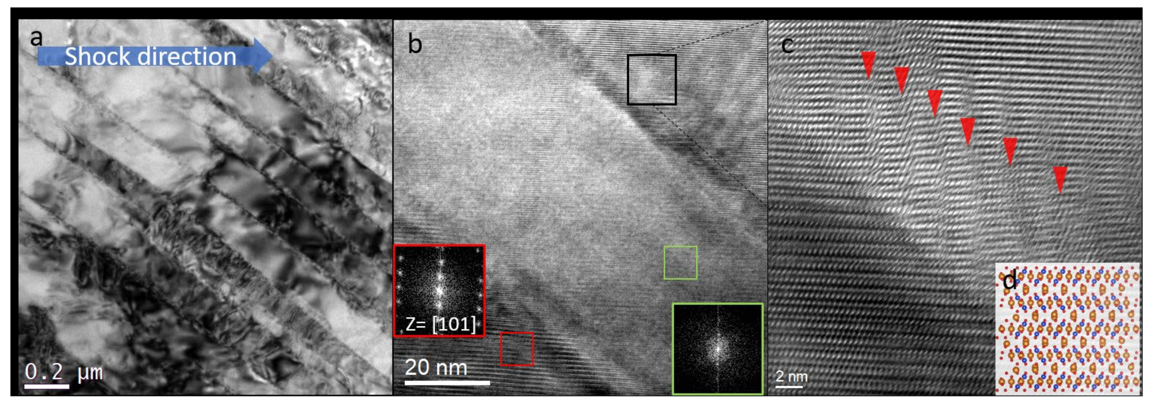

Fig. 14 Post-shock olivine exhibits shear faulting under shock pressure of 40 GPa [7].

References

[1] http://pierrehirel.info/recherche_defMgPv.php?lang=en
[2] McCormick, Tamsin C., Joseph R. Smyth, and Gary E. Lofgren. "Site occupancies of minor elements in synthetic olivines as determined by channeling-enhanced X-ray emission." Physics and Chemistry of Minerals 14, no. 4 (1987): 368-372.
[3] Kamimura, Y., K. Edagawa, and S. Takeuchi. "Experimental evaluation of the Peierls stresses in a variety of crystals and their relation to the crystal structure." Acta Materialia 61, no. 1 (2013): 294-309.
[4] Zhao, Shiteng, Bimal Kad, Eric Hahn, Laura Chen, Opachi Yekaterina, Karren More, Bruce Remington et al. "Shock-induced Amorphization in Covalently Bonded Solids." In EPJ Web of Conferences, vol. 183, p. 03027. EDP Sciences, 2018.
[5] Zhao, Shiteng, Bimal Kad, Bruce A. Remington, Jerry C. LaSalvia, Christopher E. Wehrenberg, Kristopher D. Behler, and Marc A. Meyers. "Directional amorphization of boron carbide subjected to laser shock compression." Proceedings of the National Academy of Sciences 113, no. 43 (2016): 12088-12093.
[6] Zhao, S., E. N. Hahn, B. Kad, B. A. Remington, E. M. Bringa, and M. A. Meyers. "Shock compression of [001] single crystal silicon." The European Physical Journal Special Topics 225, no. 2 (2016): 335-341.
[7] Zhao et al., unpublished results, 2019

Acknowledgements

This research is funded by National Laser Users' Facility (NLUF) Program; FOA DE-FOA-0001891; DOE/NNSA Grant Numbers: National Laser Users Facility Grant PE-FG52-09NA-29043; NNSA Grant (DE-NA0002930); DE-NA0003842. Supporting Organization: University of California, San Diego.