TECHNICAL RESPONSE

HIGH-PRESSURE PHYSICS

Response to Comment on "Observation of the Wigner-Huntington transition to metallic hydrogen"

Isaac Silvera and Ranga Dias

Goncharov and Struzhkin present comments on our observation of metallic hydrogen. We show that most of their comments are unfounded and that our observation of a transition to a shiny, high-reflectance phase remains as evidence that hydrogen has transformed to the metallic phase.

Goncharov and Struzhkin (*1*) have commented on our paper that reports the observation of the Wigner-Huntington transition to metallic hydrogen (MH) (*2*). They correctly state that the scientific community would like to learn about the conditions for metallization, the conducting state, its nature, and properties such as superconductivity. The first great challenge has been to produce MH. We have done this using a special protocol that is fully presented in our paper. Critical in this procedure is that we only allow contact between hydrogen and diamond at liquid nitrogen temperatures and lower, at all times, to prevent diamond embrittlement caused by hydrogen diffusion into the diamonds; other researchers use room temperature gas loaders. We also avoid laser illumination of stressed diamonds, which is known to weaken or lead to diamond failure (*3*). We used low-power infrared (IR) radiation from a thermal source to study the sample properties. Only at the highest pressure did we use a laser (10 mW at 642 nm) for Raman scattering of the diamond phonon to determine the pressure. Afterward, the sample was maintained at low temperature for ~4 months; an attempt to remeasure the pressure using ~0.5 mW power led to immediate catastrophic failure of the diamonds. Evidently, accumulated defects that relax the stress responded to the laser illumination, confirming the notion that laser illumination can lead to diamond anvil failure. Goncharov and Struzhkin incorrectly state that pressure "is not measured using current community standards." In fact, that is exactly what we have done at the highest pressure. Comparable spectra have been shown elsewhere (*3*).

Our method of showing that hydrogen is metallic was to measure the reflectance. This is a common method in high-pressure physics when it is technically challenging to insert electrical wires into the sample. We note that in earlier studies, liquid MH (or its isotope deuterium) has been produced at high temperature and at substantially lower pressures as a liquid-liquid phase transition. The scientific community has accepted the optical reflectance in these challenging experiments as proof that the samples had transformed to the metallic phase. Although measurement of reflectance over a broad spectrum is desirable, most shock experiments only measured reflectance at a single wavelength (*4*, *5*).

Goncharov and Struzhkin also state, "The linear loading curves that Dias and Silvera present are likely unreliable as a tool for estimating pressure at the extreme conditions of the experiments…." Our pressure-load curves were calibrated for the experiment on the Wigner-Huntington transition, not on previous experiments, as they incorrectly state. Other load curves for our diamond anvil cell (DAC) are shown in Fig. 1, where it is seen that the linear pressure-load curves eventually plateau. They also incorrectly comment that there was no diagnostic of the presence of hydrogen. In fact, we measured the IR spectra of hydrogen to 335 GPa, which is an important diagnostic. We then observed hydrogen to turn black; that was previously observed to 420 GPa (*6*), using the diamond Raman phonon and the 2010 Akahama-Kawamura pressure calibration (*7*) (in the present paper, we use the earlier linear calibration of Akahama-Kawamura, and on that scale the pressure given as 420 GPa is 395 GPa). With the following increases in pressure, the sample became shiny. Continuity of observation of the sample/gasket region and the measurement of the reflectance is evidence that the sample remained intact. The sample and gasket are clearly seen in the photographs. Had the sample escaped, the

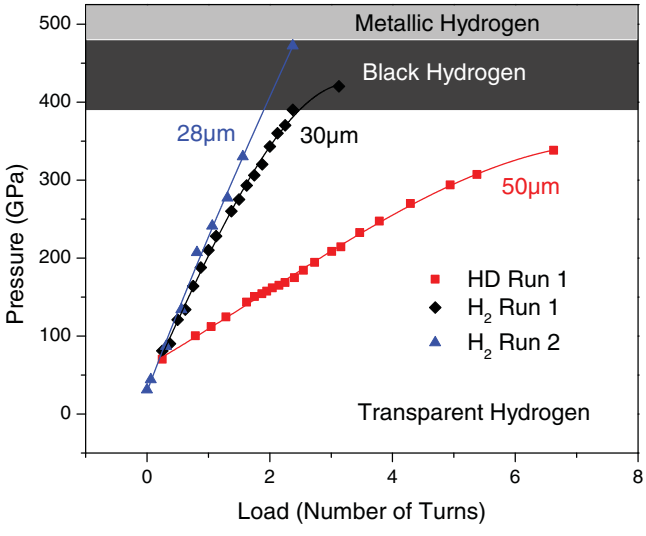

Fig. 1. Load curves for our diamond anvil cell for three runs with the same DAC but different diamond culet flat diameters. The blue triangles are for the MH run.

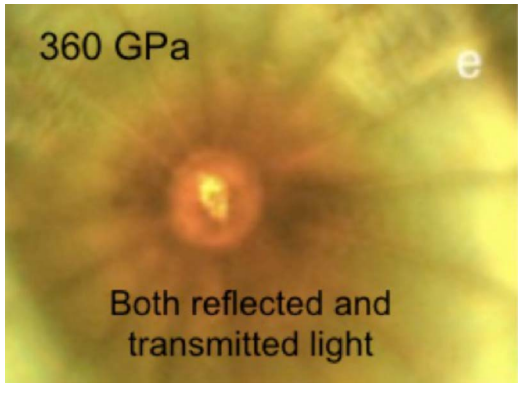

Fig. 2. Photo of a sample of hydrogen in transmitted and reflected light at 360 GPa and a temperature of 80 K.

Lyman Laboratory of Physics, Harvard University, Cambridge MA, 02138, USA.
*Corresponding author. Email: silvera@physics.harvard.edu

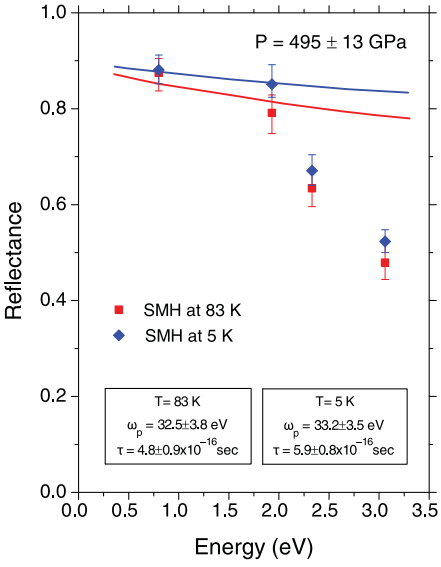

Fig. 3. A least-squares fit of the uncorrected reflectance to the two lowest energy (longest wavelength) data points. The fit was carried out for reflectance at two temperatures, yielding the plasma frequencies and scattering times. SMH, solid metallic hydrogen.

gasket hole would close, and we would have only measured the reflectance of the rhenium gasket.

When the reflectance of MH is measured in the blue or ultraviolet region of the spectrum, the light intensity is attenuated by the stressed part of the diamond and must be corrected, whereas in the lower energy (red or infrared), such a correction is not significant. Goncharov and Struzhkin raise an important point. This correction was implemented using measurements of the optical density of natural diamond reported by Vohra (*8*) some years ago. It was believed that the absorption in the high-energy region was due to closing of the bandgap of diamond. There was an error in the correction that we made, and this has been discussed in an erratum to our *Science* paper (*9*). The situation for the correction becomes more complicated. Recently, Gamboa *et al.* (*10*) at the SLAC National Accelerator Laboratory measured the bandgap of diamond using x-rays and found that it opens with pressure, rather than closes. They believe that their compression is closer to hydrostatic and suggest that the absorption in the blue is due to defects in the diamond. We actually measure a two-pass transmittance of ~0.5 in the blue, suggesting that our high-purity synthetic diamonds are very different than those of Vohra. We also note that Zha, Liu, and Hemley (*11*) observed hydrogen and diamonds to be somewhat transparent in their figure S6, which we reproduce as Fig. 2, whereas the results of Vohra would yield an optical density of 3 to 4 in the green. Considering these observations, it is probably not appropriate to correct the data using the results of Vohra, as the defect density could be very different in natural and synthetic diamonds (which we used). Thus, we have decided to discard the high-energy reflectance data and only use the red and infrared reflectance points, without correction. The fits of these two data points to the Drude free-electron model are shown in Fig. 3 for temperatures of 5 and 83 K. At 5 K, we find the plasma frequency to be 33.2 ± 3.5 eV. This yields a free-electron density of $8.1 \pm 1.7 \times 10^{23}$ electrons/cm^3, compatible with the density of atoms.

We hope that our response clarifies the situation. In future studies, we shall extend the reflectance measurements to still longer wavelengths. The measurements we have made confirm that the transition we observed was to atomic MH.

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