Recent events in the physics of high pressures

S. M. Stishov

Usp. Fiz. Nauk 127, 719–721 (April 1979)

PACS numbers: 62.50. + p, 71.30. + h, 07.35. + k

Two papers[1,2] published in 1968 and 1972 did much to determine the direction taken by the vanguard of research in the modern physics of high pressures.

In the first paper, N. Ashcroft pointed out the possible metastable existence of metallic hydrogen at atmospheric pressure and estimated its superconductive-transition temperature. The result of this estimate was quite encouraging: it was found that the temperature of the superconductive transition in the hypothetical metallic hydrogen should be of the order of 100–300°K.

In the second paper cited, a group of authors (R. Forman, G. Piermarini, J. Barnett, and S. Block) described their experiments with miniature diamond anvils. Placing a small fragment of ruby between diamond anvils, they observed that its *R* luminescence line shifted appreciably as the pressure was increased. This opened the way to measurement of the pressure in diamond anvils and led to widespread use of this method (for details, see the translation of Block and Piermarini's paper in this issue).

The prospects for producing and investigating metallic hydrogen were so attractive[3,4] that three experimental groups stated their intent to proceed with the corresponding experiments[3] soon after Ashcroft's paper appeared.

The experimental group at Lawrence Radiation Laboratory at Livermore, California planned to use a magnetic-explosion technique, while the other two [Cornell University and the USSR Academy of Sciences Institute of the Physics of High Pressures (IPHP)] proposed a static-pressure technique. Since the expected pressure at the transition of hydrogen to the metallic state was expected on the basis of various calculations (see, for example, Ref. 5) to be at least 1 megabar, the range of experimentally attainable pressures would have to be extended upward by almost an order of magnitude.[1)]

We note that before the "hydrogen boom" began, N. Kawai's experimental group at the University of Osaka (Japan) reported the production of static pressures above one megabar in a two-stage multiram setup.[6,7] However, only a few people took these results quite seriously.

In 1970, L. F. Vereshchagin *et al.*[8] reported that they had attained pressures in excess of one megabar by pressing a truncated synthetic-carbonado cone[2)] into the surface of a plate made from the same material. The maximum pressure was determined by measuring the area of the impression left by the conical indentor on the surface of the plate and the pressure that had been applied to the indentor.

Subsequently, the IPHP group reported observation of a matallic transition in such substances as diamond, silica SiO_2, aluminum oxide Al_2O_3, magnesium oxide MgO, water H_2O, and hydrogen H_2.[9–14] The experiments to metallize these substances were performed with a modified indentor whose conical vertex was rounded off. A flat spot does, of course, form at the point of contact when the load is applied to the indentor, but its dimensions are functions of the load and various other factors, and this makes determination of the pressure difficult. The phase transitions were registered by measuring the resistance of a thin layer of material between the indentor and the plate. This was made easier by the fact that synthetic carbonado is made conductive by the presence of metallic-catalyst particles. This made it possible to use the indentor and the plate as electrical probes.

Unfortunately, the authors of Refs. 9–14 were unable to arrive at any halfway definite estimate of the pressure at which the observed transformations occurred, noting only that diamond and hydrogen are metallized at pressures somewhat in the vicinity of one megabar. However, in a study of the electrical resistance of a mixture of substances, the IPHP group was able to establish a sequence of transitions. Yakovel *et al.*[14] reported that the metallic-state transition pressures increase from left to right in the following series of substances:

$$\mathrm{GaP} < \mathrm{NaCl} < \mathrm{Al_2O_3} < \mathrm{BN} < \mathrm{C} < \mathrm{SiO_2} < \mathrm{MgO}.$$

Almost simultaneously with the IPHP group, N. Kawai *et al.*[15–19] reported metallization of silica SiO_2, hydrogen H_2, water H_2O, and magnesium oxide MgO. This group used a multiram two-stage machine that does not contain diamond components and was developed by Kawai himself.

Kawai *et al.* give the following estimates for the metallization pressures in the above substances:

$$\mathrm{SiO_2},\quad \mathrm{H_2} \sim 2.5 \pm 0.5 \text{ megabar} \quad \mathrm{H_2O} \sim 3.2 \pm 0.7 \text{ megabar}$$
$$\mathrm{MgO} \sim 3.4 \pm 0.8 \text{ megabar.}$$

[1)] Abrikosov[28] made the first calculations of the parameters of the metallic transition of hydrogen in the USSR.

[2)] An opaque fine-grained diamond aggregate.

 0038-5670/79/040283-03$01.10

We draw attention to the fact that the sequence of conversions observed by Kawai *et al.* agrees with the observations of the IPHP group.

Here it must be stressed that SiO_2 and MgO are among the most abundant compounds on Earth, and if indications that these compounds go over to the metallic state at pressures of the order of 1 megabar are confirmed, serveral geophysical concepts will have to be modified.

Diamond-anvil techniques have also been developed significantly in recent years. N. Mao and P. Bell of the Carnegie Institution Geophysics Laboratory were able to produce a pressure of 1 megabar[20] by using modified anvils and to investigate the equations of state of several metals and geophysically interesting materials by x-ray diffraction.[21,22] Quite recently, Mao and Bell reported reaching a pressure of 1.7 megabars.[23] To determine the pressure, they used a ruby sensor whose scale had been calibrated against the equations of state of the metals, which equations were obtained with the aid of shock waves. We point out that the 1.7-megabar pressure obtained by Mao and Bell exceeds the pressure at the boundary of the Earth's core (1.4 megabars) and, taking into account the possibilities for physical research by diamond anvils, we may soon expect solutions to a number of intriguing problems.

A. Ruoff's group (Cornell University) is now preparing apparatus for an attack on the hydrogen problem.

J. Wanagel and A. L. Ruoff have built a spherical six-ram machine with hard-alloy anvils; they eventually hope to replace the latter with diamond anvils.[24] The pressures developed in the hard-alloy version of their machine do not exceed 450 kilobars. Ruoff recently advised this author that a metallic transition of solid xenon had been observed in his laboratory at a pressure of 350 kilobars and a temperature of 32 °K. In these experiments, Ruoff used a chamber with a diamond indentor quite similar to the apparatus used by Vereshchagin *et al.*[8] The diagnostic procedure was limited to measurement of the specimen's electrical resistance.

Detailed study of the transition in xenon, which can be brought about quite easily, for example with diamond anvils, will presumably yield much valuable information on the nature of the metal-dielectric transition.

The last paper that we shall discuss here was published by a group headed by P. Hawke[25] at the Lawrence Radiation Laboratory and reported on measurements of the electrical resistance of hydrogen under isentropic compression brought about by a magnetic-explosion procedure[3] It was observed that hydrogen becomes a good conductor at a pressure of ~2 megabars and a density of 1.06 g/cm^3, without the temperature exceeding 400 °K. Compression of neon under the same conditions did not increase the conductivity in the pressure range up to 5 megabars (the expected pressure of metallic neon exceeds 10 megabars).

[3)]See also the papers by Soviet authors[29,30] in this context.

We note that the pressure of the metallic transition of hydrogen reported in this study agrees with Kawai's estimate.

We note in conclusion that although they are open to criticism, the studies made at Moscow and Osaka of the metallization of hydrogen under static conditions nevertheless generally agree well with one another and with the results of isentropic compression and theoretical estimates regarding the transition pressure. As for the metallization of close-packed oxides such as MgO and Al_2O_3, the metallization pressures given for these compounds in the papers cited appear to be too low. D. Liberman concludes from band-structure calculations made for MgO that the pressure of its transition to the metallic state should be about 50 megabars.[26] It has also been put forth that the sharp decrease in resistance on compression of the oxides is due to their decomposition.[27]

A certain contradiction must also be pointed out. According to IPHP data, the pressure of the transition of Al_2O_3 to the metallic state is below 1 megabar, while ruby serves as a pressure sensor up to 1.7 megabars in Mao and Bell's diamond anvils[23] and the aluminum-oxide components used in Hawke *et al.*'s magnetic-explosion device remain nonconductive up to 5 megabars.

Still, the results of recent years are cause for definite optimism. It is quite clear that physics has entered into a new and unexplored range of pressures.

The specific results obtained thus far are interesting, but the authors of the various papers should not be congratulated until the proofs are more complete.

1N. W. Ashcroft, Phys. Rev. Lett. **21**, 1748 (1968).
2R. A. Forman, G. J. Piermarini, J. D. Barnett, and S. Block, Science **172**, 284 (1972).
3E. Gross, Science News **97**, 623 (1970).
4V. L. Ginzburg, O. fizike i astrofizike (Physics and Astrophysics), Nauka, Moscow, 1974.
5G. A. Neece, F. J. Rogers, and W. J. Hoover, J. Comput. Phys. **7**, 621 (1971).
6N. Kawai and S. Endo, Rev. Sci. Instr. **41**, 1178 (1970).
7N. Kawai, S. Mochizuki, and H. Fujita, Phys. Lett. Ser. A **34**, 107 (1971).
8L. F. Vereshchagin, E. N. Yakovlev, K. Kh. Bibaev, G. N. Stepanov, and B. V. Vinogradov, Pis'ma Zh. Eksp. Teor. Fiz. **16**, 240 (1972) [JETP Lett. **16**, 169 (1972)].
9L. F. Vereshchagin, E. N. Yakovlev, G. N. Stepanov, and B. V. Vinogradov, *ibid.* 382 [270].
10L. F. Vereshchagin, E. N. Yakovlev, B. V. Vinogradov, and V. P. Sakun, *ibid.* **20**, 540 (1974) [**20**, 246 (1974)].
11L. F. Vereshchagin, E. N. Yakovlev, B. V. Vinogradov, V. P. Sakun, and G. N. Stepanov, *ibid.* 472 [215].
12L. F. Vereshchagin, E. N. Yakovlev, and Yu. A. Timofeev, *ibid.* **21**, 190 (1975) [**21**, 85 (1975)].
13L. F. Vereshchagin, E. N. Yakovlev, and Yu. A. Timofeev, *ibid.* 643 [304].
14E. N. Yakovlev, L. F. Vereshchagin, B. V. Vinogradov, and Yu. A. Timofeev, *ibid.* **22**, 570 (1976) [*sic*].
15N. Kawai and A. Nishiyama, Proc. Japan Acad. **50**, 72 (1974).
16N. Kawai and A. Nishiyama, *ibid.* 634.
17N. Kawai, M. Togaya, O. Mishima, and B. L. Neindre, *ibid.* **51**, 627 (1975).

[18]N. Kawai, and O. Mishima, *ibid.* 630.
[19]N. Kawai, M. Togaya, and O. Mishima, High-Pressure Research, in Application in Geophysics, ed. M. H. Maughanani, Syun-iti-Akimoto. (Academic, New York, 1977).
[20]H. K. Mao and P. M. Bell, Science **191**, 851 (1976).
[21]H. K. Mao and P. M. Bell, in Carnegie Institution of Washington, Year Book, 75.
[22]H. K. Mao and P. M. Bell, in Carnegie Instituteion of Washington, Year Book, 76.
[23]H. K. Mao and P. M. Bell, Science **200**, 1145 (1978).
[24]J. Wanagel and A. L. Ruoff, in Abstracts of papers presented at the 6th AIRAPT Intern. High Pressure Conference, July 25–29, 1977, Boulder Colorado, USA.
[25]P. S. Hawke and T. J. Burgess, *et al.*, Phys. Rev. Lett. **41**, 994 (1978).
[26]D. A. Liberman, Phys. and Chem. Sol. **39**, 255 (1978).
[27]O. L. Kuskov and N. A. Khitarov, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 288 (1978) [JETP Lett. **27**, 269 (1978)].
[28]A. A. Abrikosov, Astron. Zh. **31**, 112 (1954).
[29]F. V. Grigor'ev S. B. Kormer, O. L. Mikhaĭlova, A. P. Tolochko, and V. D. Urlin, Pis'ma Zh. Eksp. Teor. Fiz. **16**, 286 (1972) [JETP Lett. **16**, 201 (1972)].
[30]F. V. Grigor'ev, S. B. Kormer, O. L. Mikhaĭlova, A. P. Tolochko, and V. D. Urlin, Zh. Eksp. Teor. Fiz. **69**, 743 (1975) [Sov. Phys. JETP **42**, 743 (1975)].

Translated by R. W. Bowers