The properties of natural and synthetic diamond*)

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The Properties of Natural and Synetheic Diamond, Academic Press, N.Y., 1992, J. E. Field (ed.).

The publication of this monograph, with contributions by distinguished English, South African, and Japanese specialists, is largely the result of advances in growing diamond films from gaseous plasmas.

The monograph gives a detailed survey of the current state of a major part of solid state physics and materials science. Diamond, which is structurally one of the simplest crystals, has long attracted the attention of a variety people with exceedingly different interests. It has become, during the last few decades, not only the subject of fundamental research, but also an important technological material. The development of methods for the chemical crystallization of diamond films from low-pressure gaseous plasmas that contain carbon ions suggests that, very soon, diamond will become an important material for solid state electronics in addition to its traditional applications to the mechanical processing of materials. This monograph, published in 1992, is an expanded version of a previous edition that was also edited by J. E. Field and was entitled *The Properties of Diamond*. The latter was well known to Russian specialists, but was not translated into Russian, although it was frequently referred to by Western colleagues as the *Diamond Bible*. The foreword to the new edition is by Sir William Mitchell FRS whose work at Reading University, mostly devoted to the nature of electron localization centers in diamond, provided the foundations for subsequent research in this field.

The monograph is divided into four parts and an appendix. Part I consists of eight chapters and begins with a survey of the current state of the theory of diamond, written by A. M. Stoneham (Harwell) who is well known for his monograph on the theory of point defects in solids.[1] The review analyzes methods available for calculating the band structure and local electron states in diamond, including features such as the Jahn–Teller effect and its influence on the energy spectrum of states coupled to point defects, in relation to which there is particular interest in new experimental data that have been obtained mostly by optical methods and are presented in subsequent chapters.

Chapter 2 (by C. D. Clark, A. T. Collins, and G. S. Woods) reviews data on optical absorption and the luminescence spectra of diamond. Specialists in this field are aware of the considerable advances that have been made in experimental techniques, and many of the narrow lines associated with carrier localization centers have been successfully identified some time ago. Because of successes in the synthesis of diamond films, and the growing interest in semiconducting diamond and in structures based upon it, it is expected that important new research will emerge in this field.

Chapter 2, written by J. P. F. Sellschop (University of the Witwatersrand), contains a presentation of interesting studies of diamond crystals by nuclear-probe techniques that have produced reliable data on the geometric distribution, the quantity, and the microstructure of impurity centers. Sellschop's review describes traditional methods as well as newer techniques such as ion implantation of impurities, followed by an examination of their distribution relative to the original lattice, and presents recent data on ion channeling and dechanneling, radiation produced by fast channeled electrons, and coherent bremsstrahlung in diamond. It is well-known that high-grade diamond single crystals are the best objects for experimental studies of such phenomena, and systematic research in this field is being undertaken in many developed countries.

Chapter 4 (by S. Evans, University College of Wales) offers a detailed review of the state of our knowledge of the surface physics of diamond. At present, the most thoroughly investigated surface is that of single-crystal silicon, the main material of modern planar solid-state electronics, for which particularly valuable information on atomic microstructure has been obtained by tunneling electron microscopy. Studies of the surface properties of diamond are still facing many unresolved problems that are attracting the attention of numerous researchers. Evans' review is one of the most interesting and, like many of the others in this monograph, deserves to be translated into Russian.

Chapter 5 (by A. R. Lang *et al.*) surveys x-ray diffraction and imaging studies of diamond, which have yielded detailed information about natural inhomogeneities, inclusions, and mechanical stresses in diamond.

Chapter 6 (by T. Evans, University of Reading) is devoted to the problem of nitrogen in diamond. Nitrogen is, of course, practically always present in natural crystals and has a pronounced effect on their optical and other properties. Much of the data presented in this chapter have frequently been published before, both in the West and in Russian (cf. the review by A. A. Gippius in the book[2] published in 1985).

Chapter 7 (by R. Berman FRS, Oxford University) is concerned with the important question of the thermal conductivity of diamond. It presents new data on the thermal conductivity of vapor-deposited diamond on different substrates. Such films are at present significantly inferior to type IIa natural crystals. Berman reports important basic data on the thermal conductivity of synthetic diamond with modified C^{13} concentration, produced by the high-pressure high-temperature recrystallization of starting material in the form vapor-deposited and isotopically enriched diamond film. The experimentally established changes in thermal conductivity, foreseen by Berman many years ago, have elicited considerable interest among theorists and are analyzed in detail.

Chapter 8 (by J. F. Prins, University of the Witwatersrand), which concludes Part I, contains an analysis of

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the question of controlling the electrophysical properties of diamond for which ion implantation of impurities has attracted considerable attention for many years. This reviewer notes with pleasure that Prins stresses the importance of the continuing research performed since the middle 60s in Moscow at the Lebedev Physics Institute and the Kurchatov Atomic Energy Institute (there are over 20 references to this work). Prins has expressed regret in a conversation with this reviewer that much published material had not been translated into English and was therefore unavailable to him. In recent years, Prins proposed and implemented the method of double implantation in diamond whereby in addition to an electrically active impurity, point defects, whose interaction with the impurity can in some measure by controlled, are introduced into diamond. Prins' review will be of interest to specialists concerned with applications of broad-band semiconductors in electronics.

Part II of this monograph is devoted to geological data. The occurrence of diamonds in the Earth's crust is discussed in Chapter 9 (by J. W. Harris, Glasgow University), the growth of single-crystal diamond is dealt with in Chapter 10 (by R. C. Burns and G. J. Davies, De Beers), whilst the synthesis of diamond from the vapor phase is reviewed in Chapter 11 (by Y. Sato and M. Kamo, Tsukuba, Ibaraki). Chapter 9 presents detailed data on the occurrence of diamond at different parts of the Globe. There are only a few references to Soviet work, probably because, for many years, there were well-known difficulties with the publication of papers on this topic. The chapter on growing single crystals repeats to some extent (and in abbreviated form) the review published in the 1979 edition (also edited by Field) and, in addition, presents some carefully chosen data on the largest synthetic diamonds growth in recent years. Particular attention is devoted to the technique known as *reconstitution*, whereby diamonds of maximum size and perfection are produced from starting material in the form of a large number of small synthetic diamonds, carefully selected to achieve maximum homogeneity of properties. This was used in 1990 at the laboratories of the General Electric Company to grow isotopically pure single-crystal diamonds. The chapter concludes with a short section on special applications of large homogeneous diamonds in the detection of nuclear radiation and in biological research exploiting the phenomenon of thermoluminescence.

The authors argue persuasively that the growing of large diamonds is an expensive and very time-consuming undertaking (a 14-carat diamond could require 500 hours).

The synthesis of diamond films (Chapter 11) can in principle be performed on large-area substrates, but according to this review, epitaxial layers were for a long time confined to oriented single-crystal diamond, whereas the use of other substrates resulted in the growth of crystalline films that were less convenient for practical applications. Sato and Kamo report mostly their own results. There is particular interest in the analysis of Raman scattering in films, which shows that not all the interatomic bondings in these films are homeopolar in character.

According to the data reported by these workers, experiments on the synthesis of diamond from the vapor phase have produced crystallites with linear dimensions up to 10 μm, but further deposition tended to yield polycrystalline material because of secondary nucleation. Comparison of this review article with the proceedings of recent conferences, e.g., *Diamond Films-92* (held at Heidleberg in September 1992),suggests that significant advances were made last year, after the publication of this review.

Part III deals with the mechanical properties of diamond, i.e., strength, fracture, and erosion properties. It is well-known that it is precisely these properties—especially hardness and resistance to mechanical, chemical, and thermal effects—that have provided the basis for extensive applications of diamond in modern technology. This reviewer happens to known that diamond cutters were used on steel by Rolls Royce more than 80 years ago with remarkable results. Today, high technology without diamond instruments is unthinkable. Working as he does in the field of semiconductor physics, this reviewer is not really able to judge the contents of Chapter 12 (by J. E. Field, Cambridge University) and Chapter 13 (by C. A. Brookes, Hull University), but believes that specialists will find much interesting material in these chapters. This also applies to Chapter 13 (by D. Tabor and J. E. Field, Cambridge University) which examines physical processes involved in the friction of diamond on diamond and on other materials. It is interesting to note that many new ideas on friction and the mechanism of wear were formulated quite recently (in the late 80s). Experiments performed in ultrahigh vacuum have had an important bearing on the evolution of fundamental ideas on frictional processes.

Lack of space prevents us from considering the concluding chapters of this monograph, which deal with polishing of diamond and the accompanying phenomena (wear), and also with the most common practical applications of diamond and diamond grits in modern technology.

Detailed tabulations of the main parameters of diamond are reproduced, with the appropriate citations, at the end of the monograph.

This reviewer has formed a very favorable opinion of this book and wishes the contributors to it much further success in their future researches.

[1] A. M. Stoneham, *Theory of Defects in Solids*, Oxford University Press, Oxford, 1975 [Russ. transl., Mir, M., 1978, vols. 1 and 2, 569 and 368 pp., respectively].

[2] V. S. Vavilov, A. A. Gippius, and E. A. Konorova, *Electronic and Optical Processes in Diamond* [in Russian], Nauka, M., 1985, 119 pp.

Translated by S. Chomet