Aperiodic Schrödinger Crystals

V B Malkov¹, O V Chemezov² and A V Malkov³

¹Institute of High-Temperature Electrochemistry, Ural Branch Russian Academy of Sciences, 22, S. Kovalevskoy, Yekaterinburg, 620219, Russia
²Ural Federal University named after the first President of Russia B. N. Yeltsin, 19, Mira street, Yekaterinburg, 620002, Russia
³ZAO NPTs ROSNA, 9, Studencheskaya, Yekaterinburg, 620026, Russia

E-mail: o.v.chemezov@urfu.ru

Abstract. In 1945, E. Schrödinger predicted the possibility of the existence of “aperiodic crystals,” that is, more and more increasing crystalline aggregates, but without a simple lattice repetition mechanism. In the present work, such structures are experimentally prepared using selenium as an example. By thermal gradient treatment of the amorphous selenium film, we have obtained nano-thin spatial dissipative structures (SDS) of hexagonal selenium, the lattice of which undergoes non-uniform rotational curvature around, in the general case, three mutually perpendicular directions. The formation of these nano-thin SDS of hexagonal selenium occurs as a result of cooperative rotations of selenium macromolecules around, in general, three mutually perpendicular directions. Since nano-thin SDS after hardening in air have all the features of crystals each of the above nano-thin SDS of hexagonal selenium obtained at different annealing temperatures corresponds to the concept of “aperiodic crystals” Thus, “aperiodic crystals” were obtained experimentally, the possibility of the existence of which was predicted by E. Schrödinger.

1. Introduction

The concept of “aperiodic crystal”, first introduced by Erwin Schrödinger in the book “What is life?” [1]. In the first chapter, on the pages of 12 and 13, E. Schrödinger defines an aperiodic crystal: “… periodic crystals are very interesting and complex objects…. However, compared to aperiodic crystals, they seem somewhat elementary and boring. The difference in structure here is the same as between ordinary wallpaper, on which the same pattern is repeated with the correct periodicity, and a masterpiece of embroidery, say, Raphaelev tapestry, which repeats the complex, consecutive and complete design pattern drawn by the great master…”. Further, on the page 66 [1], E. Schrödinger gives an example of an aperiodic crystal: “… it is possible to imagine two different ways of building more and more associations. One is a relatively uniform way of repeating again and again the same structure in three directions.... The other way is to build a more and more increasing aggregate without a boring repetition mechanism. This is a case of an increasingly complex organic molecule, in which each atom, each group of atoms plays an individual role that is not quite equivalent to the role of other atoms and groups of atoms. We can definitely call this formation an aperiodic crystal…”.

On page 82 [1], E. Schrödinger points to the mechanisms for the formation of ordered structures: “It turns out that there are two different “mechanisms” that can produce ordered phenomena: a
statistical mechanism that creates “order from disorder”,” and a new mechanism that produces “order from order”.

Thus, on the one hand, Schrödinger points to the possibility of the existence of “aperiodic crystals” —... “aggregates without a boring repetition mechanism,” and, on the other hand, determines the mechanism for their formation —... “a new mechanism that produces “order from order”.”

How right was E. Schrödinger, pointing to the possibility of the existence of aperiodic crystals? To answer this question, consider nano-thin spatial dissipative structures (SDS) formed in amorphous films.

2. Results and discussion

It is known that in amorphous films of selenium, during their thermogradiant processing, nano-thin spatial dissipative structures of hexagonal selenium are formed [2–6]. In the process of electron-microscopic studies, and the methods of transmission electron microscopy, electronography and bending extinction circuits present on electron-microscopic images of nano-thin SDS were investigating nano-thin SDS of hexagonal selenium, presented in figure 1 [2, 3, 7–17].

Nano-thin diamond-shaped SDS of hexagonal selenium (figure 1, a) are characterized by a system of bending extinction contours parallel to the short diagonal of rhombus [2, 3, 6, 7]. Microdiffracion studies of nano-thin SDS of hexagonal selenium [7–10] and analysis of flexural extinction circuits on electron microscopic images of nano-thin SDS make it possible to conclude: nano-thin diamond-shaped SDS (figure 1, a), formed in an amorphous film with one-sided heating of the lower surface at $T = 453 \text{ K}$, are in a non-equilibrium state – their lattice experiences non-uniform elastic rotational curvature around [001], coinciding in direction with the axis OZ (figure 2). The rotation of the lattice of nano-thin diamond-shaped SDS of hexagonal selenium (figure 1, a) around [001] reaches $18^\circ$ [2, 3, 6].

Thus, indeed, the formation of nano-thin diamond-shaped SDS of hexagonal selenium (figure 1, a) occurs “...without a boring mechanism of repetition” [1], and as a result of cooperative progressive rotations of Se macromolecules around [001].

Nano-thin diamond-shaped SDS of hexagonal selenium formed in an amorphous film during its thermal gradient treatment at $T = 423 \text{ K}$ (figure 1, b), characterized by a linear fan-like system of bending extinction circuits on electron-microscopic images.

Microdiffracion studies of nano-thin SDS of hexagonal selenium (figure 1, b) and analysis of the system of bending extinction circuits present on electron-microscopic images of nano-thin SDS make it possible to conclude: their lattice experiences inhomogeneous elastic rotational curvature around two mutually perpendicular directions – around [001] and around the OX axis (figure 2) [2, 3, 6, 18, 19]. The rotation angles of the lattice of nano-thin diamond-shaped SDS of hexagonal selenium with a linear fan-shaped system of bending extinction circuits on electron-microscopic images reach: around [001] – $18^\circ$; about OX axis (figure 2) – $22^\circ$.

Formation of nano-thin diamond-shaped SDS of hexagonal selenium (figure 1, b) occurs as a result of cooperative rotations of selenium macromolecules around two mutually perpendicular directions.

Nano-thin STS of hexagonal selenium with curved gabinetus are formed in an amorphous film during thermal gradient treatment by heating its lower surface at $T = 413 \text{ K}$ (figure 1, c). As a result of studies of nano-thin SDS conducted by electron-microscopic and microdiffracion methods, it was found that nano-thin STS with curved gabinetus (figure 1, c) are in a non-equilibrium state, their lattice experiences non-uniform elastic-plastic rotational curvature around three mutually perpendicular directions: around [001], around the OX axis and about OY axis (figure 2). The angles of rotation of the lattice of nano-thin SDS with the curved gabinetus reach: around [001] – $25^\circ$, around the axis OX – $32^\circ$, around the axis OY– $35^\circ$ (figure 2) [2, 5, 19].

Thus, the formation of nano-thin diamond-shaped SDS of hexagonal selenium (figure 1, c) also occurs... “without a boring mechanism of repetition” [1], and as a result of cooperative rotations of selenium macromolecules around three mutually perpendicular directions (figure 2) [2, 5, 19].
Figure 1. Electron microscopic image of nano-thin SDS hexagonal selenium, JEM-200CX JEOL Ltd, Japan: a) having a diamond-shaped gabbitus and a system of bending extinction contours parallel to [001], coinciding with the short diagonal of the rhombus; b) having a diamond-shaped gabbitus and a linear fan-shaped system of bending extinction contours; c) with curved habitus.
Since the structural units of the lattices of nano-thin diamond-shaped SDS of hexagonal Se with a parallel short diagonal of the rhombus are a system of bending extinction circuits on electron-microscopic images (figure 1, a); nano-thin diamond-shaped SDS of hexagonal Se with a linear fan-like system of bending extinction circuits on electron microscopic images (figure 1, b); nano-thin SDS of hexagonal Se with curved habitus and a non-linear system of bending circuits on electron microscopic images (figure 1, c) are selenium macromolecules [2, 5, 19–21]. Since it is clear that the rotation of the lattice of nano-thin SDS around one, two or three mutually perpendicular directions is the result of cooperative rotations of selenium macromolecules forming lattices of nano-thin SDS of hexagonal selenium (figure 1, a, figure 1, b, figure 1, c) [2, 5, 19–21], around one, two or three mutually perpendicular directions, respectively (figure 2).

The nano-thin SDS of hexagonal selenium shown in figure 1, a, figure 1, b, figure 1, c differ in complexity. The lattice of nano-thin diamond-shaped SDS (figure 1, a) experiences non-uniform elastic rotational curvature around [001], the lattice of nano-thin diamond-shaped SDS (figure 1, b) experiences non-uniform elastic rotational curvature around two mutually perpendicular directions [11], around – [001] and around the axis OX (figure 2); the lattice of nano-thin diamond-shaped SDS with curved habitus (figure 1 c) experiences non-uniform elastic-plastic rotational curvature around three mutually perpendicular directions, around [001], around the OX axis and around the OY axis (figure 2).

![Figure 2. Coordinate system associated with nano-thin SDS of hexagonal selenium.](image)

3. Conclusion
Since nano-thin SDS after hardening in air have all the features of crystals [2, 8, 10, 11], each of the above nano-thin SDS of hexagonal selenium (figure 1, a, figure 1, b, figure 1, c) corresponds to the concept of “aperiodic crystal” [1].

As a result, by thermal gradient treating an amorphous selenium film, nano-thin SDS of hexagonal selenium are obtained, the lattice of which experiences a non-uniform elastic or elastic-plastic rotational curvature around one, two or three mutually perpendicular directions. The formation of these nano-thin SDS of hexagonal selenium occurs as a result of cooperative rotations of selenium macromolecules around one, two or three mutually perpendicular directions. Thus, “aperiodic crystals” were obtained experimentally, the possibility of the existence of which was predicted by E. Schrödinger [1].

References
[1] Shredinger E 2002 What is life? Physical aspect of a living cell (Moscow-Izhevsk: N I C “Regular and chaotic dynamics”)
[2] Malkov V B, Nikolaenko I V, Shveikin G P, Malkov A V, Pushin V G, Shulgin B V, Malkov O V and Plaksin S V 2017 Method for obtaining dissipative structures RU Patent 2637396
[3] Malkov V B, Nikolaenko I V, Shveikin G P, Pushin V G, Malkov A V, Malkov O V and Shulgin B V 2018 Formation of dissipative structures in amorphous film Reports of the Academy of Sciences 478 5 543–545
Malkov V B, Shevkin G P, Pushin V G, Malkov A V, Shulgin B V and Malkov O V 2018 Nano-thin crystal lattice symmetry, the isomorphism of direct and inverse space and the principle of Curie symmetry Reports of the Academy of Sciences 479 1 18–20

Malkov V B, Shevkin G P, Plaksin S V, Pushin V G, Malkov A V, Malkov O V and Shulgin B V 2019 Nano-thin spatial dissipative structures with rotational lattice curvature around three mutually perpendicular directions Reports of the Academy of Sciences 488 6 619–623

Malkov V B, Nikolaenko I V, Shevkin G P, Pushin V G, Malkov A V, Shulgin B V and Malkov O V 2018 Change in the geometry of the lattice of nano-thin, spatial dissipative structures formed in an amorphous film Reports of the Academy of Sciences 166 11 649–651

Hirsch P B, Howie A, Nicholson R B and Pashley D W 1965 Electron Microscopy of Thin Crystals (London: Butterworths)

Tomas G and Goringe M J 1979 Transmission electron microscopy of materials (New York)

Utevsky L M 1973 Diffraction electron microscopy in metal science (Moscow: Metallurgy)

Andrews K V, Dyson D J and Keown S R 1968 Interpretation of Electron Diffraction Patterns (London)

Bolotov I E and Kolosov V Yu 1980 Bend of thin-film crystals of selenium, found along the extinction contours Izv. Academy of sciences of the USSR Series physical 44 6 1194–1197

Bolotov I E, Kolosov V Yu and Malkov V B 1986 Electron Microscopy Investigation of Crystals Based on Bend-Contour Arrangement 3. Formation of Subgrain Boundaries in Dislocation-Free Crystals of Selenium Phys. Stat. Sol. (a) 95 377–383

Bolotov I E, Kolosov V Yu and Malkov V B 1986 A new type of interblock boundaries in thin-film crystals of selenium Crystallography 1 204–206

Bolotov I E, Kolosov V Yu and Malkov V B 1984 Application of Bend-Contour Method the Investigation of Block Formation in Thin-Film Crystals Budapest Electron Microscopy 2 42–45

Bolotov I E and Kolosov V Yu 1982 New possibilities of the method of bending extinction circuits Theses of reports 12 All-Union Conf. electron microscopy 186–187

Bolotov I E, Kolosov V Yu and Kozhin A V 1982 Using the map of extinction contours in the study of the bending of crystals growing in thin amorphous films Theses of reports 12 All-Union Conf. electron microscopy 138–139

Bolotov I E and Kolosov V Yu 1982 Possibilities of the method of extinction contours in the study of the bending of thin-film objects Factory laboratory 48 11 53–57

Malkov V B, Malkov A V, Malkov O V, Pushin V G, Shulgin B V and Agalakov S P 2008 The phenomenon of elastic rotational curvature of the lattice of nano-thin crystals of hexagonal selenium around [001] as part of the asymmetric theory of elasticity Collection of report Kharkiv nanotechnology. Assembly 2 18–23

Malkov V B, Nikolaenko I V, Shevkin G P, Malkov A V, Pushin V G, Shulgin B V, Malkov O V and Plaksin S V 2019 Diagnostic technique for the evolution of nano-thin spatial structures RU Patent 2687876

Vunderly B 1976 Physics of macromolecules (Moscow: World) p 623

Tager A A 1978 Physical chemistry of polymers (Moscow: Chemistry) p 574

Acknowledgments
Experiments on electron-microscopic studies of nano-thin SDS of hexagonal selenium were carried out in the electron microscopy department by the collective use center “Testing Center for Nanotechnology and Promising Materials” of the Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences.