Chapter 9
Print ISBN: 978-93-90768-20-2, eBook ISBN: 978-93-90768-21-9

Vlasov's Physics: From Plasma to Solid

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DOI: 10.9734/bpi/aaer/v3/7678D

ABSTRACT

The basic principles of Vlasov's physics are considered from a general point of view. The reliability of his judgments about the application of nonlocal statistical mechanics to real solids is shown. The possibilities of Vlasov's physics for a reliable description of matter are discussed.

Keywords: Vlasov's model for solids; diffusion model; silicon; germanium; Vlasov's equation; defect formation.

1. INTRODUCTION

Vlasov's model for solids was developed in the middle of the last century [1]. This model proceeded from Vlasov's assumption that all types of the state of aggregation of matter (plasma, gas, liquid, solid) can be described using the approach he proposed. In the 70s of the last century, Vlasov's theory for plasma received worldwide recognition. In solids the theoretical description was based on the provisions of the classical theory [2] and the theory of nucleation and growth of particles of the second phase [3] (which follows from [2]). Unfortunately, the classical approach has not been fully developed. In it, the formation of impurity structural imperfections could be explained only with an increase in temperature. We have overcome this drawback by developing a diffusion model of defect formation [4].

In diffusion model the main place is occupied by the process of high-temperature precipitation of impurities. This process begins from the very beginning of crystal growth and determines the entire course of the process of defect formation in crystal. The diffusion model, which was initially applied to highly perfect silicon crystals, was extended to germanium single crystals [5]. Note that the diffusion model of defect formation is fully confirmed by the experimental results. The question arose as to whether the diffusion model could be validated using a different physical approach? Vlasov's model for solids was chosen as another approach. We have considered the processes of complexation 'impurity + intrinsic point defect' in both silicon and germanium [6, 7]. Calculations using Vlasov's model showed that classical theory of the nucleation and growth of second-phase particles in solids and Vlasov's model equally consider the formation and evolution of second-phase particles upon cooling the crystal after growth. What is the essence of Vlasov's model for solids?

Vlasov's model originates from the equation proposed by Vlasov, which is a system of equations describing the plasma dynamics of charged particles taking into account long-range Coulomb forces through a self-consistent field. Since plasma is the most common aggregate state of matter in the Universe, Vlasov suggested that gases, fluid, solids are also described using the proposed equation.

2. MAIN PART

Vlasov's model for solids state based on the following fundamental physical positions: (i) rejection of the principle of the spatial and velocity localization of the particles (in terms of classical mechanics), which takes place regardless of the force interactions; (ii) the introduction of force interactions by analogy with classical mechanics, but taking into account the new principle of non-localization of

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particles; (iii) the behaviour of each particle of the system is described by means of an extended in phase space f-function. In this approach are combined the ideas of continuity and of corpuscular. The method of describing of motion of particle associated with the extended function, and the particle in the form of a point occurs only in the particular case.

In the general case, Vlasov's equation describes the evolution of the distribution function $f(x, v, t)$ of the continuum of interacting particles in Euclidean space with respect to velocity v and coordinate x at time t. It has the form

$$\frac{\partial f}{\partial t} + \left(\frac{\partial f}{\partial x}, v\right) + \left(\frac{\partial f}{\partial v}, F\right) = 0$$
$$F = -\frac{\partial}{\partial x}\int K(x,y) f(y,v,t)\,dv\,dy \quad (1)$$

where K is a pair interaction potential, which in real tasks depends on distance $|x - y|$, and F is a total force with which all particles act on one of them, located at time t at point x.

To describe the stationary properties of a crystal, the concept of the particle distribution density is used $\rho(r) = \int f(r, v)dv$. The molecular field is determined not by exact but only by the probable positions of atoms, which is expressed by a potential function containing the probability density of particles, taking into account the temperature distribution of particles [8, 9]. The choice of the potential for pair interaction depends on the task under consideration. Then, the nonlocal model of a crystal is based on the following nonlinear equations, which make it possible to calculate the molecular potential and density of the particle location under conditions of temperature equilibrium [8, 9]:

$$V(r) = \lambda kT \int_{-\infty}^{\infty} K_{1,2}(r) exp\left(-\frac{K_{1,2}(r)}{kT}\right) dr$$
$$\rho(r) = \lambda kT exp\left(-\frac{K_{1,2}(r)}{kT}\right) \quad (2)$$

where k is a Boltzmann constant; $K_{1,2}$ is a pair interaction potential; λ is a is a some characteristic number; T is a temperature. The original equations represent equations for two particles under steady state conditions $\left(\frac{\partial}{\partial t} = 0\right)$ [9]. In this case, the characteristic number is understood as such values of some parameter λ for which Eqs. (2) have solutions different from the trivial [9]. If the position of one of particles is taken as the origin, then we can determine $\rho(0) = \lambda kT$ [9]. Finding the characteristic numbers in framework of Vlasov's model for solids is the most important task.

The characteristic number λ is determined from the main criterion for the existence of a crystalline state, while the crystallization condition can be written as follows:

$$\frac{4\pi N}{kT_m}\int_0^{\infty} K_{1,2}^*(\rho)\rho^2 d\rho = 1 \quad (3)$$

where N is a number of particles; T_m is a melting (crystallization) temperature of crystal; $K_{1,2}^* = -K_{1,2}$ [9].

Equation (2) is written for the conditions of temperature equilibrium of the system. Since the minima of interatomic potentials correspond to a stable equilibrium arrangement of atoms in complexes (silicon-oxygen and silicon-carbon), it is possible to determine the distribution density of the complexes as a function of the crystal cooling temperature

$$\rho(T) = \lambda kT exp\left(-\frac{V_{1min,2min}}{kT}\right) \quad (4)$$

3. DISCUSSION

In Vlasov's model for solids, the periodic probability density distribution of particles is the state (motion) of a system of particles, not a construct. From conservation laws for statistical distribution

functions it follows that diffusion phenomena belong to the class of primary phenomena in comparison with force interactions of particles, i.e. growth processes (crystals, biological, plasma structures) are inertial processes in the sense that their flow does not require the mandatory participation of external forces; they can influence growth, but growth occurs without their action. The periodic structure of crystals is due to the specificity of the statistical laws of particle motion and does not require restrictions on the free movement of atoms in a crystal (and the introduction of absolute zero temperature). The method of self-consistent field can be applied to a wide variety of systems. The interaction in these systems can be short-range or long-range, weak or strong.

The meaning of the last sentence can be figuratively illustrated as follows. The essence of Vlasov's work in the field of plasma studies was that he showed that plasma is not a gas but a system “pulled together by distant forces,” i.e., in fact, it is an analogue of Universe pulled together by force lines [10]. The taking into account of these forces allows us to speak about dissemination in plasma, i.e. and in the Universe, the longitudinal waves associated with a change in electron density, and also with a large dispersion, and this dissemination is a so-called collective vibrations of a multiparticle system. One of the main conclusions of Vlasov's theory for solids is that the classical “lattice-point” model of solids is only one of the possible states of a crystal, but in reality atoms in a crystal move freely, propagating along the so-called “threads” and “plates”, the direction of which coincides with the direction of the crystallographic axes and planes, which are distinguished by the maximum population of atoms [1].

What does the last conclusion tell us? About the confirmation by Vlasov of force lines concept by Faraday-Thomson, along which there is a maximum density of charged particles, i.e. matter. As is well known, J.J.Thomson in 1904 published a book "Electricity and Matter" [11]. Using the classical Newton mechanics he solved such questions as: (1) the problem of relationship between the number of electrons and their distribution with the mass of atom; (2) the problem of nature and distribution of a positive charge in atom; (3) the problem of distribution of the atom mass. He postulated that the main communication forces are transmitted through forces (electromagnetic) lines. If these force lines are lead through all points of the contour of a small closed curve in an electric field, these lines form a tubular surface, and if these lines continue to a positively charged surface then the positive charge at the beginning of the tube will be equal to the negative charge at the end of it. By choosing the area of the small curve through which he led the lines, Thomson showed that the charge contained in the tube is equal to the unit charge. Based on this, he called these tubes “Faraday tubes” named in honor M.Faraday (1791–1867), who for the first time proved the reality of the existence of force lines. Thomson identified these closed ring-shaped Faraday's force lines or "Faraday tubes" with the concepts of "quantum of light" (photon) and "electron". Thus, the elementary particles known at that time were in real not point particles. Ten years before the planetary model of the atom appeared and sixty years before it became clear that electrons in the atom are not clearly structured linear orbits, but a kind of gas cloud, while the orbit itself is the range of energy values of the electron existence, where is the electron movement it resembles a kind of "whirls", Thomson showed that elementary particles in their movement are in fact "elementary whirls", i.e. vibrations, i.e. waves. The surroundings through which the tubes pass have a hydrostatic pressure calculated by Thomson. The change in mass of a moving body, according to Thomson, occurs as a result of dragging a part of the environment by a moving body and increases by the mass of the environment which dragging. He showed that the concentration of force lines around charged bodies is so high that almost all the surroundings bound by these bodies is around these bodies, and its amount depends on the volume and charge of these bodies. Vibrating a charged body so that its acceleration periodically changes, gives rise to periodic electromagnetic light waves from these bodies, as phenomena caused by the propagation of transverse oscillations along tightly stretched Faraday's tubes [11].

As can be seen, in a global sense, the conclusions of Thomson and Vlasov can be identified with the idea of a “large-scale structure of the Universe”. According to this idea, the Universe is a collection of flat “sheets” separated by “empty” areas in which there is practically no luminous matter. These sheets, along which the main mass of matter is distributed, can be identified with Thomson and Vlasov force lines. These ideas have only recently begun to be confirmed [12].

Vlasov, in his constructions, was repelled by the theory of N.P. Kasterin. Kasterin derived second approximations of the Euler and Maxwell equations, showing their complete parallelism, taking into account Thomson's theory of the "elementary whirls" in the calculations. Then Kasterin reduced both second approximations into a general system, showing the discontinuity of the kinetic potential for the motion of the system of "whirls", which he explained by the discontinuity of the electric field, i.e. discontinuity of force lines [13, 14]. According to Kasterin, this discontinuity is the basis for explaining the quantum properties of a field. It was shown that Kasterin equations were constructed correctly and its mathematical apparatus can be used [15, 16].

Another important conclusion of Vlasov, which we have already indicated earlier, is that diffusion phenomena belong to primary phenomena in comparison with force interactions of particles. Based on this, i.e. of the ability of spontaneous growth for no apparent reason, if only conditions necessary for that were achieved in the environment, Vlasov came to an interesting hypothesis: the laws governing growth, as an inertial process, forbid a state of rest. It was from here that Vlasov drew a conclusion about the free movement (wandering) of atoms in a crystal. Such assumption suggested the need to introduce “irreversibility” (instead of the usual dissipation) into the conservation law for the statistical distribution functions when formulating this law in finite differences.

So, Vlasov developed Kasterin theory in the sense that one should look for the following approximations when solving known equations and said that the degree of the equation depends on the amount of information about the motion of particles. Vlasov describes a particle in a statistical package, i.e. taking into account fluctuations (i.e., without precise spatial and kinematic localization). In this case, the force is not the cause of the movement, but the limiter of possible movements potentially included in the image of the particle. Hence, if the number of particles is “large” (probabilistic), it follows that the classical mechanics of points, the “Gibbs distribution” and the “Liouville equation” are only special cases of a more general theory. It follows that adequate mathematical theories should emphasize the identity of the processes occurring at the macro and micro levels, which indicates the absence of any duality in nature.

Thus, our proof of the validity of Vlasov's theory for solids as applied to the real material, indirectly testifies to the validity of all other theoretical ideas that Vlasov was repelled from.

4. CONCLUSION

From the viewpoint of the identity of results of two alternative theories, it can be said that Vlasov’s assumption about possibility to describe the real world from a unified standpoint is correct. Main results are following:

(1) The concepts and principles of Vlasov’s physics are fully applicable to solids, as well as, possibly, to other aggregate states of matter.
(2) Vlasov's model for solids describes the processes of complex formation during the growth of real crystals in accordance with the classical theory of nucleation and growth of second-phase particles in solids.
(3) A method is proposed for calculating the initial defect structure of crystals, which includes Vlasov's model for solids and the classical theory of nucleation and growth of second-phase particles in solids.
(4) Our proof of the validity of Vlasov's theory for solids as applied to the real material, indirectly testifies to the validity of all other theoretical ideas that Vlasov was repelled from.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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