საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 11, №1, 2017
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 11, no. 1, 2017

Physics

Mechanism of the Long-Range Action Effect under Energy Impact

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(Presented by Academy Member Gia Japaridze)

ABSTRACT. We propose a long-range action effect mechanism qualitatively explaining all the existing experimental data obtained for any kind of energy impact on a solid state. This mechanism is based on new conceptions of movement of atoms (defects) in condensed matter described in the molecular - potential theory (MPT). In contrast to the molecular-kinetic theory (MKT), MPT does not require the formation of a certain kinetic energy fluctuation nearby the atom to overcome the potential barrier. However, it is necessary to somehow reduce the chemical bond energy, which corresponds to decrease in the potential barrier height. The decrease in the chemical bond energy nearby a given atom is due to the occurrence of antibonding quasiparticles (AQP) - excited electrons and/or holes that can be created in different ways (by light, injection of charged particles, temperature, pressure, etc.). In any case, this facilitates the motion of atoms. All the long-range effects under the energy impact are associated with the movement of defects, initial and/or created by irradiation, due to AQP, which are always formed under different energy impact and facilitate the movement of atoms. *© 2017 Bull. Georg. Natl. Acad. Sci.*

Key words: antibonding quasiparticles, defect, stimulating migration

As is known [1, 2], the essence of the long-range action effect under the energy impact is that at irradiation of solid-state plates (semiconductors, metals) by electrons, charged particles (including those with subthreshold energy), electromagnetic radiation, the changes in mechanical, electrical and optical properties of materials at abnormally large distances (of the order of magnitude greater, than the energy impact penetration length) from the irradiated surface to the opposite (back) irradiated surface of the plate are observed. Sometimes, the changes on this surface are larger, than on the irradiated side [3]. The long-range effect is revealed in the stack of foils of the identical or different materials and consists in detecting changes in the physical properties not only of the foil subjected to the energy impact, but of the subsequent foils pressed to it [4]. The long-range effect is also observed in the experiment, in which after irradiation of a chromium-coated 500μm-thick α-Fe wafer by 4 MeV electrons the chromium atoms are distributed throughout the bulk of the material. According to the X-ray analysis, the chromium concentration is higher in the layer most remote from the irradiated chromium-coated surface. Thus, in the long-

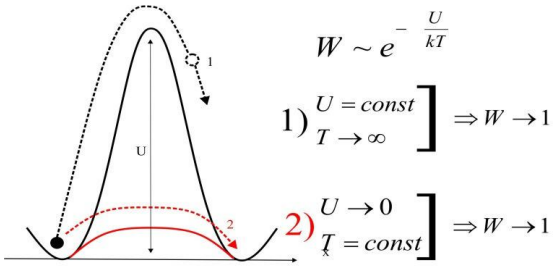

Fig. 1. 1) According to MKT, for the movement of atoms in solids a fluctuation kinetic energy sufficient to overcome the potential barrier U is required, $W \sim e^{-\frac{U}{KT}}$ (1) – W is the probability of changes in the atom position, T is the absolute temperature, k is the Boltzmann constant. 2) According to the new MPT conceptions, for the movement of atoms the potential energy of interatomic interaction should somehow be reduced to a minimum, $U \to 0$.

range effect a mass transfer to "abnormally" large distances is recorded [5]. Reliable experiments have demonstrated that the long-range effect is not related to the heating and diffusion of the minority carriers to the back side [1, 2]. It is also noted [6] that for the long-range action effects the degree of the crystal structure perfection is not critical.

In [7], authors, based on the presented experimental data, discussed two hypotheses to explain the formation of defects at large distances from the irradiated surface: either the transfer of defects into the bulk of the sample, or the transfer of energy in the form of elastic waves, which being localized at large depths, initiates defect formation processes. But they also have to make other assumptions to explain the experimental data. For example, in [8], the wave front used to explain the experimental results propagates by two orders of magnitude faster, than it follows from the experiment, impelling the authors to make additional assumptions. Moreover, under the weak light exposure [3], the assumption of the formation of elastic waves able to create defects in the crystal lattice and loosing this ability with increasing illumination time is rather problematic. The authors [5] conclude that the long-range effect is observed in a wide range of experimental conditions and does not allow an unambiguous interpretation of the observed experimental data.

In this paper, we propose a long-range effect mechanism qualitatively explaining all the experimental data obtained for any kind of energy impact. This mechanism is based on new conceptions of movement of atoms (defects) in condensed matter [9, 10] described in the molecular - potential theory (MPT) [11]. For better understanding of this process, let us briefly present the main concepts and conclusions of MPT [11, 12]. In contrast to the molecular-kinetic theory (MKT) [13], MPT does not require the formation of certain kinetic energy fluctuation nearby the atom to overcome the potential barrier (Fig. 1.1). However, it is necessary to somehow reduce the chemical bond energy, which corresponds to decrease in the potential barrier height (Fig. 1.2).

The decrease in the chemical bond energy nearby a given atom is due to the occurrence of antibonding quasiparticles (AQP) - excited electrons and/or holes. In accordance with the molecular orbital theory of chemical bonds applied to solids [14], the electron energy spectrum consists of bonding and antibonding bands. In semiconductors these bands are separated by the bandgap, in metals they are overlapped. The presence of an electron in the bonding band increases, and the absence (a hole) of an electron and its presence in the antibonding band weaken the chemical bond. Thus, the electron transfer from the bonding- to antibonding band means weakening of the chemical bond in this substance (i.e., if it is solid, it should be softer and increased in volume, which is proved experimentally [15-17]. The electron transfer can be realized in different ways (by light, injection, temperature, pressure, etc.). In any case, this facilitates the motion of atoms. In its chaotic motion an antibonding electron and/or a hole – AQP may appear nearby a certain atom with probability n/Na (n is the AQP concentration, Na is the atomic concentration of the substance). If they appear in number β, this probability will be $(n/Na)^{\beta} W_{ph}$ (2), where W_{ph} is the probability of formation of a phonon with maximum energy [11,12] and weakening of the bond will take place. The higher the AQP concentra-

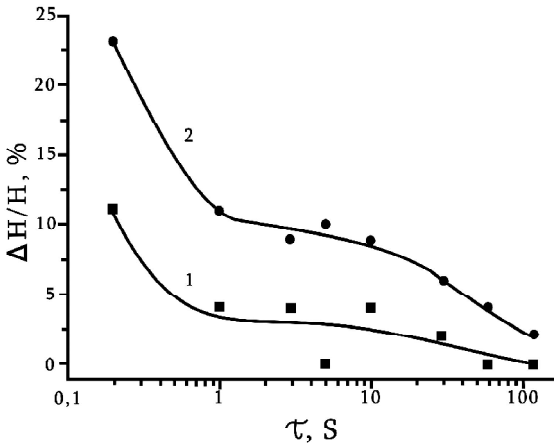

Fig. 2. Dependence of the relative changes in the microhardness H on the exposure duration: 1 –the irradiated side, 2 - the opposite side [3].

tion at a given temperature, the higher the probability of movement of atoms, and the observed process associated with this movement will be more intensive.

In all experiments devoted to the study of the long-range effects under the energy impact, AQP are formed and contribute to the movement of atoms (and hence of defects) at the distances of their distribution. Below we describe and explain the key experimental data that confirm the validity of the proposed mechanism. Let us start with the work, where the energy impact consists in a weak photon exposure [3], at which the assumption of elastic wave (EW) formation used to explain the long-range effect is most improbable of all types of energy impact. From Fig. 2 [3], it is clear that after exposure of a 18 μm-thick permalloy-79 foil to continuous-wave laser (wavelength 0.96 μm) for 0.2 seconds the microhardness on the irradiated and back surfaces increases, being significantly greater on the back surface than on the irradiated side. With increasing illumination time the microhardness decreases almost to zero. Our proposed mechanism explains this as follows: in the surface region, illumination of the foil generates AQP, i.e., excited electrons, with velocity of the rate 10^8 cm/s reach to the back side approximately in 10^{-8} s and hense easily pass distance of the order 18 μm, decreasing in concentration. In [10, 18], it was shown that to form point defects, necessary number of AQP, β_{form}, must appear nearby the given atom for it to leave its site. It was also shown that for the movement of point defects, lower number of AQP, β_{mov}, around them is required than for their formation, $\beta_{mov} < \beta_{form}$ [18]. Thus, in the thin surface region of the foil where light penetrates, point defects in maximum concentration are formed. They diffuse to the back side, interact and form more complex defects (determining the microhardness magnitude) for which no AQP is required, and their approach to each other is quite sufficient, whereas to destroy them, a higher number of AQP, β_{des} is necessary than to form point defects, $\beta_{des} > \beta_{form} > \beta_{mov}$ (3). Thus, in the whole bulk (throughout the entire thickness) of the foil the following processes take place: decreasing flows to the back side, heat, concentration of the AQP and point defects, also the formation and destruction of complex defects (Fig.3). It should be taken into account that in contrast to semiconductors, even slight heating of a metal takes electrons from the bonding – to antibonding band, which increases the AQP concentration and the probability of occurrence nearby a given atom. If we take into account the relation (3), from the equation (2), it follows that in the region with higher AQP concentration, the probability of destruction of complex defects will also be higher. Therefore, in the surface region of the irradiated side, their concentration is lower than on the back side. Fig.2 shows that with increasing light impact the difference in the values of the long-range effect on the back and irradiated surfaces decreases, and the effect itself is reduced almost to zero. The former is associated with the increase in the values and the decrease in the flow gradients: heat, AQP and point defect concentration; the latter is due to the fact that the AQP concentration increases and thus the probability of destruction of complex defects is higher than the probability of their formation, since the index in (2) $\beta_{des} > \beta_{form}$. In case of semiconductors with bandwidth Eg [19], excited states can

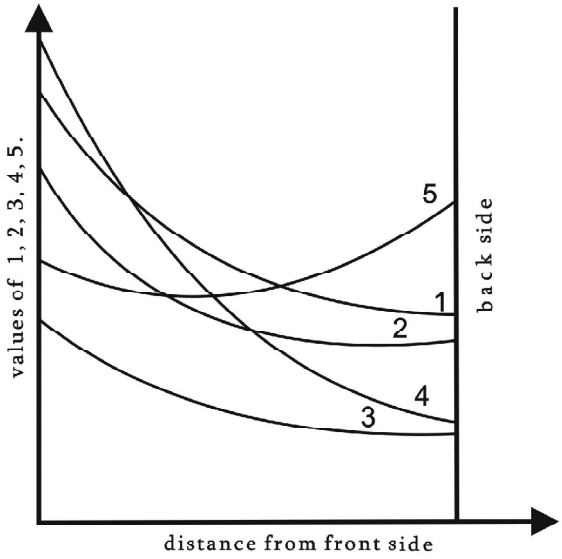

Fig. 3. Schematic representation of the variation of the corresponding values 1, 2, 3, 4, 5 in the thickness of the studied plate or foil. 1 – the AQP concentration, 2 - the concentration of point defects, 3 - the temperature, 4 - the probability of destruction of complex defects, 5 - the concentration of complex defects.

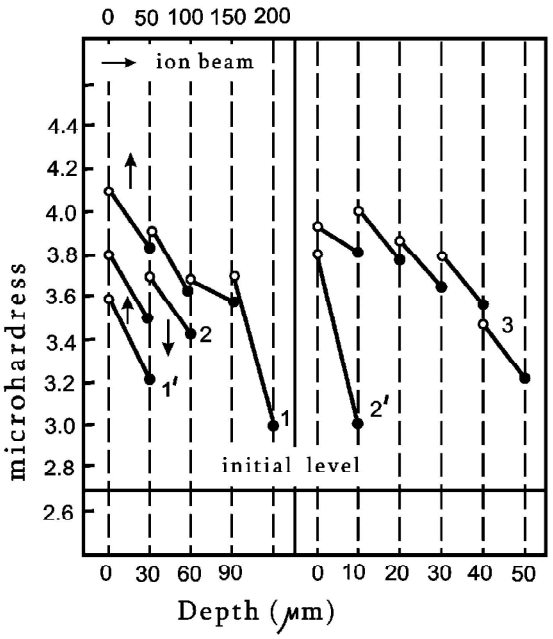

Fig. 4. The magnitudes of microhardness for Cu foils in stacks irradiated by Ar^+ ions (E=40 kev, Φ- 10^{15} cm^{-2}). Open circles - for front sides. Filled circles - for back sides. 1 - for 4 foils in stack, each 50 thick; 2 - for 2 foils in stack, each 30 thick; 3 - for 5 foils in stack, each 50 thick;
1' and 2'- for single foils, 50 and 10 thick, respectively. The direction of ion beam is pointed by the arrow [4].

also appear at photon energies hν <Eg (wi due to presence excitons, transitions between the tails of the density of state of the respective bands and ionization of energy levels of defects occupied by electrons. Naturally, the concentration of AQP formed by these photons will be lower, than of those formed by photons, hν ≥ Eg. Therefore, to reveal the effect, a certain threshold intensity is required. The use of silicon filters [19] reduces the intensity of such photons, and the effect is no longer observed. Weakening of the effect with exposure time after irradiation at room temperature is due to the slow AQP formation under the temperature impact.

At irradiation of foil stacks [4], the long-range action effect is also observed in the other foils. This is not surprising – when the surfaces come into contact, overflowing of AQP from the irradiated foil to the other foils takes place, which initiates the same processes that occur during irradiation of one foil.

In the case of exposure of one foil or a stack of foils to accelerated ions [4] on the back side of the foil, the change in the initial properties is smaller than on the surface of the adjacent foil pressed to it; the same occurs in the subsequent foils (Fig.4). This happens because the AQP concentration on the back surface is higher than on the surface of the next foil pressed to it due to the contact resistance which is naturally higher than that of the similar layer in volume. As a result of the resistance to the AQP diffusion flux, the AQP concentration in this back side area increases, which leads to an increase in the probability of destruction of complex defects, and a decrease in the AQP concentration on the front side of the next foil causes an increase in the concentration of complex defects. A similar situation is observed in the rest foils of the stack. At irradiation of one foil the concentration of complex defects responsible for microhardness is lower on the back side compared to the same foil irradiated in the stack can be explained by the fact that in the first case AQP, having reached the back side surface, are reflected and remain in the surface region, and their concentration is considerably higher than when another foil causing the AQP outflow is pressed to it (Fig.5).

In [8], it is shown, that irradiation of GaAs by Ar^+

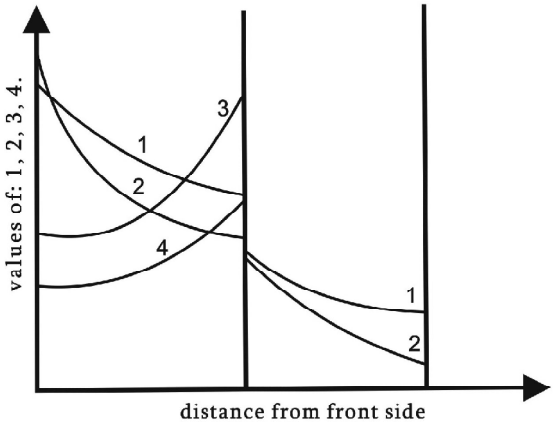

Fig. 5. Schematic representation of the variation of the corresponding values 1, 2, 3, 4.
1- the AQP concentration for the absence of contact with another foil, 2- the AQP concentration in the same foil for the contact with another foil, 3- the probability of destruction of complex defects for the absence of contact with another foil, 4- the probability of destruction of complex defects for the contact with another foil.

ions with energy 5 keV depending on the irradiation dose is observed leads to change in the GaAs composition at the depth up to 140 μm under the amorphized region of about 15 μm thick, thus the penetration depth is almost an order of magnitude greater, than the average ion penetration depth. The detection of this second damaged layer begins after irradiation with doses above 10^{18}ion/ cm^2. For instance, at a dose of $0.9 \cdot 10^{18}$ion/cm^2 the lower boundary of this layer is located at the depth of 40 μm, and at a dose of $3.5 \cdot 10^{18}$ion/cm^2 - at the depth of 140 μm. This is due to the fact that the amorphized layer composed of the overlapped disordered regions is a source of point defects (four types for GaAs - vacancies and interstitial atoms Ga and As) that diffuse at different rates [20], interact with each other creating clusters of similar defects and more complex defects. Their diffusion is determined by AQP generated by ionization of the material during its irradiation by ions.

The "anomalous" mass transfer observed in [5] is associated with the radiation-induced diffusion due to AQP [21, 22] formed by ionization of the material under electron irradiation with energy of 4 MeV. It is known that the energy is initially consumed to the shift of atoms, and with increasing depth of electron penetration into the material more energy is consumed to ionization [23, 24], i.e. the increase in the AQP concentration, so that it becomes higher on the back side. This concentration gradient creates a driving force of diffusion [21, 22] to the back side of the irradiated material, which explains the higher concentration of chromium atoms on the back side compared with the irradiated side onto which the chromium atoms were initially deposited.

Thus, based on the above considerations and on the analysis of all investigations devoted to long-range effects under the energy impact, it can be stated that this effect is associated with the movement of defects, initial and/or created by irradiation due to AQP, which are always formed under different energy impact and facilitate the movement of atoms.

ფიზიკა

ენერგეტიკული ზემოქმედების დროს წარმოქმნილი შორსქმედების მექანიზმი

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(წარმოდგენილია აკადემიის წევრის გ. ჯაფარიძის მიერ)

შემოთავაზებულია სხვადასხვა სახის ენერგეტიკული ზემოქმედების დროს წარმოქმნილი შორსქმედების მოვლენის მექანიზმი, რომელიც თვისობრივად ხსნის ამ მოვლენასთან დაკავშირებულ ყველა ექსპერიმენტულ ფაქტს. ეს მექანიზმი ეფუძნება კონდენსირებულ გარემოში ატომების (დეფექტების) მოძრაობის ახალ კონცეფციას, აღწერილს მოლეკულურ-პოტენციურ თეორიაში (მპთ). კონდენსირებულ გარემოში ატომის ადგილმდებარეობის შეცვლისათვის მოლეკულურ-კინეტიკური თეორიისგან (მკთ) განსხვავებით, მპთ არ საჭიროებს გარკვეული კინეტიკური ენერგიის ფლუქტუაციის წარმოქმნას მოცემულ ატომთან არსებული პოტენციური ბარიერის გადასალახად. მპთ-ის მიხედვით აუცილებელია როგორმე პოტენციური ბარიერის სიმაღლის შემცირება, რაც შეესაბამება ქიმიური ბმის ენერგიის შემცირებას მოცემულ ატომთან, კვაზინაწილაკების (აკნ) - აღგზნებული ელექტრონების ან/და ხვრელების გაჩენით, რაც შეიძლება განხორციელდეს სხვადასხვა გზით (ტემპერატურის ცვლილებით, სინათლის დასხივებით, ნაწილაკთა ინჟექციით, წნევით და სხვა). ყველა ხსენებულ შემთხვევაში ხდება ატომის გადაადგილების გაადვილება. ყველა სახის ენერგეტიკული ზემოქმედების დროს დამზერილი შორსქმედების მოვლენა აიხსნება საწყისი ან შექმნილი დეფექტების მოძრაობით, რაც განისაზღვრება ყველა ზემოქმედების დროს წარმოქმნილი აკნ-ბით.

REFERENCES

1. *Kuznetsov N.T., Novotortsev V.M., Zhabrev V.A, Margolin V.I.* (2014) Osnovyi nanotekhnologii. M. : BINOM. Laboratoriia znanii, (Uchebnik dlya vyisshey shkolyi) (in Russian).
2. *Serov I.N., Margolin V.I., Zhabrev V.A., Tupik V.A. Fantikov V.S.* (2005) Effektyi dalnodeystviya v mikro- i nanorazmernyih strukturah // Inzhenernaya fizika. 1: 51–67 (in Russian).
3. *Tetelbaum D.I., Azov A.Yu., Trofimov A.A.* (1998) Pisma v zhurn. tehnich. fiziki. 24: 9-13 (in Russian).
4. *Tetelbaum D.I., Kuril'chik E.V., Latisheva N. D.* (1997) Nucl. Instr. Meth., 127/128: 153-156.
5. *Panin V.E., Teplouhov V.L., Sahnova L.V. et al* (1994) Izv. VUZov, ser. Fizika. 4: 95 – 99 (in Russian).
6. *Pivovarov A. L.* Metallofizika i noveyshie tehnologii (1994) 16, 12: 3 – 17 (in Russian).
7. *Martyinenko Yu.V. Moskovkin P.G.* (1998) Neorganicheskie materialyi, **34**, 9: 1142 – 1144 (in Russian).
8. *Bert N.A., Soshnikov I.P., Stepanova M.G.* (1998) FTT, **40**, 3: 438 – 440 (in Russian).
9. *Gerasimov A. B.* (1990) Materials Science Forum Vols., New-York, , v.65-66:47.
10. *Gerasimov A.B.* (2005) Fundamentals of Low-Temperature Technology of Production of Semiconductor Devices. Tbilisi, Univ. Press.

11. *Gerasimov A.B.* (2012) The International Scientific Conference Proceedings Basic paradigms in Science and Technology Development for the 21st century, Tbilisi, Georgia, p.391-397.
12. *Gerasimov A., Kvesitadze G., Vepkhvadze M.* (2016) Bull. Georg. Natl. Acad. Sci. **10**, 2:98-104.
13. *Frenkel YA.I.* (1948) Statisticheskaya fizika. M.-L. (in Russian).
14. *Harrison W.A.* (1980) Electronic Structure and the Properties of Solids. The Physics of the Chemical Bond. San Francisco: W. H. Freeman & Co.
15. *Gerasimov A.B., Chiradze G.D., Kutivadze N.G.* (2001) Semiconductors. **35**, 1: 70.
16. *Gerasimov A.B., Kuteliya E.R., Chiradze G.D., Bohochadze Z.G., Kimeridze D.A., Ratiani T.K.* (2003) Fizika i khimiya obrabotki materialov, №4. 5 (in Russian).
17. *Gerasimov A.B., Chiradze Z.G., Gogua Z.G.* (2006) Ukr.J.Phys. **51**, 8.
18. *Gverdtsiteli I.G., Gerasimov A.B., Gogua Z.G., Djibuti Z.V., Pkhakadze M.G.* (1987) Soobshcheniia AN GSSR, **127**, 3: 517-520.
19. *Tetelbaum D.I., Panteleev V.A., Gutkin M.V.* (1999) Effekt dalnodeystviya pri malointensivnom obluchenii kremniya svetom. Pisma v ZhETF, **70**, 5-6: 381-385 (in Russian).
20. *Gerasimov A.B., Gochaleishvili N.G., Samadashvili Z.D., Bokhochadze Z.G., Vepkhvadze M.T., Maziashvili E.N.* (2001) Bull. Georg. Acad. Sci. **163**, 2: 266-269.
21. *Gerasimov A B., Bibilashvili A.P., Bokhochadze Z.G., Kazarov R.E., Vepkhvadze M.T., Kutivadze N.G., Samadashvili Z.D., Chiradze G.D.* (1999) Bull. Georg. Acad. Sci. 159, 3: 417-420.
22. *Gerasimov A.B., Kazarov R.* (2006) Ukr.J.Phys. **51**, 9.
23. *Dienes G.J,. Vineyard G. H.* (1957) New York. Interscience publ. p. 523.
24. *Smirnov L.S.* (1980) Voprosyi radiatsionnoy tehnologii poluprovodnikov. Nauka, Novosibirsk.

Received January, 2016