Molecular Dynamics Approach to Processes in Bulk Au Materials

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The paper studies the influence of several factors such as the number of atoms (N), temperature (T), and annealing time (t) on the characteristic quantities of structure, phase transition, and crystallization progress of bulk Au materials using so-called molecular dynamics simulation. The authors hope that obtained results would be very useful for near future experimental research with Au.

topics: cubic Au materials, glass temperature, number of atoms, molecular dynamics

1. Introduction

In this paper, we would like to present an example of the usefulness of scientific knowledge gained in the school of Professor Iwo Białynicki-Birula (the Master). Namely, in the middle eighties of the last century, the present author (Van Cao Long) together with other Master's outstanding descendants: Professor Jan Mostowski from the Institute of Physics, Polish Academy of Sciences, and Professor Marek Trippenbach from the University of Warsaw, we tried to construct a classical theory of ionization of many-electron atoms [1]. Our classical model of ionization is described in detail in the third chapter of M. Trippenbach's doctoral dissertation [2]. This model is practically a precursor of the simulation method — the so-called molecular dynamics, very popular nowadays in the simulation of multi-particle systems — on which the present author (Van Cao Long) is now working intensively with the current Ph.D. student Nguyen Trong Dung. During only the last two years, we published approximately 20 papers [3–22].

The quantum description of a large, multi-element physical system is usually complex and impossible to analyze by current supercomputers. Often these attempts obscure the physical picture of the phenomena under consideration. Therefore, approximate baseline simulations were used in the probabilistic treatment of the system with the parameters included in the problem after their quantum averaging, while the tested physical quantities were already treated as random variables or classical stochastic processes, and further numerical simulations were carried out using classical equations. This approach was first used in the 1950s and then developed intensively in the 1980s. One of us (Van Cao Long) actively participated in these processes during his work in the Department of Theoretical Physics (now the Center for Theoretical Physics of the Polish Academy of Sciences) in the eighties of the last century. In particular, the research emphasized above and described in detail in M. Trippenbach's doctoral dissertation "Selected issues concerning ionization of atoms in the field of strong laser waves" [2] can be treated as a precursor of the deterministic simulation method, currently widely used in the theory of solids, chemistry, and molecular biology, namely the so-called molecular dynamics method. The model we proposed consisted in drawing the initial conditions for the position and momentum of a particular electron using the Monte Carlo method according to their certain distribution in the phase space, namely with the modified Wigner distribution. Then we simulated the dynamics of electrons classically, i.e., we solved Newton's equations. We counted the total energy of the electron at a given moment with the newly obtained distribution in the phase space. When this energy is positive, we say we have ionization. In this

way, we have studied the ionization of a multi-electron atom. This scheme is exactly the same as in the molecular dynamics (MD) method. We will take an example below concerning the study of bulk Au materials to illustrate this powerful simulation method.

2. Structure, phase transition, and crystallization progress of bulk Au materials within the molecular dynamics (MD) simulation method

It is widely known that gold (Au) is a precious metal, inert and strongly colored [23, 24], with the number of protons $Z = 79$ and the electronic structure $4f^{14}5d^{10}6s^1$. It has great applicability in scientific and technological fields due to biocompatibility, ability to perform biological/chemical analyses [25, 26]. Gold is used in biosensors [27], cancer therapy [28], as jewelry and foreign currency for exchange and economic transactions in life. To study and fabricate bulk Au materials, scientists use research methods such as experiment, theory, and simulation. One can say that the traditional division of physics and other natural sciences into "experiment" and "theory" is no longer valid. Computer simulation is the third that is complementary to these two traditional branches of science.

With the experimental method, Yuk et al. [28] successfully studied the process of crystallization of the material at the temperature of $T = 700$ K, with an appearance time of only 10 s, which is a very short time for observations [28]. The bond length of Au–Au determined by experiments is $r_{\mathrm{Au-Au}} = 2.48, 2.88$ Å, 3.6–4.0 Å [29], and 3.0–3.6 Å [30], whereas by the simulation it is $r_{\mathrm{Au-Au}} = 2.8$ Å [42] and 2.9 Å [31].

Results with such large deviations are explained by impurities. To confirm this, the authors successfully studied the influence of factors on the bond length of the CuAu alloys with $r_{\mathrm{Au-Au}} = 3.05$ Å [10] and of the NiAu alloys with $r_{\mathrm{Au-Au}} = 3.09$–$3.17$ Å when the heating rate increases from 4×10^{12} to 4×10^{14} K/s [4]. In particular, the simulation method is considered the most advanced tool today, with low cost and high efficiency. It gives access to materials with sizes less than 2 nm, placed in harsh conditions such as those in the center of the earth at a temperature of $T = 7000$ K and a pressure of $P = 360$ GPa with materials $MgSiO_3$ [32] and $CaSiO_3$ [33], when experimental methods are inaccessible.

To study the structural properties of Au cubic materials, researchers mainly use the molecular dynamics (MD) method [34, 35]. The reason is that this research method can study large-sized materials using the equations of motion according to Newtonian second laws. Research results include, among others, consideration of the radial distribution function (RDF) [36, 37]. In this formalism, the distance to the second peak of RDF [38] defines the size of the crystalline state of the material. When the Honeycutt–Andersen (HA) structural transformation appears in these materials [39], the deformation of atoms [40, 41] can be determined and this characteristics requires the choice of properly embedded atomic interactions (EAM). Mishin et al. [42] successfully determined the structural stability and defects in the crystal lattice with Cu metal. Other authors [43, 44] studied the structure of materials in liquid metals. The obtained results show that crystallization usually occurs at a size of about 10 nm. In MD simulation studies, researchers often use commercial or free software such as LAMMPS [45]. Zhou et al. [46] successfully studied the deformation of Cu thin films with the simulation method. Here an important question appears, what factors affect the structure, phase transition, crystallization, and phase transition temperature of bulk Au materials? To answer this question, in the content of this paper we study the influence of factors such as atomic number, temperature, and annealing time on structural characteristics, phase transition, crystallinity, and phase transition temperature. The obtained results would be the basis for experimental studying the structural characteristics of Au bulk materials in the future.

3. Calculation method

According to the MD simulation scheme, initially, the Au atoms are randomly seeded into a cubic pattern of size (l), determined by

$$l = \sqrt[3]{\frac{N}{\rho}}. \tag{1}$$

For interaction potential between atoms in the classical Newtonian equations, we choose the Sutton–Chen (SC) embedded interaction potential field [47, 48] in the framework of the MD simulation method with periodic boundary conditions. The following formulas are used

$$E_{\mathrm{tot}} = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} \Phi\left(r_{ij}\right) + F\left(\rho_i\right),$$

$$\Phi\left(r_{ij}\right) = \varepsilon\left(\frac{a}{r_{ij}}\right)^n,$$

$$F\left(\rho_i\right) = A_i E_i^0 \rho_i \ln(\rho_i),$$

$$\left[\rho_i\left(R\right)\right]^{\alpha(l)} = \mathrm{e}^{-b^*},$$

$$b^* = \beta_i^{(l)}\left(\frac{R}{R_i^0 - 1}\right),$$

$$\left(\bar{\rho}_i\right)^2 = \sum_{l=0}^{3} t_i^{(l)}\left(\rho_i^{(l)}\right)^2. \tag{2}$$
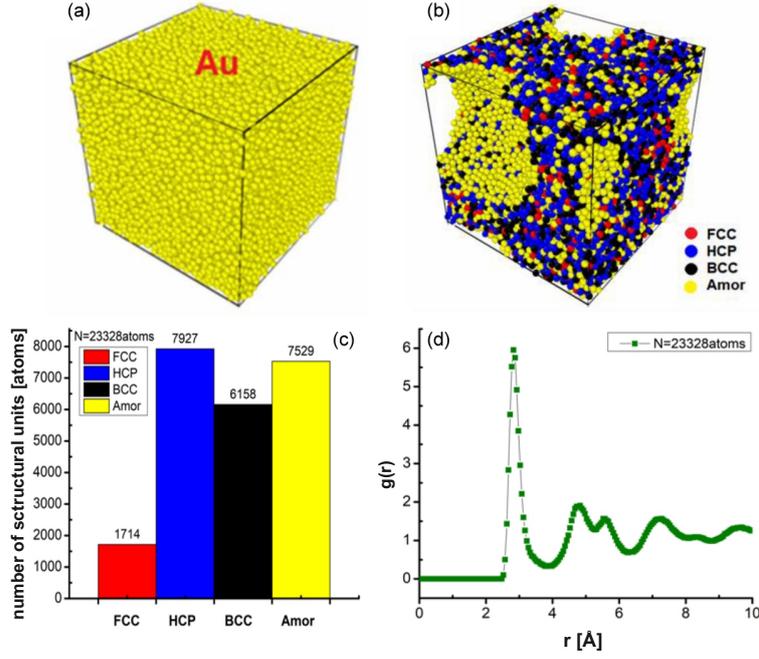
Fig. 1. Initial shape (a), structure shape (b), number of structural units (c), RDF (d) of Au_{23328} material at $T = 300$ K.

In order to increase the accuracy, we choose the interaction force field parameters as $E_i^0 = 3.93$ eV, $R_i^0 = 2.0$ Å, $\alpha = 6.34$, $A_i = 1.0$, $\beta_i^{(0)} = 5.77$, $\beta_i^{(1)} = 2.2$, $\beta_i^{(2)} = 6.0$, $\beta_i^{(4)} = 2.2$, $t_i^{(0)} = 1.0$, $t_i^{(1)} = 2.9$, $t_i^{(2)} = 1.64$, $t_i^{(4)} = 2.0$ [49]. To implement the simulation program, we use the open-source code LAMMPS [47, 48], which is completely free for the scientific research community. This source code works on the basis of the MD method combined with embedded interaction potential (EAM) to simulate the interactions between Au atoms. Initially, for the bulk Au material, we run 2×10^4 MD recovery statistic runs at a heating rate of 4×10^{11} K/s and a heating step time of 1 fs at a temperature $T = 4000$ K. Then the temperature is reduced from 4000 to 300 K to increase the crystallization state of the material. The number of atoms (N) in the considered model is taken as $N = 4000$ Au atoms (Au_{4000}), 6912 Au atoms (Au_{6912}), 10976 Au atoms (Au_{10976}), 16384 Au atom (Au_{16384}), and 23328 Au atom (Au_{23328}). After determining the Au_{23328} material with the highest crystallinity, we chose this material as a sample to continue the study of the influence of temperature. As a consequence, we successfully determine the glass temperature (T_g) as $T_g = 600$ K and continue the annealing after an annealing time $t = 400$ ps. To study the structural features, we determine the characteristics, i.e., shape, structure shape, and number of structural units. The radial distribution function (RDF) $g(r)$ [50] is given by the formula

$$g(r) = \frac{n(r)}{4\pi r^2 \rho_0 \, \mathrm{d}r}, \tag{3}$$

where $g(r)$, $n(r)$ are the functions used in the calculations: the probability of finding the atom i in space, the number of atoms, respectively; ρ_0 is the atomic density, and r is the distance from the atom i to other atoms. The total energy of the system E_{tot} is given in [51]. To determine the diffusion mechanism of the atoms, mean squared distance (MSD) is applied according to the following expression [52]

$$r(t) = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N}\left|\boldsymbol{r}_i(t) - \boldsymbol{r}_i(0)\right|^2\right]}, \tag{4}$$

where N is the number of atoms in the system, $r_i(0)$ is the initial position of the i atom, whereas $r_i(t)$ is the position of the atom i at time t. In all samples, phase transitions were studied by applying Common Neighborhood Analysis (CNA) [55, 56], according to Nosé's [53], see also Hoover [54]. OVITO software was used [57, 58] to visualize the results. Finally, to check the accuracy of the results, Dual Energy X-ray Absorbance Measurement (DXA) was used [59]. These programs are edited and used in the computer system of the Institute of Physics, University of Zielona Góra, Poland.

4. Results and discussion

4.1. Structural properties of bulk Au materials

The structural properties of bulk Au are shown in Fig. 1.

The obtained results show that the material of Au_{23328} metal has the shape of a cube, made up of Au metal atoms identified by yellow color (Fig. 1a).
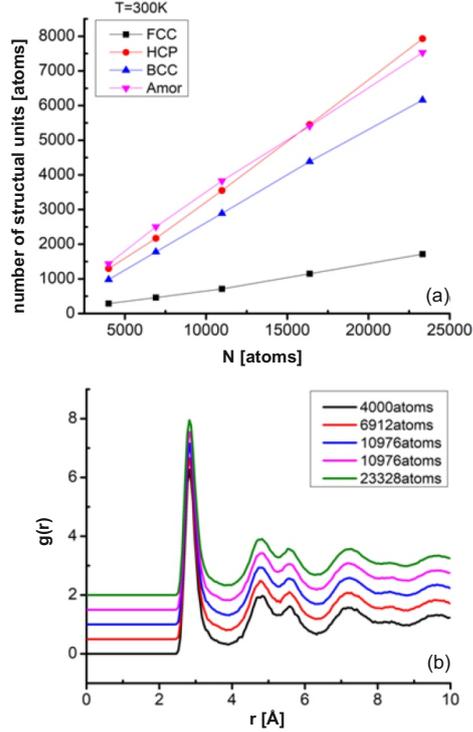
Fig. 2. Number of structural units (a), radial distribution function (b) of Au blocks with different number of atoms.

The Au$_{23328}$ material is determined by 4 structural units: face-centered cubic (FCC) shown in red, hexagonal packing (HCP) shown in blue, body-centred cubic (BCC) shown in black, and amorphous (Amor)shown in yellow (Fig. 1b). The number of the structural units is 1714 FCC, 7927 HCP, 6158 BCC, 7529 Amor (Fig. 1c), the length of the link $r_{Au-Au} = 2.825$ Å, the height of the first peak of the radial distribution function $g(r) = 5.95$ (Fig. 1d). Our simulation results are completely consistent with the experimental results $r_{Au-Au} = 2.48, 2.88$ Å, and $3.6-4.0$ Å [29] and with the simulation results obtained before: $r_{Au-Au} = 2.8$ Å [42] and 2.9 Å [31]. In addition, the material has material size (l) corresponding to $l = 7.965$ nm and $E_{tot} = -88328$ eV. The obtained results show that the structural characteristic quantities of the Au$_{23328}$ material model are consistent with the results obtained before [29, 31, 42] and create a premise for the process of studying the influencing factors.

4.2. Influencing factors

To study the influencing factors, we use the material models Au$_{4000}$, Au$_{6912}$, Au$_{10976}$, Au$_{16384}$, Au$_{23328}$. In particular, we consider the influence of size, the influence of temperature at $T = 300, 400, 500, 600, 700, 800, 900, 1000$ K and incubation time after $t = 0, 10, 50, 250, 400$ ps.

4.2.1. Effect of the number of atoms

The results in Fig. 2a show how the number of atoms affects the structural properties of the considered material. Here, the results are for the metal material Au$_{4000}$ (its structural shape is shown in Fig. 1a). The number of structural units is represented by 1714 FCC, 7927 HCP, 6158 BCC, 7529 Amor (the same as in Fig. 1c) and $r_{Au-Au} = 2.825$ Å, $g(r) = 5.95$ (as in Fig. 1d) and $l = 7.965$ nm, $E_{tot} = -88328$ eV. When the number of atoms increases from $N = 4000$ (Au$_{4000}$) through $N = 6912$ atoms (Au$_{6912}$), 10976 atoms (Au$_{10976}$), 16384 atoms (Au$_{16384}$), up to 23328 atoms (Au$_{23328}$), the shape the material structure changed as follows: the number of structural units for FCC increases from 286 to 1714, for HCP it increases from 1295 to 7927, for BCC this number increases from 982 to 6158, for the Amor units it increases from 1437 to 7529 (see Fig. 2a). Now, whereas $g(r)$ is unchanged for $r<r_{Au-Au} = 2.825$ Å, it decreased from $g(r) = 6.27$ to $g(r) = 5.95$ (see Fig. 2b).

In Fig. 3a, the structure size l increases from 4.502 to 7.965 nm, and the system total energy E_{tot} decreases from -15025 to -88328 eV (Fig. 3b). The obtained results show a close relationship between the number of atoms, the size, and the total energy of the system (Fig. 3). The linear relationship
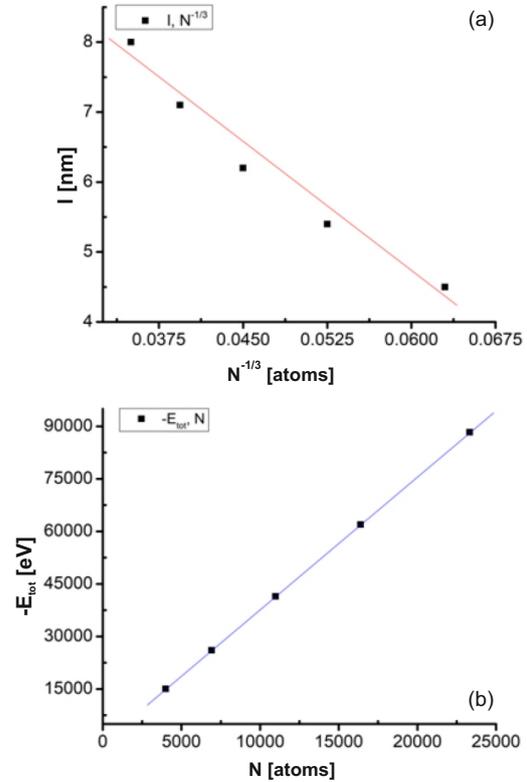
Fig. 3. Relationship between the number of atoms and size (a), between the number of atoms and total energy of the system (b) as N changes.

TABLE I

Structural characteristics and phase transitions of Au_{23328} materials at different temperatures.

T [K]	300	400	500	600	700	800	900	1000
r [Å]	2.825	2.825	2.825	2.825	2.825	2.825	2.825	2.825
$g(r)$	5.95	5.56	5.26	4.91	4.59	4.32	4.09	3.88
FCC	1714	1621	1536	1405	1292	1040	971	760
HCP	7927	7796	7578	7547	7386	6944	6606	6103
BCC	6158	6226	6073	5999	5863	5709	5294	4906
Amor	7529	7685	8141	8377	8787	9635	10457	11559
l [nm]	7.965	7.967	7.971	7.975	7.982	7.990	7.995	8.000
E_{tot} [eV]	−88328	−87965	−87588	−87153	−86701	−86194	−85668	−85099

between the size (l) and $N^{-1/3}$ (where N is the number of atoms) is described by the expression $l = 11.97 - 121.98\,N^{-1/3}$. Similarly, the dependence of the total energy of the system (E_{tot}) and the inverse of the the number of atoms (N) is described by the linear expression $E_{tot} = -164.93 - 3.793\,N^{-1}$ (Fig. 3b).

There is a clear similarity between our results and those for metals in [60, 61]. When increasing the number of atoms, the size of matter increases with the ratio $l \sim N^{-1/3}$, and the total energy of the system decreases with the ratio $E_{tot} \sim N^{-1}$. This phenomenon is due to the size effect and also to the surface effect. The obtained results can be the basis for testing methods to test future applications. To ensure the calculation speed as well as the stability of the structural features, we choose the Au_{23328} material model as the standard material to investigate the influencing factors in the following sections.

4.2.2. Effects of temperature

The effect of temperature on the structural characteristics and phase transition of Au_{23328} materials is shown in Table I. When T increases from 300 to 1000 K, the results show that E_{tot} increases from −88328 to −85099 eV, the size l increases very slightly from 7.965 to 8.000 nm, r is constant $r_{Au-Au} = 2.825$ Å, and $g(r)$ decreases from 5.95 to 3.88. Correspondingly, the number of FCC structural units decreases from 1714 to 760, of the HCP structural units it decreases from 7927 to 6103, of BCC this number decreases from 6158 to 4906, and of the Amor units it increases from 7529 to 11559 (Table I). The obtained results demonstrate that when the temperature increases, the length of the Au–Au links remains constant, while the number of FCC, HCP, and BCC structural units decrease and increases only for the Amor unit. The relationship between the sum of E_{tot} and T is shown in Fig. 4.

The obtained results indicate that as the temperature T increases, E always increases linearly and proportional to T in two ranges, i.e., 300–600 K
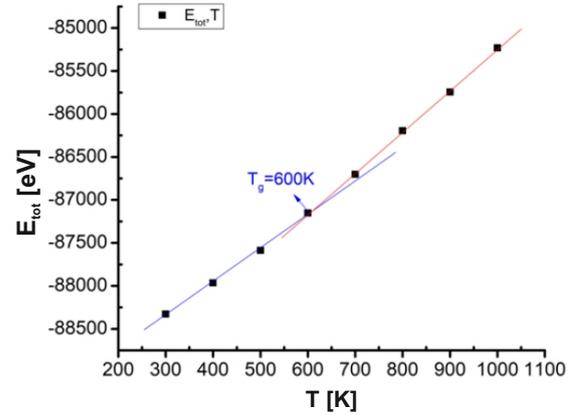
Fig. 4. Relationship between total energy of the system and temperature of the Au_{23328} material.

and 600–1000 K. Increasing of T leads to an increase in l, an increase in the total energy of the system E_{tot}, a decrease in the number of FCC, HCP and BCC structural units, and an increase in Amor. It follows that at $T = 600$ K the glassiness of the material Au_{23328} appears. The intersection between the two temperature ranges is called the glass point or glass temperature (T_g), with the value $T_g = 600$ K in Fig. 4. The cause of this phenomenon is due to the effective size, the effective surface and the fact that phase transition of materials Au_{23328} is of type 1. To determine the crystallization process of Au_{23328} materials at the glass transition temperature $T_g = 600$ K, we investigate the effect of the incubation time. The result will be presented in the following section. In another paper [62], the authors determined the glass transition temperature by taking the intersection of these lines and obtained the value of 700 K [62], which is evidently different from the value we established in the present study (600 K). Our simulations show that the simulation procedure with the use of the SC potential is stable for the number of atoms of the order of thousands. Meanwhile, the results of our analysis of structural phase transitions of bulk Au_{23328} materials are shown in more detail.

4.2.3. Effect of incubation time

Figure 5 presents the results, when annealing Au$_{23328}$ material at temperatures $T = 500, 600, 700$ K is considered at different annealing times (t), i.e., t_1, t_2, t_3, t_4 and the annealing time increases. At a given temperature (T), the total energy of the system (E_{tot}) decreases, showing that the crystallization process of the material increases. At $T = 500$ K, E_{tot} decreased the least, slightly greater decrease was at $T = 700$ K, and the largest decrease at $T = 600$ K after $t_3 = 250$ ps. The obtained results are completely consistent with the results obtained above for $T_g = 600$ K, so we confirm that this is the crystallization temperature of the material. To confirm this in a more demonstrated manner, we chose the temperature to be investigated at each different annealing time as $T = T_g = 600$ K — the results are shown in Fig. 6.

For the Au$_{23328}$ bulk material at glass temperature $T_g = 600$ K and annealing time $t_1 = 10$ ps, with the structural form shown in Fig. 6a, the number of the structural units is 941 FCC, 6717 HCP, 5104 BCC, 10566 Amor (Fig. 6e), the length of the link is $r_{Au-Au} = 2.825$ Å, and $g(r) = 3.86$, $l = 7.644$ nm, $E_{tot} = -85988$ eV (Fig. 6i). As the annealing time increased from $t_1 = 10$ ps to $t_2 = 50$ ps, $t_3 = 250$ ps, and $t_4 = 400$ ps, the structural geometry of the material changed (Fig. 6a–d), with the number of FCC units increasing from 941 to 1481. In ad-

dition, the number of HCP units increased from 6717 to 7598, of BCC increased from 5104 to 6507, and of Amor units increased from 10566 to 7742 (Fig. 6e–h). Accordingly, for the cubic Au$_{23328}$, $g(r)$ has a constant value when $r < r_{Au-Au} = 2.825$ Å. Then the value of $g(r)$ increases with annealing time from 3.86 (at t_1) to 4.38 (at t_4), l decreases slightly from 7.644 to 7.643 nm, E_{tot} decreases from -85988 to -87636 eV (Fig. 6i–l).
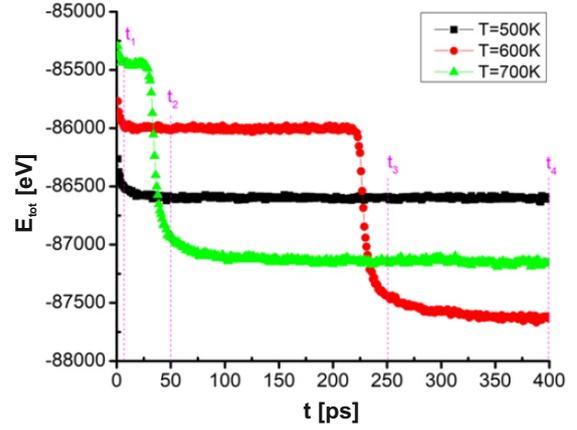
Fig. 5. Phase transition of bulk Au$_{23328}$ at glass temperatures $T = 500, 600, 700$ K as a function of annealing time t.
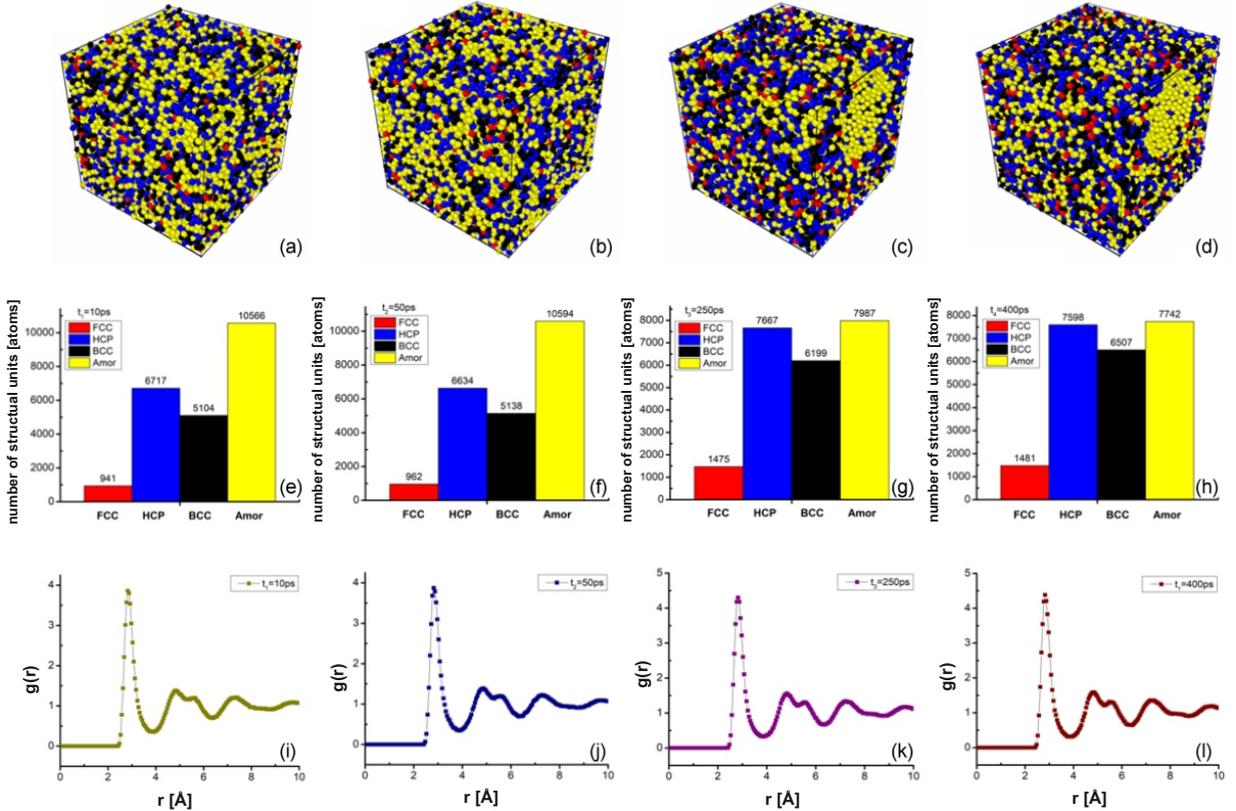
Fig. 6. The crystallization process of Au$_{23328}$ bulk material at glass temperature $T_g = 600$ K for different annealing times (a, e, i) $t_1 = 10$ ps; (b, f, j) $t_2 = 50$ ps; (c, g, k) $t_3 = 250$ ps; (d, h, l) $t_4 = 400$ ps.

The obtained results show that when increasing the annealing time, the length of the links Au–Au has a constant value $r_{\text{Au}-\text{Au}} = 2.825$ Å and this result is consistent with the results obtained previously for Au [29, 31, 42]. Also, our results showed that after annealing time at glass temperature $T_g = 600$ K, the crystallization process increased. We hope that the recent results obtained here will serve as the basis for future experimental studies.

5. Conclusions

The results obtained in this paper show the influence of such factors as the number of atoms, temperature, and annealing time on the structural characteristic quantities of bulk Au materials. We used here the Sutton–Chen embedded interaction potential, which is the most suitable for the periodic boundary conditions and the Verlet algorithm in the MD scheme. In the equilibrium state, bulk Au materials always exist in 4 types of structures: FCC, HCP, BCC, and Amor. An increase of the number of atoms (N) leads to an increase in size (l), whereas the total energy of the system (E_{tot}) decreases, and at the same time, an increase of the annealing time (t) leads to the decrease of both l and E_{tot}. As temperature increases, both l and E_{tot} increase. In addition, by increasing t at $T = 600$ K, the number of the structural units FCC, HCP, BCC increases, and the Amor unit decreases, which is confirmed by the fact that the glass temperature of the bulk Au material is $T_g = 600$ K. The influence of N, T, and t on the structure, phase transition, and crystallization of Au bulk materials was considered in detail. We observed that the length of the links Au–Au has a constant value $r_{\text{Au}-\text{Au}} = 2.825$ Å when the influencing factors change. It follows that the influencing factors do not change the length of links, but they change the height of the first peak of the radial distribution function. The obtained results are completely consistent with the experimental and simulation results obtained previously. Also, as N increases, the size l of the material increases proportionally to $N^{-1/3}$ and the total energy E_{tot} is proportional to N^{-1}. The results have successfully determined that the crystallization process increases at the glass temperature $T_g = 600$ K. The question that why the crystallization temperature leads to an increase in the crystallization process has not been yet explained. This is devoted to future studies.

6. Relations with Professor Iwo Białynicki-Birula — personal remarks by Cao Long Van

I was born in Vietnam, a poor country, underdeveloped due to constant wars, with no traditions in the sciences. Nevertheless, in my youth, I was well educated in mathematics, and since mathematics is

Fig. 7. A centuries-old traditional image of a teacher from the Nghệ An area of Vietnam "Ông đồ xứ Nghệ", where Vinh University is located. Professor Iwo Białynicki-Birula has many scientific descendants at this University.

the language of nature, I was able to deeply learn physics (fundamental science) with love. At the beginning of this path, I was very lucky to find my second homeland, Poland, where, through the school of life, I found exceptional teachers in my profession, in particular Professor Dr. hab. Iwo Białynicki-Birula.

The history of my contact with Professor Iwo Białynicki-Birula is very long, more than 50 years. During my studies at the Warsaw University in the years 1971–1976, I was one of the best students of my generation. As a consequence, from the fourth semester I was on an individual course of study under the supervision of Dr. Adam Bechler, who is now a full professor at the University of Szczecin (retired), but at that time he had just completed his doctorate under the supervision of Professor Dr. hab. Iwo Białynicki-Birula in the Department of Field Theory and Statistical Physics, Institute of Theoretical Physics, University of Warsaw. Since then, my scientific and educational career has been closely related to the school of Professor I. Białynicki-Birula with his outstanding students, such as Professors Kazimierz Rzążewski, Krzysztof Wódkiewicz, Jan Mostowski, and "scientific grandchildren" such as Professors Maciej Lewenstein, Marek Kuś, or Marek Trippenbach. It is enough to emphasize the fact that the physicists of three generations of this school (namely, the Master himself, his student K. Rzążewski and his "scientific grandson" M. Lewenstein) were laureates of the Polish Science Foundation Award. Over time, they became my older and younger friends[†] and work-

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[†1]It is a great regret that one of them, Professor K. Wódkiewicz, passed away prematurely due to a serious illness.

ing with them was a pure pleasure. It can be said that the long-term friendship and cooperation with them under the guidance of my Master (who was the supervisor of my masters and Ph.D. thesis), my mentor, an excellent scientist and teacher — Professor I. Białynicki-Birula, who treated me as "the nicest student", he provided me with basic professional knowledge necessary for my later achievements both in research and teaching (see Fig. 7). As an example of this, me and his "scientific grandson" Professor M. Trippenbach more than 20 years ago created the best School of Optics in the biggest university in Middle Vietnam, i.e., Vinh University. For this contribution, we were both honored with the title of Doctor Honoris Causa of this University. We regularly organized international conferences and workshops at Vinh University. As an example, I and another "scientific grandson" of Professor I. Białynicki-Birula, i.e., Professor M. Lewenstein, organized the Workshop on Quantum Information at this University in 2016. Thus Professor I. Białynicki-Birula has many Vietnamese students who played an important role in development of physics in Vietnam.

To summarize, my Master Professor I. Białynicki-Birula and his outstanding former students of different generations are real masters who have vast knowledge and experience in transferring this knowledge to students. I myself had the opportunity to educate under the guidance of one of the best, then work among older and younger wonderful friends in my environment. Therefore, now, when I am close to the 70th anniversary of my life, I can say with confidence that all my dreams about my profession have come true. I am one of many successive masters who, accepting the baton from their excellent predecessors, fulfilled the mission of deepening their physical knowledge and passing this knowledge to the next generations of physicists, thus contributing to the development of this exceptionally beautiful and at the same time meritorious science. For this, I am immensely grateful to my Master Professor Iwo Białynicki-Birula. On the occasion of his 90th birthday, I would like to wish him a lot of health and long life, so that we can admire the wonderful teacher for the years to come.

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