SEMICONDUCTIVE NANOSTRUCTURES –MATERIALS FOR SPINELECTRONICS: NEW DATA BANK REQUIEREMENT

Paata J. Kervalishvili
Georgian Technical University *Tbilisi, Georgia*

20th CODATA International Conference – October 2006

Beijing, China

INTRODUCTION I

Nanoscience, Nanotechnology and Spinelectronics.

Nanostructures constructed from inorganic solids like semiconductors have new electronic and optical properties due to their size and quantization effects [1,2]. The quantization effects reflect the fundamental characteristics of structures as soon as their size falls below a certain limit.

An example of the simplest nanostructure is the quantum dot formed from the energy well of certain semiconductor materials with 5-10nm thickness sandwiched between other semiconductors with normal properties. Quantum dots, for example, have lead to important novel technology for lasers, optical sensors and other electronic devices. The application of nanolayers to data storage, switching, lighting and other devices, can lead to substantially new hardware, for example energy cells, and eventually to the quantum based internet.

INTRODUCTION I'

Nanoscience, Nanotechnology and Spinelectronics.

Nanoscience and nanotechnology encompasses the development of nano spinelectronics, spinelectronics materials production, nano spinelectronic measuring devices and technologies. Nano spinelectronics, based on usage of magnetic semiconductors, represents new and roughly educing area of science and engineering of the XXI century. The reason to that is the perspective of development and creation of principally new materials and devices for information technologies operating as charge, and spin degree of freedom of carriers, free from limitations. That new multidisplinary direction of science and technology very needs of new data bank creation, which should be functioning as source of new ideas and approaches.

Spin – Polarized Transport in Semiconductors I.

The essential effort of the scientists are concentrated on studying of the spin-polarized transport in multilayer structures which are including alternating layers of ferromagnetic metals and non-magnetic semiconductors. The central task of such researches is the creation of systems with effective spin injection into a non-magnetic semiconductor. The relevant role in solution of this problem is shunted to search and investigations of new ferromagnetic materials, which are capable to be reliable and good spin injectors. Among such objects the magnetic discrete alloys are very promising. They are multilayer systems composed of submonolayers of a ferromagnetic material in the matrix of a non-magnetic semiconductor, for example, Mn/GaAs or Mn/GaSb. It is well known, that these alloys have high Curie temperatures and sufficiently high spin polarization. The circumstance is not less important that it is possible to control and to manage of the "ferromagnetic metal - semiconductor" boundary surface immediately during the synthesis of these materials.
As it was investigated recently they should be prepared only by the methods of the MOS hydride epitaxy and laser epitaxy with usage of pulsed annealing of epitaxial layers.

Spin – Polarized Transport in Semiconductors II.

The discrete alloys syntesis on the basis of a amorphous silicon hydride (α-Si:H) in combination with ferromagnetic 3-d metals (Fe and Co) is planned to carry out in the RRC "Kurchatov institute" jointly with the Georgian Technical University in the nearest future.

Study of the possibility to carry electrons with the spatially oriented spins (the spin transport) from a magnitoactive (ferromagnetic) material in a paramagnetic material represents one of most intensively educing areas of solid-state physics. These applied researches in microelectronics are called as "the spin electronics engineering" or simply "spintronics".

The significance of spintronics is stipulated by perspectives of the development and the creation of new types of a non-volatile memory with random access (MRAM), quantum single-electron logical structures and ultra dense information storage media. Thus, elementary information storage unit will be represented by an electron spin [3,4].

The realization of the spin-polarized current transfer opens out new possibilities for the solid-state electronics also [5,6].

Spin – Polarized Transport in Semiconductors III.

GMR effect was used in a new generation of the magnetic field sensors which appeared in 1994 as commercial products on market. But present boom in industry producing the information storage devices started a bit later, in 1997, when the IBM Company has presented the first hard drives with the GMR reading heads. The implantation of this technology has allowed more than on the order to increase a density of the information storage on magnetic disks, and the size of the market of these reading heads already exceeds 1 billion US dollars.

The sensors operating with the tunnel magnetic junctions (MTJ) fall into the second class spintronics devices. The first laboratory samples of (NiFe/Al_2O_3/Co) MTJ structures were demonstrated by Modera and colleagues in 1995 [8], where the TMR effect reached 12 % at room temperature.

Some largest manufacturers of an electron technology, including the IBM Company, have declared recently about the development of new in essence memory devices: so-called MRAM [9].

Spin – Polarized Transport in Semiconductors IV.

The third direction of development of spintronic devices is based on the development of multilayer nano structures of ferromagnetic semiconductors, which demonstrate properties not available for their metal analogs.

One can refer to number of these properties the possibility to control by electric field a magnetic state of material [10] and the giant planar Hall effect, which exceeds on several orders of magnitude the Hall effect in metal ferromagnets. The super-giant TMR effect observed for the first time in epitaxial (Ga,Mn)As/GaAs/(Ga,Mn)As structures [11] is not less promising for applications.

Naturally, that the association of these two directions is extremely necessary with the purpose to combine well controlled electronic properties inherent for semiconductors with additional possibilities of devices; in which the spin degree of freedom of current carriers is used. Namely this represents the essence of the semiconducting spintronics, and its central problem is today the search of an effective way for the spin injection in a semiconductor from the spin-polarized reservoir.

Spin – Polarized Transport in Semiconductors V.

There are no effective ways of injection the spin-polarized current in non-magnetic semiconductors at the present moment [12,13]. The spin injection from magnetic semiconductors in non-magnetic gives good results in a number of cases [14], but while it has a place only at low temperatures, far from room temperature.

So-called magnetic discrete alloys [15, 16] to days are of the most prospective materials for solution of the spin injection problem. These alloys involve a periodic system of sub-monolayers of magnetic ions (for example, Mn), placed between semiconducting layers (GaAs, GaSb, InAs) forming a magnetic superlattice. There are as incidentally distributed Mn ions and 2D magnetic islands of MnAs (or MnSb) as well in manganese containing layers. The discrete alloys have high Curie temperatures (above 300 K for the GaSb-system), demonstrate extraordinary Hall effect at high temperatures [15, 16] and have a relatively high degree of the spin polarization.

It is possible in such systems to control not only quality of the border "ferromagnetic metal - non-magnetic semiconductor", but also manage of the current carrier’s concentration and change the type of magnetic ordering.

Nanostructures of wide forbidden zone semiconductors I.

High-temperature semiconductors with wide forbidden zones are also the very promisable materials for modern nano electronics. Materials based on carbon and boron provide complicated substances with unique structural properties. Research conducted during the last decades of the 20th century have shown that carbon and boron crystals form clusters, the essential structural elements of which contain 4, 12, 60, or 84 atoms. These nanoelements, due to their thermodynamic properties, transform to amorphous or crystalline films, layers and other deposits, which have some advanced properties.

The clusters having a stable configuration under equilibration conditions take the forms of different geometrical figures - from triangular to dodecahedral and icosahedrical [17,18].

Nanostructures of wide forbidden zone semiconductors II.

to the classical idea of particle formation and growth and in correspondence with the so-called atomistic process of conception, atoms being the germ of the solid phase unite in aggregates (clusters) where their quantity is dependent on their atomic According potentials.

Statistical calculations of the thermodynamic properties of small clusters carried out by means of computer modelling have shown that the potential energy of the atomic cluster components is the main factor determining the chemical potential of the cluster.

The growth in the quantity N of atoms in the cluster results in the increase of the thermodynamic potential P (N), caused by the increase in atoms at the surface. At the same time, the increase of surface energy accompanying the additional atoms is not continuous, but discrete because of the differences between the energetic contributions of the atoms completing the formation of the co-ordinating sphere [19].

Further growth in the aggregate [20,21] leads an increase in the volume by means of a gradual addition of atoms from the sides to the growing cluster - volume growth. Using the established and recent approach to the mechanism of cluster formation, it is easy to show that the appearance of small particles analogous to the so-called fractal clusters very often takes place. Following this, the particle growth occurs not by the joining of separate atoms to their existing aggregate, but by a conglomeration of aggregates with stable configuration, which preserves their individual properties. Such volume clusters consisting of separate clusters of lesser dimensions have much lower density than the matrix substance.

Nanostructures of wide forbidden zone semiconductors III.

The formation of small particles (clusters) is actually carried out by various methods, among which are supersonic outflow of vapours into the vacuum, thermo-, laser- and plasma-chemical modes of substance reduction from their gas-phase compounds, vapour precipitation upon cold substrates, reaction of molecular effusion from a cell, and etc. These techniques are being used to study the process of the small particle formation, volume growth and growth on specially prepared surfaces.

The production of elementary boron is presently being developed by various powder and film technologies [22]. The greatest interest is with modes of small particle production to provide high dispersion and purity as well as the study of the processes of cluster conception and growth.

Established theory and experiment have shown that the elementary boron atoms group into an aggregate of icosahedrical form consisting of 12 boron atoms (B12) [23,24]. Usually the boron small particles consist of one or more icosahedrons united in a cluster or various configurations depending on the thermodynamic conditions at formation.

MODEL CONCEPTION I

Given that the form of atoms of the cluster composed of structural elements is stimulated by minimisation of its surface energy let us consider the expression of the system's thermodynamic potential

$$P(N)=\Sigma\Sigma\, U(r_{ij}),$$

where $U(r_{ij})$ - is a Lennard-Jones pair potential; r_{ij} - a space between i and j atoms.
The system potential can be represented within configurative space (3N-b) measurements by a certain surface. At the same time stable configurations (isomers) of atoms are determined by their co-ordinates, which correspond to the minimum of potential energy. In accordance with calculations using the Lennard-Jones potential, 12-atoms boron structural elements of icosahedric form have compressed internal and stretched external bonds.

In case of Carbon, 4-atoms carbon structural elements posses the same behavior in organization of bonds.

MODEL CONCEPTION II

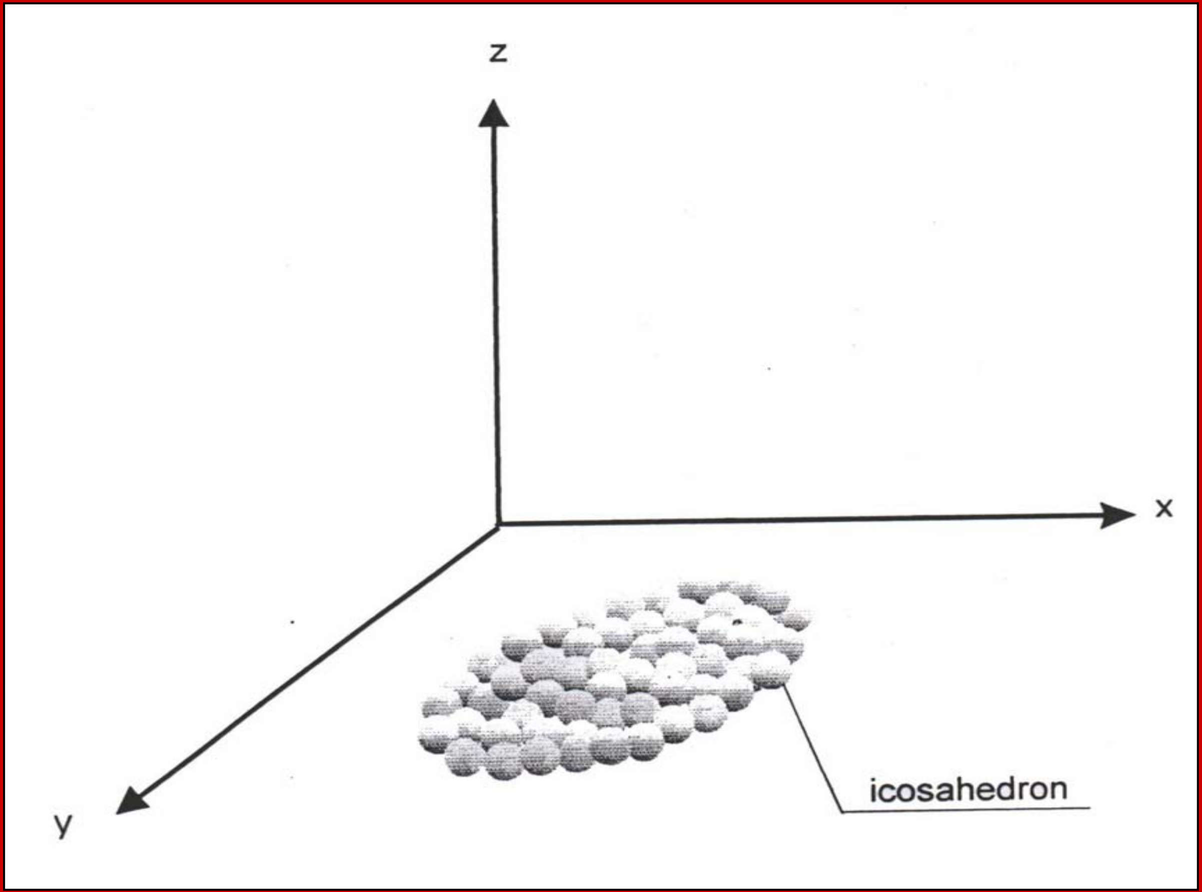
While evaluating the potential of system consisting of some structural elements - icosahedrons, we have to give up the utilization of pair interaction potential (Lennard-Jones potential) due to participation of some structural elements' (tetrahedrons, icosahedrons) potential in a process of system's free energy formation and because of necessity to take into account long-functioned forces of bonds.

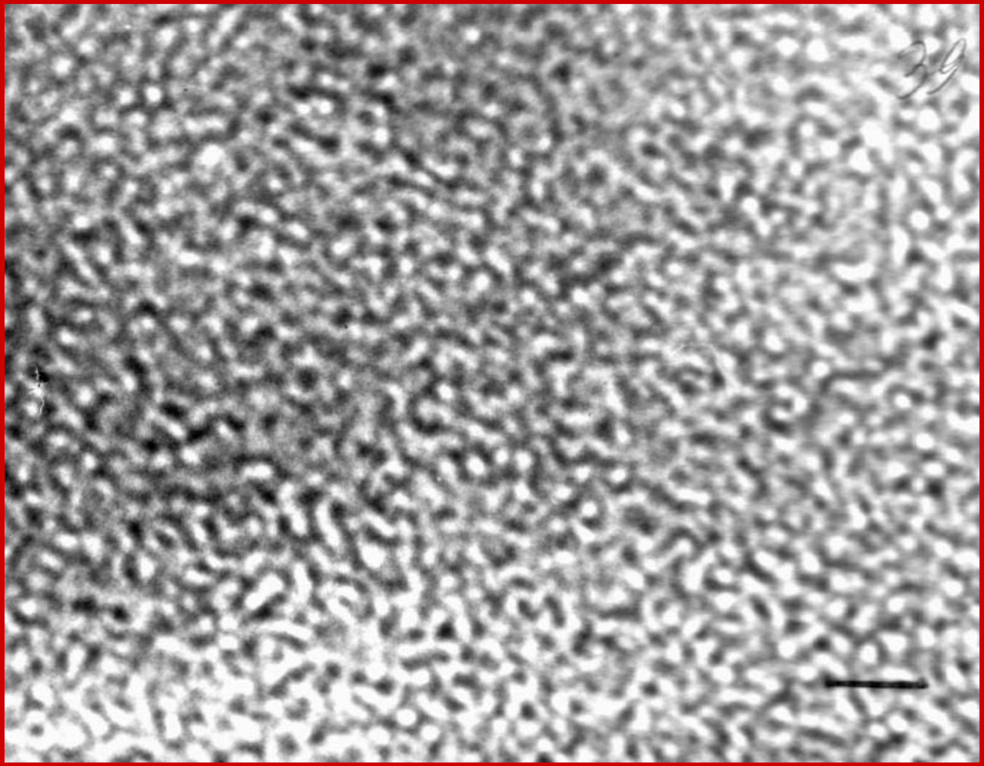
Designating the structural element's chemical potential (in boron case this is a 12-atoms icosahedron, in carbon – 4-atoms tetrahedron) as E, and the flat particles (cluster), chemical potential as P, it is obvious, that an equilibrium between longitudinal dimensions and flat cluster's thickness will be achieved, when $\mu E - \mu P = 2\alpha\nu/R$, where α - surface specific free energy per one structural element, v - specific volume of cluster per one structural element (the expression analogous to Gibbs-Thomson expression). Equilibrium form is subordinated to the second order non-linear differential equation and the difference $\mu E - \mu P$ = CONST is constant over the whole surface of a particle, the solution of this equation represents the round-curve of the studied cluster:

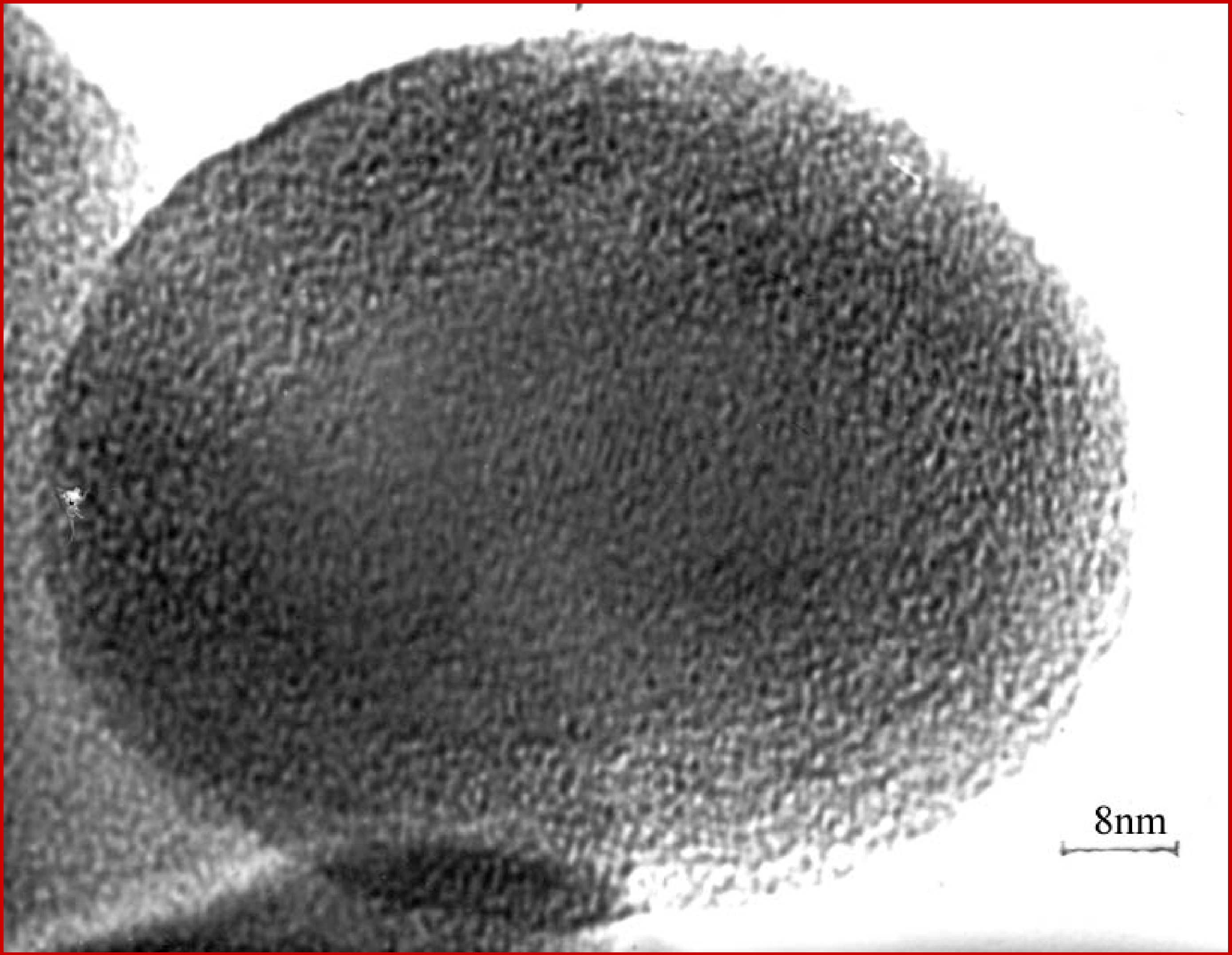
$$n\, r = 2\alpha (n)\, \nu / \mu E - \mu P$$

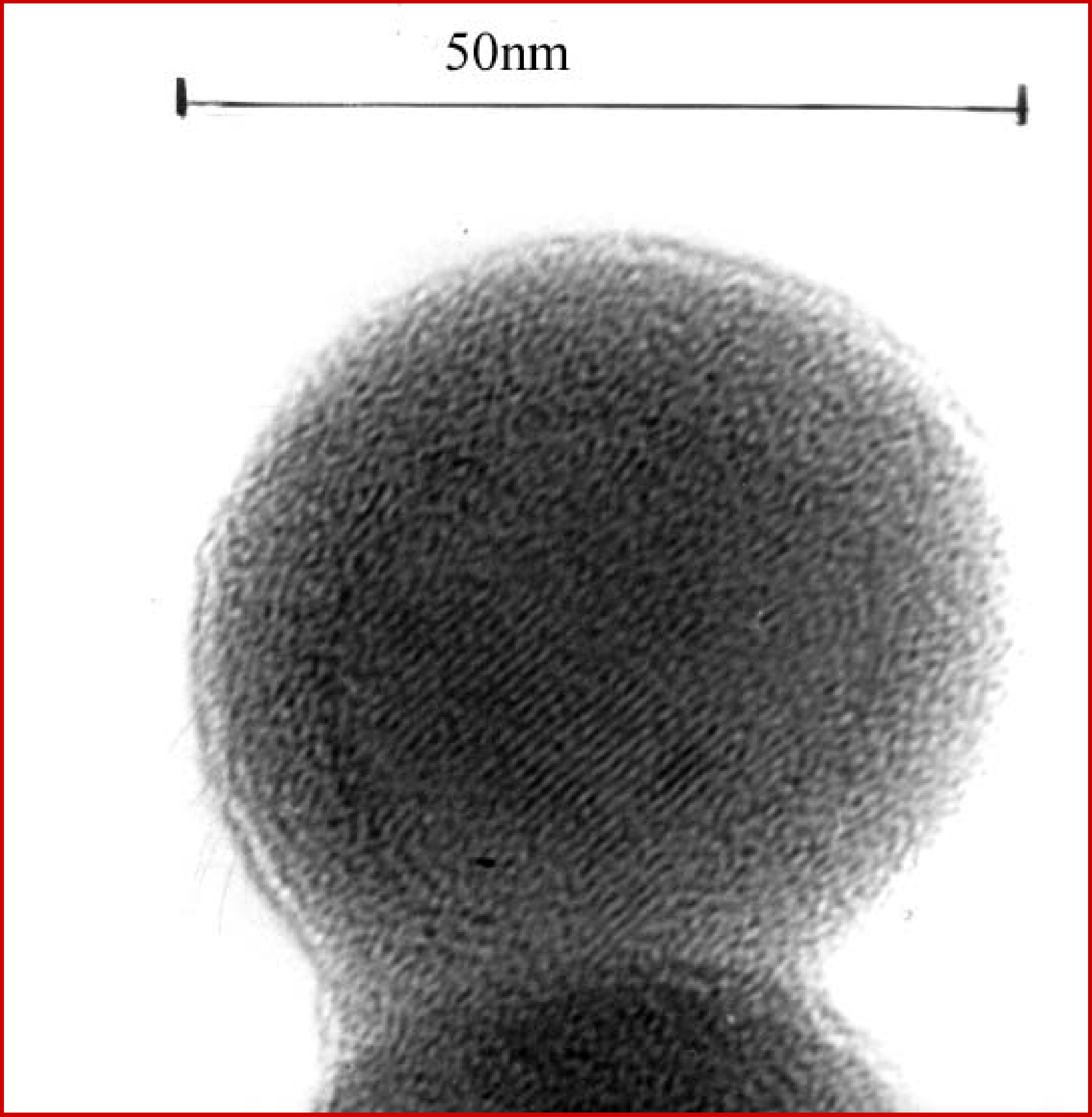
where - *n* vector of the normal to the round - curve (to the surface) of the small particle, determined by the *r* radius -vector (the expression analogous to the Curie-Wulf formula).

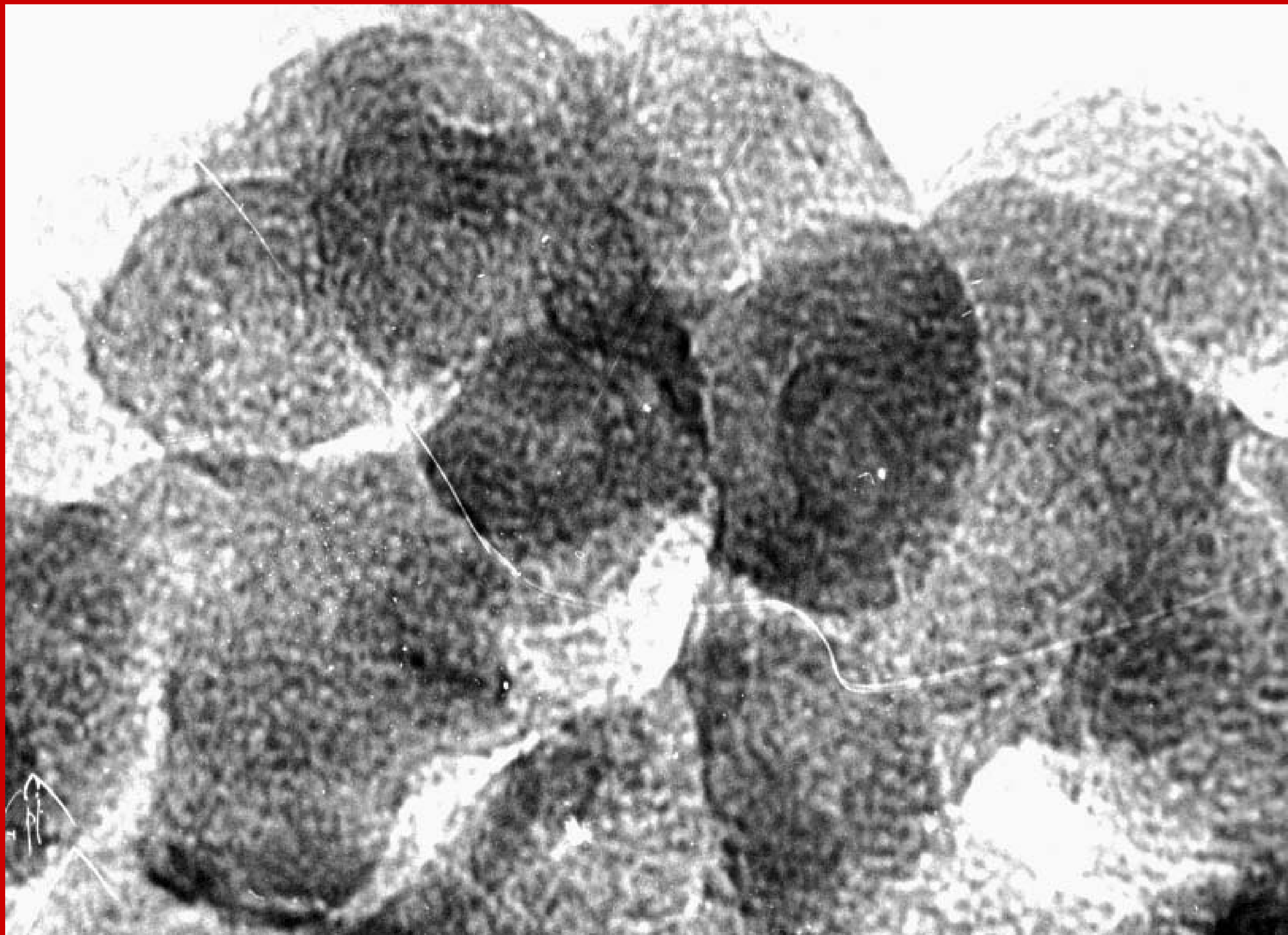
Schematic picture of clasterization of 12 - atoms icosahedrons in plane forms

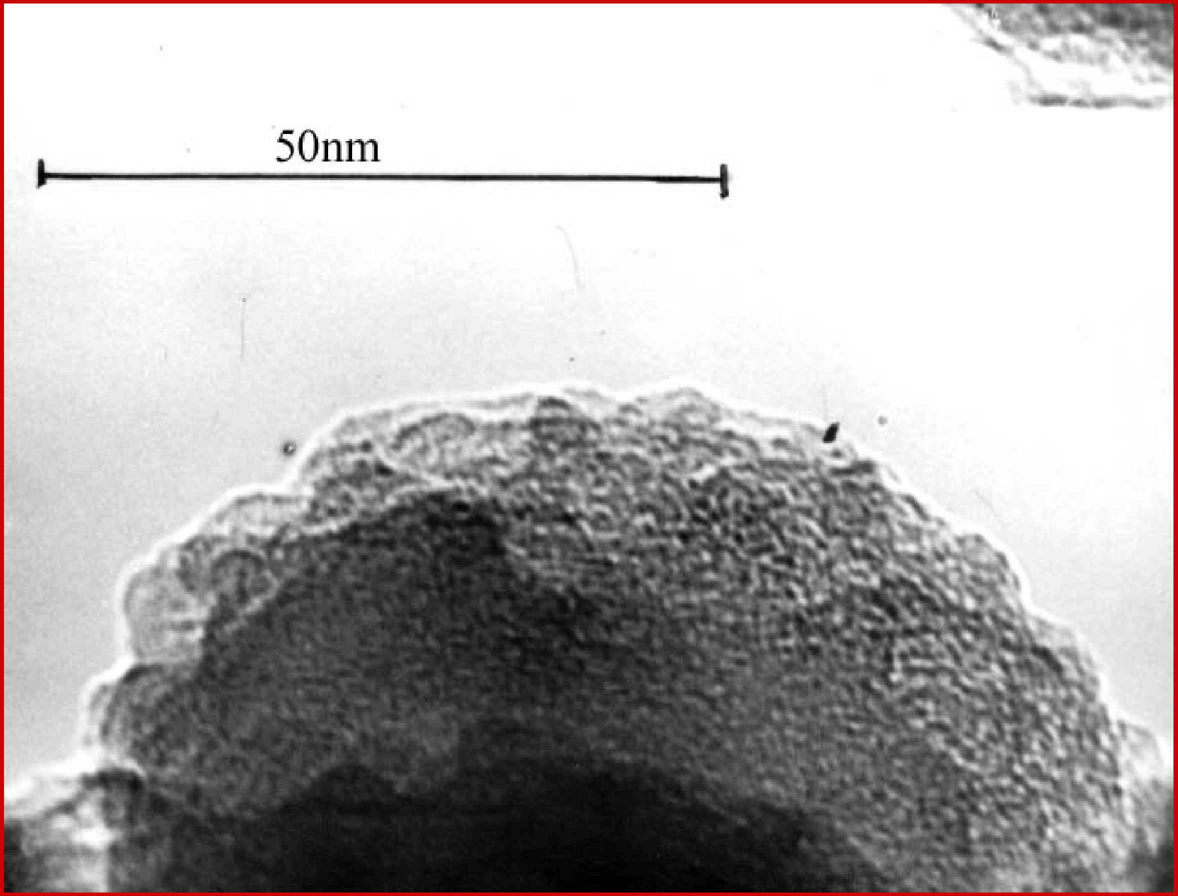


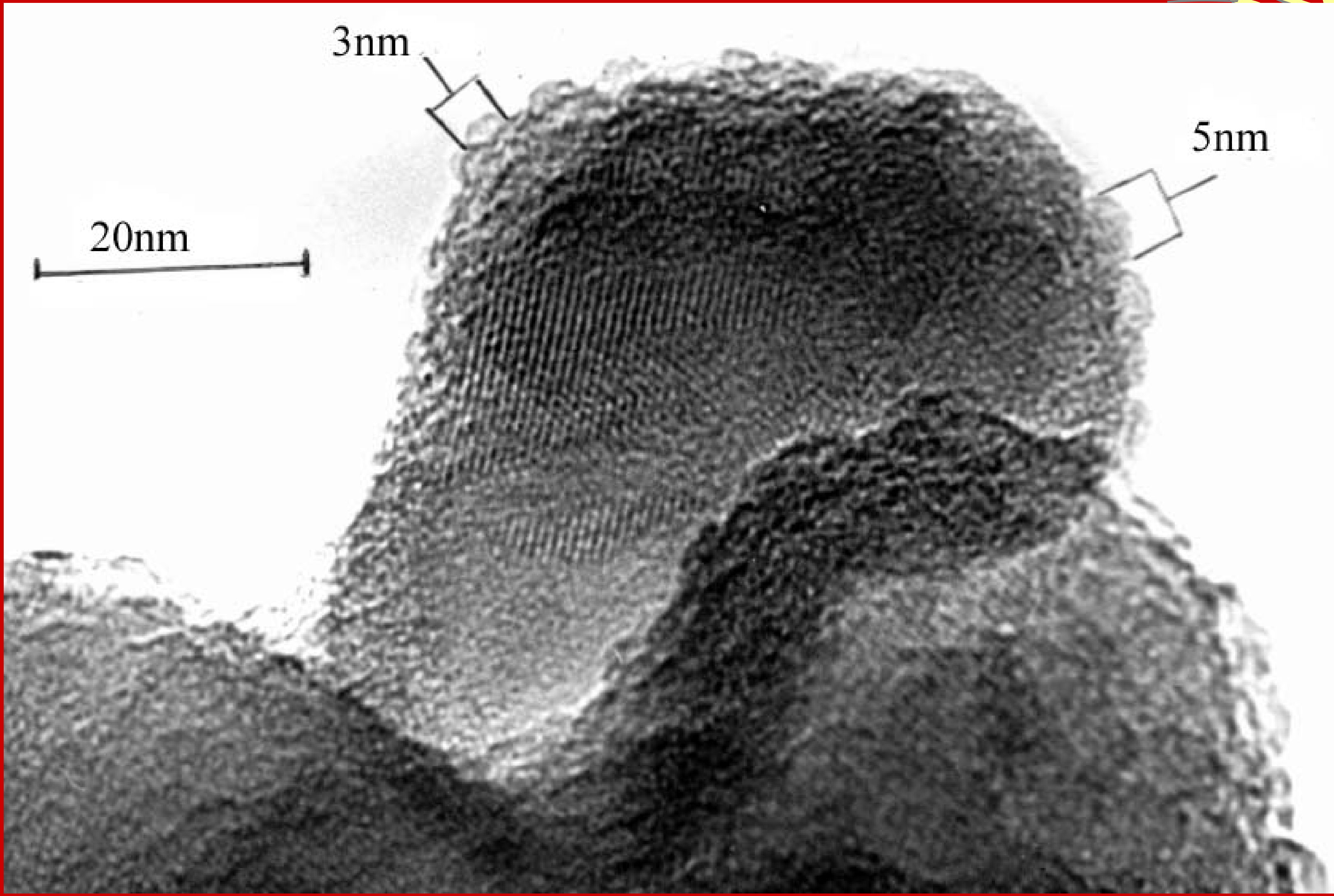

39

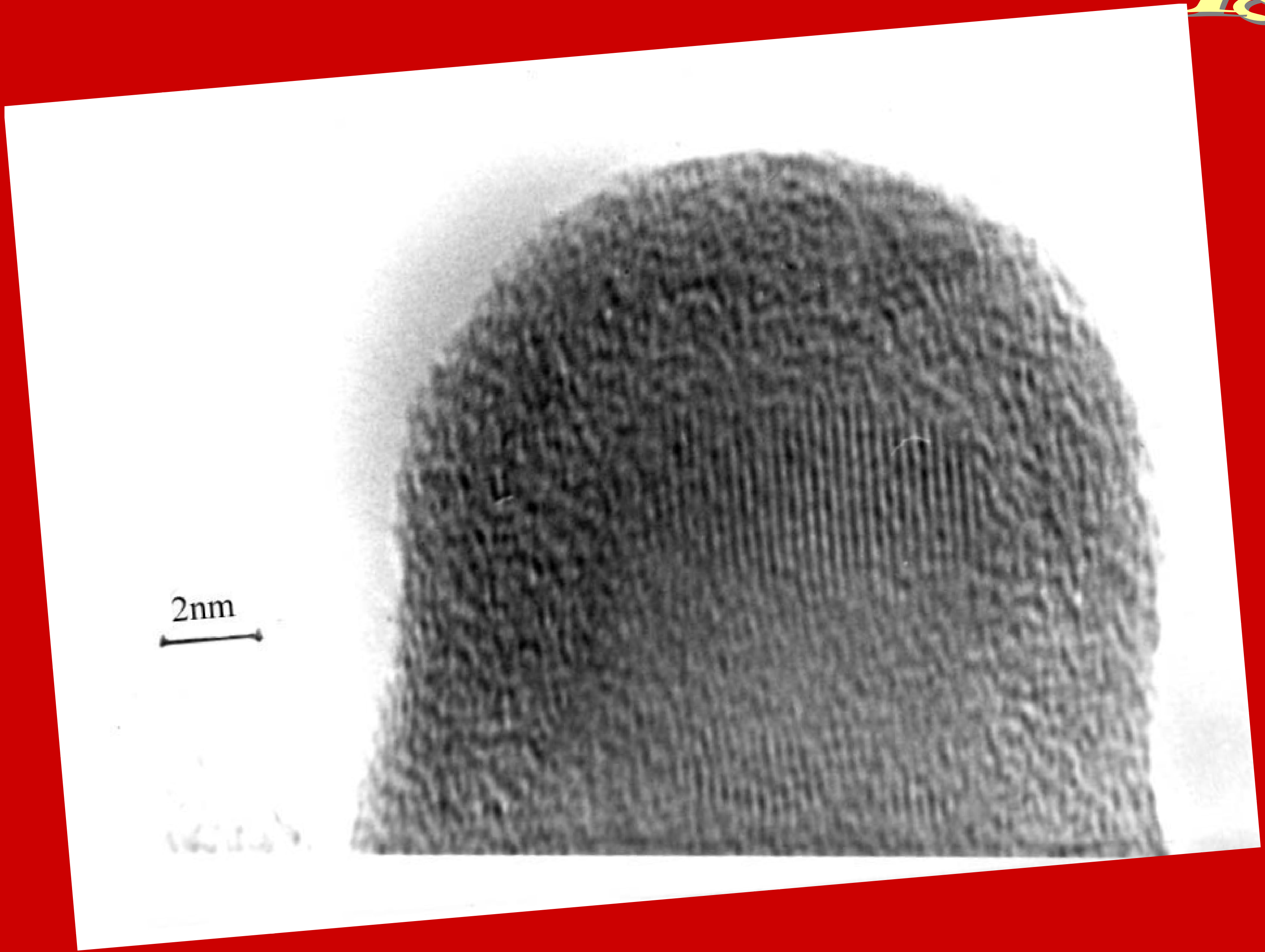

8nm

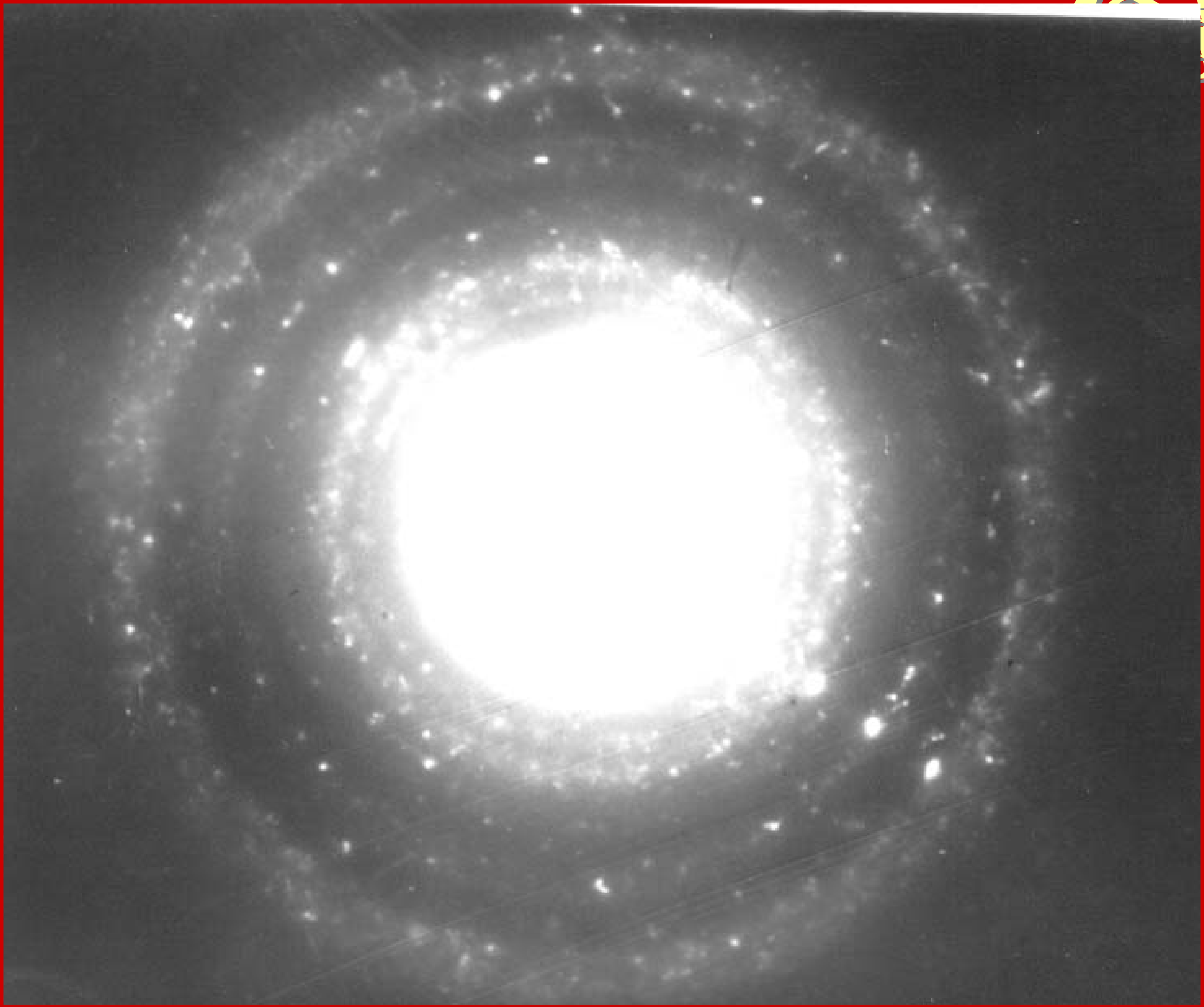

50nm

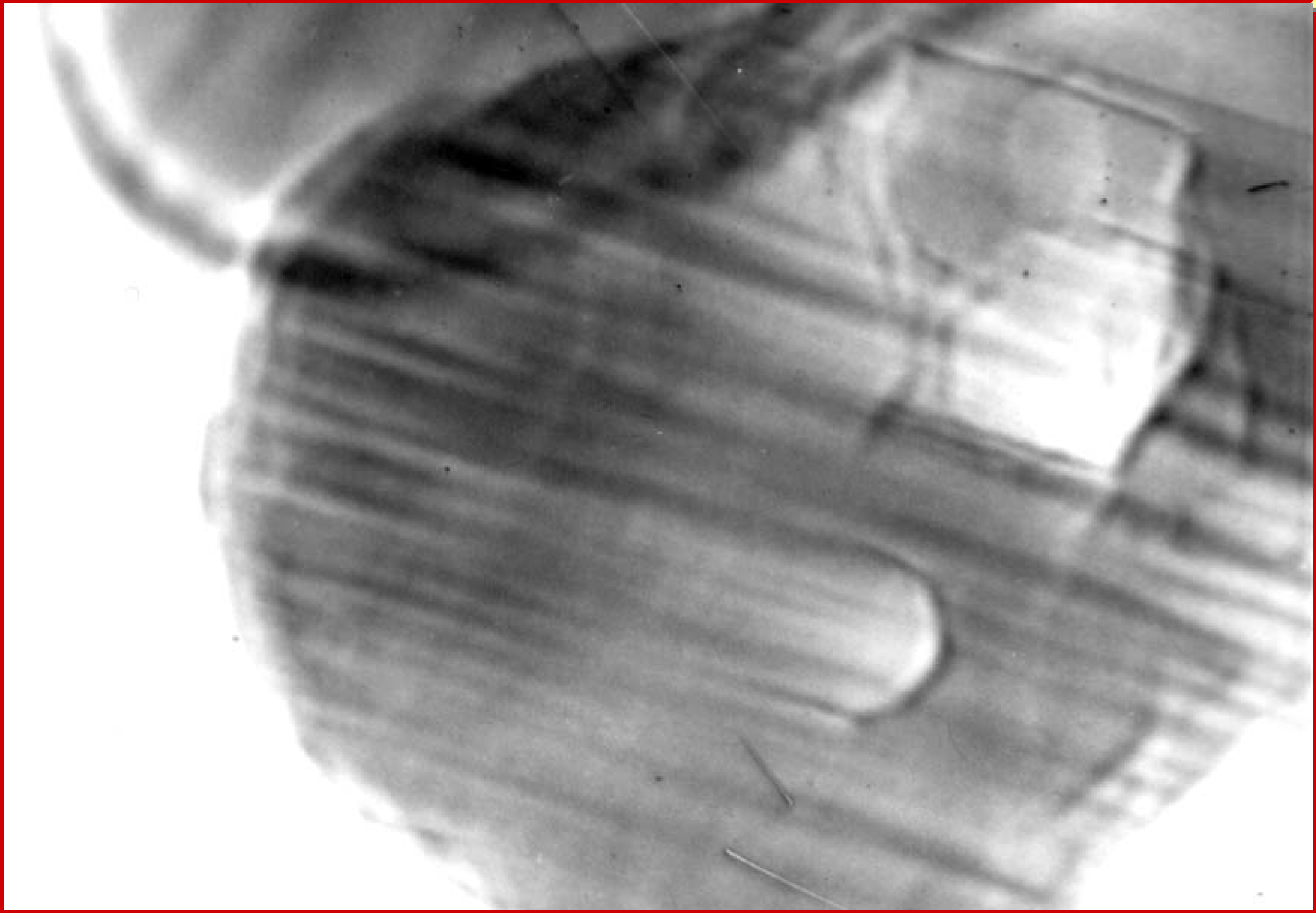



50nm

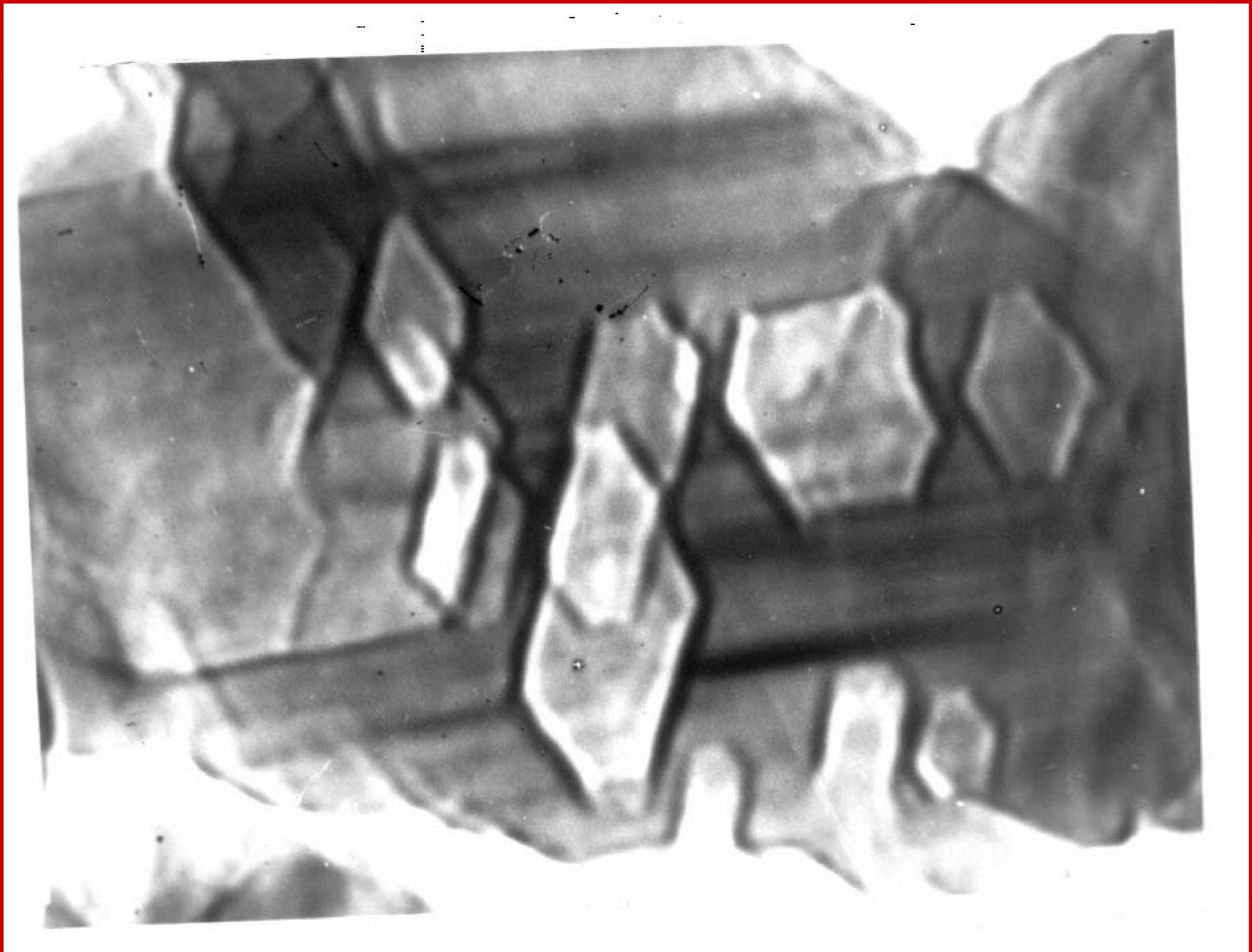

3nm
5nm
20nm

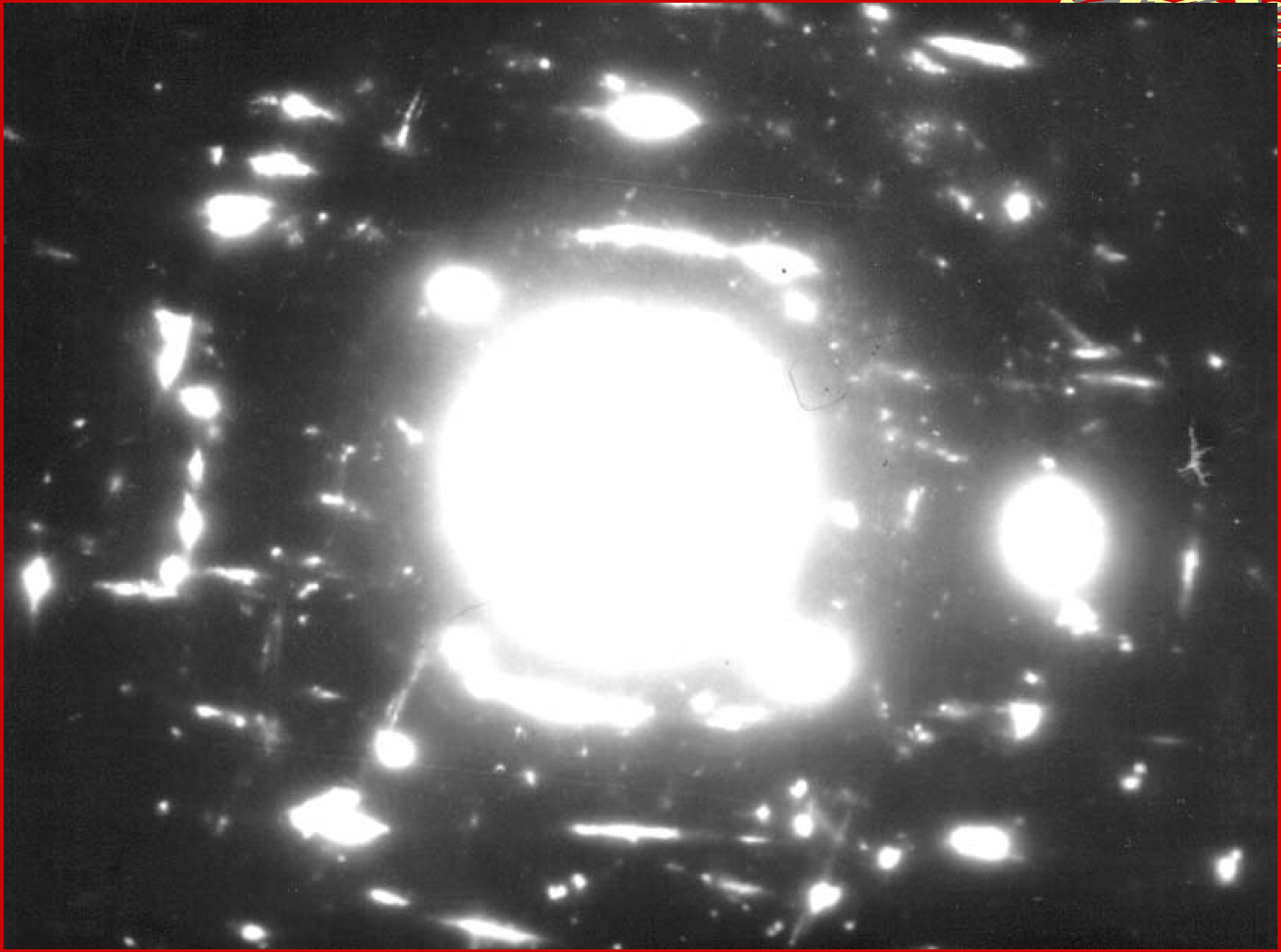

2nm



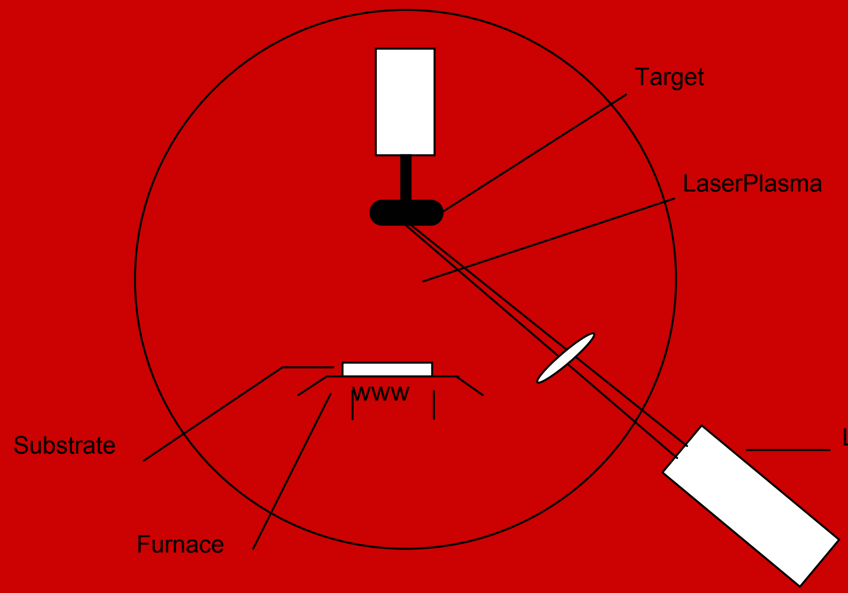



54





Schematic diagram of Laser Plasma deposition method



REFERENCES I

1. J.J Ramsden, Nanotechnology Perseptions. Vol.1, N 1 (2005) pp.3-17.
2. P.J. Kervalishvili, Proceedings of the International Conference on Materials Testing, AMA - Nuremberg, 13-15 May 2003, pp.107-112.
3. D.D. Awschalom, M.E. Flatte and Nitin Samarth, Scientific American, June (2002) p 27.
4. P. Kervalishvili. J. Nanotechnology Perceptions. v.1, N 3, (2005) pp.161-165.
5. R Flederling., M. Kelm, G. Reuseher Et al., Nature 402 (1999) p.787.
6. Y. Ohno, K.Young, B. Beschoten Et al., Nature 402 (1999) p 790.
7. M. Baibich, J. Broto, A. Fert, F.V. Dau, F.Petroff, P. Etienne, G. Creuzet, A. Freiedrich and J. Chazelas, Phes. Rev. Lett. 61 (1988) p 2472.
8. J.S. Moodera, L.R. Kinder, T.M. Wong and R. Meservey, Phys. Rev. Lett. 74 (1995) p 3273
9. S.S. Parkin, K.P. Roche, M.G. Samant, P.M. Rice, R.B. Beyers, R.E. Scheuerlein, E.J. O'Sullivan, S.L. Brown, D.W. Abraham et al, J.Appl. Phys. 85 (1999) p 5828.
10. S. A.Wolf et al., Science 294 (2001) p 1488.
11. C. Ruster, C. Gould, T. Jungwirth, J. Sinova, G.M. Schott, R. Giraud, K. Brunner, G. Schmidt and L.W. Molenkamp, Cond-mat/0408532 vo1, 25, 2004 p 234.
12. Spin Electronics, ed. By M. Ziese, M. J. Thornton. (Springer-Verlag, Berlin, Heidelberg, (2001).
13. G. Schmidt, L.W. Molenkamp (review), Semicond. Sci. Technol. 17 (2002) p 310.
14. B. Jonker, et al., Phys. Rev. B 62 (2000) p 8180.
15. X. Chen, et.al., Appl. Phys. Lett. 81 (2002) p 511.
16. B. D. McCombe, et al., Physica E 16 (2003) p 90.
17. U.T. Petrov, Small Particles Physics, Nauka, Moscow, 1982, p. 356.
18. R. Kern. Morphology of Crystals, ed. I. Sunagawa, Terra, Tokyo, 1987, pp. 77- 206.
19. V.K. Vainshtein, A.A. Chernov, L.A. Shuvalov, Up-to-day Crystallography, v.B - Formation of crystals, Nauka, Moscow, 1980, p. 408.

REFERENCES II

20. H.Brune, H. Roder, C. Bogarno, K.Kern, Phys. Rev. lett., v. 73, 1994, pp. 1955-1958.
21. P. Kervalishvili, T. Jandieri, Proceedings of the Ac. Sci. USSR, Inorganic Materials, Vol.27, N7, (1986) p 1115.
22. Boron and Refractory Bodies. Ed. by V. Matckovich, Berlin-Heidelberg, Springen-Verlag, 1977, p. 485.
23. W.N. Linpscomb, Borides and Borates, Journal of Less-Common Metals, v. 82, 1981, p. 1-20.
24. G. Abdushelishvili, T. Abzianidze, P. Kervalishvili, Laser Chemistry, Vol.10,(1989) p 81.
25. L. Landau, V. Lifshits, Statistic Physics, part 1, Nauka, Moscow, 1975, p.584
26. J. Bernholc, E.L. Briggs, M. Buongiorno Nardelli et al. In book Multyscale computational methods in chemistry and physics. Ed by A. Brandt et al. IOS Press, 2001, pp. 65-89.
27. P.J. Kervalishvili, Physica Tverdogo Tela, v. 28, N 12, 1986, p. 3218-3220.
28. P.J. Kervalishvili, E.R. Kutelia, V.S. Petrov, Physica Tverdogo Tela, v. 27, N 5, 1985, p. 1414-1418.
29. P. Kervalishvili. XIV PanHellenic conference on physics. Ioannina-Athens, 1998, pp.75-88.
30. P. Kervalishvili, S Shalamberidze, G. Esadze. Le vide, les Couches Minces. N 267, Mai-Juin-Juillet 1993, pp. 186-197.
31. A. Gippius. Proceedings of the X PanHellenic conference on physics, Delphi –Athens. 1994, pp. 54-59.
32. Ch. Lieber Proceedings of Korea – USA Forum on Nano Science and Technology, September 2000, Cambridge, Massachusetts. pp. 83-96.
33. Kervalishvili. S. Shalamberidze, Yu. Bikovski. AIP Conference Proceedings. Vol.231, N1 (1991) p 524.

THANK YOU VERY MUCH FOR YOUR ATTENTION