
**ON THE APPLICATION OF A NEW PRINCIPLE AND A NEW CLASS OF MATERIALS
FOR PROTECTION OF THE IC SYSTEMS AGAINST HIGH POWER
ELECTROMAGNETIC PULSES (HPEMP)**

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Abstract

The aim of the present work is to make a survey of a new principle and the possibilities for scientific investigations, testing and industrial incorporation of a new shielding material and technology for protection of the IC systems against high energy electromagnetic pulses and ion irradiation.

The main result of the implementation of the new principle, material and technology is to increase the safety of the critical military and civilian infrastructures, land-based and space techniques, apparatuses, devices and their components against high energy electromagnetic pulses and ion irradiation, including electromagnetic weapon arsenal of the international terrorist groups.

Key words: *electromagnetic pulses, ion irradiation, IC electronic equipment degradation, shielding protection*

1. INTRODUCTION

It is known that the high-powerful electromagnetic fields cause damages and degradation of electronic equipment performance. They may change the processing control and corrupt the stored data. High-energy electromagnetic pulses with a wide frequency range, different duration and intensity can overload circuit boards, transistors and other electronic devices, as well as erase electronic memory, upset software or permanently disable all electronic components.

It is very important to be not unevaluated the fact, that during the last years many international terrorist groups can actively plan coordinated attacks against both military and civilian infrastructures, using sophisticated high power electromagnetic pulse (HPEMP) techniques.

Some electromagnetic weapons consist of HPEMP generators allowed a propagation of electromagnetic fields with strength of 50 KV/m and a rise time of the order of 10-200 ns and influence even from a distance of 10 m.

Other techniques consist of heavy ion irradiated devices (above 1 kW, 2 GHz, 10^6 ions/cm², 10 MeV/nucl), which are harmful in respect of living organisms and electronics.

That is why HPEMP shielding plays a major role for the functionality of the military and civilian infrastructures, land-based and space electronics and for human health.

The development of the new class of materials and technology allows an effective protection of IC systems against both HPEMP and electromagnetic interferences (EMI) [23-32].

2. DESCRIPTION OF THE NEW PRINCIPLE

2.1 Summary

The protective properties of the new shielding materials are based on two main principles:

1. Microstructure evolution of the deposited nano-sized protective layers;

2. Electromagnetic interaction between HPMP and deposited nano-sized protective layers

Microstructure evolution of the deposited nano-sized protective layers is based on the recrystallization processes, induced upon influence of the energetic parameters of the HPMP. It leads to a redistribution of the high power energy laterally along the nano-sized protective layers.

Electromagnetic interaction between HPMP and deposited nano-sized protective layers is based on the laws of multiple inner absorption, diffusion scattering and reflectance of the electromagnetic flow. It leads to a consuming and annihilation of the high power energy flows.

The shields consist of multiple deposited nano-sized layers or (and) attached nano-sized composite panels.

Nano-sized structures can be formed through electroless – or/and electrochemical deposition, or/and by metallization processes of the nano-sized particles, alternatively.

Nano-materials such as nano-particles can be produced using different nano-technological methods. For example, the carbonization of the polymer materials leads to carbon nano-particles, which are anisodiametrical and polydispersive. The second step of the procedure is the electroless (autocatalytic) copper deposition and the third step of the procedure is the copper (or other metal) electrodeposition. The result of such procedure is a structure of metal nano-crystals on nano-particles with nano-sized dimensions (about 20-100 nm). Another example is producing of nano-wires, synthesised by electrochemical deposition through ion track porous membranes as templates. Nano-porous materials such as membranes have been often used in nanotechnology for preparing nano-sized wires and tubes. This technique is attractive but less accessible than other methods and has a confined space of industrial application. The nano-wires, as well as nano-whiskers, have strongly anisodiametrical dimensions; some times their faces have a high degree of parallelism.

The metallized nano-particles can be applied as extruded composite plates, spread paint “wall-papers”, etc.

The electrochemical deposition is an easily accessible, inexpensive, highly efficient and reliable method for producing of metal nano-crystalline layers onto both the outer surfaces of the containers and cases, and on the surfaces of the inner modules. The electrochemical technology can be applied independently of the materials of the containers, cases, and outer surfaces of the inner modules - plastics, aluminium alloys or ferrous metals.

Depending on the nature and functional destination of the IC systems, as well as on their exploitation or storage conditions, the protective shields can be deposited or attached in one way or another:

The nano-structures have unique and important properties, due to their small size. Related to the shielding usage, the most important property is high-developed total surfaces per a unit of volume. The fine grain microstructure evolution, such as microrecrystallization without stresses applied, can be observe if the nano-sized structure are subjected to the influence of the high-powerful electromagnetic fields or ion irradiation. Thus the propagation of harmful flows to the precious IC systems is stopped due to the redistributed energy along the planar direction of the shield.

2.2 Basic principles of recrystallization

2.2.1 Recrystallization – a critical process $f=f(T,t,\sigma)$

Recrystallization is a critical process, which takes place above threshold values of the temperature T , duration t and strain deformation (tensile or compressive stresses σ).

If the stress is constant, the isodeformational cross-section of the recrystallization diagram is a non-simple steric dependence of the recrystallized volume on the thermal regime parameters $V = f(T,t)_{\sigma=\text{const}}$. If the both stress and temperature are constants (isodeformational isothermal recrystallization), the

recrystallization volume depends on the duration of the thermal treating. As higher is the stress, as lower is the initial threshold temperature value of the recrystallization process $T_{\text{rec}}^0 = f(1/\sigma)$.

Of course, this is only a first level of approximations of a complicated task.

2.2.2 Recrystallization kinetics

2.2.2.1 Driving force

It is well known [1-7] that the specific free surface energy of the grains and the specific free grain boundary energy play an important role in connection with the form and habit of the crystallites of the polycrystalline structures. The minimizing of the excess of the specific free volume, face and boundary energies is the driving force of the all recrystallization processes (primary, secondary and commutative).

The divergence of the specific free energy on the boundary of two grains $\Delta\gamma$ depends on the specific free grain boundary energy value γ , on the sizes of the two grains d_1 , d_2 and on their divergence Δd :

$$\Delta\gamma = 3\gamma(\Delta d/d_1.d_2)$$

As smaller are the grains and as greater is their divergence, as greater is the specific free energy divergence, i.e. the recrystallization process's driving force is greater.

The recrystallization process stops when:

- the grain boundaries disappear, i.e. the polycrystalline structure becomes a monocrystal. Such solid-state transformation is thermodynamically postulated but it is not kinetically probable.
- all the grains become equidimensional - equal-sized and identical-shaped as a right hexahedron (planarity imaging - hexagon), which grain boundaries are of the same length and angle between them is exactly 120° . This is the unique equilibrium form of the grains and equilibrium equation system is

$$\Delta\gamma = 0, \Theta = 120^\circ$$

When the grain has less or more than 6 faces, the equilibrium equation $\Theta = 120^\circ$ is possible only if the grain boundaries are curved. Both concave and convex boundaries are not equilibrated due to the excess of specific free energy compared to the equilibrium right boundaries. The trend of the minimizing of the excess of the specific free energy leads to the straightening of the curved boundaries and to minimizing of the total prolongation of the grain boundaries. This process is known as "mobility and migration of boundaries" and has a result that the great grains become greater and small grains disappear. The process stops when the all grain boundaries become right and angle between them - exactly 120° . Thus the equilibrium habit of a polycrystalline structure is an infinite set of small hexahedrons (hexagons) with minimal total prolongation of the equilibrated grain boundaries, i.e. with minimal free grain boundary energy [4-7].

2.2.2.2 Behaviours of the impurities

Additional components, such as beneficial alloying metals or harmful impurities have a contrary behaviour on the kinetics of the recrystallization processes.

On the one hand the additives decrease the melting point T_m of the system as the phase diagrams show. The threshold value of the initial recrystallization temperature depends on the melting point $T_{\text{rec}}^0 = f(k.T_m)$ ($k = 0.3 - 0.7$). Thus the additives promote the recrystallization process's rate.

On the other hand the segregation of the surface-active small phases along the grain boundary leads to a consuming of the free grain boundary energy and to an inhibition of the recrystallization process's rate due to decreasing of the driving force. This process is known as "dragging of the impurities".

2.3 The nano-structure evolution – a logical consequence of the basic principles of recrystallization

2.3.1 Thin electrodeposited nano-sized layers

The electrochemical nucleation and growth processes can apply to the thin layers formation. The single or multiple layers of mono- or poly-components with nano-sized structure are suitable objects for easily accessible recrystallization under the influence of the HP EMP.

The nano-structured electrodeposits are polydispersive, they have small, anisodiametrical grains with curved non-equilibrated boundaries (Figure 1).

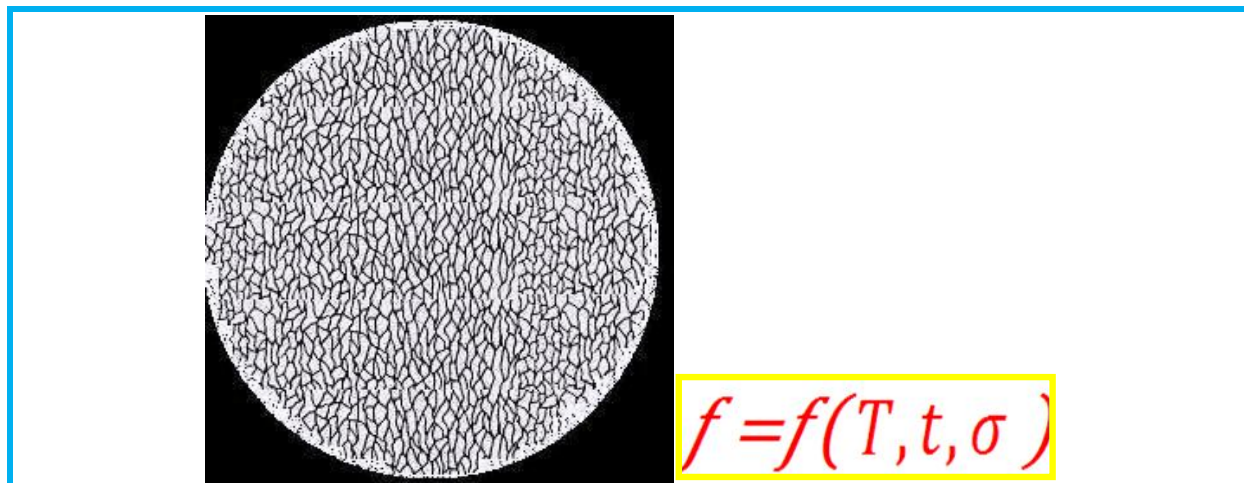


Figure 1. The nano-structured electrodeposited thin film

As-plated thin electrodeposited layers have internal tensile or compressive stresses [6].

Beneficial alloying metals have additional promoting effect on the extra fine nano-structure formation due to the synergetic impact, as well as on the decreasing of the melting point.

Contrary to the large-structured samples, which require great strain- and temperature values in order to begin the recrystallization process, the nano-structured electrodeposits can recrystallize under the influence of the energy factors of the electromagnetic pulses (Figure 2).

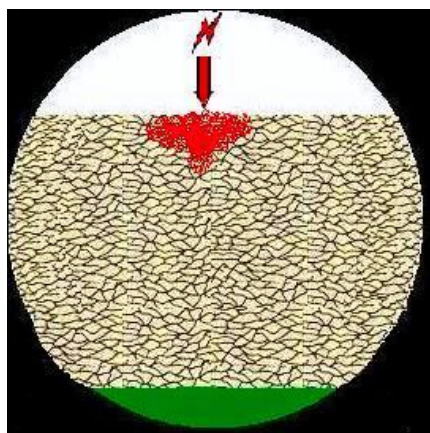


Figure 2. Recrystallization of the nano-structured electrodeposit under a energy influence of the electromagnetic pulses (● - electrodeposit, ● - substrate, ↓ -HP EMP)

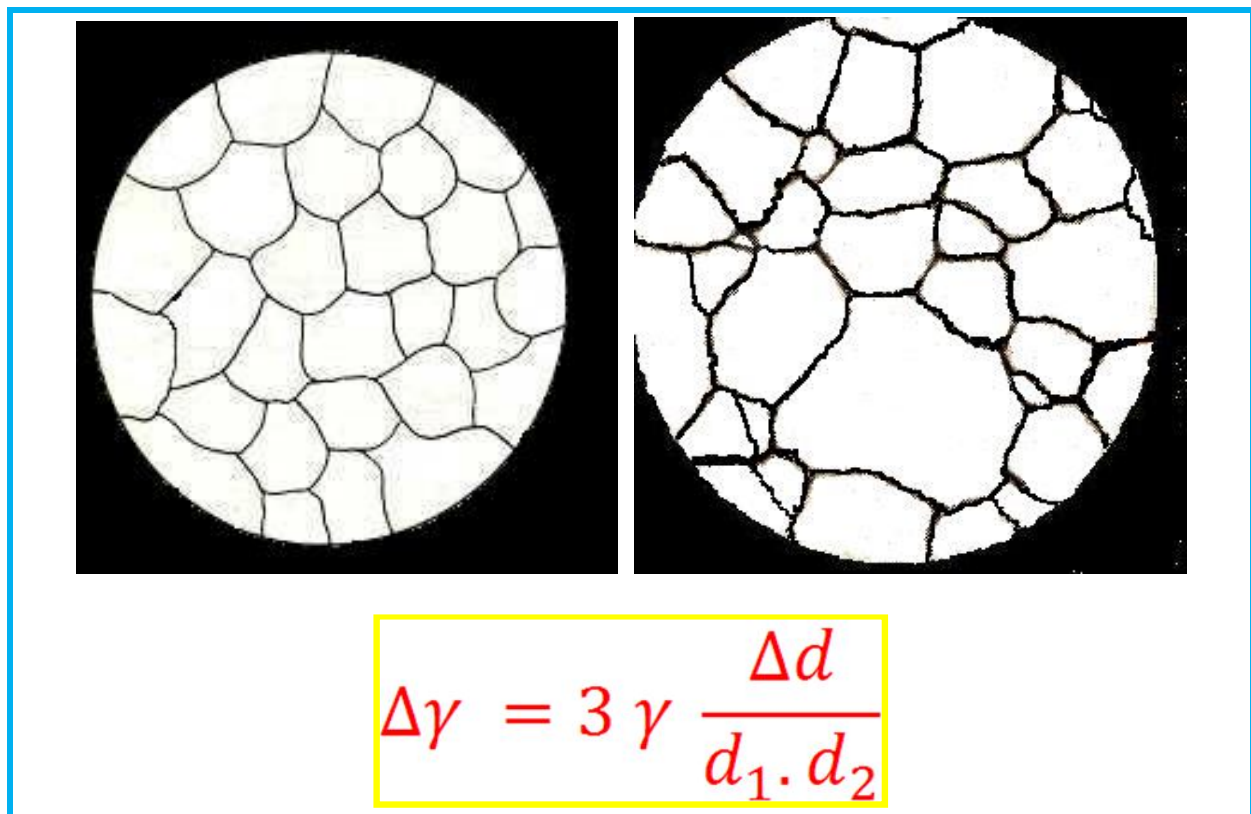


Figure 3. Structural evolution of the electrodeposited thin film

Thus, the high-energy flows are used up and redirected towards the implementation of the required conditions for the recrystallization process, which leads to the structural evolution of the outer electrodeposited nano-layers (Figures 3 - 5).

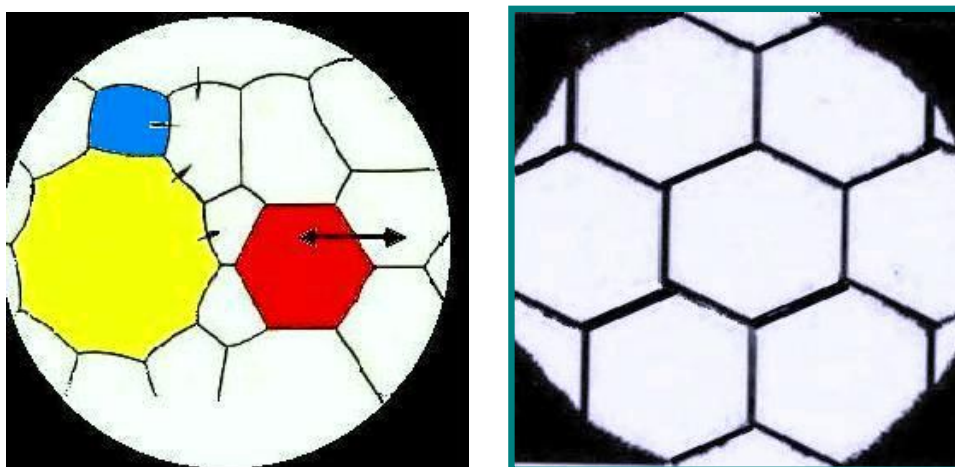


Figure 4a. Equilibrated and non- equilibrated grains Figure 4b. Infinite set of hexahedrons (hexagons)

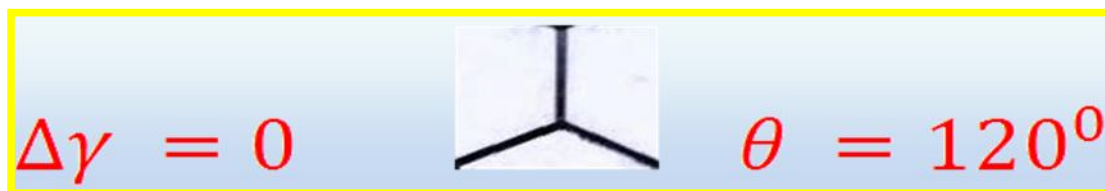


Figure 5 Equilibrium equation system

Depending on the energy parameters of the electromagnetic pulses, the structural evolution of the nano-sized electrodeposited layers has different duration, it leads to a full or partial restructuring of the initial layers, but in all cases it fully consumes the energy of the electromagnetic pulses. The main conclusion is that the electrodeposited nano-structures and recrystallization processes offer the necessary and sufficient conditions for a successful protection against HP EMP.

2.3.2 Nano-wires and nano-whiskers – useful and harmful properties regard to IC systems

The nano-structure evolution of the nano-wires and nano-whiskers, if they are especially fabricated, using different methods and technologies (synthesised by electrochemical deposition through ion track porous membranes as templates, capillary growth, vacuum evaporation, chemical reduction, etc.) follows the above described basic principles and has similar results. Additional advantages of the nano-wires and nano-whiskers, as well as of the metallized carbon nano-particles from polymers, are possible applications as extruded composite plates, spread paint “wall-papers”, etc. Such advantages can be evaluated, taking into account the greater difficulties, needed their fabrication.

Regardless of the above discussed ways of recrystallization, it can be possible another way of abnormal nucleation and growth processes - spontaneous nano-whisker formation. This is a good way for useful nano-whisker production. Unfortunately, in most cases the spontaneous whisker formation is a harmful process, especially for electronic assemblies, containing tin alloys without lead as solders and metal resists plated on PCBs. There are so much publications about tin (and other metal) whisker induced military and space failures [8-13]. It is considered that the energy minimizing is the same driving force directed towards the easiest way, but the mechanism of the spontaneous whisker formation is not recently clarified.

Some other applications of the nano-sized materials, such as nano-wires, nano-whiskers, milled electrodeposited or rapidly quenched nano-layers, carbonized polymer particles (with and without metallization) can be shortly remarked with the purpose of thoroughness:

Due to the high developed total surface per a unit of volume, the nano-sized materials with deposited bright metal films can be used in military technique for prevention of the unauthorized day- and night observation in visible, near-IR and far-UV frequency ranges (military reflective smoke-screen camouflage). From the counterview point, if the deposited metal or oxide films are black, the nano-sized materials can be used in “stealth” technology as absorbing layers, as well as for solar-cell purposes.

The chemical active nano-sized materials with deposited metal, oxide or other suitable compounds can be used in different catalytic systems - for decontamination of out-going gases of internal-combustion engines of the automotive and crawling vehicles, for individual filter of gas-mask helmets or filter-ventilating devices for bomb shelters, etc.

3. DISCUSSION: SOFT-MAGNETIC PROPERTIES OF ELECTRODEPOSITED LAYERS – CURRENT ACHIEVEMENTS AND FURTHER DEVELOPMENTS

The electrochemical deposition of nano-structured layers is a complicated phenomenon which origin must be searched along the more general theory of the new phase formation. The most fundamental theories of the nucleation and growth of the new phase are given by the scientists of the Bulgarian scientific school, physicochemists and electrochemists, such as Ivan Stranski, Rostislav Kaischey, Nikola Pangarov, Eugenie Budevski, Stojan Budurov and others. The nucleation and nuclei' growth processes (i.e "electrocrystallization") are the first steps of the electrochemical deposition of the thin films as well as of the nano-sized tubes and wires. When the electrode transmission is the limiting stage of the total multisteped reaction, the nucleation and growth processes depend on the overvoltage applied. A higher overvoltage value leads to a nucleation process, than a less overvoltage value leads to the growth process of one or more nuclei. When the overvoltage is selected that more than one nucleus to be formed, the growing parameters can be selected to be formed more than one crystal. In this case the crystal growth leads to nuclei coalescences, islands and, finally - polycrystalline structure. The dimensions, habit and orientation of nano-sized grain depend on the electrochemical reaction's conditions. For example, the linear crystal growth rate, which determines the grain dimensions, depends in first approximation on the steady-state nucleation rate [7]. That is why is very important the detailed studying of the mechanism of the nucleation and growth processes, because they determine the structure and properties of the electrodeposited layers.

As it is shown [31], both metallurgical and electrochemical methods for producing of the metals have the identical nature based on the same thermodynamic and kinetic principles.

The main result of the study of the amorphous metals and alloys is the development of level lower structurized new materials - the knowledge about production processes, properties and application of nano-sized thin films.

Recently the single metal electrocrystallization and electrodeposition processes are well explained and practical used. The co-electrocrystallization and co-electrodeposition of the multicomponent alloys are objects of intensive worldwide investigations [14-20].

The 2- and 3-component alloys can be amorphized and nano-sized easier than mono-component "pure" ones.

As it is shown in author's laboratory [21-32], the electrodeposits of Fe, Ni, Co and their alloys - have famous soft-magnetic properties - $4\pi M_s$, B_r , H_c , μ , etc. Such properties may be obtained by thermomagnetic annealing of the metallurgical samples. The electrochemical production method of soft-magnetic materials is easier, accessible, inexpensive and highly efficient than any metallurgical one and it is unique and only possible for the articles they are made of plastics of ABS-copolymers.

The amorphous electrodeposited thin films have also excellent physicochemical – microhardness, tensile strength, wearresistance, adhesion, etc. – properties. They are a suitable material for the repairing of precious critical threadbare parts of internal-combustion engines, transmissions, brakes, etc. of automotive and crawling vehicles. The amorphous thin films have also excellent physicochemical properties – both chemical activity and chemical resistivity. They are a suitable material both for catalytic systems used for decontamination of out-going gases of internal-combustion engines and for corrosion protection systems used in naphtha- and gas- pipelines, in high humidity atmospheres and in water- and aerosol- salt environments [24-27, 30, 32].

By investigation of morphological structure, growth kinetics, composition, and microstructure evolution of amorphous soft-magnetic layers on the Cu and plastics substrates were obtained results in accordance with US military standard MIL-STD-461E/1999 about electromagnetic shielding properties above requirements of US FCC [21, 22, 28, 30, 32].

The modified telephone set Type TTT-100, produced by “Telephone and Telegraph Technique” PLC, Sofia and protected against EMI with multilayer multicomponent system of electroplated amorphous metal alloy coatings, was presented on Int. Conf. Defence Research and Technologies "Modernising the Forces - Cornerstone of the Bulgarian Way to NATO", Telecomm Exhibition Hall, Plovdiv, Bulgaria, May-June 2002 [23].

Before our investigations the efforts of other scientists, institutes and firms (The Applied Physics Laboratory of John Hopkins University, The US AF Construction Engineering Research Laboratory-CERL, ALLIED SIGNAL Co, SHIPLEY Co, etc.) was directed to develop of the technologies, based on highly electroconductive materials for shielding only of the electrical component of the electromagnetic fields. Our results showed a successful protection against both electric and magnetic components of the electromagnetic fields. The combination of such properties as amorphous structure, phase composition of soft magnetic metal alloys and multilayer coatings leads to shielding effects achieved by the laws of multiple inner diffusion scattering and reflectance of the electromagnetic flow.

For the purposes of the EMI protection against low-energy electromagnetic fields, used e.g. for unauthorized access to the databases, the thickness of the protective system is not a limiting factor for the shielding efficiency.

The protection system against high-energy fields of electromagnetic weapons depends not only on the attenuation flow gradient, but depends on the layer thickness, where the effects of multiple inner diffusion scattering and reflectance of the electromagnetic flow are superposed to the microstructure evolution.

As it was mentioned, the influence of the alloying components (Ag, Bi, W, Mo, Zn, etc.) and the alloying additives (P, B, Si, C, etc.) is as amorphizeing agents.

Hence, the nano-structure, new soft magnetic metal alloy compositions, number and thickness of the deposited layers are a new challenge beyond the earlier achieved results – important concerning EMI , but insufficient regard to successful protection of the IC systems against HPEMP.

The new aims include new alloying compositions, new electrochemical conditions and new more precise technique for investigation, testing and observation, such as electron backscatter diffraction (EBSD), high voltage (HV), atomic forced (AF), focused ion beam (FIB), high resolution transmission (HRT), orientation imaging (OI) microscopy, computer modelling and simulation experiments, etc.

The development of the new class of materials – nano-sized electrodeposits, which have a higher level of dispersion than amorphous electrodeposits, can be based on the achieved results and on the further progress of the theory and experiments.

4. CONCLUSIONS

It can be drawn the following conclusions:

- The safety of the IC systems, used in critical military and civilian infrastructures, land-based and space techniques, apparatuses, devices and components, can increase by their protection against high-powerful electromagnetic pulses and ion irradiation, including electromagnetic weapon arsenal of the international terrorist groups.
- An effective protection against high-powerful electromagnetic pulses and ion irradiation can be implemented by protective systems comprising multilayer, multicomponent coatings.
- The protective coatings consist of nano-sized layers and have soft magnetic metal alloy compositions.
- The protective nano-sized soft-magnetic coatings can produce by different methods and technologies.

- The electroless chemical and/or electrochemical methods offer technologies, which are simple for industrial implementation, inexpensive, highly efficient and reliable. They are highly competitive to other technologies based on expensive methods, equipment and apparatuses such as laser glassing of the metal surfaces, thermomagnetic annealing, vacuum sputtering, etc. These technologies are unique and only possible for articles they are made of plastics of ABS–copolymers such as cases and boxes and they can be easily applied to the containers and outer surfaces of the inner modules, they are made of aluminium alloys and ferrous metals.
- The protective properties of the nano-sized soft-magnetic shields are based on the synergetic effect of the microstructure evolution, induced from the electromagnetic flows and their multiple inner diffusion scattering and reflectance. This synergetic effect leads to a fully annihilation of the falling electromagnetic flows, which powerful energy is redistributed along the planar direction of the shield.
- The achieved results outline a perspective future development and multiplication of the above mentioned our technologies.
- The aims of the future developments include new compositions based on V, W and other alloying metal components, as well as using P, B, C, Si and other additives.
- New results can be achieved through improvement and perfection of the scientific investigations, e.g. by use of new processes for electrocrystallization and electrodeposition of metal alloys, new modern equipment for observation, examination and testing.
- There is a great human potential of both scientists and industrial skilled workers in Bulgaria. These people need moral and financial support.

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