# Subject of “Low-dimensional Selfassembling System” in the mechatronical education at the Obuda University

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***Abstract*—Some years ago, on our University a mechatronics educational specialization has started. Not only Hungarian, but English language education are also available. In consequence of its interdisciplinary nature, the subjects are educated by the lecturers from different institutes. Primarily, the lecturers of the subjects are from the Bánki Donát Faculty of the Mechanical and Safety Engineering and the Kandó Kálmán Faculty of Electrical Engineering. The „Low-dimensional Self-assembling System” specified in the title, is educated in the sixth semester in the mechatronics education in the Bsc. level. The subject have theoretical and practical parts as well. In the theoretical part, the physical background of the self-assembling is studied by the students. In the low-dimensional part, the quantum phenomena are considered. The education is finished by case studies. In the seminar of the subject, primarily, numeric problems are solved, which are fit to the theoretical part of the subject.**

***Keywords*—mechatronics; education; low-dimensional; selfassembly; nanostructures; complexity;**

## I. INTRODUCTION

Nowadays, electronics was revolutionized by the use of nano structures. The objects, which at least one dimension is fallen into the nanometer range or several times ten nanometer range, called nanostructures. The present article is related to the subject of "Low-dimensional Selfassembling System". The topics of the subject is the production and application possibilities of the above mentioned nanostructures. The subject is studied by students in the sixth semester of mechatronics education. Not only lecture, but seminar is related to the subject as well. The subject not only in Hungarian, but in English is also taught by us. The subject is studied by not only full-time students, but correspondence students as well. The subject is based on the preliminary studies of the Math, Physics, Material Science of the Electronics, Microelectronics and Nanotechnology subjects.

## II. THE CONTENT OF THE LECTURES

The materials of the lecture are grouped among six main topics. These are the followings: relation of the nanotechnology and microelectronics, scaling laws, properties of the low-dimensional systems, self-organization, technology of the nanosystems and finally the application of the low-dimensional systems. Each individual topic is get expounding through some lectures.

The first topic is an introduction. Here the subject is taken to plausible for the students, which seems to abstract. The reason, why is the low-dimensional systems are necessary is discussed? Or, which advantages are derived from its application? Or, how is connected to microelectronics? The microelectronics is mostly based on the top-down conception. The nanotechnology even though primarily the bottom-up conception. In the nanosize range the structures economically not produced by external processing, but the driving forces are utilized, which is in the material inherently.

The next topic is the scaling laws. The effect of the size for the different physical interactions and physical quantities. The significance of different effects and properties strongly depends on the characteristic length. A characteristic example: in case of celestial bodies the gravity is a fundamental interaction, while in the nanotechnology effect of the gravity is neglected. The physical quantities are examined in the function of characteristic length.

The third topic is the properties of the low-dimensional systems. The quantum confinement in one, two or three dimensions. Related to this two, one or zero dimensional systems are talked by us. The energetical calculations are mean the solution of the Schrödinger equation. Next to the appearance of the energy levels, the transport properties can be change in significant scale.

The fourth topic is the selfassembling or with other words selforganizing. Here, the scale invariance, the self-affinity, the chaotic behaviour and phase space, which is used for these description, are discussed. The self-affine pattern, as a growth front appears frequently in the surface. These self-assembled characterizes the complexity and power law. In the nanosystems we meet frequently with the behaviour like this.

The fifth topic is the technology, i.e. production of these low-dimensional systems. The using of different driving forces. Growth modes, such as layer-by-layer, clustering, layer-plus island comes up (Fig. 1). The production of the structures are happened by epitaxy. Primarily in this category, it is happened by molecular beam epitaxy. The production of two dimensional structure happens in layer-by-layer mode. The one-dimesional laying in the surface in this mode as well. The structure, perpedicular to the surface, in metal-induced mode. The zero dimensional in one hand with strain induced technique in layer-plus-island mode, in the other hand with droplet epitaxy in clustering mode.

The last, sixth topic is the application of low-dimensional structures. Here different semiconductor devices comes up, which efficiencies or oher properties become better drastically with the application of nano structures. The efficiency improvement of the solar cells is also comes up. Related to this, the multi-quantum well solar cell and the intermediate band quantum dot solar cells (Fig. 2.). Further class of solar cells also mentioned. In the viewpoint of parameter improvement lasers are mentioned. In the viewpoint of new application possibilities while the quantum computing and the realization of the qubit comes up.

## III. Content of the seminars

The acquisition of "Low-dimensional Selfassembling System" titled subject is helped by seminars. During the semester exercises are solved related to some topics. Here, the topics are categorized also to six groups.

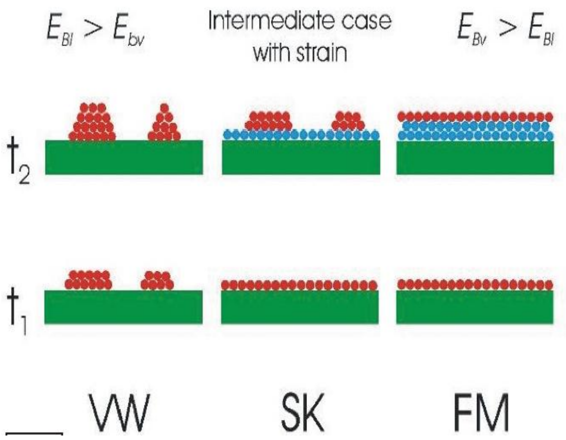


Fig. 1. Scematic illustration of the three growth modes.

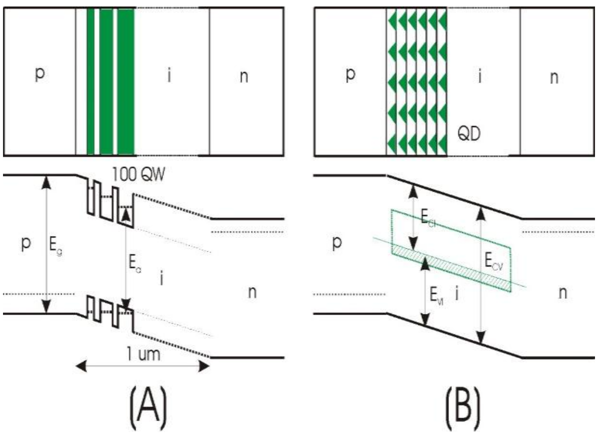


Fig. 2. Enhancement of solar cell efficiency with the help of two-dimensional and zero-dimensional structures. (A): Solar cells with super lattices are the so called multi-quantum well solar cells. (B): Solar cells with quantum dots are the so called intermediate-band solar cells.

The first topic is related to energy level calculations. In the nanostructures the energy determination of the electrons is carried out by quantum mechanics. The topic is the introduction of the generalized mechanics therefore, that the students are able to understand and use the Heisenberg - Schrödinger formalism, the topics are built on the classical mechanics knowledge of the students. Therefore the first topic is the generalization of the classical Newtonian motion laws, the Lagrange and the Hamilton formalism are taught.

The Lagrange formalism starts from, that in the classical Newtonian mechanics i mass-point has 3i (x, y, z) coordinate triplets, with which the motion equantions can be write down. Furthermore simplification is the consideration of the constraints ($f = 3i - k$ ), but the vividness is reduced. So the motions described by f equations, with the using of the so called generalized coordinates. These generalized coordinates can be for example Descartes coordinates, angles etc. The first time derivative of the $(q_1, q_2, \dots, q_f)$ generalized coordinates are the generalized velocities $(\dot{q_1}, \dot{q_2}, \dots, \dot{q_f})$.

Using of these variables, the Lagrange equations of the second kind can be described by the following formula:

$$\frac{d}{dt}\frac{\partial L(q,\dot{q},t)}{\partial \dot{q}_i} - \frac{\partial L(q,\dot{q},t)}{\partial q_i} = 0,\ i\ \in\ [1,2,\dots,f] \quad (1)$$

In the formula the $L = T - V$, where L is the Lagrange function, T is the kinetic energy, V is the potential energy, t is the time, the q is the generalized coordinate and $\dot{q}$ is the generalized velocity. If the motion laws are expressed by $q_i$ and $p_i$ variables instead of $q_i$and $\dot{q}_i$, then the new form of the motion laws, the Hamilton canonical equations are given.

The formula of the Hamilton function is $H = T + V$, which is nothing else, as the total energy. Similarly to the previous case, T is the kinetic energy, V is the potential energy. The Hamilton function is the Legendre transform of the Lagrange function, which is transformed by velocities. The Hamilton canonical equations can be described by these two quantities.

The second topic is the diffusion, which is one of the driving forces in the structure formation. In the seminar, the solved problems are related to bulk diffusion. There are two possible versions. The one is the diffusion with constant $N_s$ surface concentration. The other is the diffusion with constant Q total dopant quantity. Here the dopant quantity can be given by Gauss distribution. The surface diffusion or migration is not studied. The reason of this, that the phenomena of surface diffusion is handled by complex numerical models, for example with the help of the so called Kinetic Monte-Carlo (KMC) algorithm.

The third topic is the ultra-high vacuum (UHV) systems and the thin film layer growth. Here a practical implementation of an UHV growth system comes up. Numerical examples demonstrate, that the UHV condition is important, because of increase of mean-free path and the reduction of the collision number among the atoms during the thin film growth is important. Here the operation of the vacuum pump comes up as well.

The calculation of the lowest accesible vacuum and the calculation of the recipient suction time and the factors, which are affected to this quantity also comes up. Such for example the presence of real and virtual unfillers. Likewise light is thrown on the importance of the outheating of the vacuum systems during the suction. On the other hand the growth of thin films comes up as well. In the figure (Fig. 3) the growth time of the monolayer is shown in the function of accomodation factor.

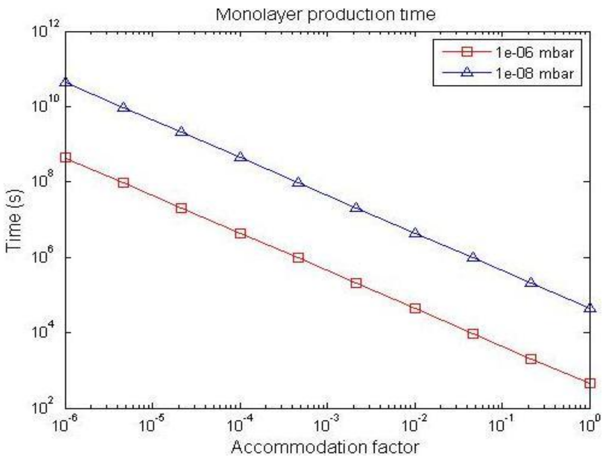


Fig. 3. The growth time of the monolayer, in the function of accomodation factor.

In the fourth topic, the calculation of the electron energy is practised, i.e. the time independent Schrödinger equation is solved. In these exercises different one-dimensional structures (harmonic oscillator, potential gate, potential box etc.) are examined. The problem solving steps are the following: 1) the stationary Schrödinger equation is written down for the different ranges; 2) the wave functions is written down for the different ranges; 3) the boundary conditions are satisfied (the wave function and its first derivative need to be continuous); 4) the portrayal of energy levels (Fig. 4.)

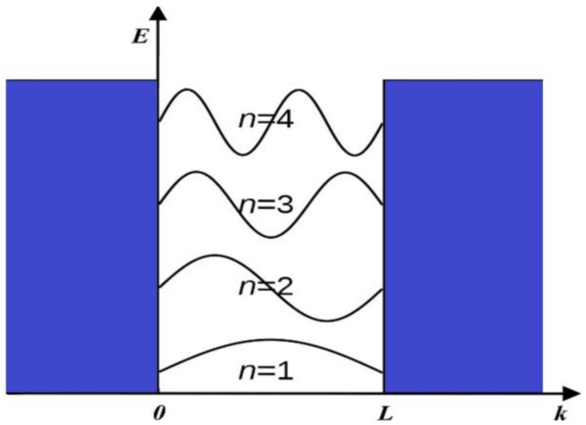


Fig. 4. Energy levels in a potential box.

In the fifth topic Silicon monocrystal growth (with Czochlarski method) and topic of epitaxy are dealt with. The Silicon monocrystal growth (with Czochlarski method) is happened in the following way, eddy currents is formed in the bulk material, induced by high frequency electromagnetic field, which results the bulk material is melt. A small Silicon piece is taken into the melt and slowly is pulled out from the melt. The pulling process is controlled by computer. In the topic of epitaxy the solved problems are related to molecular beam epitaxy. The growth rate determination of the thin films, the effusion rate calculation of the effusion cells and the determination of the composition grade comes up as well.

The sixth topic is the theory and application of single electron transistors. The SET (Single Electron Tunneling) junction contains two conductor and a very thin insulator between them. Because of this the electrons can go through the insulator by tunneling. If the junction is studied in the appropriate range, then an ideal capacitance is shown with slow charge leakage (Fig. 5.).

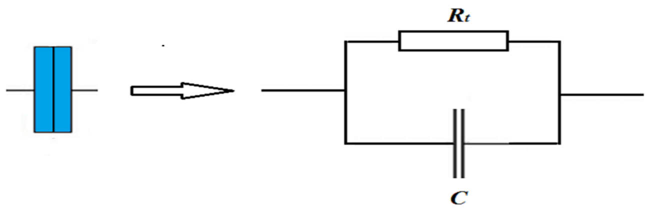


Fig. 5. The SET element and its equivalent circuit.

If two SET elements are taken next to each other, their common point is called island (Fig. 6.). This actually a finite dimensional, several times ten nanometer linear-sized metal.

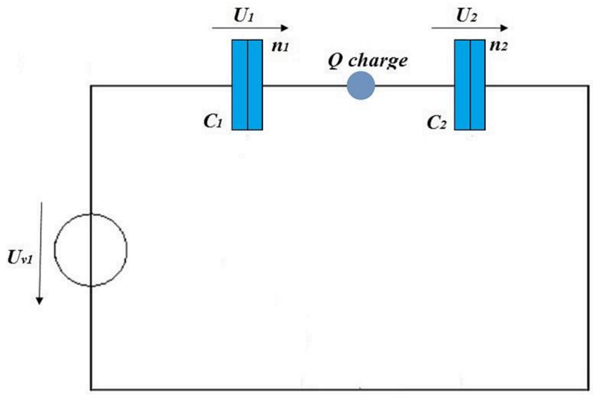


Fig. 6. Two connected SET element.

The charge of $C_1$and $C_2$is: $Q_1 = C_1 * U_1$, $Q_2 = C_2 * U_2$ . The result charge of the island is the difference of $Q_1$and $Q_2$ charges. If there are no tunneling, then this charge difference is zero. If tunneling is occurs, then integer number electron is accumulated in the island so $Q = Q_2 - Q_1 = -n * e$, where nis the number of the electrons in the island, the e is theelectron charge. If the system is started from neutral state (i.e. $n = 0$), then the energy change is represented by the next formula:

$$\Delta W_{1,2}^{\pm} = \frac{e^2}{2C_{er}} \pm \frac{e*U_v*C_{2,1}}{C_{er}} < 0 \qquad (2)$$

where$C_{er}$ is the result charge, the e is the electron charge, $U_v$ is a junction bias. The first element is the Coulomb energy of the island. Electron is get to the island until the absolute value of $\mathrm{U_v}$ not exceed a treshold, which is depend on the smaller capacitance between two capacitances. For example if $\mathrm{C_1} < \mathrm{C_2}$, then the tunneling condition is $|\mathrm{U_1}| > \mathrm{U_{cr}}$, where the value of $\mathrm{U_{cr}}$ critical voltage is $\mathrm{U_{cr}} = \frac{\mathrm{e}}{2\mathrm{C_{er}}}$. If the absolute value of the voltage smaller than the $\mathrm{U_{cr}}$ critical voltage, then the tunneling is forbidden and current is not flow. This phenomena is the so called Coulomb blockade.

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