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Intelligent Sensory Micro-Nanosystems and Networks

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1. Introduction

The presented chapter on the theme of "Intelligent sensory micro-nanosystems and networks" is devoted to scientific research, modeling and designing of sensory systems on a chip of the types of "electronic nose" (e-nose), "electronic tongue" (e-tongue), "electronic eye" (e-eye) to recognize multidimensional information patterns in modern micro-nanosensory technology, electronics, industrial biotechnology, biochemistry, bioinformatics, medicine, ecology, precision agriculture, economy, finances, logistics, computer systems and networks, personal and social safety etc. A human biosystem has an enormous number of different micro-nanobiosensors and micro-nanoactuators which are able sensitively to perceive, to transform and to transmit any patterns changes of external matters or homeostasis, therefore all in the world can be and has to be sensory and motoric. Design of surface acoustic waves (SAW) sensors in wireless micro-nanosensory laboratories on a chip e-nose and e-tongue allows to identify physico-acoustic and electroacoustic properties (viscosity, mass, impedance, dielectric conductivity, electroconductivity and etc.), e.g., of investigated human biomatters (blood, sweat, saliva, urine, tears and etc.) and to form on their basis an information pattern. A micro-nanosensory system e-eye makes it possible to analyse quantitative concentration characteristics, molecular features and acoustooptical properties of information biomatters. At the same time, an intensive development of multicore data processing systems opens up ample possibilities for express analysis and pattern recognition.

Presented developed intelligent micro-nanodiagnostic laboratories find exceptional practical and individual applications and are a new class of self-adjusting sensory and portable mobile devices with flexible learning softwares for reliable continuous control of personal and social safety using Internet intelligent global sensory networks. They don't require special application conditions, highly skilled specialists to form fast and exactly information patterns of any diagnostic object. Using of the intelligent software for processing of registered sensory data enables to get "electronic maps" of objects, their online full information descriptions and to predict efficiently future changes.

This chapter will be useful for students, young scientists, lecturers, businessmen, information theory and telecommunications specialists, neurocomputer, neural, intelligent and sensory networkers. In addition, creative persons interested in understanding, modeling, designing of intelligent sensory systems and in development of smart devices, machines and productions can find a lot of worthy of their attention.

2. Intelligent sensory systems e-nose and e-tongue

2.1 Hardware components of SAW sensory systems

2.1.1 SAW structures

Development of intelligent system engineering is of enormous importance practically in all advanced countries at the present time. The great attention is caused owing to a possibility of intelligent systems to solve tasks of a broad spectrum of applications. It is well known that any product, object, technology can be described as information patterns. The developed biosensor intelligent system ("BIS") presents a new class of intelligent analytical devices and systems including advantages of state-of-the-art micro-nanoelectronics, biochemistry, intelligent computing and up-to-date production of express-diagnostic systems on a chip. One of the most perspective directions of intelligent micro-nanosensory systems on a chip is the application of thin-film nanostructured materials acoustic properties and the design of micro-nanosystems on SAW. Micro-nanosensory systems of e-nose and e-tongue on SAW enable to generate fast a high-resolution information pattern and are distinguished by their sensitivity, rapid responses, low power consumption and nonlinearity. Developed SAW devices can be applied in any external environment and under the influence of different strains over a long period of time. A planar structure of SAW transducers defines a simple embodiment and their including in a batch process, but light weight, high reliability and high-noise protection make possible their embedding in intelligent microprocessor-based recognition systems and remote transferring in communication and computer networks (Barkaline & Polynkova, 2002).

Functioning of any SAW sensor systems is based on the influence of physically and chemically adsorbed molecules on geometrical, electrical and acoustic properties of a SAW sensitive layer (e.g., nanostructure), on changing of elastic properties and mass loading of a piezo-active substrate surface. Labs on a chip of e-tongue and e-nose on SAW are a piezoelectric thin plate (quartz, $LiNbO_3$, $LiTaO_3$, GaAs, $Si/SiO_2/ZnO$, $Si/SiO_2/AlN$) with evaporated metal electrodes for two systems of interdigital transducers (IDTs) and reflecting matrices. As a rule IDTs are used for a SAW excitation as metal electrodes pairs on a functional surface of piesoactive waveguides. Electrodes are linked to an alternating current generator in bandwidth up to 10 GHz. The alternating voltage induces an acoustic wave spreading at a rate of about 3000 mps on surface of a piezo-active substrate. The acoustic wavelength is determined by IDTs electrodes separation. E-tongues and e-noses on SAW structures can function in some modes (resonator, delay lines) or use a differential circuit of two resonators, two delay lines, one delay line and one resonator (Koleshko, 1974, 1976, 1984, 1986, 1988, 1990), which enables to measure two mechanical (physico-acoustic) and two electrical (acoustoelectric) parameters of solid, gaseous, liquid and heterogeneous investigated matters. Figure 1 presents a sensory system of e-tongue and e-nose with two delay lines: the first delay line, e.g, Au metallized measures mechanical parameters (viscosity, mass, impedance), but the second one – capacitivity and electrical conduction of a matter. A sensitive element is placed on delay lines representing the sensitive layer: nanotubes, DNA chains or their combination (Fig. 1d, 1e).

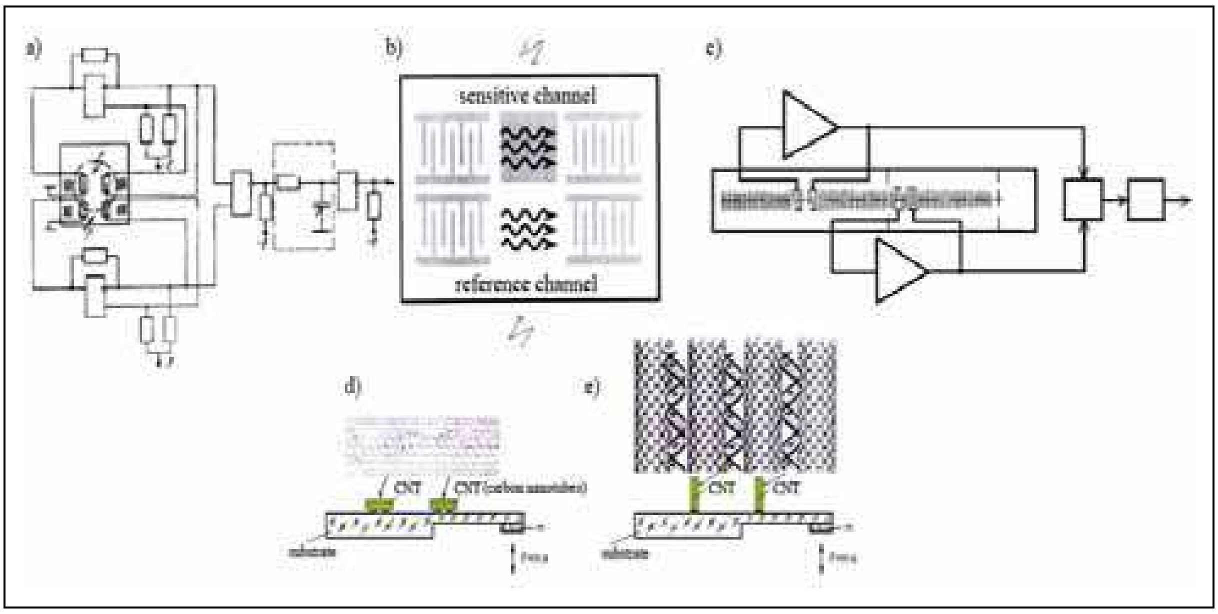

Fig. 1. SAW sensory system. (a, b, c) Sensory system of e-tongue and e-nose on SAW.
(d, e) Placements of carbon nanotubes and double DNA chains on SAW delay lines.

2.1.2 Parameters of SAW micro-nanosensors

A bandwidth of SAW transformer depends on a number of electrodes: increase of an electrodes number reduces the one, but a number of electrodes are to be minimized to decrease a device capacitance. Moreover, a number of electrodes are to be consisted of many pairs to reduce any noise, but a reduction of diffraction loss takes place in case of a wide aperture. Therefore, SAW devices are developed in which properties of input and output transducers are optimally adjusted in. Critical parameters of SAW sensors depending on materials of acoustic lines are given in the table 1.

A special circuit board contained an investigated matter is developed to control the delivery of matters, which measures 32 by 20 mm with an allocated reservoir in size 6,8 by 2,5 by 8 mm and in volume of 136 µl. A sample is placed in the centre exactly between IDTs (Fig. 2a). A new class of wireless microlabs on a chip with radio frequency identification is designed (Fig. 2b) (Polynkova, 2007).

Material of acoustic line	$LiTaO_3$	SiO_2	GaAs	$LiNbO_3$
electrodes width of IDTs, µm	17	3	2	2
velocity of SAW, mps	4212,6	3159	2604	3488
frequency synchronism, MHz	55-65	263,03	325,5	436
pairs number of IDTs electrodes	28	19	67	4
IDTs aperture, µm	30	46	4	221
SAW length, µm	7513	12	8	8

Table 1. Parameters of SAW micro-nanosensors for e-tongue and e-nose.

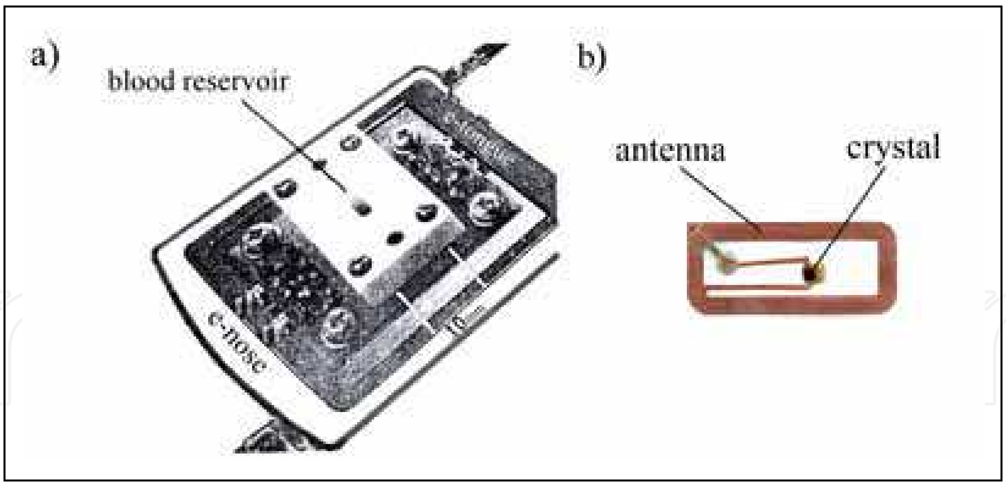

Fig. 2. Wireless multisensory system on SAW (a) with radio frequency identification (b).

Such smart labs on a chip are not expensive, don't require special operating conditions and first line maintenance men, make it possible to get biochemical information patterns, e.g., of ecological production status, technological processes, human health and to take samples promptly and on-site avoiding any delays and inaccuracies caused by data transfer in centralized expensive research labs (Fig. 3) (Gulay & Polynkova, 2010).

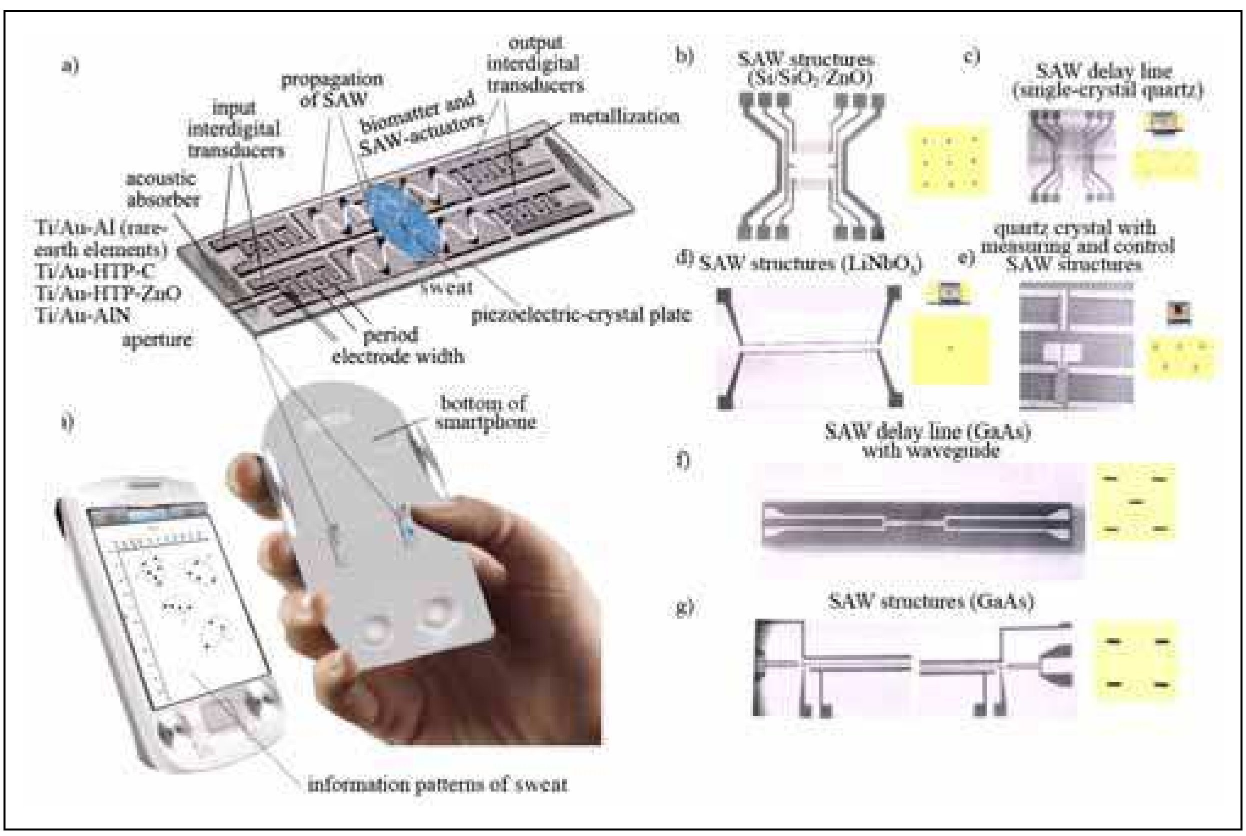

Fig. 3. Developed intelligent sensory system in smartphone. (a) Structure of SAW sensor on a chip e-tongue and e-nose. (b, c, d, e, f, g) Developed SAW structures. (i) Smartphone with sensors on SAWs and intelligent software for recognition of sweat information patterns.

2.2 Materials of intelligent sensory micro-nanosystems on SAW

2.2.1 Strain effects in SAW structures

One of the ways for developing of intelligent sensory micro-nanosystems and networks is using of new materials. This is an important factor for high-sensitivity physical quantities transducers which sensitivity values at extreme points are determined by constants of a used material. Elasticity modules of the 2nd and 3rd orders inhere in mechanical quantities transducers (pressure, acceleration, force, angular frequency etc.) on SAW. A limited influence on sensitivity of SAW transducers and substantial dependence on parameters and on a waveguide crystallographic orientation (crystal plane, SAW propagation direction) determines a profound study of SAW propagation properties depending on deformations ("strain effect") on the basis of different materials. The strain effect implies a variation in SAW propagation characteristics in a strained waveguide. Using of the strain effect in multilayer SAW structures plays a significant role in analysis and development of SAW devices. This effect also determines operating principles of precision micro-electronic mechanical transducers based on SAW structures (Koleshko, 1985, 1987).

One of the most important SAW structure parameters is a phase shift ψ_0 as SAW with a phase velocity V and a frequency f propagating between two points of the laminated structure located at a distance L from each other. Any deformation of this thin film SAW structure because of mechanical loading leads to change in a SAW phase shift due to a SAW phase velocity change dV and a concurrent length change dL. For a given method of substrate loading $d\psi/\psi_0$ can be found by determining dV/V and calculating dL/L and by means of known methods from the elasticity theory.

Analysis is carried out for a laminated structure (Fig. 4) (Koleshko, 1981, 1983, 1990) based on a semiinfinite crystal non-conducting substrate characterized by density, permittivity and the 2nd and 3rd order elastic moduli of a single-crystal silicon. SiO_2 layer is simulated by isotropic dielectric with parameters similar to those of a fused silica, but ZnO or AlN layer by 6 mm piezoelectric moduli and the 2nd order elastic moduli similar to those of ZnO or AlN single-crystal. The 3rd order elastic moduli of ZnO (AlN) are ignored because of weak bonds between crystallites in a thin polycrystalline film.

The effect of longitudinal and lateral mechanical strains on a SAW phase velocity in ZnO or AlN/ SiO_2/ Si thin film structures for {001}, {111} and {110} silicon crystal planes within the temperature range 293-673 K is studied. The obtained results enable a determination of SAW structure parameters with predetermined maximum sensitivity to a longitudinal and lateral homogeneous tension (compression) and bending as well as parameters of stable SAW structures are insensitive to mechanical loading. The Si {110}-based SAW structure with the SAW wave vector oriented in $<\bar{1}10>$ direction is shown to possess maximum operating frequency sensitivity to both longitudinal and lateral strains (Meshkov & Barkaline, 1990). ZnO or SiO_2 layer deposition on silicon increases the SAW phase velocity sensitivity to the longitudinal strain and decreases the one to the lateral strain. SAWs in waveguides from quartz single-crystal of YZ, XZ, XY orientations have equal peak responses to mass loading of a surface, but XY orientation is the least SAW responsive in the waveguide from sapphire. Using of a copper metallization appears to be more perspective as contrasted to other materials. Results of more than 60 isotropic cubic materials with different functional properties (metals, dielectrics, semiconductors, piezoelectric, magnetostrictive stuffs and superconductors) are presented in (Barkaline & Polynkova, 2002).

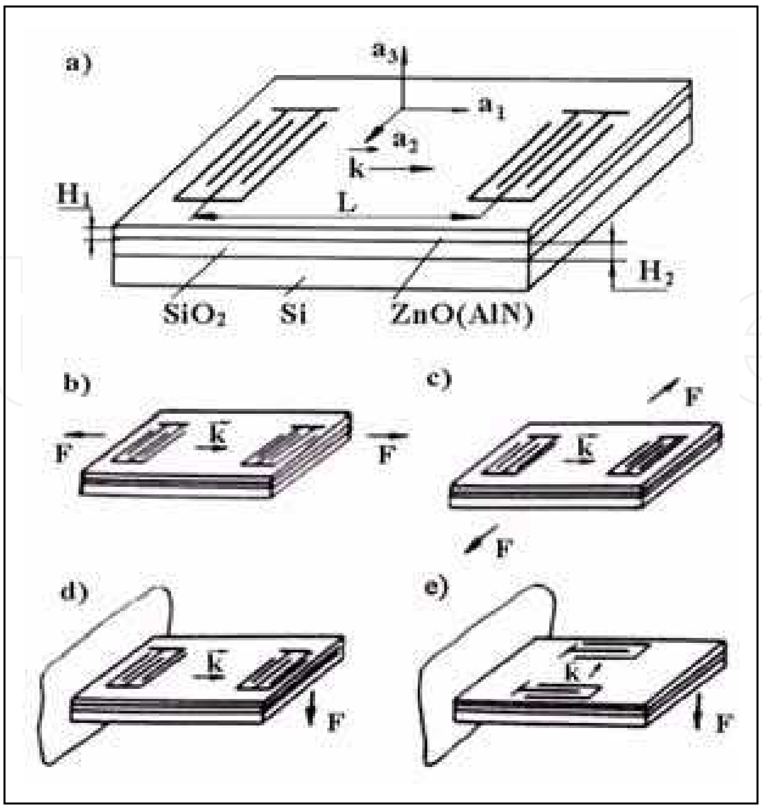

Fig. 4. Different mechanical loadings of SAW. (a) Multilayer thin film SAW structure. (b) Mechanical loading of SAW structure substrate.

2.2.2 Single-crystal silicon-based multilayer SAW structures

The strain effect is determined in cubic single-crystal SAW waveguides because of these materials have a broad variety of functional properties including semiconducting, piezoelectrical, magnetostricting and superconducting ones, the most examined constants are the simplest for analysis. Semiconducting materials (Si, GaAs and InSb) are of a particular interest in terms of developing SAW-based integrated devices with built-in information processing including sensing, executive and processor units. Piezoelectronic properties of $A^{III}B^{V}$ crystals make it possible to avoid a deposition of piezoelectric layers which are necessary for IDTs to induce SAW required by Si waveguides. Iron ittrium granatum ($Y_3Fe_5O_{15}$) or IIG has a low elastic anisotropy. High strong magnetostriction of $Y_3Fe_5O_{15}$ allows its using in devices which are based on interactions between SAWs and magnetostatic waves (spin waves).

A new approach for sensitivity coefficients definition of a SAW phase velocity to quasistatic volumetric effects on waveguide is developed on the basis of an algebraic properties research of the SAW phase velocity as a function of effective material constants. It is founded on introducing of a tensor W of SAW phase velocity partial derivatives in a crystallophysical coordinate system. Values of W component are determined by the material anisotropy factor $\eta=2 \cdot C_{55}/(C_{11}-C_{12})$ and the parameter $a=C_{11}/C_{55}$. Orientation relations of the phase velocity and factors of the deformation sensitivity at longitudinal and lateral deformations for base planes of Si, InSb, GaAs, IIG, $SrTiO_3$ are investigated. These crystals can be arranged on SAW phase velocity values as $V_{InSb} < V_{GaAs} < V_{IIG} < V_{SiTiO_3} < V_{Si}$ for all investigated SAW directions. Figure 5 depicts an investigated materials distribution in the plane (a,η), but the solid line describes the limiting value a=2/η. The considered materials concentrate evidently in the range $2<a \cdot \eta<7$, therefore to predict characteristics of SAW devices on the basis of new materials it is important previously to know a value of partial sensitivity coefficients to different exposures. Superconducting ceramics $YBa_2Cu_3O_{7-x}$ has a record high level of deformation sensitivity because of acoustic nonlinearity large values of this material (~100).

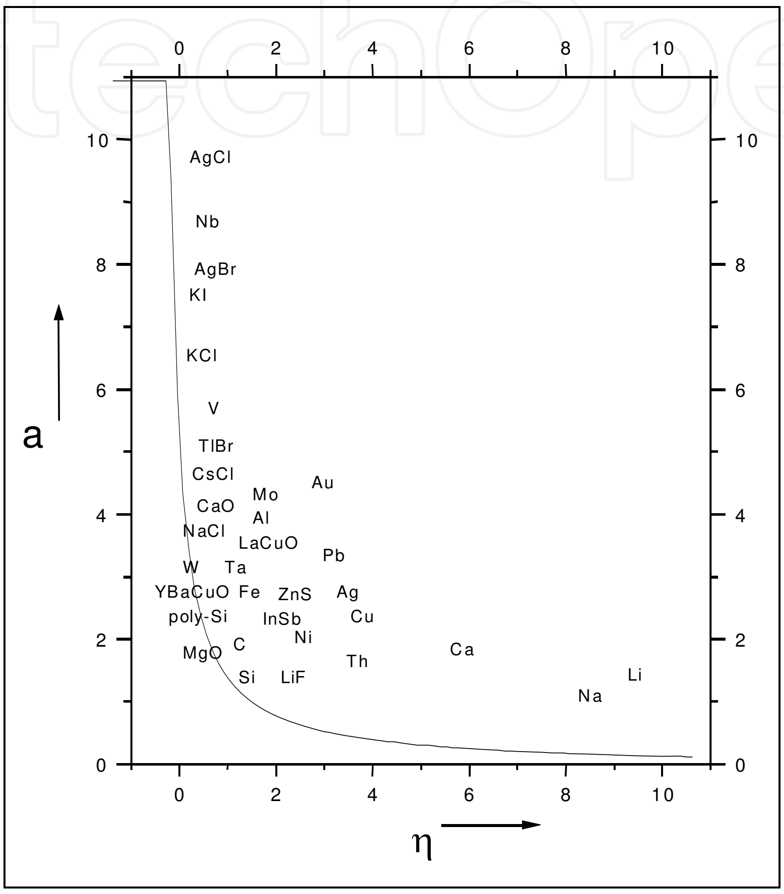

Fig. 5. Materials in plane of anisotropy factor η and calculated parameter a.

Results of a theoretical study into an orientation dependence of the SAW strain sensitivity on longitudinal and lateral deformations of Si, GaAs, InSb, $Y_3Fe_5O_{15}$ (YIG), $SrTiO_3$ waveguides for {100}, {110}, {111} cuts are presented in (Barkaline & Polynkova, 2002) (Fig. 8). The wave vector direction of SAWs is characterized by an angle Θ calculated from directions <100>, $<\bar{1}10>$ and $<11\bar{2}>$. A value d is determined under longitudinal and lateral deformations of the cantilever, which is loaded at the free end by the force F (Fig. 4d, 4e) (Meshkov & Barkaline, 1990). The calculated orientation dependences of d are shown in figure 6 for {001}, {110} and {111} under longitudinal (d_{11}) and lateral ($d_{\perp}$) waveguide deformations, respectively (Koleshko, 1986, 1987, 1988, 1989, 1990).
The strain effect orientation dependencies in $SrTiO_3$ differ from each other and from corresponding dependencies for Si, GaAs and InSb which are similar. However, the strain effect is practically isotropic for the both types of materials in plane {111}. The strain effect is displayed weakly in YIG thereby indicating that it is promising for constructing stable SAW devices. At the same time, the strain effect value in $SrTiO_3$ exceeds considerably all data

presented in literature on single-crystal materials indicating that it is promising as a material for highly sensitive SAW transducers of mechanical quantities and especially when superconducting metallization is used in IDTs electrodes. In addition the strain effect in semiconductors InSb and GaAs is weaker than in Si, therefore these materials are promising for single-crystal SAW transducers of mechanical quantities (Meshkov & Barkaline, 1990).

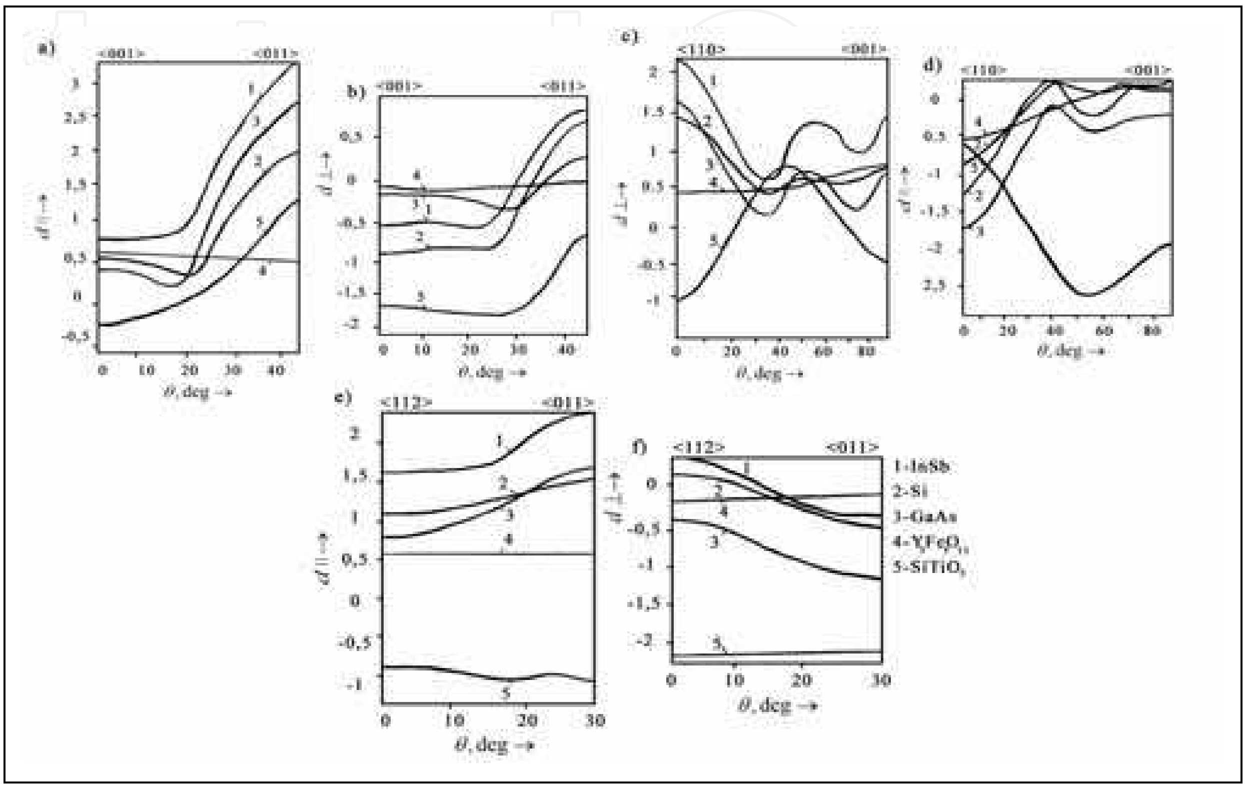

Fig. 6. Orientation dependence under longitudinal (d_{11}) and lateral ($d_{\perp}$) deformations: (a, b) $d_{\parallel}$ and $d_{\perp}$ for plane {001}, (c, d) $d_{\parallel}$ and $d_{\perp}$ for plane {110}, (e, f) $d_{\parallel}$ and $d_{\perp}$ for plane {111}.

2.2.3 High-temperature superconductors thin films-based SAW structures

SAW properties in micro-nanoelectronic structures with components based on new high-temperature superconductors (HTSC), e.g., $YBa_2Cu_3O_{7-X}$ are of interest from the point of view of a potential application of these materials in various acoustoelectronic devices as a superconducting metallization for possible reduction of a noise level in them or as a substrate. The strain effect in such SAW structures is described in the work (Koleshko, 1989). In (Meshkov & Barkaline, 1990) a non-dissipative SAW propagation is considered, for which a nonelastic contribution to the SAW phase velocity is small enough with respect to the elastic one. It means the validity of the relation $w \cdot \tau << 1$ where w is SAW angular frequency and t - relaxation time of propagation medium. For $YBa_2Cu_3O_{7-X}$ ceramic samples at a room temperature when it has semiconductor-like properties evaluations of t give $3 \cdot 10^{-10}$ sec. The data on the 3rd order elastic moduli for all materials forming a SAW propagation medium is necessary for theoretical analysis of SAW sensitivity to strains. This data for $YBa_2Cu_3O_{7-X}$ material is not presented in literature yet. To evaluate appropriate data on the 2nd order elastic moduli C_{IJ} of the ceramic $YBa_2Cu_3O_{7-X}$ pressure dependence is used. High values of dC_{IJ}/dP (P denotes pressure) are the $YBa_2Cu_3O_{7-X}$ intrinsic property not caused by ceramic nature of samples and connected with valence fluctuations of copper ions which are characteristics of copper HTSC (Meshkov & Barkaline, 1990).

2.2.4 Diamond-like carbon films-based SAW structures

Diamond-like films that reveal unique practically useful properties find a wide application nowadays in micro-nanosensory technologies due to a carbon atoms capacity to form strong chemical bonds of different character. Properties of carbon films can differ greatly from diamond and graphite varying while there is a small difference between chemical potentials of carbon phases and a high probability of transitions. In (Barkaline & Polynkova, 2002) a problem of controlled magnetron deposition of a-C:H films on various substrates in order to produce an "intelligent" carbon material for acoustoelectronic applications is studied and solved. Dispersion curves for a SAW phase velocity in a-C\ZnO\SiO_2\Si SAW-structures with different layers thicknesses for a SAW fundamental mode and ten highest modes show a possibility to realize multimode SAW propagation in such structures.

One of the most promising application areas of a-C:H films it seems to be SAW-based chemical sensors. Dominating diamond-like phase is characterized by high SAW phase velocity V and small waveguide factor F values (upper curves on fig. 7), but in case of dominating graphite-like phase this relation is inverse (lower curves). It means that SAW energy concentrates in the waveguide internal region leading to increasing of the SAW device chemical stability.

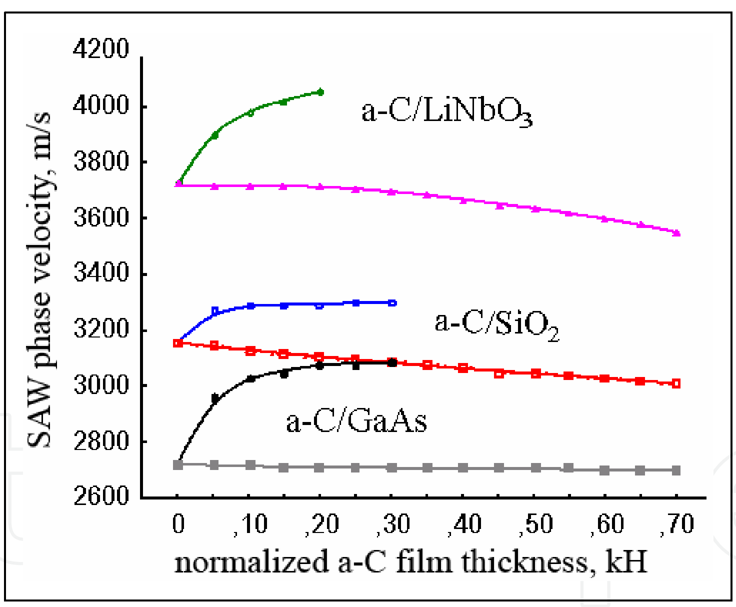

Fig. 7. Dispersion curves for SAW structures with a-C layer.

2.2.5 Dispersion relations of SAW in $LiNbO_3$/a:C structures

One of the most perspective material of a SAW substrate is a single-crystal $LiNbO_3$ with a high electromechanical coefficient and used in different passive and active acoustoelectronic devices from filters up to nonlinear circuits of memory and SAW sensors. The single crystal of $LiNbO_3$ is one of the most studied acoustic crystals, for which all material constants of the 2nd and 3rd orders are known. At the same time, the SAW deformation sensitivity in this crystal and a range of a SAW characteristics control by introducing of different functional

layers in $LiNbO_3$ acoustic line are obscure. These problems can be clarified by means of a nanostructured carbon material layer containing, in particular, an ordered set of carbon nanotubes. The material parameters of the carbon material layer are determined by effective elastic medium method. The composite layer with a cylindrical form carbon nanotube in diameter 10 nm is estimated, but a composite matrix is modelled by material with parameters of amorphous carbon.
The relation of the SAW phase velocity from the carbonic layer thickness has non-linear nature. In Z-directions on X- and Y- cuts, on X- and Z-cuts a sharp reduction of the SAW velocity is evident at increasing of the carbonic layer depth. It allows to suspect sharp responses to exposures. The introducing of nanotubes in the material layer enables to execute SAW phase velocity controlling in a broad band. Thus, conducted researches show prospects of using of a nanostructured carbon material for new acoustoelectronic devices on the basis of $LiNbO_3$ (Koleshko, 1981, 1983, 1987).

2.3 Sensing elements of intelligent systems on SAW
2.3.1 Sensitivity of SAW transformers
Each piezoelectric crystal is defined by resonance oscillation frequency about 10 MHz which depends on its environment, mass and absorbed materials on a substrate. Absorption of a matter causes a change of its resonance frequency (Δf) which can be measured with the exceptional high sensitivity (500-2500 Hz/µg) and is based on sensors characterized by detection limit about some picogram. The mass change of a sensitive layer because of substance adsorption can be estimated by SAW velocity and resonance frequency:

$$\Delta f/f_0=k\cdot\Delta v/v_0=-k\cdot c_m\cdot f_0\cdot m\cdot n, \quad (1)$$

where k – SAW track length between IDTs on a piezocrystal, c_m – device mass sensitivity ($\sim 1{,}3\cdot10^{-6} g/cm^2$), n – adsorbed molecules concentration, m – adsorbed molecules mass.
In this connection, chemical sensors are the important factor of wireless monitoring and security systems which use sensible elements possessing specific reactions to environment (Meshkov & Barkaline, 1990). Carbonaceous nanotubes are structures consisting of a convoluted hexagonal lattice with carbon atoms in site. This carbon form finds a wide application along with graphite and fullerene (Deinak et al., 2009).
Sorbate molecules and radicals make possible a creation of highly sensitive devices for controlling of dangerous and hazardous substances in environment (H_2, O_2, CO etc.). Data of the SAW transformers sensitivity to NO_2, NH_3, CO_2, CO, H_2O, CH_4 with a phtalocyanme sensitive layer in 0,32 µm thickness and in 236,25 MHz SAW operating frequency is shown in the table 2. Positive values of frequency variations in relation to a light gas concentration (NH_3, CO, H_2O, CH_4) can be explained by current desorption of oxygen.

2.3.2 Molecular sieves, nanotubes and nanowhiskers
Molecular sieves can be used for different applications as adsorbents for dehumidification and cleaning of gas streams, for separation of gas mixtures depending on a molecules size. So nanotubes and nanowhiskers can be considered as sensitivity elements of SAW intelligent micro-nanosystems (Table 3). Therefore, achievements in the field of micro-nanotechnologies enable to develop “labs on a chip” for detection and analysis of different matters using multidimensional sensors.

Substrate material	Orientation	Gas concentration ΔC, one millionth					
		100	200	3500	1200	8000	400
		gases					
		NO_2	NH_3	CO_2	CO	H_2O	CH_4
quartz	ST,X	-4,900	0,800	-0,01	0,03	0,02	0,200
	Z,X	-2,97	0,49	-0,006	0,018	0,012	0,12
	Y,Z	-8,15	1,33	-0,017	0,05	0,033	0,33
sapphire	Z,X	-1,65	0,27	-0,003	0,01	0,007	0,07
	X,Z	-1,981	0,323	-0,004	0,012	0,008	0,081
	Y,Z	-1,986	0,324	-0,004	0,012	0,008	0,081
lithium niobate	Z,X	-3,235	0,528	-0,007	0,020	0,013	0,132
	Y,X	-3,467	0,566	-0,007	0,021	0,014	0,142
	X,Y	-3,213	0,525	-0,007	0,020	0,013	0,131
silicon	X,Z	-6,048	0,988	-0,012	0,037	0,025	0,247
germanium	X,Z	-4,599	0,751	-0,009	0,028	0,019	0,188
zinc oxide	Y,Z	-2,022	0,330	-0,004	0,012	0,008	0,083
	Z,X	-2,567	0,419	-0,005	0,016	0,010	0,105

Table 2. SAW transformer sensitivity of gas concentration in air $\Delta f/\Delta C$.

Nanomaterial	Original compound	Crystallization temperature, °C	Nanotubes strength σ_m kg-force/mm^2	Nanotubes length, µm
Cu	CuI, H_2	590–800	360	1–60
	CuCl, H_2	430–800	450	1–10
	CuBr, H_2	600	360	1–10
Ag	AgCl, H_2	460–925	176	1–10
Pt	$PtCl_x$, H_2	800	430	1–10
Pd	$PdCl_2$, Ar	860–1000	270	1–6
Co	$CoBr_2$, H_2	690–730	330	1–18
	$CoCl_2$, H_2	600	330	1–15
C	C_2H_2, CH_4, Ar	600–800	2450	0,1–5

Table. 3. Basic materials for creation of nanotubes and nanowhiskers.

Nanotubes bundle have better absorption of gases than graphite because of the potential well maximum value on graphite equals -2.89 kcal/mole, but on nanotubes bundle -5.18 kcal/mole in consideration of an oxygen interaction on bundle nanotubes and graphite (Fig. 8).

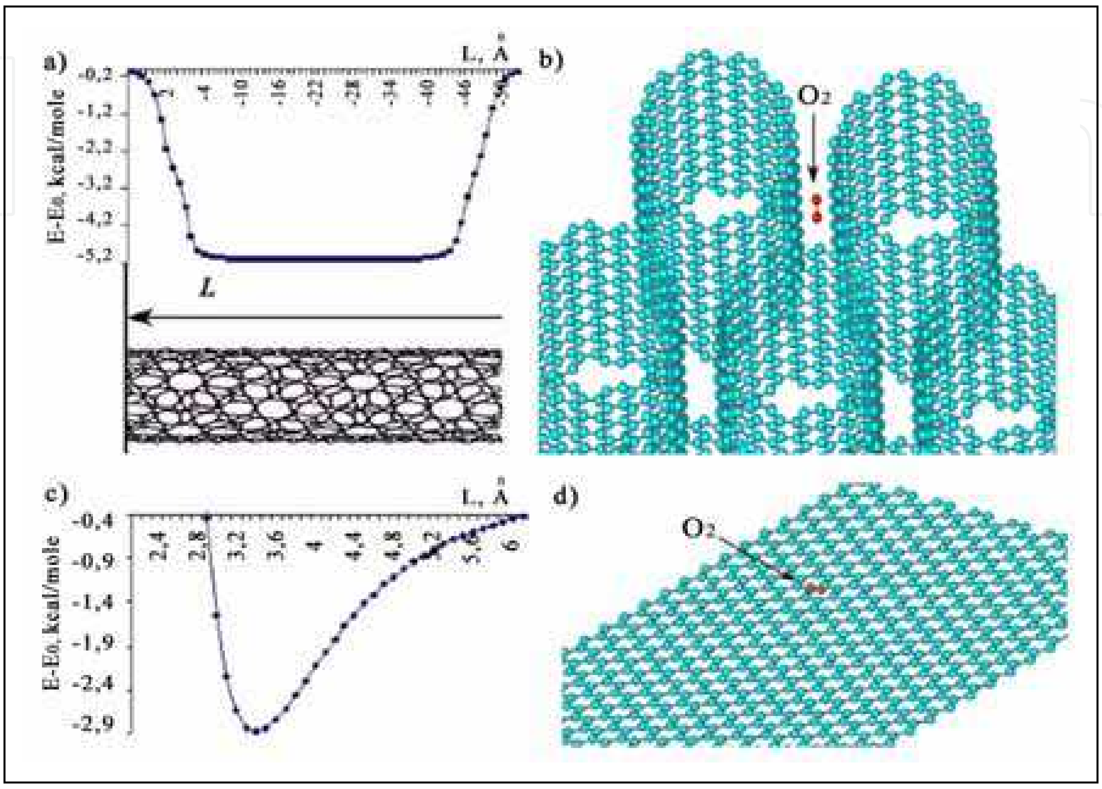

Fig. 8. Adsorption of sensitive sensor: oxygen absorption on nanotubes bundle (a, b) and on graphite film (c, d).

Modeling results of the sorption interaction of single-shell nanotubes with H_2, NO_2 and CO show the substance dependence on its binding energy. A potential well depth difference for H_2 and nanotubes bundle ($D \approx 1{,}36$nm) equals approximately -0,73 kcal/mole, $NO_2 \approx -2{,}77$ kcal/mole, CO ≈ –1,81 kcal/mole (Fig. 9) (Deinak et al., 2009).

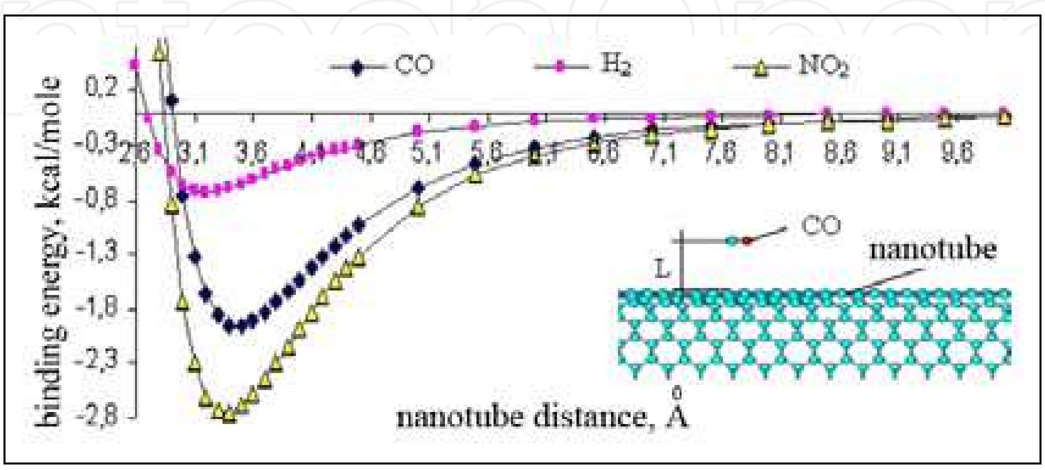

Fig. 9. Binding energy in case of adsorption in nanotubes bundle 10×10 for different gases.

The investigation results of the dangerous substance interaction with a nanotube bundle (Fig. 10) indicate that nanotubes have higher sensitivity regarding explosive materials (minimal interaction energy of a molecule ≈ 17,8 kcal/mole) and concerning RDX, TNT and NG (Barkaline & Polynkova, 2002).

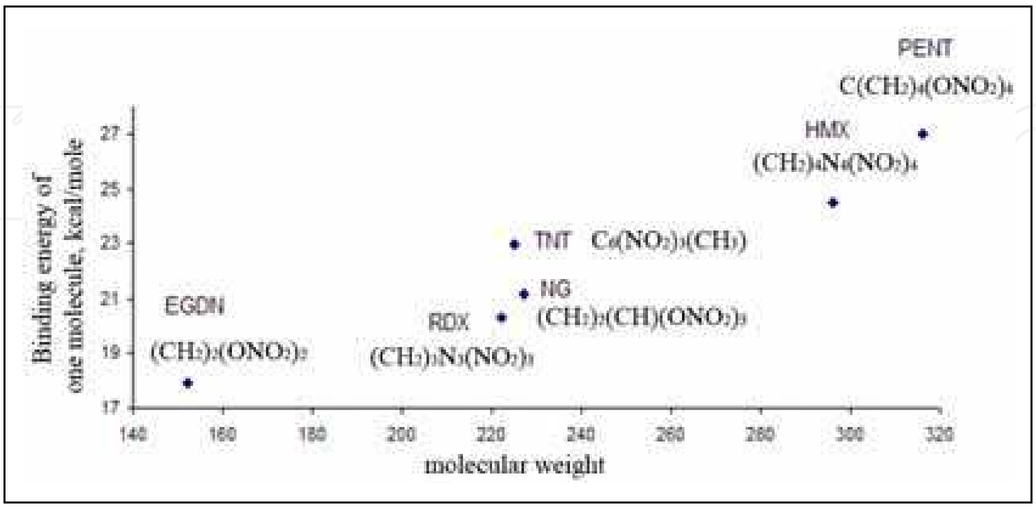

Fig. 10. Binding energy of dangerous substances.

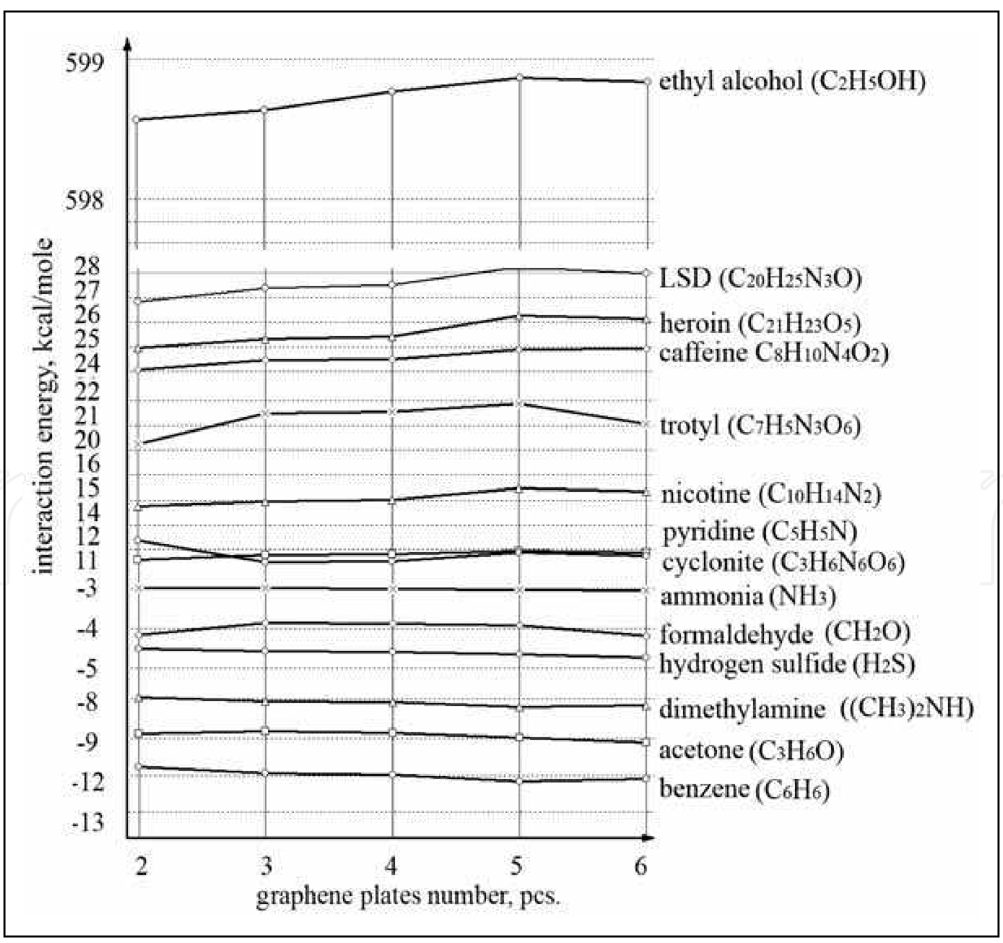

Fig. 11. Interaction energy on graphene plates for dangerous substances.

2.3.3 Multicomponent graphene structures

HypecChem can be used to analyze the absorption of biological hazardous molecules on graphene by effective potential MM^+ with a single point calculation and a geometry optimization. The developed sensors on the basis of values of adsorption potential wells can be located in airports, railway stations, public transports, different institutions to ensure personal and social safety and to recognize promptly terrorists, drug addicts, alcoholic, smokers. Figure 11 presents results of interaction energy for different dangerous substances in concordance with graphene plates number which can be used for optimization of micro-nanosensory devices on SAW with a sensing element – graphene. Number of graphene plates defines adsorptivity of a specified substance and makes possible to calculate an optical structure of sensing elements because of great in magnitude values of adsorption potential wells. It means that the use of graphene structures opens new possibilities for fast detection of dangerous substances and explosives in information and communication sensory systems and networks.

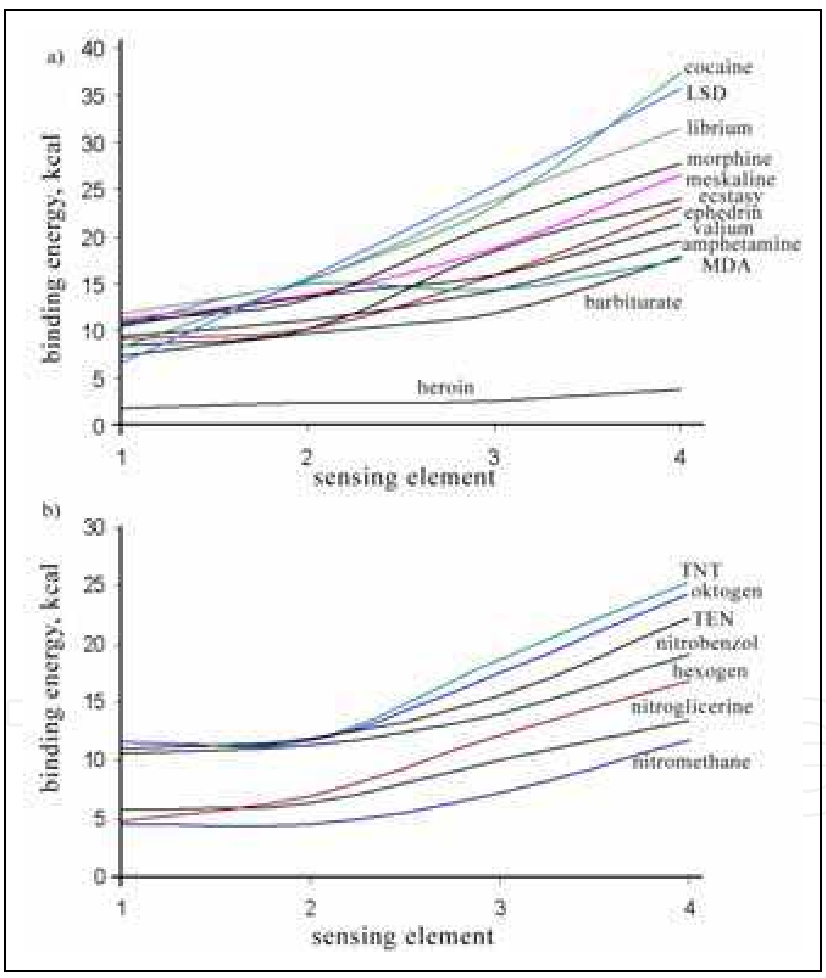

Fig. 12. Binding energy at absorption of narcotic, psychotropic matters (a) and explosives (b). Sensing element: 1 - nanotube; 2 - DNA; 3 - nanotube/6 DNA; 4 - DNA/6 nanotubes.

2.3.4 DNA sensing elements of SAW devices

E-noses and e-tongues on SAW use sensing elements in the form of nanotubes, DNA chains or their combinations. The software suite HyperChem is applied to calculate an effective potential MM+ as the most suitable for analyse of the organic molecular interaction with SAW sensing elements on the basis of atoms potential fields. Single points allow to estimate such molecular properties as a gradient of energy and a spin density which give information if the system is close to a minimum energy (Fig. 12). The system adsorption is defined by binding energy:

$$E_{BE} = E_{SE} + E_{MOL} - E_{SYS}, \quad (2)$$

where E_{SE}- total energy of a sensing element, E_{MOL}- molecule total energy of a narcotic matter and an explosive, E_{SYS}-system energy of "matter-sensing element". Thus, double DNA chains and nanotubes have practically identical absorption properties, but the optimal structure of sensing elements consists of one DNA chain and six nanotubes located in the form of the hexagonal ring round this DNA chain (Deinak et al., 2009).
A new class of unique ultraspeed genom sequenators is developed which can find applications in biological engineering, industrial micro-nanobiotechnology, biomedical technology, bioinformatics, bioengineering, information and telecommunication technologies and etc. The sensing element in the form of inorganic nanotubes (C, BeO, Si_xC_{1-x}, ZnO, BN, AlN) with nanopores is placed on the Au, Ag, Al (rare-earth metals) metallized sensitive channel. The nanotubes diameter and the nanotubes spacing are optimized for exacter control of a single DNA molecule inside of the nanotube (Fig. 13) (N.V. Khmurovich, 2010).

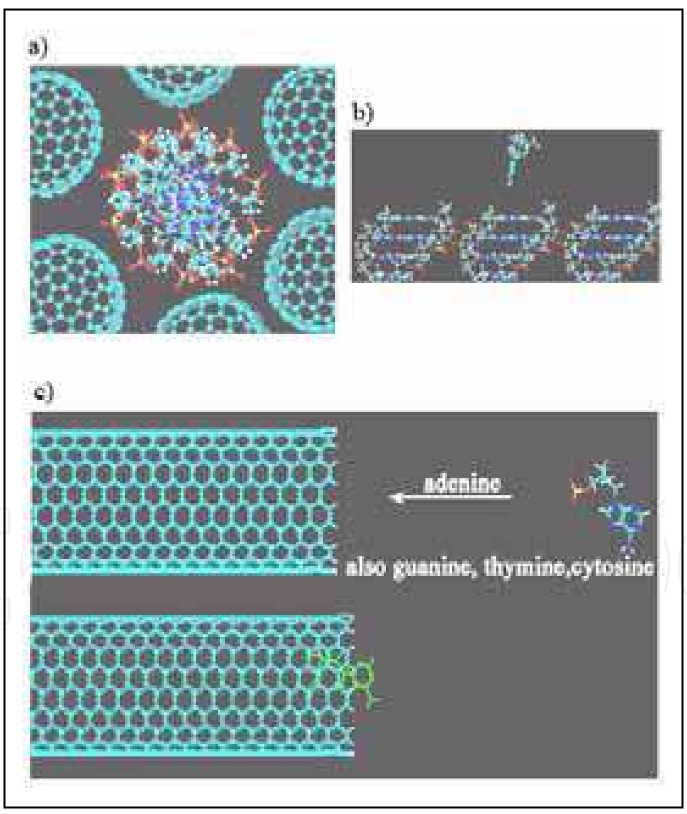

Fig. 13. Absorption of carbon nanotube DNA bases. (a) Position of DNA chain and 6 nanotubes. (b) LSD molecule over DNA chains (side view).

The SAW structure with sensing elements in the form of the nanotubes is able to pull DNA molecules through the holes of the nanotubes and between the nanotubes using acoustic wave and (or) electric field and to recognize nucleotide DNA sequences, genes, chromosomes and genome. The developed intelligent ultraspeed sensory nanosystem of genom sequencing can identify rapidly and correctly information patterns of any genotypes, detect of damaged DNA fragments and genetic changes. DNA molecules of blood, saliva, sweat, urine, tears and other investigated human biomatters can be pulled even through small nanopores of the nanotubes varying the power of acoustic wave. Analysis shows different absorption velocities of DNA nuclefotides in a nanotube depending on their molecular weights (Fig. 14). It means 60 people can be sequenced in one minute or 600 people in about 10 minutes (N.V. Khmurovich, 2010).

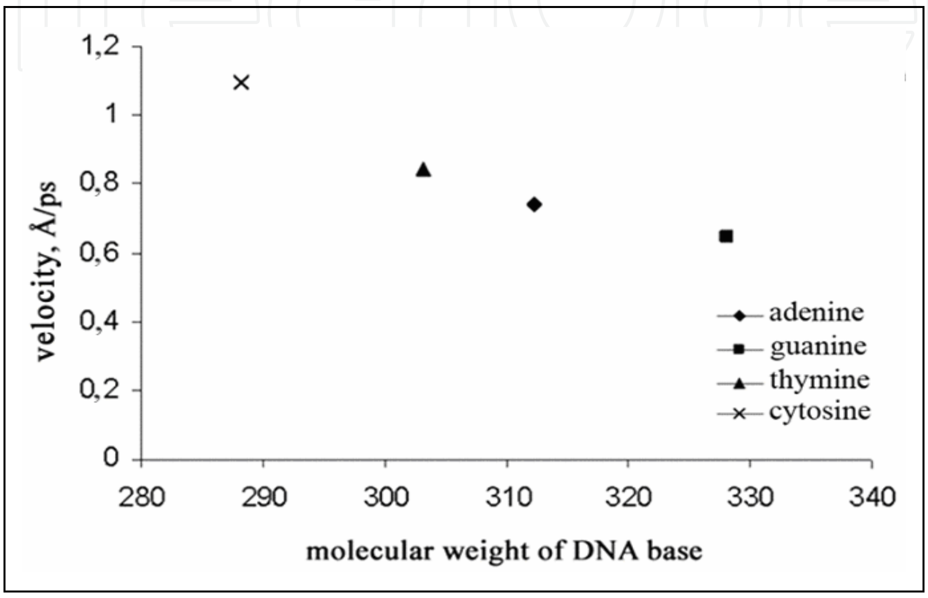

Fig. 14. Velocity changes in carbon nanotube versus molecular weight of basic DNA.

2.3.5 Biomatters sensing elements of SAW devices

The developed intelligent microlab on a chip e-tongue, e-nose is intended for rapid analysis of human individual biological components, e.g., biochemical samples of blood, saliva, urine, sweat etc. At the same time, an express-diagnosis of human blood is considered as important because values of common and biochemical blood analyses correlate not only essentially to a latent pathology of human body, but are associated closely with bioinformation patterns processing by influence on neurons. In this connection, human blood is a very sensing matter, but its information and acoustical properties are close to water (Tables 4) (N.V. Khmurovich, 2010).

Wave frequency, MHz	Attenuation coefficient, dB/cm			
	10% haemoglobin solution (t=20^0 C)	blood plasma	human blood	water
0,6	0,05	0,02	0,10	0,001
1	0,09	0,06	0,21	0,0024
10	1,14	1,55	3,13	0,21
40	9,12	10,21	9,75	3,25
100	36,22	38,54	27,63	18,29

Table 4. Changes of attenuation coefficient for different reference matters of blood.

By the way, increase in wave frequency causes marked differences of acoustic speed in a human blood and its separate biochemical components. It confirms an importance of a blood information picture for analysis of latent pathologies (Table 5). The temperature rise result an abrupt increase of acoustic speed in blood exactly as in distilled water (Table 6). Thereby, blood as well as another biomatters (saliva, lymph, sweat etc.) can reflect little changes in the functioning of human body and influence on neuroinformation metabolism in brain eventually denoting the onset of diseases (Azizov & Khudnitsky, 2009).

Wave frequency, MHz,	Acoustic speed, m/s	
	10% haemoglobin solution	human blood
0,3	1558,4	1528
1	1561,3	1529,1
5	1565,6	1530,2
8	1567,5	1531,1
9	1567,8	1531,3
10	1568	1531,5

Table 5. Acoustic speed in reference biomatters depending on wave frequency.

Temperature of matter, ^0C	Acoustic speed, m/s	
	distilled water	human blood
0	1417	1462
20	1468	1512
40	1522	1558
60	1550	1577
80	1554	1596
100	1505	1614

Table 6. Dependence of acoustic speed on temperature of reference biomatters.

In the table 7 an integrated comparative assessment of human blood characteristics for different matters is shown and a characteristic impedance is calculated depending on a consistency value of matters and an acoustic speed.

Matters	Density, kg/m^3	Acoustic speed, m/s	Characteristic impedance, $kg \cdot m^{-2} \cdot s^{-1}$
blood	1060	1530	$1{,}62 \cdot 10^{-6}$
ethyl alcohol	789	1119	$0{,}883 \cdot 10^{-6}$
water	993	1527	$1{,}516 \cdot 10^{-6}$
standard air	1,2	330	$0{,}0004 \cdot 10^{-6}$
aluminum	2700	6420	$17{,}3 \cdot 10^{-6}$

Table 7. Physical characteristics of some matters in comparison with blood.

2.3.6 Microactuators on SAW

One of the most perspective directions of micromechanics developing is a design of intelligent microelectromechanical systems and an active use in such systems of actuating devices presented as microactuators on SAW. A main principle of their functioning is based on an SAW excitation in a piezoelectric substrate (quartz, $LiNbO_3$ etc.) with 100 MHz which makes a relocatable object contacting with an acoustic line to be in motion in an opposite direction of a SAW propagation velocity vector. Mentioned waves in a substrate combine longitudinal and normal components and their resultant affects the relocatable object. The SAW excitation on the substrate is realized by IDTs connected on an alternating current generator 10-100 V. The described structure of a microactuator on SAW allows to get the following key parameters: continuous velocity of travel to 1,1 m/s, linear motion acceleration to 1000 m/s^2, output mechanical force to 3,5 N. The excitation of transmitters by means of an impulse voltage with pulse-repetition interval to 200 μs makes possible to provide the movement with step of 5 nm. Advantages of microactuators on SAW are high speed, precision and positioning simplicity of a relocatable object, the integration possibility with microsensory and microprocessor devices (Gulay & Lazapnev, 2005).

2.3.7 Recognition of biomatters information patterns

An intelligent software of a broad spectrum of applications (micro-nanotechnology, biotechnology, ecology, food industry, medicine, agriculture, personal and social safety etc.) is developed for the biosensory system of rapid blood analysis on a chip e-tongue and e-nose to recognize, e.g., state of health and implicit pathologies because of injuries, accidents and latent diseases. Moreover, early recognition is important because of biomatters patterns can considerably and fast change under the influence of different factors (Table 8).

Parameters of clinical and biochemical blood analyses	Values		
	normal	till trauma	after trauma
haemoglobin, g/l	130-160	165	148
red blood cells, l	$4{,}5\text{-}5\cdot10^{12}$	$4{,}5\cdot10^{12}$	$4{,}3\cdot10^{12}$
leukocytes, l	$4\text{-}9\cdot10^{9}$	$4{,}1\cdot10^{9}$	$5\cdot10^{9}$
thrombocytes, l	$160\text{-}390\cdot10^{9}$	$320\cdot10^{9}$	$280\cdot10^{9}$
band forms, %	up to 4	8	5
segmented neutrophils, %	63-67	67	65
lymphocytes, %	19-37	22	21
monocytes, %	3-11	2	6
erythrocyte sedimentation rate, mm/h	up to 8	9	14
total bilirubin, mcmole / l	5-21	10,8	13,6
blood urea, mmole / l	1,7-8,3	2,9	4,1
creatinine, mmole / l	44-106	32	48
whole protein, g/l	66-87	64	67
albumen, g/l	34-48	64	56
glucose, mmole / l	3,05-6,38	6,2	5,2
AST, E/L	4-38	49	36
ALT, E/L	3-31	30	34
potassium, mmole / l	3,84-5,12	4,2	5,8
sodium, mmole / l	130,5-174	141	147

Table 8. Blood parametric changes of suffering from internal injury.

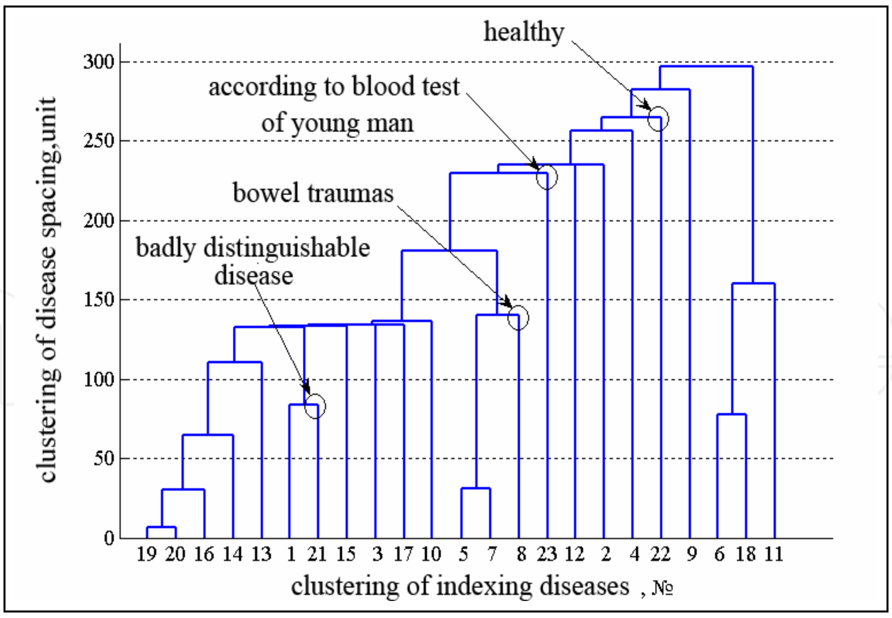

Fig. 15. Cluster analysis for recognition of bowel trauma.

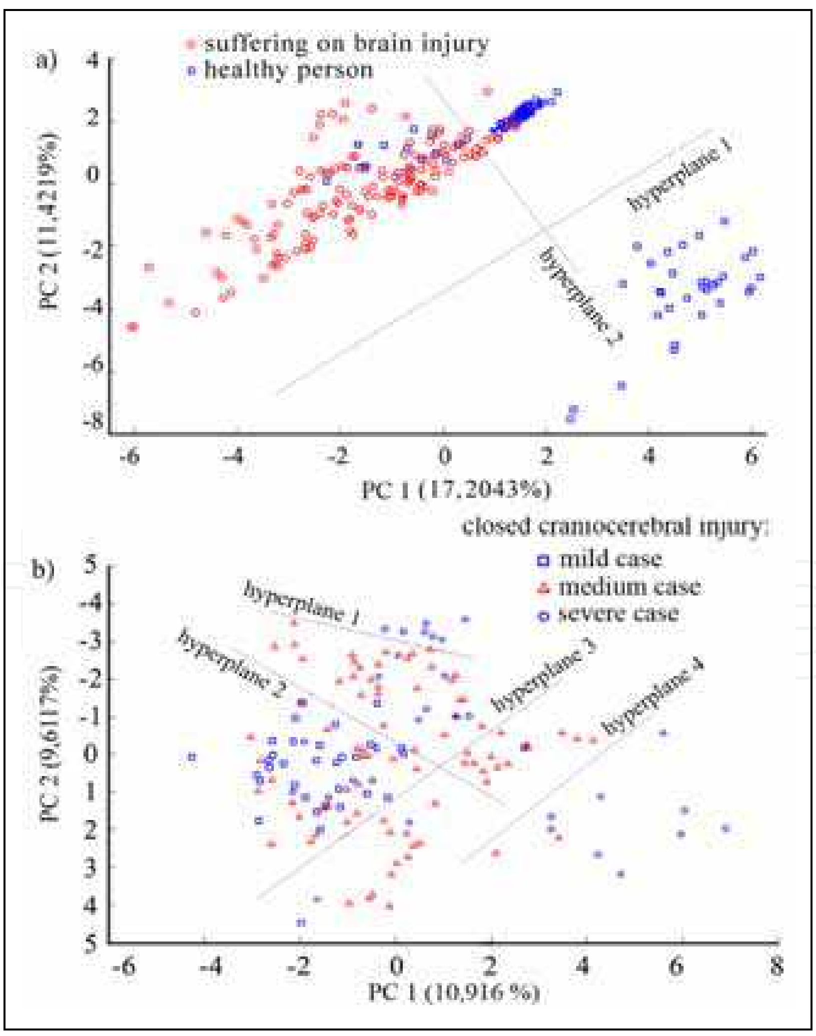

Fig. 16. Blood information patterns of closed craniocerebral injury.

The developed program carries out an analysis to detect latent pathologies, e.g., in a blood picture, but using of a matrix of symptoms in the process of diseases recognition makes it possible to achieve the highest system accuracy. Clusters algorithms rely on pattern recognition in multidimensional feature space corresponding to definitive human conditions (Fig. 15).
Figures 16, 17 and 18 show results of recognition information blood patterns before and after traumas and diseases. Therefore, it is possible to carry out rapidly a human diagnostics and to prevent the data deference in a high-cost research laboratory.

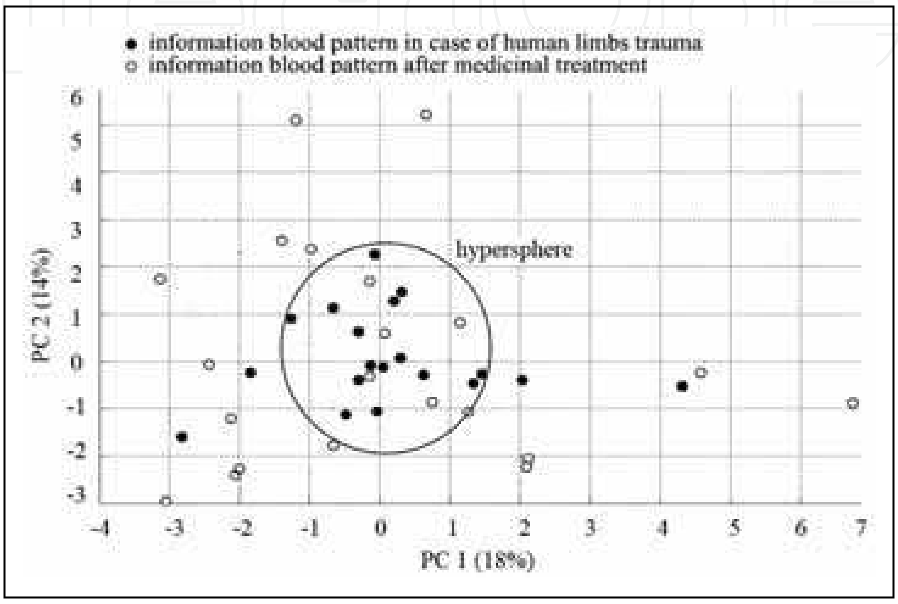

Fig. 17. Blood information patterns before/after trauma of human limbs.

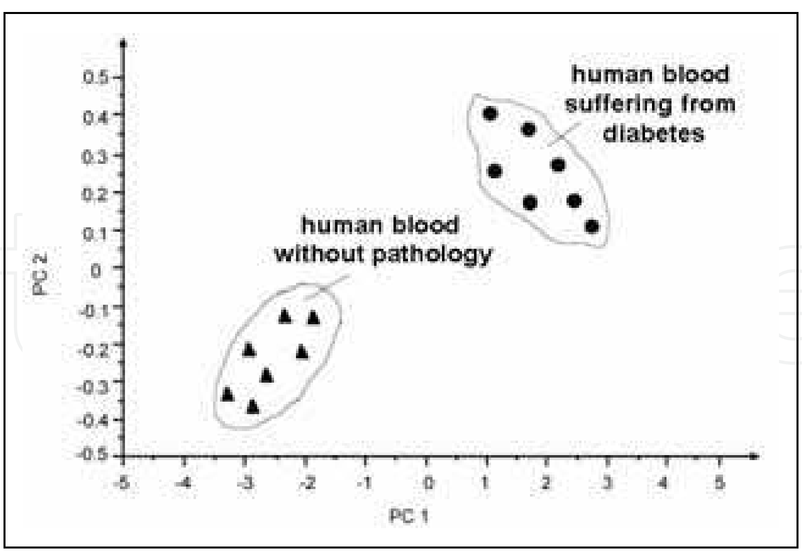

Fig. 18. Blood information patterns suffering from diabetes.

The base components of an information pattern of saliva are K^+ , Na^+ ions, protein, glucose and an acoustic coefficient equals numerically a ratio of ultrasonic waves velocity in saliva to the one in water. Figure 19 depicts information patterns of saliva in the two-dimensional space of the first two principal components for different subjects.

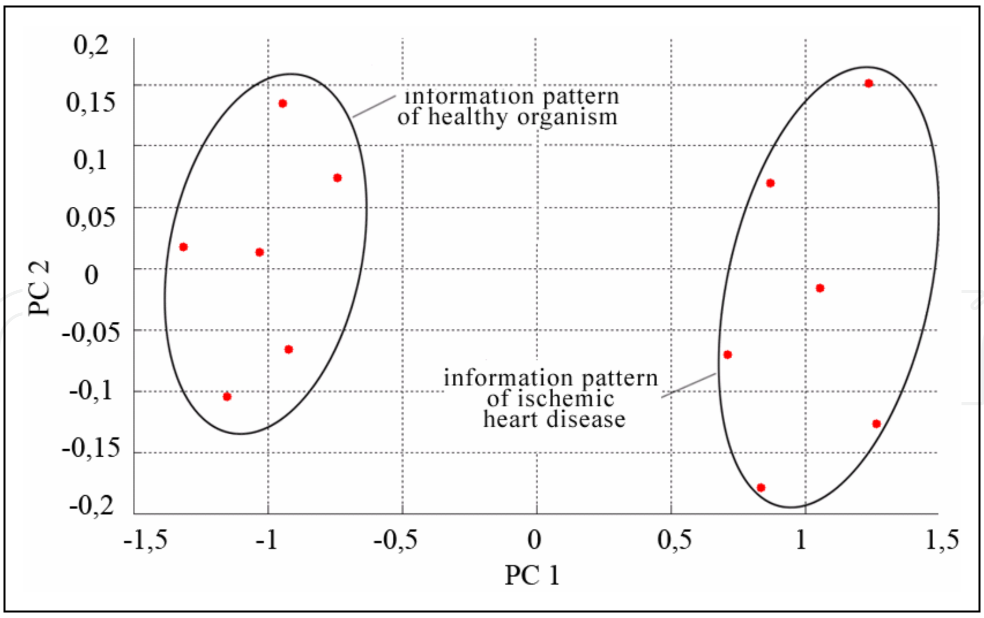

Fig. 19. Saliva information patterns suffering from ischemic heart disease.

Information pattern recognition of human urine (Table 9), e.g., in diagnostics of urolithiasis is based on a clinical urine analysis using physical-acoustic and electroacoustical properties. The developed diagnostic system allows to process data of urine analysis fast and with the high detection probability (79,07 %).

Clinical parameters of urine analysis	Values, ml		
	norm	healthy man	sick man
potassium, K	35-90	40	31
sodium, Na	150-220	175	140
calcium, Ca	2,5-7,5	3,4	2,7
chlorine, Cl	115-220	162	84
phosphorus, P	29-45	37	28
uric acid	1,2-7,1	3,6	5,2
urates	till 0,7	0,57	0,65
dielectric capacitivity, (nondimensional quantity)	less 17,5	24	15

Table 9. Information sensory pattern recognition of urine.

3. Sensory system on a chip electronic eye

Intelligent analysis systems of information optical patterns of human biomatters (blood, saliva, sweat, urine etc.) present an innovative class of smart laboratories on a chip of the type “electronic eye”. The light-emitting microdiodes (LED) emit given electromagnetic waves in the frequency range 10^{11}-10^{15} Hz, but microphotodiodes register quantitative changes of a reflected radiation (absorption, refraction, light scattering coefficients etc.). It is possible to analyze different changes of optical matter properties and a hardware miniaturization of the intelligent recognition system allows to adopt it to any other systems depending on application purposes (Fig. 20) (Gulay & Polynkova, 2010).

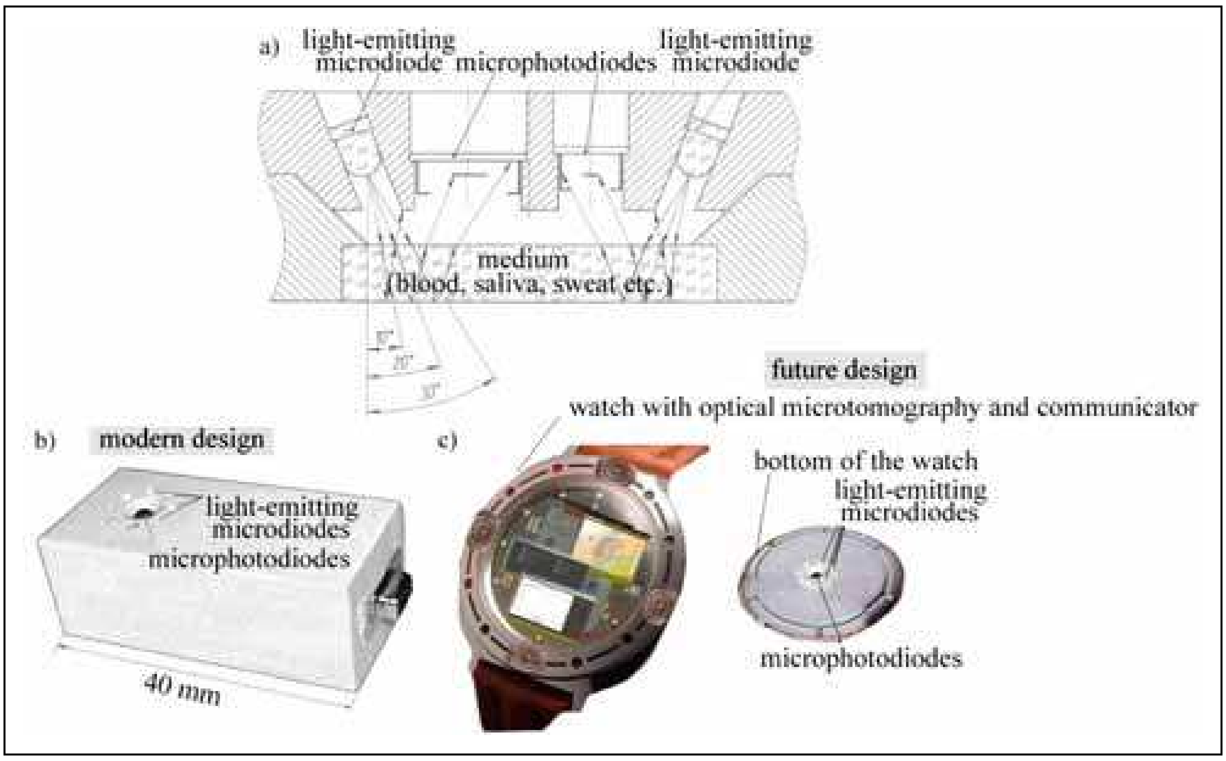

Fig. 20. Analysis of investigated matters by optical broadband microtomograph (a), general form (b) for diagnostics and in the intelligent watch (c) with optical pattern recognition.

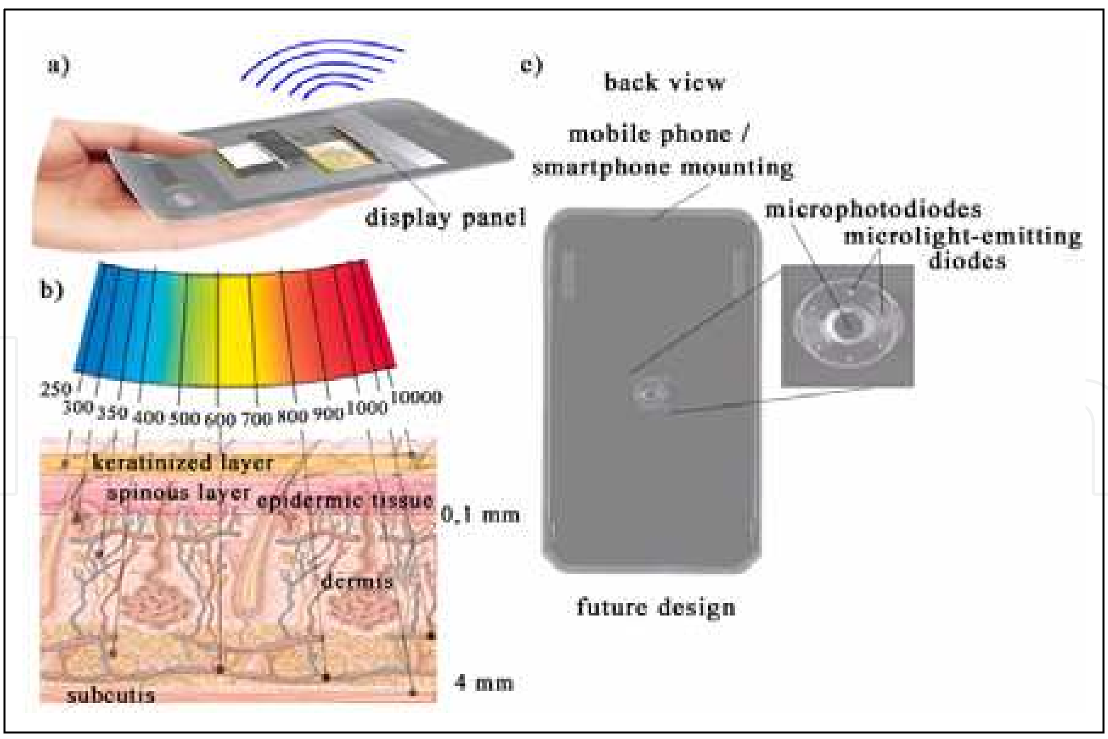

Fig. 21. E-eye sensory system in mobile devices. (a) Developed smartphone with optical recognition system e-eye. (b) Penetration of electromagnetic waves with different wavelengths in skin of user's palm holding smartphone in one's hand. (c) General view of smartphone with embedded sensory system e-eye.

Then it makes a comparison between the known information pattern and all reference models of human biomatter to determine a degree of manifestation for the given pattern and its influence on human health. Smart multiprocessing enables flexible on-line modeling of intelligent systems with a calculation of individual optimal micro-nanosensory parameters of the optical microtomography. For example, the mobile intelligent system (Fig. 21) enables to carry out an operative prediction about a health status and doesn't require special application conditions or highly skilled specialists.

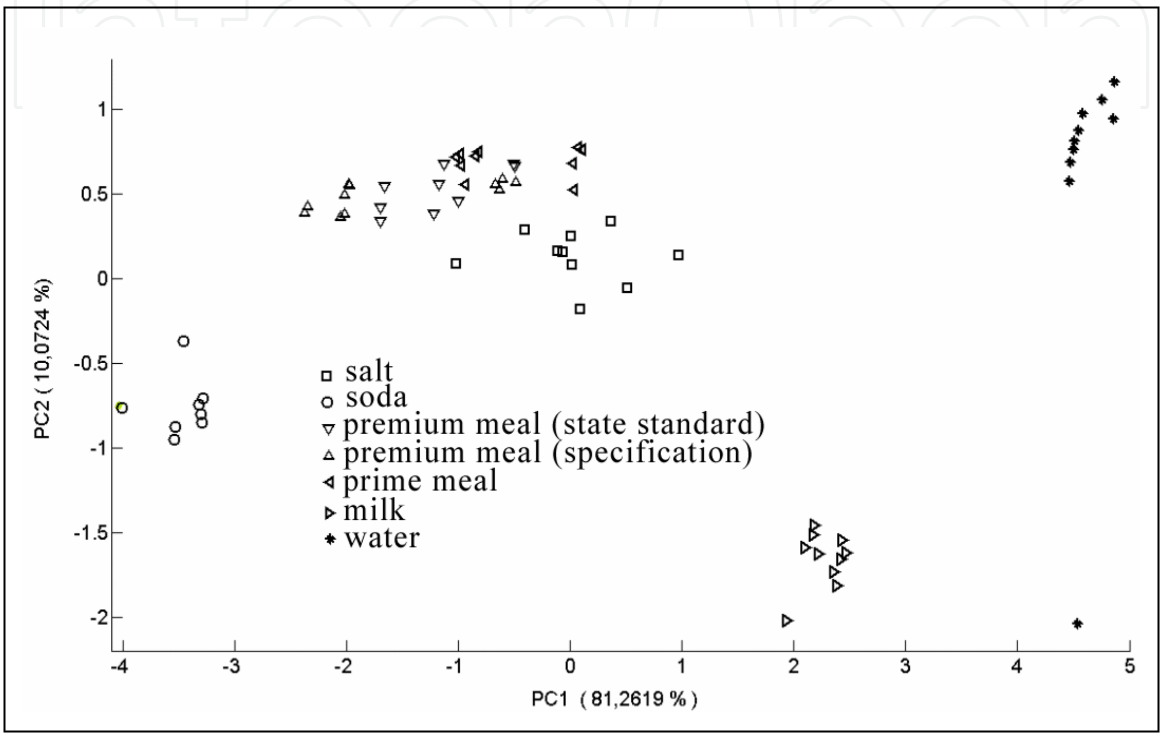

Fig. 22. Recognition of information patterns of foodstuffs.

Our developed systems find a broad spectrum of applications, e.g., for:

- toxic and biological agents, explosive hazard and narcotic searching in complex sensory systems and networks;
- rapid recognition of acute infections by the use of breathing diagnostic and early detection of latent diseases;
- monitoring of children's homes, maternity wards, old people's homes (Polynkova & N.V. Khmurovich, 1997);
- individual noninvasive monitoring of human health and continuous control of its functional state of organism due to intelligent sensory systems and networks;
- helping, e.g., medical staffs and prompting them of important decision making;
- production process monitoring (Fig. 22) in pharmaceutics, rejecting mechanism of primary goods, storage accommodation safety, drinking, nicotine and drug abuse determination;
- air analysis in industrial and agricultural enterprises, monitoring of noxious vapors, wastes;
- control of firefanging threshold in agriculture;
- analysis of soil information patterns in precise agriculture (Fig. 23) (Gulay & Polynkova, 2010);

- problem-solving of on-the-job injury rate and human-factor error accidents in modern enterprises by testing of any staff;
- ensuring of personal and social safety and safe control against terrorism and corrupt government officials.

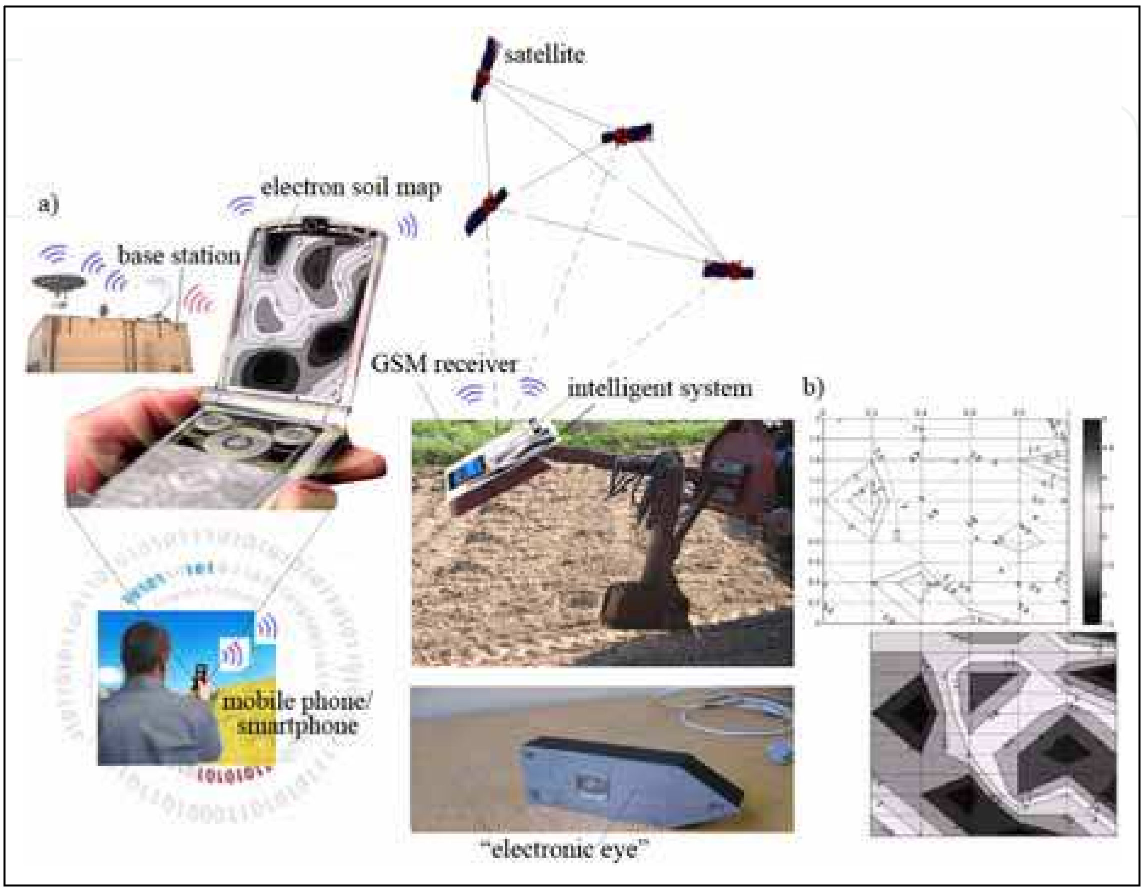

Fig. 23. Mobile soil analyser for precise agriculture (a), satellite "electronic map" of field (b).

4. Radio frequency identification systems

4.1 Remote sensing of information patterns by means of SAW sensors

Radio frequency identification (RFID) systems have been developing over recent years and find wide applications in micro-nanosensory technologies, production monitoring, ecology, security systems, transport tracking systems etc. Combining of a SAW sensor with a RFID system enables to design a new wireless micro-nanosensory device (Polunkova, 2007). A main idea of such intelligent system includes a latent placement of inexpensive SAW sensors in public gathering areas (waiting room, airport, railway terminal, cloakrooms etc.). Transducer makes a connection to an antenna in a specified operation frequency range, but SAWs are stimulated by antenna irradiation of electromagnetic signal. A substrate of SAW sensors contains IDT and many reflecting segments and metal strips reflect an electrically induced acoustic wave so that constructive interference obtains. When launching is stopped after a while, surface-mode waves goes on still and disappears in 25 μs, so next exciting acoustic wave is to be generated. The IDTs signal is transformed in SAW propagating to reflectors and backward directions and back in an electromagnetic signal. Then the generated in 5-20 μs reflected signal contains important information concerning propagation characteristics and environmental effects on acoustic lines. This one is transmitted in the antenna outside and can be successfully detected by receiver which measures its parameters and determines specific gaseous substances. The structure chart of the intelligent system for detection of odor matters is presented in figure 24.

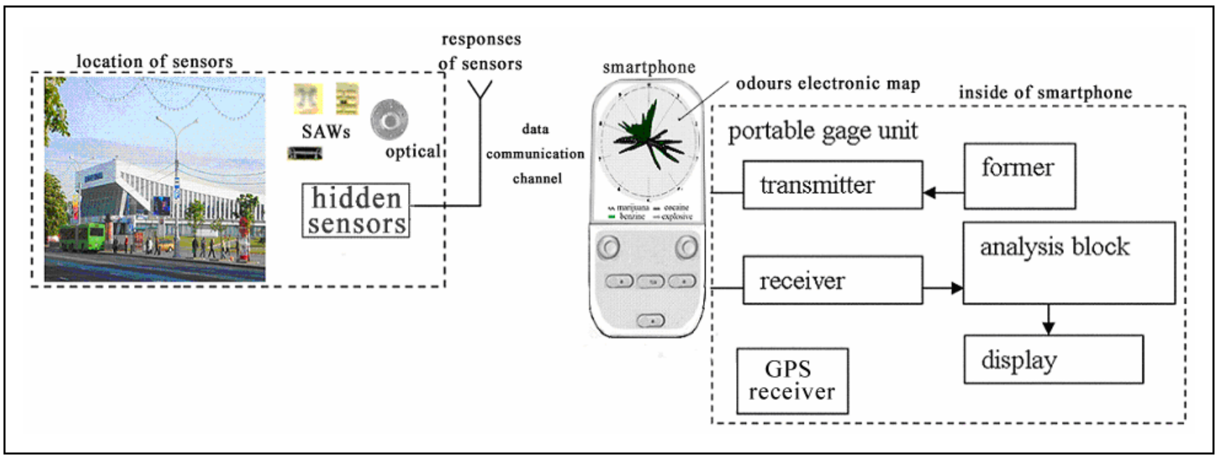

Fig. 24. Environmental intelligent monitoring system.

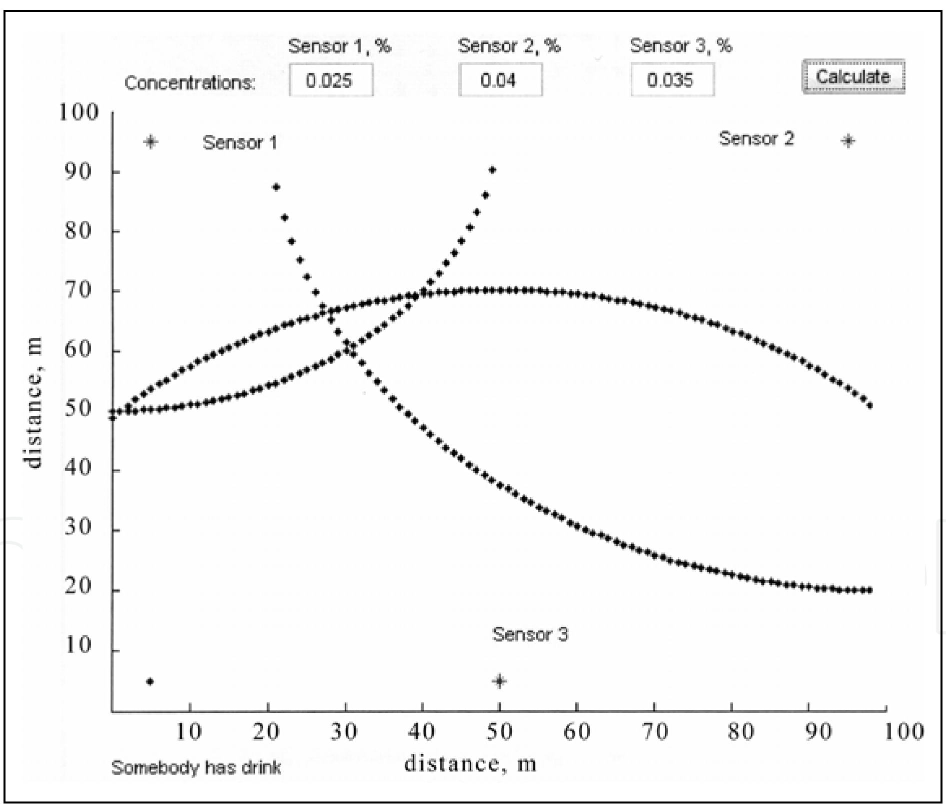

Fig. 25. Intelligent system for detection of ethyl alcohol vapors in sensory networks.

4.2 Sensory networks

A universal contactless multicore intelligent system "ISA" for control in sensory networks, e.g., of ethyl alcohol vapor in any spaces is developed which enables to define instantly drinking using not remote labs, but a distributed intellect in multidimensional space of

sensory networks to recognize of information patterns of human health status, dangerous substances and explosives etc. Vapors concentration characterises the remoteness of a source from a sensor, but radiuses of remoteness (Fig. 25) define an intersection region.
Every sensor of e-tongue and e-nose is characterized by different partial sensitivity to an analyzable taste, an odor spaces, but the combined characteristics of all sensor responses can be used to identify an information pattern in computer technologies and sensory networks. Amplitude modulation is used for information transferring on a resonance frequency of an oscillating circuit. Figure 26a presents dependence of a power propagation factor on the distance between the rider and the SAW retransmitter.

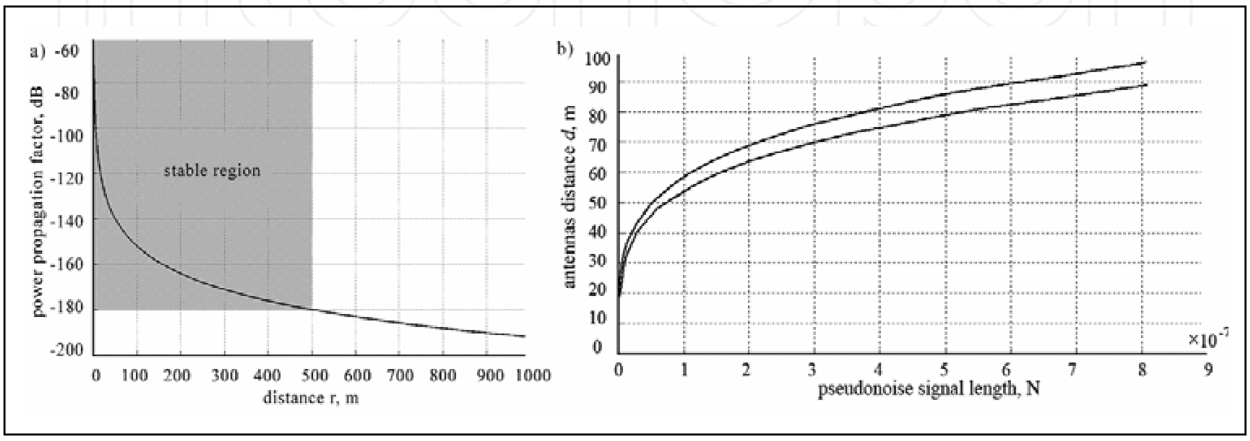

Fig. 26. Stable region of RFID system (a) and characteristics of channel reliability (b).

For example, 430 MHz sensor working in the mode of delay line or in the excitation mode has the frequency band up to 1 MHz. The receiver of this frequency range has the sensitivity $P_0=3\cdot10^{-15}$ W= 150 dB/W in case of the signal-to-noise ratio equals numerically 10 dB in transmission band and at the distance approximately 10 m. Using of pseudonoise signals in the length more million enables to achieve the considerable distance about 50 m for reliable functioning of remote hidden passive e-noses and e-tongues. Characteristics of channel reliability depending on used pseudonoise signals are shown in figure 26b. The maximal distance of a rider and a SAW retransmitter equals to $r_{max} \approx 500$ m, when the noise-to-signal ratio in the rider antenna makes 100. Thus, an active SAW sensory antenna makes it possible to increase the maximal distance up to r_{max}=50 km.

5. Multicore system of pattern recognition

A design of microelectronic components and a progress trend of processor throughputs are related to the development of multicore technologies with parallel architecture which are close to the functionality cerebration concerning computational powers (Table 10). An intelligent multicore recognition system of multidimensional sensory patterns is developed on the basis of SAW micro-nanosensors on a chip e-tongue, e-nose and an optical microtomography e-eye in the broadband frequency range (Gulay & Polynkova, 2010). The developed intelligent system "WIS" includes multicore and parallel processing technologies for fast self-learning and on-line recognition of information sensory patterns of blood, saliva, sweat, urine etc. Intelligent client applications in Visual Studio enable to design rapid unique softwares on different platforms by means of NET. Framework 3.5, to use a Parallel Extensions library for fast data processing depending on numbers of available cores and to

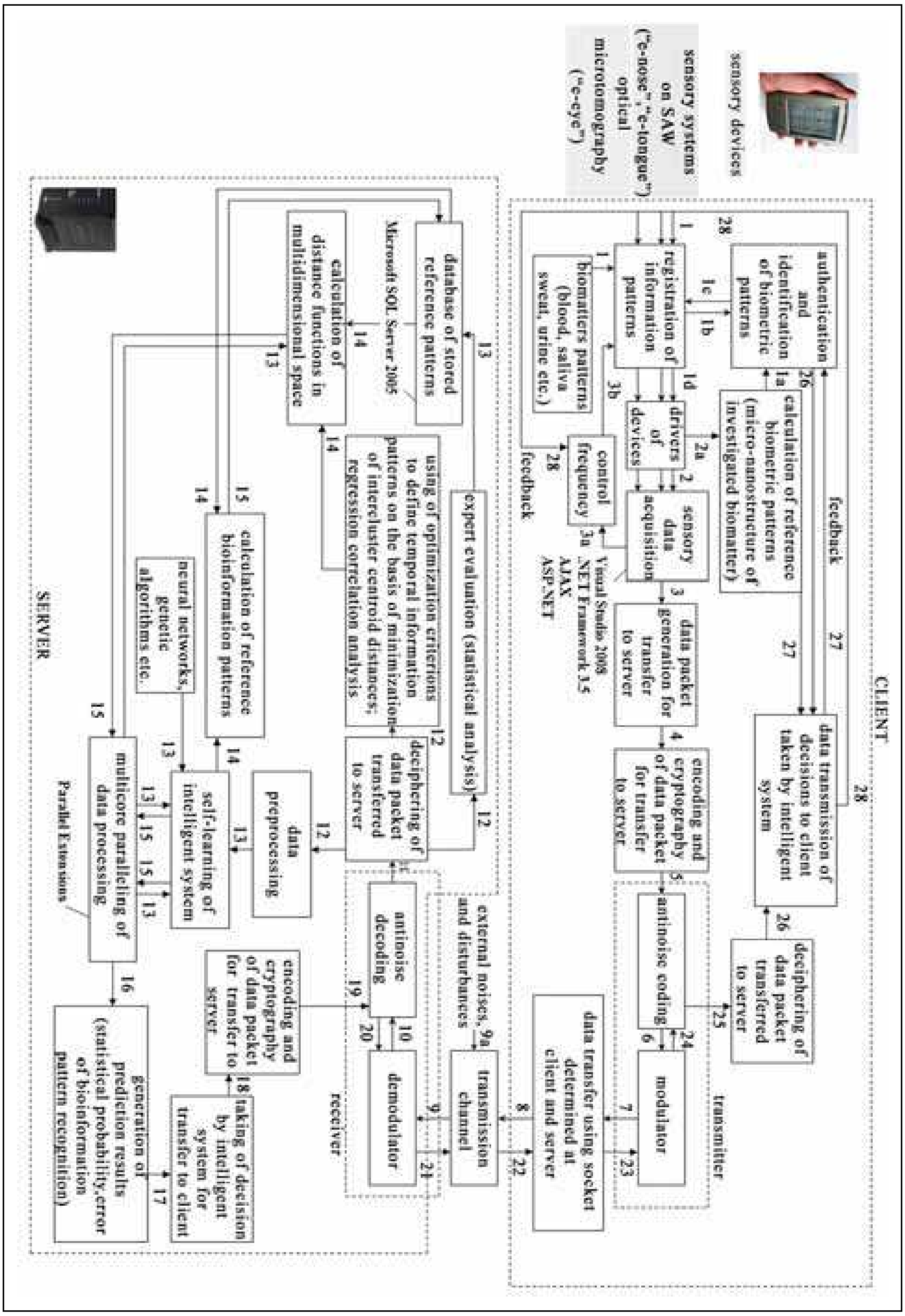

Fig. 27. Functional diagram of intelligent system "WIS".

apply practically SQL Server opening wide possibilities for Web-applications. The developed intelligent system “WIS” can be embedded, e.g., in a wristwatch or in mobile phones and smartphones for different individual applications (Fig. 27). A data packet is generated for remote wireless transferring to a server after registration of information sensory patterns of blood, saliva, sweat or foodstuffs etc. Data encoding and information encryption of sensory devices and antinoise coding are fulfilled before transmission. Information-translation process realizes using a socket determined at a client and a server to assure an entry of data to the server.

Parameters	Characteristic features	
	current systems on a chip	human brain
processor throughputs, flops	single-precision 8,942 $\cdot 10^{11}$ (supercomputer Roadrunner $1{,}4567\cdot 10^{15}$)	close to 10^{16}
weight	(supercomputer Roadrunner) 226 tonnes	1,4 kg
energy consumption, W	(supercomputer Roadrunner) $3{,}9\cdot 10^{6}$ (videochip AMD RV770) 150	25
clock frequency, Hz	$3{,}33\cdot 10^{9}$	10^{14}
heat energy, J	(switching energy of microchip) up to 10^{-13}	(energy of nerve impulse) $5\cdot 10^{-15}$
information capacity, bit	(technical process 22 nm) $364\cdot 10^{6}$ per cm^2	10^{23}
memory bandwidth, bit per sec	10^{12}	10^{18}
number of elements, pcs	(transistors) up to $2{,}9\cdot 10^{9}$ per cm^2	(neurons) up to $4\cdot 10^{7}$ per cm^3
linear size, m	(transistor) up to $22\cdot 10^{-9}$	(neuron) 10^{-6}
data-processing mode	parallel-serial mode (more 80 cores)	flexible self-adjusting parallelism

Table 10. Brain and technical system.

Methods of self-learning		Execution time, sec			Root-mean-square error (RMSE)
		one-core		multicore	
		Intel Pentium 3 753 GHz	Intel Pentium 4 3 GHz	Intel Core 2 Duo T8300, 2,4 GHz	
neural networks		0,5426	0,1023	0,0409	0,3428
group method of data handling	twain	54,1732	15,3611	3,5423	0,2804
	triplet	186,8461	24,0156	12,3106	0,2093

Table 11. Information pattern recognition of urolithiasis in human urine.

Intelligent system “WIS” makes it possible to achieve high training speed, to apply advanced parallelism for the purpose of recognition of multidimensional sensory patterns of biomatters (Table 11) and for a design of effective not energy-intensive intelligent systems.

6. Intelligent information systems security

Using of traditional techniques of a biometric identification and authentication is connected with problems in relation to external influences determining a distortion of biometric information and safety features of controllable and reference objects (Azizov, 2009). Intelligent patented technology of protection against falsification, substitution, imitation of biometric parameters is developed which can be applied in different fields of human activity, in particularly, in information and communication networks. A new principle of group features on the basis of set of physicochemical and biological characteristics uses a nanostructure of traditional and prospective biometric information characteristics, their nanomechanic, electronic, gaseous, optical components (Fig. 28).

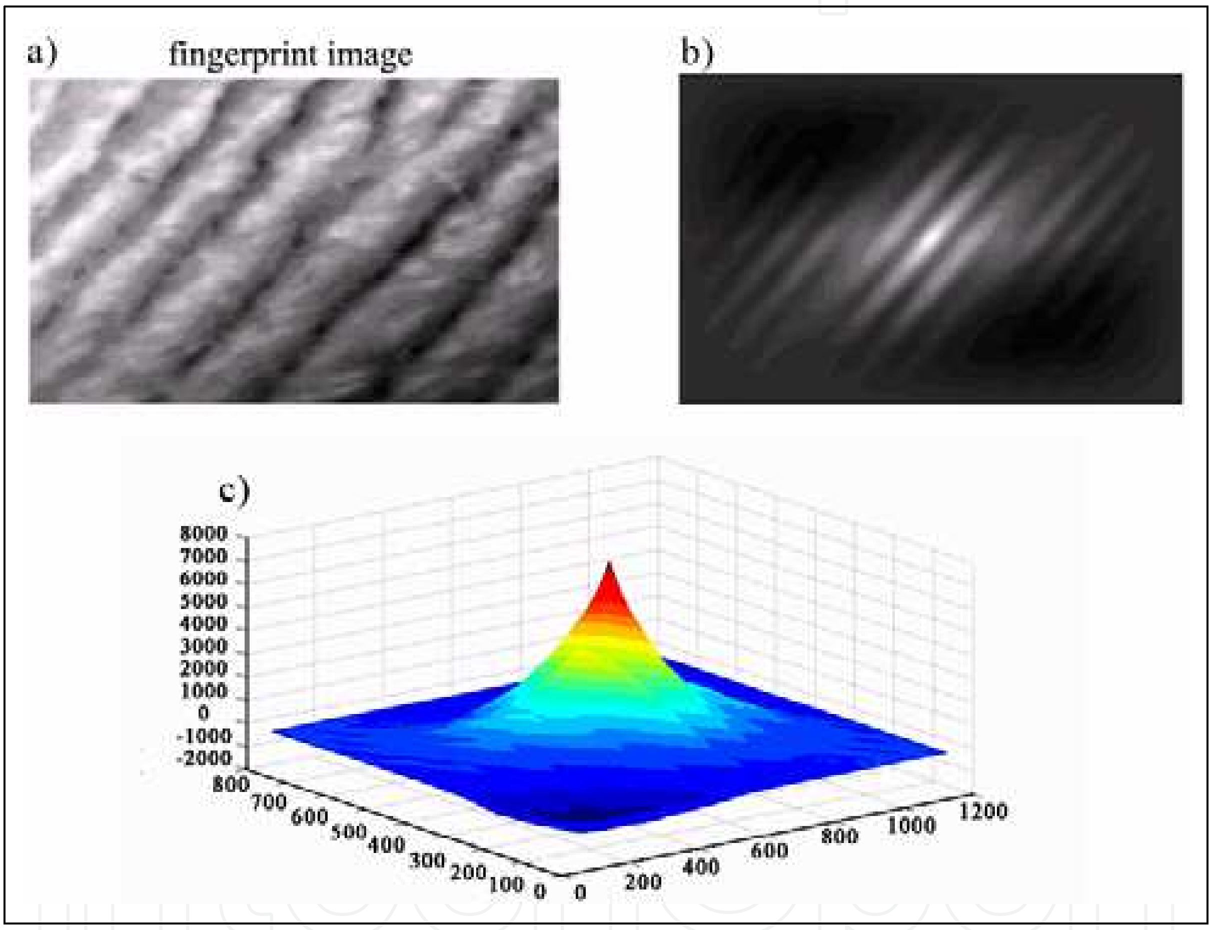

Fig. 28. Superprotection technology of biometric data: (a) information pattern of fingerprint, bivariate (b) / three-dimensional (c) cross-correlation function between fingerprint and image of reference object.

7. Conclusion

The developed intelligent sensory micro-nanosystems and networks including e-tongue, e-nose on SAW and e-eye for individual applications, recognition of information biomatters patterns (blood, saliva, sweat etc.) are shown. These multicore intelligent systems can be embedded in up-to-date mobile devices (cell phones, smartphones, communicator etc.) or in a wristwatch, can fast recognize any patterns by means of Internet global sensory networks.

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A biosensor is a detecting device that combines a transducer with a biologically sensitive and selective component. Biosensors can measure compounds present in the environment, chemical processes, food and human body at low cost if compared with traditional analytical techniques. This book covers a wide range of aspects and issues related to biosensor technology, bringing together researchers from 12 different countries. The book consists of 20 chapters written by 69 authors and divided in three sections: Biosensors Technology and Materials, Biosensors for Health and Biosensors for Environment and Biosecurity.