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Application of Electromagnetic Charge Effect for Development of Optical Sensors

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Abstract:

During our studies, it was found that during the interaction of electromagnetic field with matter, the irradiated body begins to generate an alternating electrical signal. These results are grouped under the name Electromagnetic echo effect (EMEE). The measured signal is a function of the state of the body. In the present work, some of the new types of optical sensors created on that basis are discussed. Such sensors are used for control of fog parameters, fog emergence, impurity emergence in fog, processes at the threshold of laser ablation and phase transitions in liquid crystals. Also, a scanning system has been developed for visualization of irregularities on surfaces.

Keywords: Optical sensors, Fog, Scanning system, Laser ablation, Field-matter interaction.

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1. INTRODUCTION

In this work, we present developments based on electromagnetic field-matter interactions. We investigate and use the Electromagnetic echo effect (EMEE) – the interaction of any solid with an electromagnetic field induces an electric, alternating potential difference with the same frequency as the frequency of the incident field. In different sources, phenomena very similar to EMEE have been referred to as Surface Photo-Charge Voltage (SPCV or SPV), Photocharge Voltage (PV) and others. The essential consequence of the EMEE is that upon irradiation with an electromagnetic field, all solid bodies generate an alternating potential difference, the frequency of which is equal to the frequency of the incident electromagnetic wave. The measurement is contactless and fast. An important feature of the EMEE / former name before 2019 - Surface Photo-Charge Effect (SPCE) / is its significant dependence on the inherent properties of the irradiated sample. More specifically, the amplitude of the EMEE response depends on the type of the irradiated material. This can be considered as a great advantage of this method, since it allows for quick discrimination between different materials in real time, which opens a wide area of analytical applications and reveals vast opportunities for rapid and contactless analysis, as well as quality control of solids, liquids and gases.

The EMEE is a phenomenon that results from the interaction of an electromagnetic field with matter. Its essence is that upon irradiation with an electromagnetic field, all solids generate a variable potential difference with frequency equal to the frequency of the incident electromagnetic wave. The induced electrical signal exists between the irradiated body and the common electrical ground of the system. The potential difference between them (i.e. the output EMEE signal) can be measured with an electrode, which can be either in contact with the solid, or in near proximity of the object; but there is no mandatory need for contact – the measurement can be entirely contactless. An important finding is that the specific signal induced by the interaction of each solid object and the applied electromagnetic field is determined by the material's inherent properties. The signals are measured in nano- or micro-volts. A principle scheme is illustrated in Figure 1, where a solid's potential is measured via an electrode [1].

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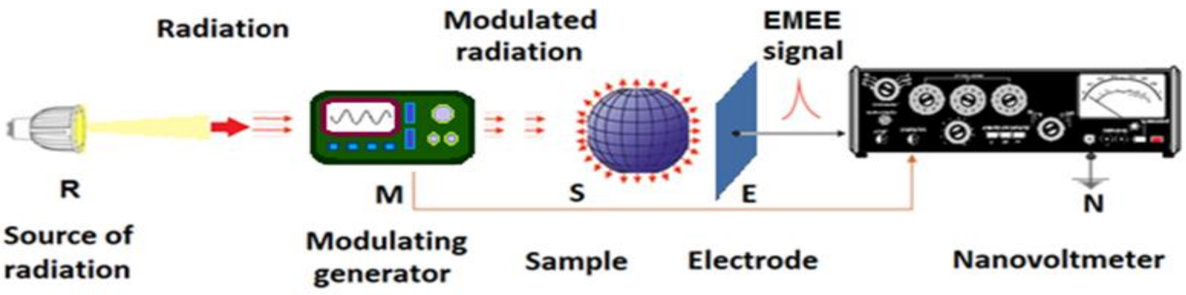

Figure 1. A general scheme for EMEE observation: (R) electromagnetic radiation source, (M) radiation modulating generator, (S) irradiated solid sample, (E) signal measuring electrode, (N) signal measuring device – Nanovoltmeter.

A source of radiation (typically a laser module) is modulated at a certain frequency and then it is used to illuminate the sample. The electrode captures the EMEE response of the irradiated solid and transfers it to a nano voltmeter, which measures the amplitude of the signal at the same modulation frequency. Since the signals are very weak, measures should be taken to eliminate external electromagnetic interference. This includes both good screening and the use of appropriate measurement techniques. For example, a selective voltmeter, a phase-sensitive nano-voltmeter (in this case it is necessary to provide a support signal), etc. It is convenient if the test specimen has two planar parallel sides to be mounted in a suitable holder. The process itself is quite fast. It has been observed that a 20 ns laser pulse is more than enough to change the potential of the solid body and to generate a full waveform of the output signal [2,3]. EMEE has been registered with modulation frequencies between 1 Hz and 1 GHz. Its existence has also been confirmed in a wide range of the electromagnetic spectrum – from the infrared, throughout the visible and up to the beginning of the ultraviolet spectrum [3]. The measured value of EMEE can depend on many factors: the intensity of irradiation, wavelength, area of the irradiated region, surface condition, surface structure, chemical composition, material type, etc. [4]. Carefully choosing an appropriate wavelength, for example, can maximize the levels of the generated voltage.

The EMEE has been observed in all investigated solids, including not only conductors and semiconductors, but also dielectrics [3]. It is used for investigation of semiconductor materials, as well as for characterization and study of poorly understood compound semiconductors, where other common methods may be difficult. [5] This also means that methods of investigation of semiconductors via EMEE can be quite valuable for developments in electronics. This effect can be used to measure the minority carrier diffusion length. For example, EMEE can be used to measure the density of impurity-derived recombination center's [5]. Some other noted possible applications that take advantage of the fast and contactless measurement include quality control of the composition of various goods during manufacturing (e.g. bricks [4], milk [6]), chemical composition tests (e.g. detection of counterfeit coins [2]) and different remote sensors (e.g. fluid level sensor [7]). In contrast to other similar effects, the EMEE is a characteristic of all kinds of solids and this makes it very interesting from a scientific and from a practical point of view. One can trace the shape of produced surface structures, for example, by ion implantation.

Numerous practical applications of the EMEE have been successfully put into, for example, contactless study of semiconductors [8,9]; detection of defects, irregularities, and impurities [10,11]; evaluation of solution components deposited on a metal surface [12]; surface conductivity measurement [13]; measurement of impurities concentrations in fluids [14]; analysis of drinking water [15], identification of harmful substances in milk and other foods [6], monitoring and quality control of chemical composition of materials [16], measurement of the laser ablation threshold energy [17]. One of the features of the EMEE is that every solid generates a specific electric signal, with the amplitude and phase depending on the chemical composition of the solid. This means that we can quickly control the composition of a variety of samples without any physical contact. Quality control is carried out by checking whether a set of samples of interest always generates the same signal.

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2. 2. MAIN RESULTS AND DISCUSSION

2.1. Quality Control of Bricks

Figure 2 shows how variation in the amplitude of the EMEE signal gives information about the change of coal sludge content in the composition of bricks leads [16].

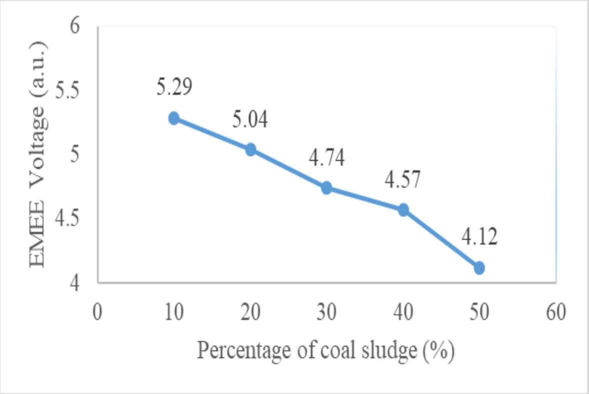

Figure 2. Changes of the measured signal versus the quantity of coal sludge added

It can be seen that upon irradiation samples with different compositions give specific response signals according to the amount of coal slurries added to the raw material of the bricks. This example shows that it is possible to use this methodology to control the production quality of other raw materials as well.

2.2. Phase Transition Detection in Liquid Crystals

The EMEE seems to be an efficient method for the detection of phase transitions in liquid crystal (LC) systems, allowing the detection of some very weak surface structural transformations that could be difficult to detect with routine structural techniques. It was applied for the first time for structure and phase transitions study of hydrogen bonded in dimer liquid crystals (HBDLCs) [18]. Due to the high sensitivity of this method, besides first-order phase transitions, it allows for phase detection, including smooth-order transitions in HBDLCs such as p,n-alkyloxybenzoic acids, in particular the 8th homolog of this compound, octyloxybenzoic acid 8OBA. This smooth-order transition is difficult to detect with the popular methods due to its small transition energy.

Due to the dimeric molecular structure of the investigated LC 8OBA, depicted by two parallel linear hydrogen bonds, forming a dimer ring, it easily transforms from monomer to closed and open dimers upon temperature cooling. Figure 3 shows the thermo-gram on cooling of 8OBA LCC: I → N phase transition is at 144o C, hysteresis of 2o C indicating the first-order transition, (2.25 mV); N1 → N2 transition starts at 136o C (1.2 mV) and continues to 129o C as the post-transition below I → N is between 140 and 136o C; nematic → smectic C is at 110o C; smectic C → solid crystal is at 106o C (2.3 mV); the solid II → solid I (3.4 mV) is at 100o C. Ordering phase transition within the nematic temperature range can hardly be indicated by means of popular structural methods such as Differential Scanning Calorimetry (DSC), X-ray analysis, Image Processing Method (IPM), Fourier-trans-formed infrared spectroscopy, Raman spectroscopies, etc.

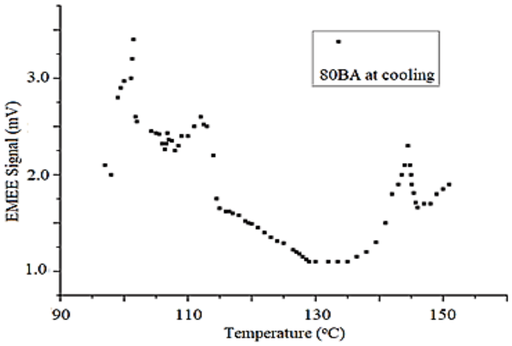

Figure 3. The EMEE thermo-gram on cooling of 8OBA LCC.

2.3. Fog Sensors

It is possible to extend the EMEE applications to measurements of the state of fogs. Changes in fog parameters induce changes in the EMEE signal. Properties, which can be investigated using this effect, are fog's chemical composition and density, droplet size and speed. A series of such devices has been developed and constructed under a European project in the field of security. Each of them has a different arrangement of components, but they are all capable of detecting fog presence. For example, with such devices the emergence of fog and aerosol pollution can be detected over very large distances. This is a very important feature, since all current available methods are capable of measuring fog density by assessing visibility at a point or in a small spot [19,20].

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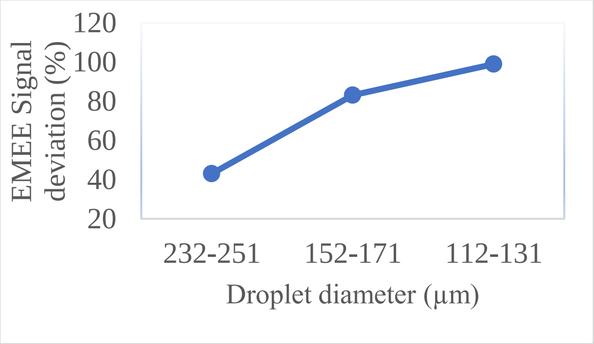
We have used the EMEE to develop a series of devices under a European project related to Security with acronym COUNTERFOG. Its aim is to create systems for rapid counteraction to terrorist attacks with CBRN agents at public sites, industrial accidents and natural disasters. For this purpose, special fogs are used to clean the harmful substances. The task of our team is to develop sensors and devices that work together with the fog generators. They must perform the following tasks: monitor for the presence of dispersed agents, warn of their emergence and trigger the fog-generating systems; control the dispersion of the cleaning fog to all areas of the facility; control the duration and the exact moment of termination of the cleaning process by detecting if contaminants are present in the fog; monitor fog parameters, such as: chemical composition; density; diameter, speed and number of droplets. A major breakthrough are the newly developed types of fog sensors, which are capable of detecting the emergence of fog over very large distances, and also of controlling fog's chemical composition in real time. No other sensors with such capabilities currently exist.

a)



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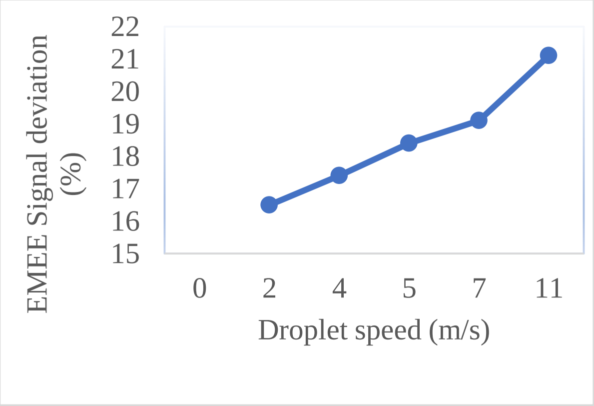

c)

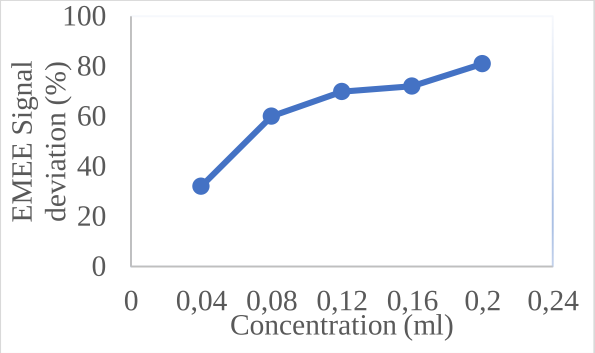

Figure 4. Results from measurements of EMEE signal deviation for: **a)** droplets with varying sizes; **b)** droplets moving with different speed; **c)** a contaminant reaction – iodine with different concentrations dissolved into 20 ml dH_2O

In Figure 4 are shown example results from measurements in laboratory and in field environment, with some of the devices, which operate using the EMEE [21, 22]. The results prove that the EMEE can be successfully used to create devices for monitoring of fog parameters, such as droplet diameter, droplet speed or contaminant concentration. Fog with predominantly larger droplet diameters shows smaller deviation in the received signal, in comparison to fog with smaller water droplets (Figure 4 a). This phenomena could influence fog's ability to effectively collect impurities and how these devices measure this process. Another parameter that has effects on the system in natural conditions is the droplets' speed (Figure 4 b). Greater droplet speed interferes with the measurement and permits interaction between larger quantity of droplets and the sensor, which leads to stronger deviation from the initial signal. An example of the dependence of the EMEE signal amplitude on the concentration of the contaminant substance (iodine) is shown in Figure 4 c). The graph gives information for each concentration by the peaks of the EMEE response (i.e. the maximum deviation from the initial position). The signal's amplitude doubles with the increase of the iodine concentration of from 0.04 ml to 0.20 ml.

A sensor of the series has been presented recently [21]. It is capable of measuring the presence of contaminations in the composition of fog and of giving relative estimates of their concentrations. Over the sensing structure there is a liquid layer which is used for elimination of random condensation of droplets, in order to obtain stable results. The sensor can detect only the

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contributions of admixtures in the fog to the measured EMEE signal.

The measurement system has a laser emitting modulated light and irradiating the sensing structure. Two micro pumps are connected to the sensor, which flush the liquid layer inside after taking a measurement and then fill it again with clean water for the next measurement. To ensure that the successive measurement is correct and is not influenced by the previous one, it is required that this procedure is repeated several times, to clean the sensor from eventual contaminants present in the fog's composition. The process of flushing and refilling of the sensor is automated.

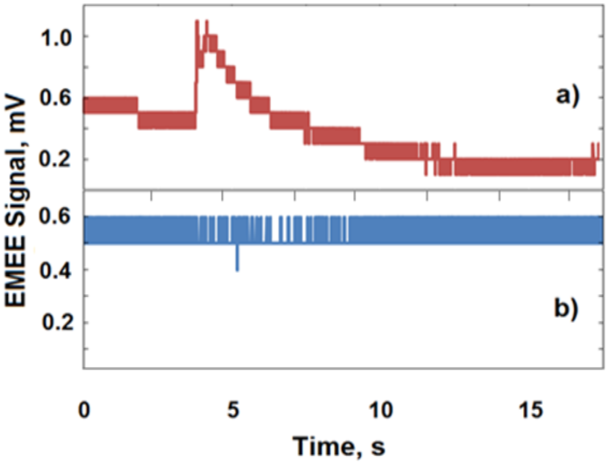

Figure 5. Results from measurements with the EMEE fog sensor with a liquid layer: **a)** fog with contaminator KH_2PO_4 - 4 grams into 200 ml distilled water (concentration 0.14 M); **b)** clean-water fog

The behavior of the EMEE signal over a period of time after spraying fog inside the sensor is presented in Figure 5. In Figure 5 a) is shown how the sensor responds when fog is generated from a mixture of water and a contaminator - potassium dihydrogen phosphate (KH_2PO_4), with 0.14 M concentration. Figure 5 b) presents the EMEE response to fog generated from clean (distilled) water interacting with the liquid layer of the sensor, which also contains clean water. The resulting response intensity of the sensor is stable in time. As can be seen from the graphs, when a contaminator is added to the fog mixture, there is a strong peak in the response of the sensor followed by a relaxation curve. Another studied capability of the sensors is selectivity to different contaminants. The preliminary results show the ability of the sensor to detect specific contaminants selectively, in the sense that it reacts differently to each of them. For different substances and concentrations, the response time, the peak and the behavior of the EMEE response varies to some degree and this allows the sensor to be calibrated in such a way, that it can give information about the relative quantity of the particular substance present in the measured fog. Such a sensor is applicable for systems of environmental protection and counteraction to terrorist attacks, disasters, accidents, etc.

2.4. Automated Scanning Systems for Visualization of Structural Irregularities on Solid Surfaces

Several prototypes of a measurement system based on the EMEE have been developed by using different technical implementations and here we present two of them. They are fully automated and capable of detecting changes in various surface parameters by measuring the amplitude of signals obtained by EMEE. Their general purpose is to scan areas of specimens and visualize their sensitivity to EMEE as 3D graphs. A dual-axis linear stage driven by a pair of step motors is used to move the sample. The scanning parameters (scanned area, number of points, measurement time, etc.) are inputted using a specially developed software program. The measurement principle involves modulation of the input signal, so that a nanovoltmeter can lock to the same frequency and measure the low EMEE output signal amplitude with an enormous noise cancellation. The systems are simple, non-expensive and allow detection of: mechanical defects, chemical composition, the presence of impurities, changes in surface electrical characteristics, surface states, etc. They also have the ability to monitor ongoing processes on surfaces in real time. No single instrument exists, which is capable of detecting such a large variety of structural irregularities. This method is sensitive, non-destructive, fast and easy for implementation [23].

Due to the nature of EMEE, we modulate the input signals and expect to measure modulated output signals with the same frequency. The components of the systems are shown in Figure 6. For modulation of the irradiation we use a standard digital signal generator. Its signal controls the laser, and in turn, the pulsed beam creates very weak fluctuating electromagnetic fields inside the sensor, which are then sampled. A signal with the same modulation frequency in the range of nano- and micro-volts is generated and measured by a nano voltmeter. The system has to be very well shielded from external noises

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(both electromagnetic fields and radiation in the visible spectrum can be considered noises to the system). Even so, noise levels in the output signal can be more than a hundred times stronger than the signal of interest. This is why specialized measurement equipment is used to filter and amplify the generated EMEE signals.

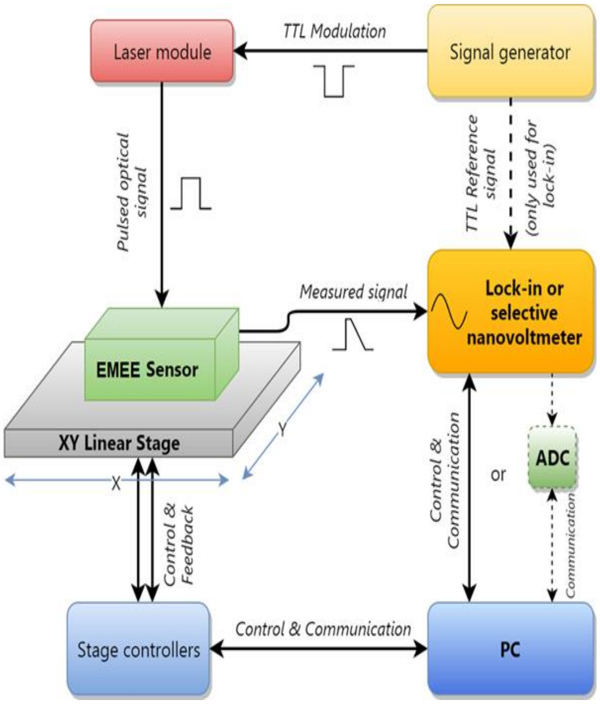
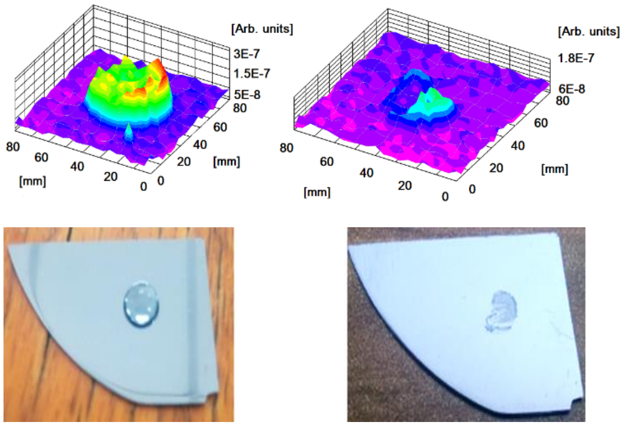


Figure 6. Block scheme of the automated scanning systems

The systems can currently work with two types of analogue nano voltmeters – lock-in nano voltmeters and selective nano voltmeters. The output signal from the nano voltmeters has to be digital, so either an ADC (analogue-to-digital converter) from their output can be used, or fully controllable nano voltmeters. The first prototype uses an ADC coupled to an analogue selective nano voltmeter. This configuration allows for quicker development, simpler solution and increased scanning speeds. The second prototype uses a programmable and fully controllable lock-in nano voltmeter with an integrated processor and digital controls. This configuration offers better controllability and higher accuracy, but slower scanning speeds. The set of these two systems allows for versatility and each of them is suitable for different situations with specific requirements. Due to conversions and amplifications of the measured signals, the graphs do not represent the real values of the measured signals. That is why the Z-axes are in arbitrary units. This should not be a concern, since the ratios of the amplitudes of the signals are the same as the original ones and can still be adequately compared. Figure 7 presents visualizations of a water droplet on the surface of a silicon crystal at different stages of evaporation. The results were obtained by the digital scanning system and indicate that it allows processes on surfaces to be investigated and controlled in real time.



a) b)

Figure 7. Experimental results – visualization of distilled water droplet: **a)** full droplet; **b)** partially evaporated droplet

Figure 8 demonstrates that our systems allow mechanical defects on surfaces to be detected. It depicts a visualization of the scratched surface of a silicon crystal obtained by the digital scanning system. It can be clearly seen that there is a good accordance between the visualized results and the actual mechanical deformations on the surface of the silicon crystal. This means that structural irregularities on the surface of solid materials can be visualized by the EMEE scanning systems. It is possible to upgrade the system with several laser modules operating at different wavelengths, so that they penetrate at different depths inside the material's surface. In that way, a real 3D graph of its volumetric structure can be obtained.

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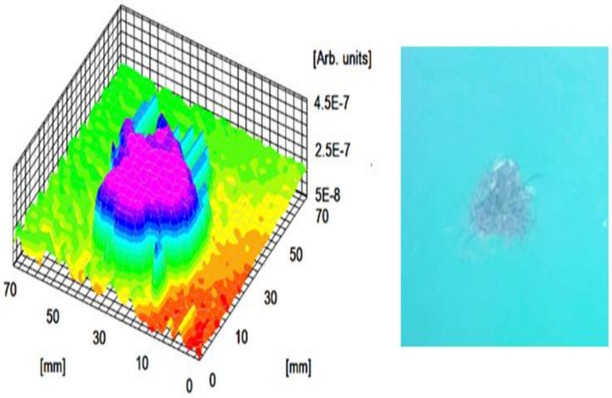

Figure 8. Experimental results – visualization of the scratched surface of a silicone crystal

A 3D visualization of the surface of an ion implanted specimen obtained by the analogue scanning system is shown in Figure 9. It can be seen that the EMEE response inside the ion-implanted area is much higher than that of the surrounding surface.

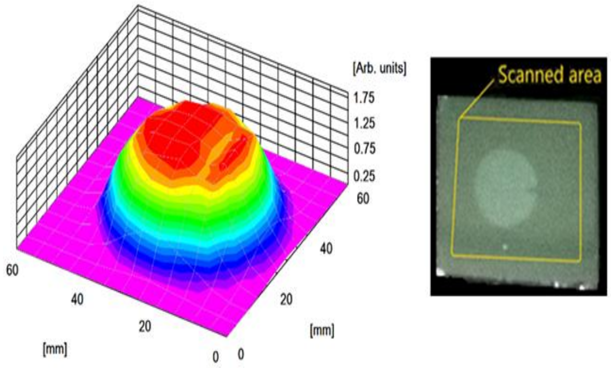

Figure 9. Results of surface scanning of an ion implanted specimen studied with the developed system

3. CONCLUSION

We have presented the electromagnetic echo effect and its huge potential for investigation of various properties of matter by showing examples of developed sensors and devices operating on this completely new principle. A wide range of possibilities for industrial applications have been developed until now. Some examples of our developments include: control of semiconductors, chemical composition of materials, fluids and aerosols, food quality, octane number of petrol; measurement of the laser ablation threshold energy; detection of counterfeit coins, limestone deposition in pipes, surface irregularities, phase transitions in liquid crystals; and many more.

4. ACKNOWLEDGMENTS

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