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REMOTE MATERIALS SCIENCE INTERNET EXPERIMENTS: SOLID STATE PHOTOVOLTAIC CELL CHARACTERIZATION

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ABSTRACT

E-learning is developing along the lines of integrated learning, combining multiple approaches in teaching, but till now, it has not included virtual or remote experiments to form a unified body of information. With the progress in information technologies the chance to grasp real objects by application of remote experiments across the Internet has emerged. The paper describes how the scientifically exact and problem-solving oriented remote experiments across the Internet for Material Science may be built using the server-client approach and generally available software ISES WEB CONTROL. As an example, a solid-state photovoltaic cell characterization with all the features of the exact scientific experiment has been built. All communication is through the Internet, using web services. On the client side only standard browser and implicit Java support is used, without any additional modifications. The evaluation of the measured data using standard photovoltaic conversion theory is presented. The first pedagogical experience with this Remote experimentation in teaching and examinations is presented.

Keywords: *Remote Internet experiments; Materials Science experiments; client-server data transmission.*

INTRODUCTION

Remote experiments

Materials Science experiments play an indispensable role in the curriculum. The absence of experiments and experimental work of students in all forms of science education brings about the loss of motivation and of deep understanding of real world phenomena. One of the ways where the Internet may help is web-based remote laboratories in Materials Science. An example of this is the MALDI – MS Remote experiment[1]. Another example is the phase transitions in ferromagnetic materials, where abstract and experimental aspects are treated in the scenario of e-Learning, e-Teaching, e-Research (e-LTR)[2].

In this paper we want to show how Materials Science courses may be successfully augmented by the use of qualitative and interactive remote experiments across the Internet, shown by the example of solid-state photovoltaic cell characterization. First, we want to present the motivation for construction of the set of Material Science experiments. Then we want to present the technical realization of the remote experiment and illustrate it with an exercise, Solid state photovoltaic cell characterization. We will present briefly its physical basis, show the evaluation of the measured data and give examples of its use in the individual work of students, in the teaching process and in examinations. As the experiment was tested in class, the pedagogical conclusions are also presented.

Remote experiments in material engineering - main idea and motivation

The traditional science curricula for engineers e.g. Physics, Chemistry or Materials Science are based on two forms of education: lectures, where the basic laws and abstract models are presented and laboratories, where the “real world” phenomena are examined. This format, suffering sometimes from lack of interconnectivity, is mostly copied by the e-Learning concept. The vast majority of e-Learning teaching tools present theoretical concepts of the respective science branch in form of mathematically formulated laws, models, simulations, applets or animations, exercises, graphs and presentations. Practically no e-textbook presents virtual or remote experiments to form a unified body of information e.g. Hyperphysics[3] or Slovak University of Technology, e – Physics [4].

With progress in information technologies the chance to grasp real objects by application of Remote experiments has emerged. Tompkins at Stanford constructed the physics remote experiment in magnetism[5] and the team of authors from Prague, Zlin and Trnava constructed and used a set of physical remote experiments on mechanical oscillations, electromagnetic induction and characteristic of a diode and tested it on a class of undergraduate students where it was received with considerable interest[6]. The use of remote experiments has become a possibility and the integration of remote laboratories into the academic education in general and Materials Science in particular, offers significant potential to qualitatively improve the learning of abstract knowledge. The advantage of this approach, forming an integrated combination of e-Learning, e-Teaching and e-Research (e-LTR)[7] is manifold. The remote experiments support the learning of theory by illustrating-demonstrating phenomena, applying theory to real situations, demonstrating the limitations of theory and by interacting with phenomena in authentic situations. On top of this, the remote experiments develop a body of skills involving critical observation, interpretation and assessment, planning and organization and practical problem solving, and, additionally, the skills in Information and Communication Technology (ICT) [8]. Another motivation was to strengthen the role of experiments in all forms of instruction including (e-learning texts, collection of exercises, repetition materials and self choice tests).

TECHNICAL REALIZATION OF REMOTE EXPERIMENTS

Technically, a remote experiment takes place in a location different from the experimenter. Consequently, it consists of two parts, one is the experimental hardware (with a phenomenon to be examined), and the second is the software for transferring instructions from the experimenter to the experimental setup, and for transferring resulting measured data to the experimenter. All communication is through the Internet, using web services, and a corresponding communication interface. Two basic types of this communication have been described[9]. The general scheme of the remote experiment (using a so called server-client approach and web services) used in the presented paper is shown in Figure 1.

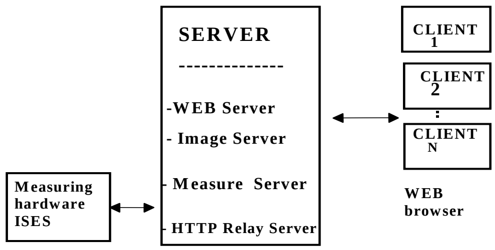

Figure 1. The general scheme of the server-client remote experiment.

The measuring hardware is in our case ISES (Intelligent School Experimental System) (ISES) [10]. The system is composed of an interface card, a set of variable modules and sensing elements, and a service graphical and evaluation program. A few of the available experimental factors in the modules include: voltage (±10 V, step 5 mV), current (0.5 mA÷1A), resistance, capacitance, temperature (-20 ^oC +120 ^oC), microphone, optical position detector, adjustable preamplifier, current booster, relay switch, pressure meter and others. The ISES modules are easily interchangeable, their presence and adjusted range is automatically sensed by the computer, with the automatic calibration facility. The service program enables the measurement simultaneously of 10 different channels (8 analog and 2 binary) and capability to use 4 programmable output channels. All these are fully programmable, using the programming panel.

The software for remote experiments is ISES WEB Control[11] (which creates on the server side four servers: WEB server, Image Server for the support of WEB cameras, Measure Server for the control of the hardware and HTTP Relay Server)[10]. In operation, the server side generates, using Java applets, the web pages, which create control keys and bars for the control of outputs, applets for measuring and digital displaying of input values, applets for graphic displaying of input values, applets for the transmission of measured data, applets for the image transmission from a web camera, etc, which are forwarded to the client computer using web service. On the client side, a standard browser (Internet Explorer, Net-Scape, Mozilla, etc.) and implicit Java support is used, without any additional modifications.

The general scheme for the experiment with a photovoltaic (PV) cell is shown in Figure 2. The characteristic of the PV cell (1PP75 TESLA 3.5 x 5.5 mm^2 = 19.3 mm^2) was measured using the built-in programmable voltage ISES source (±10V, 5 mV steps) and the ISES modules for current and voltage measurements, as the light source served the Diochroic Incandescent halogen lamp TSLF (35 W, 12 V/3A, T_{lamp} = 1800 K), supplied with another ISES digitally controlled power source (0 - 20 V/2 A).

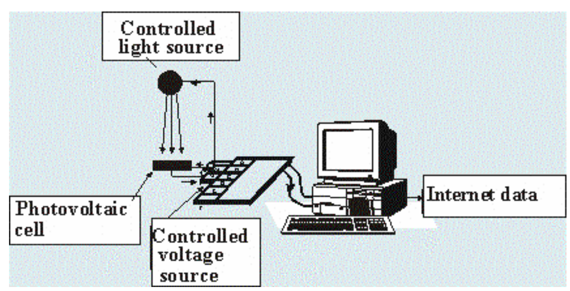

Figure 2. The scheme of the solid-state photovoltaic cell characterisation with ISES.

In Figure 3 is the Java generated virtual experiment with controls for the voltage adjustment (top) and the light intensity step change (left). The instantaneous value of the voltage and current is digitally displayed with the measured data in graphical form and controls for the transfer of the data directly to the client. The virtual experiment is provided with a real time web camera view of the experimental arrangement (see also Figure 3) and on line voice and another web camera service for the communication with an instructor.

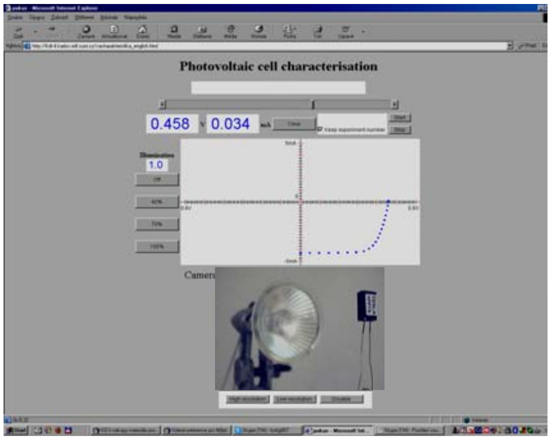

Figure 3. Web page of the solid-state photovoltaic cell characterisation with controls and web camera picture.

REMOTE EXPERIMENT: SOLID STATE PHOTOVOLTAIC CELL CHARACTERISATION

Physics Background

The PV cell is a complex device, based on recombination and transport phenomena.
For its application it is usually important to know the cell construction and several cumulative parameters such as a fill factor and external quantum efficiency either mono-chromatic or integral to solar luminance (mostly provided by Solar simulators) and an equivalent electrical circuit.

The common theory of a PV solar cell is based on the semiconductor equations combined with the corresponding optical equations[12]. For the purpose of the present paper it is sufficient to summarize the final cell characteristics. The I - U dependence in the dark, supposing the series resistance of the cell can be neglected is

$$I = I_0\left(e^{-\frac{eU}{akT}} - 1\right), \qquad (1)$$

where I is the current, I_0 is the reverse current, U is the voltage across the cell, k is the Boltzmann constant, T is the absolute temperature and a, is the ideality factor of the diode, expressing the predominant mechanism of charge transport in a diode.

The irradiation of the diode is a source of electromotive force and the I - U characteristic is then

$$I = I_0\left(e^{-\frac{eU}{akT}} - 1\right) - I_{photo}, \qquad (2)$$

where I_{photo} is the additional current source caused by irradiation. The transformation of radiant energy to the electrical energy is a complicated physical problem. The conversion efficiency η of this process is expressed by the quotient of the maximum electrical power, $P_{el} = I_m U_m$, where, I_m and U_m are the current and the voltage giving the maximum electrical power to the external load resistance, to the impinging energy radiant flux P_{rad}

$$\eta = \frac{P_{el}}{P_{rad}}. \qquad (3)$$

The conversion efficiency may be expressed as a product of partial efficiencies

$$\eta = \eta_r \eta_e \eta_p \eta_{el} = \eta_r \eta_e \eta_p FF \qquad (4)$$

where $\eta_r = P_{abs}/P_{rad} = 0.70$ is the efficiency factor expressing the part of the reflected radiation (taking average reflectivity to be 0,30[13]) defined by the quotient of absorbed flux to the impinging flux ($P_{rad} = P_{abs} + P_{refl}$); $\eta_e = 1 - T / T_{lamp} = 0.83$ is the Carnot efficiency, $T = 300$ K and $T_{lamp} = 1800$ K is the temperature of the Sun; $\eta_p = 0.15$ [14] is the efficiency factor due to the loss of a part of the radiation due to the mismatch of bandgap to the spectrum of the lamp (taken as blackbody radiator at the temperature $T_{lamp} = 1800$ K); η_{el} is the efficiency due to the cumulative electronic parameters of the cell,

$$\eta_{el} = \frac{I_m U_m}{I_{sc} U_{oc}} = FF, \qquad (5)$$

accessible to the measurement, where I_{sc} is the short-circuit current of the cell dependent on the transport properties of the semiconducting material, its mobility, cell geometry and the thickness of the active film, U_{oc} is the open circuit voltage influenced by the choice of a semiconducting material, and *FF* is the fill factor.

It is straightforward to show that the simple relation between I_{sc} and U_{oc} exists enabling to determine the ideality factor of the diode *a*

$$I_{sc} = I_0 \left(e^{-\frac{eU_{oc}}{akT}} - 1 \right). \qquad (6)$$

Conversion efficiency

Figure 4 is the *I-U* characteristic in the dark of the PV cell and in Figure 5 are the corresponding *I-U* characteristics for three relative light intensities *L*, 0.7 *L* and 0.4 *L* (L = 1.18 .10^{-3} Wmm^{-2}). Also denoted are the quantities of the short-circuit current I_{sc} = 4.44 mA and open circuit voltage U_{oc} = 0.465 V and the current and voltage for the maximum electrical power I_m = 4.1 mA and U_m = 0.359 V, respectively, for the light intensity *L*. The corresponding fill factor, (assigned for chosen *L* as FF_L) determined according eq. (4), is FF_L = 0.71 and the conversion efficiency of the measured solar cell is thus

η = 0.70 x 0.83 x 0.15 x *FF*
= 0.087 x 0.71 = 0.062 i.e. 6.2 %.

Power considerations

In Figure 6 is the electrical power $P_{el} = I\ U$ from the PV cell to the external load resistance as a function of the voltage on the cell *U* for three relative light intensities *L*, 0.7 *L* and 0.4 *L*. The characteristic is highly unsymmetrical due to the non- linearity of the *I-U* characteristic of

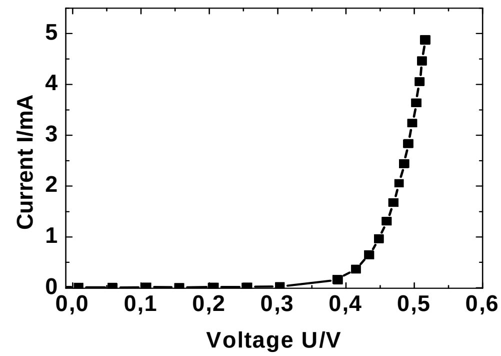

Figure 4. Dark *I-U* characteristic of the photovoltaic cell.

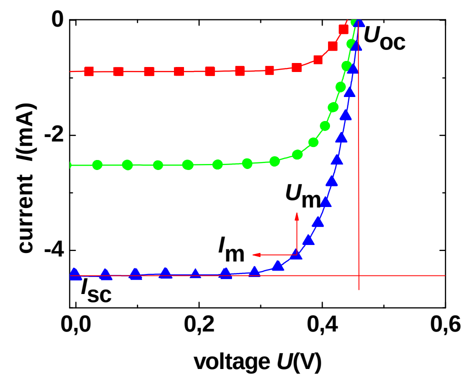

Figure 5. *I-U* characteristics of the cell for illumination with three relative light intensities: *L* (triangles), 0.7 *L* (circles) and 0.4 *L* (squares).

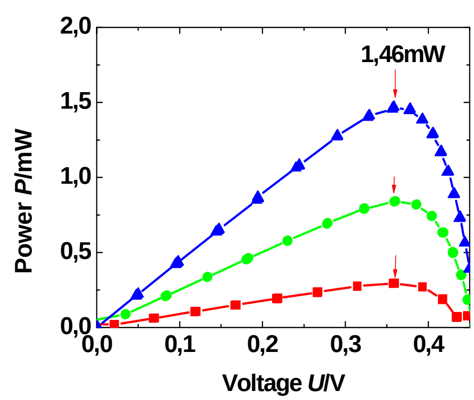

Figure 6. The output power *P* vs. cell voltage *U* dependence of the cell for illumination with three relative light intensities: *L* (triangles), 0.7 *L* (circles) and 0.4 *L* (squares).

the diode; the maximum power for the light intensity L is

$P_m = I_m U_m = 1.46$ mW

and the optimum load resistance

$R_{mload} = U_m / I_m = 0.359$ V/ 4.1 mA = 87 Ω.

Ideality factor of the cell

The ideality factor a of the PV cell evaluation is in Figure 7, evaluated from the data in Figure 5, according to eq. (6). Its value is $a = 1.0$. Additionally we can determine the reverse current of the cell to be $I_0 = 1.9 .10^{-5}$ mA = 1.9 $.10^{-8}$ A.

DISCUSSION AND CONCLUSIONS

Recently, we have used the remote experiment in a set of physics experiments and tested it on students, who accepted the experiment with considerable interest[15]. So, it is possible to summarize the main experience of the remote experiment:

1. it is interactive (the students can influence the adjustment of the principal parameters of the experiment),
2. it is exerted in real time (the experiment is running on line with image presentation available), and,
3. it is accessible across the entire Internet network, without any principal geographical limitations.

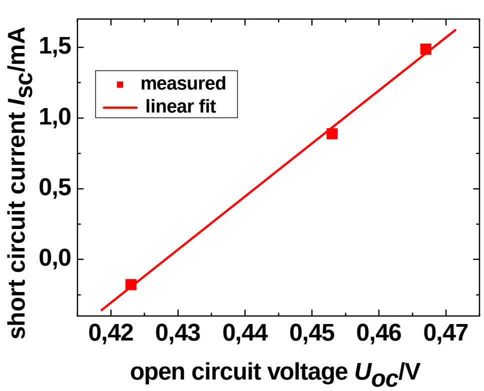

Figure 7. The short circuit current I_{sc} vs. open circuit voltage U_{oc} of the cell.

The main advantage of our server-client approach used here is that it is based exclusively on the Java environment provided by the server, information is forwarded using web services and uses common web browser and active Java environment on the client side.

The team was encouraged by the previous results to undertake an experiment in more demanding area of Materials Science. The basic difference rested in the fact we intended to devise a scientific experiment with precise and reproducible data on a microphysical solid-state object. This paper presents the result of our activities using an example of a remote experiment for Materials Science education, exemplified on solid-state photovoltaic cell characterization. The remote experiment described brings information on the main functions and parameters of the transformation – radiant *vs.* electrical energy, enabling experimenters to determine basic quantities like the short-circuit current of the cell, its open circuit voltage and the fill factor, reverse current, ideality factor, internal resistance for the optimum power transmission. Additionally, it is possible to determine the elements of the equivalent electrical circuit and their light intensity and temperature dependence. Also, the simulation of the PV cell characteristics using the theory and subsequent comparison with the measured data is feasible.

The experiment is suitable for lectures, laboratory exercises and self-study activities. The remote experiment of a solid-state photovoltaic cell characterization was used as qualitative introductory experiment in lecture course on electronic solid–state devices, where the efficiency of the solar cell was the topic. The lecture was for 2nd year students, studying physics as future teachers of physics.

In the laboratory exercise the students used the remote experiment of solid-state photovoltaic cell characterization and examined in detail the main characteristics of the solar cell, using the detailed instructions and the remote experiment on the web site[15] and then presented the results in the standard laboratory report. Also, for the majority of time, we used the instructor at the place of the experiment who was connected with the students by voice and camera for instructions and help. The instructions included a questionnaire with the questions concerning the technique itself, the quality of the accompanying text, the instructor's role both in - house and at the place of the remote experiment.

The general appraisal of the remote experiment by the students was very positive. They appreciated especially the development of a new technique, the possibility to measure and obtain the data at the most suitable time for them and the skills learned in ICT (information-communication technology).

The remote experiment solid-state photovoltaic cell characterization was also used in examinations. The students were asked theoretical questions aiming at function, optimisation and exploitation of solar cells and were encouraged to use the on line experiment and data to explain the theoretical concepts in PV conversion. This approach was appreciated by the students, as they were not forced to memorize the formulas, but were encouraged to apply the theory in a constructive and problem solving way.

A more detailed and exact pedagogical experiment is under way and will be reported later.

The main conclusions may be formulated as follows:

- The dedicated e-learning remote experiments are suitable for interactive Materials Science experiments in integrated learning[16] or e-LTR (e-Learning, e-Teaching and e-Research)[7] approaches;
- The remote experiments in Materials Science are suitable for international exchange at the university level of education in all its forms (lecture, laboratory exercises, self study);
- For high efficiency of remote experiments enormous care should be exerted in preparing the introductory explanatory tools;
- The human factor, provided by instructor counselling and feedback is another factor influencing the success of e-Learning remote experiments;
- It is necessary to introduce provisions for checking results and gathering feedback on activities of students in fulfilling the goals of the teaching process.

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