SEMI-NUMERICAL SIMULATION OF SILICON SOLAR CELLS JUNCTION GEOMETRY USING C-U PROFILING TECHNIQUES

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ABSTRACT

This paper reports issue of a geometry and *pn* junction position assessment in order to electro-optical properties optimalization for different applications. In addition, examination of the mentioned parameters may have fundamental matter to interpretation of unconventional electrical characteristic such as current-voltage curves or quantum efficient curves. Sample analysis, presented here, is based on experimental measurement of C-U curves and numerical simulation of impurities diffusion from gaseous state (assume constant gas pressure). We managed to get information about junction position and junction width even thought junction is strongly unsymmetrical and its part must be neglected in case of analytical solution. Last but not least, we discuss issue of reduction or/and expansion of junction width with reverse voltage due to surface geometrical texturizing. To this end, the microscopic study of the samples surface is presented, too.

1. INTRODUCTION

Solar cells, in general, are frequently discussed and they become acceptable green energy sources. By the same taken, over 80 % world solar cells production is based on the thick-film silicon technology and electrical efficiency in most cases not exceed 15 %. One of the main limiting factors is imperfections in the structure caused by not perfect production (impurities intrusion, speed of metallic contacts cladding etc.). Even thought, solid state physics is at very good level at present, some of the observed phenomena still are not strictly explain. In addition to above, in case of the solar cells is situation complicated because of surface texturizing.

Most widely used pyramidal shaped surface is depicted in Fig. 1. Figure 2 shows distribution of the texturizing high probability density (sample under investigation is labeled Q1). Mean high value, μ, is 2.7 μm and standard deviation, σ, 1.6 μm. The solid line is Gaussian-like probability density for comparison. One can also say that 75 % pyramid high is between $1.8 \div 3.6$ μm. It is generally known that absorption of incident light in the semiconductor material vary significantly with the light wavelength. The energetic light penetration depth is short hence the *pn* junction must be situated close to the surface. It makes

solar cells susceptible to damage and parameters get worst. Equation (1) makes connection between short-circuit current, I_{SC} and the light wavelength λ.

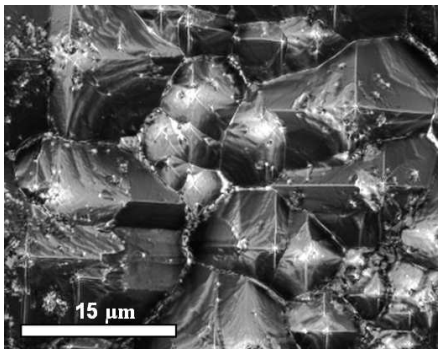

Figure 1: The solar cell surface topography image - pyramidal texture (typical sample)

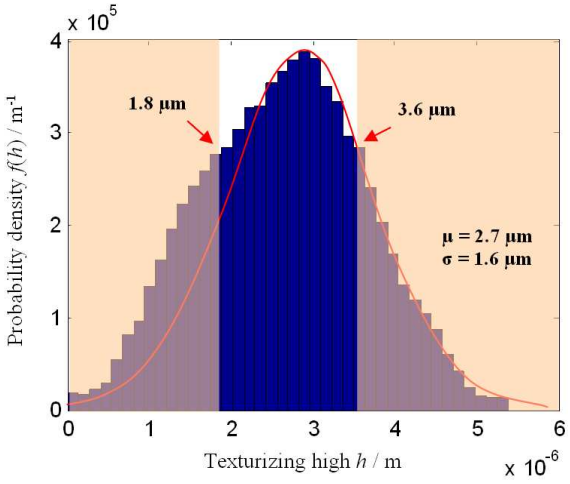

Figure 2: Probability density distribution of the solar cell surface high, sample labeled Q1

It holds (adapted from [1]):

$$\frac{dI_{SC}(\lambda)}{d\lambda} \cong \alpha\lambda(L_n + L_p)\exp(-\alpha d)\,, \tag{1}$$

where L_n a L_p are diffusion lengths, α is the absorption coefficient and d is the junction deep (referred to surface). The principal question is, however, to what degree *pn* junction traces surface texture, how is related the junction area to the sample area and its dependence on reverse voltage. To this end we introduce voltage-capacitance measurement and simulation of diffusion process.

2. C-V MEASUREMENT METHODOLOGY AND RESULTS DISCUSSION

Conventional approach is extraction of impurities concentration mean value from the experimental C-V data. It is applicable on Schottky diode, MOS as well as on the *pn* junction structure. Let's pay attention to the solar cell, with demonstrable just one n^+p junction near the surface. Figure 3 illustrates experimental set-up principle for barrier capacitance measurement (barrier capacitance pertinent to the space charge region width W and is a function of the reverse voltage bias U_R). Measurement technique intendeds to be material permitivity and the space charge region area (the junction area) known and it is applicable for contact-less samples, too. In our case samples are placed between two conductive electrodes in optically dark environment (electrodes also suppress sample self-heating). Measurement technique is known as an *auto balancing bridge method* and sample impedance, Z_x, is determined numerically (sample voltage and current are known). Bias voltage is realized as a superposition of dc voltage with a small ac harmonic component (not more than 500 mV). More information can be obtained in literature, [2]. It is to be noted here, that low level injection conditions must be satisfied otherwise inertial properties of samples will be caused by excess carriers located in quasi-neutral regions.

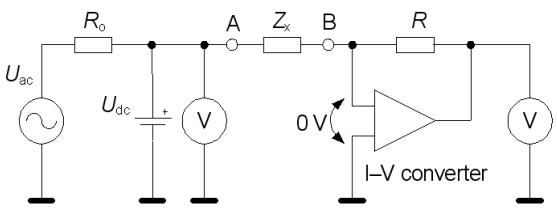

Figure 3: C-V characteristics measurement set-up principle of operation, Z_x is impedance of sample

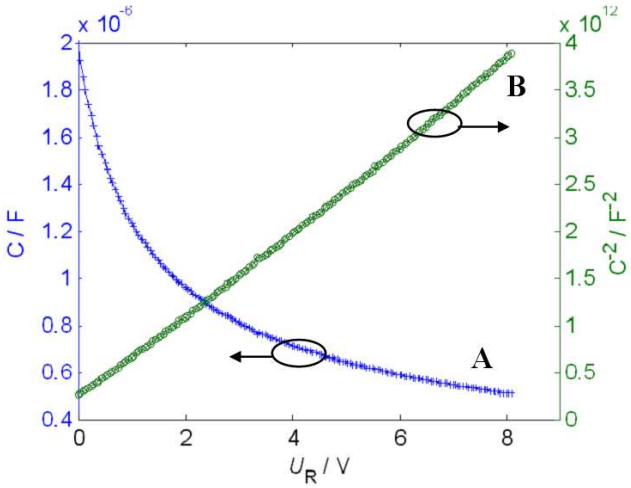

Figure 4: Experimental characteristics $C = f(U_R)$ and $C^{-2} = f(U_R)$ of sample 25A_1 in dark environment, $T = 27$ °C

If we use mathematic description of experimental data based on Poisson's equation in the form $dE/dx = eN_a^- / \varepsilon_0\varepsilon_r$ (here E denotes electric field intensity, N_a^- ionized acceptors concentration), it is possible to show capacitance functional relation for two essential junction geometry. If abrupt junction plays role here capacitance and voltage relation is $C = a \cdot U^{1/2}$ on the other hand for linear graded junction holds $C = b \cdot U^{1/3}$ (here a, b are material constants), [1]. It is worthwhile to say that solution for generalized junction geometry is not possible obtain analytically. The experimental results of sample 25A_1 barrier capacitance measurement are depicted in Fig. 1 (curve A). The same figure illustrates also experimental data in the $C^{-2} = f(U_R)$ form (curve B) and relevant curve seems to be linear. On this account we can say that the solar cell junction is abrupt (non-symmetrical concentration step). One may be confused because of diffusion technique is used for the junction creation and the linear graded junction is expected. Pay back attention to Poisson's equation in thermodynamic equilibrium. Coupled charge in both side of junction must be equal and evidently hold relation $d_1 / d_2 = N_a / N_d$ (N_d denotes donor concentration and d_1, d_2 are space charge region width). In case of high value of N_d, d_1 is small and the junction acceptor side is not affected significantly - concentration profile seems to be abrupt. For our sample 25A_1 function $C^{-2} = f(U_R)$ plot is evidently linear and curve slope, a, is $1.488 \cdot 10^{-6}$ $V \cdot C^{-1/2}$. The *pn* junction area S_{pn} is here 0.0160 m^2 (for more information see [3] and [4]) and after some simplification (depletion approximation and assumption that all impurities are ionized) we can obtain the mean value of ionized acceptors $N_a^- = 1.1 \cdot 10^{21}$ m^{-3}. Details of mathematic background are listed for an example in [1].

3. THE PN JUNCTION FORMATION SIMULATION

As mentioned before, what we need is to determine junction geometry and area expansion with the reverse voltage. To this end, we introduce semi-numerical model in Matlab computing environment. Two basic approaches have been simulated. First one represents an ideal abrupt junction and the second one an idealized real junction created by diffusion (impurities in the gaseous state). Simulation input information are only constant gas pressure, diffusion temperature approx. 900 °C and finally doping elements are boron and

phosphorus. The concentration profile is possible to obtain using differential Flick equation and boundary conditions are $N(x = 0, t) = N_0$ and $N(x = \infty, t) = 0$ (here x denotes x-coordinate, N is concentration, N_0 boundary concentration and finally t is time). Analytical solution is, [1], [5]:

$$N(x,t) = N_0 erfc\left(\frac{x}{2\sqrt{Dt}}\right). \tag{2}$$

Here D is diffusion constant; $erfc(x)$ is complement error function and it holds $erfc(x) = 1 - erf(x)$ and $erf(x) = 2/\sqrt{\pi}\int_0^x e^{-t}dt$. Figure 5 demonstrates simulation results in semilogarithmic scale.

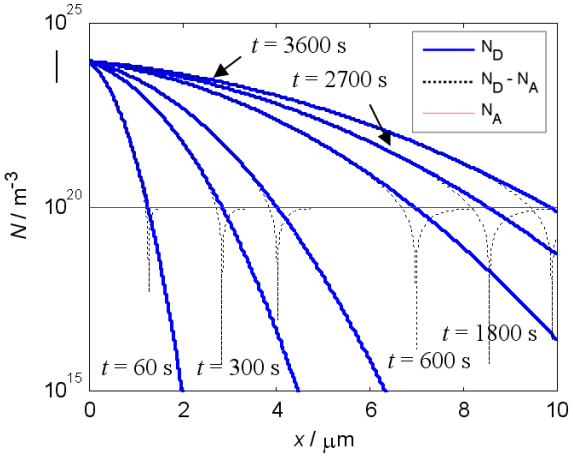

Figure 5: Diffusion process simulation, $N_0 = 10^{24}$ m^{-3}, $N_a = 10^{20}$ m^{-3}, $D = 9 \cdot 10^{-16}$ m^{2}s^{-1}

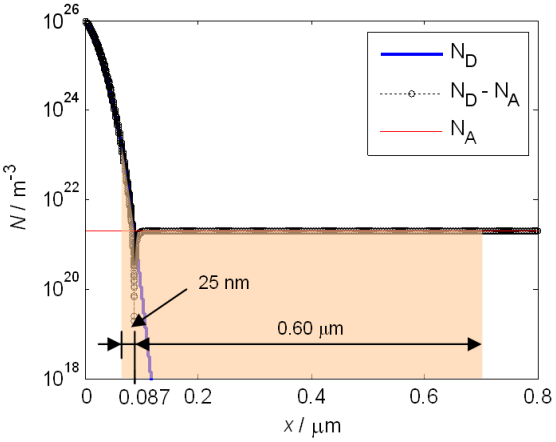

Figure 6: Solar cell pn junction simulation, substrate acceptor con. $N_a = 1.1 \cdot 10^{21}$ m^{-3}, $N_0 = 10^{26}$ m^{-3}, $D = 5.8 \cdot 10^{-20}$ m^{2}s^{-1}, $t = 3600$ s

The solar cell substrate has a uniformly distributed impurities and the surface dopand concentration is $N_a = 1 \cdot 10^{20}$ m^{-3}. Donor and acceptor concentration difference is illustrated in the same figure and junction centre becomes evident. It is obvious that diffusion is strongly dependent on time, temperature and diffusion constant, D. Nevertheless, adequate information for concrete material are listed in literature e.g. [6]. For our solar cell sample 25_A we use following parameters: substrate acceptor concentration $N_a = 1.1 \cdot 10^{21}$ m^{-3}, depletion region width $W_p = 0.6$ µm (depletion and one-sided junction approximation was used), $D = 5.8 \cdot 10^{-20}$ m^{2}s^{-1} and diffusion time approx. $t = 3600$ s. Simulation results are included in Fig. 6. Solution procedure is based on iterative finding of coupled charge neutrality in both section of semiconductor (realized in Matlab). Certain error arises in consequence of one-sided approximation because W_p is not total junction width. Even thought this method provides very good estimation of junction geometry. Simulation proved that one-sided approximation conditions are satisfied and practically $W_p = W$ hold. Junction centre is located approximately 87 nm below the surface (see Fig. 6), space charge region in n-semiconductor, W_n, is 25 nm (at zero bias conditions). On the basis of these results is possible to suggest concentration profile and discussed issue of effective junction are affection

by reverse voltage. Let's pay attention back to probability density distribution $f(h)$ in Fig. 2. It turned out, that most pyramids high are between 1.8 ÷ 3.6 μm. Dominant W_n region width naturally increases with reverse voltage but still less and less because of increasing donor concentration on the opposite junction side. In case of common reverse voltages close to 8 V (non-destructive voltage limit) the depletion region is not deeper than 3 μm. So, inevitable error has a reasonable value.

4. CONCLUSION

In this paper we deal with some difficulties relating to *pn* junction geometry and area assessment. This information can cause fundamental affection of different generally measured electrical characteristics. It is worthwhile to say that several simplifications have been used because solved problem is very difficult.

5. ACKNOWLEDGMENTS

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