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Basic model of absorption depth and injection levels in silicon under intermediate illumination levels

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ABSTRACT

In this paper we present a novel model that connects the absorption depth of photons into silicon with the power of the applied illumination. So far in the literature the absorption depth was solely dependent on the wavelength of the illuminating photons. The new relation is important for better designing silicon based devices that are illuminated with high power lasers. Experimental results validate the proposed modeling.

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1. Introduction

The optical absorption depth into a semiconductor in general, is classically defined as $1/\alpha$, where α being the absorption coefficient per unit of propagated length inside the semiconductor material (the z axis), i.e. the depth at which the incidence intensity drops to 1/e of its value. This relation is a fundamental parameter, and its definition is free of the intensity of the illumination. The general propagation of illuminated light is determined according to the Beer–Lambert law [1]:

$$I(z) = I_0 \exp(-\alpha z) \tag{1}$$

where I_0 is the incident intensity and $I(z)$ is the axial dependence of the intensity on the absorption depth z into the material. The absorption coefficient, α, can also be regarded as the carrier concentration in the semiconductor. Therefore we claim that in some concentration the presence of charge carrier's will influence and increase the absorption depth.

Specifically in silicon the spectral absorption as well as the absorption depth [2,3] (defined as $1/\alpha$) may be temperature dependent [4,5] or micro structures affected [6–8]. However in all cases the absorption depth of the generated free carriers are treated according to the Beer–Lambert law. This absorption coefficient α is treated as purely wavelength dependent, such that for the visible range the coefficient is high and when approaching a wavelength of 1070 nm this coefficient drops sharply.

In several applications it is advantageous to use silicon based all-optical modulators [9] based upon the plasma dispersion effect in silicon, stated that illuminating a semiconductor with photons having above band gap energy will generate electron–hole pairs that modifies the real and imaginary parts of the refractive index of the semi-conductor [9]. This refractive index modification controls the optical properties of the silicon at infrared (IR) wavelengths, and enables to modulate IR wavelengths by using illumination at lower wavelengths (below 1000 nm). In those devices the dimensions of the volume in which free carriers are generated is highly critical in determining the extinction ratio of the resulted device as well as its response rate [10], and these parameters are controlled by the absorption of the photonic control command (i.e. the absorption depth for the wavelength used for the control or the pump command of the modulator),

In Ref. [11] Raghunathan et al. presented the first experimental results of nonlinear absorption in silicon at the mid-IR wavelengths which also indicates that the absorption depth in silicon is intensity dependent. Note that the work of Ref. [11] focused on wavelengths that are normally non absorbed in silicon in low intensities, while this paper investigates the change in the absorption depth for wavelengths that are normally absorbed in silicon also for low intensities (e.g. for wavelengths below 1070 nm).

In this paper we model and then experimentally examine the absorption depth, and claiming that it is dependent on the power of the illumination itself, and not only on its wavelength.

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We developed a simplified model for the absorption depth in silicon, which ignores the enhanced reflection from the generated carriers (in high excitation levels the sample posses almost metallic like properties from this point of view) and thus it is more suitable to model change in properties for medium level of illumination power. In order to be able to ignore those enhanced reflections a femto second laser is used.

The paper is structured as follows: in Section 2 we present the proposed model. In Section 3 we investigate it numerically and experimentally. The paper is concluded in Section 4.

2. The proposed modeling

In the following model we intend to investigate the change in the absorption depth for medium intensities of illumination, with photons energies higher than the band-gap (i.e. photons that are conventionally absorbed in silicon as they are having wavelength less than 1.1 μm). Therefore, and in contrast to Ref. [11], we will not discuss nonlinear absorption in silicon at the mid infrared wavelengths (as two photons absorption) since this situation is of lower probability, and these terms are neglected in the derivation (while focusing on the linear regime of absorption).

For the sake of simplicity and solubility of the mathematical model a few assumption had to be taken: (a) refractive index modification. Although the refractive index drops with the optical power, we assumed a constant refractive index. Assuming pulse energy in the order of μJ at 1020 nm wavelength, about 10^{13} photons are illuminating the surface while merely 50% of them are generating electron–hole (e–h) pairs due to quantum yield and back reflection. The refraction index depends on the free carriers' concentration, and will change gradually as the incident light approaches the sample. Modifying the refractive index by unity will decrease the transmittance only to ~0.9. (b) Surface recombination, which can imbalance the excess carrier population due to its high rate. It also had been neglected since we cannot measure it experimentally (this process is faster than the capabilities of our experimental setup). We further minimized this effect by using relatively long wavelengths (having low absorption coefficient) that will generate low concentration near the surface. This very reason of using wavelength of low absorption coefficient allows us also to assume injection levels low enough to avoid Auger recombination process and to avoid significant effects on carriers' mobility.

In our modeling we denote by E_J the energy of the illuminating beam (the control/pump beam) and by M the number of photons in this beam:

$$M = \frac{E_J}{hc/\lambda} \tag{2}$$

h is the Plank constant, c the speed of light and λ is the wavelength of the illuminating beam. The total number of not excited electrons per unit volume is [12]:

$$N_{con} = \int_{-\infty}^{E_v} N(E)f(E)dE = \int_{-\infty}^{E_v} \frac{N(E)dE}{\exp(E-E_f/kT)+1} \equiv N_0 - n \tag{3}$$

with $N(E)$ being the density of available states per energy level, $f(E)$ the probability density for accommodating a given energetic state (this is assumed to be the Fermi–Dirac distribution), dE being infinitely narrow energetic band and E_V the upper level of the valence energy band. E_f is the Fermi energy level, k is Boltzmann constant and T is the temperature. After performing the integral of Eq. (3) one obtains:

$$N_{con} = N_0 - n = N_0 - N_c \exp\left(-\frac{E_c - E_F}{kT}\right) \tag{4}$$

where E_c is the lower energy level in the conductance band and N_0 is the total number of states per unit volume in the semiconductor, which basically equals to:

$$N_0 = \int_{-\infty}^{\infty} N(E)dE \tag{5}$$

Note that the constant N_c is the effective density of states in the conduction band and it equals to:

$$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \tag{6}$$

where m_e is the mass of the electrons in the semiconductor. We will denote by N_R the number of electrons (per unit volume) that can be excited due to the incident of a photon, and it equals to:

$$N_R = \int_{E_v-(hc/\lambda-E_g)}^{E_v} N(E)f(E)dE \tag{7}$$

where E_g is the energetic band gap. The probability of releasing an electron with a photon, per unit of axial distance of propagation δZ inside the semiconductor, equals to:

$$P_{release} = P_{interaction}P_{release/interaction} = P_{interaction}\frac{N_R}{N_{con}} \tag{8}$$

On the other hand, following the Beer–Lambert law of Eq. (1), this probability to release an electron also equals to:

$$\exp(-\alpha_0 z) = \left(\exp(-\alpha_0 \delta z)\right)^L \tag{9}$$

z is the average axial absorption depth which is known from the literature per given wavelength of illumination [13]. L is an integer such that: $z = \delta ZL$. Thus, for weak illumination power we have:

$$\exp(-\alpha_0 \delta z) = P_{release} = P_{interaction}\frac{N_R}{N_{con}} \tag{10}$$

and therefore:

$$z_p^{(w)} = \frac{1}{\alpha_0} = \frac{-\delta z}{\ln\left(P_{interaction}\frac{N_R}{N_{con}}\right)} \tag{11}$$

where $z_p^{(w)}$ is the average axial absorption depth for weak illumination. For strong illumination we have average absorption depth denoted as $z_p^{(s)}$ and which equals to:

$$z_p^{(s)} = \frac{1}{\alpha} = \frac{-\delta z}{\ln\left(P_{interaction}\frac{N_R}{N_{con}-m}\right)} \tag{12}$$

where m is the number of already absorbed photons. Therefore, the average absorption depth in the case of strong illumination will be:

$$\left\langle z_p^{(s)} \right\rangle = \left\langle \frac{1}{\alpha} \right\rangle = \frac{1}{M}\int_0^M \frac{-\delta z}{\ln\left(P_{interaction}\frac{N_R}{N_{con}-m}\right)}dm \tag{13}$$

while $\langle \dots \rangle$ denotes averaging operation. We can simplify the expression and obtain:

$$\begin{aligned}\left\langle z_p^{(s)} \right\rangle = \left\langle \frac{1}{\alpha} \right\rangle &= \frac{1}{M}\int_0^M \frac{-\delta z}{\ln\left(P_{interaction}\frac{N_R}{N_{con}}\left(\frac{N_{con}}{N_{con}-m}\right)\right)}dm \\ &= \frac{1}{M}\int_0^M \frac{-\delta z}{\ln\left(P_{interaction}\frac{N_R}{N_{con}}\right)+\ln\left(\frac{N_{con}}{N_{con}-m}\right)}dm\end{aligned} \tag{14}$$

which simplifies to:

$$\left\langle z_p^{(s)} \right\rangle = \left\langle \frac{1}{\alpha} \right\rangle = \frac{1}{M}\int_0^M \frac{dm}{\alpha_0 + (1/\delta z)\ln(1-(m/N_{con}))} \tag{15}$$

Indeed for $m \ll N_{con}$ we obtain that the average axial absorption depth is $1/\alpha_0$ as known from the Beer–Lambert equation

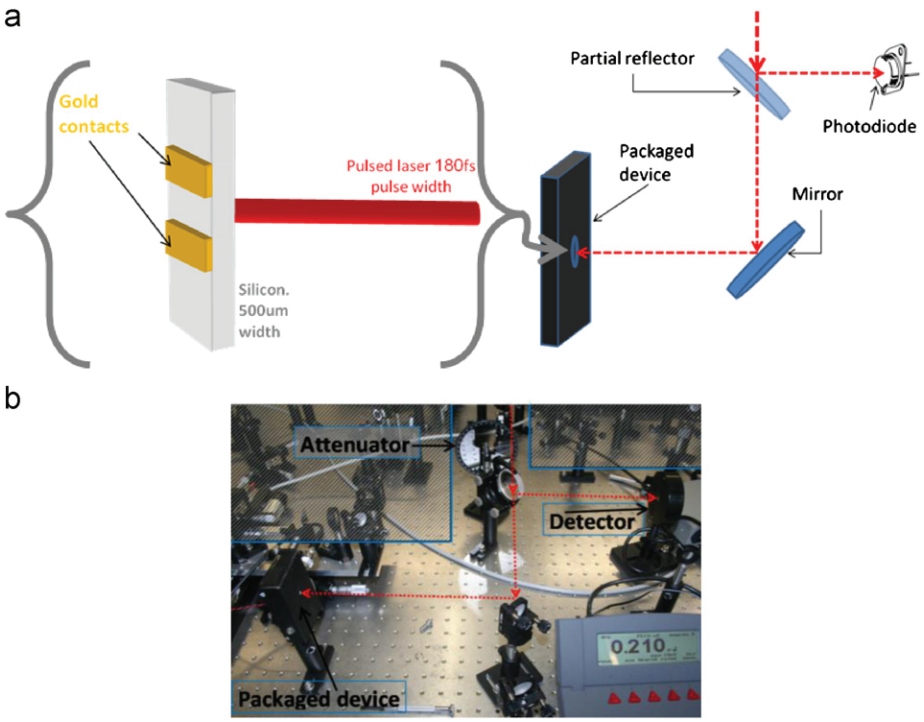

Fig. 1. (a) Schematic illustration of the test sample. (b) The experimental system: the laser beam (red dashed line) attenuated and sampled before it normally incidents on the packaged silicon sample. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

(Eq. (1)). Note that in Eq. (15) it is more accurate to do a summation rather than an integral since m is actually an integer (although varying in a very large range of 0 to M), and thus:

$$\left\langle z_p^{(s)} \right\rangle = \left\langle \frac{1}{\alpha} \right\rangle = \frac{\delta z}{M} \sum_{0}^{M} \frac{1}{\alpha_0 \delta z + \ln(1-(m/N_{con}))} \tag{16}$$

Note again that in our notation m is the number of absorbed photons and M is the total number of the illuminated photons.

3. Experimental results

The experiment objective is to investigate the influence of the optical power on the charge distribution in a thick silicon layer. The basic element consists of a 500 μm thick intrinsic silicon optically polished wafer with resistivity $>1000\,\Omega$-cm (we measured it using 4-probe to be $\sim 1600\,\Omega$-cm,) as a sample with orientation of $\langle 100 \rangle \pm 0.9^{\circ}$. On the sample a 100 nm thick Au contacts were grown on top of 5 nm adhesion Cr layer (see Fig. 1(a)). The resistivity measurement and the electrode sputtering process were performed after treating the silicon with HF to remove the native oxide layer. The Au and the Cr layer were sputtered through a metallic mask, using BesTec 4″ UHV sputtering and evaporation system. In the sputtering process we used a flat polished solid metal mask that sealed the device surface. The contacts configured from two stripes 2 mm × 20 mm with 2 mm separation, and having experimentally measured resistance of $\sim 5\,K\Omega$. The constructed experimental system may be seen in Fig. 1(b).

Note again that the resistivity of the silicon was measured by a 4-probe system to be $\sim 1600\,\Omega$. This resistivity and the contacts resistivity is very small comparing to the measurement device (o-scope) and therefore a two-probe measure is accurate enough. The electrodes separation is slightly larger than the beam diameter and they were placed on the backside of the sample so practically no light could have reached the electrodes.

The laser system consists of Pharos (Light Conversion LTD) Yb:KGW laser, which produces an average power of 4 W at wavelength of 1028 nm and with pulses with temporal width of 180 fs and a repetition rate of 5 KHz.

This laser is pumping an ORPHEUS optical parametric amplifier (OPA) that converts the input wavelength to 1020 nm. The laser intensity was sampled with OPHIR PD10-V2 photodiode energy meter, averaged over 1/2 a second of measurement.

The fact that a femto second laser was used is important in the context of this experiment and coincides with the assumptions of the theoretical model. Such a short pulse in time spreads also on a short space (180 fs pulse occupies 15.4 μm inside the silicon sample), thus as the pulse propagates through silicon the free electrons are generated step by step and a spatial sampling is performed. This avoids various scattering effects (generated for optical axially non localized photons) that may prevent new incoming photons from penetrating into the silicon wafer when high amount of free electrons has already been released in the wafer.

In order to reduce ambient noise coming from direct ambient light as well as from external electro-magnetic noises, the sample and the entire electrical circuit (depicted in Fig. 2) was sealed in a black metallic package acting as a Faraday cage (to eliminate the influence of external electric\static fields), with a 2 mm hole for the laser beam input. The sample was attached to the package with an insulating spacer.

In order to measure the resistance, which should be proportional to the charge carrier density, we used Wheatstone bridge configuration, as depicted in Fig. 2. A stable power source, Yokogawa 7651, supplied a stable DC voltage of 10 V which was sampled through a TDS7514B oscilloscope (1.5 GHz at 20 GS/s) averaging the readout from 1000 temporal samples.

We detected signal average rise time of 220 ps. However it should be noted that additional time constants, i.e. the capacitance of the device itself, the capacitance of the oscilloscope and the capacitance between the sample and the package, can contribute to the rise time.

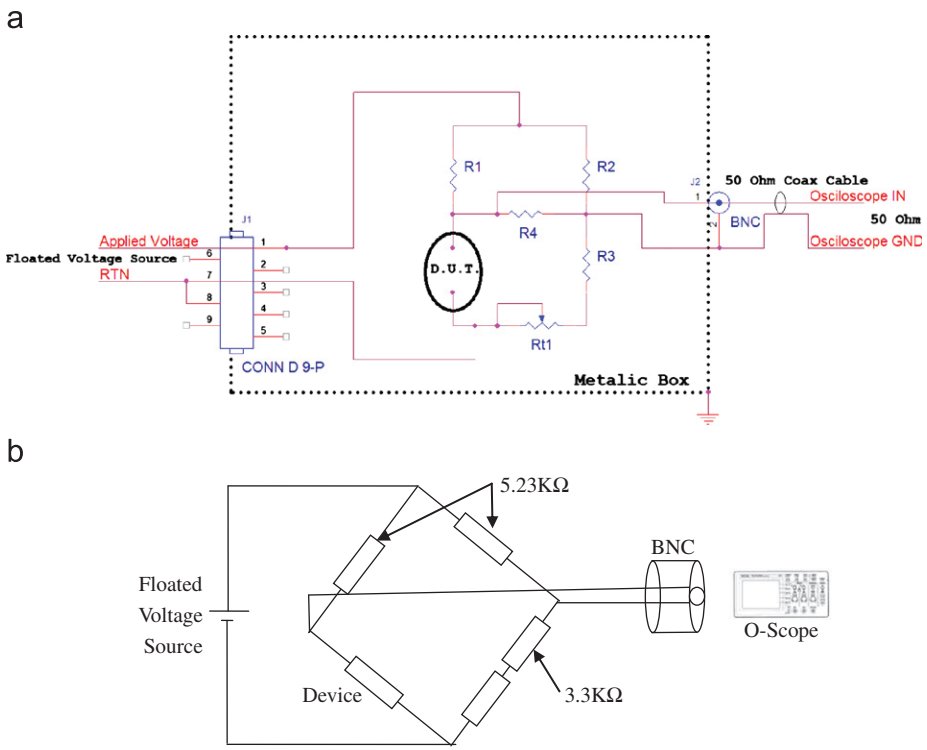

Fig. 2. The measurement circuit. (a) $R_1=R_2=5.32$ KΩ, $R_3=3.3$ KΩ, R_t is a trimpot (5 KΩ 10 T) and D.U.T stands for device under test i.e. the sample from Fig. 1. The whole system is packed inside a metallic box with input and output connectors. (b) The same circuit presented in a more visual representation.

The sample was illuminated from the back side with the 1020 nm wavelength laser having optical beam of 2 mm in its diameter. For this wavelength the low-power absorption coefficient is 39.9 cm^{-1} i.e. ~250 μm absorption depth [13].

Note that in general, the light decays exponentially according to Beer–Lambert law. We measure only the tail of the created charge carriers since the electric field penetration is very low and only the charge carriers that are in a close proximity to the back side will contribute to the change in resistivity. Solving the approximation to the ambipolar transport equation [14] may show that the total change in resistivity depends on the total amount of generated carriers and not on their distribution. However our case is a bit different since the measurement above provides the sheet resistance, according to the axial sampling generated by the propagation of the pumping pulse as mentioned above. This measure of the resistivity averaged over the sample thickness, defined as $1/\sigma_{tx}$ for a uniform sample (σ is the conductivity and t_x is the sample thickness), where for non uniform samples it is defined as an integral $\left(\int_0^{t_x}\sigma(x)dx\right)^{-1}$. Thus, we are considering only the first rise which indicates the charges build up due to the pulse itself and not the total integral that will include also charges from deeper Silicon's layers.

Since the light decays exponentially the free carriers' distribution is non uniform and it is lower at the electric contacts face of the sample. Accordingly, we claim that this measurement, which considers only the first rise, measures only the 'tail' of the generated charge carriers. The resistivity drops, which is expressed in a voltage buildup and it is an indication of the concentration of the charge carriers. Thus the carriers which are in a close proximity to the electrodes participate in the process before the remote carriers. The measured resistivity integral considers only a portion of the sample thickness t_x.

The mobility μ decreases exponentially with the carriers' concentration [15], thus the carriers in the bulk are relatively slow and in the measured time period they do not affect the measurement, especially in the absence of drifting field. Below concentration of 10^{14} cm^{-3} the mobility is approximately constant (~1400 cm^2/V-s for electrons and ~500 cm^2/V-s for holes [15]) and the electronic diffusion coefficient is $D=\mu kT/q\approx 36$ cm^2/s (where k is Boltzmann constant, q is the electrical charge of an electron and the temperature T is 300 °K). The electron velocity in our experimental system will be in the order of 1000 cm/s which means that during the rise time (of ~200 ps) no bulk electrons are present since in such a short time they travels only a few nm. Moreover, it can be seen that after the first peak there is an appearance of carriers that are more distant from the bulk and which are having relatively long life time of several microseconds and which migrate to the test zone and affect the measurements.

In Fig. 3 we present two measurements in intensity of ~2.5 μJ per pulse. The fast rise time (of about 200 ps) can be clearly seen in Fig. 3(a), followed by some voltage oscillations due to migration and decay of carriers (as previously mentioned). Fig. 3(b) shows the overall decay in larger time window of sub micro-second time scale. The initial rise is due to the carriers generated near the electrodes. This population decays quickly due to surface recombination which is a fast process and which causes the slight drop of voltage after a few nanoseconds. The second rise is due to migration of carriers from the bulk, where their recombination causes the followed decay, as seen in Fig. 3(b). In the measurement the current was 10 V/~5 KΩ which is about 2 mA. The sample cross-section was 500 μm thick, 2 mm electrodes separation, and 20 mm long.

If we regard the absorption coefficient to be independent of the laser intensity, one should expect a linear increase of the measured charge carriers' intensity since the absorption depth is defined as the depth at which $I/I_0=e^{-1}$ and this ratio should be constant for a given wavelength. However, from Fig. 4(a) one can see a clear logarithmic behavior of the absorption depth in the experimental data.

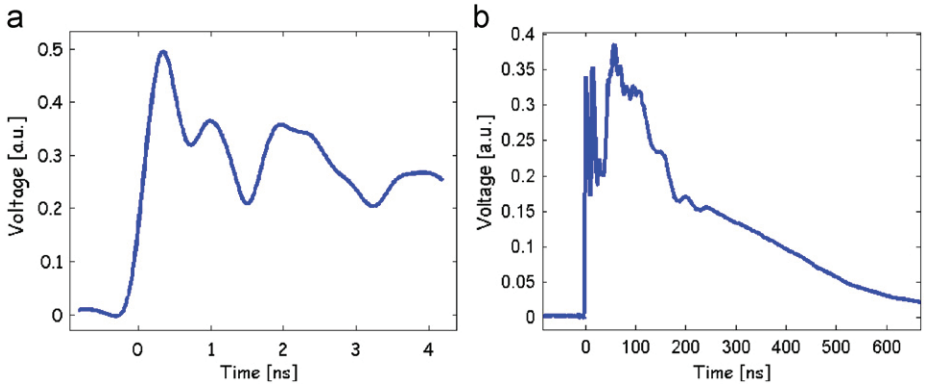

Fig. 3. Plots of the measured voltage at: (a) 500 ps/div and (b) 80 ns/div (1000 samples on average).

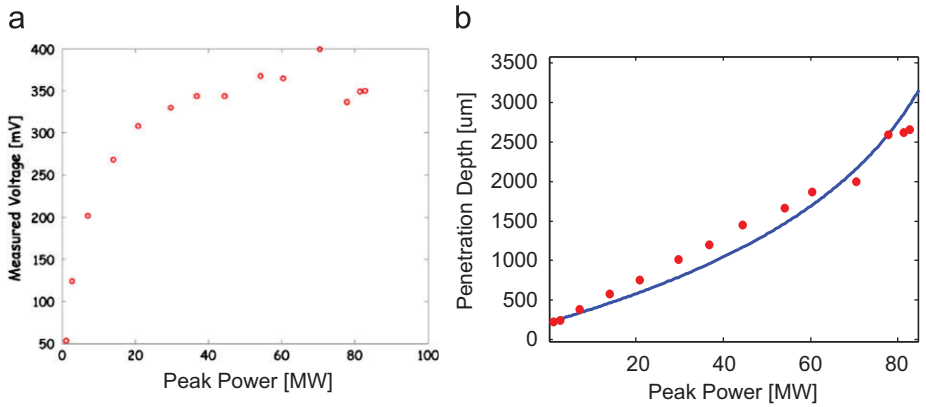

Fig. 4. (a) Measured resistivity (obtained by measuring the voltage) versus the power of the illuminating beam. (b) Conversion of the experimental electronic measurement into the absorption depth (red circles) and plot of the numerical model (blue solid line). (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)

The experimentally obtained electronic measurement results that are presented in Fig. 4(a) were converted into photonic absorption depth by computing the electronic concentration from the applied voltage and measured currents/resistivity:

$$n = \frac{J}{q\left(\mu_e + \mu_p\right)(V/d)} \tag{17}$$

where q is the charge of an electron, J the current per unit area, μ_e and μ_p are the mobility of the electrons and the holes respectively, V is the measured/applied voltage and d is the distance between the electrodes. The current density J was computed by measuring the voltage over the known value of the resistors in the constructed Wheatstone bridge (see Fig. 2(b)).

Then, the concentration of the free electrons was converted into optical intensity by multiplying it with the volume V_0 and with the energy of a single photon being hc/λ (h is Plank's constant, c the speed of light and λ is the illumination wavelength):

$$I_{optic} = nV_0\frac{hc}{\lambda} \tag{18}$$

In Fig. 4(b) we plot with red circles the conversion of the experimental electronic measurement into the absorption depth as obtained from Eqs. (17)–(18). The number of electrons from Eq. (17) is calculated through the measured peak voltage, as described, to produce the optical intensity of Eq. (18). The absorption coefficient is proportional to $\log((I_{input}-I_{optic})/I_{input})$, and the absorption depth is its reciprocal. The absorption depth presented in Fig. 4(b) was linearly normalized such as for low intensities it will fit its known values from the literature.

Over the same plot we also present in solid blue line the result coming from the numerical model that follows Eq. (16). One may see from the result of Fig. 4(b) that, in addition to the relatively good agreement with the experimental results and the numerical simulations, the obtainable relation between the effective absorption depth and the illuminating optical power is neither constant nor linear. The absorption depth is indeed illumination's power dependent.

Note that the experiments of Fig. 4 involved tuning the illumination power of the laser within the power range of peak power of up to about 90 MW which is equivalent to average power of about 80 mW.

4. Conclusions

In this paper we have presented a new model connecting the absorption depth of photons in silicon not only with the wavelength of the photons but also with the illumination power. In contrast to Ref. [11] the model was performed for wavelengths that are normally absorbed in silicon. The model was preliminary verified via experiment involving resistivity measurements.

The proposed model can be useful in order to better understand the operability of silicon based devices positioned in photonic configurations involving high illumination power.

References

[1] A. Beer, Annalen der Physik und Chemie 86 (1852) 78.
[2] M.A. Green, M.J. Keevers, Progress in Photovoltaics: Research and Applications 3 (1995) 189.

[3] H.R. Philipp, E.A. Taft, Physical Review 120 (1960) 37.
[4] D. Kovalev, G. Polisski, M. Ben-Chorin, J. Diener, F. Koch, Journal of Applied Physics 80 (2009) 5978.
[5] G.E. Jellison, F.A. Modine, Applied Physics Letters 42 (1982) 180.
[6] S. Veprek, F.A. Sarott, Z. Iqbal, Physical Review B 36 (1987) 3344.
[7] L. Hu, G. Chen, Nano Letters **7** (2007) 3249.
[8] A. Poruba, A. Fejfar, Z. Remeš, J. Špringer, M. Vaněček, J. Kočka, J. Meier, P. Torres, A. Shah, Journal of Applied Physics 88 (2000) 148.
[9] R.A. Soref, B. Bennett, IEEE Journal of Quantum Electronics QE-23 (1987) 123.
[10] R. Aharoni, O. Baharav, L. Bidani, M. Sinvani, D. Elbaz, Z. Zalevsky, Journal of the European Optical Society-Rapid Publications **7** (2012) 12029.
[11] V. Raghunathan, R. Shori, O.M. Stafsudd, B. Jalali, Physica Status Solidi A 203 (2006) R38.
[12] M. Zambuto, Semiconductor Devices, McGraw-Hill, New York, 1989.
[13] M.A. Green, Solar Energy Materials and Solar Cells 92 (2008) 1305.
[14] E.S. Rittner, Physical Review 101 (1956) 1291.
[15] S.M. Sze, Physics of Semiconductor Devices, 2nd ed., Wiley, New York, 1981.