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1998 J. Phys.: Condens. Matter 10 5515

(http://iopscience.iop.org/0953-8984/10/25/004)

J. Phys.: Condens. Matter **10** (1998) 5515–5524. Printed in the UK PII: S0953-8984(98)89589-1

Modelling the operation of an a-Si:H based position sensitive detector

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Received 27 November 1997, in final form 11 March 1998

Abstract. A physical model is presented which allows calculation of the carrier and potential distributions and the output voltage of a one dimensional position sensitive detector based on an ITO/a-Si:H/Pd structure. The calculation results are in agreement with those experimentally measured. Using the experimental data the effective electron diffusion length in the ITO layer is estimated to be about 0.65 cm. The effect of surface recombination on the device characteristics is studied by a numerical method.

1. Introduction

Position sensitive detectors (PSDs) use the lateral photovoltaic effect [1] to determine the position of a light spot on a semiconductor surface. PSDs are used mainly for image detection, spatial position detection, vibration, angle and displacement measurements. The conventional structure of PSD is usually a p^+–n or p–i–n diode made on crystalline silicon [1–3].

Position sensitive detectors with hydrogenated amorphous silicon (a-Si:H) as a photosensitive layer have also been studied experimentally [4–8]. Compared to crystalline silicon a-Si:H is considered to be a very promising material for fabrication of large size optical sensors due to the following advantages: it is cheaper, has higher photosensitivity, wider band gap and allows deposition of large area homogeneous layers.

This motivated us to model the physical processes occurring in an a-Si:H based PSD exposed to a non-uniform illumination. By using the proposed model, analytical and numerical methods, we obtain information about the lateral distribution of the light generated carriers, potential distribution and the output voltage of the PSD. The calculation results are compared with experimentally measured characteristics of a one dimensional PSD.

2. Experimental details

The structure of the experimentally investigated device is shown in figure 1. The device is 1 cm long (along the x-axis) and 0.7 cm wide. The undoped a-Si:H layers with thickness 1 μm were deposited by the homogeneous chemical vapour deposition method [7]. Soda glass substrates, precoated with a 100 nm ITO layer (90% In_2O_3, 10% SnO_2), were used for PSD fabrication. Pd films were evaporated on the top of the a-Si:H layer. The structure has Al position contacts with length 0.1 cm, width 0.5 cm and the distance between them 0.7 cm.

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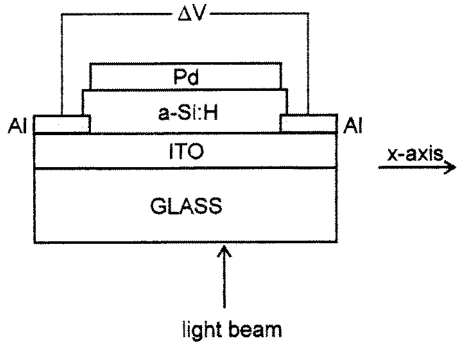


Figure 1. Schematic cross section of a-Si:H PSD.

The dependence between the lateral photovoltage and the light spot position was measured using an x–y-recorder. As a light source a hot-filament lamp with an optical focusing system was used. The diameter of the light stop was 300 μm and its position on the sample surface in the x-direction was determined by a high precision potentiometer. The accuracy of the light spot positioning is about 10 μm. The design of the PSD allows measurement of two types of dependence: the voltage between the two Al contacts versus the light probe position (PSD inversion characteristics) and the dependence of the voltage between one of the Al contacts and the back Pd contact on the light probe position.

3. Physical model

Figure 2 shows the energy band diagram of the ITO/a-Si:H/Pd structure [9]. Due to the difference in the ITO and Pd work functions an electric field is created across the a-Si:H layer. Since the absorption coefficient $\alpha^{a-Si:H}$ is in the range 10^4–10^5 cm^{-1} [9] the main part of the visible light is absorbed within the a-Si:H layer ($\sim$1 μm thick). The strong electric field in a-Si:H separates most of the photogenerated carriers. Indeed, the estimation shows that if the trap density is of the order of 10^{16} cm^{-3} and carrier mobility is $\geqslant$10 cm^2 V^{-1} s^{-1} the transit time of the photocarriers $d^{a-Si:H}/\mu E^{a-Si:H}$ is smaller than their recombination lifetime $(N_t \sigma v^{th})^{-1}$. In a position sensitive detector the photogenerated carriers flow laterally due to the existing concentration gradient between the irradiated and non-irradiated regions. We assume that all photocarriers are separated at the light spot position and that their further lateral flow (along the x-axis) takes place in the ITO and Pd layers. The photogenerated electrons increasing the carrier concentration n_0^I in ITO by $\Delta n(x)$ while the photogenerated holes recombine in Pd leaving uncompensated positive charge $\Delta p(x)$ (figure 3). We assume also that the negative charge in the ITO layer is coupled with the same quantity of positive charge in the Pd layer. This assumption is fulfilled if the recombination of the excess electrons in ITO takes place only through the a-Si:H layer (via deep traps in the a-Si:H band gap).

In the one dimensional case the steady-state current continuity equation for the electrons in the ITO layer is [9]

$$\frac{\mathrm{d}J_n^I}{\mathrm{d}x} = qR_n. \tag{1}$$

One dimensional model is valid if the incident illumination has the form of a narrow line across the whole device width. The recombination term is taken to be proportional to the

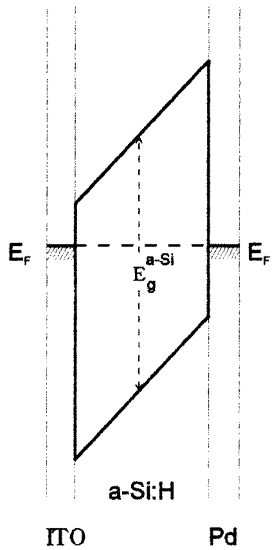


Figure 2. Energy band diagram of the ITO/a-Si:H/Pd structure.

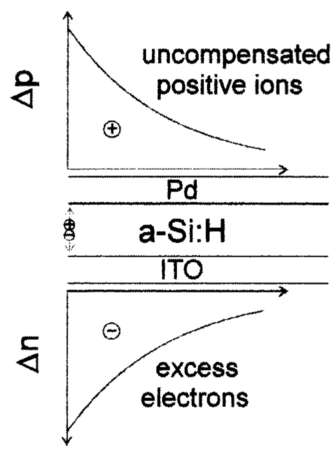


Figure 3. Charge distribution in the ITO and Pd layers in the quasi-static case.

excess carrier concentration

$$R_n = \frac{\Delta n}{\tau_n}. \tag{2}$$

Here τ_n is an effective relaxation time of the excess electrons in the ITO layer. The electron current density is

$$J_n^I = q\left(\mu_n n^I E + D_n \frac{\mathrm{d}n^I}{\mathrm{d}x}\right) \tag{3}$$

where $n^I = n_0^I + \Delta n$ is the electron concentration in the ITO layer, μ_n and D_n are the electron mobility and the electron diffusion constant in ITO, E is the electric field in ITO and q is the electric charge.

From (1)–(3) the following equation for $\Delta n(x)$ is obtained:

$$\frac{\mathrm{d}^2(\Delta n)}{\mathrm{d}x^2} + \frac{1}{\psi_0}\frac{\mathrm{d}(E(n_0^I + \Delta n))}{\mathrm{d}x} - \frac{\Delta n}{D_n \tau_n} = 0. \tag{4}$$

Here $\psi_0 = kT/q$ denotes the thermal voltage. Taking into account that the electrons move against the electric field direction and assuming as a first approximation that the magnitude of the electric field $|E|$ is constant and using the boundary conditions

$$\Delta n(x)|_{x=0} = \Delta n_0 \text{ at the light/dark boundary}$$
$$\Delta n(x) \to 0 \text{ at } x \to \pm\infty$$

the solution of (4) is

$$\Delta n(x) = \Delta n_0 \exp(-x/L_{eff}). \tag{5}$$

Here L_{eff} is an effective electron diffusion length

$$\frac{1}{L_{eff}} = -\frac{E}{2\psi_0} + \left(\frac{E^2}{4\psi_0^2} + \frac{1}{L_n^2}\right)^{1/2} \qquad \text{at } x > 0 \text{ and } E < 0 \tag{6}$$

$$\frac{1}{L_{eff}} = -\frac{E}{2\psi_0} - \left(\frac{E^2}{4\psi_0^2} + \frac{1}{L_n^2}\right)^{1/2} \qquad \text{at } x < 0 \text{ and } E > 0$$

and L_n is defined as the conventional diffusion length of electrons $L_n = (D_n \tau_n)^{1/2}$ although they are the majority carriers in ITO.

The solution is symmetrical relative to point $x = 0$. When the sign of x changes, the signs of L_{eff} and E change too, while the $\Delta n(x)$ sign is not changed. Taking into account this symmetry we can simplify the calculations below by using only positive x-values, $L_{eff} > 0$ and $E < 0$ ($x = 0$ at the light/dark boundary).

The obtained excess carrier distribution, (5), may be used to determine the potential distribution along the x-axis in the ITO layer. The ITO/a-Si:H/Pd structure can be considered as a parallel plate capacitor, the amorphous silicon, due to its high resistivity, being the dielectric layer. The relation between the coupled charge and the potential at distance x ($x > 0$ for both directions) from the light spot position is:

$$Q(x) = C\psi(x) \tag{7}$$

where C is the capacitance of an element with length Δx:

$$C = \frac{\varepsilon_0 \varepsilon_r^{a-Si} \Delta x}{d^{a-Si}}. \tag{8}$$

On the other hand the electric charge of a capacitor with length Δx is

$$Q(x) = -q\,\Delta n(x)\,d^{ITO}\,\Delta x \tag{9}$$

where d^{ITO} is the thickness of the ITO layer.

Using (7)–(9) the expression for the potential becomes:

$$\psi(x) = -\frac{q d^{ITO} d^{a-Si}}{\varepsilon_0 \varepsilon_r^{a-Si}} \Delta n(x) = -\frac{q d^{ITO} d^{a-Si} \Delta n_0}{\varepsilon_0 \varepsilon_r^{a-Si}} \exp(-x/L_{eff}). \tag{10}$$

This potential distribution corresponds to electric field

$$E(x) = E_0 \exp(-x/L_{eff}) \tag{11}$$

where

$$E_0 = -\frac{q d^{ITO} d^{a-Si}}{\varepsilon_0 \varepsilon_r^{a-Si} L_{eff}} \Delta n_0. \tag{12}$$

If the electric field $E(x)$ from (11) is introduced in (4) and equation (4) is solved numerically a new distribution $\Delta n(x)$ will be found. Thus in an iterative way the potential and carrier distribution may be recalculated until convergence is achieved.

Using equation (10) the PSD output voltage $\Delta\psi(x) = \psi_1(x) - \psi_2(x)$, where $\psi_1(x)$ and $\psi_2(x)$ are the photovoltages on the first and the second position contacts, can be expressed as:

$$\Delta\psi(x) = -\frac{q d^{ITO} d^{a-Si} \Delta n_0}{\varepsilon_0 \varepsilon_r^{a-Si}} \left(\exp\left(-\frac{x}{L_{eff}}\right) - \exp\left(-\frac{L-x}{L_{eff}}\right)\right). \tag{13}$$

Here L is the device length and x is the distance from the light/dark boundary to one of the electrodes. Denoting the coefficient before the exponential terms as $\Delta\psi_0 = q d^{ITO} d^{a-Si} \Delta n_0 / \varepsilon_0 \varepsilon_r^{a-Si}$ equation (13) acquires the form:

$$\Delta\psi(x) = 2\Delta\psi_0 \exp\left(-\frac{L}{2L_{eff}}\right) \sinh\left(\frac{x - L/2}{L_{eff}}\right). \tag{14}$$

If the effective electron diffusion length L_{eff} is larger than the device length L equation (14) can be simplified to

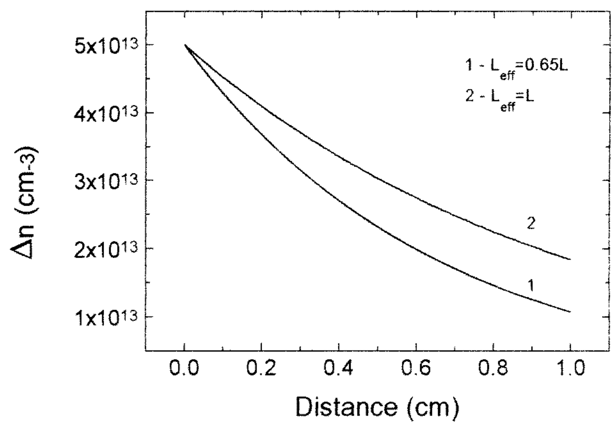
$$\Delta\psi(x) = \Delta\psi_0 \frac{2x}{L_{eff}}. \tag{15}$$

From (15) it may be concluded that if the condition $L_{eff} > L$ is satisfied then the one dimensional PSD based on the ITO/a-Si:H/Pd structure has a linear output signal. In this case the electric field does not depend on x and is given by:

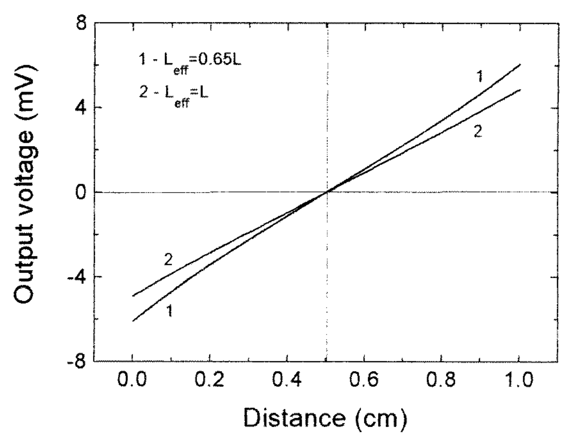
$$S = -2E_0 = \frac{2\Delta\psi_0}{L_{eff}} = \frac{2qd^{ITO}d^{a-Si}\Delta n_0}{\varepsilon_0\varepsilon_r^{a-Si}L_{eff}} \tag{16}$$

where S is the slope of the experimental inversion characteristic.

Figure 4(a,b) shows the calculated excess carrier distribution and inversion characteristic, using equations (5) and (13) respectively, at $\Delta n_0 = 5 \times 10^{13}$ cm^{-3} and for two values of L_{eff}, $L_{eff} = 0.65L$ (curve 1) and $L_{eff} = L$ (curve 2). It can be seen that larger L_{eff} values correspond to higher electron concentration at the lateral edge of the structure (figure 4(a))



(a)



(b)

Figure 4. Calculated excess carrier distribution along the x-axis (a) and inversion characteristic (b) of PSD at $\Delta n_0 = 5 \times 10^{13}$ cm^{-3} for $L_{eff} = 0.65L$ (curve 1) and $L_{eff} = L$ (curve 2).

and that the increase of the effective diffusion length causes a small decrease of the output voltage but improves the linearity of the output characteristic (figure 4(b)).

4. Experimental results and discussion

Figure 5 shows in semilog scale the dependence of the voltage between one of the position contacts and the back Pd contact on the light spot position. It can be seen that in these coordinates the dependence is approximately a straight line with a slope 1.52 cm^{-1}. Using formula (10) an estimation of the electron diffusion length gives $L_{eff} \approx 0.65$ cm. This large value may be explained in the following way: since ITO is degenerately doped it may be expected that, similar to metals, the electric field cannot penetrate deeply into it. Thus the excess electrons must be confined in a narrow region (about a few nm) close to the ITO/a-Si:H interface. On the other hand the electrons are the majority carriers in ITO. Therefore the photoelectrons can recombine only if they pass through the a-Si:H layer into the Pd against the internal field. Effective electron diffusion length of the same order has been found for a PSD based on another structure, ITO/crystalline silicon [10]. Also in [10] it has been established that L_{eff} strongly depends on the recombination velocity at the lateral edges of the structure.

The straight line in figure 5 intersects the y-axis at $\psi(0) = qd^{ITO}d^{a-Si}\Delta n_0/\varepsilon_0\varepsilon_r^{a-Si} \approx$ 4.7 mV. From here we obtain for Δn_0 the value 3×10^{13} cm^{-3}.

The experimental data shown in figure 5 are in accordance with our model in which the carrier distribution $\Delta n(x)$ is exponential and the relation between $\Delta n(x)$ and the potential may be found if the structure is considered as a parallel plate capacitor.

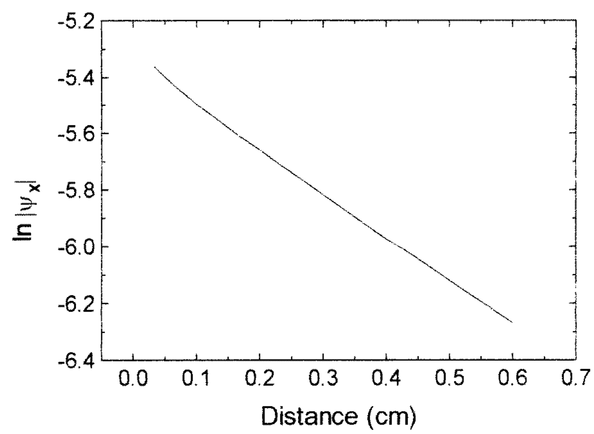


Figure 5. The dependence of the voltage between one of the position contacts and Pd on the light probe position in semilogarithmic scale.

Figure 6 shows experimentally measured output voltage dependence on the light spot position. It is approximately a straight line with a slope $S = 7$ mV cm^{-1}. From equation (16) and the experimentally established electric field value $E = -3.5$ mV cm^{-1} we can evaluate the nonequilibrium carrier density in the ITO layer at $x = 0$ (Δn_0), namely about 2×10^{13} cm^{-3}. Approximately the same value is obtained from the dependence in figure 5. This shows that the $\Delta\psi(x)$ voltage may indeed be considered as a difference between the $\psi_1(x)$ and $\psi_2(x)$ voltages on the two contacts, measured relative to the Pd contact.

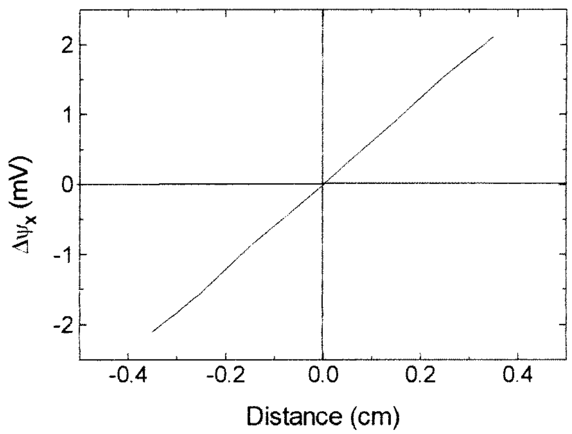


Figure 6. Experimentally measured output voltage dependence on light spot position.

5. Numerical approach

The electron concentration in ITO is obtained by solving the one dimensional continuity equation in discrete form [11]

$$\frac{J_n|_{i+1/2} - J_n|_{i-1/2}}{(h_i + h_{i-1})/2} - R_i = 0 \tag{17}$$

where h_i is the distance between two neighbouring points $h_i = x_{i+1} - x_i$ (figure 7) and $R_i = \Delta n_i/\tau_n$ is the recombination term. Using the scheme proposed in [11] the following expression for the electron current density $J_n|_{i+1/2}$ is obtained:

$$J_n|_{i+1/2} = D_n|_{i+1/2} \frac{B((\psi_{i+1} - \psi_i)/\psi_0)\Delta n_{i+1} - B((\psi_i - \psi_{i+1})/\psi_0)\Delta n_i}{h_i} + D_n|_{i+1/2} \frac{(\psi_i - \psi_{i+1})/\psi_0}{h_i} n_0. \tag{18}$$

Here Δn_i is the excess carrier concentration and ψ_i is the potential in ITO at point x_i, n_0 is the free electron concentration in ITO, ψ_0 is the thermal voltage and $B(x)$ is the Bernoulli function defined as:

$$B(x) = \frac{x}{e^x - 1}. \tag{19}$$

Equation (17) is solved using the following boundary conditions:

(1) the current at the lateral edge of the structure is taken to be equal to the surface recombination rate, $J_n|_{x=L} = -s_n \Delta n|_{x=L}$ where s_n is the surface recombination velocity;
(2) at $x = 0$ the excess carrier concentration is $\Delta n|_{x=0} = \Delta n_0$.

The potential in the ITO layer is calculated in the following way: we consider the continuously distributed charge in each interval $[x_{k-1/2}, x_{k+1/2}]$ as being located at the point x_k (figure 7). Then, at $k < i$ the x-component of the electric field created in the ith point by the negative charge located at x_k (excess electrons in ITO) or the positive one (uncompensated ions in Pd) according to the Coulomb law is given by:

$$E_{i,k}^{ITO} = -\frac{q\Delta n_k(h_k + h_{k-1})/2}{4\pi\varepsilon_0\varepsilon_r^{a-Si}(x_i - x_k)^2} \tag{20}$$

$$E_{i,k}^{Pd} = \frac{q\Delta n_k(h_k + h_{k-1})/2}{4\pi\varepsilon_0\varepsilon_r^{a-Si}((x_i - x_k)^2 + d_{a-Si}^2)^{1/2}}\cos\theta. \tag{21}$$

Here θ is the angle between the electric field, created by the positive charge located at x_k, at the ith point and the x-axis. For $k > i$ the same formulae are used with opposite signs. Thus the total electric field along the x-axis at the ith point is calculated by summing up the contributions of all other points. The potential distribution is calculated by numerical integration of $E(x)$ assuming that at the lateral edge of the structure the potential is zero, $\psi|_{x=L} = 0$.

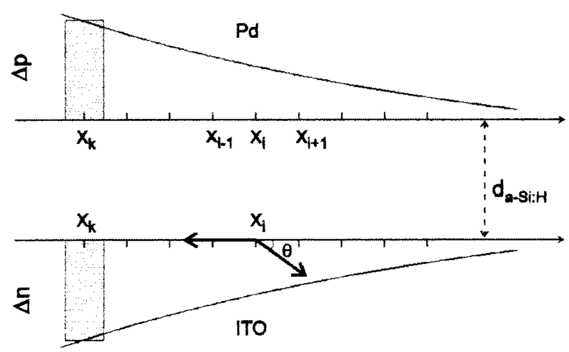


Figure 7. Electric field created by the negative and positive charge located at discrete points.

The excess electron distribution and the potential in ITO are obtained iteratively by consecutively solving (17) and calculating the corresponding potential using (20) and (21).

Figure 8(a, b, c) shows the dependences of the calculated excess carrier concentration, potential distribution and the output voltage on light spot position at $L_n = 1/(D_n\tau_n)^{1/2} =$ 0.5 cm for two values of the surface recombination velocity, $s_n = 10$, 10^3 cm s^{-1}. It can be seen that larger s_n-values correspond to larger variation of the carrier concentration and the potential along the x-axis and to better linearity of the output voltage characteristic.

The comparison between the results presented in figure 6 and those in figures 4(b) and 8(c) shows that the experimentally measured output voltage (figure 6) is smaller than the calculated one, obtained by analytical (figure 4(b)) or numerical (figure 8(c)) method. This may be explained by the fact that both models are one dimensional, while the experimental device structure is two dimensional. In the real device only part of the light generated carriers flow along the x-axis contributing to the output signal. In addition, one dimensional models are also restricted in the description of PSD operation because they do not take into account the recombination process at the edge of the structure parallel to the x-axis. This recombination process has substantial influence on the output voltage characteristics [10].

Nevertheless, the qualitative agreement between the calculated dependences shown in figure 8(b,c), the dependences obtained by using the analytical formulae (10) and (13) as well as the experimentally measured results (figures 5, 6) confirm our assumption, made in section 3, that the ITO/a-Si:H/Pd structure can be considered as a parallel plate capacitor thus allowing us to obtain the potential distribution in the ITO layer.

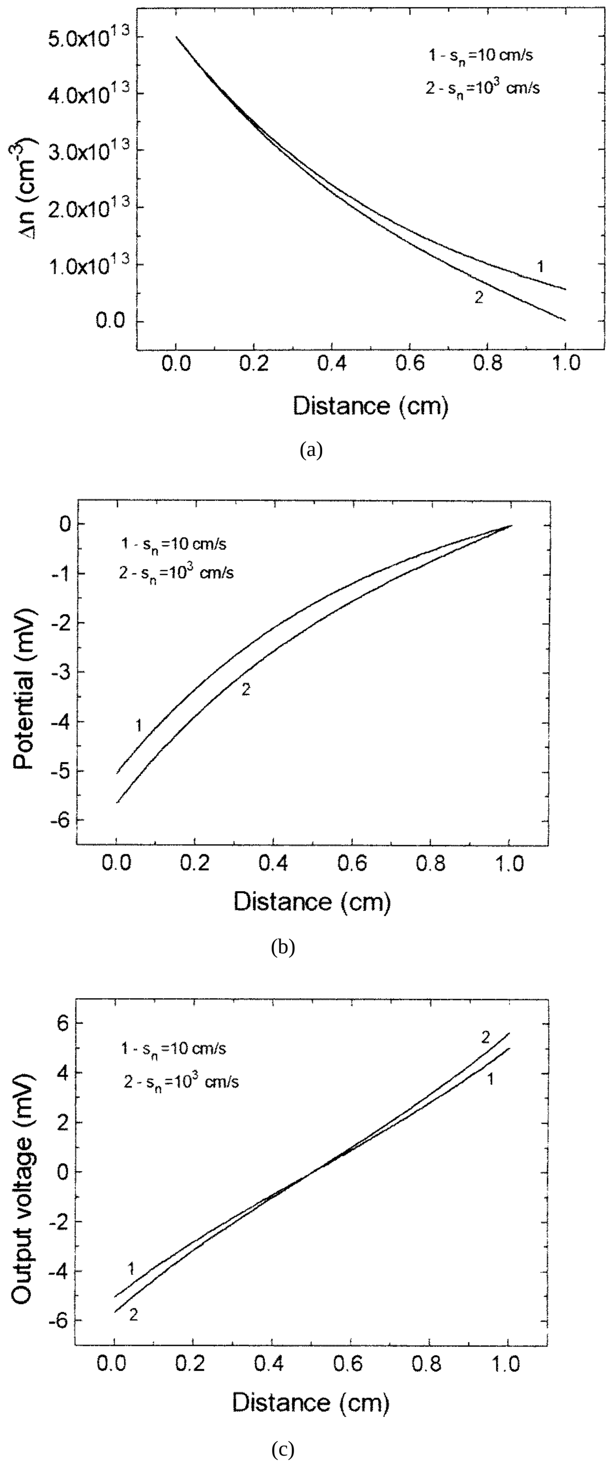


Figure 8. Numerically calculated excess carrier concentration (a), potential distribution (b) and the output voltage (c) at $L_n = 0.5$ cm for two values of the surface recombination velocity: $s_n = 10$ cm s^{-1} (curves 1), $s_n = 10^3$ cm s^{-1} (curves 2).

6. Conclusion

The presented physical model allows analytical calculation of excess carrier concentration, potential distribution and the output voltage of a PSD based on the ITO/a-Si:H/Pd structure. The experimentally measured characteristics of the one dimensional PSD are in agreement with the calculation results. Using the experimental data and the developed model an estimation of the effective electron diffusion length in ITO is carried out giving values for L_{eff} about 0.65 cm.

In an alternative way, the potential in the ITO layer is calculated by a numerical method based on Coulomb's law. There is a good agreement between the calculation results obtained by the numerical method and by analytical formulae, but both methods give larger values for the output signal than the experimental measurements. This may be explained by the fact that the models are one dimensional, while the real device structure is two dimensional. The qualitative agreement between the calculated and the experimentally measured output characteristics confirms our assumption that in an ITO/a-Si:H/Pd based PSD, the potential and hence the output voltage can be determined if the structure is considered as a parallel plate capacitor.

Acknowledgment

This work has been supported by contracts with the Bulgarian National Fund 'Scientific Investigations' No F-631 and No F-450.

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