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A position sensitive detector based on an ITO–Si structure

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Abstract. One- and two-dimensional position sensitive detectors based on an ITO–pSi structure have been fabricated and studied. The experimentally measured linear dependence between the photovoltage response and the light spot position is explained by a model in which the electric field in silicon in the lateral direction (E^{Si}) is assumed to be constant. It has been shown that E^{Si} is inversely proportional to the electron diffusion length. Using the experimental data the electron diffusion length is estimated to be about 1 cm.

1. Introduction

Position sensitive detectors (PSDs) are optoelectronic devices which use the lateral photovoltaic effect [1] to determine the position of a light spot on a semiconductor surface. If a laser beam is used as a light source the PSD may be positioned relatively far away from the investigated object. In this case the sensitivity of the laser–PSD system increases significantly. 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 [1–3] or p–i–n diode on crystalline silicon. A PSD based on hydrogenated amorphous silicon (a-Si:H) has also been reported [4, 5]. In the present paper we give results for a PSD based on an ITO–pSi structure (ITO designates the compound indium oxide, In_2O_3, doped with tin). The ITO–pSi structure has the following advantages compared to a p^+–n based PSD: (i) the ITO layer, as for other oxide semiconductors, in thin-film form has good electrical conductivity and high optical transparency [6]. Its resistivity is of the order of 10^{-4} Ω cm at 90% In_2O_3, 10% SnO_2 layer composition [7]; (ii) the fabrication of the ITO–Si structure is relatively simple and does not require high-temperature processes; (iii) the ITO layer serves not only as a part of the heterojunction but also as an antireflection coating and provides hermeticity because it is a glass.

The ITO–pSi structure has been investigated as a solar cell in detail [8–10]. It has been established that the transport mechanism between the oxide semiconductor and the converting base is tunnelling through the interfacial SiO_x layer. However, the I–V characteristics of the ITO–SiO_x–pSi structure are dominated by the diffusion current flowing in the bulk of the converting substrate and show the usual Shockley diode behaviour.

In the present paper we analyse the transport of light generated carriers in the lateral direction using a simple one-dimensional model.

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2. Experimental details

The ITO layers were deposited on p-type (100) Si with resistivity 50 Ω cm by d.c. reactive magnetron sputtering of a 90% In–10% Sn target in pure O_2 ambient. The working gas pressure during the deposition was 10^{-3} Torr, the cathode voltage was 350 V and the substrate temperature was 450 °C. The deposition rate at the above conditions was 13 nm min^{-1}. Before the ITO deposition the silicon wafers were cleaned in HF acid using standard procedure. The thickness and the refractive index of the deposited ITO layers were measured ellipsometrically. The thickness was in the range 120–150 nm and the refractive index was 2.2.

The dependence between the lateral photovoltage under illumination 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 spot was about 300 μm and its position on the sample surface in the x direction was determined by a high-precision potentiometer (helipot). Figure 1 shows the schematic cross section of the investigated structures.

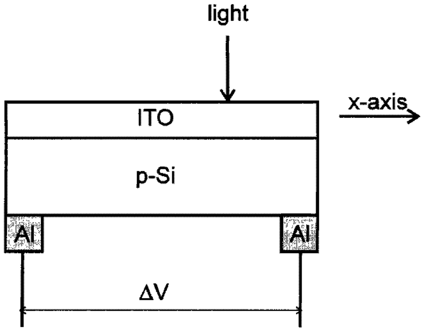

Figure 1. Schematic cross section of one-dimensional PSD.

3. Physical model

Figure 2 shows the energy band diagram of the ITO–pSi system [9]. The native silicon dioxide (SiO_2) layer between Si and ITO has a tunnelling thickness. The ITO is degenerately doped and functions as a metal. It forms an energy barrier $q\Phi_{Bp}$ and thus converts the conductivity type of the silicon–ITO interfacial region. The processes occurring in the ITO–pSi structure when exposed to non-uniform illumination are the following. The main part of the visible light is absorbed in a region with a depth of about 10 μm where it generates photocarriers. The photocarriers in the depletion region are separated by the internal electric field of the junction and the electrons tunnel through SiO_2 into the ITO layer while the holes are swept into the Si. The carriers generated in the neutral region contribute also to the electron and hole currents flowing towards the ITO and towards the bulk of the silicon respectively. The electrons diffuse in the neutral region until they reach the depletion region edge and then drift into the ITO, while the holes diffuse towards the back surface of the Si. Due to the concentration gradient a small fraction of the light generated carriers diffuse outside the light spot. Since for the electrons the distance to the depletion region is smaller than their diffusion length in Si they are separated from the

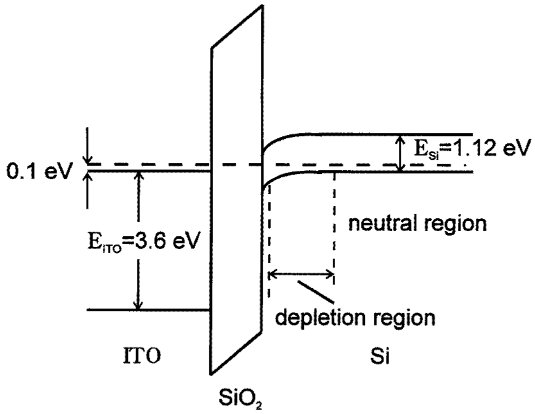

Figure 2. Schematic energy band diagram of the ITO–pSi system. The native SiO_2 layer has a tunnelling thickness.

holes by the n–p junction as described above. Thus it may be assumed that the diffusion in the lateral direction (x axis) of the light generated electrons takes place mainly in the ITO layer. The electron concentration in ITO (n_0^I) is increased by $\Delta n(x)$. The light generated holes remain in the silicon increasing the majority carrier concentration (p_0^{Si}) by $\Delta p(x)$. These excess carriers are separated by the depletion region of the n–p junction and if they can recombine they may do it only through the junction. Further the carriers diffuse as coupled charges $\Delta n(x) \approx \Delta p(x)$, towards the lateral edge of the structure. The continuity equations, in the stationary one-dimensional case, for the electron and hole current densities in ITO and Si respectively, are:

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

$$\frac{\mathrm{d}J_p^{Si}}{\mathrm{d}x} = -qR_p. \tag{2}$$

Here R_n and R_p are the recombination terms of holes and electrons. The x components of the current densities are:

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

$$J_p^{Si} = q\left(\mu_p^{Si} p^{Si} E^{Si} - D_p^{Si} \frac{\mathrm{d}p^{Si}}{\mathrm{d}x}\right). \tag{4}$$

In the stationary case the lateral electric fields, created as a result of the carrier distribution along the x axis, in ITO (E^I) and in Si (E^{Si}) are responsible for the validity of the relationship $\Delta n(x) \approx \Delta p(x)$. Thus the total charge in a volume enclosed by surfaces perpendicular to the x axis is zero. Then according to the Gauss law the electric field in the x direction is constant. On the basis of these considerations we assume that E^I and E^{Si} are constant. We also assume that the recombination term is proportional to the excess carrier concentration:

$$R_n = \frac{\Delta n}{\tau_n}$$

$$R_p = \frac{\Delta p}{\tau_p}.$$

τ_p and τ_n are the relaxation times for holes and electrons. They account for the tendency of the electron and hole concentrations to reach their equilibrium values. As has been pointed out the electrons and holes can recombine mainly through the depletion region between ITO and Si. An additional contribution may arise from recombination at the lateral edge of the structure. Then the recombination term R_n will be equal to R_p.

Therefore:

$$\frac{\mathrm{d}J_n^I}{\mathrm{d}x} = -\frac{\mathrm{d}J_p^{Si}}{\mathrm{d}x}. \tag{5}$$

From relations (3)–(5) and using the condition that at $x \to \infty$ $J_n = J_p \approx 0$ the following equation for the excess carrier distribution is found (at $\mu_n^I \neq \mu_p^{Si}$):

$$\frac{\mathrm{d}(\Delta n)}{\mathrm{d}x} - \frac{1}{\psi_0}\frac{\mu_n^I E^I - \mu_p^{Si} E^{Si}}{\mu_n^I - \mu_p^{Si}}\Delta n - \frac{1}{\psi_0}\frac{\mu_n^I n_0^I E^I - \mu_p^{Si} p_0^{Si} E^{Si}}{\mu_n^I - \mu_p^{Si}} = 0. \tag{6}$$

Here $\psi_0 = kT/q$ denotes the thermal voltage. The general solution of equation (6) is

$$\Delta n(x) = A\exp\left(\frac{\mu_n^I E^I - \mu_p^{Si} E^{Si}}{\mu_n^I - \mu_p^{Si}}\frac{x}{\psi_0}\right) + B. \tag{7}$$

Using the boundary conditions that at the edge of the light/dark spot the excess electron concentration is Δn_0 and that at $x \to \infty$ $\Delta n(x) \to 0$ one obtains:

$$A = \Delta n_0$$
$$B = \frac{\mu_n^I n_0^I E^I - \mu_p^{Si} p_0^{Si} E^{Si}}{\mu_n^I E^I - \mu_p^{Si} E^{Si}} = 0. \tag{8}$$

From (8) it can be seen that the electric field in the ITO layer $E^I = (\mu_p^{Si} p_0^{Si}/\mu_n^I n_0^I)E^{Si}$ is much smaller than E^{Si} since $n_0^I \gg p_0^{Si}$ and E^I in (7) can be neglected. Equation (7) acquires the following form:

$$\Delta n(x) = \Delta n_0 \exp\left(-\frac{\mu_p^{Si}}{\mu_n^I - \mu_p^{Si}}\frac{E^{Si}}{\psi_0}x\right). \tag{9}$$

On the other hand from (1) and (3) one may obtain the following equation for the excess carrier distribution along the x axis:

$$D_n^I \frac{\mathrm{d}^2\Delta n}{\mathrm{d}x} - \mu_n^I E^I \frac{\mathrm{d}\Delta n}{\mathrm{d}x} - \frac{\Delta n}{\tau_n} = 0. \tag{10}$$

If the second term in (10) is neglected ($E^I \approx 0$) the solution of equation (10) at the above boundary conditions is:

$$\Delta n(x) = \Delta n_0 \exp\left(-\frac{x}{L_n}\right). \tag{11}$$

Here $L_n = (D_n^I \tau_n)^{1/2}$ is the electron diffusion length. Since (9) and (11) give one and the same distribution their exponential terms must be equal. From here the following expression for the electric field in the silicon is found:

$$E^{Si} = \frac{\mu_n^I - \mu_p^{Si}}{\mu_p^{Si}}\frac{\psi_0}{L_n}. \tag{12}$$

At $\mu_n^I \approx 2\mu_p^{Si}$ the expression for E^{Si} is reduced to:

$$E^{Si} \approx \frac{\psi_0}{L_n}. \tag{13}$$

4. Results and discussion

Figure 3 shows a typical current–voltage dependence in the forward direction of an Al–ITO–Si–Al structure on a semilogarithmic scale. The structure is formed by photolithography and the diameter of the metal electrode is 300 μm. The I/V dependence is linear up to 1 V and the deviation at higher voltages is a result of the voltage drop on the series ohm resistance of the structure. The I/V characteristic can be described by the ideal diode equation [9]:

$$J = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right].$$

J_0 is determined from the intersection point between the I/V curve and the y axis on figure 3. If the value of 120 A cm^{-2} K^{-2} for the Richardson constant is used [6] one obtains that the potential barrier height at the ITO–pSi interface is 0.78 eV. This value is typical for the ITO–pSi structure [6, 9].

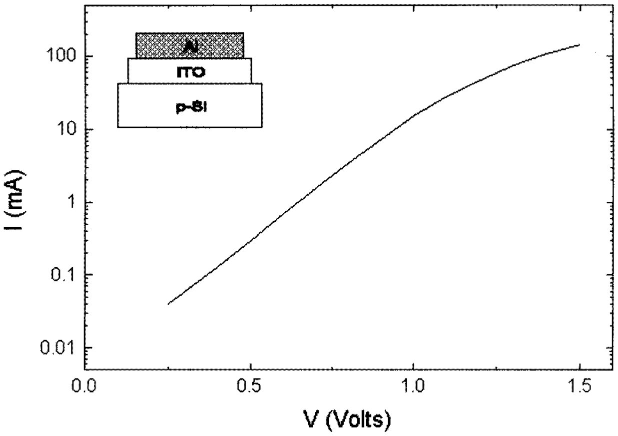

Figure 3. I–V characteristic in the forward direction of an Al–ITO–Si–Al structure (shown in the inset). The diameter of the Al electrode is 300 μm.

Figure 4 shows the lateral photovoltage response of a one-dimensional PSD measured in the quasistatic mode. The same characteristics are measured for both directions of the light spot movement. The distance between the metal electrodes is 7 mm. It can be seen that the dependence between ΔV and the distance is approximately linear. Using expression (13) and the value for the slope of $\Delta V/x$ dependence in figure 4 an estimation of the electron diffusion length L_n may be carried out. Thus for $E^{Si} \approx 28$ mV cm^{-1} one obtains that L_n is close to 1 cm. This large value of the electron diffusion length is a result of the separation of light generated carriers by the electric field in the depletion region.

Figure 5 shows the photovoltage response of a two-dimensional PSD (10 mm×10 mm). The measurements are carried out at constant incremental displacement in x and y directions with a step of 0.5 mm. The observed nonlinearity of the characteristics is a result of the relatively higher recombination rate at the lateral edge when the light spot is scanning close to it. This recombination causes a decrease of the output signal.

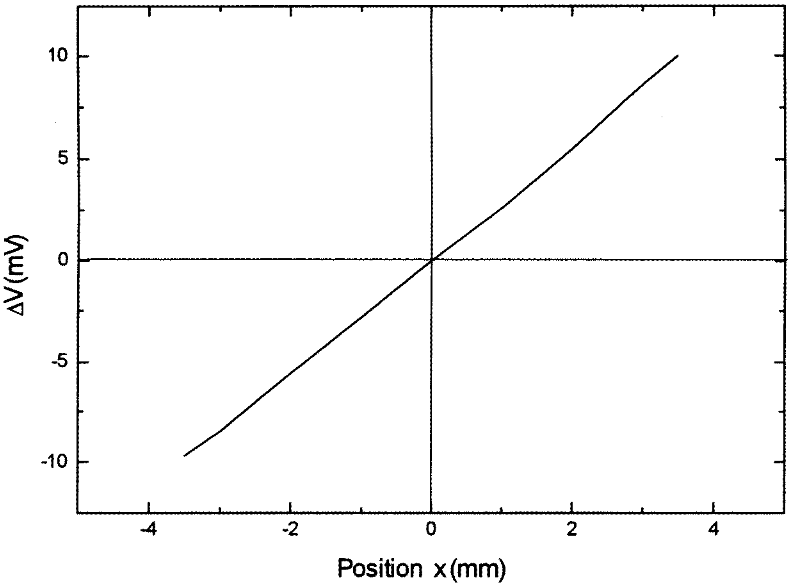

Figure 4. Lateral photovoltage response of one-dimensional PSD.

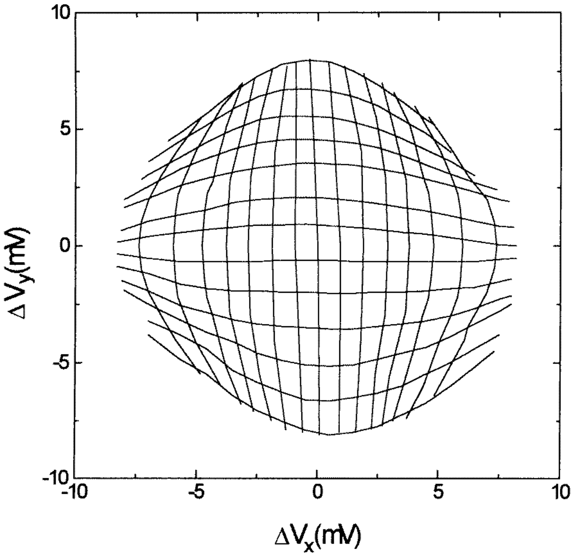

Figure 5. Photovoltage response of two-dimensional PSD.

The experimental results on figure 5 show that the model presented above is idealized since it does not take into account the finite size of the device and the influence of the recombination at the lateral edges.

From the symmetry of the output characteristics it may be concluded that the ITO layer and the ITO–Si junction are homogeneous over the whole active area of the detector.

5. Conclusion

The ITO–pSi structure can be used for fabrication of large-area position sensitive detectors. PSDs based on ITO–pSi have the following advantages compared to detectors based on a shallow p^+–n junction: the ITO layer is transparent, has good electrical conductivity and acts as an antireflection coating; fabrication of the ITO–Si structure does not require high-temperature processes, resulting in long lifetime and large diffusion length of the minority carriers. Using the experimental data and the model developed in the present paper an estimation of the electron effective diffusion length is carried out giving values for L_n close to 1 cm.

Acknowledgments

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References

[1] Wallmark J T 1957 *Proc. IRE* **45** 474
[2] Lucovsky G 1960 *J. Appl. Phys.* **31** 1088
[3] Vassilev V S and Velchev N B 1977 *Solid State Electron.* **20** 999
[4] Arimoto S, Yamamoto H, Ohno H and Hasegawa H 1985 *J. Appl. Phys.* **57** 4778
[5] Al Sabbagh S K, Wilson J I B and Manookian W Z 1988 *J. Phys. D: Appl. Phys.* **21** 359
[6] Sze S M 1981 *Physics of Semiconductor Devices* 2nd edn (New York: Wiley) p 819
[7] Leong J I, Moon J H, Hong J H, Kang J S and Lee Y P 1994 *Appl. Phys. Lett.* **64** 1215
[8] Shewchun J, Burk D, Singh R and Spitzer M 1979 *J. Appl. Phys.* **50** 6524
[9] Shewchun J, Burk D and Spitzer M B 1980 *IEEE Trans. Electron Devices* **ED-27** 705
[10] Ashok S, Sharma P P and Fonash S J 1980 *IEEE Trans. Electron Devices* **ED-27** 725