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Study of recombination and transport properties of a-Si:H(i)/ μc-Si:H(n) contact system for crystalline silicon solar cells

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Abstract. This article is devoted to the study of the contact and recombination properties of the combination of a-Si:H(i)/μc-Si:H(n) layers. Numerical modeling of the band diagram as well as experimental study of the contact system with a silicon substrate has been carried out. The optimal values of the thicknesses of the contact layers are determined, which make it possible to obtain a low rate of carrier recombination and contact resistance.

Keywords: solar cells, silicon, amorphous silicon, effective lifetime

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Исследование транспортных и рекомбинационных свойств контактной системы a-Si:H(i)/ μc-Si:H(n) для фотоэлектрических преобразователей на основе кремния

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Аннотация. Данная статья посвящена исследованию контактных и рекомбинационных свойств комбинации слоев a-Si:H(i)/μc-Si:H(n) на подложках кристаллического кремния. Проведено численное моделирование зонной диаграммы, а также экспериментальное исследование транспортных свойств на кремниевой подложке. Определены оптимальные значения толщин контактных слоев, позволяющие получить низкую скорость рекомбинации носителей и контактное сопротивление.

Ключевые слова: фотоэлектрические преобразователи, кремний, аморфный кремний

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Introduction

Silicon-based solar photovoltaic converters are an asymmetric diode structure with a heavily doped emitter and a lightly doped base. When such a structure is irradiated with optical radiation with a photon energy greater than the band gap of the base material, electron-hole pairs appear, which are separated by the field of the *p-n* junction. However, the reverse process of recombination of electron-hole pairs also takes place, which occurs most intensively in the presence of defects in the volume and at the boundaries of the silicon substrate. This process leads to the transition of the energy of the absorbed radiation into heat losses. To reduce surface recombination, it is necessary to apply special passivating layers during the formation of contact and emitter layers of a solar cell. The contact to the silicon substrate should have a low specific contact resistance and good surface passivation. The quality of surface passivation is determined by the effective lifetime τ_{eff} of nonequilibrium charge carriers by the limited rate of bulk and surface recombination [1]. To form contact layers to a silicon substrate, there are many contact systems that differ in the quality of passivation and specific contact resistance ρ_{cont}.

Table 1

Typical parameters of different contact systems to *n*-type crystalline silicon

	J_{rec}, fA/cm^2	ρ_{cont}, Ω·cm^2	Ref.
P-diffused n^+	500	0.26	[2]
a-Si:H(i)/a-Si:H(n)	2	0.1	[3]
SiO_x/poly-Si n^+	5	0.016	[4]
SiO_x/TiO_2	50	0.026	[5]
MgF_x(1nm)/Al	1500	0.035	[6]

In this work, we study the a-Si:H(i)/μc-Si:H(n) contact system, which is characterized by the lowest recombination current at acceptable values of contact resistance.

Materials and Methods

To study the specific contact resistance and recombination rate of nonequilibrium charge carriers contacts with different configurations of a-Si:H(i) and μc -Si:H(n) layers were deposited on *n*-type Si substrates by plasma-enhanced chemical vapor deposition at the temperature of 250 °C. We used phosphorus doped silicon substrates produced by the Czochralski method with a thickness of 380 μm and resistivity 5 – 10 Ω·cm. Monosilane (SiH_4) and hydrogen (H_2, 6N) gases were used as precursors in the deposition of a-Si:H and μc-Si:H. The μc-Si:H layers were doped with a donor impurity diluted with 1% phosphine (PH_3) in hydrogen. Immediately prior to loading in the PECVD chamber, the substrates were treated in a 10% HF/H_2O solution to remove natural oxide. Next, the vacuum chamber was evacuated to a residual pressure of <0.5 mTorr and heated to an operating temperature of 250 °C for 20 min. The a-Si:H deposition process was carried out from pure SiH_4 at a constant pressure of 350 mTorr and an RF power density of

11 mW/cm^2 at a rate of 8 nm/min. Immediately after that, a μc-Si:H layer was deposited from a SiH_4(2%)/PH_3(0.25%)/H_2(97.75%) gas mixture at a constant pressure of 700 mTorr and a power density of 11 mW/cm^2 at a rate of 1 nm/min. After cooling and removal from the PECVD chamber, all the described operations were repeated to form contact layers on the reverse side of the substrate. In this study, it is assumed that in this contact system there are no fixed charges inherent in dielectrics and, therefore, there is no drop in the effective lifetime at concentrations of non-equilibrium carriers less than 10^{15} cm^{-3} [7,8]. A 100 nm thick ITO layer in the form of TLM test contacts was deposited onto the structures obtained by magnetron sputtering. To do this, the samples were also treated in a 10% HF/H_2O solution before being loaded into the BOC Edwards Auto 500 chamber. Then, for 40 min, pumping was carried out to a residual pressure of $8\cdot10^{-6}$ mbar, while the temperature of the substrates remained at room temperature. ITO deposition was carried out using a magnetron sputtering system with an ITO target in an Ar/O_2 atmosphere at a pressure of $1.24\cdot10^{-3}$ mbar and an RF source power of 65 W. To determine the contact resistance, a linear TLM method was used, consisting of 7 ITO contacts in the form of identical rectangular strips 5 mm wide and 0.96 mm long located in series at distances of 0.24 μm, 0.46 mm, 0.85 mm, 1.66 mm, 3.25mm, 6.5mm apart. The I–V characteristics were measured in pairs between each two nearby contacts and the resistance R = Rs + 2Rc was determined, where Rs is the substrate resistance, and Rc is the contact resistance. Further, according to the obtained dependences of the resistance R on the distance between the contacts, the values of the specific contact resistance were determined. To evaluate the band structure of the contacts, numerical simulation was carried out using the Afors-HET 2.4.1 software package.

Results and Discussion

The effective lifetime of nonequilibrium charge carriers in the obtained structures was studied using the photoluminescence decay (PLD) method. Based on the results of the study, a map of the lifetime distribution over the substrate surface was formed (Fig. 1).

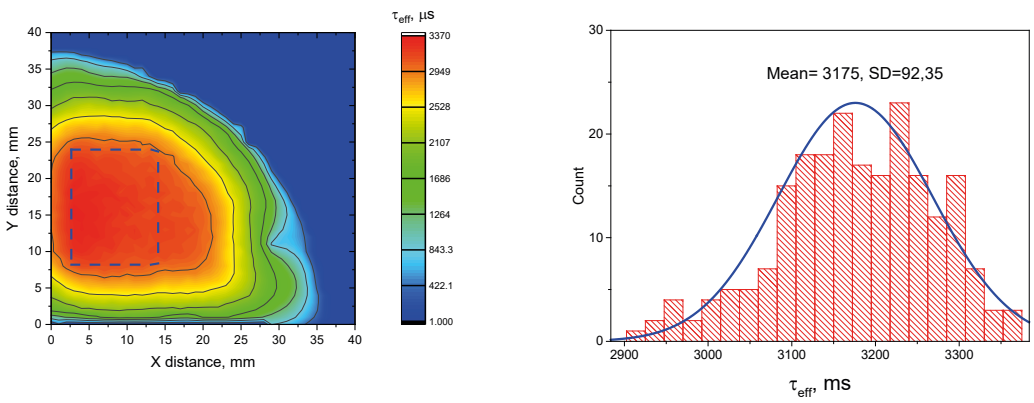

Fig. 1. The distribution of the effective lifetime over the surface and the histogram of the distribution of the effective lifetime in the "plateau" region

On the structures obtained, the lifetime is distributed inhomogeneously. A pronounced “plateau” is observed in the middle of the sample, which indicates a strong influence of the edges, especially at values greater than 1000 μs. The decrease in the effective lifetime at the edges can be associated either with a higher concentration of defects at the edges, or with the inhomogeneity of the plasma-chemical deposition process. The size of the rims is 7 – 12 mm. A detailed analysis of the lifetime distribution over the surface in the "plateau" region showed that the average value is 3175 μs with a standard deviation of 92.3 μs. This indicates the high uniformity of the layers and the absence of contamination at the stages of preparation and plasma-chemical deposition.

The I–V characteristics of a-Si:H(i)/μc-Si:H(n) contacts with different configurations of a-Si:H(i) contact layers were studied. The characteristics of the obtained contacts with the a-Si:H layer (i) have a nonlinear form, however, the values of the current density allow us to speak about the formation of a contact close to ohmic (Fig. 2.).

Table 2

Transport and recombination properties of a-Si:H(i)/μc-Si:H(n) contacts with different thickness of i-layer

	ρ_{cont}, Ω*cm^2	τ_{eff} max, μs	S, cm/s	J_o, fA/cm^2
μc-Si:H 10 nm	1.51	20	948.1	10450.4
a-Si:H 2.5 nm /μc-Si:H 10 nm	4.42	3250	3.9	43.5
a-Si:H 5 nm/ μc-Si:H 10 nm	6.26	3450	3.6	39.7

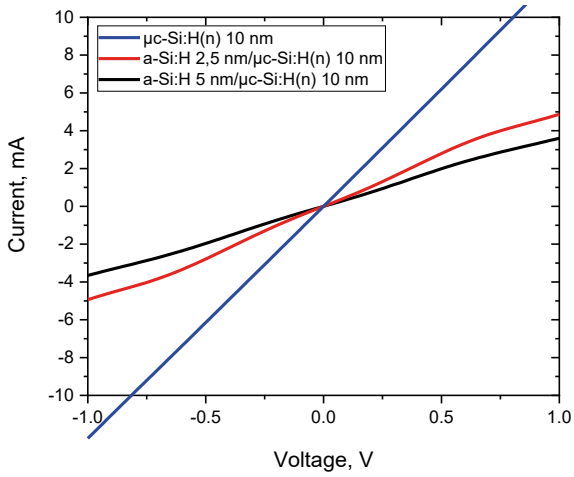

Fig. 2. I-V curve of a-Si:H(i)/μc-Si:H(n) contact system with different a-Si:H(i) layer thickness

It was noted that changing the thickness of the a-Si:H(i) layer from 5 nm to 2.5 nm led to a decrease in the contact resistance. At the same time, the I-V shape remained nonlinear with a distinct inflection at voltages of 0.5–0.7 V. It follows that the contact resistance is due to the formation of a barrier at the a-Si:H(i)/n-Si interface, and the value of this barrier depends on the thickness of the a- Si:H(i).

To explain the reason for the formation of a barrier at the a-Si:H(i)/n-Si interface, numerical simulation of the structure was carried out using the Afors-HET 2.5 software package (Fig. 3). This model shows the effect of the thickness of the a-Si:H(i) layer on the shape of the I V curve at a fixed concentration of dangling bonds. It was noted that a high concentration of dangling Ndb bonds in the i layer (insufficient hydrogenation) can lead to screening of the n contact and the formation of a barrier in the substrate. A similar situation occurs when the degree of doping of the n-layer is less than the concentration of defects in the i-layer.

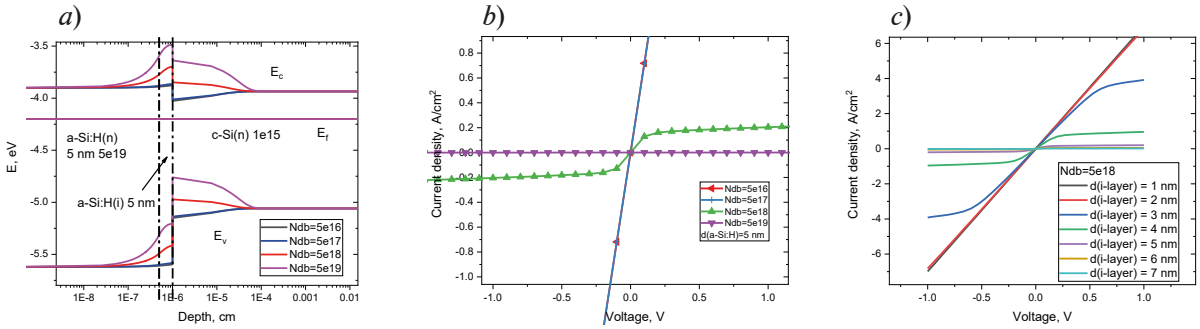

Fig. 3. Calculated band diagrams with different concentrations of defects in the a-Si:H(i) layer (*a*). I-V curves of structures with different concentrations of defects in a-Si:H(i) layers at a fixed thickness (*b*), and different thicknesses of an i-layer (*c*) at a fixed defect concentration.

Only in this case is the dependence of the contact resistance on the thickness of the i-layer observed. At small thicknesses, the n-layer works and the substrate is enriched with carriers. Pronounced S-shape may not appear in the presence of series resistance (R substrate). This model shows the effect of the thickness of the a-Si:H(i) layer on the shape of the I-V curve at a fixed concentration of dangling bonds. The characteristic S-shape appears at voltages of 0.2-0.7 V and i-layer thicknesses of 3 – 4 nm, which coincides with the values obtained in the experiment.

Conclusion

The effect of the layer thickness in the a-Si:H(i)/a-Si:H(n) system on the contact and recombination parameters of the obtained structures was evaluated. It was noted that at a distance of 7–12 mm from the edges of the substrate, a decrease in the effective lifetime is observed. The maximum effective lifetime of nonequilibrium charge carriers in a substrate with a-Si:H 2.5 nm/μc-Si:H 10nm contacts is 3250 μs, which is close to the value of the volume lifetime for these silicon substrates. Passivating contact layers were formed to crystalline silicon substrates with a minimum resistivity of 4.42 Ω*cm^2. It was shown that a high concentration of dangling bonds in the i-layer (insufficient hydrogenation) can lead to electric-field screening of the n-contact and the formation of a barrier in the substrate, which significantly increases the specific contact resistance. These results can be used in the formation of highly efficient photovoltaic converters based on amorphous and crystalline silicon.

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