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Electrophysical characteristics of large-size αSi-Si(Li) detector heterostructures

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Abstract. Electrophysical properties of large-size detector heterostructures based on a αSi-Si(Li) have been investigated in this paper. The results prove that these detector heterostructures are more effective as compared to the structures obtained using the conventional diffusion technique. One can certainly predict availability of highly effective current-voltage and capacitance-voltage characteristics in these structures.

Keywords: αSi-Si(Li) heterostructures, current-voltage and capacitance-voltage characteristics.

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1. Introduction

Registration of low-intensive ionizing radiation is a particular task for the modern development of science and technology, and it is not resolved yet. It is related with the necessity to develop large-size semiconductor detectors, in particular, with extended sensitive surface up to the maximum diameter of industrial monocrystalline silicon wafer.

Currently we know several well-developed techniques for small-size detectors (diameter of sensitive area Ø < 50 mm and thickness W < 2 mm). Developing the large-size silicon detectors (Ø > 50 mm and W > 2 mm) holds a certain degree of difficulty and peculiarity that forces us to seek for novel scientific, technological and technical solutions. All this requires deep understanding of physical processes, their relation with parameters of large-size ingots, which in turn could help to design high-quality detector structures based on them.

It is well known that electrical and physical properties of original semiconductor ingots determine how some semiconductor will behave [1, 2]. Semiconductor detectors that use silicon material have become widespread over the recent few years. A comparatively large width of the forbidden band in silicon makes it possible to decrease dramatically inverse currents in electron-hole junctions. Moreover, one can develop detectors characterized by large area and thickness of sensitive area (Ø ≥ 50 mm and W ≥ 2 mm, respectively). Presently, there are three types of radiation detectors [1]. The technique of formation of *p-n* junction and properties as well as their designation sufficiently differ if one talks about these three various techniques:

1. Surface barrier detectors.
2. Diffused *p-n* junction detectors.
3. Drift-diffusion *p-i-n* detectors.

Recently, we have been witnessing widespread launch of detectors based on a αSi-Si(Li) heterostructure [3, 4]. In virtually all types of detectors, their efficiency proves to be a function of phenomena determined in turn by correlation between parameters of an original large-diameter ingot and technique of designing the radiation detectors on them. One can develop such detector structures only if there is a solid understanding of electrical and physical properties of the original large-size silicon ingot and by giving serious consideration to trade-off between these properties and demands for design of such highly – efficient radiation detectors on them.

In this work, we are investigating electrophysical characteristics of detectors based on large-size αSi-Si(Li) heterostructures.

2. Experiments

αSi-Si(Li)-based heterostructures were formed from *p*-type silicon obtained in vacuum by using the float zone melting technique. Samples were designed of silicon wafers (diameter 50 mm and thickness 2 mm, specific resistance ρ = 3000…7000 Ohm·cm, lifetime τ = 300 μs. Lithium diffusion was carried out in vacuum, and the depth was extended down to ~300 μm at the temperature 450 °C. Drift of lithium ions was carried out at temperature ranging between 70 to 80 °C and voltage within 100…400 V with subsequent the low-temperature (near T = 60 °C, U = 200 V) corrective drift.

After drift of lithium ions has been finished, we were able to remove completely the diffused area and onto i-layer that subsequently had surfaced (lithium compensated silicon), we had launched α-Si spraying by using the vacuum thermal evaporation technique [3, 4], whereby the thickness of the coated α-Si layer amounted approximately 500 Å. Gold and aluminum coatings were used to make ohmic metallic contacts on sensitive and back-surface areas, correspondingly.

3. Results and discussion

In Fig. 1, one can see a forward-bias (a) and reverse-bias (b) regions of current-voltage characteristic in the log-log scale at room temperature. It is evident that the forward-bias and reverse-bias regions of this characteristic for the investigated detector heterostructure consist of two distinct areas, whereas current values in first and second regions alike of forward-bias and reverse-bias sections of current-voltage characteristic significantly vary at a constant bias voltage value V. Difference starts to manifest itself when the voltage V increases. The rectification factor $K = \frac{I_{for}}{I_{rev}}(V = \text{const})$ of such a structure starts to behave in a complex way as a function of the applied voltage value. For example, $K \approx 30 - 40$ at V = 1 V, whereas at higher voltages K tends to be equal to 150 (V = 10 V) and 500 (V = 30 V).

The above shape of curve is explained by bulk processes in large-size heterostructures since the charge transfer mechanism depends on quality and volume of the ingot [5 – 7].

The analysis demonstrates that with regard to first sections of forward-bias and reverse-bias regions of the current-voltage characteristic, the nature of dependence of current value on voltage value is of power-dependence behavior, i.e. $I \sim V^{\alpha}$ (α = 0.93) and $I \sim V^{\alpha}$ (α = 0.85), respectively.

Although, the transfer mechanisms of carriers are similar in both cases, however, the nature of formation of charge carries differs significantly in both cases. In forward case, the charge is being transferred by injected carriers from the emitter, i.e. from the heterostructure αSi-Si(Li), whereas in the reverse case, the current is formed by intrinsic charge carriers that are generated at room temperature. As to the second section of forward-bias current-voltage characteristic, diffusion of minority carriers (their concentration is significantly larger than the concentration in the base (lithium-compensated layer)) at the αSi-Si(Li) heterostructure interface, seems to be playing a prevalent role. Since the thickness of the base is close to 2 mm, therefore it is not fully modulated within the experimental voltage ranges, i.e. lion's share of injected electrons do not reach the back-surface contact due to the process of recombination.

The second section of the reverse-biased current-voltage characteristic eventually represents the saturation current of the αSi-Si(Li) heterostructure. Steady behavior of the current in dependence on the voltage around the value $V \geq 30$ V implies that αSi-Si(Li) heterostructure contains a dramatically low concentration of surface states at the interface amorphous layer – monocrystalline semiconductor, and therefore there are practically no leakage currents and reverse current-voltage characteristic enters the saturation phase.

In Fig. 2, one can see capacitance-voltage characteristics of αSi-Si(Li) heterostructures within the frequency range 0.465…5 MHz at room temperature. The analysis of capacitance-voltage characteristics clearly demonstrates that in the investigated αSi-Si(Li) heterostructure the amorphous layer is characterized by certain properties, which is evidenced by various values of capacities of amorphous layer C_i and space charge layer $C_{\min}$ at various test signals. As the frequency value of test signals increases, C_i, $C_{\min}$ and the ratio of $C_i/C_{\min}$ start to decrease. At the same time, the voltage that is characterized by a situation when the space charge is distributed throughout the complete thickness of the base layer in this structure is displaced towards low values. The frequency dependence of capacity $C_{\min}$ manifests heterogeneity of the base i-layer of the detector structure which in turn is characterized by *p*-type conductivity and strongly compensated by lithium ions (Li).

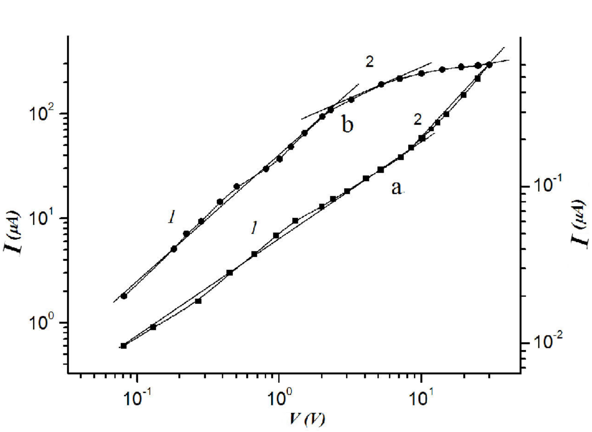

Fig. 1. Forward-bias (a), and reverse-bias (b) regions of current-voltage characteristic of heterostructures based on αSi-Si(Li) in the log-log scale.

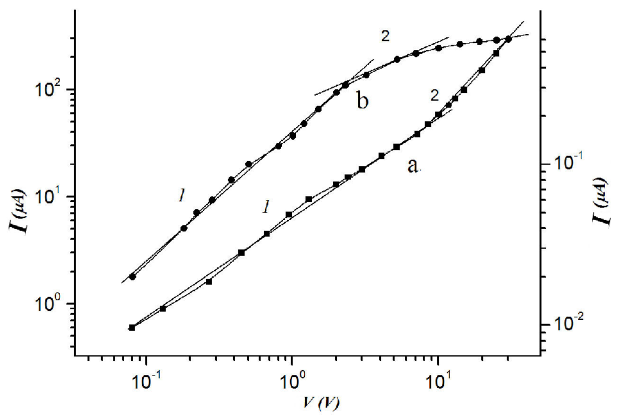

Fig. 2. Capacitance-voltage characteristics of αSi-Si(Li) heterostructures within the frequency range 0.465…5 MHz at room temperature: 0.465 (*1*), 1 (*2*), 3 (*3*), and 5 MHz (*4*).

Ingot monocrystalline silicon ($\tau = 300$ μs, $\rho =$ 3…7 kOhm·cm) has sufficient quantity of impurities B, C, O and others ($N_B \approx 10^{17}\,\text{cm}^{-3}$, $N_C \le 10^{18}\,\text{cm}^{-3}$, $N_O \le 10^{16}\,\text{cm}^{-3}$, respectively), as well as point structural defects and silicon carbon bonds. Therefore, one can expect such local heterogeneity in the base of the detector structure which remains even after compensation with lithium that starts to manifest itself in the frequency dependence of C_{min}.

The frequency dependence of the amorphous layer capacitance (C_i) is explained as follows: most probably, the existence of the amorphous αSi-Si(Li) layer in the detector heterostructure is explained by the fact that even before setting of thermodynamic equilibrium (prior to $V = 0$), total capacitance of the structure is equal to the capacitance of the amorphous layer C_i, and the frequency of the test signal does not have any impact on it. This in turn implies that at αSi-Si(Li) heterostructure interface even before setting of enhancement mode, we can observe such concentration of holes in non-equilibrium state as to lead to capacitance that overwhelms the capacitance of the amorhous layer. However, it is evident that bulk defects in amorphous silicon have nothing to do with these phenomena. Otherwise, we would observe significant leakage currents due to tunneling of holes through these defect centers.

4. Conclusion

It is obvious that αSi-Si(Li) heterostructures proved to be more effective by almost (0.5…1.5)% in terms of electrical characteristics (capacitance, current), radiometric characteristics (noise, thickness of the "dead layer") as compared to conventional Si(Li) *p-i-n* detectors.

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