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DIRECT CONVERSION
OF SOLAR ENERGY TO ELECTRIC ENERGY

Temperature-Induced Properties of Industrial Silicon Produced by Repeated Remelting in a Solar Furnace

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Abstract—The results obtained in studying the temperature-induced properties of silicon produced by the three-, five-, and eightfold melting of industrial silicon KR3 in a solar furnace in air are presented. It is shown that structures with simple ohmic contacts produced from this type of material at temperatures slightly higher than room temperature become generators of current and voltage.

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At present, silicon is still the main material in semiconductor electronics. According to the experts' assessments, the annual worldwide demand for semiconductor-grade polycrystalline silicon is 20000–30000 t. This is why the development of methods for the cheap chloride-free purification of industrial (metallurgical) silicon remains a topical problem in semiconductor material science.

This work presents the results obtained in studying polycrystalline silicon samples, which were produced by the repeated remelting of industrial (metallurgical) silicon KR3 in a solar furnace in air in accordance with the technology suggested in [1, 2]. The characteristics of this silicon are as follows: the content of Si is 96 wt % and the contents of impurities are 1.5 wt % Al, 1.5 wt % Fe, 1 wt % Ca, etc. In [3], it was reported that remelting may allow the weight fraction of impurities to be reduced from 4 to 1%. In our work, we analyze the results for three types of remelted material, i.e., three-, five, and eightfold melted metallurgical silicon.

Plates of ~500 μm in thickness were cut from ingots of the above-mentioned materials, one side of which was ground, while the other was polished. All of the samples were characterized by *n*-type conductivity (without purposeful doping) and a large-grain structure with $\sim 1 \times 2\text{-mm}^2$ grains that were differently oriented; none of the samples contained any shunting metal inclusions. All three types of materials, which were semiconducting compositions with simple ohmic contacts and were based on a titanium-nickel-copper alloy, were made in accordance with the technique described in [4]. The material was deposited as a net on the polished side and as a continuous thin layer on the ground side by vacuum deposition.

Previously, in [5, 6], five- and eight-fold melted materials were reported to exhibit rather specific properties; i.e., at temperatures slightly higher than room temperature ($T > 30$°C), they served as generators of current and/or voltage. The results obtained in studying all three types of materials are presented in Figs. 1, 2.

In Fig. 1, the current vs. temperature curves for all three types of materials are shown. It can be seen that the five-fold melted material sample generates the highest current at temperatures of up to ~180°C. However, at ~140°C, the current began to decrease and, at T ~ 180°C, the current from the threefold melted sample becomes higher than the current from the fivefold melted sample. The analogous results presented in Fig. 2 were obtained in studying the voltage.

At a temperature of ~180°C, the highest voltage is generated by the threefold melted sample. However, in the temperature range of 60–150°C, the fivefold melted sample produces the highest voltage.

The dependence of the current variations on the number of remeltings is analyzed for two of the most important temperatures; the results are shown in Fig. 3.

It is clear that, at $T = 150$°C, the maximum current is generated by the fivefold melted material sample. Then, the current began to dcrease, but without gaining the minimum value that corresponded to the threefold melted sample. At the same time, at $T = 200$°C, the current slowly decreases as the number of remeltings increases.

The curves of generated voltage vs. the number of remeltings are compared in Fig. 4.

At $T = 130$°C, the maximum voltage is generated by the fivefold melted material. However, at $T = 200$°C, the maximum voltage is given by the threefold melted material; furthermore, the voltage drops dramatically and hardly changes for the five- and eightfold melted samples.

Thus, the presented data indicate that all compositions with simple ohmic contacts produced from the above-mentioned materials, regardless of the number of remeltings, exhibit the ability to generate current and voltage at temperatures slightly higher than room

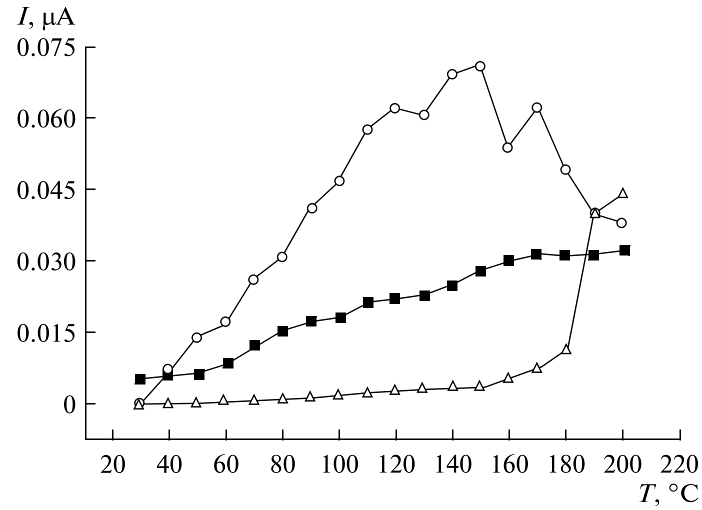

Fig. 1. Temperature-induced currents for samples with simple ohmic contacts produced from materials based on repeatedly remelted metallurgical silicon: △ is threefold remelted; ○ is fivefold remelted; and ■ is eightfold remelted.

temperature. However, as can be seen from the plots given above, various materials generate the maximum current and voltage at different temperatures. The occurrence of these rather unusual properties, which are not typical of the original metallurgical silicones can be attributed to the processes of self-organization (self-regulation) of impurities that take place during remelting; as a result of these processes, the impurities become periodically distributed over the sample. The results obtained in the direct measurement of the concentrations of iron, calcium, aluminum, selenium, lead, and silver along the samples were presented in [6, 7]; the measurements were performed using an Elan DRC-II mass spectrograph. As was discussed in [6, 7], the periodical distribution of impurities definitely indicates the appearance of numerous potential barriers at which free carriers separates upon heating inside the sample. The diffusion potential for each of these isotypic junctions can be written as follows:

$$V_{n^+-n} = \frac{kT}{q}\ln\frac{n_{n^+}}{n_n}. \quad (1)$$

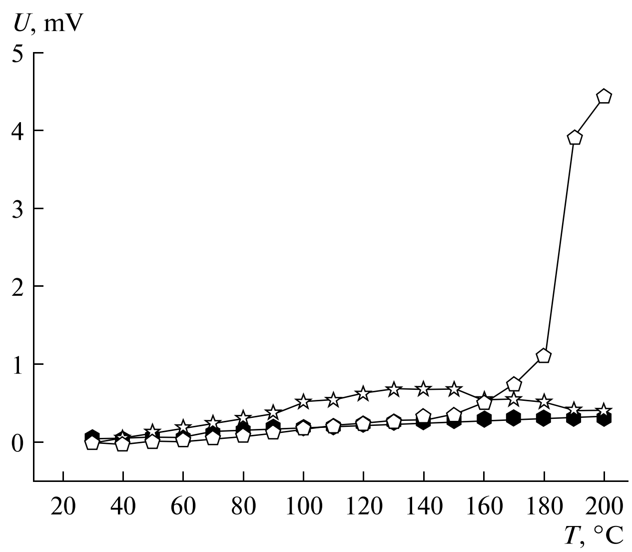

Fig. 2. Temperature-induced voltages for samples with simple ohmic contacts produced from materials based on repeatedly remelted metallurgical silicon: ⬠ is threefold remelted; ☆ is fivefold remelted; and ⬢ is eightfold remelted.

Consequently, the total voltage drop, which occurs in the material as a result of the temperature-induced

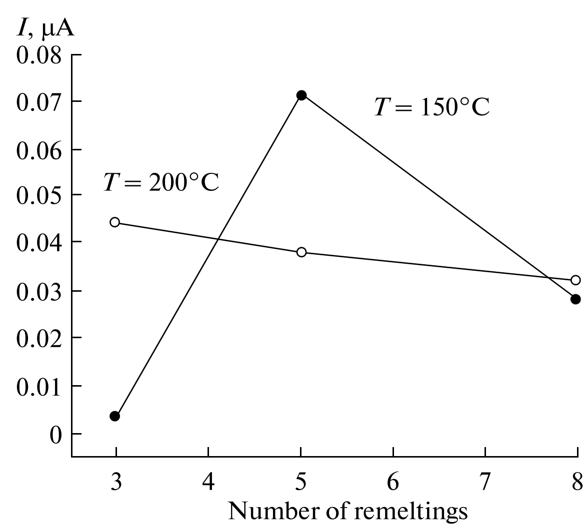

Fig. 3. Temperature-induced current vs. number of remeltings at various temperatures.

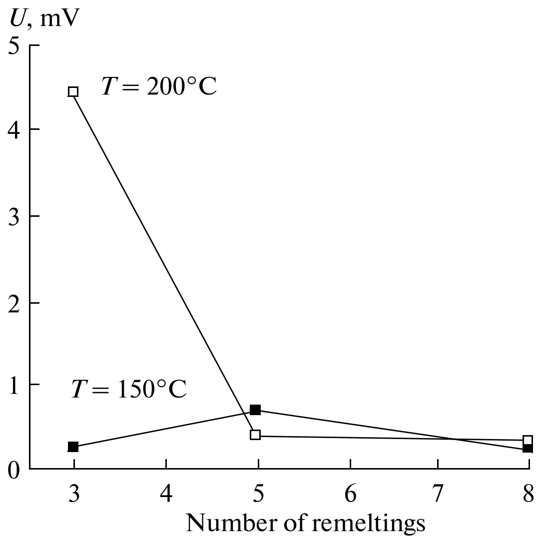

Fig. 4. Temperature-induced voltage vs. number of remeltings at various temperatures.

processes, is caused by the separation of free carriers at all internal isotypic junctions:

$$V_{\text{total}} = \sum_{i=1}^{l} V^{i}_{n-n^{+}} + \sum_{j=1}^{m} V^{j}_{n-n^{+}} + \sum_{k=1}^{n} V^{k}_{n-n^{+}} + \dots, \quad (2)$$

where $i, j, k,...$ are the isotypic junctions produced by various impurities and l, m, n,... are the number of these junctions.

It should be especially underlined that, in these situations, the notations of direct and reverse currents are rather relative and, upon varying the temperature, the direct current can be higher than reverse in some junctions and vice versa, in other junctions. The data obtained in the experiment is a result of the multiple summations of individual effects in each junction.

Thus, the presented data indicate that the compositions with simple ohmic contacts produced from repeatedly remelted metallurgical silicon, regardless the number of remeltings, exhibit the temperature-induced ability to generate current and/or voltage. These special properties are caused by the processes of self-organization (self-regulation) of impurities that occur during remelting.

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