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A Study on the Impact of PN-Junction Doping Concentration on the Efficiency of Monocrystalline Silicon Solar Cells

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Abstract

The process of pn junction formation is one of the fundamental steps in the manufacturing process of solar cells. It is the most important factor influencing the efficiency of solar cells. The aim of this research is to investigate the effect of different p-type (different boron concentrations) and $n-$type (different phosphorus concentrations) resistivity on the efficiency of monocrystalline silicon solar cells. The solar cells were fabricated using p-type silicon doped in boron at concentrations ranging from 6.61×10^{15} to 3.03×10^{16} cm^{-3} and $n-$type silicon doped in phosphorous at concentrations ranging from 5×10^{19} to 10^{21} cm^{-3}. Then, the effect of boron and phosphorus concentration on solar cell efficiency was investigated. It is found that an increase in the concentration of boron or phosphorus results in an increase in the recombination rate and thus a decrease in the efficiency of the solar cell by reducing the short-circuit current (I_{sc}). The best efficiency of 18.59 % was obtained by using boron doped silicon with a resistivity of 2.16 $\Omega.\mathrm{cm}$, corresponding to 6.61×10^{15} cm^{-3} boron concentration and $n-$type sheet resistance 43.5 $\Omega/\square$, corresponding to 10^{20} cm^{-3} phosphorus concentration. As the study was carried out on a range of resistivities values (0.54 $\Omega.\mathrm{cm}$ to 2.16 $\Omega.\mathrm{cm}$), a range of sheet resistance (10 $\Omega/\square$ to 77 $\Omega/\square$).

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Keywords: pn Junction, Silicon Solar Cell Fabrication, Boron Concentration, Phosphrous Concentration, Doping Concentration.

1. INTRODUCTION

Researchers around the world have focused on silicon solar cells in recent years [1-4]. By exploiting all the possibilities of semiconductor technology, it is necessary to find a compromise between cost reduction and efficiency increase. This goal increases the importance and competitiveness of the Photovoltaic (PV) industry [5-7]. Currently, the PV industry is constantly paying attention to new solar cell designs. This has led to the wide acceptance of high-performance emitter applications, such as homogeneous and carved back emitters on crystalline p-type and n-type silicon solar cells [8]. PV technology has been in development for more than 20 years and is now considered one of the most promising renewable energy sources, contributing significantly to global power generation [9].

Polycrystalline silicon (poly-Si) solar cells and Monocrystalline silicon (mono-Si) solar cells are the two most common types of industrial solar cell [10-12]. This is due to its obvious advantages: It is abundant, non-toxic, and has an appropriate band gap within the ideal range for efficient PV conversion [9]. The manufacturing process mono-Si silicon solar cells goes through a number of steps. However, the process of pn junction formation is the fundamental step in the manufacturing process of silicon solar cells, and it is the most influential factor on the efficiency of solar cells. The pn junction is formed when one side of the silicon material is doped with p-type material and the other side of the silicon material is doped with n-type material [13].

In this paper, we will conduct a practical study on the effect of varying the concentration of boron and

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phosphorus on solar cell efficiency at the Egyptian-Chinese Renewable Energy Laboratory located in Sohag. Previous studies have investigated this topic, but they have relied on simulation programs [14],[15], [16-19]. In this study, pn junction will be fabricated practically using boron doped Si wafer with different boron concentration ranging from 6.61×10^{15} to 3.03×10^{16} cm^{-3}, corresponding to resistivity ranging from 0.54 Ω.cm to 2.16 Ω.cm and different phosphorus concentration (n-type) ranging from 5×10^{19} cm^{-3} to 1×10^{21} cm^{-3}, corresponding to sheet resistance ranging from 10 $\Omega/\square$ to 77 $\Omega/\square$ using phosphorous oxychloride ($POCL_3$) diffusion technique. After the formation of the pn junction, all the manufacturing stages of the solar cell were completed in order to measure the cell efficiency and obtain the results of the effect of the different ranges of boron and phosphorus doping concentrations in the pn junction. In contrast to previous studies [14],[15], [16-19], which were conducted using simulation, we conducted our research experimentally. Moreover, we used large-scale (156 mm × 156 mm) mono-Si cells, which makes our findings relevant to industrial applications. We also documented the entire manufacturing process, including all parameters such as temperatures, gases, and chemicals. This makes our paper more applicable to other researchers.

The remainder of this paper is organized as follows: Section II presents the theory of Pn junction and experimental details are presented in III Section. In Section IV, the experimental results on the effect of boron and phosphorus concentration on the efficiency are presented, and then an attempt is made to explain these results. Finally, a conclusion of the results obtained in this paper is presented in Section V.

2. PN JUNCTION THEORY

The concentration of electrons and holes in the crystalline silicon (c-Si) solar cell is modified and optimized by doping. The electrical conductivity of the semiconductor material is influenced by the doping concentration and profile (shallow or deep), which increases the efficiency of the solar cell. The doping concentration and the mobility of the electrons and holes in the semiconductor region of the solar cell are the main determinants of the electrical conductivity of the c-Si solar cell [14]. A pn junction, as shown in Fig.1, is formed by diffusing an n-type material with a p-type material to form a semiconductor diode. In the pn junction theory, the presence of small amounts of phosphorus-doped silicon leads to the formation of n-type semiconductor material, and the presence of small amounts of boron-doped silicon leads to the formation of p-type semiconductor material [20]. In this study, we want to achieve the best concentration of boron to form p-type and then n-type by using the diffusion technique.

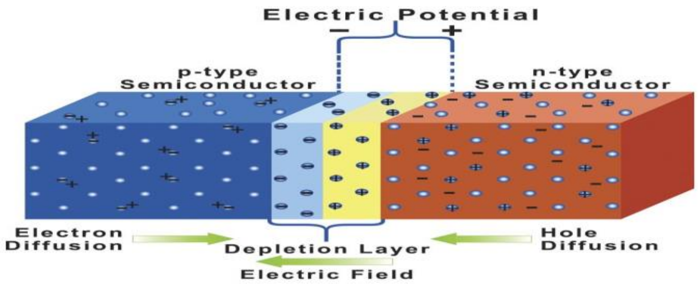

Fig. 1. pn Junction [21].

3. EXPERIMENTAL DETAILS

The samples used in this study were 156 mm × 156 mm pseudo-square Czochralski (Cz) grown p-type (boron-doped silicon) samples with a thickness of 180 µm and a bulk resistivity in the range of 0.54 Ω.cm to 2.16 Ω.cm. The boron concentration was in the range of $6.61 \times 10^{15} - 3.03 \times 10^{16}$ cm^{-3} as shown in Table 1.

TABLE 1. BORON (P-TYPE) CONCENTRATION AND RESISTIVITY

Concentration (cm^{-3})	Resistivity ($\Omega \cdot cm$)
3.03×10^{16}	0.54
1.96×10^{16}	0.792
9.78×10^{15}	1.494
7.32×10^{15}	1.962
6.61×10^{15}	2.16

All parameters of manufacturing process of the mono-Si solar cell as shown in Fig. 2, were kept consistent throughout all stages, with the exception of two changes: the boron concentration was varied in the first stage by using silicon wafer with (p-type) different resistivities ranging from 0.54 $\Omega \cdot cm$ to 2.16 $\Omega \cdot cm$ and the phosphorus concentration was varied in the third stage by using different diffusion temperatures during fabrication. After the cells were manufactured, their efficiencies were measured using a light current voltage tester, as shown in Fig.3. Firstly, the surfaces were textured with random pyramids using alkaline etching mixture of Potassium Hydroxide(KOH) and mono-Si texturing additives with the ratio of 470 g:240 ml at a temperature of 85℃ at a time of 600 sec. after the texturing process was completed , the wafers were loaded into a quartz tube diffusion furnace as shown on Fig.4 to start the diffusion process: pre-deposition and Drive-in steps under the condition of 500 sec for Drive-in and 1000 sec using a ratio of gases $POCL_3/O_2$1900 /2800 SCCM in pre-deposition step and 1200/2000 SCCM in Drive-in step and the diffusion temperature was varied between 755-830 ℃. The plasma etching process was used to remove phosphorus that was diffuse on the edges during the diffusion process then the phosphorus silicate glass formed during the diffusion process was removed in buffered Hydrofluoric Acid (HF) . silicon nitride (Si_3N_4) anti- reflection coating (ARC) was deposited in a tube plasma enhanced chemical vapor deposition (PECVD) system at temperature. A mixture of Siliane (SiH_4) and ammonia (NH_3) was used according to the flow ratio of 600:5400 SCCM at temperature 400℃. The front and back contacts were made by conventional screen-printing technology, as silver (Ag) and aluminium (Al) paste was used on the sides of the cell to make the front and bake metallization by using screen printing device and co-fired to realize the ohmic contacts as well as Al back surface field (BSF). After the completion of all the process, the efficiency of the solar cell has been measured by the light current voltage tester.

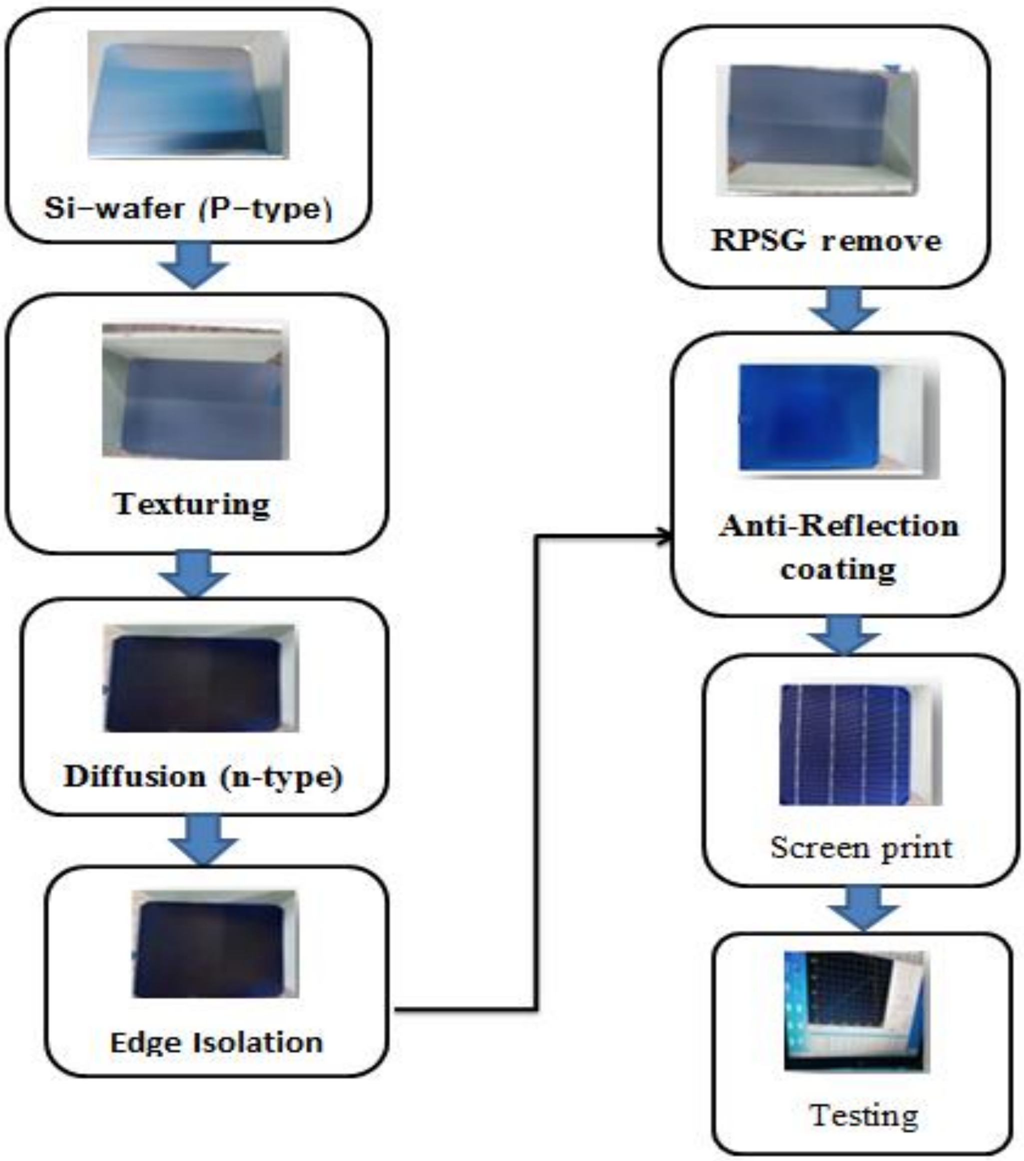

Fig. 2. Sequence of the solar cell fabrication process steps.

Fig.3. light current voltage tester

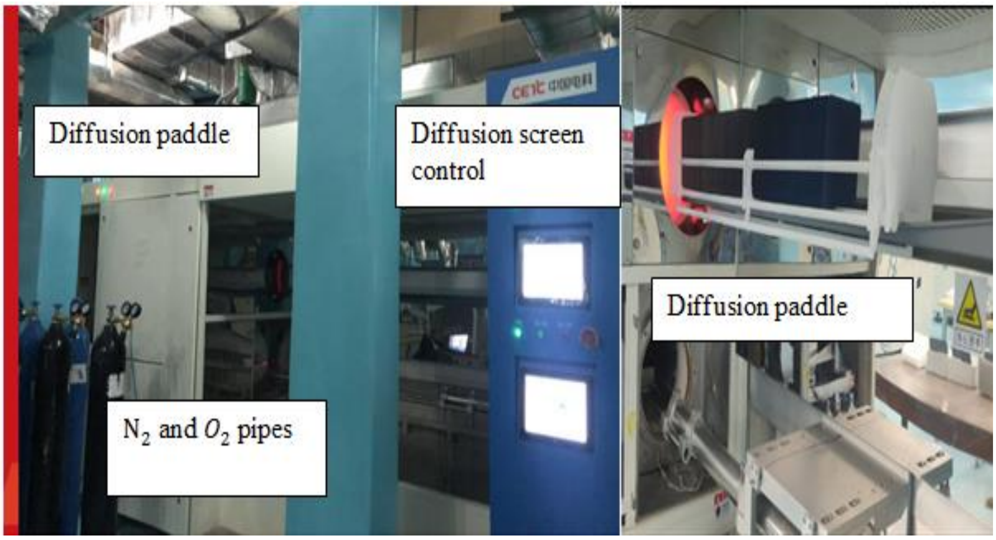

Fig.4. Diffusion furnace to form pn junction.

4.RESULTS AND DISSCUSSION

4.1The effect of doping concentration of phosphorous on the efficiency of silicon solar cell

One of the key steps in the manufacture of solar cells is the development of the pn junction in silicon solar cells. Using $\mathrm{POCL_3}$, an n-type dopant is diffused onto a p-type substrate to create the pn junction. In order to obtain the optimum doping for the improved efficiency of the solar cell, process variables such as temperature, time and gas flow rate are varied [14],[15]. In this study, the diffusion parameter that vary is the temperature of the pre-deposition steps from 755-830 ℃ and the p-type wafer with 2.16 Ω-cm were considered. The effect of phosphorus doping concentration on the efficiency of the solar cell was investigated, the phosphorus concentration was varied: $5\text{x}10^{19}$, $1\text{x}10^{20}$, $4\text{x}10^{20}$ and $1\text{x}10^{21}$ cm^{-3} because of the temperature variation 755-830℃. To calculate the concentration of phosphorus doping and the depth of junction Simulation module (EDNA 2) based on measurements from practical experimental was used. The value of sheet resistance was measured using a four-point probe tester as shown in Table 2.

TABLE 2. PHOSPHORUS CONCENTRATION AND SHEET RESISTANCE ON N-TYPE

Concentration (cm^{-3})	Sheet resistance (Ω/□)	Junction depth (μm)
5×10^{19}	77.0	0.81
1×10^{20}	43.5	0.85
4×10^{20}	16.0	0.91
1×10^{21}	10.0	0.96

After all the manufacturing process were completed, the efficiency of mono-Si was measured. Moreover, the efficiency parameters such as short circuit current (I_{sc}), open voltage circuit (V_{oc}), maximum power (p_{max}), fill factor (FF), series resistance (R_s) and shunt resistance (R_{shunt}) were measured. It is found that with high phosphorus concentration (i.e., 4×10^{20} and 1×10^{21} cm^{-3}), there is a slight increase in V_{oc}. On the other hand, I_{sc} is decreased as shown on Table 3. The decrease in I_{sc} has a negative impact on efficiency, resulting in a decrease in overall cell efficiency**.** This decrease in overall efficiency is due to decreased light transmission, absorption, and higher recombination rate [16]. For a charge carrier to contribute to the current generated by a solar cell, it must be generated within a diffusion length of the pn junction. If a charge carrier is generated outside of the diffusion length, it will recombine before it can reach the junction and contribute to the current. The increase in phosphorus concentration increases the recombination rate and decreases the diffusion length which decrease I_{sc}. Hence, the decrease in I_{sc}causes the overall efficiency of the of the solar cells to decrease. For lightly doped emitters $5\text{x}10^{19}\text{cm}^{-3}$, the (high sheet resistance) as shown in Table 3 results in high series resistance and poor FF. So, there is an optimum doping concentration of phosphorus to reach the highest conversion efficiency. The best concentration of phosphorous is $1\text{x}10^{20}$ cm^{-3} as shown on Fig.5.

TABLE 3. THE SOLAR CELL EFFICIENCY AT DIFFERENT CONCENTRATION OF BORON AND PHOSPHORUS

Doping Material	Boron and phosphorus concentrations	I_{sc}(A)	V_{oc}(V)	P_m(W)	η(%)	FF	R_s(mΩ)	R_{sh}(Ω)
Phosphorus @ Boron concentration= 6.61×10^{15}	5×10^{19}	7.365	0.612	2.920	12.12	64.80	8.621	352.000
	1×10^{20}	8.875	0.624	4.476	18.59	80.55	5.384	225.000
	4×10^{20}	8.438	0.629	4.202	17.44	79.22	6.013	336.000
	1×10^{21}	8.326	0.633	4.126	17.13	78.29	6.194	128.000
Boron @ Phosphorus Concentration (n)=1×10^{20}	3.03×10^{16}	8.433	0.631	4.173	17.13	77.54	6.513	306.412
	1.96×10^{16}	8.506	0.632	4.234	17.58	78.79	6.584	427.303
	9.78×10^{15}	8.631	0.630	4.206	17.88	77.70	6.584	91.107
	7.32×10^{15}	8.725	0.628	4.363	18.11	79.65	5.502	192.981
	6.61×10^{15}	8.875	0.624	4.476	18.59	80.55	5.384	225.000

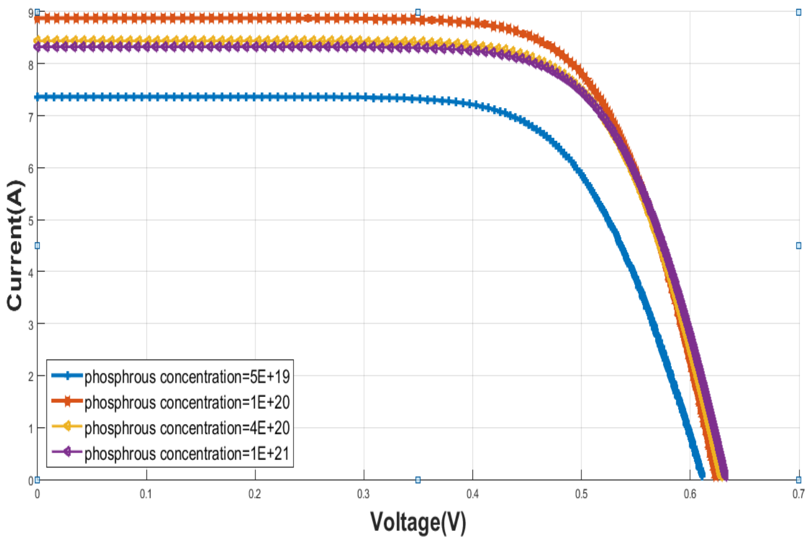

Fig. 5. I-V curve of solar cell with Different doping concentration (n-Type).

4.2 The effect of the concentration of boron on the efficiency of silicon solar cell.

Wafer resistivity negatively affects the emitter and BSF doping concentration during pn junction formation, which has a significant impact on the performance of silicon solar cells. Wafer resistivity can vary depending on the bulk doping concentration. When manufacturing silicon solar cells, it is interesting to consider the variation in wafer resistivity and how it affects the efficiency of the solar cell [14]. In this study, the effect of boron doping concentration on the efficiency of mono-Si cells was investigated. After all the manufacturing processes were completed, the efficiency on mono-Si was measured as shown in Table 3 that the concentration varies from 6.61×10^{15} to 3.03×10^{16} as shown in Table 1. In order to calculate the boron doping concentration EDNA2 modelling was used. It was found that increasing the boron concentration in mono-Si solar cells, its efficiency decreases. This is because the increase in boron concentration leads to an increase in the recombination rate, which reduces I_{sc}. Also, carrier mobility decreases with increasing total dopant concentration thus reducing efficiency. It is found that the best concentration of boron is 6.61×10^{15} as shown on Fig.6.

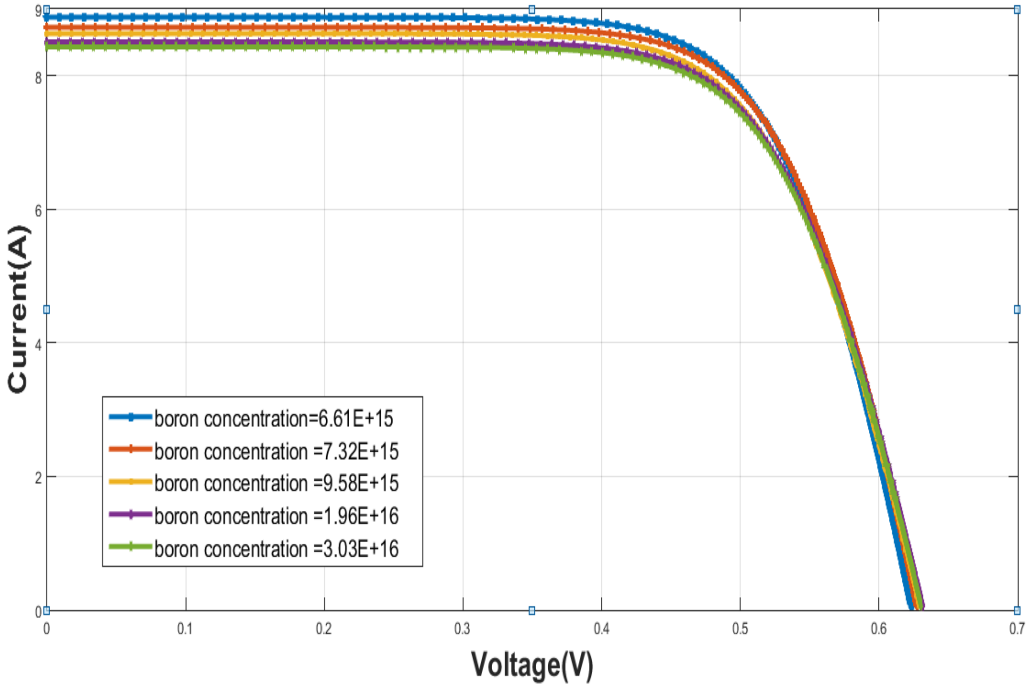

Fig.6. I-V curve of solar cell with Different doping concentration (P-Type).

5. CONCLUSION

In conclusion, the process of pn junction formation is a delicate, sensitive, and effective process in the efficiency of the solar cell and is even considered the basic stage. The concentration of boron and phosphorus must be focused on the choice that the concentration of impurities affects the efficiency of solar cell. It is found that the increase of the concentration has a negative effect. In this study the change of the concentration of boron was done in the range of $6.61 \times 10^{15} - 3.03 \times 10^{16}\ \mathrm{cm^{-3}}$ and the phosphorus in the range of $5 \times 10^{19} - 1 \times 10^{21}\mathrm{cm^{-3}}$ and the effect of efficiency was found from $17.13 - 18.59\%$. As the study was carried out on a range of boron concentration values from 6.61×10^{15} to $3.03 \times 10^{16}\ \mathrm{cm^{-3}}\ \mathrm{cm^{-3}}$ and phosphorous concentration values from 5×10^{19} to $1 \times 10^{21}\ \mathrm{cm^{-3}}$. *It is found that a best efficiency of 18.59% was obtained at boron and phosphorus concentration of* $6.61 \times\ 10^{15}\ \mathrm{cm^{-3}}$, 1x$10^{20}\ \mathrm{cm^{-3}}$ *respectively.*

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