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Migration Of Manganese Impurities in Silicon Under the Influence of an Electric Field

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Abstract. In this work, the diffusion coefficients of manganese in silicon were compared by doping the element manganese into silicon at 5 different temperatures (T=800, 850, 900, 950, 1000 ºC) using traditional diffusion and electrodiffusion methods. At temperatures between 800÷900 ºC, manganese atoms were observed to form positive ions by settling between the silicon nodes and diffusing towards the negative pole of the electrodiffusion device. At temperatures between 950÷1000 ºC, manganese atoms settle on the silicon nodes, forming negative ions, and diffusion towards the positive pole of the electrodiffusion device was observed.

INTRODUCTION

It is known that new technologies for doping impurity atoms into semiconductor materials allow improving the basic parameters of semiconductor materials. Therefore, there is a great deal of interest in new technologies for doping impurity atoms into semiconductor materials. Currently, there are several types of doping of impurity atoms into semiconductor materials. Examples of these include doping during semiconductor growth [1,2], diffusion [3-7], bombardment with high-energy ions [8-10], and doping using laser beams [11-13]. However, these methods have their advantages and disadvantages. Some doping methods, while providing high-quality and precise doping levels, require very expensive equipment and technology. While the method of bombardment with high-energy ions allows the introduction of high concentrations of impurity atoms into the surface layer of the sample, its main disadvantage is the disruption of the crystallinity of this surface layer. In the diffusion method, the solubility of impurity atoms in the semiconductor material and the presence of limiting values of the diffusion coefficient are considered [14-16]. As a solution to the disadvantages of these methods of doping impurity atoms into semiconductors, the authors propose a new method of doping (electrodiffusion) using an external electric field [17-19].

The introduction of silicon atoms into the volume of semiconductor materials under the influence of an electric field and the elucidation of the mechanism of their distribution are of great scientific and practical importance. It is known from the literature that in the traditional diffusion process, the impurity atoms move chaotically and are mainly in the form of positive ions. It is known that the diffusion parameters of the impurity atoms, for example; the diffusion coefficient, the solubility of the impurity atoms and their location in the crystal lattice, depend on the diffusion temperature and time [20-22]. Knowing the introduction of impurity atoms into silicon under the influence of an electric field and their distribution in volume allows obtaining very important scientific information. The method of doping dopant atoms into silicon in an electric field with a sufficiently high current density (J=25÷40 A/cm^2) significantly accelerates the penetration of dopant atoms into the silicon volume, and leads to a decrease in the diffusion temperature of dopant atoms by T~150÷200˚C compared to the traditional diffusion temperature.

RESEARCH METHODS

For the study, monocrystalline p-Si silicon with a resistivity of $\rho \approx 5$ Ω·cm, doped with boron during growth by the Chokhral method, was selected. The sample dimensions were prepared in the form of 40×80×1 mm^3. A thin layer of manganese (Mn) was formed on one side of these samples using a VUP-4 vacuum device. Two samples were glued together with the sides with the formed thin layer of manganese facing each other and placed in an electrodiffusion device (see Figure 1). When an electric current is passed through the samples, heating occurs due to resistance. The temperature values T=800, 850, 900, 950 1000 ºC were selected for the test. For comparison, the traditional diffusion method was also carried out at these temperatures (see Table 1).

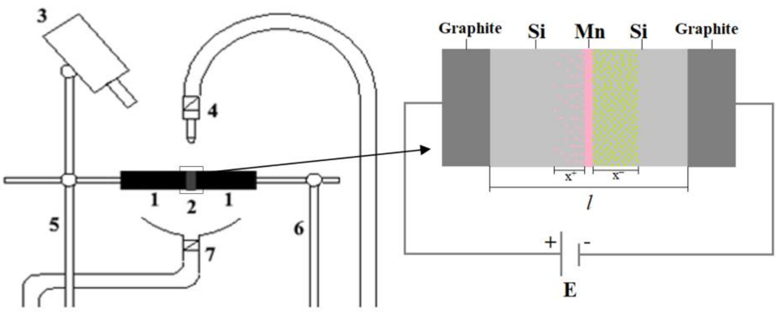

FIGURE 1. Schematic of a structure created for the diffusion of dopant atoms into silicon under the influence of an electric field: 1-Graphite; 2-sample; 3-thermocouple; 4-sample cooling unit; 5,6-electrodes; 7-cooler.

TABLE 1. Thermoelectric parameters of samples alloyed with manganese intercalated atoms.

№	Traditional diffusion	Electrodiffusion			
	T,°C	I, A	T,°C	U, V	*l, mm (total thickness of two samples)*
1	800	35	800	3	2
2	850	47	850	3	2
3	900	60	900	3	2
4	950	70	950	3	2
5	1000	80	1000	3	2

RESEARCH RESULTS AND DISCUSSION

The samples were quenched in a special oil after electrodiffusion and conventional diffusion processes. The process was carried out in the same way for both methods (t=15 minutes). After the alloying process, the electrophysical parameters of the samples were measured using an HMS-3000 device. All measurements were carried out at room temperature (T=300 K). The diffusion coefficient of the manganese inclusion in silicon was calculated using the measured electrophysical parameters and equations (1), (2), (3) and (4) (see Tables 2 and 3).

$$D = D_0 \cdot exp\left(-\frac{E_a}{kT}\right) \quad (1)$$

$$D^{EP} = \mu El \quad (2)$$

$$D^{ED} = D + D^{EP} \quad (3)$$

$$x = 2\sqrt{D \cdot t} \quad (4)$$

TABLE 2. Research results of the sample placed on the negative pole of the electrodiffusion device

T, ºC	Traditional diffusion		Only the effect of the electric field		Diffusion under the influence of an electric field					t, s
	x, mkm	D, 10^{-7} cm^2/s	D^{EP} (μEL), 10^{-7} cm^2/s	μ, 10^{-7} cm^2/(V·s)	D^{ED}, 10^{-7} cm^2/s	x_{-}, mkm	U, V	l, cm	E, V/cm	
800	272	2.067	5.433	1.81	7.5	260	3	0.2	15	900
850	372.9	3.862	12.178	4.06	16.04	380	3	0.2	15	900
900	496.3	6.843	23.157	7.719	30	520	3	0.2	15	900
950	645	11.57	29.77	9.9	41.34	610	3	0.2	15	900
1000	822	18.77	23.93	7.97	42.7	620	3	0.2	15	900

Based on the results presented in Table 2, a temperature dependence graph was constructed for the diffusion coefficient (D) of manganese dopant atoms in silicon doped by the traditional diffusion method, the diffusion coefficient (D^{ED}) of manganese ions in silicon by the electrodiffusion method, and the diffusion coefficient (D^{EP}) of manganese ions in silicon under the influence of an electric field only.

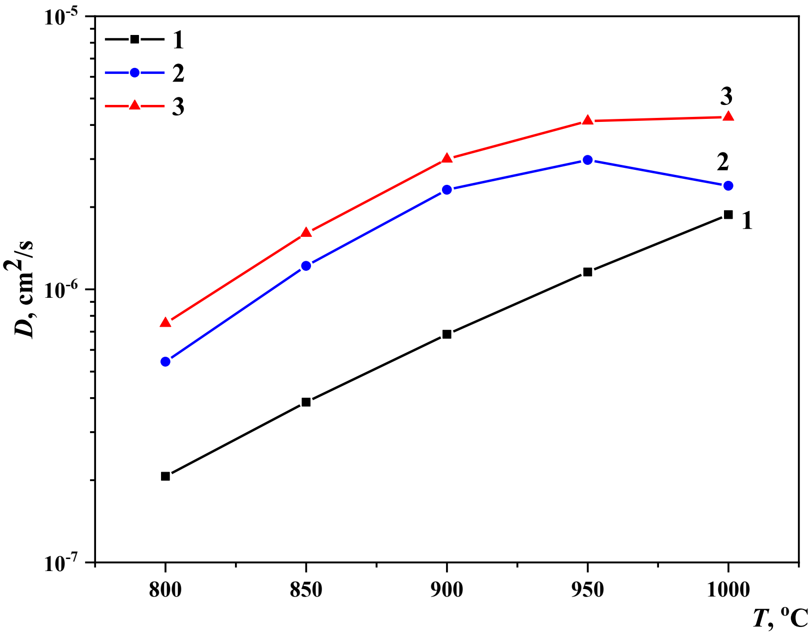

FIGURE 2. Temperature dependence of the diffusion coefficients of manganese in silicon: 1—conventional diffusion, $D=D_0\cdot\exp(-Q/(kT)$; 2—electric field effect only, $D^{EP}=\mu EL$; 3—electrodiffusion, $D^{ED}=D+D^{EP}$.

It is clearly seen from Figure 2 that the diffusion coefficient of manganese doped in silicon by electrodiffusion is larger than that of conventional diffusion. However, when the temperature exceeds 950 ºC, the diffusion coefficient of manganese doped in silicon by electrodiffusion remains almost unchanged (line 3 in Figure 2). In this case, only under the influence of an electric field, we can see that the diffusion coefficient of manganese in silicon (line 2 in Figure 2) decreases at a temperature of 1000 ºC. In conventional diffusion, the diffusion coefficient of manganese in silicon increases linearly with increasing temperature (line 1 in Figure 2).

To better understand this process, we are required to analyze the results of samples placed on the positive pole of an electrodiffusion device.

TABLE 3. Research results of the sample placed on the positive pole of the electrodiffusion device

T, ºC	Traditional diffusion		Only the effect of the electric field		Diffusion under the influence of an electric field					t, s
	x, mkm	D, 10^{-7} cm^2/s	D^{EP} (μEL), 10^{-7} cm^2/s	μ, 10^{-7} cm^2/(V·s)	D^{ED}, 10^{-7} cm^2/s	x_+, mkm	U, V	L, cm	E, V/cm	
800	272	2.067	-1.842	-0.614	0.225	45	3	0.2	15	900
850	372.87	3.862	-3.115	-1.0038	0.747	82	3	0.2	15	900
900	496.3	6.843	-3.633	-1.211	3.21	170	3	0.2	15	900
950	645	11.57	-0.754	-0.251	10.816	312	3	0.2	15	900
1000	822	18.77	17.33	5.78	36.1	570	3	0.2	15	900

The reason why the diffusion coefficient and ion mobility values in Table 3, which are only affected by the electric field, are less than zero, that is, negative, in the temperature range of 800÷950 ºC can be explained as follows.

It is known [23-26] that manganese atoms in a sample placed on the positive pole of an electrodiffusion device diffuse from the negative pole to the positive pole due to the concentration difference under the influence of heat. However, the manganese atoms in the sample initially settle between the nodes of the silicon crystal lattice and form positive ions. Positive manganese ions move towards the negative pole under the influence of an electric field and inhibit the manganese atoms diffusing from the negative pole to the positive pole due to the concentration difference. As a result, the diffusion coefficient of manganese in silicon seems to decrease.

Based on the results presented in Tables 2 and 3, a temperature dependence graph was constructed for the diffusion coefficient (D) of manganese impurity atoms in silicon in conventional diffusion, the diffusion coefficient (D^{EP}) of manganese ions in a silicon sample placed on the negative pole of the electrodiffusion device, and the diffusion coefficient (D^{ED}) of manganese in a silicon sample placed on the positive pole of the electrodiffusion device.

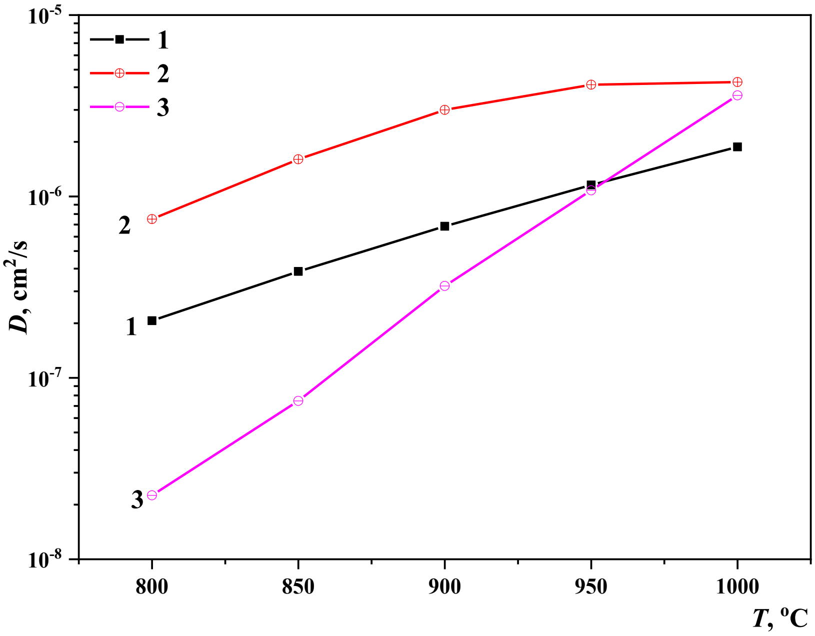

FIGURE 3. Temperature dependence of the diffusion coefficients of manganese in silicon: 1—conventional diffusion; 2—sample placed on the negative pole of the electrodiffusion device; 3—sample placed on the positive pole of the electrodiffusion device.

It is clearly seen from Figure 3 that the diffusion coefficient of manganese in silicon in the sample placed on the negative pole of the electrodiffusion device is larger than the diffusion coefficients of manganese in the sample placed on the positive pole of the electrodiffusion device by conventional diffusion and by electrodiffusion. We can see that the diffusion coefficient of manganese in the sample placed on the positive pole of the electrodiffusion device increases sharply with increasing temperature in the temperature range of 800÷1000 ºC. In addition, at a temperature of 950 ºC, it can be seen that the diffusion coefficients of manganese in the sample placed on the positive pole of the conventional diffusion [27-29] and electrodiffusion [30-32] devices become equal to each other (lines 1 and 3 in Figure 3).

CONCLUSIONS

Based on the results obtained, we will consider the diffusion mechanism of manganese in silicon by the electrodiffusion method. During the electrodiffusion process, manganese ions located in the silicon crystal lattice are simultaneously affected by the diffusion current (J_D) and the electric field current (J_{EP}) due to the concentration difference and temperature.

1. In this case, since in the temperature range of 800÷900 ºC most of the manganese atoms are mainly located between the nodes of the silicon crystal lattice and form positive ions, the directions of the diffusion current (J_D) and the electric field current (J_{EP}) acting on the positive ions of manganese in the sample placed on the positive pole of the electrodiffusion device are opposite to each other (see Figure 4).

$$J_{ED}=J_D - J_{EP} \quad (5)$$

The directions of the diffusion current (J_D) and the electric field current (J_{EP}) acting on the positive ions of manganese in a sample placed on the negative pole of the electrodiffusion device are the same (see Figure 4).

$$J_{ED}=J_D + J_{EP} \quad (6)$$

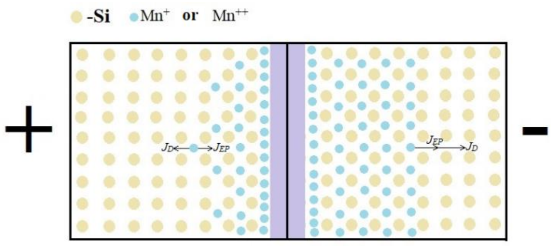

FIGURE 4. The mechanism of diffusion of manganese element into silicon by electrodiffusion at temperatures between 800÷900 ºC

2. In the temperature range of 950÷1000 ºC, since most of the manganese atoms are located mainly at the nodes of the silicon crystal lattice and form negative ions, the directions of the diffusion current (J_D) and the electric field current (J_{EP}) acting on the negative ions of manganese in the sample placed on the positive pole of the electrodiffusion device are the same (see Figure 5).

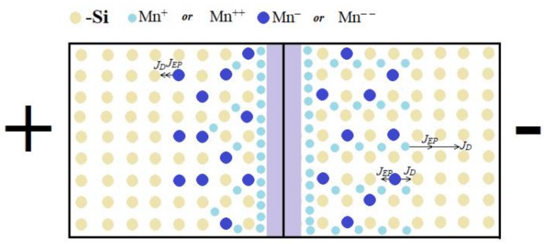

FIGURE 5. The mechanism of diffusion of manganese element into silicon by electrodiffusion at temperatures between 950÷1000 ºC

The directions of the diffusion current (J_D) and the electric field current (J_{EP}) acting on the negative ions of manganese in the sample placed on the negative pole of the electrodiffusion device are opposite to each other (see Figure 5).

3. Compared to traditional diffusion, the diffusion coefficient of Mn ions under the influence of an electric field in the electrodiffusion method was found to be on average ~4 times greater at temperatures T=800÷900 ºC and on average 2.5÷3.5 times greater at temperatures T=950÷1000 ºC.

4. The new electrodiffusion method of alloying is very promising because it requires less energy compared to the traditional diffusion method [33,34].

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