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EFFECTIVE CHARGE OF Mn AND Ni IMPURITY ATOMS IN SILICON UNDER THE INFLUENCE OF AN EXTERNAL ELECTRIC FIELD

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In this work, the diffusion of Mn and Ni impurity atoms to *p*-Si and *n*-Si samples under the influence of an external electric field was investigated in the temperature range *T*~800÷1300°C. The research results show that at temperatures above 1000°C, the effective charge of manganese ion has a negative value, and at temperatures below 900°C, the effective charge has a positive value. In the temperature range *T*=800÷1250°C, nickel ions move in the opposite direction to the current direction of the electric field. The increase in the effective charge with the increase in temperature was explained by the attraction of neutral nickel atoms by electrons.
Keywords: *Silicon; Impurity atoms; Diffusion; Effective charge; External electric field*
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1. INTRODUCTION

The external electric field causes the movement of the impurity particles in the semiconductor and the interaction between the diffusion particles and the free charge carriers of the semiconductor. In a number of cases, this interaction significantly affects the migration of these particles [1,2].

Formation of III-V and II-VI binary compounds in Si crystal lattice and surface is one of the most promising directions. But when forming III-V and II-VI group compounds in the silicon crystal lattice, the diffusion coefficient of III and V group elements in Si material is small (~10^{-14}÷10^{-11} cm^2/(V·s)) [3,4,5,6 ,7,8,9], due to the low solubility of group II and VI elements in Si material (~10^{15}÷10^{18} cm^{-3}) [10,11,12,13,14,15], it is not possible to detect the change in the functional parameters of the Si semiconductor using existing devices. For this reason, the interest in increasing the diffusion coefficient and solubility of impurity atoms in crystals of Si and Ge [16,17,18,19] is of great scientific and practical importance.

Until now, there are very few articles devoted to the effect of external electric field on the diffusion of impurity in semiconductors. This article provides information on the electromigration of nickel (Ni) (a Ni acceptor in silicon [20,21,22]) and manganese (Mn) (a Mn donor in silicon [23,24,25]) in silicon.

2. MATERIALS AND METHODS

For the study, *p*-Si ($n_B \approx 5\times10^{15}$ cm^{-3}) and *n*-Si ($n_P \approx 5\times10^{13}$ cm^{-3}) brands of silicon were selected. The samples were cut in dimensions of 5×10×1 mm^3 (all samples have the same size) using a STX-402 diamond wire cutter, and the surface of the samples was mechanically and chemically treated.

After that, using the VUP4 device, a thin metal layer of Mn (the purity of manganese was 99.998%) on the surface of *p*-Si and Ni (the purity of nickel was 99.997%) on the surface of *n*-Si was formed (Fig. 1).

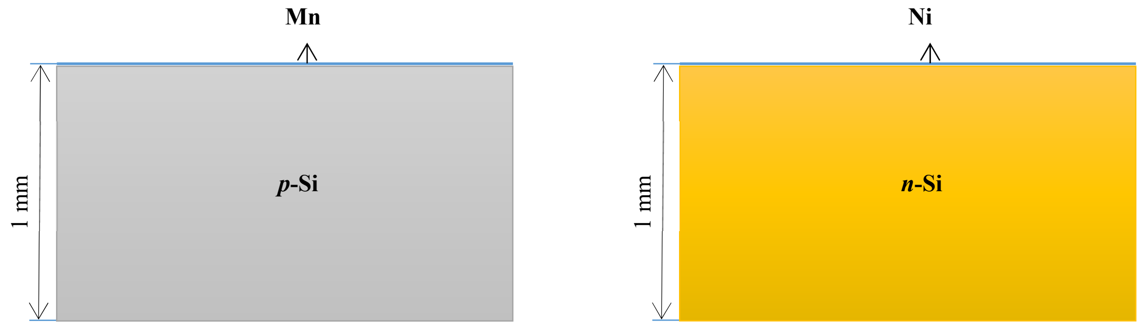

Figure 1. Si samples with a thin metal layer formed on the surface

Two grains of Si samples with a thin metal layer of Mn on the surface, were placed in an electro-diffusion device for the purpose of diffusion. In this case, the positive pole of the electro-diffusion device was connected to one of the samples and the negative pole to the other. The same process was repeated for Si samples on which a thin metal layer of Ni was formed on the surface (Fig. 2). In the process of electro-diffusion, a constant current with a current density of J = 20÷260 A/cm^2 was passed through the samples for 20 minutes, during which the samples were heated to a temperature

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of 800÷1300°C. After the end of the electro-diffusion process, the samples were quickly cooled using a special oil and subjected to chemical and mechanical processing. After electro-diffusion, the distance between the contact boundaries of the samples and the depth of the p-n transition in the cathode and anode samples was measured using an optical comparator with an accuracy of ±1 μm.

Figure 2. Placement of samples in an electro-diffusion device

3. RESULTS AND DISCUSSION

By studying the distribution of the impurity concentration in the samples, the mobility of ions can be determined from the following equation:

$$\mu = \frac{Q_{+} - Q_{-}}{N_0 E t}, \tag{1}$$

where Q_+ and Q_- are the amount of impurity diffused in the direct current E electric field to the anode and cathode samples, N_0 is the impurity concentration in the $x = 0$ plane, t is the duration of electrical migration. On the other hand, if you know the concentration distribution in the studied samples, you can determine the ratio of the mobility to the diffusion coefficient:

$$\frac{\mu}{D} = \frac{1}{E}\frac{d}{dx} ln \frac{N_{-}(x,t)}{N_{+}(x,t)}. \tag{2}$$

where $N_-(x,t)$ and $N_+(x,t)$ are the impurity concentration distributions in the cathode and anode samples, respectively.

Diffusion of impurities to silicon under the influence of an external electric field, analysis of the concentration profile of impurities was supplemented by the *p-n* junction technique. In this case, the mobility of ions is determined by the following formula:

$$\mu = \frac{x_{-} - x_{+}}{2Et}, \tag{3}$$

where x_- and x_+ are the *p-n* junction depths of the cathode and anode samples, respectively. The surfaces of the samples were chemically cleaned from the oxide layer, and the *p-n* junction depth was determined using a thermoprobe and layer-by-layer chemical decomposition method.

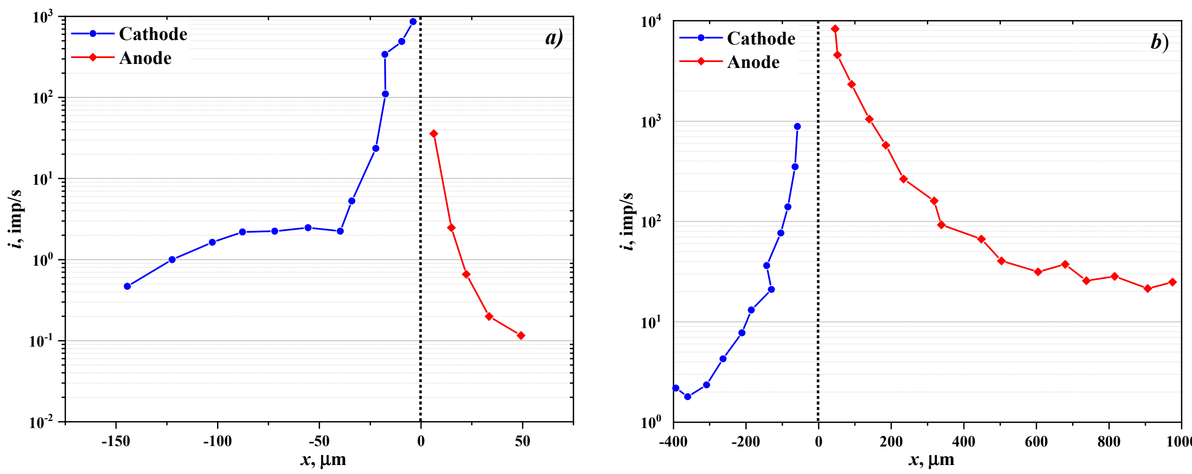

Figure 3. Distribution of impurities in silicon doped with Mn atoms under the influence of an external electric field: *a*) T=830°C; *b*) T=1200°C.

Figure 3 shows that manganese ions move in the same direction as the external electric current at temperatures $T = 830$℃ (at temperatures below $T = 950$℃), that is, manganese ions are connected to the cathode moves towards the sample. Manganese ions at temperature $T = 1200$℃ (at temperatures higher than $T = 1000$℃) move mainly towards the anode (Fig. 3 b).

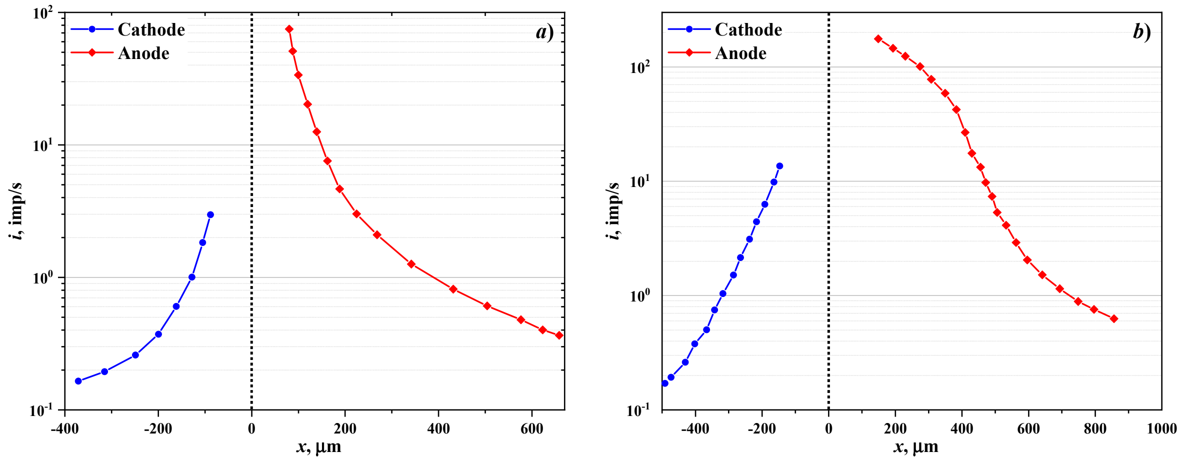

Figure 4. Distribution of diffusion of Ni atoms in silicon under the influence of an external electric field:
a) T=813 °C; b) T=1200 °C.

Figure 4 shows the graphs for electromigration of nickel in silicon in anode and cathode samples at temperatures $T = 813$°C and $T = 1200$°C. As can be seen from the figure, in this case, unlike Mn, it is not observed to move in the same direction as the direction of the external electric current in the entire temperature range, and in the studied temperature range, the ions of Ni atoms $q = 0.3 \div 2$ moves towards the anode in the form of an effective charge. In the temperature range $T = 800 \div 1250$°C, the lack of inversion of the mobility of nickel ions and the increase of the effective charge with increasing temperature indicate that the results of the electromigration study can be explained by the attraction of neutral nickel atoms by electrons is necessary, because the movement of neutral atoms in electromigration is determined only by the attraction effect.

Knowing μ/D and using Einstein's relation (4), the charge of the input ions can be calculated (Fig. 5).

$$\frac{\mu}{D} = \frac{q}{kT}, \quad (4)$$

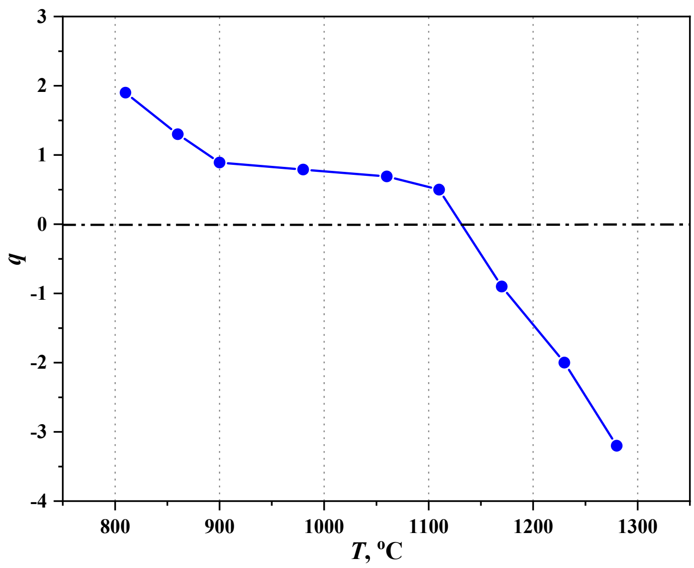

Figure 5. Dependence of effective charge of Mn ions doped on silicon by electro-diffusion method on diffusion temperature

4. CONCLUSION

Values of manganese ion mobility and their effective charge calculated from experimental data as a function of diffusion temperature are shown in Fig. 5. It can be seen that at temperatures above 1000°C, the effective charge of manganese ion has a negative value and the transmission increases rapidly with increasing temperature, and at temperatures below 900°C, the effective charge has a positive value and changes in the range of 1:2. The movement of manganese ions to the cathode at temperatures below 900°C can be explained by the diffusion of manganese in the form of Mn^{++}, which has a large diffusion coefficient in silicon, between the nodes. However, in this case, the reason for the change in direction of movement of Mn ions at T=950°C remains unclear. This anomalous phenomenon may be a consequence of a change in the diffusion mechanism of manganese or a manifestation of the attraction effect of manganese ions with electrons.

The results of the experiment show that the solubility and diffusion coefficient of silicon-doped impurities can be increased under the influence of a constant external electric field. Proving this assumption requires large-scale experiments on the doped of silicon impurities under the influence of an external electric field.

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ЕФЕКТИВНИЙ ЗАРЯД ДОМІШКОВИХ АТОМІВ Mn ТА Ni В КРЕМНІЇ ПІД ВПЛИВОМ ЗОВНІШНЬОГО ЕЛЕКТРИЧНОГО ПОЛЯ

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У даній роботі досліджено дифузію домішкових атомів Mn та Ni до зразків p-Si та n-Si під дією зовнішнього електричного поля в інтервалі температур T~800÷1300°C. Результати досліджень показують, що при температурах вище 1000°C ефективний заряд іона марганцю має негативне значення, а при температурах нижче 900°C ефективний заряд має позитивне значення. В інтервалі температур T=800÷1250°C іони нікелю рухаються в протилежному напрямку до поточного напрямку електричного поля. Збільшення ефективного заряду з підвищенням температури пояснювали притяганням електронами нейтральних атомів нікелю.

Ключові слова: *кремній, домішкові атоми, дифузія, ефективний заряд, зовнішнє електричне поле*