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Physical mechanisms of gettering properties of nickel clusters in silicon solar cells

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This study demonstrates that the concentration of nickel atoms near the surface of solar cells is 2–3 orders of magnitude higher than in the bulk material, significantly enhancing the gettering rate at the surface. Using IR-microscopy, SEM, and SIMS, we found that the surface density of nickel clusters is approximately 10^6–10^7 cm^{-2}, with an average cluster diameter of 20–100 nm and a cluster concentration of 10^{11}÷10^{15} cm^{-3} Experimental results revealed that nickel clusters on the surface of silicon samples contain a substantial amount of oxygen and recombination impurities (Cu, Fe, Cr), indicating excellent gettering properties. We identified the physical mechanisms underlying the effects of nickel impurity atom diffusion and additional thermal annealing on the state of nickel atoms near the surface and base of the solar cells. Physical models were developed for the structure of nickel atom clusters in silicon and for the gettering process of fast-diffusing impurities by these clusters. The binding energy of fast-diffusing impurity atoms with a nickel cluster was estimated to be approximately 1.39 eV. Calculations indicated that nickel doping can increase the lifetime of minority charge carriers by a factor of 2–4, and experimental results confirmed an increase in the lifetime of minority charge carriers by up to a factor of 2. These findings highlight the potential of nickel doping to enhance the performance and efficiency of silicon-based solar cells, offering a promising avenue for future research and development in photovoltaic technology.

Key words: silicon solar cell, diffusion, nickel clusters, recombination centers, gettering, minority carrier lifetime, binding energy.
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1 Introduction

In modern industrial production of solar cells (SCs), there is a trend toward increasing the use of solar-grade silicon due to its lower cost [1]. However, solar-grade silicon has a shorter minority carrier lifetime, making it challenging to achieve high conversion efficiency [2, 3]. To enhance the efficiency of silicon SCs, it is necessary to increase the collection coefficient and the lifetime of photogenerated charge carriers [4, 5], and to reduce optical and electrical energy losses [6]. Increasing the minority carrier lifetime in SCs [7, 8] can be achieved through the gettering of recombination centers by nickel clusters.

The effectiveness of complex formation and gettering processes depends significantly on the mobility of impurity atoms in the lattice and their binding energy with the getter [9–11]. Therefore, an important task is to assess the structure of nickel clusters and the binding energy of impurity atoms with these clusters [12–15].

In work [16], the mechanisms and basic methods for obtaining atomic clusters were studied, and the possibilities for controlling the properties of cluster materials were analyzed. The physical essence of cluster formation in semiconductors is the system's tendency to achieve a state with minimal free energy, i.e., gradually restoring equilibrium.

Works [17, 18] investigate changes in the size and density of nickel clusters depending on the annealing temperature (T=650÷900 °C) and cooling rate. It was found that as the annealing temperature decreases, cluster density decreases while their size increases. Similarly, a decrease in the cooling rate leads to a reduction in cluster density and an increase

in size. Using IR microscopy, studies [19, 20] discovered the self-organization of nickel clusters in a silicon lattice under conditions of diffusion doping and additional thermal annealing.

Nickel clusters easily form during both diffusion and additional thermal annealing, but they have minimal impact on the electrical parameters of the material itself during thermal annealing in the temperature range of T = 400÷1000 °C [21, 22].

While the above studies focused on nickel clusters in bulk silicon, they did not explore the formation of nickel clusters in the near-surface nickel-enriched region of silicon. For small clusters, the surface's contribution to the system's free energy change is significant, and the influence of elastic deformation increases with cluster size. Rigorous quantitative assessments of these effects are challenging because they require accurate cluster models. Therefore, as mentioned in [16], the concepts of “crystal lattice” or “surface” of a cluster are often used arbitrarily.

If clusters of nickel atoms possess gettering properties and can remove harmful impurities from the crystal, they positively affect the efficiency of solar cells (SCs). Based on this, it is assumed that additional doping of silicon SCs with nickel atoms should increase their efficiency by extending the minority carrier lifetime.

Systematic research into the effect of nickel impurity clusters on the parameters of silicon SCs is of significant practical interest, as nickel shows great promise due to the technological advantages of doping [23–25]. From a technological perspective, the deposition of a nickel metal layer onto the silicon surface can be achieved chemically [26, 27], allowing simultaneous processing of multiple wafers. Additionally, the diffusion of nickel atoms can be performed in open air at relatively low temperatures (T_{diff} = 800–850°C). Consequently, the method of doping silicon with nickel atoms from a chemically deposited layer can be seamlessly integrated into existing industrial SC production processes.

However, models of nickel clusters are currently lacking, and the physical mechanisms by which nickel atom clusters affect the parameters of silicon SCs remain unclear. The purpose of this study was to demonstrate the effectiveness of introducing nickel impurities into silicon wafers used in photovoltaic converters, to elucidate the physical mechanisms by which nickel clusters influence the lifetime of minority charge carriers in silicon SCs, and to develop an appropriate physical model.

2 Methods and materials

To study the formation of clusters and silicides on the surface due to high nickel concentrations, the following investigations were carried out. The wafers were obtained using the Czochralski method, with a resistivity of 0.5 Ω·cm, a thickness of 380 μm, a minority carrier lifetime (τ) greater than 6 μs, an oxygen content of approximately N_{O2}~ 7×10^{17} cm^{-3}, and a dislocation density (N) less than 10^2 cm^{-2}. In a vacuum, a layer of pure nickel 1 μm thick was deposited onto the surface of the samples. Diffusion was carried out at T_{diff} = 800–950 °C for 30 to 60 minutes, and at T_{diff} = 1000–1200 °C for 5 to 60 minutes in an air atmosphere, followed by air cooling (without a boat). After diffusion, additional thermal annealing was conducted at T_{ann} = 700–900 °C for 30 to 60 minutes in an air atmosphere (~50–60 °C/s) to activate the gettering process of uncontrolled recombination impurities [26–28].

After each technological stage, chemical treatment was performed to remove residues of metallic nickel and silicon oxide from the surface (using a 3:1 mixture of HCl and HNO_3, followed by 49% HF and a water rinse). The surface was then cleaned with a hydrogen peroxide–ammonia solution. The samples were not ground or polished.

To study the formation of nickel clusters in silicon and their parameters, silicon samples doped with nickel were examined using an INFRAM-I infrared microscope and a scanning electron microscope. The elemental composition of nickel clusters in the samples was analyzed using a TESCAN MIRA3 scanning electron microscope in X-ray microanalysis mode. Measurements were taken on both the front surface and the fracture surface of the samples. The fracture surfaces were scanned with a step size of 0.5 μm, starting from the front side (the side doped with nickel).

3 Results

Previously [26], the distribution of nickel atoms in the near-surface layer of silicon after diffusion was measured with a CAMECA IMS-6f Magnetic Sector SIMS mass spectrometer. It was found that the surface concentration of nickel reaches approximately $n_S \approx (2–4) \times 10^{21}$ cm^{-3}, the thickness of the enriched layer is about $d \sim 2–3$ μm, and nickel is distributed almost uniformly throughout the bulk with a concentration of $n_{Ni} \approx 10^{16}–7 \times 10^{17}$ cm^{-3}, which confirms the published results [29].

The sizes of nickel atom clusters in the obtained samples were measured with a TESCAN MIRA 3 scanning electron microscope (see Fig. 1).

Based on the obtained results (IR microscopy, SEM, and SIMS), it was found that the surface density of nickel clusters is approximately 5×10^6 – 10^7 cm^{-2} on the front surface and about (4–5) $\times10^6$ cm^{-2} in the bulk of the material. The distribution of clusters in the bulk is nearly uniform, and their size is less than 0.5 μm (approximately 20–100 nm). These findings confirm the results of the previous studies [16, 28, 29]. It should be noted that these results were observed at all studied diffusion temperatures within the range of annealing temperatures of T_{ann} = 800–900°C. Based on the obtained data, the concentrations of clusters (n_k) were calculated to be approximately 10^{11}–10^{13} cm^{-3} in the bulk of the sample and approximately 10^{13}–10^{15} cm^{-3} in the nearsurface region enriched with nickel.

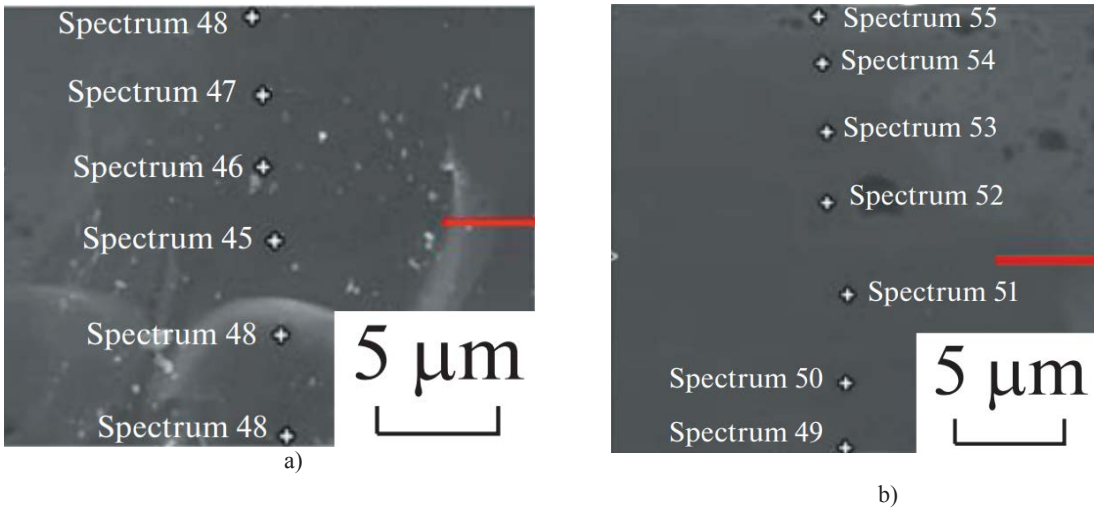

Figure 1 - Images of the investigated points and clusters of nickel atoms in the bulk (a) and on the surface (b) of the samples after additional thermal annealing at Tann = 800 °C

Changes in the size and state of nickel atom clusters in silicon were observed after additional thermal annealing. Annealing in the temperature range of T_{ann} = 650–800 °C led to the coarsening of nickel clusters, while at T_{ann} > 900 °C, the clusters underwent decomposition.

The measurement of the cluster composition revealed that clusters (Fig. 2) on the surface of silicon primarily consist of silicon atoms (~84–86%) and nickel atoms (~13–15%). However, they also contain traces of copper (Cu), iron (Fe), chromium (Cr), and other elements [27]. This demonstrates the efficient gettering of harmful impurities by nickel clusters, which act as recombination centers in silicon. This can lead to a significant increase in the lifetime of minority charge carrier primarily due to the formation of nickel clusters in the near-surface layers.

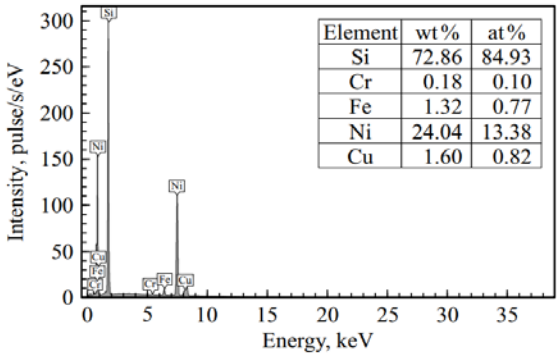

Figure 2 - Impurity atoms clusters composition observed through probe elementary analysis using the scanning election microscope TESCAN MIRA 3

Using the same method, we determined the composition of nickel clusters after the additional thermal treatment (T_{ann} = 800°C, t = 30 min). It was

found that, after the annealing, the concentration of nickel atoms increased by about 40–60%, oxygen, by approximately 30–35%, and fast-diffusing impurities (FDI), by about 30–50%, in comparison with the values before annealing. This demonstrates the efficient gettering of uncontrolled impurities by nickel clusters during the additional thermal annealing.

As the diffusion temperature increases, the solubility of nickel atoms in silicon also increases [30], leading to an increase in the concentration of clusters [20–22] and a decrease in the concentration of recombination centers (Cr) [28]. However, as a rule, with an increase in temperature and duration of diffusion, Cr increases [8, 31]; consequently, the lifetime of minority charge carriers (τ) decreases, which reduces the efficiency of SCs.

Furthermore, for the formation of the front-side *p–n* junction of SCs, diffusion is typically carried out in the temperature range of T_{diff} = 900–1050°C, which invariably leads to an increase in C_r and a reduction in τ by several times [3]. Therefore, it is necessary to optimize the technological conditions for gettering recombination defects by nickel atom clusters.

It was demonstrated [27] that the enhancement of the efficiency of the SC is significantly contributed by the nickel-atom–enriched near-surface region of the SC. Additionally, it was shown that doping SCs with nickel atoms increases the carrier lifetime regardless of the method of introduction, and under optimal conditions, it can extend the carrier lifetime to 30–32 μs (up to double that of the reference SC, which has a carrier lifetime of 14–16 μs).

Thus [23–27], the optimal conditions for gettering with nickel atom clusters have been experimentally determined (nickel diffusion conditions – T_{diff} = 800–850°C, additional thermal annealing – T_{ann} = 750– 800°C), which can increase the efficiency of silicon SCs by 25–30%.

4 Discussion

4.1 Physical Model of the Structure of a Nickel Atom Cluster

During cooling after diffusion, nickel atoms in silicon form nuclei of clusters, and additional thermal annealing activates the processes of cluster formation and growth [16]. According to our measurements [26], nickel clusters primarily consist of silicon atoms and contain up to ~15% nickel atoms. Considering the high lability [28, 29] of nickel in clusters, it can be assumed that nickel atoms in clusters are in interstitial states (Ni_i) and do not form silicides. Electroneutral nickel atoms in clusters are in the nearest equivalent interstitial positions and form a cubic nickel sublattice, partially or completely filled.

The Ni_i configuration with the lowest energy is in a tetrahedral interstitial position [16] with a very small change in the lattice constant (displacement of the four nearest Si neighbor's outward). The Ni_i –Si distance is 2.438 Å, while the distance between lattice atoms in the ideal silicon crystal is 2.367 Å. The population of the overlap in Ni–Si bonds is very low [7, 16], indicating minimal covalent interactions between Ni_i and Si atoms. Therefore, the binding forces between the silicon lattice and interstitial nickel atoms are weak, and the lattice has little effect on the nickel– nickel interaction within the cluster. It is most likely that the bonds between nickel atoms in the cluster are predominantly of a metallic nature. Metallic bonding explains the optical opacity of the clusters [20, 28, 31] and their high conductivity [14, 32].

Let us estimate the distance $R_{Ni–Ni}$ between nickel atoms in clusters (Figure 3 and Figure 4) based on the silicon lattice geometry (silicon lattice constant a = 5.43 Å, distance between silicon atoms $R_{Si–Si}$ = 2.34 Å, angle α = 109° [33]):

$$R_{\mathrm{Ni-Ni}} = a \cdot \frac{\sqrt{2}}{2} \quad \text{or}$$
$$R_{\mathrm{Ni-Ni}} = 2R_{\mathrm{Si-Si}} \cdot \sin\left(\frac{\alpha}{2}\right) = 3.84\ \text{Å}, \qquad (1)$$

We also determined the distance $R_{Si–Ni}$ from the interstitial nickel atom to silicon atoms in the lattice:

$$R_{\mathrm{Si-Ni}} = \sqrt{\left(\frac{R_{Si-Si}}{2}\right)^2 + \left(\frac{\sqrt{2}\cdot R_{Ni-Ni}}{2}\right)^2} = 3.2\ \text{Å}. \qquad (2)$$

It was found that one unit cell of silicon contains four interstitial nickel atoms (N_{Ni} = 4) and eight silicon atoms (N_{Si} = 8). Therefore, the maximum possible concentration Clim of nickel atoms in clusters is

$$C_{lim} = \mathrm{C}_{Si} \cdot \frac{N_{Ni}}{N_{Si}} = 2.5 \cdot 10^{22}\ \text{см}^{-3} \qquad (3)$$

where C_{Si} is the concentration of silicon atoms in 1 cm^{-3} (5×10^{22} cm^{-3}) [33].

To assess the stability of the clusters formed in the silicon lattice, we calculated the binding energy ΔE_k of Ni–Ni in clusters using different methods:

1. We used the Arrhenius equation at the temperature of cluster formation (additional annealing temperature T = 600–900°C).

The concentration (solubility) of nickel atoms in the silicon lattice [7, 30] can be estimated using the formula

$$C = C_0 \cdot exp\left(-\frac{E_a}{kT_{ann}}\right) \quad (4)$$

For nickel in silicon, $C_0 = 1.227 \times 10^{24}$ cm^{-3} and $E_a = 1.68$ eV.

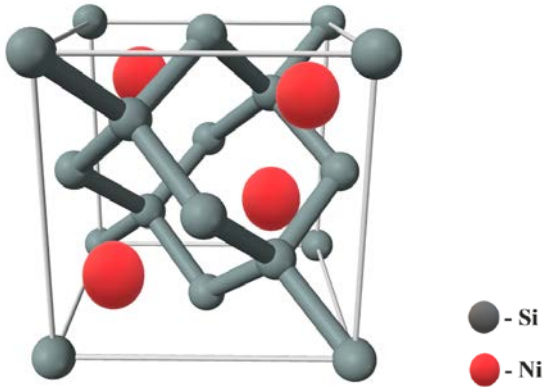

Figure 3 - Interstitial state of nickel atoms in the unit cell of the silicon lattice

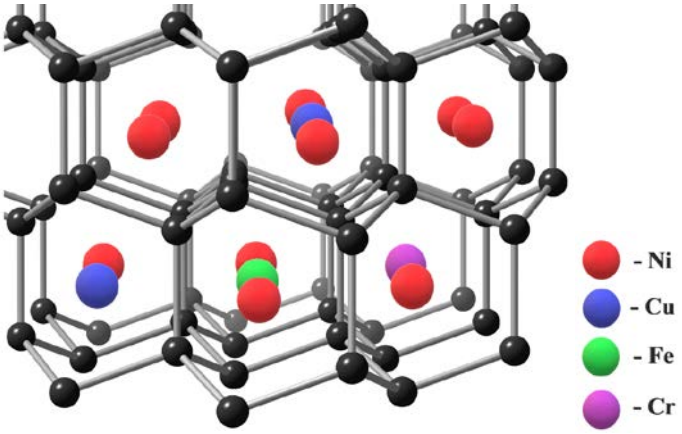

Figure 4 - Structural model of a cluster of nickel atoms with metallic bonding in the silicon lattice

At the same time, nickel atoms in the silicon lattice are in equilibrium with clusters; therefore, the concentration (solubility) of nickel atoms in the silicon lattice can be determined by the formula [34, 35]

$$C = C_{lim} \cdot exp\left(-\frac{\Delta E_{k1}}{kT_{ann}}\right) \quad (5)$$

From Eqs. (4) and (5), the binding energy ΔE_{kl} of nickel atoms with the cluster can be found:

$$\Delta E_{k1} = E_a - kT_{ann} \cdot ln\left(\frac{C_0}{C_{lim}}\right) \quad (6)$$

where $k = 8.6 \times 10^{-5}$ eV/K is the Boltzmann constant.

The calculation showed that the binding energy of nickel atoms with the nickel cluster at T_{ann} = 1073 K is $\Delta E_{kl} \approx 1.32$ eV. In the annealing temperature range of T_{ann} = 873–1173 K, the binding energy takes values in the range of 1.26–1.34 eV.

2. ΔE_k can also be estimated using the specific heat of vaporization of nickel atoms (ΔE_t = 3.92 eV) [36]. To do this, we calculated the boundary energy ΔE_{kl} of binding between nickel atoms in the cluster, taking into account the change in distance between nickel atoms in the cluster in comparison with pure metal (assuming a quadratic interaction potential):

$$\Delta E_{k2} = \Delta E_t \cdot \left(\frac{R'_{Ni-Ni}}{R_{Ni-Ni}}\right)^2 \approx 1.66\ eV, \qquad (7)$$

where R'_{Ni-Ni} is the distance Ni–Ni in the nickel lattice (2.5 Å [36]) and R_{Ni-Ni} is the distance Ni–Ni in the nickel cluster (3.84 Å).

3. Another method is based on calculating the surface energy of the nickel cluster (surface energy $\sigma = E/S$, where E is the binding energy of the adsorbate on the surface of the material, $S = 4\pi R^2$ is the interaction area of the atom with the surface of the material, R = 1.25 Å is the radius of the nickel atom [33]), and the component σ_{Ni} = 2280 erg/cm^2 = 1.42 × 1015 eV/cm^2 [37]. Then, the binding energy of a single nickel atom with the nickel lattice is

$$\Delta E_{Ni} = \sigma_{Ni} \cdot S \approx 2.79\ эВ. \qquad (8)$$

Taking into account a similar change in interatomic distances within the cluster, we find the binding energy of a single nickel atom (adsorbate) with the nickel cluster in the silicon lattice:

$$\Delta E_{k3} = \Delta E_{Ni} \cdot \left(\frac{R'_{Ni-Ni}}{R_{Ni-Ni}}\right)^2 \approx 1.18\ эВ. \qquad (9)$$

Let us calculate the average binding energy of nickel atoms with the nickel cluster using data obtained by various methods:

$$\Delta E_k = \frac{\Delta E_{K1}+\Delta E_{K2}+\Delta E_{K3}}{3} \approx 1.39\ эВ. \qquad (10)$$

Using the obtained value of the binding energy and the Arrhenius equation, the concentration of nickel atoms in clusters can be calculated:

$$\mathrm{C} = \mathrm{C}_k exp\left(-\frac{\Delta E_k}{kT_{ann}}\right) \qquad (11)$$

where C_k is the concentration of nickel atoms in clusters and C is the residual concentration of nickel in the silicon lattice (outside the clusters). From here, it is easy to calculate the ratio of the concentrations of nickel atoms in clusters and in the silicon lattice:

$$\frac{\mathrm{C}_k}{\mathrm{C}} = exp\left(\frac{\Delta E_K}{kT_{ann}}\right) \qquad (12)$$

Depending on the annealing temperature T_{ann} = 873–1173 K, the ratio $C_k/C \approx 10^6 - 10^8$. Therefore, most of the nickel atoms after additional thermal annealing are located in clusters. Calculations showed that the maximum concentration of nickel atoms participating in cluster formation is $C_k \approx 3 \times 10^{22}$ cm^{-3} at T_{ann} = 1073 K. This concentration is close to maximum theoretically possible solubility C_{lim} (3) of nickel atoms in the cluster, which confirms the correctness of calculating the binding energy.

Therefore, the binding energy of nickel atoms with the cluster is $\Delta E_k \approx 1.39$ eV, and the concentration of nickel atoms in the clusters is 6–8 orders of magnitude higher than the residual concentration (solubility) of nickel in the silicon lattice.

The maximum radius of nickel clusters can be determined as follows [38]:

$$R_k = \left[\frac{3}{4\pi n_k} \cdot \frac{\mathrm{C}_{0(Ni)}-C}{C_{lim}-\mathrm{C}}\right]^{1/3} \qquad (13)$$

where $C_{0(Ni)}$ is the solubility of nickel atoms (~10^{16}–10^{18} cm^{-3}) in the bulk of monocrystalline silicon.

Taking into account the constancy of the total amount of nickel in the silicon lattice, the size of clusters varies in the range from 20 nm to 1 μm, depending on the cluster concentration in the range of n_k from 10^{10} to 10^{16} cm^{-3}. This confirms the results of our experiment and the results obtained by other researchers [12, 16, 28, 29]. Importantly, the size and concentration of clusters, as well as the concentration of nickel atoms in clusters, depend on the number of defects in the crystal, mechanical stresses in it, as well as the temperature, time, and cooling rate after diffusion and additional thermal annealing. Therefore, the above estimates of cluster concentration are purely approximate.

4.2 Physical Model of Gettering by Nickel Atom Clusters

The analysis of the experimental results showed [17–27] that the formation of electroneutral nickel clusters reduces the concentration C_r of recombination centers; i.e., nickel clusters getter uncontrollable recombination impurities and purify the silicon crystal lattice.

We attribute the mechanism of gettering by nickel atom clusters to the following principles:

– the gettering properties of nickel clusters are determined by the metallic bonding forces acting in them. Since the metallic bonding forces primarily depend on the concentration of electrons (metal atoms) [30, 39], all metallic uncontrollable impurity atoms have binding energies close to $\Delta E_k \approx 1.39$ eV;

– there is always a large number of macrodefects on the surface, leading to intense nickel precipitation. The precipitates are virtually pure metal and have higher binding energies with fast-diffusing impurities (FDI) (up to ~2.7 eV for monocrystalline nickel [32]); therefore, the precipitates have better gettering properties than clusters;

– in the near-surface region, the concentration of nickel atoms is higher than that in the bulk by 2–3 orders of magnitude [30, 26]; therefore, the gettering rate in the near-surface region is higher due to the greater amounts of formed clusters and precipitates [23–27];

– the gettering process by nickel clusters is intensified by additional thermal annealing, which accelerates the attainment of equilibrium. However, too high annealing temperatures can lead to the decomposition of nickel clusters and precipitates [27–29]. Therefore, there is an optimal temperature at which the gettering of FDI is maximum;

– the gettering properties of clusters can be enhanced if uncontrollable impurity atoms form intermetallic compounds with nickel because this increases the binding energy with FDI atoms.

To determine the effect of cluster concentration on gettering, the ratio of the concentration of FDI atoms in the clusters to that in the silicon lattice

$$\frac{C_r}{C_{rk}} = exp\left(\frac{\Delta E_r}{kT_{ann}}\right) \quad (14)$$

where C_{rk} is the concentration of FDI such as Cu, Fe, Cr, etc., in the clusters; Cr is the residual concentration of FDI in the silicon lattice (outside the clusters); and T_{ann} is the annealing temperature. Depending on the annealing temperature in the range of T = 873– 1173 K, the ratio C_r/C_{rk} varies from 10^6 to 10^8, respectively.

The concentration of recombination centers in silicon doped with nickel atoms after thermal annealing is determined from the equation (15) where is the initial concentration of FDI in the silicon lattice, C_r is the residual concentration of FDI in the silicon lattice (outside the clusters), and ΔC_r is the decrease in the FDI concentration due to gettering by nickel clusters.

From Eq. (15), it is possible to determine the change in the concentration of recombination centers:

$$C_r = C_{r0} - \Delta C_r \quad (15)$$

Depending on the initial concentration of FDI ($\approx 10^{11}$–10^{13} cm^{-3}) and the ratio of the concentrations of FDI atoms in the clusters and in the silicon lattice ($C_r/C_{rk} \approx 10^6$ –10^8 cm^{-3}) under the conditions of additional thermal annealing (T = 873–1173 K), the change in the concentration of recombination centers (C_r/C_{r0}) is estimated to be within the range of 0.3–0.5.

Thus, the doping with nickel atoms and the formation of clusters in silicon reduce the concentration of uncontrolled recombination impurities by 50–70% in comparison with the initial value, which corresponds to a change in the concentration of FDI (C_{r0}/C_r) by a factor of 2–4.

Using the change in the concentration of recombination centers, the change in the bulk lifetime τ of minority charge carriers:

in the reference (nickel-free) solar cells

$$\tau_0 = \frac{1}{C_{r0} v_{th} \sigma} \quad (17)$$

in the SC doped with nickel atoms,

$$\tau_{Ni} = \frac{1}{C_r v_{th} \sigma} \quad (18)$$

where vth is the thermal velocity of carriers and σ is the capture cross-section of recombination centers.

Using Eqs. (17) and (18), we determine the relationship

$$\frac{\tau_{Ni}}{\tau_0} = \frac{C_{r0}}{C_r} \quad (19)$$

Thus, the lifetime of minority charge carriers in the solar cell base after doping with nickel atoms and additional thermal annealing should increase by a factor of 2–4. These data are also supported by the results obtained in [16, 17, 22].

It was experimentally shown that the lifetime of minority charge carriers in the base of a solar cell doped with nickel atoms increases by a factor of up to 2 in comparison with the reference sample [15]. This confirms the correctness of the proposed gettering model and the calculations performed.

5 Conclusions

The optimal conditions for gettering by nickel clusters were experimentally determined to be within a nickel diffusion temperature range of 800–850°C and an additional thermal annealing temperature range of 750–800°C.

Based on IR microscopy, SEM, and SIMS results, the surface density of nickel clusters was found to be approximately 10^6-10^7 cm^{-2}, with an average cluster diameter of 20–100 nm and a cluster concentration of about 10^{11}–10^{15} cm^{-3}.

A physical model for the structure of a nickel atom cluster in silicon was developed. It was shown that the binding energy of nickel atoms to a cluster is approximately $\Delta E_k \approx 1.39$ eV, and the concentration of nickel atoms in clusters is 6–8 times higher than the residual concentration (solubility) of nickel in the silicon lattice.

Calculations indicated that nickel doping can increase the lifetime of minority charge carriers by a factor of 2–4. Experimental results confirmed an increase in the lifetime of minority charge carriers by up to a factor of 2.

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