INCOHERENT LIGHT-INDUCED DIFFUSION OF ALUMINUM INTO SILICON

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We have investigated the diffusion of aluminum from a thin metal stimulated by the halogen lamp light. Samples were irradiated on the aluminum-free surface by pulses with duration within 1-30 s, which caused the heating of a sample from 120 to 1200 °C. The impurity concentration profile was determined by the repeated etching of the thin substrate diffusion layer and by measuring the surface resistivity by the four-probe method and the capacitance-voltage (C—V) method using a mercury (Hg) probe. It is shown that, at a given intensity, the impurity concentration in the near-surface region increases and the penetration depth reduces with increase in the pulse duration. The observed dependences are ascribed to the generation of additional drift diffusion flows due to the non-uniform depth distribution of free carriers created by light and temperature which weaken chemical bonds.

In the recent years, a sufficient body of experimental data on the application of the processes of rapid thermal annealing (RTA) and halogen-lamp annealing (HLA) to the formation of thin layers heavily doped with As, P, B impurities in Si has been collected [1—9].

In the given work, the possibility of the formation of these layers in silicon using aluminum as a dopant from a metal source is shown and the experimental results on the dependence of impurity distribution profiles and diffusion coefficients on light exposure conditions are presented.

To study the light-induced diffusion (LID), phosphorus-doped ⟨100⟩ oriented n-type silicon samples, (360±20)μm thick, were used. The donor concentration and resistivity were, respectively: N_d=10^{15} cm^{-3} and $\rho = 4.5\Omega$ cm. Aluminum was deposited onto the working surface of the samples by vacuum evaporation. The sample temperature during the evaporation was at most 300 °C. The aluminum layer thickness measured under a microscope (LEITZ) by the interference method was 0.6—0.8 μm. The wafers were scribed into samples of 8×15 mm^2. Before each measurement, the samples were dipped into the aqueous solution of hydrofluoric acid (HF:H_2O — 1:50) for 40—60 s to remove the native oxide. The irradiation was performed in a special HLA pulsed photon irradiation setup that provided the uniform illumination of 20-cm^2 samples, a possibility to change the light power density within 0—175 W/cm^2, and the pulse duration within 1—30 s, which corresponded to the heating of a sample from 120 to 1200 °C. The system involved the hot air ventilation from the irradiation chamber volume, cooling of the sample support, and measurement of the sample temperature during the illumination. Samples were irradiated on the aluminum-free surface. The stationary concentration of light-induced carriers estimated by the method described in [10] varied within 0—1.5 $\times 10^{19}$ cm^{-3} and was by $\sim 15\%$ lower than on the second surface. The concentration profile was determined by step-by-step etching of the thin substrate diffusion layer in the isotropic etchant HNO_3+HF+CH_3COOH (3:1:8) and by measuring the surface resistivity by means of the four-probe method and by the capacitance-voltage (C—V) method using a mercury (Hg) probe, which is equivalent to the formation of a Schottky Hg—Si junction. To measure the p—n junction depth, the spherical lap technique was used.

Fig. 1 shows the experimental depth profiles of the aluminum atom distribution resulting from LID performed under different conditions. It is seen that the higher pulse duration at a given intensity results in a lower impurity penetration depth (accordingly, the diffusion coefficient) and in a higher impurity

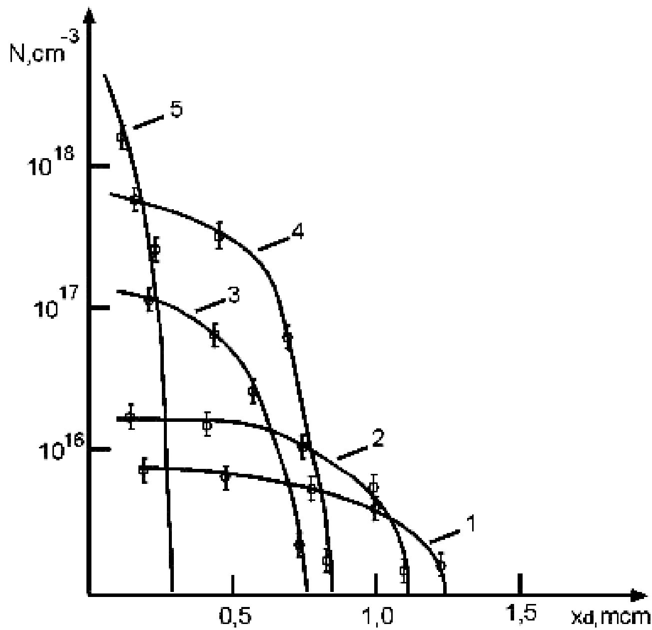

Fig. 1. Al impurity atom distribution profiles after the HGL irradiation under the following conditions: a) power $p_1 = 125$ W/cm^2, pulse duration t and the time to reach the required temperature — t_0 (*1* — $t = 1$ s, $t_0 = 0.5$ s, $T = 120$ °C; *2* — $t = 6$ s, $t_0 = 3$ s, $T = 820$ °C; *3* — $t = 10$ s, $t_0 = 5$ s, $T = 1020$ °C); b) power $p_2 = 175$ W/cm^2. (*4* — $t = 1$ s, $t_0 = 0.3$ s, $T = 400$ °C; *5* — $t = 6$ s, $t_0 = 2$ s, $T = 1200$ °C)

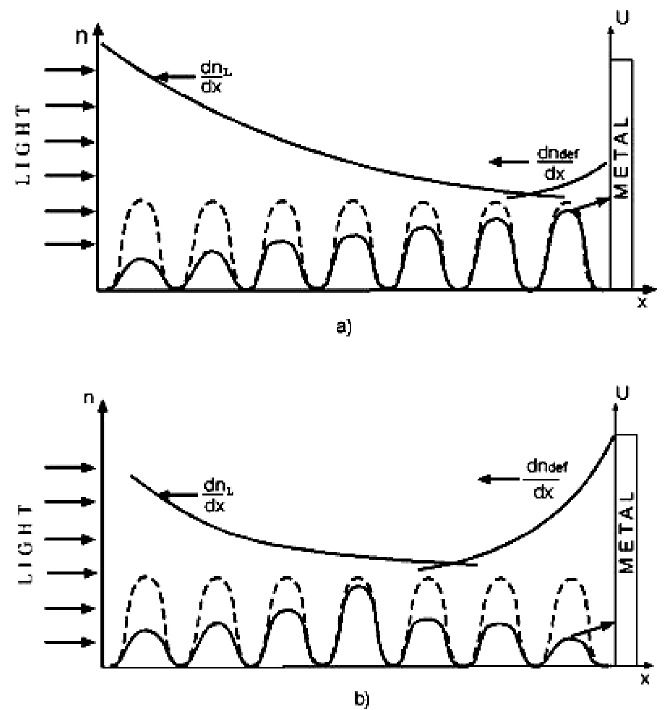

Fig. 2. Distribution of the concentration of non-equilibrium free carriers formed by illumination and the potential energy barrier height for the impurity atom transition in the non-illuminated sample (solid line) and in the illuminated sample (dashed): *a* — beginning of the light pulse, *b* — end of the light pulse

concentration in the near-surface region. The same picture is observed as the intensity increases at the same pulse duration. At a high pulse duration or intensity, the thin layers with higher surface concentration can be formed (Fig. 1, curve *5*).

To explain the obtained results, we consider the peculiarities of the LID process in this experiment in more details. In [11], it was shown that free carriers weaken chemical bonds and promote the motion of atoms. Hence, where the higher the free carrier concentration, the stronger is the weakening of chemical bonds [12]. This decreases the barrier height for the atom transition in this direction, determines the transition asymmetry, and rises the transition probability towards the free carrier concentration increase (Fig. 2) [13]. It is well known [14] that, at the transition asymmetry, there appear driving diffusion forces (DDF), and the particle flow is described by the equation

$$j = -D\frac{\partial N}{\partial x} + V(x)N \quad (1)$$

which contains two components: the gradient component $D\frac{\partial N}{\partial x}$ and the drift component $V(x)N$, where N is the impurity concentration, D is the diffusion coefficient related to the concentration gradient, and $V(x)$ is the drift velocity directed to the side with a higher transition probability. The presence of the flow drift component $V(x)N$ leads to the following situation. When the drift velocity is directed towards the same side as the gradient component, the diffusion acceleration and an increase in the effective diffusion coefficient calculated from the impurity distribution profile occur. But when it is directed opposite the gradient component, the diffusion deceleration or the inverse (ascending) diffusion takes place. In our experiments, precisely these situations are observed in the process of LID depending on the illumination conditions. The impurity distribution profiles will not already have the *erfc* form in spite of the fact that the diffusion originates from the infinite source.

During LID, in the semiconductor wafers illuminated on the surface uncovered with a diffuser, the quantum absorption with the energy $h\nu \geq E_g$ ($1.1 \leq h\nu < 2.4$ eV, E_g is the band gap) takes place, which creates a non-equilibrium free carrier gradient dn_L/dx (Fig. 2)

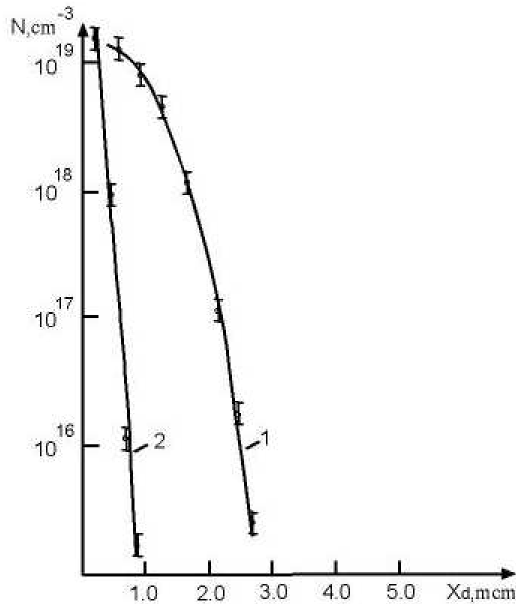

Fig. 3. Al impurity atom distribution profiles after illumination: 1. 2-pulse illumination of the sample with Al on the side not coated by Al; 2. The same sample after LID, removal of Al, and illumination under the same conditions, but on the surface which was coated by Al

and creates DDF directed from the duffuser surface into the bulk of the sample. This leads to the weakening of chemical bonds in this region, i.e. to a decrease in the barrier height (Fig. 2) and to a higher probability of the impurity atom migration in the direction from the metallized surface towards the illuminated one. Here, there arise the diffusion driving forces [14] that determine the flow drift component having the same direction as the flow gradient component. This leads to an enhancement of the diffusion into the bulk of the sample (Fig. 2). The impurity distribution profile is not described now by the erfc function and is more extended into the bulk of the sample.

The light $h\nu < E_g$ ($0.4 \leq h\nu < 1.1$ eV) passing through the semiconductor is absorbed by the metal and by the defects essentially in the near-surface metal-semiconductor interface, which creates a free carrier gradient $dn_{\rm def}/dx$ (Fig. 2). The absorption by the metal creates a temperature gradient (until the uniform temperature over the whole sample is established), which results in the appearance of a similarly directed free carrier (dn_M/dx) gradient. As a result, we have the effective gradient $d(n_{\rm def} + n_M)/dx$ (Fig.2) and relevant diffusion forces that form a drift flow towards the metallized surface. The total flow is

$$j = -D\frac{\partial N}{\partial x} + V_1(x)N - V_2(x)N, \tag{2}$$

where $V_1(x)$ is the drift velocity due to the $h\nu \geq E_g$ quantum absorption, and $V_2(x)$ is the drift velocity for $h\nu < E_g$.

The drift components in (2) have opposite directions and will have different values under different illumination conditions. The equilibrium established for these flows will determine the impurity penetration depth and, respectively, the effective diffusion coefficient.

At the initial moment, due to a low concentration of defects, by which quanta with the energy $h\nu<E_g$ are absorbed, and due to the low temperature of the metal, the influence of the factors related to the quantum absorption ($h\nu \geq E_g$) is predominant, which determines a more intensive flow of impurity atoms into the bulk of the sample. An increase in the light exposure duration (or in the light intensity) results in a higher concentration of defects penetrated from the surface: vacancies and metastable complexes (impurity atoms with silicon interstitials and vacancies) with energy levels in the band gap, which increases the $h\nu < E_g$ quantum absorption and, hence, $n_{\rm def}$. Thus, $V_2(x)N$ increases in its absolute value and competes more intensively with the gradient component and $V_1(x)N$, which leads to a decrease in the impurity penetration depth and, respectively, in the effective diffusion coefficient (Fig. 1, curves *2,3* and *5*).

The analysis of the results given in Fig. 1 shows that, under the illumination of a fixed intensity, when the light pulse is longer, the sample is also subjected to the short light action, when the impurity penetration depth is higher than that at the end of the longer action. As a result, the impurity atoms, which penetrated deep into the crystal at a certain distance from the surface at the beginning of the pulse, move under the further illumination essentially back to the surface, i.e. the inverse (ascending) diffusion takes place. This results in the redistribution of impurity atoms from the bulk to the surface, and the concentration of the diffused impurities is higher at the surface.

To confirm that the drift components play a significant part in the determination of the impurity penetration depth and that the inverse diffusion can occur, the following tests were carried out. After LID and the etching of Al, the samples were irradiated under the same conditions, but on the side of the surface, from which Al had been etched. It is clear from Fig. 3 that

the impurity distribution profile shifted to the surface, i.e. the inverse diffusion occurred. This is due to the fact that, in this case, the drift flows due to the $h\nu < E_g$ and $h\nu \geq E_g$ quantum absorptions have the same direction and are opposite to the gradient component. In this case, $j = -D\frac{\partial N}{\partial x} + [V_1(x)N + V_2(x)]N$, where N is the concentration of previously introduced impurities and $-D\frac{\partial N}{\partial x} < [V_1(x)N + V_2(x)]N$, which results in the impurity redistribution from the bulk to the surface.

Thus, while using LID in the technology of semiconductor devices and ICs, the correct selection of particular light irradiation conditions is very important.

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ДИФУЗІЯ АЛЮМІНІЮ У КРЕМНІЇ, СТИМУЛЬОВАНА НЕКОГЕРЕНТНИМ СВІТЛОМ

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Р е з ю м е

Досліджено дифузію алюмінію з тонкого металічного шару, стимульовану світлом галогенних ламп. Зразки опромінювали з боку, не вкритого алюмінієм, імпульсами тривалістю 1—30 с, які спричинювали нагрівання зразків від 120 до 1200 °C. Профіль концентрації домішок визначали шляхом травлення дифузійного шару та вимірювання поверхневого опору чотиризондовим методом і C—V-методом з використанням Hg-зонда. Показано, що за певної інтенсивності світла концентрація домішок у приповерхневому шарі зростає і зменшується глибина їх проникнення зі збільшенням тривалості імпульсу. Спостережувані залежності пояснено виникненням додаткового до дифузійного дрейфового потоку, викликаного нерівномірним розподілом по глибині вільних носіїв, утворених дією світла і тепла, котрі ослаблюють хімічні зв'язки.