SIMULATION OF PLASMA ASSISTED DOPING OF SILICON

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The model of plasma assisted doping of silicon has been developed and calculations of the plasma immersion boron ion implantation combined with the following rapid thermal annealing or with the thermal annealing and additional radiation enhanced diffusion under hydrogen plasma processing have been made.

Introduction

The trend of decreasing dimensions of semiconductor devices stimulates the investigations of the new methods of doping of semiconductors. It is a plasma immersion ion implantation (PIII) that attracts our attention. Really, during processing in the RF gas discharge a bias voltage ~ 1 keV between the plasma and the silicon substrate is created and bombardment of the surface by low energy ions occurs. If the plasma contains a dopant component, the surface of the semiconductor is bombarded by all the positive species including dopant ions. Because of the low energy the dopant ions are implanted into a shallow layer adjoining the surface. Therefore, PIII allows to form more shallow p-n junctions in comparison with the conventional implantation. Some advantages of PIII have resulted in the series of the papers devoted to the experimental investigations of the plasma assisted doping, see for example [1]. In [1] PIII was combined with the following rapid thermal annealing (RTA) to avoid radiation damages and activate dopant atoms. The dopant concentration profile after annealing is presented in Fig.1. As can be seen from Fig.1, the shallow layer doped with B is created. It means that the formation of shallow p-n junctions is possible due to PIII.

The radiation enhanced diffusion of dopant atoms caused by ion bombardment during gas discharge is also one of the interesting methods of plasma assisted doping of silicon [2]. In this case the substrates under plasma processing are supported at the temperature of 500 °C and above. This temperature is sufficient for the diffusion of the introduced dopant which occurs due to interactions of the impurity atoms with nonequilibrium point defects which are being generated during ion bombardment. In the case of hydrogen plasma processing the silicon substrate is bombarded by hydrogen ions, which cause the generation of nonequilibrium point defects in a very shallow surface layer. For example, the thickness of the layer can be decreased up to ~ 0.015 μm if bias voltage is equal to 200 eV. In contrast to heavy particle bombardment, hydrogen implantation does not cause the formation of the stable radiation defects. For light ions and in low doses, ion damage can be compared to electron irradiation damage. It means that generated defects are annealed either during implantation or during the following low temperature annealing. Besides, undesirable imperfections at the interface and in the bulk of the semiconductor can be passivated by the injection of hydrogen atoms into the silicon substrate. These specific features of radiation enhanced diffusion under hydrogen plasma processing are rather attractive for the formation of shallow p-n junctions.

I. Model

To study possible applications of the methods of plasma assisted doping it is very important together with the experimental investigations to develop a model of the coupled diffusion of dopant atoms and nonequilibrium point defects. For this purpose we use the system of the diffusion equations obtained in [3, 4]. In the case of the diffusion due to either vacancies or self-interstitials the equation of dopant diffusion and the equation of point defect diffusion have the following form:

$$C_t^T = \nabla\left[D(\chi)\nabla\left(\tilde{C}C\right)\right] + \nabla\left[D(\chi)\frac{\nabla(\chi)}{\chi}\tilde{C}C\right] + G \qquad (1)$$

$$\nabla\left[d(\chi)\nabla\left(\tilde{C}\right)\right] + \left(S^P - G^P - s + g^T + g\right)/C_i^\times = 0\,, \qquad (2)$$

$$\tilde{C} = C^\times / C_i^\times\,,$$

$$\chi = \frac{C - N + \sqrt{(C-N)^2 + 4n_i}}{2n_i}\,,$$

where C^T is the total concentration of dopant atoms; C is the concentration of substitutional dopant atoms; $C^\times$ and $C_i^\times$ are the concentration of point defects in the neutral charge state and the thermal equilibrium value of this concentration, respectively; G is the rate of introducing dopant atoms into the unit of the volume of semiconductor; S^r and G^r are the rate of dissociation of the "dopant atom - point defect" pairs and pair generation rate respectively; g^T is the rate of thermai generation of point defects governing the transport of dopant atoms; g is the rate of generation of these point defects due to ion bombardment; N is the concentration of the dopant of the opposite type of conductivity.

It is well known that the transport of dopant atoms in crystalline silicon occurs due to neutral, single and double charged defects. Therefore, we will present the effective diffusion coefficients of dopant atoms and point defects in the following form

$$D(\chi) = D_i \frac{1+\beta_1\chi+\beta_2\chi^2}{1+\beta_1+\beta_2},$$

$$d(\chi) = d_i \frac{1+\beta_1^m\chi+\beta_2^m\chi^2}{1+\beta_1^m+\beta_2^m},$$

where D_i is the intrinsic diffusivity of dopant atoms; β_1 and β_2 are the empirical parameters which describe the relative contribution of single and double charged defects to the diffusion of a dopant; d_i is the intrinsic diffusivity of point defects of the species m; β_1^m and β_2^m are the empirical parameters which describe the relative contribution of single and double charged defects to the diffusion of point defects in all charged states.

II. Results of modeling

We use the system of Eqs, (1), (2) for modeling the plasma assisted doping of silicon substrates. In Fig. 1 the results of simulation of doping due to the low energy boron implantation of silicon from hydrogen plasma in combination with the following rapid thermal annealing are presented. For comparison the experimental data [1] are used. In [1] the hydrogen plasma with 1% of B_2H_6 excited by RF discharge was used for PIII. The resulted self bias voltage was equal to 800 V. The immersion time was equal to 2 min. Positive boron ions as well as hydrogen ions were accelerated in the layer between the plasma and the substrate and bombarded the surface of the semiconductor. Low temperature annealing at 600 ^oC within 10 min and higher temperature annealing at 930 ^oC within 5 min were used for electrical activation of boron. The measured concentration profile of the electrically active boron atoms is shown in Fig. 1. It can be seen that the results of modeling agree with the experimental data. The following values of the parameters that describe the boron implantation under plasma immersion were used in modeling: Q = 1.1 10^{14} ions/cm^3, R_p = 0.00383 μm, ΔR_p = 0.00302 μm, Sk = 0.32. Here Q is the dose of the B ions introduced under immersion; R_p and ΔR_p are the average projective range of boron ions and straggling of the projective range respectively; Sk is the skewness of the distribution of the implanted ions. The following values of the parameters that describe ion-implanted boron redistribution during annealing were used: D_i = 8.098 10^{-13} μm^2/s, β_1 = 21.66, β_2 = 0 for the annealing at 600 ^oC and D_i = 2.435 10^{-7} μm^2/s β_1 = 3.35, β_2 = 0 for the annealing at 930 ^oC.

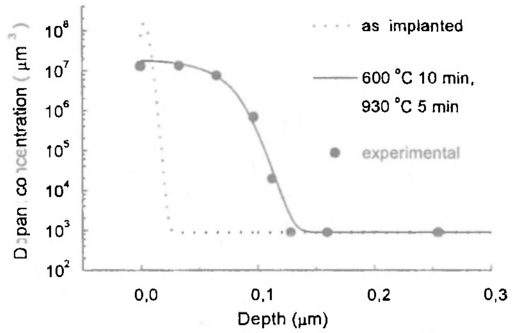

Fig. 1. Simulated profiles of B concentration after PIII and after annealing.

We suppose that the concentration of the nonequilibrium point defects in the neutral charge state is approximately uniform within the doped layer. The correctness of the assumption made results from the small thickness of the doped layer. At the same time the distributions of the charged defects are not uniform due to their drift in the internal electrical field. The last phenomenon results in the nonlinear dependence of the effective diffusion coefficient $D(\chi)$ **on** the dopant concentration. The time-average value of the concentration of nonequilibrium point defects during RTA $\tilde{C}$ = 3.4 was derived from the condition of the best fitting of the calculated boron profile to the experimental data. As one can see from the value obtained, the concentration of nonequilibrium point defects essentially exceeds the thermal equilibrium value. It means that the transient enhanced diffusion plays a significant role in the redistribution of dopant atoms during RTA.

Now let us consider the case of redistribution of dopant atoms due to radiation enhanced diffusion. We suppose that boron predeposition occurs by means of plasma immersion ion implantation combined with thermal annealing. Then, the processing in the hydrogen plasma at the substrate temperature of 600 ^oC is carried out for drive-in. During the drive-in a continuous generation of nonequilibrium point defects in the shallow surface layer occurs as a result of the bombardment of the substrate by hydrogen ions. The nonequilibrium point defects diffuse to the surface and in the bulk of the semiconductor providing the radiation enhanced diffusion of dopant atoms. The distribution of these defects is not uniform because their generation occurs in the local domain.

The results of the modeling of boron radiation enhanced diffusion under processing in the hydrogen plasma are presented in Fig. 2.

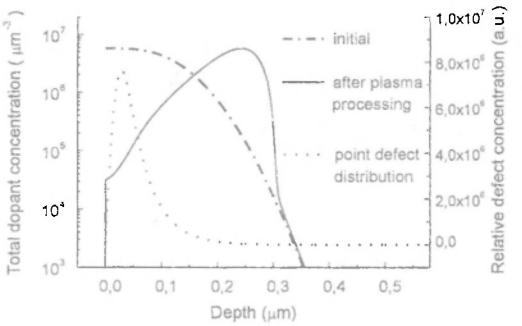

Fig. 2. Simulated profiles of B concentration before and after plasma assisted radiation enhanced diffusion.

It is supposed that a silicon substrate is bombarded by hydrogen ions at the energy of 1 keV. We assume that point defects governing the transport of B atoms are produced by atomic collisions as the ions are stopped in the crystal. Thus, the distribution of the defect generation rate is similar to the distribution of the stopped hydrogen ions. The following parameters describing the distribution of the defect generation rate are used in modeling: R_{pd} = 0.0163 μm, ΔR_{pd} = 0.015 μm, Sk_d = -0.3. We also use the following values of parameters describing the diffusion of nonequilibrium point defects and the radiation enhanced diffusion of B atoms: l_i = 0.04 μm and L = 0.21 μm. Here $l_i = \sqrt{d_i \tau_i}$ is the average migration length of defects; $L = \sqrt{D_i \tilde{C}_m t}$ is the average diffusion length of dopant atoms; $\tilde{C}_m$ is the maximum ratio of the actual concentration of nonequilibrium point defects and equilibrium concentration, **t** is the duration of the plasma processing.

It is seen from Fig.2 that radiation enhanced diffusion under processing of the doped substrate in the hydrogen plasma provides movement of the impurity atoms from the surface into the bulk of the semiconductor. As a result the B concentration is considerably lower in the vicinity of the surface and a super-steep retrograde dopant profile is formed. It is very important for advanced device fabrication. For example, we can use the plasma assisted radiation enhanced diffusion in the manufacturing of MISFET because the formation of the retrograde dopant profile in the channel region of MISFET helps to create a highly conducting layer when the transistor is turned "on".

Conclusion

The model of plasma assisted doping of silicon has been developed and calculations of silicon doping have been made. The results of the modeling of the plasma immersion boron ion implantation and the following rapid thermal annealing agree with the experimental data and show the possibility of the formation of shallow p-n junctions. It is shown that radiation enhanced diffusion of ion implanted boron under hydrogen plasma processing results in the formation of the retrograde dopant profile.

References

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