Optimization of Temperature-Time Profiles in Rapid Thermal Annealing

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I. Introduction

Rapid thermal annealing (RTA) is widely used in modern IC technology to reduce the amount of transient enhanced diffusion (TED) of dopants after ion implantation. The effect of diffusion reduction due to fast temperature ramping (50°C/s and above) and short annealing times (less than 10 seconds at 1000°C) is well known. However, a systematic investigation of TED over a broad range of temperature-time conditions can, to the authors' best knowledge, not be found in the literature yet.

In this simulation study we investigate phosphorus TED between 600°C and 1100°C for annealing times from a few seconds to several hours.

II. Simulation Model and Experimental Verification

Simulations are based on a point defect diffusion model taking into account full dynamic dopant-defect pairing and interstitial cluster formation. Details of the model are described in Ref. [1]. The model equations are solved by help of Promis [2].

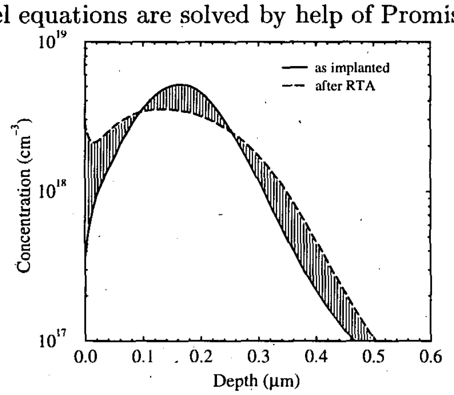

Fig. 1. The hatched area between the as implanted and the diffused profile is taken as a measure for the amount of diffusion in Figs. 2, 4–6.

As an overall measure of diffusion, the area between the as implanted profile and the diffused profile as shown in Fig. 1 is used. In all cases only contributions from concentration levels above $1 \times 10^{17}\text{cm}^{-3}$ are taken into account. To compare simulated profiles with SIMS profiles the surface-near region is neglected.

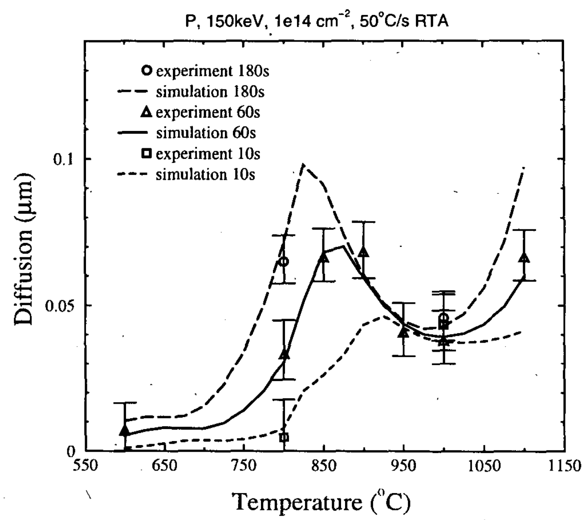

Fig. 2. Comparison between simulation and experimental results of phosphorus transient diffusion between 600°C and 1100°C. Temperature ramp rate: 50°C/s; above 800°C with 20s temperature stabilization at 800°C (cf. Fig. 3).

Certainly, a simulation study of this kind does only make sense, if the underlying models are well verified. Fig. 2 shows that our model very well agrees with experimental data for phosphorus diffusion between 600°C and 1100°C. Not only the temperature dependence of 60 seconds anneals but also the time dependence at 800°C and 1000°C is well reproduced.

For completion it should be mentioned that the RTA temperature ramp rate of these experiments (and simulations) was 50°C/s and a 20 second temperature stabilization at 800°C was used for processes above 800°C. The temperature-time profile of the RTA process is illustrated in Fig. 3. All results shown here are based on a 150keV, $1 \times 10^{14}\text{cm}^{-2}$ phosphorus implant.

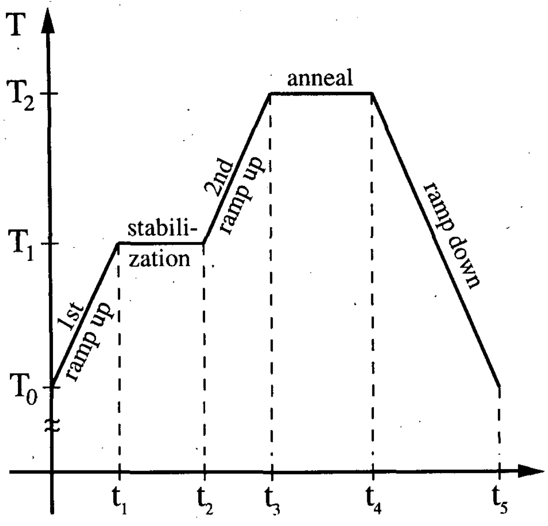

Fig. 3. RTA temperature-time profiles; Figs. 4 and 5 are based on processes without temperature stabilization ($T_1 = T_2$).

III. Influence of Temperature-Time Profiles on TED

On the basis of this diffusion model we now investigate the influence of different RTA temperature-time profiles on transient phosphorus diffusion. For the moment, we neglect any temperature stabilization (cf. Fig. 3), needed in real processes in order to maintain a good spatial temperature uniformity.

The amount of phosphorus diffusion for RTA processes with temperature ramps of 50°C/s are shown in Fig. 4. The isochronal curves nicely show that both, maximum and minimum TED decrease with increasing temperature and decreasing annealing time. At temperatures above 950°C and annealing times below 60 seconds, the isochronal curves lie much closer together and are much more flat than in any other region of the diagram. This is the reason why 10 seconds at 1000°C has been figured out as an ideal condition for a standard RTA process. Apparently, small temperature and time variations around the standard conditions have only little influence on diffusion profiles. Therefor RTA processes can be controlled best in this temperature-time frame ensuring best reproducibility of the process with respect to diffusion.

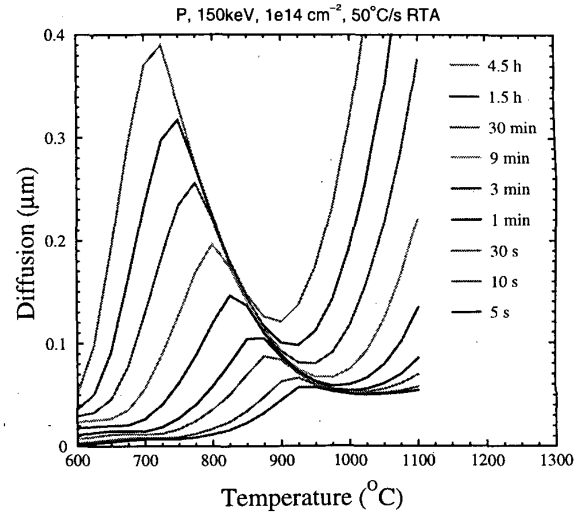

Fig. 4. Diffusion of phosphorus for RTA processes with 50°C/s temperature ramping but without any temperature stabilization.

On the other hand, the relatively low sensitivity of diffusion on actual annealing conditions around the typical RTA process (1000°C, 10 seconds) means: Poor controllability and uniformity of the RTA temperature does not inevitably lead to high variations of process results. While this eases the requirements of precisely controlled temperature-time profiles, the high sensitivity of dopant activation on annealing temperature (c.f. Ref. [3]) makes uniform and well controlled RTA processes indispensable.

The influence of temperature ramp rates on the amount of transient enhanced diffusion is shown in Fig. 5. Dashed lines show the results for infinite high ramp rates which give us a theoretical limit for the reduction of TED by steeper temperature profiles. As our simulations confirm, higher ramp rates indeed reduce the amount of TED. Moreover the data show that the maximum effect is achieved when, along with increased ramp rates, the annealing temperature is increased and the annealing time is decreased.

Finally, the effect of temperature stabilization on a typical RTA process of 10 seconds at 1000°C

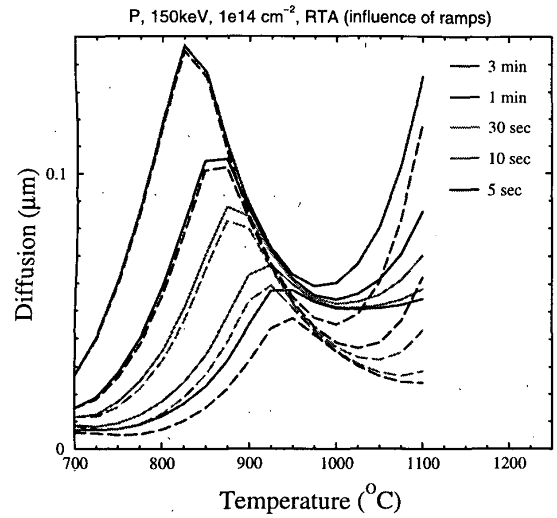

Fig. 5. Diffusion of phosphorus for RTA processes with 50°C/s temperature ramping (solid lines) and for isothermal processes i.e. infinite high ramp rates (dashed lines).

is shown in Fig. 6. While the annealing time and temperature are kept unchanged, temperature stabilization of 5 seconds and 20 seconds is varied between 650°C and 900°C, respectively. For comparison the amount of diffusion without stabilization is given by the dashed line. Below 750°C the additional temperature stabilization of up to 20 seconds has practically no influence on the amount of diffusion. However, the influence of stabilization time increases with increasing temperature above 750°C. At 800°C for instance, a 20 second stabilization increases the diffusion already by 25% and has its maximum influence at 875°C, where it increases diffusion by as much as 65%. The 20 second stabilization curve drops above 875°C in agreement with Fig. 4. Here, the TED reduction due to higher temperatures begins to take over.

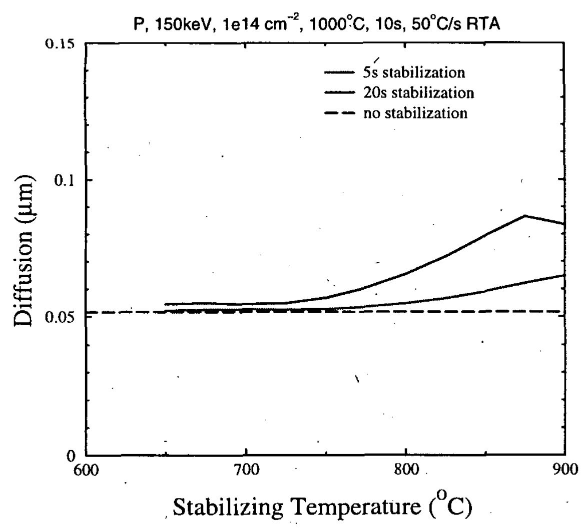

Fig. 6. Influence of temperature stabilization on a 1000°C, 10 seconds RTA process. Diffusion without stabilization is indicated by the dashed line.

IV. Conclusions

In conclusion, the effect of RTA temperature-time profiles on phosphorus transient diffusion has been investigated based on a diffusion model well verified between 600°C and 1100°C. Sensitivity of transient diffusion on annealing conditions turned out to be minimal around 1000°C, 10 seconds for processes with 50°C/s ramps. Reduction of TED by higher ramp rates is most effective by simultaneous temperature increase and time decrease. Temperature stabilization above 800°C can significantly contribute to the overall amount of transient diffusion.

Acknowledgments

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