The Effects of Preheating Millisecond Anneals on Dopant Activation in Silicon

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Fig. 4. The square of the correlation coefficients (R^2) for linear fits of the maximum carrier concentrations (N_A) to effective times, t_{eff}. R^2 is shown for the fits to t_{eff} calculated in each of the four heating stages shown in Fig.1 (PH, FH, FC and SC) and for the whole anneal, versus E_A between 0.5 and 6eV. The analysis highlights differences in the factors that affect the carrier activation in the four implant types (As1, As3, P1 and P3). The figure also includes R^2 for fits to the peak temperature, T_{peak} and to the temperature immediately after the pulsed heating, T_{post}

Fig.4 summarizes the complete t_{eff} analysis by showing R^2 as a function of E_A, for each implant type and recipe stage, and also for the whole heating cycle. Each figure includes the R^2 values for fits against T_{peak} and T_{post}, two key temperatures that characterize the heating cycle. Caution is necessary in assessing the significance of R^2; correlation is not causation. t_{eff} values for different recipe stages may not be independent of each other and the experimental conditions in Table I did not vary t_{eff} much for some recipe stages. Nevertheless, the analysis suggests factors to investigate in more detail. Fig.4 demonstrates the significance of the slow cooling for the As3 samples through the peak in R^2 at E_A ~1.9eV, and that of the fast pulsed heating for P3, where R^2 rises with E_A. For the lower dose cases, P1 and As1, N_A is insensitive to variation in t_{eff} for the pulsed heating and cooling stages. Here, electrical activation could be dominated by the initial SPE, which is likely to finish during either the preheat stage or the early part of the pulsed heating [2].

IV. Isolating the Preheat Effects

Since the initial experiments did not vary the preheat t_{eff} significantly, a second set of experiments was devised to explore this aspect. An interesting question arises about the role of SPE in dopant activation, as opposed to the effect of the very high temperature stage of the MSA anneal on dopant solubility. Increasing the temperature of the SPE regrowth may improve dopant activation [5], but this is difficult to uncouple from the effects of dopant deactivation during cooling; the approach taken here was to employ four recipes with very different preheating/ramp-up stages but nearly the same slow cooling cycle. They include the "normal pulse" condition of the previous MSA cycles (NPMSA) and a recipe similar to NPMSA but with a 30s soak at 625°C before the 150K/s ramp to the 1725°C (PSMSA). This 30s "pre-soak" is long enough for SPE to fully crystallize 50nm of undoped a-Si. Two other annealing methods were used; one was a backside pulsed heating anneal (BSH), where the recipe was identical to NPMSA but the wafer was loaded upside-down so that the pulsed heating was delivered to the back of the wafer, rather than the implanted side. The implanted region experiences the same "slow" heating cycle as in NPMSA but not the fast high-temperature heating pulse; the result is a spike anneal with a very fast ramp from T_{in} 0 Tw 6.4761 Tw23 0 0 6.48 245.16 200.960353.8

TABLE II. COMPARISON OF THE CHARACTERISTICS OF THE ANNEALS USED TO EXPLORE THE EFFECT OF PREHEATING. t_{eff} WAS CALCULATED FOR E_A=1.9eV IN THE SLOW COOLING STAGE; d_{reg} WAS CALCULATED FOR THE PREHEAT RAMP-UP STAGES

	As1			As3			P1			P3		
Recipe	T_{peak} (°C)	t_{eff} (s)	d_{reg} (nm)	T_{peak} (°C)	t_{eff} (s)	d_{reg} (nm)	T_{peak} (°C)	t_{eff} (s)	d_{reg} (nm)	T_{peak} (°C)	t_{eff} (s)	d_{reg} (nm)
NPMSA	1175.0	4.1	19	1176.8	4.0	19	1176.3	4.0	19	1182.4	4.1	19
PSMSA	1173.3	4.0	105	1167.7	4.0	105	1173.9	4.0	105	1168.3	4.0	105
BSH	800.6	3.7	36	800.1	3.7	33	801.1	3.8	33	801.4	3.8	34
Spike	801.5	3.8	204	801.4	3.8	203	-	-	-	-	-	-
HTIMSA	1177.0	7.7	88	1177.4	7.8	90	1178.8	7.9	90	1169.1	7.7	90

Table II also includes data for the high-T_{peak} MSA (HTIMSA). This case was included for comparison here, because of all the recipes in Table I, HTIMSA gave the lowest N_A. This might be expected from the greater deactivation expected from a higher T_{peak} but the preheating