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Boron diffusion model refinement and its effect on the calculation of reverse short channel effect

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The reverse short channel effect (RSCE) of flat channel profile nMOSFET was studied by modeling the dopant diffusion process and considering its parameter dependence. It was found that the binding energy between boron(B) and interstitial silicon (I) is one of the key parameters for the quantitative description of the boron diffusion and the RSCE.

The reverse short channel effect has been attributed to defect gradients[1], and excess point-defect generation from the source/drain implantation[2]. Figure 1 shows the experimental results that obtained for an nMOSFET with a flat channel boron profile[3]. In this paper, a non-equilibrium pair diffusion model was used for boron assuming a boron-interstitial silicon pair (BI pair)[4]. BI^0 and BI^- were assumed for the charge state of the BI. For arsenic(As), a conventional model[5] was used since a pair diffusion description has not been well established for As. The excess interstitial silicon amount generated by the S/D implantation was assumed to be the same amount as that of the implanted arsenic dosage. The diffusion model equation system was solved by the two-dimensional PDE solver "PROMIS"[6]. Two-dimensional device simulations were performed by the "BIUNAP"[7] to obtain threshold voltages.

As shown in Fig.1, the RSCE was observed even in the flat channel profile. This RSCE was considered as being due to a boron pileup on the silicon surface. Figure 2 shows the result of a one-dimensional test calculation for the boron pile-up due to the excess interstitial silicon. The silicon implantation condition was found in Ref.[8]. The pile-up amount was strongly dependent on the binding energy value (E_{BI}) of the BI. The pair binding energy can be defined as follows:

$$B + I \underset{k^r}{\overset{k^f}{\rightleftharpoons}} BI \qquad (1) \qquad\qquad \frac{[BI]}{[B][I]} = \frac{k^f}{k^r} = K_{BI}^{eq} = [\frac{n_{Si}}{4}\exp(-E_{BI}/kT)]^{-1} \qquad (2)$$

Since the BI pair diffusivity (D_{BI}) was calculated from the boron macroscopic intrinsic diffusivity D_B^{eff} using Eq. 3 (i.e. D_{BI^-} and D_{BI^0} are determined by using D_B^0 and D_B^+, respectively), the equilibrium diffusion, such as gaseous source diffusion, can be well reproduced and is not affected by any value of E_{BI}. However, E_{BI} strongly affects transient diffusion phenomena such as the B pile-up due to the defect gradients (Fig.3).

$$D_B^{eff} = D_B^0 + D_B^+\frac{p}{n_i} = D_{BI^-}K_{BI^-}^{eq}[I^0]^{eq} + D_{BI^0}K_{BI^0}^{eq}\gamma^+[I^0]^{eq}\frac{p}{n_i} \qquad (3)$$

Figure 4 shows the two-dimensional calculation results obtained for the threshold voltage (V_{th}) shift of flat channel profile nMOSFETs with different channel lengths. The increase in V_{th} due to the boron pile-up was also found to be strongly dependent on the E_{BI}. Figure 5 shows the interstitial silicon surface-recombination rate (K_I) parameter effect on the RSCE. A weak K_I value showed small RSCE due to the smaller defect gradient, and a stronger K_I gave larger RSCE. However, a much stronger K_I value makes the RSCE much smaller. This is due to the smaller transit time of the excess interstitial silicon, which is swept out quickly with a very large K_I value. A summary of those feature (Fig.6) shows that, to reproduce the measured RSCE amount, the binding energy E_{BI} must be lower than any previously reported values, such as 1.4eV(Hane,'91[4]), 1.52eV(Park, '92[9]) and 1.6eV(Baccus, '95[10]). Moreover, some optimum value might be found for the surface recombination rate for I from the RSCE quantitative calculation.

In order to estimate appropriate transition between BI and B, i.e. the appropriate E_{BI} value, low temperature anneal of 600℃ was examined subsequent to the low dose of $5\times10^{12}cm^{-2}$ boron implantation for which B clustering could be neglected. Figure 7 shows the experimental and calculation results obtained which indicate that even if the boron amount was well below the solid solubility (even below n_i), the electrical activation was not completed even in the tail region. In this low concentration region, only the substitutional B is electrically active and the interstitial boron (BI) seems to be responsible for the deactivation. The calculation assuming E_{BI}=1.0eV gave the best fit, while larger E_{BI} produces too low activation and smaller E_{BI} makes all the boron active as shown in Fig.8.

In summary, the reverse short channel effect for flat channel profile nMOSFET was studied with respect to the model parameter dependence. For the quantitative simulation of the RSCE, the previous reliance on large E_{BI} should be abandoned, and giving additional consideration to the interstitial silicon clustering phenomena[11] will be necessary to properly describe transient enhanced diffusion and the RSCE.

References

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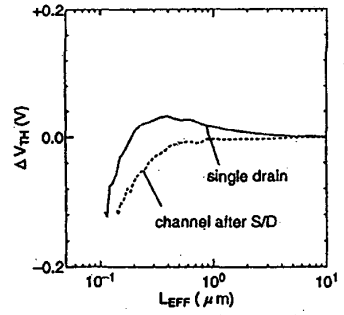

Figure 1: Experimental data for the nMOSFET reverse short channel effect(RSCE)[3], where channel B profile: initially flat from surface to $0.2\mu m$ deep, t_{ox}:5nm, S/D implantation: Arsenic, $1\sim5\times10^{15}cm^{-2}$ 10keV, anneal:FA(800°C) or RTA(1000°C). Dased line shows the data for which the channel B was implanted after S/D annealing[3], supporting that S/D implantation causes this RSCE.

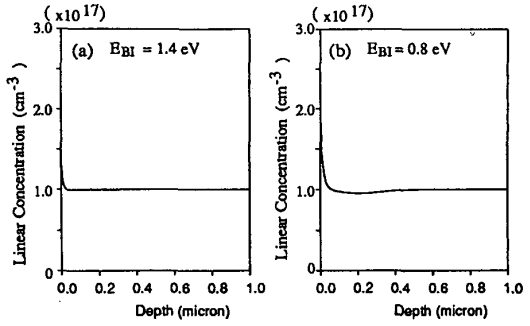

Figure 2: One-dimensional test calculation results for the boron surface pileup due to excess interstitial silicon(I) with different E_{BI} values. Boron profile: initially flat. Si implantation: $2.7\times10^{13}cm^{-2}$, 180keV. Anneal: 800°C, 1hour. D_I/K_I=$0.01\mu m$. Smaller E_{BI} gives larger pileup amount.

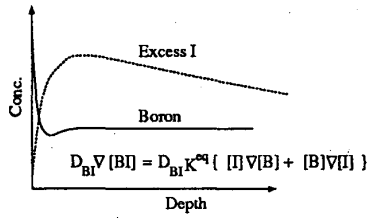

Figure 3: Figure for describing B pileup due to excess interstitial-Si concentration gradient $\nabla[I]$.

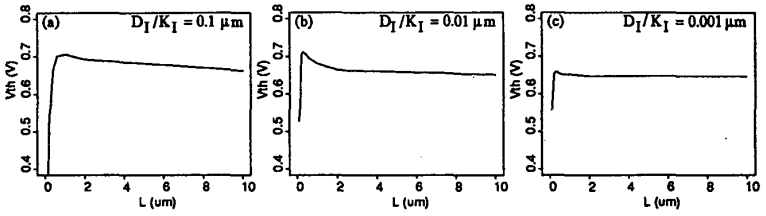

Figure 5: Calculation results for the V_{th}(threshold voltage)–L(channel length) characteristics with different surface recombination rate (K_I) values for the interstitial silicon. Annealing for 1hour at 800°C.

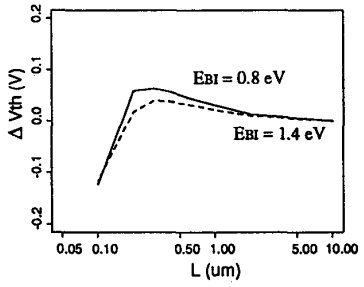

Figure 4: Two-dimensional calculation results for the reverse short channel effect with different E_{BI} values. D_I/K_I was set to $0.01\mu m$.

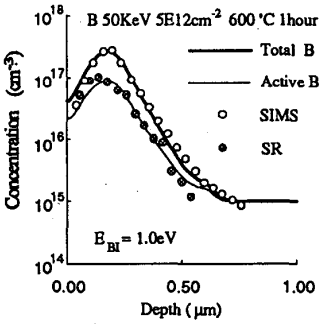

Figure 7: Experimental and calculation results for the low dose boron implantation and low temperature anneal experiment. The best fit was obtained using E_{BI}=1.0eV. D_I was reduced to 1/100 considering I-clustering effectivly.

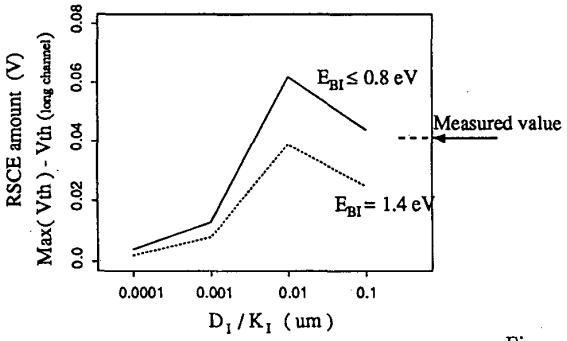

Figure 6: Dependence of surface recombination rate (K_I) and E_{BI} on the calculated RSCE amount.

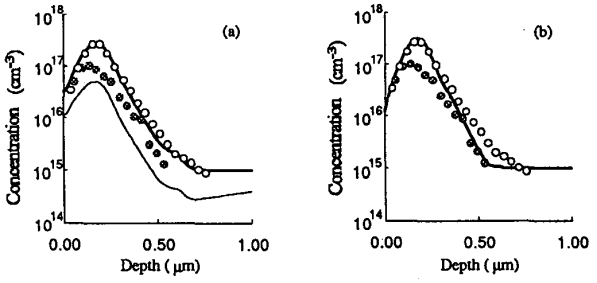

Figure 8: Comparison between calculation results and experimental data for the low dose boron low temperature annealing conditions. (a) E_{BI}=1.4eV, too-low activation. (b) E_{BI}=0.8eV, all the boron erroneously became active. Lines and symbols are the same as those in Fig.7