Anomalous short-channel body coefficients due to transient enhanced diffusion

*C.S. Rafferty, M.D. Giles, H.-H. Vuong**, S.A. Eshraghi, M.R. Pinto, S.J. Hillenius
AT&T Bell Labs, Murray Hill, NJ 07974
* AT&T Bell Labs, Allentown, PA

Abstract

The threshold voltage and its variation with back-gate bias (body effect) are among the key parameters of a digital MOSFET model. For long-channel devices formed by conventional processing, both are routinely predicted by a combination of process and device simulation to better than 0.1V [2]. For short-channel devices, particularly those formed with a very small thermal budget, anomalous diffusion effects can strongly influence the final doping profile and lead to incorrect threshold predictions. We report here on short (0.45μm coded) and long (2μm) channel length devices which show threshold shifts which are not predicted by conventional diffusion models. It is shown that transient enhanced diffusion caused by the source-drain implant must be influencing the channel profile. If the point defects generated by the source-drain implant are taken into account in the diffusion simulation, an accurate channel profile is obtained. Using correct diffusion profiles, the experimental threshold behavior is reproduced in device simulation.

The threshold voltages of short-channel (0.45μm coded) and long-channel (2μm coded) devices, at zero and $-3.3V$ back-gate bias, are shown in Figure 1. Two different device designs are shown, one with a heavy dose threshold adjust implant, the other with a light dose. The simulated $V_{th}(0)$ of both long and short-channel devices are in reasonable agreement with experimental results. The body effect of the long-channel devices is well predicted, but experimental short-channel devices show unexpectedly low body effect. Body effect depends mainly on the channel doping and has a weak dependence on the other factors which can influence the zero-bias threshold, such as T_{ox}, ϕ_m, Q_f, and quantum shifts[1]. A large reduction in body effect is clear indication that the channel boron is overestimated. Moreover, it can be inferred that the boron loss is subsurface, and due to source-drain influence, because body effect and threshold are both proportional to doping, but $V_{th}(0)$ shows little short-channel effect.

The key process steps influencing the channel profile are shown in Figure 2. The heavily doped device uses a threshold control implant of $8\times10^{12}cm^{-2}$ boron, while the lightly doped device uses $3\times10^{12}cm^{-2}$, both at 30 keV. Additional channel doping is too deep to influence the threshold voltage. The threshold control implant is followed by gate oxidation, and gate poly deposition and patterning. The lightly doped drain (LDD) is then implanted using $2\times10^{13}cm^{-2}$ phosphorus at 40 keV, followed by sidewall deposition, densification, and etchback. Finally, the contact area is implanted with phosphorus and arsenic, and there is a rapid thermal anneal (RTA) step at 1050℃ before back-end anneals at 800℃ and below. The conventional process models take into account oxidation enhanced diffusion (OED) of the channel profile during gate oxidation, in addition to boron segregation in oxide.

It is well known that impurities implanted into silicon crystal show a short burst of enhanced diffusion before reverting to their equilibrium diffusivities[3]. It has also been established that impurities implanted at later steps can cause previously quiescent impurities to show a similar burst of enhanced diffusion[4]. It is believed that this effect is primarily mediated by a defect of interstitial character, since the impurities which show most TED are also those which show OED, and OED is strongly linked to interstitial injection[5]. The effect is most pronounced at temperatures in the range 700–900℃. In the above process sequence, the greatest potential for anomalous diffusion is during the sidewall spacer deposition at 700℃ and densification at 800℃, which immediately follow the LDD implantation.

A previous 1D study[6] calibrated a simple point defect model, known as the "plus-one" model, for intermediate implant damage doses. The two critical model assumptions are that transient diffusion is proportional to the number of new atoms implanted (and not to Frenkel pair creation), and that surface recombination is high. We have used measurements from [4] to fit the model to lower energies and doses. Under these conditions, the transient diffusion effect is increased by more than an order of magnitude compared to [6]. Using our fitted parameters, the diffusion of interstitials and impurities during the sidewall deposition and densification steps were modeled using PROPHET, a general purpose, 1/2/3-dimensional coupled PDE solution system, and PADRE, a 2/3-dimensional device simulator[7]. Since the primary effect of an interstitial supersaturation is to locally and temporarily enhance the boron diffusion coefficient, the effect is pictorially represented by "enhanced time", $t_{enh} = \int D_B/D_B^* dt$. The amount of diffusion is related to enhanced time as $\sqrt{D_B^* t_{enh}}$. Contours of enhanced time are plotted in Figure 3, and the variation of t_{enh} along the channel and below the source are shown in Figure 4.

The large diffusion below the surface, and near-normal diffusion at the surface, means that the boron loss is concentrated in the bulk(Figure 5). This effect is crucial for the excellent fit to observed threshold shifts shown in Figure 6. This can be interpreted as strong support of the model assumption of fast recombination. Weak recombination would cause spatially uniform enhancement, affecting $V_{th}(0)$ and modifying 2μm devices as much as 0.45μm devices.

In summary, we have shown that anomalous body effects in short-channel MOSFETS can be traced back to transient enhanced diffusion of the channel profile due to source-drain implantation. A key TED model assumption, fast surface recombination, is supported by the results. The need to accurately calculate impurity profiles by using a coupled defect-impurity diffusion model is emphasized.

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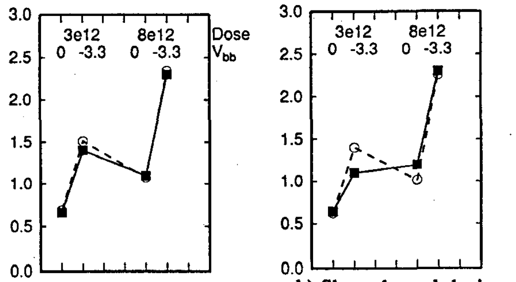

a) Long-channel devices b) Short-channel devices.

Figure 1 - Threshold voltages (V_{th}) as a function of threshold implant, channel length, and backgate bias. Solid lines are experiments, dashed lines are simulations with conventional impurity diffusion models.

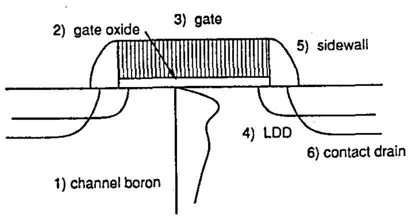

Figure 2 - Key process steps influencing the channel profile. The steps are numbered in order of fabrication.

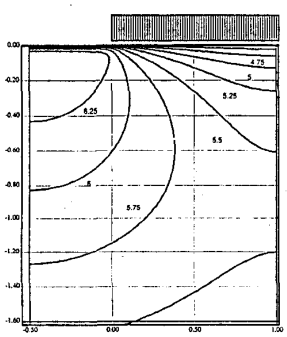

Figure 3 - Diffusivity enhancement profile following an anneal of the LDD implant. The contours represent enhanced time $\log_{10}(t_{enh})$. The peak is below the S/D implant, and decays towards the surface and laterally due to recombination, and vertically due to diffusion.

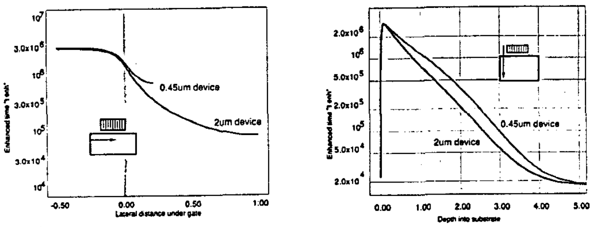

Figure 4 - Variation of enhanced time t_{enh} a) laterally and b) vertically. In a long-channel device, the enhanced time is near true time in the center of the channel, whereas in a short-channel device the channel center sees substantial diffusion.

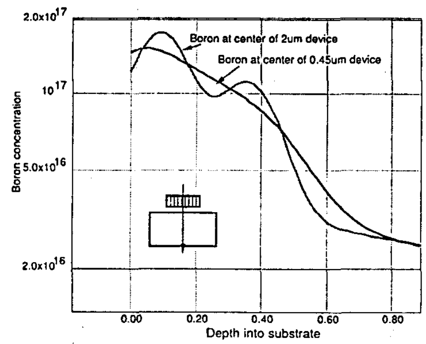

Figure 5 - Channel boron profile in short- and long-channel devices. No boron loss is seen at the surface, while the bulk boron is depleted. This is the origin of the anomalous short-channel backbias.

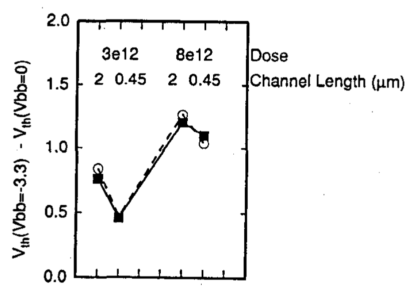

Figure 6 - Backbias shifts as a function of channel length and threshold implant. Solid lines are experiments, dashed lines the new model.