Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 509-511



# Mobility Improvement by Counter Doping and Its Reverse Short Channel Effect Associated Channel-Length-Dependent Degradation

E. P. Ver Ploeg, H. Noda, K. Umeda, R. Nagai, and S. Kimura

Central Research Laboratory, Hitachi Ltd.

1-280, Higashi-koigakubo, Kokubunji-shi, Tokyo, 185

This paper examines two unexpected side effects associated with the use of a counter doping implant in a MOSFET's channel region. Not only does the counter doping reduce the threshold voltage, but it also (1) accelerates the mobility roll-off with channel length, and (2) enhances the magnitude of the Reverse Short Channel Effect. This paper also shows that, aside from these two side effects, counter doping combined with heavy punchthrough stopper implants is a promising approach for future short channel MOSFETs.

## 1. Introduction

As MOSFETs are scaled to smaller dimensions, the need for increasing punchthrough resistance and decreasing threshold voltage come into increasing conflict. To some degree, these contradictory requirements can be decoupled by the use of very precise dopant profiles. Unfortunately, these precise profiles put stringent constraints on the total subsequent thermal budget. An attractive alternative method for decoupling the threshold voltage control from the punchthrough prevention is the use of a counter doping implant in the channel region, as illustrated in figure 1[1]. Because the counter

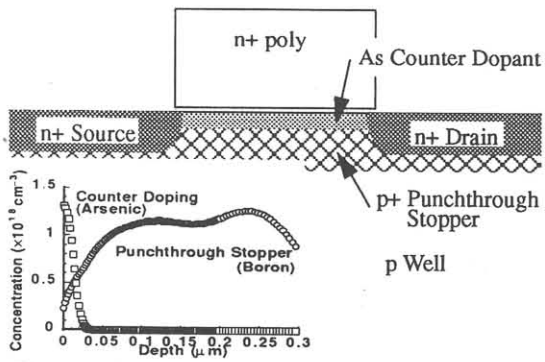


**Fig. 1.** Schematic cross section of counter doped n-channel MOSFET, with simulation of its doping profile under the gate.

doping implant is fully ionized in the zero gate bias condition, there is a reduction in the vertical electric field at the Si-$SiO_2$ interface, which creates a mobility improvement because there is a large enough reduction in the amount of surface scattering to more than compensate for the increase in impurity scattering due to the extra dopant in the channel region. This improvement in the mobility can be clearly seen for the long channel region of the mobility versus channel length plot shown in figure 2.

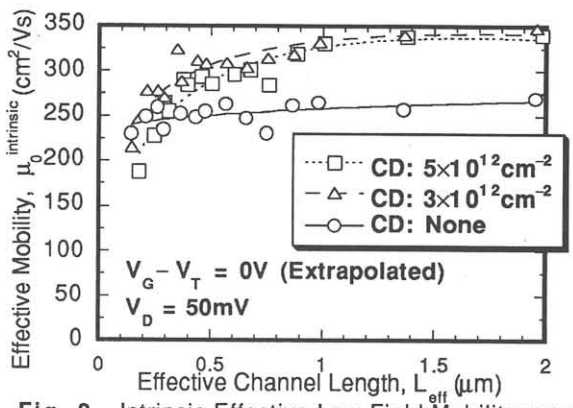


**Fig. 2.** Intrinsic Effective Low-Field Mobility versus Effective Channel Length for three counter doping implant conditions with heavy punchthrough stopper doping profiles, showing mobility improvement and more pronounced roll-off with counter doping.

Traditionally, as channel length is reduced, the threshold voltage tends to roll off due to the Short Channel Effect. Recently, however, it has been noted by many researchers[2)-5)], that for devices with heavy channel doping, the threshold voltage first increases for decreasing channel length before rapidly decreasing with decreasing channel length. This increase in threshold voltage has been called the Reverse Short Channel Effect (RSCE), and has been measured to result in threshold voltage increases of 30mV to 500mV, depend-

ing on processing details. We present here evidence indicating that the RSCE is significantly enhanced by a counter doping implant in the channel region.

## 2. Devices

Four types of MOSFETs were measured in this study. Three of the four had fairly heavy punchthrough stopper implants (the boron profile seen in the inset of figure 1) with counter doping channel implants of 0, 3, and $5\times10^{12}cm^{-2}$. The fourth type of MOSFET used a more lightly doped punchthrough stopper region and no counter doping implant. All the devices in this study had a gate oxide thickness of 6nm and were non-LDD, non-silicided, nMOSFETs with n+ polysilicon gates. The punchthrough stopper and counter doping implants were done through a sacrificial oxide that was stripped before gate oxidation. The total boron dose for the devices with the heavy punchthrough stopper implants was $3.5\times10^{13}cm^{-2}$, and the total boron dose for the devices with the light punchthrough stopper implant was $5.5\times10^{12}cm^{-2}$.

## 3. Counter Doping

The counter doping channel implant coupled with higher punchthrough stopper doping levels is an attractive technique for use in future MOSFET technologies. Figure 3 shows that counter doping is an effective way

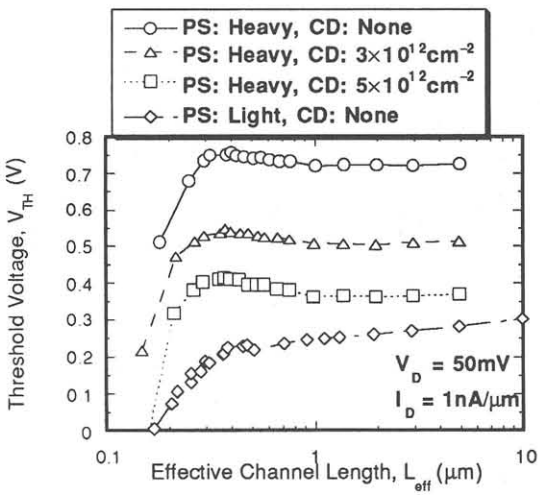


**Fig. 3.** Threshold Voltage versus Effective Channel Length for the four devices discussed.

of reducing the threshold voltage in devices with heavy punchthrough prevention doping. For these devices, the counter doping channel implant combined with a heavier punchthrough prevention profile is able to achieve nearly the same long channel threshold voltage while significantly decreasing the amount of $V_T$ roll-off with L. Figure 4 shows the saturation drain current versus effective channel length behavior for the four technologies. The minimum useful channel lengths, as determined by a fixed amount of $V_T$ roll-off, for the

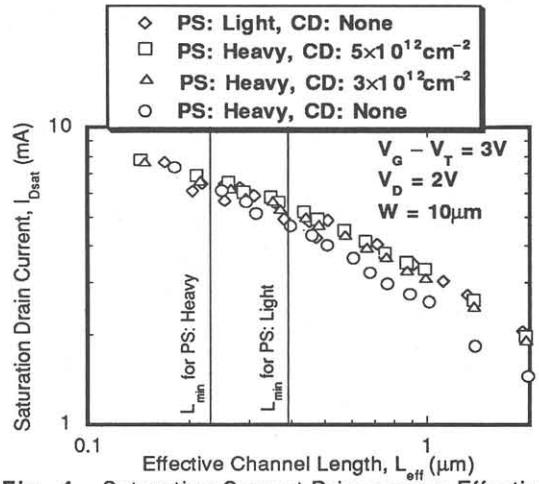


**Fig. 4.** Saturation Current Drive versus Effective Channel Length for the four devices discussed.

three technologies with heavy punchthrough stopper implants are nearly identical and significantly shorter than that of the technology with lighter punchthrough stopper implants. The current driving capability of the counter doped technologies are nearly identical in both the long channel and short channel regime. The drain current for the technology with heavy punchthrough doping and no counter doping is seen to be lower in the long channel regime due to the decreased effective mobility resulting from a higher vertical electric field. However, as the channel length is reduced, the current drive of all four technologies tend to converge due to the fact that the saturation current becomes less dependent on effective mobility and almost completely determined by the saturation velocity of the carriers, which is a material constant.

A comparison between the technology with the heavy punchthrough stopper implantation combined with a counter doping implant and a technology with a lighter punchthrough stopper shows that the only negative attribute of the counter doping technology is larger subthreshold slopes. Figure 5 shows that the counter dopant is able to reduce the subthreshold slope of the devices with the heavy punchthrough implantation, but it does not reduce it all the way down to the level of the devices with a lighter punchthrough stopper implant.

## 4. RSCE Enhancement

The parameters which control the magnitude of the RSCE are incompletely understood at this time, however it is well established that the magnitude of the threshold voltage increase ($\Delta V_{TH}$) goes up with increasing channel doping. This suggests that the RSCE will become more important as channel lengths are reduced because additional dopant in the channel region will be necessary to prevent premature punchthrough due to Drain Induced Barrier Lowering. This means that understanding and controlling the RSCE is very important if

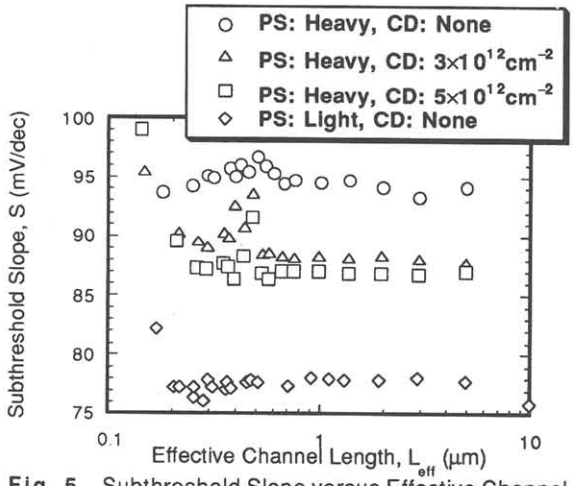


**Fig. 5.** Subthreshold Slope versus Effective Channel Length for the four devices discussed.

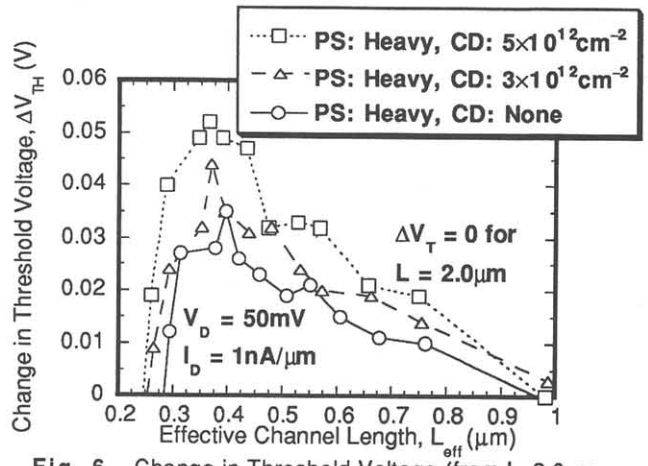


**Fig. 6.** Change in Threshold Voltage (from L=2.0μm value) versus Effective Channel Length for the three devices with heavy punchthrough stopper implants.

we are to be able to reliably control the threshold voltages in future generations of MOSFET technology.

For our devices, the use of a counter doping implant was seen to increase the severity of RSCE related phenomena. It has previously been noted[6] that the dopant redistribution responsible for the RSCE is also most likely the cause of the reduction in effective mobility with reducing gate length seen in many technologies, as in figure 2 for our devices. Figure 2 also shows that this mobility roll-off is accelerated by the inclusion of the counter doping implant, suggesting that the counter dopant increases the magnitude of the RSCE. More conclusive experimental evidence in support of the theory that the counter doping channel implant enhances the RSCE is presented in figure 6, where the magnitude of the RSCE is seen to increase with increasing counter doping dose (the definition of RSCE). This doping profile dependent RSCE behavior is consistent with Rafferty's[5] interstitial assisted Transient Enhanced Diffusion explanation of the RSCE phenomenon, where interstitials, created by the Source/Drain ion implantation, recombine at the Si-$SiO_2$ interface during annealing, creating a channel position dependent pile-up of boron just below the gate oxide.

## 5. Conclusions

This paper has shown that counter doping in the channel region combined with heavy punchthrough stopper implantation is a promising technique for realizing punchthrough control and sufficiently low threshold voltages in reduced channel length MOSFETs. Understanding the role of counter doping in RSCE behavior is extremely important because counter doping channel implantation is such a promising technique and because the severity of the RSCE is likely to increase for subsequent generations of MOSFETs. This paper has also introduced the fact that the counter doping channel implant has a significant impact on the RSCE. It may well be possible to significantly decrease the severity of the RSCE, and counter doping's influence on it, through minor changes in device processing. Because of counter doping's otherwise promising behavior, attempts to reduce its impact on the RSCE should be examined.

## 6. Acknowledgements

The authors would like to gratefully acknowledge the continuing support of E. Takeda, T. Nishida, and the Process Integration Center.

## 7. References

1) R. Nagai, K. Umeda, and E. Takeda, "Low-Voltage High-Gain 0.2μm N-Channel Metal Oxide Semiconductor Field Effect Transistors by Channel Counter Doping with Arsenic," *Jpn. J. Appl. Phys.*, **32** pp. 434-437, January 1993.

2) M. Nishida, and H. Onodera, "An Anomalous Increase of Threshold Voltages with Shortening the Channel Lengths for Deeply Boron-Implanted N-Channel MOSFET's," *IEEE Trans. Electr. Devices*, **ED-28**, pp. 1101-1103, September 1981.

3) C.-Y. Lu, and J.M. Sung, "Reverse Short-Channel Effects on Threshold Voltage in Submicrometer Salicide Devices," *IEEE Electr. Device Lett.*, **EDL-10**, pp. 446-448, October 1989.

4) T. Kunikiyo, K. Mitsui, M. Fujinaga, T. Uchida, N. Kotani, and Y. Akasaka, "Reverse Short-Channel Effects due to the Lateral Diffusion of the Point-Defects Induced by the Source/Drain Ion Implantation," *Proceedings of NUPAD IV*, pp. 51-56, 1992.

5) C.S. Rafferty, H.-H. Vuong, S.A. Eshraghi, M.D. Giles, M.R. Pinto, and S.J. Hillenius, "Explanation of Reverse Short Channel Effect by Defect Gradients," *International Electron Devices Meeting*, pp. 311-314, December 1993.

6) H.-J. Wildau, H. Bernt, D. Friedrich, W. Seifert, P. Staudt-Fischbach, H.G. Wagemann, and W. Windbracke, "The Inversion Layer of Subhalf-Micrometer n- and p-channel MOSFET's in the Temperature Range 208-403 K," *IEEE Trans. Electr. Devices*, **ED-40**, pp. 2318-2325, December 1993.