DEVICE DRIVE CURRENT DEGRADATION OBSERVED WITH RETROGRADE CHANNEL PROFILES

S. Venkatesan, J. W. Lutze, C. Lage and W.J. Taylor
Advanced Products Research and Development Laboratory, Motorola
3501 Ed Bluestein Blvd., Austin, TX 78721. (512)-933-7513

Abstract

Super steep retrograde channel profiles have been widely known to produce improved short channel characteristics in sub-0.35μm CMOS technologies. In this paper, an attempt is made to leverage this improved short channel behaviour and thereby improve transistor performance (as measured by the current drive). Whereas significant improvements in short channel effects measured by DIBL and ΔVt_{sat} are obtained with retrograde channels, it is observed that for a fixed gate length and equal threshold voltage, transistors with retrograde channel profiles typically exhibit lower drive currents than equivalent transistors fabricated with conventional doping profiles. Potential trade offs in device design resulting from this observation are discussed.

Introduction

Vertical channel profile engineering has been widely reported to improve transistor characteristics compared to devices having a conventional flat doping profile [1,2]. More specifically, steep retrograde channel profiles using Indium for NMOS, and either Antimony or Arsenic for PMOS have been attempted in sub-0.35 μm technologies to ensure adequate transistor turn-off characteristics [3,4]. Since retrograde channel profiles allow the modulation of the potential barrier from source to drain through vertical doping profile engineering, much of the attention has focused on the improved short-channel characteristics of devices incorporating such profiles. However, the impact on other transistor performance parameters associated with retrograde channel profiles has not been sufficiently addressed. In this paper, we demonstrate for the first time a significant degradation in device drive currents with the use of retrograde channel profiles. In a systematic study exploring the potential need for retrograde channel profiles in a 0.35μm technology, it is shown that few benefits and several trade-offs in transistor design arise.

Experiment

Dual gate CMOS transistors were fabricated using a 0.35μm technology with a nominal gate length of 0.30 μm and a 55 Å gate oxide. Technology highlights include shallow trench isolation, 200nm a:Si (as-deposited) gates, shallow S/D extensions and deep S/D regions formed with As and BF_2, 100nm spacers, 1065°C RTA anneal and Ti salicidation. Devices with both conventional channel profiles formed with B and P and retrograde channel profiles formed with In and Sb were fabricated. The simulated channel profiles are shown in Figure 1.

Results and Discussion

The effect of retrograde channel profiles on device drive currents is highlighted in Figure 2, which shows the I_{DS}/W vs. L_{eff} characteristics for NMOS and PMOS devices with both conventional and retrograde implants. I_{DS}/W has been measured at a constant gate overdrive so as to decouple the effect of small differences in threshold voltages. As can be seen in the figure, a degradation in current drive of 10% is observed on the p-channel transistors with a somewhat smaller, but still significant decrease of about 5% for the NMOS devices. We attribute this degradation in the current drive to the increased body factor observed in the devices with the retrograde channels. The measured body factors and other significant parameters for the two profiles are tabulated in Table 1. Since the saturated drive current is given by [5]:

$$ID = \frac{W}{L}\,\mu\,Cox\,\frac{(Vg-Vt)^2}{2(1+\partial)}\;;\;\partial \approx \frac{\gamma}{4\sqrt{\Phi_B}}$$

- where ϕ_B is the surface potential under strong inversion

one can qualitatively conclude that an increase in the body factor (γ) of the devices would result in a commensurately lower current drive. Note that the increased body factor is an inevitable consequence

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of the retrograde channel, and cannot be avoided. For short channel devices, velocity saturation changes the mobility dependence in the above equation, whereas the dependence on γ (which controls the pinch-off region of the device) is essentially unchanged. An additional factor that might partially contribute to the degradation in current drive is the possibility of increased S/D spreading resistance with retrograde channels. Since the peak of the channel profile falls approximately at the junction depth of the S/D extension regions, compensation effects could increase the resistance associated with the extension regions for both NMOS and PMOS transistors. Moreover, since the extension dose for the p-channel devices is typically less than that of the n-channel devices, they are more prone to these compensation effects. This may explain the larger degradation in current observed on the p-channel devices.

Figure 3 depicts the saturated threshold voltage (Vt_{sat}) roll-off vs. L_{eff} characteristics for the devices. Devices with the retrograde channel profiles are seen to exhibit clearly improved short-channel characteristics. Figure 4 likewise illustrates the drain induced barrier lowering (DIBL) vs. L_{eff} characteristics, again showing improved short channel behavior for the retrograde profiles. Due to the increased short-channel margin, it is possible in these devices to recover the loss in current drive by operating at a smaller L_{eff}, without increasing worst case leakage currents. *However, this assumes that a shorter gate length is manufacturable for a given technology.*

Figure 5 depicts the I_{DS}/W vs. I_L/W characteristics which are often used as a metric to gauge transistor performance. Two points are immediately obvious. First, in the short channel regime the two curves associated with the retrograde and conventional channel profiles merge together. Thus, although the short channel characteristics are improved, the net current drive capability is comparable between the two profiles. Second, the devices with the retrograde channels have larger sub-threshold slopes and consequently show higher leakages at longer gate lengths even for comparable threshold voltages.

Finally, the drive current degradation and short channel characteristics for two retrograde profiles with different threshold voltages and body factors are explored in Fig. 6. The degradation in current drive is modulated by the Vt of the device. Devices with a lower Vt have a lower sub-surface peak concentration, lower body factor, a smaller degradation in current drive and relatively poor short channel characteristics. A heavier implant improves the short channel behavior but results in increased current drive degradation presumably due to increased body factor and increased S/D spreading resistance.

The resulting trade-offs for a 0.35μm technology can be summarized as follows. For the given technology with *fixed L_{gate} and fixed Vt*, devices with retrograde channel profiles will show degraded drive currents compared to conventional devices as illustrated in Figs. 2&5. However, if sufficient manufacturing margins exist with respect to defining smaller gates, then the retrograde channels provide the *same Ion vs. Ioff capability at a shorter gate length*, which reduces the gate capacitance and could actually produce a net performance advantage. On the other hand, if the gate lengths are constrained by manufacturing, comparable drive currents can be achieved only through lower threshold voltages for the retrograde channel implants (Fig. 6), which results in increased off-currents for long channel devices, higher standby power and reduced short channel margin.

Conclusions

Retrograde channel profiles are shown for the first time to degrade transistor drive currents, albeit improving short channel characteristics. Few benefits are observed over a conventional flat channel profile for a 0.35μm technology.

Acknowledgements

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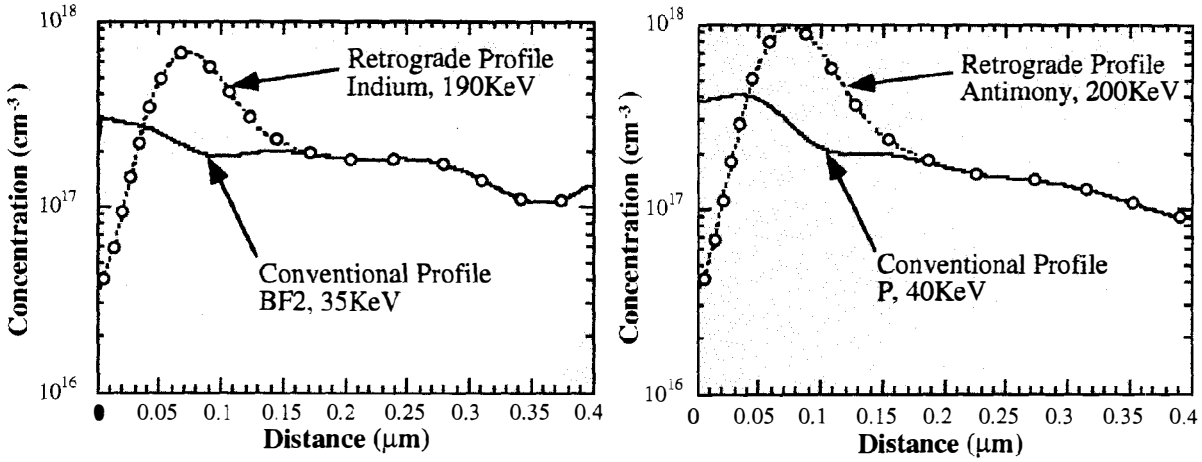

Fig. 1 Simulated 1-dimensional doping profiles for the devices fabricated with retrograde and conventional channel profiles for (a) NMOS and (b) PMOS transistors. The retrograde profiles were formed with Indium for the NMOS and Antimony for the PMOS.

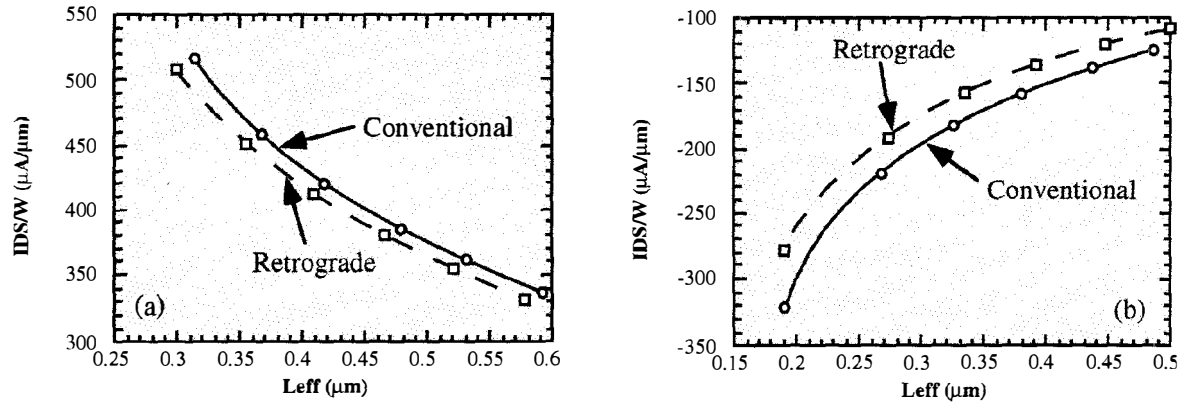

Fig. 2 Plot of IDS/W versus Leff for (a) NMOS and (b) PMOS devices. The drive currents are measured at a constant gate overdrive of Vg-Vt=2.0V at Vds=2.5V. The degradation in drive currents is more clear for the PMOS devices which exhibit a larger percentage change in the body factor.

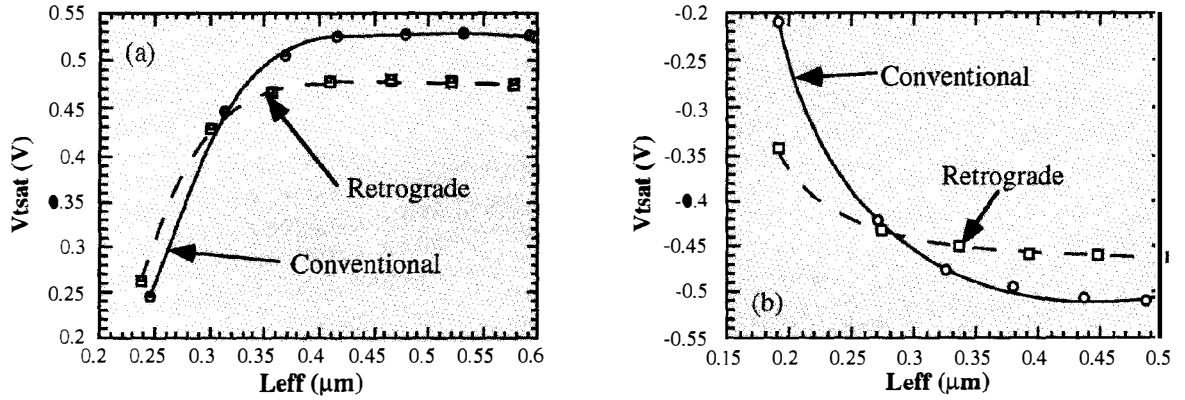

Fig. 3 Vtsat (Vds=2.5V)plotted versus Leff for (a) NMOS and (b) PMOS. The short channel characteristics are generally better for the retrograde channel profiles. Differences between the NMOS and PMOS devices are due to the differences in the nature of the profile.

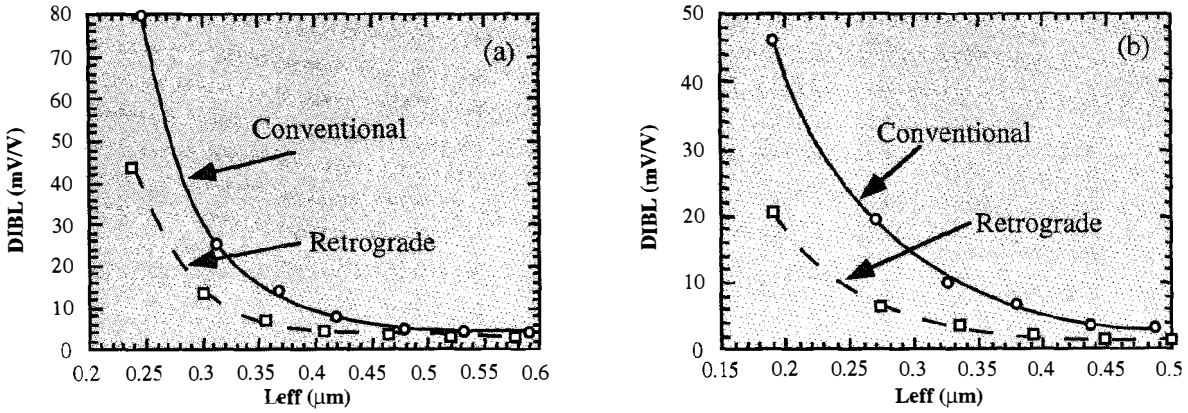

Fig. 4 DIBL versus Leff characteristics for (a) NMOS and (b) PMOS. Improved short channel characteristics are noted for the retrograde channel profiles.

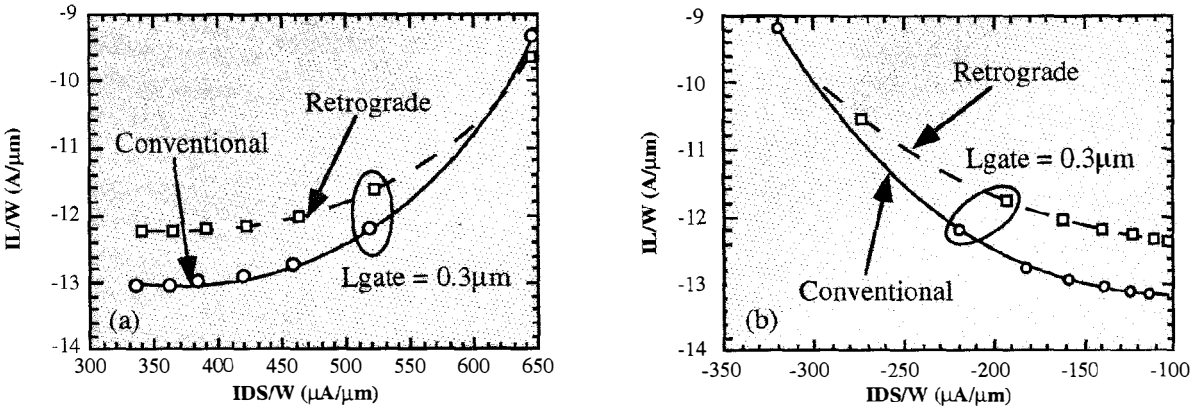

Fig. 5 Ion versus Ioff characteristics for (a) NMOS and (b) PMOS. Both the retrograde channels and the conventional channels trace out similar curves in the short channel region. The long channel leakage is actually worse for the retrograde channels due to larger subthreshold slopes and lower Vt.

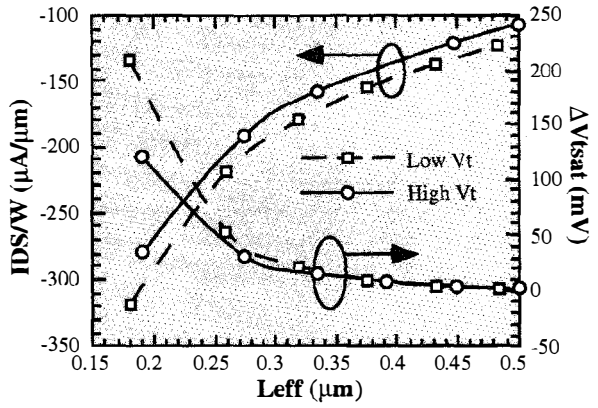

Fig. 6 Drive current degradation and short channel characteristics for a PMOS transistor with two different retrograde channel profiles, one with a higher Vt (0.51V) and one with a lower Vt (0.45V).

Table 1

NMOS					
Profile	Body Factor √V	Cj (area) fF/μm2	SS mV/dec	ΔVtsat mV	Vt (long) V
Conventional	0.46	0.89	76	220	0 53
Retrograde	0.63	1.06	81	185	0.48
PMOS					
Profile	Body Factor √V	Cj (area) fF/μm2	SS mV/dec	ΔVtsat mV	Vt (long) V
Conventional	0.55	0.97	78	320	-0.56
Retrograde	0.87	1.03	85	160	-0.51