

Optimization of High Performance Bulk FinFET Structure Independent of Random Dopant Process Variations

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Abstract FinFETs are multigate MOSFETs conventionally fabricated on SOI wafer. Alternatively, use of Si-bulk wafers for FinFET has gained significant interest for the low cost of wafers and more importantly for the compatibility with bulk CMOS technology. This paper describes the design of Bulk FinFET with improved performance using different bulk structures. In initial part of work, we have used the Pie-gate structure and heavy body doping structure i.e. Punchthrough stopper. Both the structures are combined in a novel Pie-gate bulk FinFET structure with punchthrough stopper. It has been observed that the novel structure shows better results compared to previous structures but it is difficult to fabricate. So, the Performance of bulk FinFET with bottom spacer is studied including the detailed discussion of process variation effect which shows that such bulk structure is supposed to have less fabrication complexity to achieve and optimize a desired doping profile. Finally, It is observed that the bulk FinFET with bottom spacer can be optimized to obtain superior performance than all other FinFETs making it independent of doping related process variations.

Keywords Bulk (FinFET), Subthreshold Performance, Punchthrough Stopper, Bottom Spacer(BS), Active Fin Length, Width Quantization, SOI FinFET, Sentaurus TCAD Device Simulator

1. Introduction

Conventionally FinFET[1] is fabricated on SOI wafer[2-3] because of its excellent short channel characteristics but SOI wafer shows some disadvantageous over bulk FinFET like floating body effect, heat transfer problem and high wafer cost[4]. Bulk FinFET[5] covers most of the drawbacks of SOI FinFET. Also, bulk FinFET shows better immunity to negative bias-temperature (NBT) stress[6]. Additionally, Bulk FinFET has gained attention due to its low-cost process and the ability to be integrated with standard bulk CMOS technology[7-8]. But the characteristics of bulk FinFET are not comparable with SOI FinFET. One major advantage of SOI over bulk is speed. SOI devices have 30% speed advantage over their bulk counterpart in normal MOSFET. But it has been reported[9] that owing to their geometry (i.e. 3D structure) for significantly (~60nm) large Fin height, less than 5% delay difference is obtained. For Fin height of 30nm this delay difference becomes approximately 8%. Therefore, we can say that speed advantage in SOI FinFET is not prominent as it is in normal SOI MOSFET leading to the importance of bulk FinFET structures of comparable

performance parameters.. The Bulk FinFETs are fabricated with high body doping to suppress source to drain coupling effect[10] However, the lack of isolation layer underneath the transistor body allows the drain field to penetrate towards the source more easily by deteriorating the subthreshold slope and DIBL. Use of high channel doping is used to reduce OFF state current to improve performance of bulk FinFET. But this will result in significant mobility degradation and high parasitic capacitances[9]. Although bulk FinFET shows excellent promise but it does not have performance as good as SOI FinFET. So, it is important to optimize bulk FinFET performance as in SOI FinFET. Previously, Pie-gate bulk FinFET i.e. isolation oxide with source/drain-to-body (S/D) junctions shallower than gate-bottom[11] and bulk FinFET of heavy body doping i.e. Punchthrough stopper, is reported[9]. Here Pie-gate structure is basically represented by misalignment(ΔX_j =ive) between the S/D junctions and the bottom of the gate electrode. Since the change of performance due to process variation can be very undesirable for some analog or digital CMOS circuits, the designer wants that the device performance should be independent of process variation[12]. The observed random distribution of identically drawn devices can be caused by impurity concentration densities. This results from non-uniform conditions during the deposition and the diffusion of the impurities(dopant) and the changes in these parameters cause electrical parameters to vary, such as sheet

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resistance and threshold voltage. It has been shown in [9] that the performance of bulk FinFET can be improved by use of punchthrough stopper doping and it can be observed that the performance of bulk FinFET is very sensitive to channel doping. Using FinFET with punchthrough stopper also require a precise control of doping and doping profiles[9]. In normal bulk FinFET, it is very difficult to optimize precise punchthrough stopper doping and also during fabrication, the process variables(like temperature) may cause undesirable change in performance. In our work we have used bottom spacer bulk FinFET structure to optimize the doping of punchthrough stopper. It has been shown in[13] that it is possible to have a optimized punchthrough stopper doping with the use of vertical doping, while using bottom spacer. Fabrication process of bottom spacer doesn't involve any tilted angle implant like we need in conventional structures. So BS is supposed to have less fabrication complexity to achieve and optimize a desire doping profile (punchthrough stopper doping). Also it has been shown that while using bottom spacer structure our device performance becomes more independent of active Fin doping which indicate that we do not need a particular doping profile in bottom spacer FinFET. In other words, the performance become independent of process variation caused by impurity concentration densities which can be considered as a big advantage of bottom spacer structure.

Also to deal with width quantization problem[14] as in SOI FinFET, Bulk FinFET structure with bottom spacer reported, is again important. We compare Bulk FinFET having bottom spacer with the previously reported heavy body doping and pie- gate bulk FinFETs. The effective channel width of triple gate FinFET is given by

$$W_{eff} = 2H_{Fin} + W_{Fin} \quad (1)$$

Where W_{Fin} is Fin width and H_{Fin} is height of Fin. It is reported that use of bottom spacer eliminate the width quantization problem in SOI FinFET[13]. The use of bottom spacer also eliminates the problem of width quantization in bulk FinFET. Moreover, it improves the performance like subthreshold behaviour, DIBL etc over conventional Bulk FinFET. It also exploits the advantages of its planer bulk counterpart with lower series resistance and higher peak transconductance[15]. One of the major advantages of FinFET is due to its Fin structure and lower capacitance over its planner counterpart[9]. But when Fin height decreases(40nm-50nm) device is tending towards planner structure. It is obvious that if we use very low Fin height (or very high bottom spacer) it behave more like a planner MOSFET than a FinFET..

In this paper, the characteristics of bulk FinFET are analysed by 3D device simulation and compared with SOI FinFET. For improved bulk FinFET performance different bulk FinFET reported in[9,11,13] is also characterized. The ultimate aim of work is to find best FinFET bulk structure with comparable or better characteristics than SOI FinFET.

2. Device Structure and Simulation Setup

The Bulk and SOI FinFET structures have been made with 3-D Sentaurus structure editor[16-17]. The tri-gate FinFET designed is of 32nm channel length with source/drain doping is $1E20 \text{ cm}^{-3}$ (n type). Metal is used as gate contact material and the work function of metal is kept 4.62eV. Silicon dioxide is used as gate oxide material with gate oxide thickness of 1.1nm. The channel doping is different for different simulations with $V_{DD}=1.0V$. The FinFET is designed with 16nm spacer length, 10nm Fin width and 60nm Fin height. Pie gate SOI FinFET is reported in literatures[11] i.e. Fig. 1 shows a marked misalignment (ΔX_j) between the Source/Drain junction depth and gate depth. This structure will be equivalent to Pie-gate structure if misalignment ΔX_j is negative. For comparison point of view Source/Drain junction depth kept is constant (60 nm) and gate is penetrated deeper into bulk(Fig. 2).

In second part of our work we have analysed Bulk FinFET with punchthrough stopper doping which is reported in ref[9]. We have doped pie gate Bulk FinFET with heavy body doping and made comparisons between all bottom spacer structure for FinFET which is reported earlier for SOI FinFET[13].

In last part of our work we have made Bulk FinFET with bottom spacer. 3D view of device is shown in Fig. 3. In case of uniform doping profile, doping of entire bulk region is kept constant. Device is also simulated and optimized for different bulk doping profile. Side view of Channel region of Bulk FinFET with bottom spacer is shown in Figure. The Bulk portion beneath bottom spacer is called as inactive Fin and Bulk region surrounded by gate contact is called active fin.. Silicon dioxide is used as spacer material. The height of Fin is 60 nm. The Simulation is also done for different height of bottom spacers.

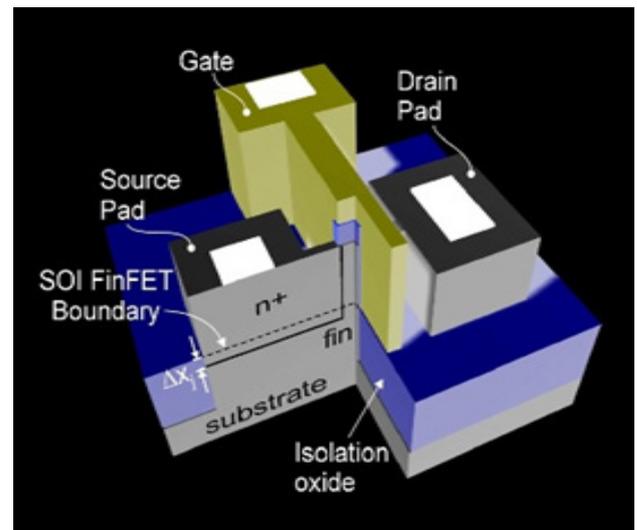
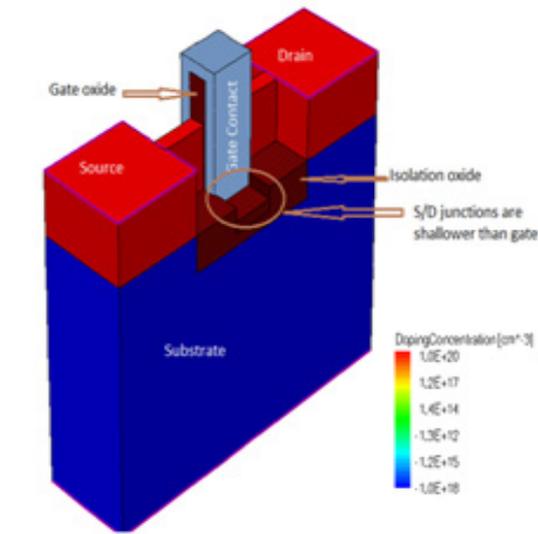
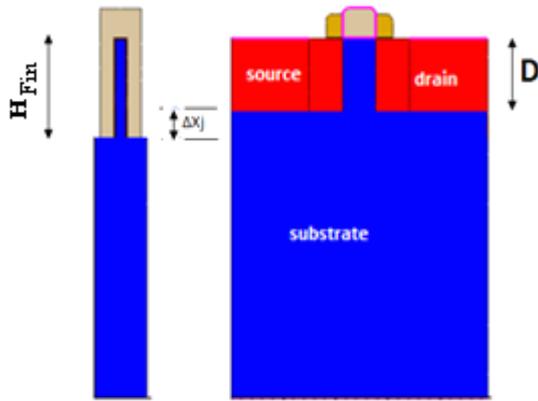


Figure 1. 3-D View of Pie gate SOI FinFET(ΔX_j negative)

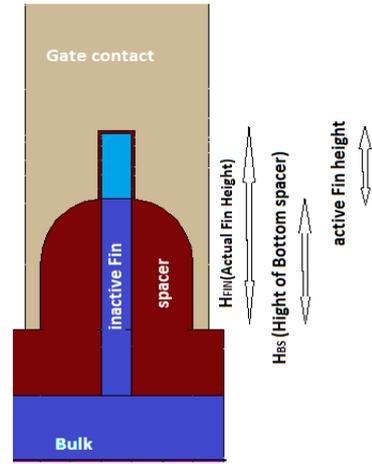


(a)

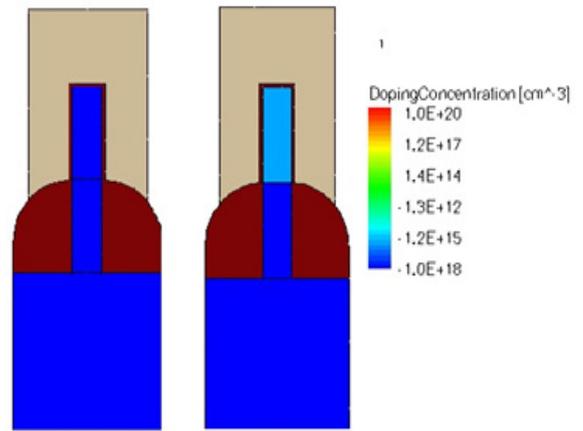


(b)

Figure 2. (a) 3-D view of Pie-gate Bulk FinFET structure (b) Cross-sectional view of pie gate FinFET structure

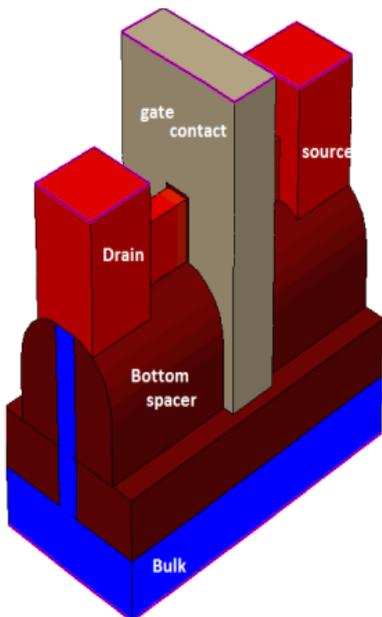


(b)



(c)

Figure 3. (a) 3-D view of Bulk FinFET (b) Side view of Bulk FinFET (c) Side view with uniform and non uniform doping with bottom spacer



(a)

For FinFET simulation TCAD tool need to be properly calibrated. For mobility doping dependent, high field saturation, Lombardi Model with proper calibration is used. The transport model which is used for simulations accounts drift-diffusion formalism and band-to-band tunneling included in the SRH recombination.

3. Results and Discussion

3.1. Previously Reported Bulk FinFETs

Conventional bulk FinFET with low channel doping (1E16) has DIBL of 371 mV/V and Subthreshold slope of 328 mV/Decade. High channel doping is used to get improved performance. Bulk FinFET with high channel doping (1E18) shows significant improvement having DIBL of 44 mV/V and subthreshold slope of 75 mV/decade. But high channel doping has its own drawback. To improve bulk FinFET performance high body doping is studied.

Using low channel doping in active Fin (higher Fin) and high doping in lower Fin as well as body as reported in [13], significantly improves performance. Subthreshold slope of profile reported in [9] is 78 mV/Decade and DIBL of device is 46 mV/decade which is a significant improvement over uniform low channel doping as discussed earlier. Secondly, bulk FinFET, with misalignment of bottom of gate and source/drain body junction depth is simulated. ΔX (nm) is the amount of misalignment. Positive value of ΔX indicates that source/drain body junction is deeper than bottom of gate. Negative value indicates opposite behavior. The bulk FinFET having shallower source/drain junction than bottom of gate (negative ΔX) shows better performance than normal Bulk FinFET ($\Delta X=0$) as reported in [11]. For lightly doped Fin DIBL of Bulk FinFET having $\Delta X=-10$ nm is 108 mV/V and Subthreshold slope is found to be 119 mV/decade for $\Delta X=-20$ nm these values are 80.5 mV/V and 89mV/decade respectively. For highly doped Fin DIBL of bulk FinFET having $\Delta X=-10$ nm is 36 mV/V and Subthreshold slope is found to be 72.53 mV/decade for $\Delta X=-20$ these values are 26.5 mV/V and 72.68 mV/decade respectively. Graph showing relation between channel doping and SS is shown in Fig. 4. Higher value of ΔX improves short channel performance of bulk FinFET but for low Fin doping the performance is not satisfactory.

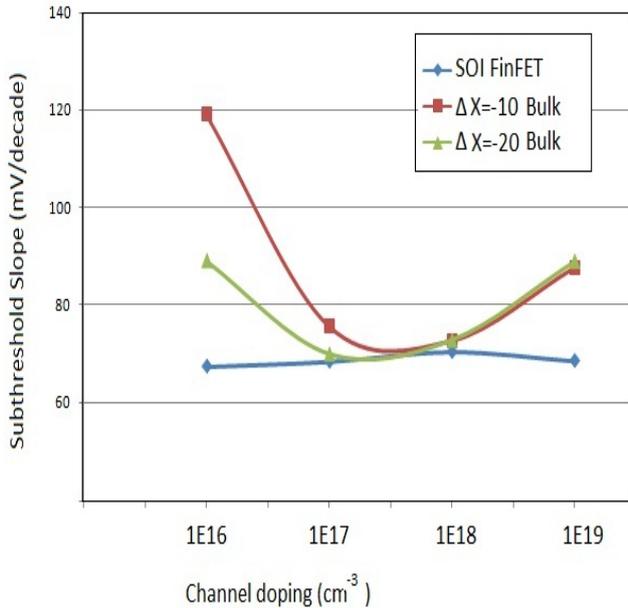
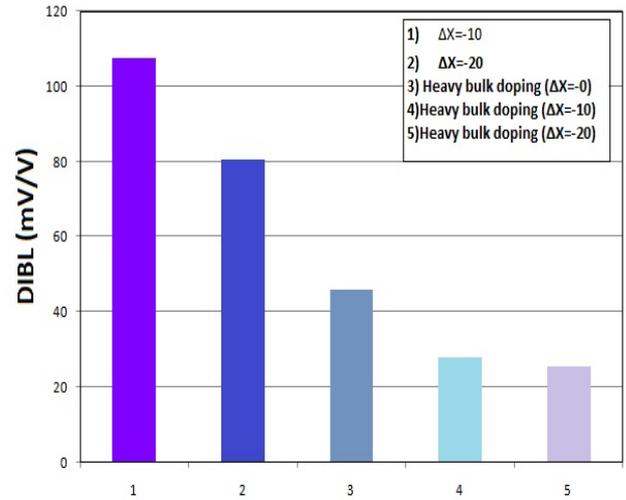


Figure 4. Effect of channel doping on Subthreshold Slope of pie gate Bulk FinFET and SOI FinFET

3.2. Pie Gate Bulk FinFET with Punch through Stopper

In this section of work, bulk FinFET with heavy body doping (punch through stopper doping) [9] is studied. We doped pie gate FinFET with punchthrough stopper doping and characterized the performance. The heavy body doping bulk FinFET is simulated for $\Delta X_j=0$ nm, $\Delta X_j=-10$ nm & $\Delta X_j=-20$ nm. For $\Delta X_j=-10$ nm, SS is 70.62 mV/decade and DIBL is 28mV/V. For $\Delta X_j=-20$ nm, SS is 60 mV/decade and DIBL is 25.6 mV/decade. It is clear that performance of

device is significantly improved than previously reported profile and also its value is compared with SOI FinFET (Fig. 4). A graph of DIBL and Subthreshold slope is plotted for different bulk structures and has been shown in Fig. 5 & 6. The subthreshold performance is also studied with variation in channel doping with different Fin structures (Fig. 3). It is observed that device with heavy bulk doping with misalignment $\Delta X=-20$ nm has subthreshold performance almost similar to the SOI FinFET.



Different Bulk Structures

Figure 5. DIBL Characteristics for different bulk FinFET structures

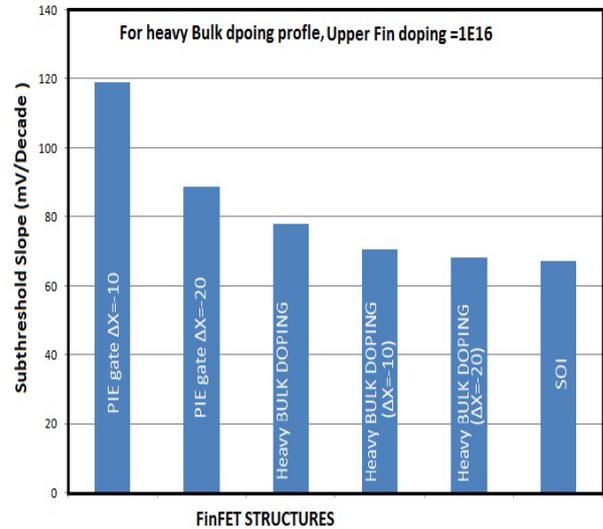


Figure 6. Subthreshold slope for different Bulk FinFET structures

3.3. Bulk FinFET with Bottom Spacer

Bulk FinFET with bottom spacer is shown in Fig.3. Height of bottom spacer is 30nm, so effective Fin height become 30nm ($H_{\text{Fin}}-H_{\text{BS}}$), where H_{Fin} is height of actual Fin and H_{BS} is height of bottom spacer. This reported structure has initially analysed for uniform channel doping profiles and non-uniform doping profiles.

3.3.1. Bottom Spacer with Uniform Channel Doping Profile

In uniform Bulk doping, active Fin & inactive Fin doping are same. Simulation is done using different Bulk doping. The results are shown in Fig. 7. Similar to the Bulk structure, this device also need high channel doping to control SCEs. The performance of device is better with high channel doping than low channel doping but it is not satisfactory .

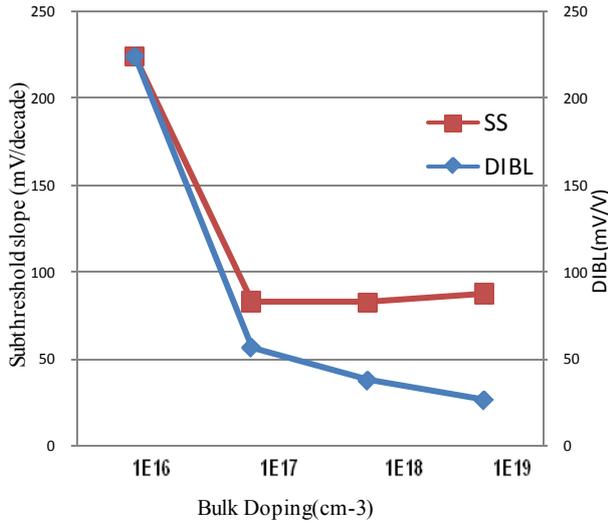


Figure 7. Bulk FinFET with uniform channel doping

3.3.2. Bottom Spacer with Non-uniform Channel Doping Profile

The Bottom spacer with uniform bulk doping is not satisfactory. It needs higher channel doping for high performance and our aim is to optimize bulk FinFET, so that we get high performance with low channel doping. Here we have used different channel doping in active and inactive Fin regions. Simulations are carried out for two purposes i) Optimization of inactive Fin doping ii) Optimization of active Fin doping.

i) *Optimization of inactive Fin doping:* For optimization of inactive fin doping, simulation is performed for different inactive fin doping keeping active fin doping constant. Different performance parameters have been measured. It is clear that high I_{ON} Figure 9 shows the relation between OFF state current and inactive channel doping. The I_{ON}/I_{OFF} Current is also measured for different active Fin doping. High doping results in low OFF state current but very high (i.e. 1E19) band to band tunnelling and causes degradation in performance. For very high inactive Fin doping OFF current is higher, so proper optimization of doping profile is required to get best performance. Graph of Figure 10 shows I_{ON}/I_{OFF} for different inactive Fin Doping.

wer Fin doping gives better performance than low lower Fin doping because for high doping there will be lesser influence of drain electric field and it also lowers the junction leakage current. Graph of ON state current for different inactive channel doping is shown in Fig(8). The ON state current is decreasing with increasing inactive channel doping.

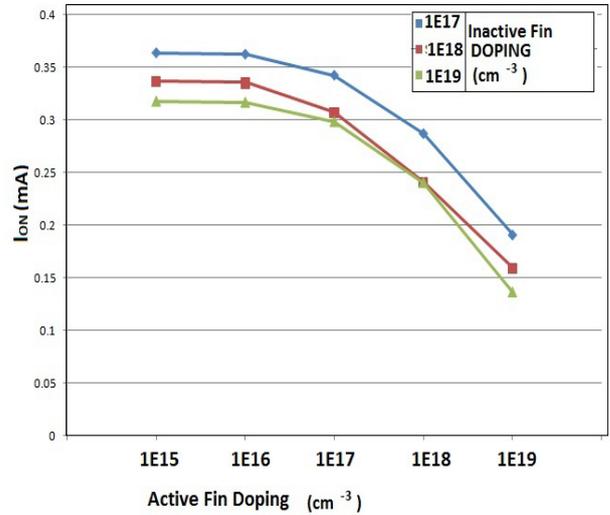


Figure 8. ION for different inactive channel doping

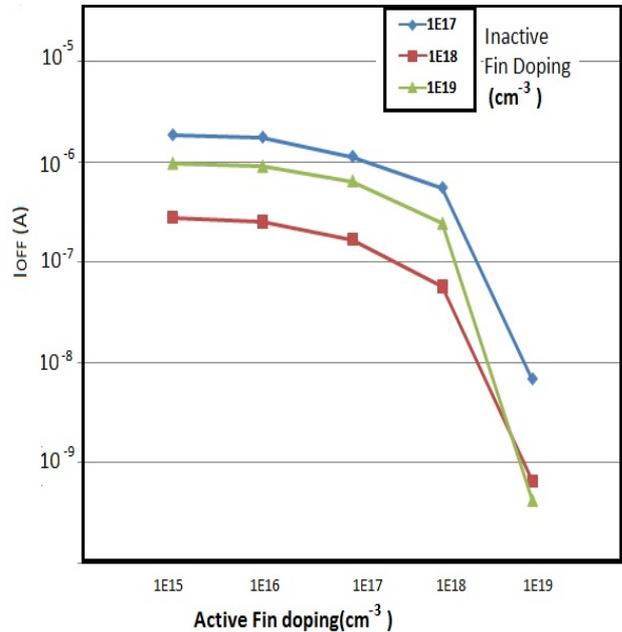


Figure 9. IOFF for different inactive channel doping

We are getting best I_{ON}/I_{OFF} using inactive doping profile 1E18 cm⁻³. However It was expected to have better I_{ON}/I_{OFF} ratio for higher inactive Fin doping. But increase in body doping up to a certain level doesn't give higher I_{ON}/I_{OFF} ratio. This is due to the fact that initially when we increase inactive Fin doping I_{OFF} decreases exponentially and I_{ON} decreases linearly. But for too high value of inactive Fin doping I_{OFF} increases because of enhanced band to band tunneling. Hence inactive Fin doping needed to be properly optimized to get best I_{ON}/I_{OFF} ratio, which in our case is found at 1E18 cm⁻³. Fig. 8, 9 and 10 also show major advantage of Bottom spacer structure with almost constant value of I_{ON} , I_{OFF} and and I_{ON}/I_{OFF} ratio for active fin doping 1E15, 1E16 and 1E18. It shows that its performance is independent of random doping process variations which is the biggest advantage of Bottom spacer structure of Bulk FinFET.

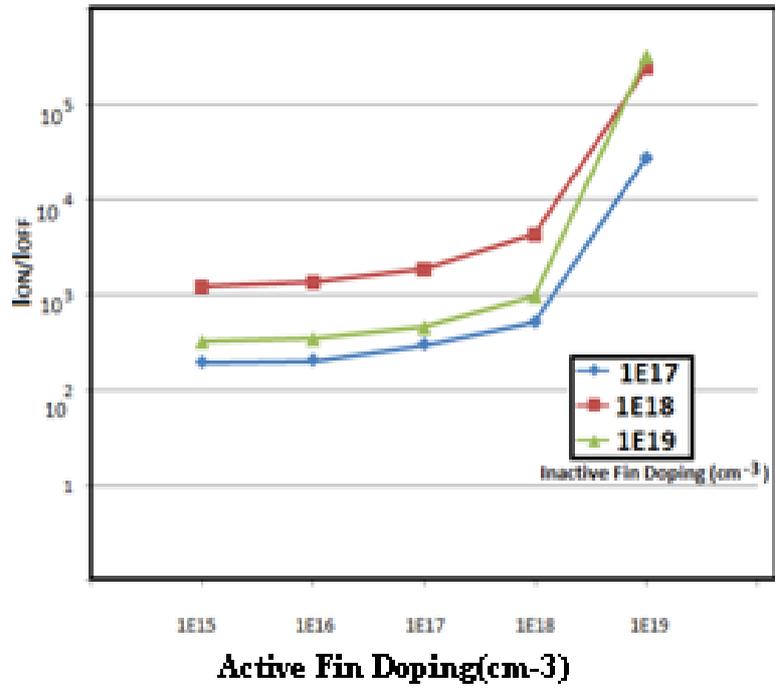


Figure 10. ION/IOFF for different inactive channel doping

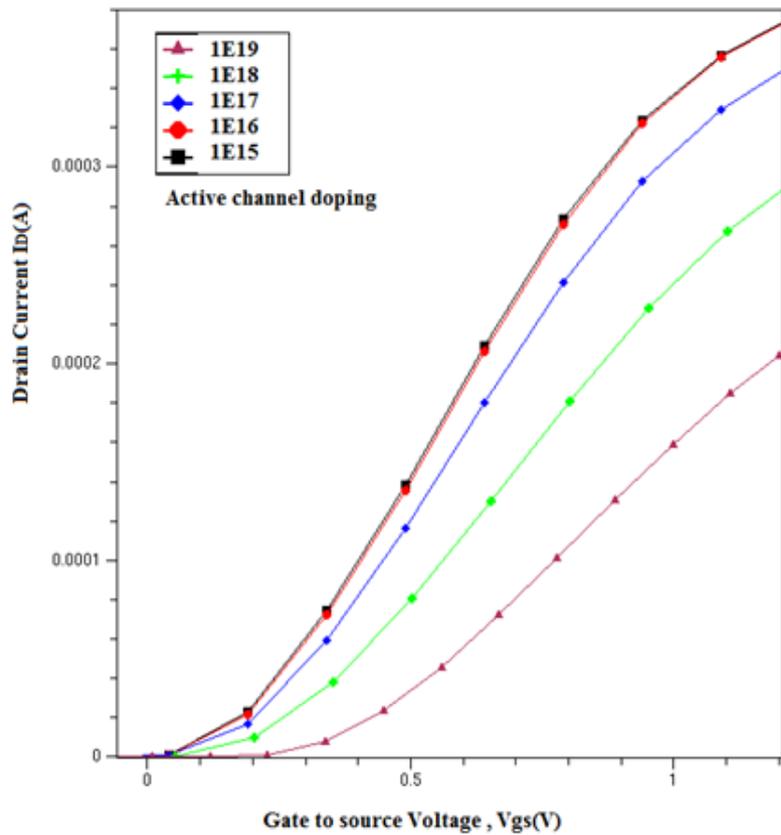


Figure 11. Transfer Characteristic of Bottom spacer Bulk FinFET For different active Fin Doping(keeping inactive Fin doping constant)

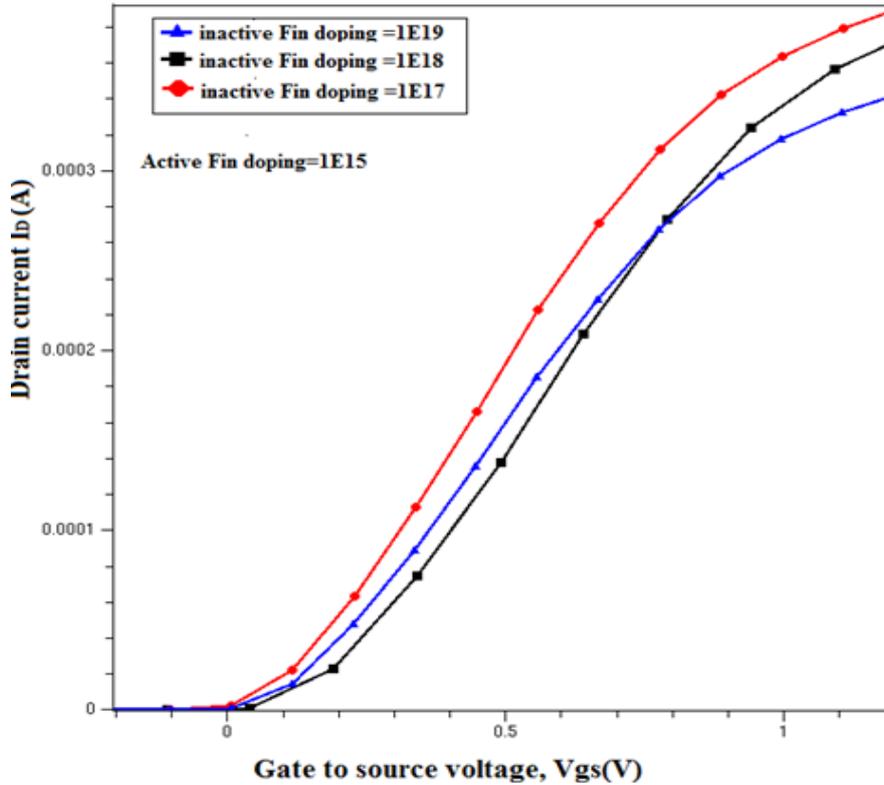


Figure 12. Transfer Characteristics of Bulk FinFET with different inactive Fin doping (Active Fin doping constant)

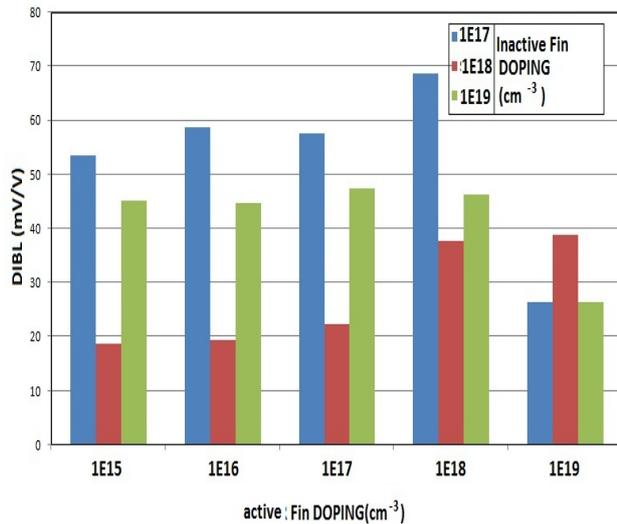


Figure 13. DIBL Vs Upper Fin Doping

ii) *Optimization of active Fin doping:* Our aim is to optimize doping profile so that one can use light Fin doping with Bulk FinFET, still we should be able to keep SCE under control. Here in this part of our work, our emphasis is mainly on optimization of performance parameters. Fig. 13 shows dependence of drain induced barrier lowering(DIBL) on doping profiles. Fig. 14 shows variation in subthreshold slope with doping profiles. These results show that for low active Fin doping along with high inactive Fin doping provide better results. For active fin doping = $1E15 \text{ cm}^{-3}$ and $1E16 \text{ cm}^{-3}$ DIBL and Subthreshold slopes are approximately same. I_{ON}/I_{OFF} ratio is higher in $1E16$ as compare to $1E15$.

Hence, our simulations leads to the conclusion that the optimum inactive fin doping value to be approximately $1E18 \text{ cm}^{-3}$ and active fin doping is approximately $1E16 \text{ cm}^{-3}$.

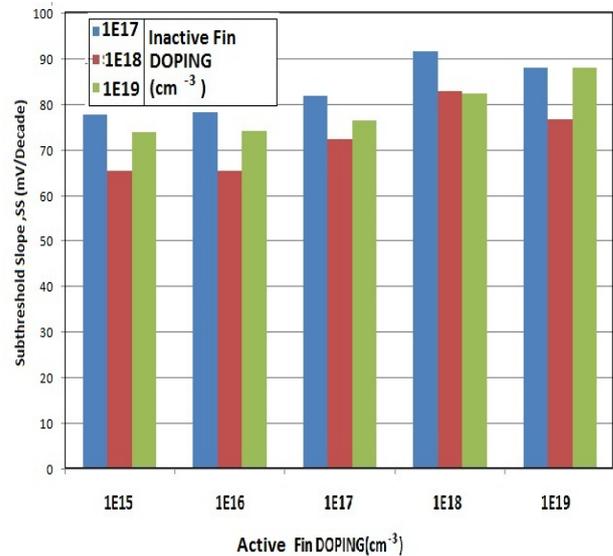


Figure 14. SS Vs Upper Fin Doping

iii) *Optimization of spacer height:* Most of the specific advantages FinFET possess is due to its vertical nature of FIN. In FinFET effective width of device is strongly contributed by Fin height. Approximately 75% reduction in S/D junction capacitance is reported[ref] in FinFET as compare to conventional bulk MOSFET. Area improvement is also reported in case of bulk FinFET. All these improvements are strongly dependent on Fin height. For

good improvement factor, Fin height should be high but the use of bottom spacer decreases the effective fin height. With decrement in fin height, FinFET is tending more towards bulk nature(less fin height means lesser advantage due to fin nature). So, while making shallower junction we should also keep in mind that for very low fin height FinFET is more a conventional MOSFET and less a FinFET. Hence, proper optimization of bottom spacer plays vital role in bulk FinFET.

In this section of work we have performed simulation on FinFETs with different bottom spacer height. We doped the inactive Fin with optimized inactive fin doping profile (1E18) and active Fin with different concentration. The Bottom spacer height in first, second and third case is 30nm, 40nm and 50nm respectively. Since Active Fin height is defined as:

$$H_{eff} = H_{Fin} - H_{BS} \quad (2)$$

H_{BS} - bottom spacer height and H_{Fin} is total Fin height. Hence from equation (1) and (2) the effective channel width of device reduces with bottom spacer height and therefore reduces the ON current with increasing bottom spacer. Unlike SOI FinFET with bottom spacer DIBL in bulk FinFET reduces with increasing bottom spacer height (Figure 15) and subthreshold performance degrades with spacer height (Fig. 16). But the performance becomes less dependent on active Fin doping for high bottom spacer height.

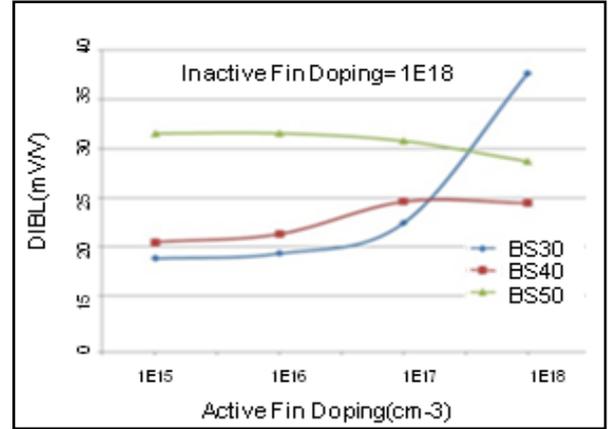


Figure 15. DIBL on different bottom spacer height

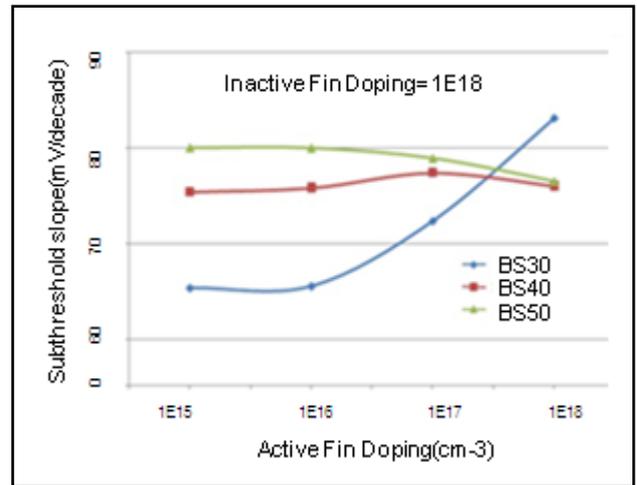


Figure 16. Subthreshold slope for different bottom spacer height

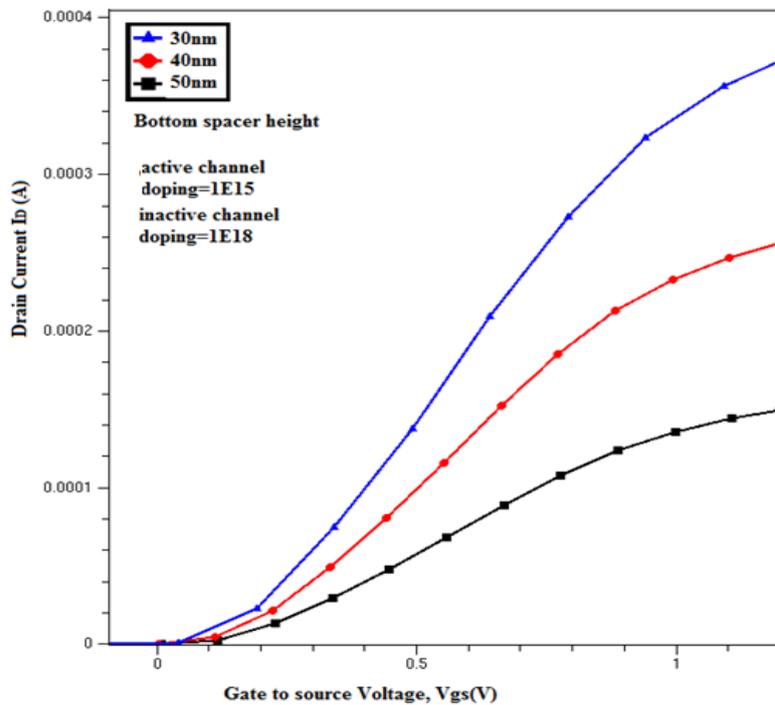


Figure 17. Transfer Characteristic for Different bottom spacer height

Bottom spacer height also effects I_{ON} and I_{OFF} of FinFET. Fig. 17 shows transfer characteristics of bulk FinFET using optimum doping profile, indicates that ON current is significantly degraded for higher value of bottom spacer height. Figure 18, 19 shows relation between I_{OFF} and I_{ON} with bottom spacer height respectively. Figure 20 indicates that I_{ON}/I_{OFF} ratio is higher for high bottom spacer height(H_{BS}).

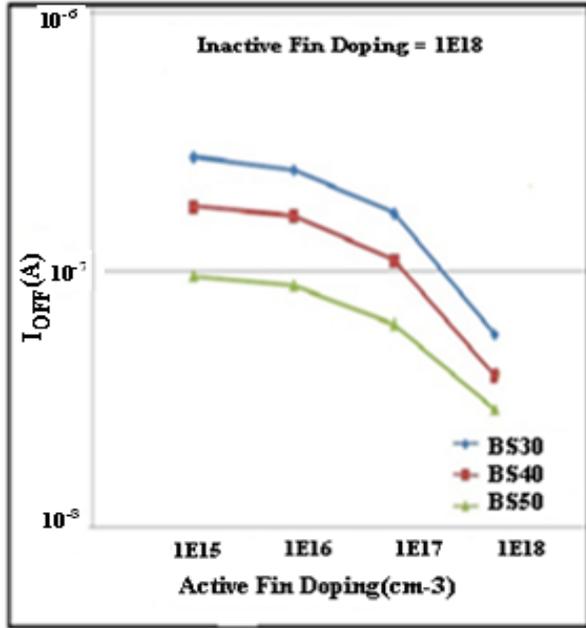


Figure 18. I_{OFF} for different bottom spacer height

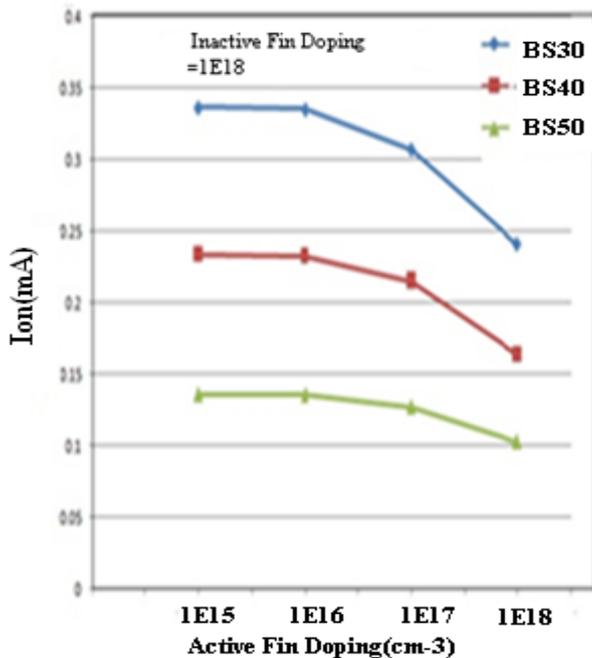


Figure 19. I_{ON} for different bottom spacer height

From the simulations, it is found that owing to shallower junction bulk FinFET with bottom spacer height 30nm gives best subthreshold slope and DIBL for optimized doping profile. The transfer characteristics of different bulk

structures have been plotted in figure 21, which shows that bottom spacer costs for significant Fin height and hence effective channel width. So I_{ON} in case of bottom spacer structure is lower than Pie gate and bulk FinFET with punch through stopper, but it is well above the IRTS[18] standards meeting the desired subthreshold performance improvement.

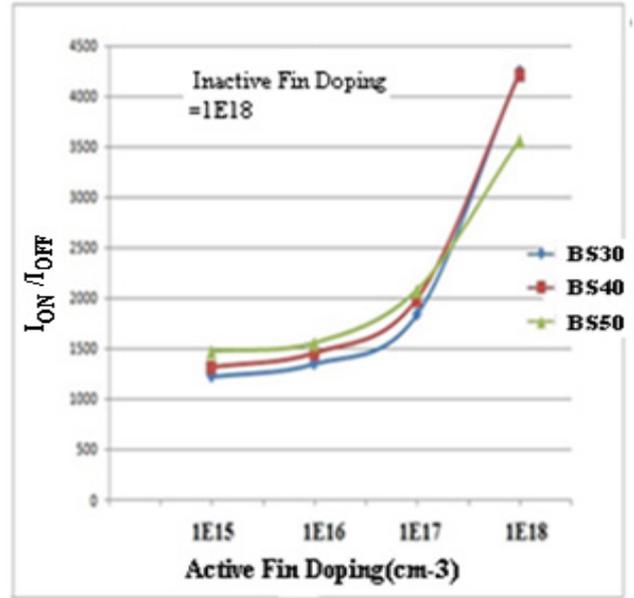


Figure 20. I_{ON}/I_{OFF} for different bottom spacer height

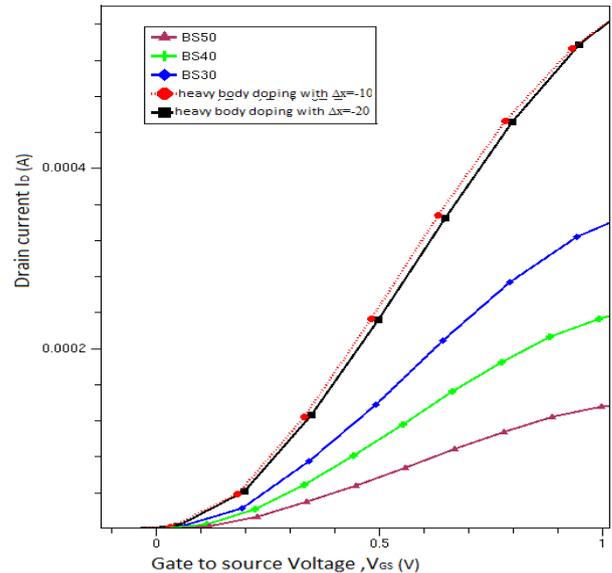


Figure 21. Transfer characteristics of different FinFET structures

4. Conclusions

In first part of results, the novel proposed pie-gate Bulk FinFET (misalignment ΔX_j negative) with heavy body doping (Punchthrough stopper) proved better as compared to results in previous bulk FinFET structures. The bulk FinFET designed with Bottom spacer (height: 30nm) and non-uniform Fin doping(i.e. high inactive Fin doping and low active Fin doping) which is equivalent to pie-gate

FinFET with punchthrough stopper, shows improved subthreshold performance and it has lesser fabrication complexity. The subthreshold performance is also compared with increasing height of Bottom Spacer (30nm, 40nm & 50nm). It is observed that Performance degrade with increasing height of bottom spacer but the dependency over active channel doping decreases. This shows that it become independent of process variations caused by impurity concentration densities which can be considered as the biggest advantage of bottom spacer structure. Therefore, to exploit above advantage we should keep the optimized value of spacer height while keeping ON state performance well above the ITRS standards.

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