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Superior Performance of ALD(Atomic Layer Doped) MOSFETs in 0.1-μm Regime

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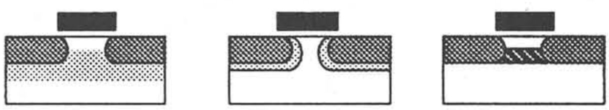
Abstract Using device simulation, the characteristics of MOSFETs with confined highly doped layers made by atomic layer doping (ALD) are compared to those of MOSFETs with punchthrough stopper layers made by ion implantation. ALD-MOSFETs are found to exhibit excellent characteristics, not only in terms of device scalability but also in terms of current drivability. From simulated electric field distribution, the hot carrier reliability of ALD-MOSFETs is expected to be unaffected by its doping profile.

1. Introduction

Several reports have recently shown the great potential of 0.1-μm MOSFETs [1-3]. However, in these MOSFETs, unacceptable threshold voltage (V_{th}) roll-off occurs with channel length of about 0.1 μm. This is one of the reasons why a new device structure is needed. MOSFETs containing confined highly doped layers made by atomic layer doping (ALD) are considered to be promising candidates [4]. However, so far their performance has been investigated by simulations from only the viewpoint of device miniaturization [5].

In this paper, we focus on the current drivability of ALD-MOSFETs, and we show the superior performance of those with channel lengths of about 0.1 μm based on the simulation results.



(a) Type-*A* (b) Type-*B* (c) ALD

Fig. 1 Simulated device structures.

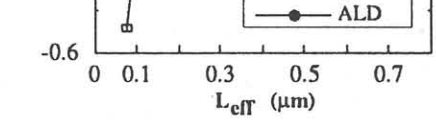
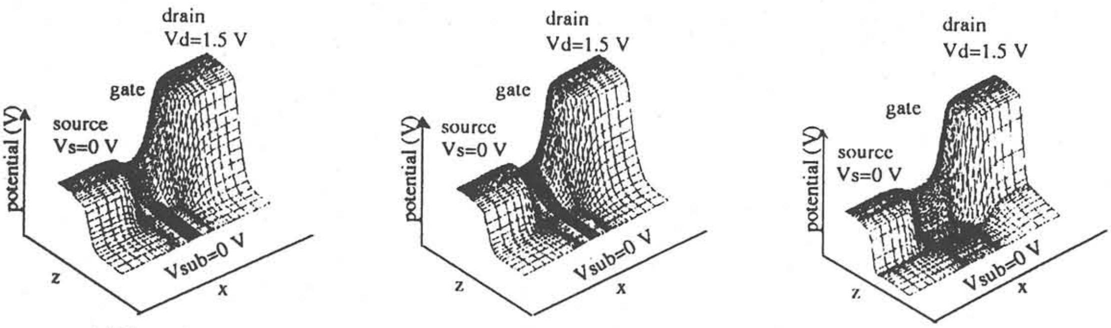


Fig. 2 ΔV_{th} versus L_{eff} for various structures.

2. Analysis

Figure 1 shows three types of device structures compared in device simulation. Types *A* and *B* are MOSFETs with punchthrough stopper layers made by ion implantation through an oxide (*A*) and a gate electrode (*B*). Their peak concentrations are $1\times10^{18}/cm^3$. The punchthrough stopper of the type-*B* MOSFETs formed by vertical implantation (θ=0°) was found to be insufficient for suppressing V_{th} roll-off. Therefore oblique implantation (θ=30°) was employed. The ALD-MOSFET has a step function profile with a concentration of $1\times10^{16}/cm^3$ at the surface and $5\times10^{18}/cm^3$ at a depth of 50 nm beneath the surface. All the MOSFETs have a single drain structure and a 5-nm-thick gate oxide. In addition, the type-*A* MOSFET was counter doped in order to make its threshold voltage identical to the others. The simulator is based on a hydrodynamic model including momentum and energy conservation.[6]



(a) Type-A (b) Type-B (c) ALD

Fig. 3 Calculated potential distribution at threshold voltage. Effective channel length is 0.15 μm.

3. Results & Discussion

The threshold voltage (V_{th}) roll-off characteristics are shown in Fig. 2 as a function of the effective channel length (L_{eff}), defined as the distance between the metallurgical junctions. The type-B and ALD MOSFETs have lower V_{th} roll-off even around 0.1 μm. In particular, type-B MOSFETs do not show V_{th} roll-off until 0.12 μm due to the reversed short channel effect resulting from a concentration increase caused by the merging of their impurity profiles. However, significant V_{th} roll-off is observed beyond 0.1 μm. The superiority of ALD-MOSFETs in terms of size reduction is confirmed by the electrostatic potential profile shown in Fig. 3. The atomic doped layer behaves as a quasi-ground plate and increase in channel potential is effectively prevented.

The current drivability of these MOSFETs is compared in Fig. 4. Type-B MOSFETs have excellent drivability at L_{eff} in the region of a quarter-micron, since their channel regions are intact for ion implantation. However,

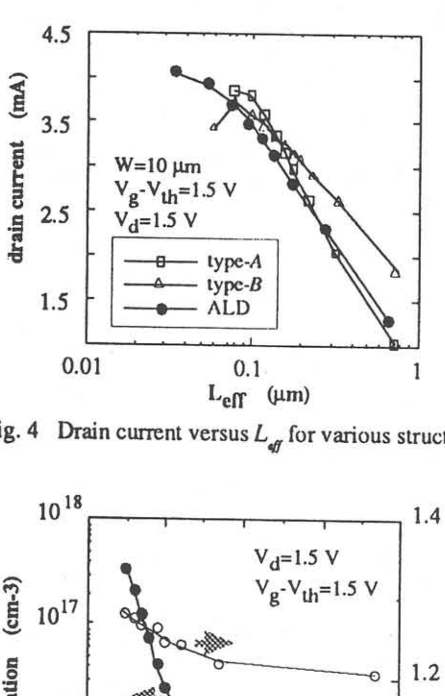


Fig. 4 Drain current versus L_{eff} for various structures.

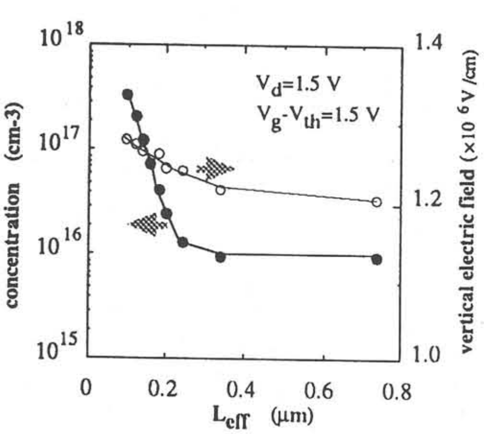


Fig. 5 Dependence of the surface impurity concentration and vertical electric field of type-B MOSFETs at the middle of the channel on the effective channel length.

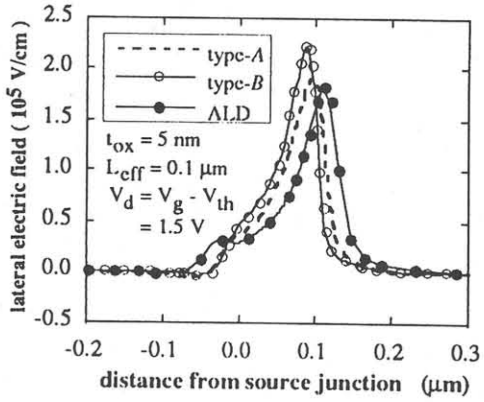


Fig. 6 Calculated lateral electric field along the interface for three types MOSFETs with 0.1-μm effective channel length plotted against the distance from source junction.

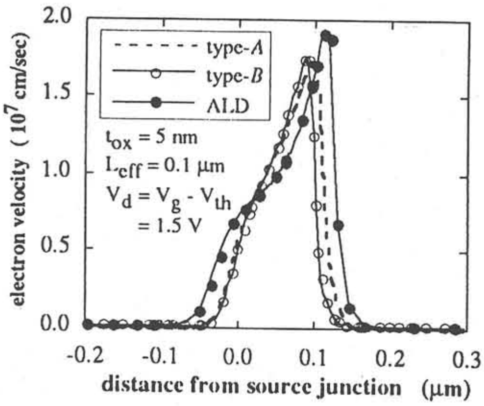


Fig. 7 Calculated electron velocity along the interface for three types MOSFETs with 0.1-μm effective channel length plotted against the distance from source junction.

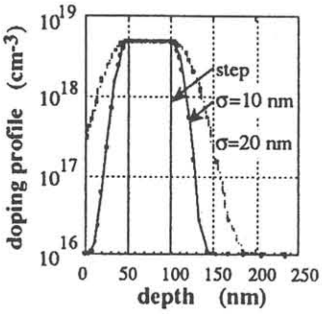


Fig. 8 Simulated doping profile of ALD-MOSFETs. Profile re-distribution is assumed to be Gussian.

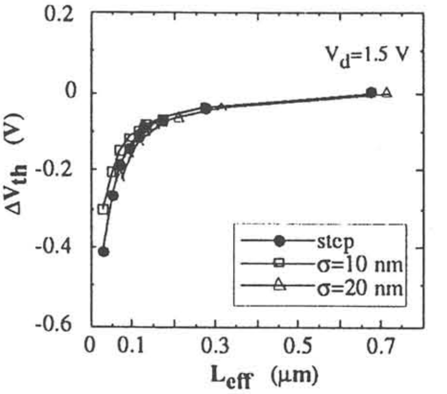


Fig. 9 ΔV_{th} versus L_{eff} for ALD-MOSFETs as a function of the standard deviation of the profiles shown in Fig. 8.

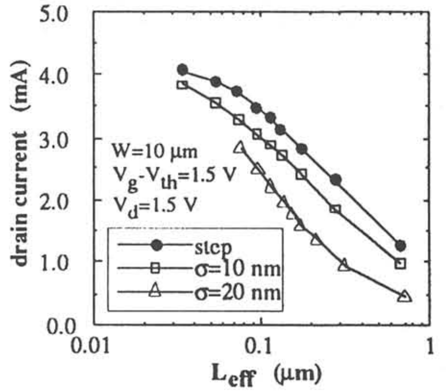


Fig. 10 Drain current versus L_{eff} for ALD-MOSFETs as a function of the standard deviation of the profiles shown in Fig. 8.

the rate of increase in current is greatly reduced as the channel length approaches 0.1 μm because of increase in concentration.

Figure 5 shows how the surface impurity concentrations and the vertical electric field of type *B*- MOSFETs change as L_{eff} becomes smaller. The surface concentration measured at the middle of the channel increases as the channel length decreases due to the merging of their impurity profiles. The increased concentration gives rise to an increase in vertical electric field as shown in Fig. 5, resulting in mobility degradation, probably because of the enhanced surface scattering. As a result, they have no current drivability advantage below 0.1 μm.

ALD-MOSFETs are found to be inferior to type-*B* MOSFETs when L_{eff} is large, but superior to them when L_{eff} is about 0.1 μm and then continue to increase until the effective channel length becomes 0.05 μm, since a large V_{th} roll-off is prevented.

Figure 6 shows the calculated lateral electric field along the interface for three types of MOSFETs with 0.1-μm effective channel length. In spite of the highly doped punchthrough stopper in the substrate, the lateral electric field of the ALD-MOSFET is the lowest among the three. From this result, it is found that the high electric field at a depth of 50 nm due to the atomic doped layer does not increase the surface electric field. Therefore the hot carrier reliability of ALD-MOSFETs is expected not to be degraded by this profile.

Figure 7 shows calculated electron velocity along the interface for three types of MOSFETs with 0.1-μm effective channel length. ALD-MOSFETs were found to have the highest peak velocity, because carriers of ALD-MOSFETs experience relatively little scattering.

Figures 9 and 10 indicate how the doping profile of ALD-MOSFETs (Fig. 8) affects the V_{th} roll-off and drain current, respectively, considering profile re-distribution during heat treatment. It is clear that a steeper profile is required for higher drivability.

4. Conclusion

Even in type-*B* MOSFETs, the impurity concentration in the channel area increases when L_{eff} is about 0.1 μm because their impurity profiles merge, and this degrades their current drivability. On the other hand, ALD-MOSFETs are found to exhibit excellent characteristics, not only in terms of device scalability but also in terms of current drivability down to 0.05 μm.

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