Analysis and Design of Superjunction Power MOSFET: CoolMOS™ for Improved On Resistance and Breakdown Voltage Using Theory of Novel Voltage Sustaining Layer

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Abstract - In this paper, we have observed that the drift layer of conventional power device can be modified to SJ-drift layer for improvement in the Break down Voltage (BV). With doping level of SJ-drift layer increases by one order of magnitude, at least 5 times improvement in on resistance $R_{on}$ without reducing the BV. Further increase in the BV is possible by increasing the thickness of the SJ-drift layer where we observed the proportional increase in $R_{on}$. Theory of Novel Voltage sustaining layer [1] (SJ-Theory) recently published is used for the first time to analyze and design CoolMOS structure. We observed that for a fixed cell-pitch, increasing the height of drift layer proportionately increases the BV. The rate of increasing BV is higher for smaller cell-pitch. The $R_{on}$ also increases proportionally. For a fixed geometry increasing doping level by one order of magnitude reduces the BV and the rate of reduction of this BV is dependent on the cell-pitch.

I. INTRODUCTION

The well-known Silicon limit of the conventional VDMOS (Vertically Double-diffused Metal Oxide Semiconductor) Technology is now improved to have linear relation between On Resistance ($R_{on}$) and Breakdown voltage (BV) instead of the quadratic relation [2] [3]. SJ-Theory analytically models the superjunction drift layers (SJ-drift layer).

Design and simulation of the conventional drift layer for approximately 400V, which can be shown as p+ n- n+ diode for off state of the device, as shown Fig.1. We can estimate, that for a 200W, 10A power device the on resistance will be approximately 2 ohms. The major contribution (>95%) to on resistance incase of high voltage Power Mosfet comes from n-drift layer [4]. $R_{on}$ is defined at low drain voltage, and high gate voltage, hence the JFET effect resistance and channel resistance will be minimum. This drift layer can be modified to SJ-layer as shown, by inserting a P-column. The simulation results as in [5] shows 45% increase in the BV with same geometry and doping level. The $R_{on}$ can be improved at least by a factor of 5 by increasing doping level by one order. The simulated BV for the N=7x10^{14} and 7x10^{15} are 550V and 530 V respectively. Based on the theory of novel voltage sustaining layer a simple method is developed in [6] for design of the SJ-drift layer. The sample design calculations are tabulated in Table-I as below. The geometry factor [5] $f=0.1$ is assumed

![Fig. 1 Equivalent VDMOS and Superjunction Drift Layers](image)

<table>
<thead>
<tr>
<th>TABLE. I SAMPLE DESIGN OF VARIOUS SJ-LAYERS</th>
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<tbody>
<tr>
<td>BV</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
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<tr>
<td>700</td>
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These designs along with $f=0.2$ and $f=0.3$ are simulated using ISE-TCAD [5].

The simulated breakdown voltages are plotted as points along with analytical calculations graphically shown here in Fig. 2. As Geometry Factor ($f$) (as defined in theory as a ratio of cell pitch ($C_p$) to the drift layer thickness) increases the error in simulated and analytical result increases. This is due to two-dimensional nature of the electrical field in the SJ-layer. For small $f$ the $C_p$ is very small than the thickness or the height $t_{epi}$ of the SJ-drift.
layer. The SJ-theory accurately models BV for $t_{epi} \gg C_p$. Due to this we observe that as $f$ increases to 0.3 the simulated BVs are quite lower than their respective analytical values. The two dimensional interaction of the vertical and lateral electrical field in SJ-layer decides the net breakdown field required. In SJ-theory the estimation of this field is under condition $t_{epi}/C_p > 1$ and for large value of $f$ the SJ-theory overestimates the value of breakdown field. Thus simulated value of BV is lower than the analytical.

B. Breakdown Voltage with Doping Level.

After increasing one order magnitude of doping concentration in SJ-layer as compared with VDMOS, the effect on the BV of the layer can be analyzed.

The maximum doping concentration for required BV in VDMOS is given by

$$N_{con} = 2\varepsilon_s E_c / 3qt_{epi}$$  \hspace{1cm} (3)

Where the $E_c$ is the critical field for breakdown. (The maximum electrical field, which is responsible for avalanche generation and at which the ionization integral becomes unity) According to SJ-Theory the maximum doping is given by

$$N_{SJ} = \varepsilon_s E_c / fqt_{epi}$$  \hspace{1cm} (4)

The value of $E_c$ is not the same in two cases. In SJ-drift layer two-dimensional field allows larger value of $E_c$. For comparison purpose, in SJ-drift layer to reach to the same value of $E_c$ as in conventional, we can take the ratio of eqn.3 and 4, which gives

$$N_{SJ} = 3N_{con} / 2f$$  \hspace{1cm} (5)

This means that to have same BV as of VDMOS we can now use higher doping level, which results in low $R_{on}$. But due to two dimensional critical field distribution, the maximum field to initiate impact ionization in SJ layer is quite high (1.2 to 1.5 times) depending upon its cell pitch and height [1] as compared to VDMOS-drift layer. Thus BV is higher than VDMOS, even at one order increase in doping concentration in SJ-drift layer for a given geometry. Thus factor 2 in the denominator of eq.5 can be replaced by 1.2 to 1.5, this result in still lower $R_{on}$.

III SJ-LAYER USED FOR CoolMOS™

Using designed SJ-drift layer as above a CoolMOS structure as shown in Fig.3 is simulated. The potential contours at high voltage near BV are shown in Fig.4. It can be easily seen that, near breakdown the contours are equiphased suggesting a nearly flat electric field profile. Since P pillar does not take part in the conduction, the cross-sectional area available for conduction will be approximately half as compared VDMOS. But as discussed earlier, the higher doping concentration in the drift layer reduces the on resistance. Recent works as in [2-3][9]
states, that the BV becomes almost independent of the doping concentration. It is observed here that, this is approximately true for only thin and tall structures i.e. for $f << 1$. In ISE-TCAD [8] the breakdown simulation is achieved using Avalanche generation by inspecting the ionization integral along electric field line through depletion zone. The doping and high field dependent mobility models are used along with Recombination SRH Auger model for improving simulation accuracy.

![Diagram](image)

**Fig.3** SJ-Drift layer used to simulate CoolMOS

From the slope of the $I_D-V_D$ curves of SJ-Mosfet in the linear region at low drain voltage for various heights of drift layers as shown in Fig.5. The plots of analytical and simulated values of area specific on resistance are shown in Fig. 6. There is a linear relation between BV and $R_{on}$. An offset between simulated and calculated values is observed since analytical calculation neglects the depletion region formed at low drain voltage. Channel resistance and JFET effect are also neglected in SJ-Theory calculations. Thus the simulated value of on resistance is larger than the analytical. The CoolMOS structure does not allow having a perfect charge balance condition, [9] which is required for obtaining maximum BV since the area of P-column and N-column are not same due to the channel engineering as shown in Fig.3. SJ-Theory assumes perfect charge balance condition and provides analytical modeling for RMOST structure[1]. This is also a reason for getting lower value of BV in simulation.

![Diagram](image)

**Fig.5** $I_D-V_D$ in the linear region as $t_{epi}$ increases

![Diagram](image)

**Fig.6** Analytical and Simulated plots for On-Resistance Vs BV change as result of increase of thickness of drift layer

A. Simulation Results for fixed $C_p$ and increasing $t_{epi}$

For a fixed cell pitch of $C_p=5$ µm, the height $t_{epi}$ increased from 20 µm to 60 µm for increasing BV. It is observed that as height increases BV also increases proportionally from 325V to 900V. The $R_{on}$ is measured from the intensity of contour reduces for higher potential.

B. Simulation Results for fixed geometry and increasing N

For a fixed geometry, increasing N i.e. (But keeping P-column doping equal to N-column doping) results in
drastic reduction of $R_{on}$. Simulation were carried out for $C_p = 5 \ \mu m$ and $t_{epi} = 40 \ \mu m$. SJ-theory doesn’t model this variation. The maximum doping according SJ-theory for this geometry is calculated analytically by eqn.4 ($N=6\times10^{15}$) for which the $R_{on}$ is minimum. The BV specified for this geometry is 600V. It is observed that as doping level reduced to $1\times10^{15}$ The $R_{on}$ increases drastically to 90 m$\Omega$cm$^2$. The BV doesn’t remain constant but it increases linearly as $N$ drops to $1\times10^{15}$ as shown in Fig. 7. The rate of increase of BV as N drops or alternately the rate of reduction of BV as N increases is dependent on the cell-pitch $C_p$. We know that the depletion width is directly proportional to square-root of $N$. Thus as doping level is reduced the depletion width across the P-N junction is larger even at low drain voltage and JFET resistance will be quite high. Thus $R_{on}$ will increase quadratically at low $N$. The rate of reduction of BV as doping level increases is under investigation.

![Graph](image)

**Fig.7.** The plot of $N$ vs BV and $N$ vs $R_{on}A$ for a fixed geometry SJ-MOSFET

**IV. CONCLUSION**

The SJ-Theory can be used for designing the drift layer of CoolMOS. Simulation results shows that the improvement in the $R_{on}$ and BV will be obtained only when tall and thin drift layer columns are used. The two dimensional nature of electric field profile due to vertical P-N junction increases the critical field for avalanche breakdown. This increases the BV. The conventional VDMOS drift layer can be modified to SJ-layer and BV can be almost doubled and $R_{on}$ is reduced by a factor of (at least) 5 by increasing the drift layer doping by one order of magnitude. The SJ-theory does not provide insight into the variation in the $R_{on}$ and BV, if the geometry of the device is fixed and the doping level increased. The $R_{on}$ reduces drastically to the lowest possible value as $N$ increases. The rate of reduction of BV is depending on the cell-pitch.

**ACKNOWLEDGEMENT**

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**REFERENCES**

[8] Integrated System Engineering, ISE-TCAD Manuals, AG, Zurich, Switzerland 1999