Novel Constant Surface Concentration Depletion Mechanism and Its Experiments in Homogenization Field LDMOS

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Abstract

A novel constant surface concentration depletion (CSD) mechanism for the homogenization field (HOF) LDMOS is proposed and experimentally demonstrated in this paper. Because the depletion of the HOF LDMOS is independent on the P-substrate, the surface doping concentration of the HOF LDMOS can keep constant and thus the total doping dose of the N-drift region can increase with the junction and trench depths. Based on the CSD mechanism, a CSD HOF LDMOS with 15 μm trench depth was designed and experimentally fabricated. The doping dose of the N-drift region is increased up to 8 × 10¹² cm⁻². As a result, a measured low specific on-resistance $R_{on,sp}$ of 15.6 mΩ·cm² was observed under a breakdown voltage $V_B$ of 420 V, realizing a high figure of merit $FOM = V_B^2 / R_{on,sp}$ of 11.3 MW/cm² and a reduction of 53.3% compared with the theoretical limit of the triple RESURF technology under the same $V_B$. $R_{on,sp}$ of the CSD HOF LDMOS also realizes a reduction of 20.8% when compared with that of the best-in-class HOF LDMOS.

Keywords: Homogenization field, LDMOS, Breakdown voltage, Specific on-resistance, Constant surface concentration depletion

I. INTRODUCTION

To achieve higher breakdown voltage $V_B$ and lower specific on-resistance $R_{on,sp}$, integrated power devices have been developed from the single reduced surface field (RESURF) to double and triple RESURF technologies [1]-[3]. Furthermore, the superjunction concept was introduced into the integrated devices to further enhance the doping concentration in the drift region and reduce $R_{on,sp}$ [4]-[9]. Drift regions of these devices are mainly depleted by PN junctions with charge balance between immobile positive and negative ionized charges. As a result, there exists a theoretically fixed optimized doping dose $D_N$ for a given region, such as the well-known RESURF dose:

$$D_N = 1 \times 10^{12} \text{ cm}^{-2}$$  \hspace{1cm} (1)

For the device formed through implantation annealing processes, the drift region exhibits a Gaussian distribution. It is revealed from (1) that $D_N$ of the RESURF device is independent on the junction depth. Then, the surface doping concentration $N_s$ of the device decreases with an increase in the depth of the doping junction. The different constant doping doses has also been discussed by both analytical models and experiments [8]-[11]. This phenomenon is referred to as constant dose depletion in this paper.

Recently, a new type of homogenization field (HOF) devices have been reported [12]-[14]. The HOF devices feature periodic MIS structures in the drift region to fully deplete the highly doped N-type region. Consequently, the depletion in the HOF device is relatively independent of the PN depletion, showing a self-charge balance by the discrete MIS arrays. However, the depletion mechanism of the HOF device has not been deeply researched, yet.

In this paper, a novel constant surface concentration depletion (CSD) mechanism for the HOF laterally diffused metal oxide semiconductor (LDMOS) is proposed and experimentally demonstrated. Section II gives the HOF structure and CSD mechanism. Section III presents experiments and discussions.

II. STRUCTURE AND MECHANISM

2.1 HOF Structure

The structure of the HOF LDMOS is shown in Fig. 1, which is characterized by the deep insertion of periodically discrete MIS trenches into the drift region. MIS trenches, located at an equal distance from the source end, are connected through surface metal
interconnects, forming a MIS depletion array that effectively depletes the entire drift region. The depletion region of the HOF structure is determined by the depth of the MIS trenches. As a result, the depletion mechanism of the HOF device is different from that of the conventional (Con) LDMOS.

2.2 CSD Mechanism

Since the depletion of the drift region in HOF devices is independent of the P-substrate and primarily depends on the trench depth, a deeper trench enables the depletion in deeper region into the device. Under a Gaussian distribution, a constant surface doping concentration \( N_s \) can be maintained while increasing the depth of the junction in the drift region, i.e., increasing the standard deviation \( \sigma \), thus achieving a continuously increased \( D_N \). The CSD mechanism is shown in Fig. 2.

Fig. 2(a) presents the schematic diagram of the CSD mechanism based on 3-D MIS assisted depletion. The constant \( N_s \) in the HOF LDMOS is maintained, while the \( D_N \) is increased as the junction depth of the N-drift and trench depth increase. The analytical model for the HOF device has been reported in [12]. The design formula for \( N_s \) is as follows:

\[
\frac{\varepsilon_r E_x \tanh \left( \frac{L_x}{2T} \right) - \varepsilon_r E_z}{qT} \leq N_s \leq \frac{\varepsilon_r E_x}{qT} \tag{2}
\]

where \( \varepsilon_r \) is the dielectric constant of the silicon and \( q \) is the electron charge. \( L_x \) is the distance between trenches in the x-direction. \( E_x \) and \( T \) are the critical electric field and characteristic thickness that can be calculated by:

\[
T = \sqrt{\frac{L_x^2}{8} + \frac{\varepsilon_r E_x L_z}{2E_t}}
\]

\[
E_t = 6.645 \exp(1.636L_d^{-0.1269})
\]

where \( L_z \), \( L_d \), \( n \) and \( \alpha \) being the distance between trenches in the z-direction, the drift region length, the thickness and dielectric constant of the oxide. Under the Gaussian doping distribution, \( D_N \) can be obtained by integrating the doping concentration in the y-direction of the drift region as follows:

\[
D_N = \int_0^\infty N_s \exp \left( -\frac{y^2}{2\sigma^2} \right) dy = \sqrt{\frac{\pi}{2}} N_s \sigma \tag{3}
\]

\( D_N \) of the HOF device increases monotonically with the junction depth or \( \sigma \), with \( D_N \propto \sigma \). Then, \( D_N \) of the HOF device can be significantly increased to reduce \( R_{on,sp} \). In contrast to this, the Con device based on 1-D substrate assisted depletion, with \( D_N \approx \) constant, cannot introduce more conduction carriers by increasing the junction depth alone, as shown in Fig. 2(b).

Fig. 2(a) CSD mechanism of the constant \( N_s \) depletion. \( N_s \) of the HOF LDMOS can keep a constant and the \( D_N \) is increased with the increases of the junction depth of the N-drift and trench depth; (b) The constant \( D_N \) depletion in the Con RESURF LDMOS with increase junction depth and reduced \( N_s \).

III. DESIGN AND EXPERIMENTS

3.1 Design of CSD HOF LDMOS
Design formula (3) provides a very simple guideline for the HOF devices, where improving device characteristics can be achieved by simply increasing the junction and trench depths in the drift region. Compared with our previous work [14], the trench depth is increased from 12 μm to 15 μm and the corresponding $D_N$ is increased from $6.8 \times 10^{12}$ cm$^{-2}$ to $8 \times 10^{12}$ cm$^{-2}$. Based on the CSD mechanism, it is possible to achieve a predictable decrease in $R_{on,sp}$ while maintaining a constant $V_B$.

Fig. 3 compares the equipotential line distributions of CSD HOF LDMOS and Con LDMOS at breakdown. In the CSD HOF LDMOS device, the drift region is fully depleted by the MIS deep trench, resulting in a uniform distribution of the equipotential lines throughout the device. In contrast, the Con LDMOS exhibits an obvious neutral region, which leads to premature breakdown at the source end of the device.

Fig. 4 compares the vertical electric field distributions of CSD HOF LDMOS and Con LDMOS. The peak field of the CSD HOF LDMOS is increased from 10 V/μm of the Con LDMOS to 20 V/μm by the 3-D MIS assisted depletion. Based on the CSD mechanism, it is possible to achieve a predictable decrease in $R_{on,sp}$ while maintaining a constant $V_B$.

Fig. 5 Simulated $V_B$ of CSD HOF LDMOS and Con LDMOS. $V_B$ of the CSD HOF LDMOS is increased by 107% when compared with that of the Con LDMOS.

3.2 Experiments of CSD HOF LDMOS

Based on the 0.5 μm Central Semiconductor Manufacturing Corporation (CSMC) process platform, a CSD HOF LDMOS was fabricated. Fig. 6 presents the micro photo and layout of the drift region for the CSD HOF LDMOS, featuring the introduction of 7 trench arrays in the drift region. In comparison to the device in [14], the HOF device designed using the CSD mechanism incorporates 15 μm deeper trenches to deplete a higher $D_N$ of $8 \times 10^{12}$ cm$^{-2}$.

Fig. 6 Micro photo and layout of CSD HOF LDMOS. Deep trenches of 15 μm were formed in the drift region with 7 trench arrays.
Fig. 7 illustrates the measured $I_d - V_d$ curves of the CSD HOF LDMOS device in the off-state and on-state. The testing results reveal a $V_B$ of 420 V and an $R_{on,sp}$ of 15.6 m$\Omega$·cm$^2$. This achievement corresponds to a high figure of merit $FOM = V_B^2 / R_{on,sp}$. The measured low $R_{on,sp}$ of 15.6 m$\Omega$·cm$^2$ was observed under a $V_B$ of 420 V, realizing a high $FOM = V_B^2 / R_{on,sp}$ of 11.3 MW/cm$^2$.

Fig. 8 compares the measured $R_{on,sp} - V_B$ characteristics of the CSD HOF LDMOS and other reported devices [3]-[8], [14]-[15] in a logarithmic scale. The $R_{on,sp}$ characteristic of the CSD HOF LDMOS is better than those of the recently reported devices, exhibiting a 20.8% improvement over the best-in-class $R_{on,sp}$ of the previously reported HOF device [14] while maintaining the same $V_B$. Furthermore, this achievement signifies a remarkable reduction of 53.3% compared with the theoretical limit achievable with the triple RESURF technology [3] at the same $V_B$.

IV. CONCLUSION

This paper proposed and experimentally demonstrated the new CSD mechanism for HOF devices. Compared with the conventional constant $D_n$ depletion mechanism in PN junction depleted devices, the HOF device achieved complete MIS-assisted depletion in the drift region, allowing for a constant surface concentration depletion. By increasing the junction and trench depths, the doping dose of the N-drift region was increased up to $8 \times 10^{12}$ cm$^{-2}$. This resulted in a $R_{on,sp}$ of 15.6 m$\Omega$·cm$^2$, measured at a $V_B$ of 420 V. Consequently, the CSD HOF device achieved a high $FOM$ of 11.3 MW/cm$^2$ and a remarkable 53.3% reduction compared with the theoretical limit of triple RESURF technology at the same $V_B$. Additionally, the CSD HOF LDMOS demonstrated a 20.8% reduction in $R_{on,sp}$ compared with the best-in-class HOF LDMOS. The CSD mechanism presented a simple and feasible approach for improving the characteristics of HOF devices.

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REFERENCES

modulation of buffered step doping, IEEE Electron Device Letters, 36, 2015, 47-49


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