

# Enhancement of On-Resistance Characteristics Using Charge Balance Analysis Modulation in a Trench Filling Super Junction MOSFET

Jongmin Geum\*, Eun Sik Jung\*\*, Yong Tae Kim\*\*\*, Ey Goo Kang §  
and Man Young Sung†

**Abstract** – In Super Junction (SJ) MOSFETs, charge balance is the most important issue of the SJ fabrication process. In order to achieve the best electrical characteristics, such as breakdown voltage and on-resistance, the N-type and P-type drift regions must be fully depleted when the drain bias approaches the breakdown voltage, which is known as the charge balance condition. In conventional charge balance analysis, based on multi-epi process SJ MOSFETs, analytical model has only N, P pillar width and doping concentration parameter. But applying a conventional charge balance principle to trench filling process, easier than Multi-epi process, is impossible due to the missing of the trench angle parameter. To achieve much more superior characteristics of on-resistance in trench filling SJ MOSFET, the appropriate trench angle is necessary. So in this paper, modulated charge balance analysis is proposed, in which a trench angle parameter is added. The proposed method is validated using the TCAD simulation tool.

**Keywords:** Super junction MOSFET, Trench filling, Trench angle, Charge balance

## 1. Introduction

The most important issue for semiconductor power devices is reducing the conduction loss that occurs when it is turned on [1-2]. However, in silicon devices, there is a limit in how much the on-resistance can be decreased, because a trade-off relationship exists between the breakdown voltage and on-resistance which is forward conducting loss resistance [3-4]. To overcome the limit of this electrical characteristic, the SJ structure has been proposed. This novel structure has far superior electrical characteristics to those of conventional high-voltage MOSFETs [7]. In order to achieve the best electrical characteristics, the N-type and P-type drift regions must be fully depleted when the drain bias approaches the breakdown voltage, which is called the charge balance condition. Both higher voltage and lower on-resistance are achieved compared to those in a conventional MOSFET structure. Charge balance condition must be accompanied with SJ MOSFET due to optimization point of charge coupling structure. The power electronics market is demanding low on-state resistance at an appropriate voltage level. A much lower specific on-resistance can be achieved with SJ structures by using an excess breakdown voltage margin, and increasing the N-drift dose. Hence,

this novel structure has a much lower specific on-resistance at a specific voltage level [5]. There are two SJ structures classified in fabrication process, multi-epi process SJ MOSFETs, such as CoolMOSTM [6-7] and trench filling SJ MOSFETs [9]. The trench filling process is the simplest and most suitable for making high-aspect-ratio structures, because the carrier concentration uniformity and the integration density are higher than those obtained with any other proposed techniques [8]. Unlike multi-epi SJ MOSFETs, the on-resistance of trench filling SJ MOSFETs can be enhanced by reducing the trench angle which is angle of silicon etching sidewall. Thus, the trench angle parameter must be considered in the design of trench filling SJ MOSFETs. The conventional charge balance analysis parameters, especially in the analysis of the multi-epi process, only include the N and P pillar widths, and the N and P pillar carrier concentrations. In this paper, charge balance analysis is reconsidered and modulated by inserting a trench angle parameter in order to increase the accuracy of the analysis. This modulated charge balance analysis is validated using TCAD simulation.

## 2. Electrical Characteristics of Super Junction MOSFET

### 2.1 Analytic model for charge balance in multi-epi SJ MOSFETs

For the SJ structure to block the maximum breakdown voltage, the charge in the N and P pillars should be balanced exactly, which is called the charge balance

† Corresponding Author : Dept. of Electrical Engineering, Korea University, Korea. (semicad@korea.ac.kr)

\* Dept. of Electrical Engineering, Korea University, Korea. (fishgold@korea.ac.kr)

\*\* Maple Semiconductor Co., Korea. (esjung@maplesemi.com)

\*\*\* Korea Institute of Science and Technology, Korea. (ytkim@kist.re.kr)

§ Dept. of Photovoltaic Engineering, Far East University, Korea. (keg@kdu.ac.kr)

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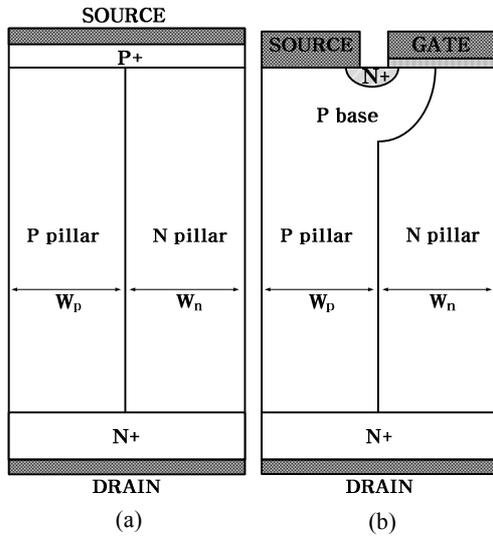


Fig. 1. (a) Super Junction structure and (b) Super Junction MOSFET structure

condition. In a multi-epi SJ MOSFET, the charge balance condition can be expressed using the parameter Charge Difference (CD)[%], defined by :

$$CD[\%] = (N_D - N_A) / N_D \times 100 \quad (1)$$

To obtain the maximum breakdown voltage in an SJ structure, the N and P pillar doping concentrations,  $N_D$  and  $N_A$ , should be equal when both  $W_p$  and  $W_n$  have the same length, as shown in Fig. 1(a). The maximum obtainable breakdown voltage of the multi-epi SJ MOSFET is not at  $N_D=N_A$  but shifts in the negative direction by approximately -3% in the structure of Fig. 1(b), due to the MOS part of CoolMOS™ [7]. The electrical characteristics of a trench filling SJ MOSFET have to be analyzed to apply charge balance analysis.

## 2.2 Application of an analytic model for charge balance in a trench filling SJ MOSFET

The trench filling fabrication process is better than the multi-epi fabrication process for making high-aspect-ratio structures. A high-aspect ratio is required to fabricate SJ MOSFETs with low on-resistance and high breakdown voltage [9]. Therefore, an analysis based on trench filling SJ MOSFETs is required.

One of the most important parameters in the trench filling fabrication process is the trench angle. The trench angle affects both the breakdown voltage and the on-resistance. Thus, in order to study the electrical characteristics according to the trench angle, an SJ MOSFET structure for 600 V is simulated as shown in Fig. 2. The half-value of the cell pitch is 6.5  $\mu\text{m}$ , the width of the N and P pillars is assumed to be equal to 3.25  $\mu\text{m}$ , and the dose of the P base region is  $6.5 \cdot 10^{13} \text{cm}^{-2}$ . The doping concentration of the P pillar,  $N_A$ , is varied

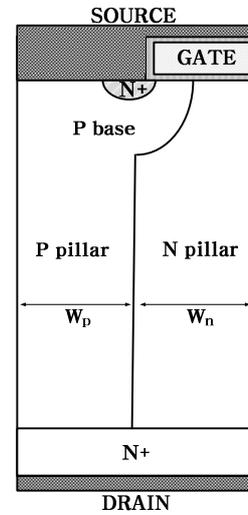


Fig. 2. Structure of the super junction MOSFET

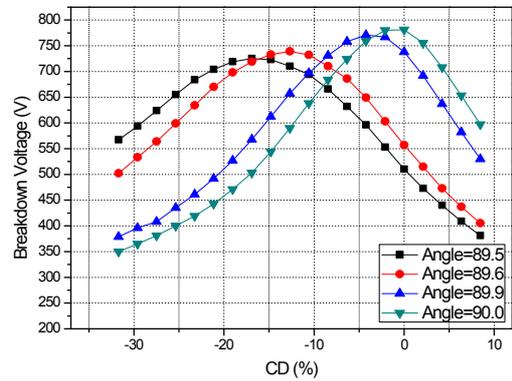


Fig. 3. Charge balance characteristics of trench angle

from  $4.43 \cdot 10^{15} \text{cm}^{-3}$  to  $6.13 \cdot 10^{15} \text{cm}^{-3}$  when the doping concentration of the N pillar is fixed to  $N_D = 4.73 \cdot 10^{15} \text{cm}^{-3}$ . As shown in Fig. 3, a smaller trench angle results in a lower maximum point of the breakdown voltage. Moreover, the maximum point of the charge balance curves for a trench filling SJ MOSFET is shifted to the left by decreasing the trench angle. The decreasing of the maximum point of the breakdown voltage is due to the change of the P pillar charge. With a decreasing trench angle, the P pillar charge decreases, because the size of the P pillar region is reduced. At the maximum point of the charge balance curve the charges of the N and P pillars are the same amount. As such, the peak point of the breakdown voltage has to decrease. A low on-resistance is achieved in a trench filling SJ MOSFET with a declining trench angle, as shown in Fig. 4.

In an SJ MOSFET, the effective cross-sectional area of the N pillar region has an effect on the on-resistance, because current flows through the N pillar region. Since an appropriate level of breakdown voltage must be chosen, the on-resistance characteristics require attention. A trench angle which is lower than  $90^\circ$  can be selected, since the lowest on-resistance has been achieved with a trench angle

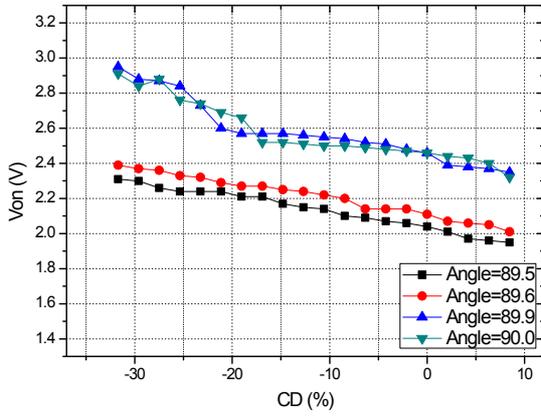


Fig. 4. On-state voltage drop characteristics of trench angle

of 89.5°. The simulation data for an SJ MOSFET with an 89.5° trench angle indicate a 715V breakdown voltage, and the lowest on-resistance among all the other peak value structures. But, the peak value of this 89.5° structure shifts from -3 % to -16%. In order to explain this shift, conventional charge balance analysis will have to be modulated by adding the trench angle parameter.

### 3. Charge Balance Parameter Modulation in Trench Filling Super Junction MOSFET

The trench angle is the most important parameter for analyzing trench filling SJ MOSFETs due to its relation to the on-resistance. A smaller trench angle is necessary for improving the on-resistance. Conventional charge balance analysis, which is intended for the multi-epi process, does not consider the effects of the trench angle parameter. Charge balance analysis is modulated, and a new parameter is proposed.

Because both N and P pillar areas have rectangular shape when the trench angle parameter is 90°, it is possible to explain the charge balance analysis using only the N and P pillar widths, as shown in Fig. 5(a). Selecting a trench angle of <90° for low on-resistance, an extra region is made by the trench angle affects in the charge balance analysis. The charge of the extra region makes the charge of the N pillar region increase as the charge of the P pillar region decreases, as shown in Fig. 5(b). It is crucial that the maximum point of charge balance is shifted left, which is undesirable due to the extra region as shown in Fig. 6. In this paper, the Charge balance Factor (CF) [%] parameter is proposed to modulate the analysis in order to achieve an accurate value:

$$CF[\%] = \frac{N_D \times (N_{pillar\_Area}) - N_A \times (P_{pillar\_Area})}{N_D \times (N_{pillar\_Area})} \quad (2)$$

CF parameter has N pillar and P pillar area factor that

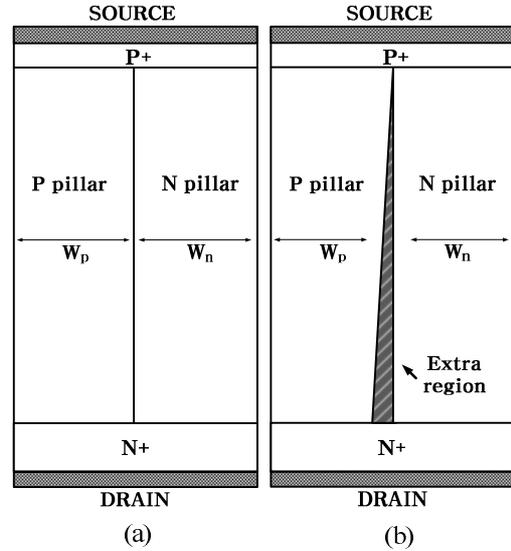


Fig. 5. (a) Super junction structure (trench angle = 90°); (b) Super junction structure (trench angle < 90°)

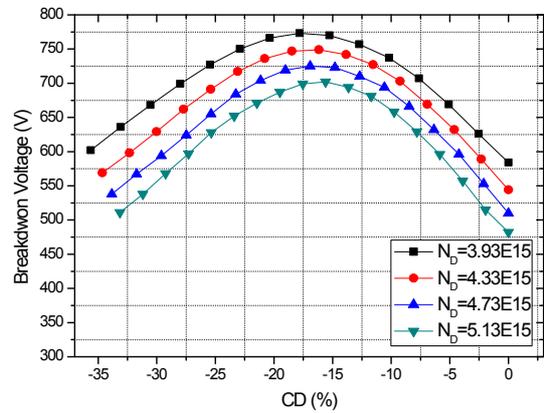


Fig. 6. Breakdown voltage characteristics of conventional charge balance parameter CD

can calculate trench angle parameter which isn't considered in CD parameter. This Area factor is 2-dimension parameter which is trapezoid shape. Charge balance analysis is simulated by TCAD using structure with a trench angle of 89.5° for low on-resistance. Using the conventional charge balance parameter CD[%] makes the maximum value of the breakdown voltage shift by 16% at CD=0%, as shown in Fig. 6. This shifted value is larger than that obtained using multi-epi process analysis, which is -3%. However, using the proposed parameter CF[%] allows for the achievement of a -3% shifted value in the charge balance analysis, same as that of multi-epi process, as shown in Fig. 7. The modulated analysis of the charge balance is validated by achieving the same result of the conventional charge balance analysis for a multi-epi process SJ MOSFET. It can be confirmed in this simulation data that Trench angle parameter is well covered in modulated Charge Balance analysis.

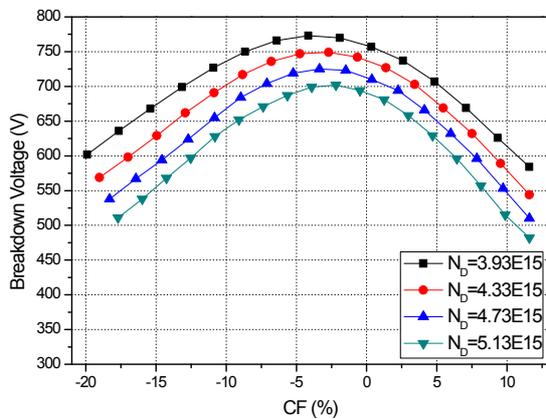


Fig. 7. Breakdown voltage characteristics of modulated charge balance parameter CF

#### 4. Conclusion

In SJ MOSFETs, charge balance is the most important issue of SJ fabrication process. In order to achieve the best on-resistance characteristics, SJ structure should be in the charge balance condition. So charge balance analysis must be confirmed. In conventional charge balance analysis, which is based on multi-epi process SJ MOSFETs, does not consider the trench angle parameter, which is important for trench filling SJ MOSFETs. Because the trench filling process is simpler and more suitable for making high-aspect-ratio structures than the multi-epi process, we can be focused on Trench filling SJ MOSFETs. In order to apply appropriate analysis of charge balance in trench filling SJ MOSFETs, a modulated one has been proposed by adding the trench angle parameter. The modulated charge balance analysis considers the change in on-resistance characteristics according to the trench angle parameter. To achieve much more superior characteristics of on-resistance in trench filling SJ MOSFET, the appropriate trench angle is necessary. An accurate value of the charge balance parameter can be achieved using the modulated analysis. This modulated analysis can be used in applying device design process more correctly.

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**Jongmin Geum** He received B. S degree in electrical engineering from Korea University. And he is taking up his Ph.D course in Electrical Engineering from Korea University. His research interests are Power Devices and Compound Semiconductors



**Eun Sik Jung** He received Ph. D degree in electrical engineering from Korea University. And he is currently president of Maple Semiconductor Inc. His research interests Silicon and SiC high-voltage Power Devices.



**Yong Tae Kim** He received Ph.D in electronics from KAIST and has joined in KIST as a principle scientist since 1982. He is president of Korea Semiconductor Industry Standard Association and executive director of National R&D Program of Nano Process Equipment.

His research interests are semiconductor materials and devices such as GaN, chalcogenide, nano-materials, Cu interconnects, PRAM, ReRAM, and Power MOS



**Ey Goo Kang** He received M.S and Ph.D degree in Electrical Engineering from Korea University, in 1995 and 2002, respectively. He is currently Professor in department of photo voltaic engineering at Far East University. His research interests are Power Devices and Power Management System, Solar

System.



**Man Young Sung** He received M.S and Ph.D degree in Electrical Engineering from Korea University, in 1977 and 1981, respectively. He is currently Professor in college of Engineering at Korea University. He has been with the University of Illinois at Urbana-Champaign as Associate Professor in

1986, and as Visiting Professor in 1997, and the Royal Institute of Technology (Sweden) where he served as Visiting Scientist in 1991.