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A Modeling of 4H-SiC Super-Junction MOSFETs with Filtered High Energy Implantation

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Abstract. In this paper, the modeling of SJ-MOSFETs beyond the voltage class of 3.3 kV simulated with verified deep aluminum box-like shaped profiles by using TCAD simulation is described. The simulation results are used to investigate the influence of ion implantation parameters on electrical characteristics. For the formation of pillar regions, high energy implantation is performed through energy filter with a multi epitaxial growth method using a patterned mask. While high thickness of epitaxial layer is indispensable for obtaining a high blocking capability, it is revealed that the optimization of doping concentration of p-pillar and drift layer parameters yields similar on-state-resistance by charge compensations of SJ-structure.

Introduction

The Super-Junction (SJ) technology has been demonstrated in silicon power devices previously [1]. It is superior to homogeneous drift region doping owing to the benefits of the efficient electric field distribution by the formation of a large space charge between p- and n-pillars in the drift region. It is beneficial for reducing a specific on-state-resistance ($R_{on}A$) and implementing a higher breakdown voltage (BV) in the off-state of the device. While the doping for formation of pillar structures can be performed by ion implantation and diffusion in silicon, the dopants must be solely implanted in silicon carbide (SiC), due to low diffusion coefficients of dopants [2]. A deep implantation with heavy aluminum induces damages of crystal lattice. Hence, fabrication of compensation devices appears to be more challenging in SiC technology than in silicon. Here, a multi epitaxial growth method is proposed for the formation of deep pillar structures to obtain outstanding electrical performance [3]. The uniformity of p-pillar doping concentration has a crucial role to compensate charge with n-pillar doping concentration over the entire region homogeneously. Therefore, performing box-like dopant profiles with several different monoenergetic implantation steps is an elaborative workaround. In this case, a manufacturing process called by Energy Filtered Ion Implantation (EFII) is proposed [4, 5], that requires only one single ion implantation step to generate deep aluminum box-like shaped profiles into SiC. In this work, we present the description of the TCAD modeling of SJ-MOSFETs and resulting electrical characteristics by using device simulation in detail, for enhancement of further design for manufacturing of SJ-MOSFETs.

Experiment and Simulation

Fig. 1 shows a structured photo resist (PR) mask with thickness of 15 µm on n-type 4H-SiC epilayers with a donor concentration of 1×10^{16} cm^{-3} on 150 mm wafers. Both opening width and mesa are 6 µm as targets, namely, the aspect ratio between PR-thickness and -width is 2.5. The exposure energies are varied from 170 mJ/cm^2 to 190 mJ/cm^2. Illumination is followed by post exposure bake for 1 minute at 90 °C in order to optimize the resist sidewall angle of approx. 82 ° that causes reduction of opening width by 300 nm from the target width. Fig. 2 depicts the EFII implantation profile simulated with the Geant4 [6] Monte-Carlo (MC) simulation toolkit, for a masked implantation into 4H-SiC with aluminum ions with a primary energy of E_0 = 7 MeV and a mask structure made of PMMA [7] with the thickness of 15 µm and the opening width of 6 µm. Even though the resist sidewall angle of 90 ° is simulated in this case to investigate an ideal high energy implantation with a single step, aluminum is becoming laterally scattered decreasingly as it is implanted deeper, thus, the lateral scattering in the vicinity of SiC surface is approx. 1 µm larger compared with the ends of the pillars.

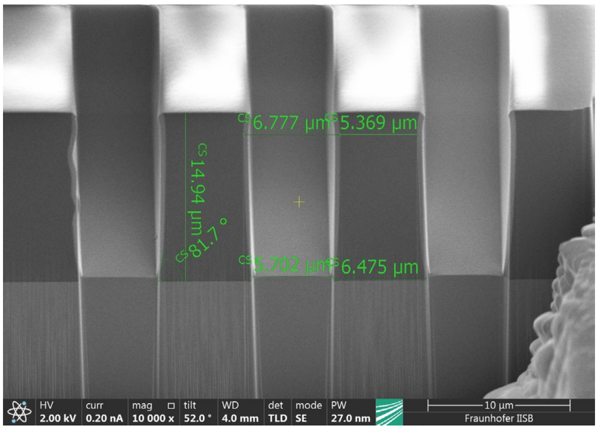

Fig. 1. PR mask with thickness of 15 µm structured by lithography on SiC epilayer.

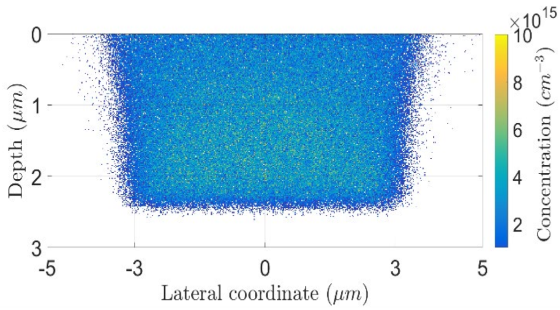

Fig. 2. Two-dimensional Al-doping profiled from high energy implantation (E_0 = 7 MeV) and Energy Filter Ion Implantation (EFII) by using Geant4 MC simulation.

Fig. 3 (upper) presents two-dimensional numerical model in the active area of SJ-MOSFET implemented in Synopsis Sentaurus. The SJ-layer is placed into the surface of a drift-layer having thickness of 15 µm and nitrogen doping concentration of 4×10^{15} cm^{-3} to yield the blocking capability over 3.3 kV class device using partial superjunctions. To achieve $R_{on}A$ in the range between 10 $m\Omega cm^2$ and 13 $m\Omega cm^2$, SJ-structures are formed by three times n-type multi epitaxial layers exhibiting a nitrogen doping concentration of 1×10^{16} cm^{-3}, results in the formation of p-pillar having depth of 6 µm and aluminum doping concentration of 2×10^{16} cm^{-3}. The resulting simulated one-dimensional aluminum doping profile from Geant4 MC simulator described in Fig. 2, of which target depth is approx. 2 µm, is imported into the numerical model to form the p-pillar structure. A top epilayer with thickness of 0.7 µm and nitrogen doping concentration of 1×10^{16} cm^{-3} is formed lastly over the SJ-structure for functionality of part of VDMOS device. A cell pitch of 12 µm is implemented to form the optimized profile for n^+-source, p^+-contact, p-body and JFET implantation as used for conventional planar devices previously. The p- and n-pillar structures are periodically spaced by 6 µm each, so that p-n junction between both pillars having identical width is fully depleted laterally and vertically to obtain a maximum BV analytically [8]. Fig. 3 (bottom) presents an aluminum doping concentration profile extracted at the A-A' section line in the scheme. The p-pillar is formed by ion implantation with primary energy of 7 MeV for each 2 µm target depth and three times multi epitaxial layers that shows box-like shape with plateau doping concentration of 2×10^{16} cm^{-3} implemented with a single step for high energy implantation offered by EFII filter. While each multi epitaxial layer is deposited as 2 µm exactly in this simulation, the depth of each implanted aluminum is slightly higher than 2 µm as depicted in Fig. 2, the fact of which causes two peaks with twice the desired aluminum concentration in the transition region (stitching) between each multi epitaxial layer.

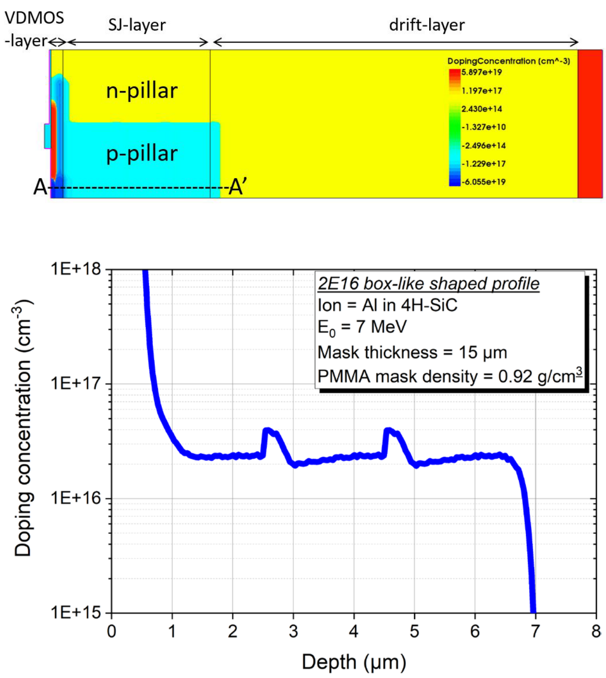

Fig. 3. TCAD modeling of half-cell SJ-MOSFET exhibiting doping concentration (upper) and depth profiles of Al-doping concentration across A-A' (bottom).

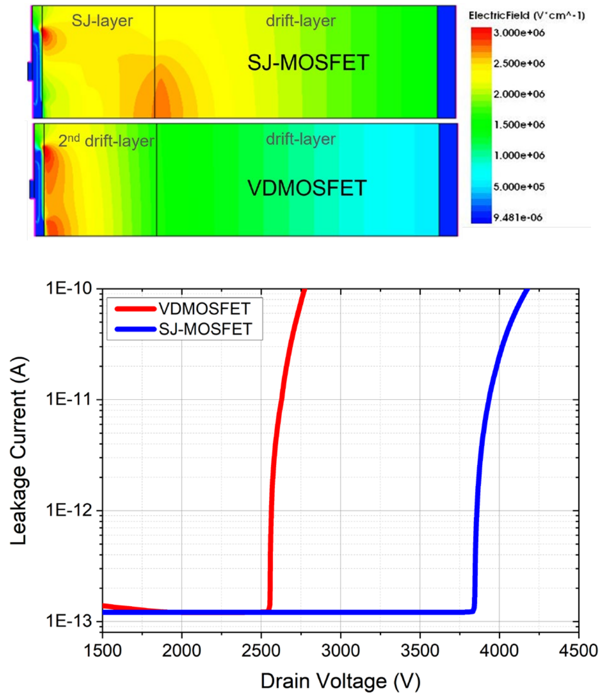

Fig. 4. Blocking simulation for electric field distribution of VDMOSFET and partial SJ-MOSFET (upper) and comparison of break-down voltage (bottom).

Fig. 4 (upper) presents the distribution of electrical field implemented by using blocking device simulation for a comparison between SJ-device and conventional planar device. In this case, the identical model of SJ-MOSFET described in Fig. 3 is used to compare the VDMOSFET which excludes pillar structures and includes 2nd drift-layer of which thickness is 6 µm and nitrogen doping concentration is 1×10^{16} cm^{-3} to investigate the effect of SJ-structure in off- and on-state. Whereas the high electric field concentration occurs at the p-body region during approx. 2.5 kV drain-source voltage application in the case of conventional planar device, the electric field concentration is widely dispersed during avalanche breakdown over the pillar structures due to the charge compensation effect for SJ-devices. As shown in Fig. 4 (bottom), in principle, approx. 22 µm epitaxy is used for ideal breakdown voltage of 2.5 kV which is consistent with the simulation result. In comparison, SJ-structures contribute to improve about 52 % of breakdown voltage of approx. 3.8 kV in off-state. On the contrary, output characteristics are hardly affected, i.e., both $R_{on}A$ values of SJ-MOSFET and VDMOSFET are approx. 11 mΩcm^2. The partial-SJ device is beneficial for reducing a complexity of manufacturing process that is promising approach to enhance blocking capability compared with VDMOS and to have no negative influence on the on-state behavior.

Device simulation is also conducted to verify breakdown behavior of SJ-MOSFET with different p-pillar doping concentration as shown in Fig. 5. For high voltage class device, the drift-layer is deposited with thickness of 15 µm and nitrogen doping concentration of 4×10^{15} cm^{-3}. Three times multi epitaxies with total thickness of 6 µm and nitrogen doping concentration of 1×10^{16} cm^{-3}, and aluminum box-like shaped implantation are performed for formation of partial SJ-structure with pillar depth of 6 μm without consideration of the compensation defects [9]. The p-pillar doping concentration as-implanted is varied from 1.5×10^{16} cm^{-3} to 6×10^{16} cm^{-3} to investigate charge compensation effect between p-pillar and n-pillar. It is shown that the ratio of p- and n-pillar appears to have critical effect on blocking characteristics, e.g., the equal doping of both pillars after charge compensation causes the highest BV. The higher deviation of doping concentration between both pillars deteriorates blocking capabilities, in particular, from 4.0×10^{16} cm^{-3} of p-pillar doping concentration due to high amount of dopant of acceptors after charge compensation. Also, the doping concentration of the drift-layer under SJ-layer has a critical role as a key contributor for electrical characteristics as shown in Fig. 6. The higher doping of drift-layer, e.g., over 7×10^{15} cm^{-3}, is prone to the lower blocking capability due to increasing an ineffectiveness of the SJ effect and a trade-off with improved $R_{on}A$. Therefore, it is favorable to use drift-layer with a doping concentration between 4×10^{15} cm^{-3} and 6×10^{15} cm^{-3} for application of over 3.3 kV class devices.

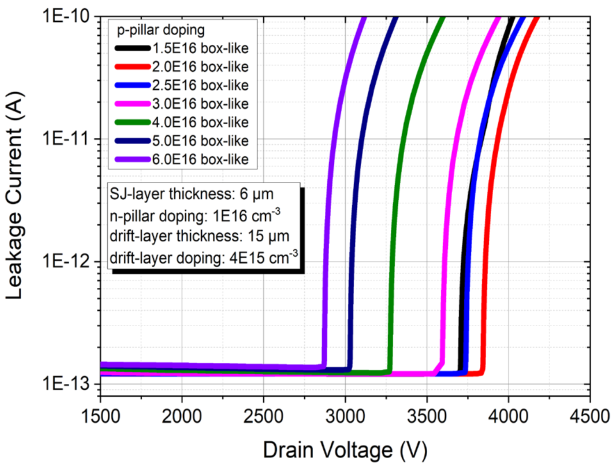

Fig. 5. Blocking characteristics dependent on p-pillar doping concentration as-implanted.

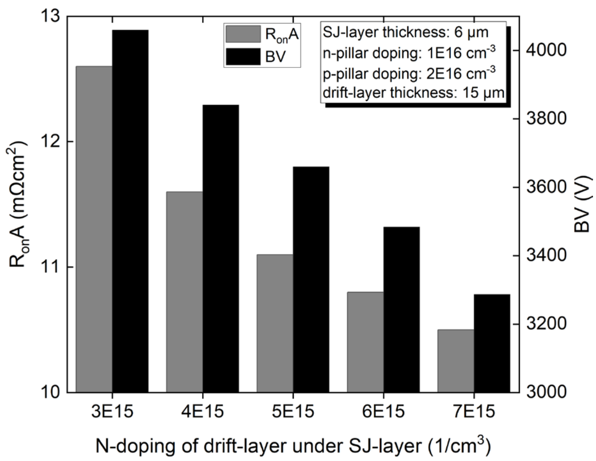

Fig. 6. Influence of the doping of drift-layer under SJ-layer on electrical characteristics for the on- and off-state behavior.

Summary and Outlook

In this work, we present the structured PR mask for high energy implantation with energy filter enables the formation of uniform box-like shaped profile with a single monoenergetic step. The n-pillar doping of 1×10^{16} cm^{-3} is investigated mainly to use verified VDMOS parameters. In device simulation, it is revealed that the best breakdown characteristic can be obtained with equal width and doping concentration of p- and n-pillar. Previous studies have reported manifold benefits of 4H-SiC SJ-MOSFETs analytically and numerically compared with conventional planar MOSFET by optimization of pillar structures. The deeper pillar structure is obviously favorable for maintenance of $R_{on}A$ while the blocking capability indicates promising high voltage class devices. However, since high energy implantation with combining multi epitaxial growth method is challenging compared with silicon technology, the SJ-layer with extreme high thickness is to be fabricated with manufacturability in mind. For this reason, the total pillar depth of 6 μm from Geant4 MC simulator is modelled using two-dimensional simulation in which the effect of parameters of drift-layer under SJ-layer is investigated particularly. The maximum primary energy of 7 MeV is restricted as technological feasibility in this work. It is expected to use higher energy implantation over 15 MeV with optimized PR mask and EFII filter for the formation of deeper SJ-layer to improve off-state electrical characteristics significantly. This will help to further reduce the number of repetitions of epitaxial growth, time effort and ultimately costs. Moreover, the cell pitch can be reduced for improvement of electrical performance by optimization of appropriate implantation parameters of VDMOS part, e.g., p-well and JFET concatenated with SJ-layer. The lateral scattering of p-pillar profile is also to be considered in the two-dimensional simulation to predict the electrical results with great accuracy, since the deviation due to wider scattering near the SiC surface cannot be neglected. Furthermore, the peaks in the aluminum box-like shaped profile occur in the transition region between multi epitaxies is speculated to have a negative influence on pure charge concentration between both pillars that must be verified in the future work.

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