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# Fabrication of trench-gate power MOSFETs by using a dual doped body region

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**Abstract**

Fabrication of trench-gate power MOSFETs by using a dual doped body region has been proposed to further improve the device performance. For the usual scheme that employs a uniform doped body region, a device with a blocking voltage larger than 30 V and a specific on-state resistance of about 1.0 Ω cm can be obtained via the proper choice of trench depth, epitaxial thickness, and body doping concentration. On the other hand, a dual doped body region is produced by dual high-energy and low-energy implantation of boron dopant. By this scheme, a device with a blocking voltage larger than 30 V and a specific on-state resistance of about 0.8 Ω cm can be further achieved. Hence, with reducing the cell pitch size to be below 2 μm, this device fabrication scheme should be promising and practical for achieving a specific on-resistance smaller than 0.1 m$\Omega\,cm^2$ and a blocking voltage higher than 30 V.


## 1. Introduction

Power semiconductor devices play a crucial role in the regulation and distribution of power and energy in the world. As a result, the performance of power rectifiers and switches has a significant impact on the efficient use of electricity [1]. Power switches designed to operate at blocking voltages below 100 V are needed in power supplies, peripheral drives, and automotive electronic multiplex bus systems [1]. The silicon MOSFET has become the dominant device technology for these applications. Due to its many attractive features, there has been a concerted effort to optimize its structure, design, and process technology [2–9]. Even greater reduction in the specific on-resistance has been achieved by utilizing deep trench structures where the trench extends all the way down to the $n^+$ substrate [10].

The trench-gate power MOSFETs has become the main stream of low voltage power switch. Moreover, further reduction of the specific on-resistance and increase of the channel density are the primary goals for this type power MOSFETs, when acceptable blocking voltage is still obtained. A fully self-aligned trench-gate MOSFET technology that permits a significant increase in the packing density has been previously developed [11]. In addition, to achieve even better performance of power ICs, a further reduction of the specific on-state resistance, by optimizing the device scheme, should also be necessary.

In this study, a practical device scheme that employs a dual doped body region has been proposed to further improve the device characteristics of trench-gate power MOSFETs. By using this device scheme, the channel resistance of MOSFET device can be reduced via lowering the effective threshold voltage of the device,

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without causing possible punch-through of device and degradation of blocking voltage.

## 2. Device fabrication

The self-aligned silicide (salicide) process is used to form a silicided trench-gate power MOSFET [11]. The resultant device structure for the trench-gate power MOSFETs prepared by this fabrication process is shown in Fig. 1. We first optimize the device by changing various process parameters. The process steps are: (1) Sb-doped wafer of 0.01 Ω cm with n-epitaxial layer of various thickness and a resistivity of 0.26 Ω cm, (2) field oxidation of 800 nm at 1000 °C, (3) mask 1, defining the active area, (4) screen oxide of 15 nm thickness grown at 950 °C, (5) p-body implantation of boron at various energies and doses, (6) dopant drive-in and removal of field oxide, (7) LPCVD oxide of 600 nm thickness as hard mask, (8) mask 2, defining the trench region, (9) trench Si etching of different depth, (10) sacrificial oxidation of about 15 nm thickness in an $N_2O$ ambient at 950 °C, (11) removal of sacrificial oxide and gate oxidation of 50 nm thickness at 900 °C, (12) LPCVD poly-Si gate and $POCl_3$ diffusion at 950 °C, (13) poly-Si etching back, to form poly-Si plug as the trench-gate, (14) removal of hard-mask oxide, (15) source implantation of $As^+$ (30 keV, $1\times10^{14}$ $cm^{-2}$), (16) LPCVD oxide of about 200 nm thickness, and then etching to form oxide spacer, (17) co-salicide process, forming silicide at source and gate regions. The formed silicide can also contact the body region, by the Co reaction through the source junction, (18) TEOS/BPSG deposition of about 1.5 μm thickness, and then thermal flow at 900 °C for 30 min, (19) mask 3, defining contact hole, (20) Al sputtering of about 4 μm thickness and (21) mask 4, defining metal pad.

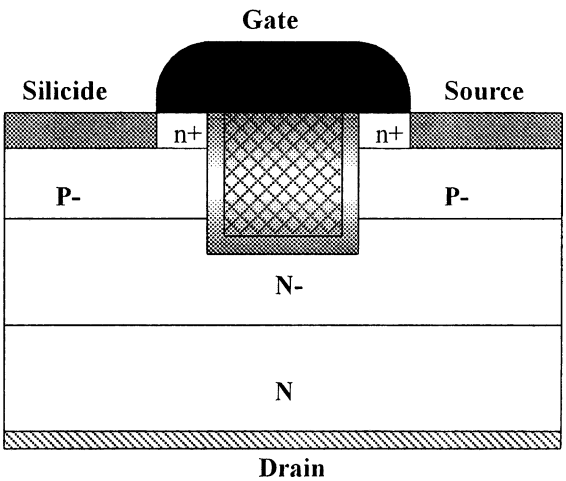


Fig. 1. The resultant device structure for the self-aligned silicided trench-gate power MOSFETs with a uniform doped body region.

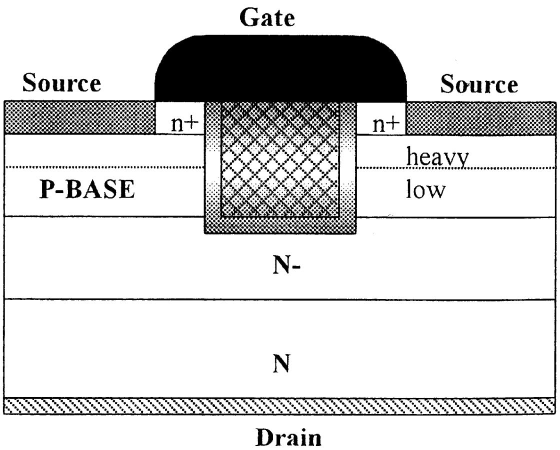


Fig. 2. The resultant device structure for the self-aligned silicided trench-gate power MOSFETs with a non-uniform doped body region formed by dual body implantation.

As for the above process, in the step (5), the p-base (or p-body) region is formed by using only single implantation. Hence, the resultant p-base region is uniformly doped. The doping concentration of the p-base region should be high enough to suppress the punch-through leakage of device. However, a higher dopant concentration of the p-body region of a MOSFET may result in a higher threshold voltage and thus a larger channel resistance. Accordingly, it is conjectured to further improve the device characteristics by using a dual high-energy and low-energy p-base implantation. The resultant doping concentration of the p-body region is thus relatively larger in the upper region and relatively smaller in the lower region. The resultant device structure with a dual doped body region is shown in Fig. 2.

The resultant devices are examined by using a HP 4145 B, semiconductor parameter analyzer. The electric breakdown field of gate oxides was obtained by voltage stress at an accumulation mode. The breakdown characteristics of the devices were conducted at $Vgs = 0$ V. The on-state resistance of the devices was achieved at $Vgs = 15$ V. In addition, process and device simulation were also performed to facilitate the choice of process conditions [12,13].

## 3. Results and discussion

A breakdown voltage of gate oxide larger than 40 V was achieved. Hence, a breakdown field larger than 8 MV/cm can be obtained for this gate oxide of 50 nm thickness, which meets the requirement of designing a power MOSFET with a blocking voltage larger than 30 V. The relatively high breakdown field of about 8 MV/cm for the gate oxide in the trench structure is carried out according to the process described in the last section. Prior to gate oxidation, sacrificial oxidation of about 15 nm thickness in $N_2O$ ambient at 950 °C can be used to improve the gate oxide integrity. Here, the target of the blocking voltage is set to be 35 V, well above the specification of 30 V. Accordingly, the resistivity of n-type epitaxy layer should first be properly chosen to sustain sufficient junction breakdown voltage without degrading the resistance of drift region. The resistivity of n-epitaxy of about 0.26 Ω cm, that is a doping concentration of about $2\times10^{16}$ $cm^{-3}$, is used for trade-off here.

### 3.1. Uniform doped body region

Firstly, the device scheme with a uniform doped base region is examined. The blocking voltage, the punch-through leakage, and the on-state resistance should be considerably affected by the primary process parameters including the epitaxial thickness, the trench depth, and the doping profile of p-body region. In order to turn on the channel of MOSFETs, the trench should always be deeper than the p-body region. However, when the trench is much deeper than the body region, from simulation results, crowded potential contours are found near the trench corner. Accordingly, a largely enhanced electric field is created near the trench corner, which would significantly degrade the blocking voltage. However, when the trench just slightly exceeds the body region, no crowding of potential contours is found, and thus no anomalous degradation of blocking voltage would be caused. As a result, hereafter, the base doping profile is chosen to be about slightly above the bottom of trench.

Furthermore, the thickness of epitaxial layer may affect the drift resistance and the blocking voltage. Fig. 3 shows the specific on-state resistance and the breakdown voltage as a function of epitaxy thickness, correspondingly, for a trench depth of 2.0 μm. When the epitaxy layer is thinner than 4 μm, the blocking voltage is considerably degraded, since the residual n-layer thickness, of about 2 μm (∼4 μm–2 μm = 2 μm), is not enough for the extension of depletion region at reverse voltage bias of 35 V. And, for keeping the blocking voltage of 35 V, a specific on-state resistance of about 1.8 Ω cm is achieved. Moreover, when the trench depth of about 1.5 μm is employed to reduce the channel resistance, the device characteristics are further improved. Fig. 4 shows the specific on-state resistance and the breakdown voltage as a function of epitaxy thickness, correspondingly, for a trench depth of 1.5 μm. A specific on-state resistance of about 1.4 Ω cm can be obtained, with the blocking voltage of 35 V is kept.

However, when the trench depth is decreased to only 0.5 μm, the breakdown is largely reduced to only about 1.5 V. This result is ascribed to the device punch-through of the resultant short channel MOSFETs. Fig. 5 shows the specific on-state resistance and the breakdown voltage as a function of epitaxy thickness, correspondingly, for a trench depth of 1.0 μm. It is found that a specific on-state resistance of about 1.0 Ω cm and a blocking voltage of 35 V can be well achieved by using a trench depth of 1.0 μm and a epitaxy thickness of 3.0 μm.

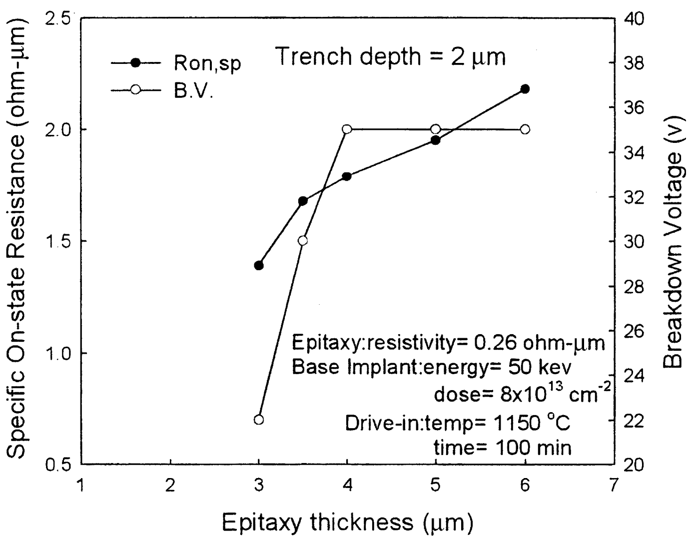


Fig. 3. The specific on-state resistance and the breakdown voltage as a function of epitaxy thickness, correspondingly, for a trench depth of 2.0 μm.

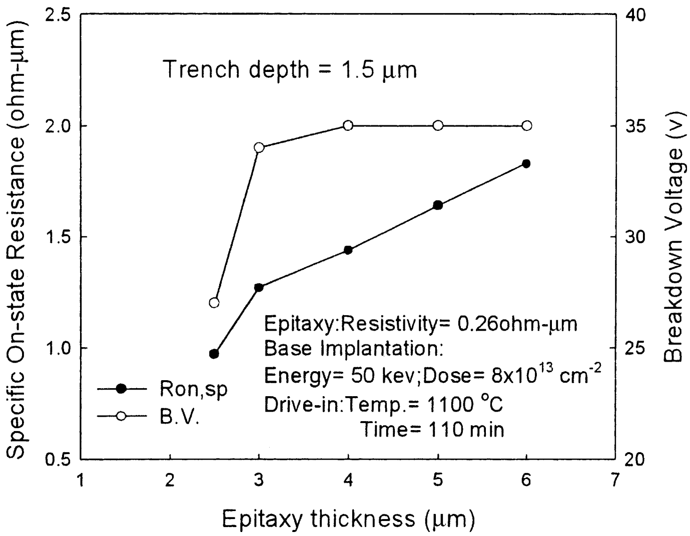


Fig. 4. The specific on-state resistance and the breakdown voltage as a function of epitaxy thickness, correspondingly, for a trench depth of 1.5 μm.

### 3.2. Dual doped body region

By employing a dual doped body region formed by dual implantation of boron dopant, the channel resistance can be further reduced without causing device punch-through. The first high-energy implantation with relatively low dosage can form a low-doped body region, thus reducing the effective threshold voltage and the channel resistance. In addition, the second low-energy implantation, together with the first high-energy implantation, can yield a relatively high-doped region the upper part of the p-body region, suppressing the device punch-through. Hence, the channel resistance may be improved without degrading the blocking voltage. Fig. 6 shows the specific on-state resistance and the breakdown voltage as a function of the low-doped body implantation dose with implantation energy of 120 keV, correspondingly, for a trench depth of 1.0 μm. With lowering this high-energy implantation dose, the specific on-state resistance can be considerably reduced without deteriorating the blocking voltage. However, an implantation dose smaller than $3\times10^{12}$ $cm^{-2}$ here would

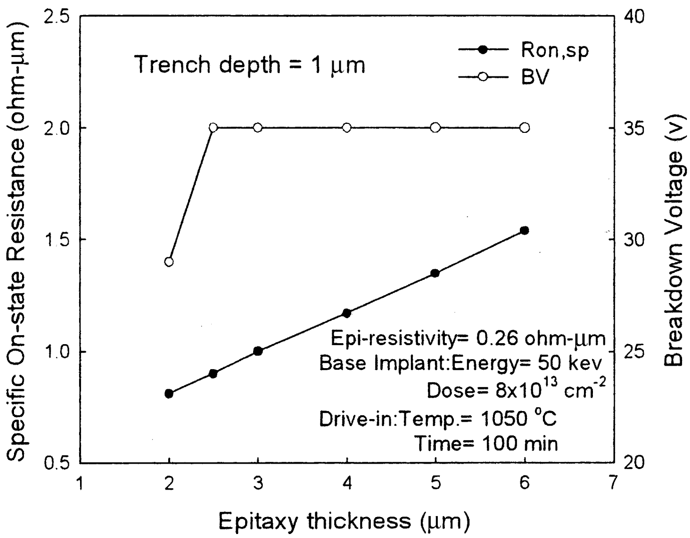


Fig. 5. The specific on-state resistance and the breakdown voltage as a function of epitaxy thickness, correspondingly, for a trench depth of 1.0 μm.

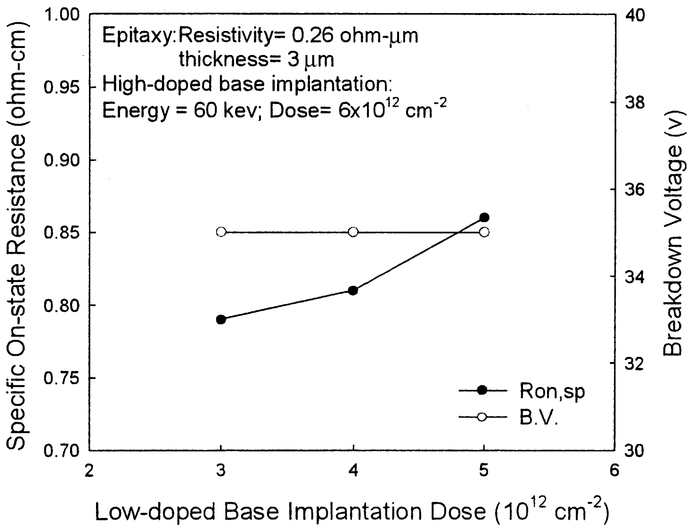


Fig. 6. The specific on-state resistance and the breakdown voltage as a function of the low-doped body implantation dose with an implantation energy of 120 keV, correspondingly, for a trench depth of 1.0 μm.

still degrade the blocking voltage due to the device punch-through. Nevertheless, by this scheme, a device with a blocking voltage larger than 30 V and a specific on-state resistance of about 0.8 Ωcm can be achieved. Accordingly, considering a typical cell pitch size of about 2 μm and a trench width of 1 μm, a specific on-state resistance, in area, of (0.8 Ωcm/4 μm)×4 $\mu m^2$ can be obtained. That is also about 0.08 $m\Omega cm^2$.

In addition, if the high-doped body region is considerably wide, as compared to the total channel length, the effective threshold voltage of devices may be substantially enhanced. Hence, the low-energy implantation energy should be properly chosen to achieve a suitable depth of the high-doped base region. Fig. 7 shows the specific on-state resistance and the breakdown voltage as a function of the high-doped body implantation energy with an implantation dose of $6\times10^{12}$ $cm^{-2}$, correspondingly, for a trench depth of 1.0 μm. It is found that as the high-energy implantation energy is relatively larger, the specific on-state resistance is degraded due to the increased channel resistance. Moreover, Fig. 8 shows the specific on-state resistance and the breakdown voltage as a function of the high-doped body implantation dose with implantation energy of 60 keV, correspondingly, for a trench depth of 1.0 μm. From Figs. 6–8, it is also noted that the breakdown voltage is almost independent

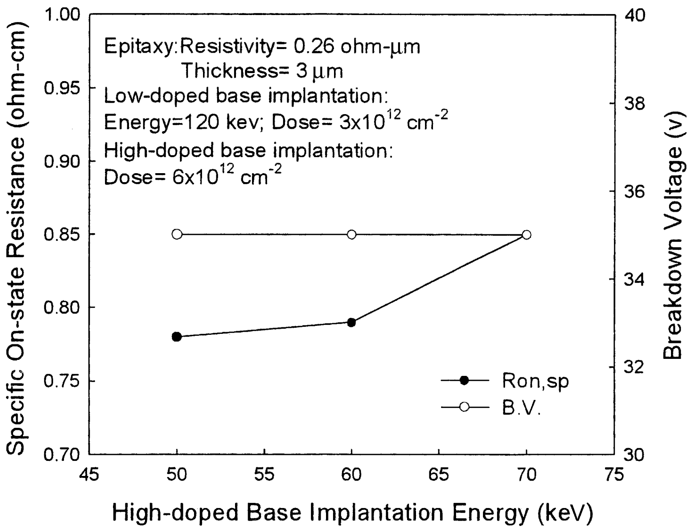


Fig. 7. The specific on-state resistance and the breakdown voltage as a function of the high-doped body implantation energy with an implantation dose of $6\times10^{12}$ $cm^{-2}$, correspondingly, for a trench depth of 1.0 μm.

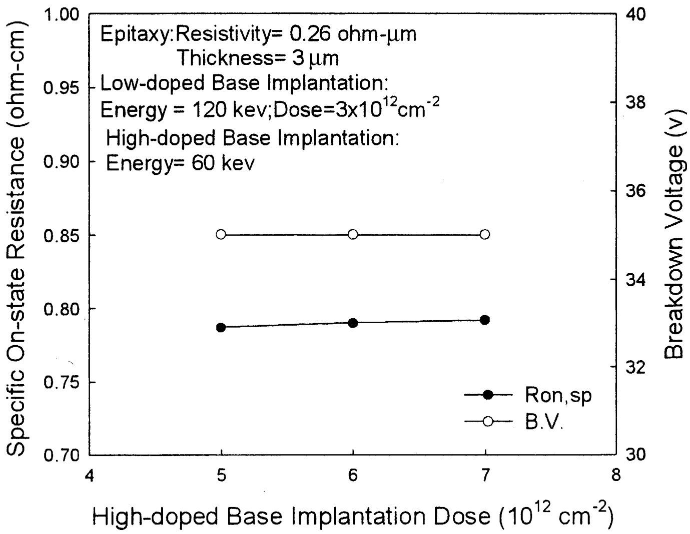


Fig. 8. The specific on-state resistance and the breakdown voltage as a function of the high-doped body implantation dose with an implantation energy of 60 keV, correspondingly, for a trench depth of 1.0 μm.

of the base implantation energy and dose here. When the base doping profile is properly chosen and thus no device punch-through is significantly caused, the breakdown voltage would be primarily decided by the electrical breakdown near the trench corner with highest electric field distribution. The breakdown voltage limited by the trench corner is about 35 V here. Hence, a wide range of base implantation dose and energy can sustain the trench-corner-limited breakdown voltage of 35 V here, reflecting that no device punch-through breakdown is caused by these base implantation conditions. As a result, this scheme actually provides a large process window for choosing the implantation condition of forming this dual doped body region.

As a comparison, the dual doped body region can result in better electrical characteristics than the uniform doped body region. For the uniform doped body region, a blocking voltage of 35 V and a specific on-state resistance of about 1.0 Ω cm can be obtained by optimizing the structure and process condition. However, for the dual doped body region, a blocking voltage of 35 V and a specific on-state resistance of about 0.8 Ω cm may be obtained by easily adjusting the high-and low-doped base implantation conditions. This reduction of on-state resistance is due to the decrease of effective channel resistance. For the dual doped body region, a low-doped body region can be used to result in a MOSFET with low threshold voltage, and a high-doped body region can be taken to sustain the blocking voltage via suppressing the possible device punch-through breakdown caused by using the above low-doped body region. Accordingly, as compared to the uniform doped body region, the channel resistance can be further reduced and the blocking voltage may be sustained by using the dual doped body region with easily being optimized by a wide range of base implantation conditions. Hence, the device scheme using dual doped body region should be promising and practical for implementing a trench-gate power MOSFETs.

## 4. Conclusions

For the usual scheme that employs a uniform doped base region, a device with a blocking voltage larger than 30 V and a specific on-state resistance of about 1.0 Ω cm can be obtained via the proper choice of trench depth, epitaxial thickness, and base doping concentration. On the other hand, a dual doped body region is produced by dual high-energy and low-energy implantation of boron dopant, thereby further reducing the channel resistance without causing device punch-through. By this scheme, a device with a blocking voltage larger than 30 V and a specific on-state resistance of about 0.8 Ω cm can be achieved. This scheme is available for using a large range of dual implantation conditions. Hence, with reducing the cell pitch size to be below 2 μm, this device scheme should be promising and practical for achieving a specific on-resistance smaller than 0.1 mΩ $cm^2$ and a blocking voltage higher than 30 V.

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