Space-saving edge-termination structures for vertical charge compensation devices

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Abstract

High efficiency is one of the major requirements of today's modern power architectures. To achieve the needs of modern power topologies, advanced power device designs are essential. In the field of low-voltage devices, covering a range up to 250 V, a significant reduction of the MOSFET on-resistance is achieved by employing the compensation principle based on field-plates. Such devices do require new design techniques. Advanced edge-termination structures enable high blocking voltages exceeding 100 V. This work proposes different edge-termination structures and shows first results and benchmarks of manufactured devices from this new MOSFET design generation.



Fig. 1: a) Compensation by p- and n-columns (left) b) Compensation using a field-plate structure (right)

Introduction

There is a demand for devices with lower on-state resistance, which also exhibit good switching behavior. Low-voltage devices are used widely in DC-DC power supplies, AC-DC adapters, Class-D amplifiers and motor drives. To achieve a clearly reduced on-state resistance, devices based on charge-compensation principles offer a clear advantage.

The compensation principle for power MOSFETs was first introduced in commercially available products in 1998 with the introduction of the 600 V CoolMOSTM Technology [1]. The basic principle behind the highly reduced $R_{DS(on)} \times A$ compared to conventional power MOSFETs is the compensation of n-drift region donors by acceptors located in p-columns, shown schematically in Fig. 1a. The compensating acceptors are located in lateral proximity to the drift region donors, in contrast to the large vertical distance when the acceptors are positioned in the body region. In addition, the acceptors are distributed over the total drift region length which leads to a very homogeneous electric field distribution over the entire voltage-sustaining region. This differs to a conventional device where there is a strong localization in the body region. The requirement for precise lateral n and p dose compensation limits the n-drift region doping. This type of compensation within the power MOSFET is typically used for breakdown voltages of several hundred Volts.

For breakdown voltages below 200 V, field-plate trench MOSFETs are an excellent alternative [2, 3]. These devices have a deep trench penetrating the n-drift region. An isolated field-plate provides the mobile charges required to compensate the drift region donors under blocking conditions, as shown in Fig. 1b. In this case precise lateral drift region compensation is ensured under all operating conditions. The field-plate isolation has to withstand the full source drain blocking voltage of the device at the trench bottom; therefore oxide thicknesses in the micron range have to be regulated carefully with a special focus on conformity even at the corners at the bottom of the trench and the prevention of stress-induced defects. Fig. 2 shows the basic difference between the electric field distributions of a blocking pn-junction and that of a blocking compensation structure employing a field-plate. In case of a simple pn-junction, a triangular-shaped electric field is formed in a vertical direction. There is of course no lateral electric field. In contrast, a compensation structure ideally shows a near homogeneous electric field in vertical direction. This is due to the compensation of the drift region, which causes the triangular-shaped field to be formed in a lateral direction.

The consequence of the lateral compensation is that doping in the drift region can be increased using both concepts. Although the compensation structure consumes a part of the total available area, the on-state resistance can still be improved. In fact, the $R_{DS(on)} \times A$ is actually reduced below the so-called "silicon



Fig. 2: Electric field distribution for a pn-junction (left) and for a compensation structure using a field-plate (right)

limit," which is the on-resistance of an ideal abrupt p^+n junction at a given breakdown voltage, which is not limited by any termination structures.

Edge-termination structures

Edge-termination structure based on field-plates

As already stated, compensation structures allow a higher drift region doping. Consequently, conventional edge-termination structures are not usable due to the high doping density, and specially formed termination structures are needed. In structures employing field-plates, a field-plate enclosing the cell array is usually sufficient to ensure the necessary breakdown strength within the edge region. However, if larger breakdown voltages appear, this simple termination structure increasingly starts to face problems due to incomplete compensation in the edge-termination region. Furthermore, it is advantageous to create a termination structure whose blocking capability is equal to or higher than that of the cell array.



Fig. 3: edge-termination structure formed by field-plates in trenches (left) and basic chip layout (right)

One proposed termination structure consists of trenches that run from the cell array towards the edge region, forming several rings. Field-plates incorporated within the trenches compensate the electric field as described previously. Since the dielectric layer around each field-plate controls the maximum blocking voltage, the field-plate potential needs to increase from ring to ring. Therefore, each field-plate is connected to a p-well region which is reached by the electric field. The potential of the field-plate is now set to the potential prevailing in the p-well region as illustrated in Fig. 3. This edge-termination structure offers the advantage that no additionally layers are needed in the manufacturing process.

Device simulation was used extensively to verify and optimize the edge-termination structure. The analysis of such types of structures requires the use of three-dimensional device simulations [4]. Assuming



Fig. 4: Basic simulation structures for the field-plate edge-termination



Fig. 5: Dependency of normalized blocking capability of field-plate edge-termination structure on the distance between the p-well regions

the MOSFET trenches form stripes, one can distinguish between two basic layout situations as depicted in Fig. 4. Note, in Fig. 4 as well as in all other drawings the oxide layers such as the field oxide in the trenches and on the semiconductor surface are omitted, otherwise it is not possible to view the other structure details. The edge-termination trenches can simply be continued in the same direction as the active cells do, alternatively the edge-termination trenches can run perpendicular to the active cell stripes. In both cases, assuming an appropriate distance between active cell region and edge-termination region is maintained, the blocking capability of the termination structure is mainly dependent on the distance of the p-well regions. A graph showing this dependency can be seen in Fig. 5. Depending on the distance between the basic structures, the breakdown voltage increases until reaching the maximum value. A further increase of the distance reduces the blocking capability of the structure.

Fig. 6 illustrates the avalanche generation within the basic element of the edge-termination for a blocking capability of 150 V. The situation shown is for a structure on the left side of the blocking voltage maximum in Fig. 5. As can be seen, maximum avalanche generation is found at the outer end of the structure under this condition. Consequently, larger breakdown voltages can be realized by simply adding more field-plate rings. Anyway it is seen from Fig. 6 that avalanche generation can also be found below the trench. In case of a too large distance between the basic structures, this second location of avalanche generation shows increasing generation rate and the blocking capability of the structure decreases. If the



Fig. 6: Simulated avalanche generation rate of the field-plate trench termination structure (red = maximum generation rate, green = no avalanche generation)



Fig. 7: Layout detail of corner region and gate finger (left) and view of the simulation structure as marked by the red rectangle (right)



Fig. 8: Potential distribution (left, red = maximum potential, blue = minimum potential) and avalanche generation (right, red = maximum generation rate, green = no generation) of gate finger structure as a part of edge-termination

location of avalanche shifts completely below the trench, the next connecting structure can not takeover the potential anymore since breakdown already occurs. Consequently, the distance between the basic structures of the edge-termination has to be small.

One of the challenges of this structure is the design within the chip regions, where the edge-termination trenches can not run straight as described before. This is obviously the case in the chip corners, but also below the crossing gate finger due to existing design rules, as schematically shown in Fig. 7. In both affected areas, the trenches need to run perpendicular to the normal edge-termination trenches. Three of the perpendicular trenches form a group, which are connected to the same p-well, therefore being of equal potential. Again, 3D device simulation is used for the investigation of theses structures. The simulation structure as shown in Fig. 7 consists of the rectangular-shaped part highlighted with the red rectangle. In comparison to the case of the basic elements as shown in Fig. 4, the simulations additionally



Fig. 9: SEM image of the field-plate edge-termination structure



Fig. 10: Dependency of normalized measured blocking capability of field-plate edge-termination structure on the distance between the ring structures

show that the optimum distance of the p-well regions has changed and that the maximum breakdown voltage is more sensitive to the distance between the ring elements. Fig. 8 shows potential distribution and avalanche generation in this case of already large ring distances. For this example, the location of maximum avalanche generation is found at the bottom of the mesa region between the last trench of the first group and the first trench of the second group. In this case the blocking capability of the structure can not be increased by adding another ring. The process window is therefore determined by the allowed deviation from the optimum distance.

Fig. 9 shows the cross-section of a manufactured structure where both p-wells and field-plates are visible. The creation of a number of different test chips allowed the verification of the basic dependencies. The example shown in Fig. 10 demonstrates the breakdown voltage dependency on the distance between the basic ring elements. In contrast to the simulation results shown in Fig. 5, not only the distance between the p-wells was changed but simultaneously also the mesa width between the rings.

Edge-termination structure based on oxide-filled trenches

Another suitable structure consists of a number of oxide-filled trenches. Between and below these trenches, p-doped areas are inserted as shown in Fig. 11. The oxide trenches simply form several rings which enclose the active cell region. At the surface of the silicon and at the bottom of the trenches, p-regions are introduced. These p-regions can be produced by one implantation step, it is necessary to protect the active cell regions during this step. Consequently, this edge-termination structure requires an additional layer while manufacturing.



Fig. 11: Edge-termination structure formed by oxide-filled trenches and basic layout (left) and basic chip layout (right)



Fig. 12: Simulated avalanche generation (left) and potential distribution (right) for the structure with oxide-filled trenches in case of breakdown

The blocking capability is ensured by depleting the p-regions. Therefore, the equivalent dose within the p-regions can not be chosen freely but is limited to a certain range. The achievable breakdown voltage of this structure is primarily depending on the number of oxide trench rings, while the effective p-dose controls the process window. Furthermore the distance between the oxide-filled trenches is also important, since this also defines the distance between the buried p-regions. In cases where the trenches are placed too close to each other, one large p-region might be formed due to subsequent thermal process steps which will avoid proper function of the edge-termination.

This structure can be designed in a way that the edge-termination always shows a higher blocking capability than the cell region. An example is given in Fig. 12. Here avalanche generation (left) and potential distribution (right) for a structure with two edge-termination trenches are shown as result of device simulation [5]. The avalanche generation rate is highest at the inner side of the last regular trench. Therefore, the breakdown location is pinned within the cell region and the edge-termination region achieved a higher breakdown voltage than the MOSFET cells. Consequently the avalanche current flows through the much larger area of the active region in the case of an avalanche event which supports an excellent avalanche ruggedness. The potential distribution of the structure is shown in the right of Fig. 12.

As previously mentioned, the number of oxide-filled trenches controls the achievable breakdown voltage. In our test structures, breakdown voltages of 180 V for one trench up to more than 275 V for three trenches were achieved. In Fig. 13, the sensitivity of normalized breakdown voltage on the p-dose of the buried p-regions is shown. Here it can be seen, the structure behaves in a rather robust manner towards



Fig. 13: Dependence of normalized breakdown voltage on p-dose



Fig. 14: SEM image of a oxide-filled trench test structure

changes in the p-dose. Fig. 14 shows a SEM image of a manufactured test structure, consisting of an edge-termination structure formed by three oxide-filled trenches. Unfortunately, the buried p-regions can not be seen in the image as the doping densities are comparatively low and additionally the p-regions are floating.

Comparison of edge-termination structures

The previous sections discussed two different edge-termination structures suitable for charge-compensation devices. Using test structures and numerous device simulations the two structures were compared.

Table I gives a compact comparison of the most important properties of the investigated structures. From the comparison it can be seen that the edge-termination employing oxide-filled trenches offers more advantages, although process costs are slightly larger due to the requirement of an additional required mask layer. For the oxide-filled trench structure two-dimensional simulations are usually adequate. This translates in less time to be spent for the simulations as a basic design tool. In case of the field-plate structure, it is mandatory to employ three-dimensional device simulation.

After a careful evaluation of the advantages and disadvantages of the two edge-termination structures

	Field-plate structure	Oxide-filled trenches
blocking capability	good	good
	edge-termination and cell-region	edge-termination shows larger
	own identical blocking capability	blocking capability as cell-region
avalanche ruggedness	fair	good
	breakdown starts in edge-region	breakdown starts in cell-region
scalability	good	good
	simply adding more rings	simply adding more rings
process costs	good	fair
	no additional layers required	requires one additional layer
occupied area	medium	small
	less than standard structures	defined by the extension of buried
		p-regions
simulation complexity	high	medium
	complex design, 3D simulation	simple design, 2D simulations only
	mandatory	

Table I: Comparison of edge-termination structures

it was decided to continue a development based on the oxide-filled trench structure. Although in this concept an additional layer is needed, the development process is considered to be much faster since no time-consuming three-dimensional simulations are necessary. Consequently, the further development focused on the advancement of this concept. Preserving the advantages, the main task was the realization of an edge-termination structure which can be easily adapted to varying blocking voltages.

Device properties

The outcome if this development has been to offer a new scalable edge-termination structure. Incorporating of this structure into the already existing OptiMOSTM3 family extends the breakdown voltage capability to 250 V. This combination results in a device with unrivaled $R_{DS(on)} \times A$ characteristics.

Compared to a state-of-the-art edge-termination structure consisting of p-wells and field-plates, our new structure only occupies about 30% of the usually needed area. In conjunction with the use of the charge-compensation principle, these devices offer excellent values for on-resistance $R_{DS(on)}$ and figure-of-merit $FOM = R_{DS(on)} \times Q_g$. A comparison to the next best currently available competitor device is given in Fig. 15, clearly indicating the progress in terms of gained device performance. Therefore, these new devices offer superior solutions for a wide range of requirements. In high-current applications like motor-control, lowest ohmic devices in D²-Pak and TO-220 minimize conduction losses and reduce the number of paralleled devices in the system. In fast switching applications, the very low gate-drain-charge Q_{gd} and $FOM_{gd} = R_{DS(on)} \times Q_{gd}$ cuts down on the switching losses and improves the overall efficiency. Devices available in SuperSO8 packages are therefore the perfect choice for applications like DC/DC converters or Class-D amplifiers. Furthermore, the very low on-resistance $R_{DS(on)}$ often allows for a change of the package. TO-247 packages can be replaced by TO-220, a D²-Pak or TO-220 can often be replaced by a SuperSO8, offering a much better switching performance at only a fraction of its former space requirement.

Another interesting and important issue is paralleling of several chips, especially in case of high-current applications such as motor-control. To meet the application requirements it is often advantageous to make use of complete power modules. This allows for an improved heat management and lower parasitics, both boosting the overall performance. Fig. 16 gives an example of the switching waveforms of large OptiMOSTM 3 150 V chips paralleled in a power module [6]. Here, a three-phase, full-bridge configuration was realized having eight chips in parallel on one DCB substrate with again two DCB's in parallel. Fig. 16 shows the switching behavior of one phase leg at a supply voltage of 80 V and a switched current of 500 A. The waveforms indicate a smooth switching behavior during the turn-off phase. The



Fig. 15: OptiMOSTM3 150 V, 200 V and 250 V Benchmark in R_{DS(on)} and FOM



Fig. 16: Switching waveforms of paralleled OptiMOS[™]3 150 V chips in a power module at an duty-cycle of 13%. Left: full pulse showing turn-on and turn-off (200A/div, 20V/div, 4µs); Right: detailed turn-off slope (200A/div, 20V/div, 80ns) [6]

relatively low voltage overshoot is due to the minimized, extremely low parasitic inductance of the design of the complete switch. No problems were observed.

Conclusion

A new, space-saving edge-termination structure suitable for charge-compensation devices based on fieldplates was developed. 2D and 3D device simulations were used to study the properties of the two different edge-termination concepts investigated. Based on the simulation results and the measurements on first demonstrators, both structures were evaluated. As the result, a scalable edge-termination structure has been developed, leading to an extension of the OptiMOSTM3 family.

These new OptiMOS^{TM3} MOSFET cover a voltage range from 150 V to 250 V and offer an outstanding benchmark performance in their voltage classes. The devices are suitable for a wide variety of applications, including DC/DC converters, Class D amplifiers and high-current applications like motor-control. Due to the very low on-resistance $R_{DS(on)}$ larger packages can be often replaced by smaller packages which allow for a better switching performance and less space requirements.

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