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Hybrid Junction Termination Consisting of a Variation Lateral Doping Structure and a Spiral Polysilicon Resistive Field Plate

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ABSTRACT A hybrid junction termination structure consisting of a variation lateral doping (VLD) region and a spiral polysilicon resistive field plate (PRFP) is proposed in this brief. Surface electric fields of the VLD region are modulated by the PRFP and distribute more uniformly. Compared with the conventional VLD structure with the same size, its measured breakdown voltage increases by 11%. The breakdown voltage still has a positive temperature coefficient. And, the leakage current changes very little from −40 to 150 °C. Besides, it is more immune to the deviation of the VLD dosage. The deviation range of the VLD dosage increase from −20% - +20% to −50% - +60% when the breakdown voltage keeps above 90% of the maximum value. No extra masks or process steps are needed in power devices with a MOS gate structure, because the gate layer can be used to implement the spiral PRFP. At last, the hybrid termination is not detrimental to the switching characteristic of the device.

INDEX TERMS Junction termination, variation lateral doping, polysilicon resistive field plate, power devices, dosage deviation.

I. INTRODUCTION

The junction termination is an essential part in a high-voltage vertical power device [1]–[3]. It influences the breakdown voltage of the power device. Size and manufacturing complexity are two main factors to consider when choosing a termination structure. Since the junction termination does not conduct current, its size should be as much as small and its manufacture technology should be simple. Some traditional junction termination structures, such as floating field limited rings [4], field plates [5], the junction termination extension or variation lateral doping (VLD) structure [6], are often used partly because their processing technologies are simple and cheap, usually compatible with the process of the power device. A practical solution is to use hybrid structures. For example, a semi-insulating polycrystalline silicon (SIPOS) field plate in conjunction with a p^- junction extension has been shown to be able to reduce the size of the termination [7]. However, its size is still larger than that of an optimized VLD termination. Some new junction termination structures, such as the trench-based terminations [8]–[11], have much smaller size. But the trench-filling process is complex. Among these structures, the VLD technology has a superior trade-off relationship between size and manufacturing complexity. So, it is widely used in modern high-voltage power MOSFETs. However, the breakdown voltage of the conventional VLD termination is sensitive to the deviation of the VLD dosage.

In this brief, a hybrid junction termination consisting of a variation lateral doping structure and a spiral polysilicon resistive field plate (PRFP) is proposed for power devices. Compared with the conventional VLD structure, it is more immune to the deviation of the VLD dosage. Besides, its measured breakdown voltage is also increased.

II. CONCEPT AND STRUCTURE

Fig. 1 shows the schematic cross-section of the proposed hybrid junction termination for n-channel power devices. It

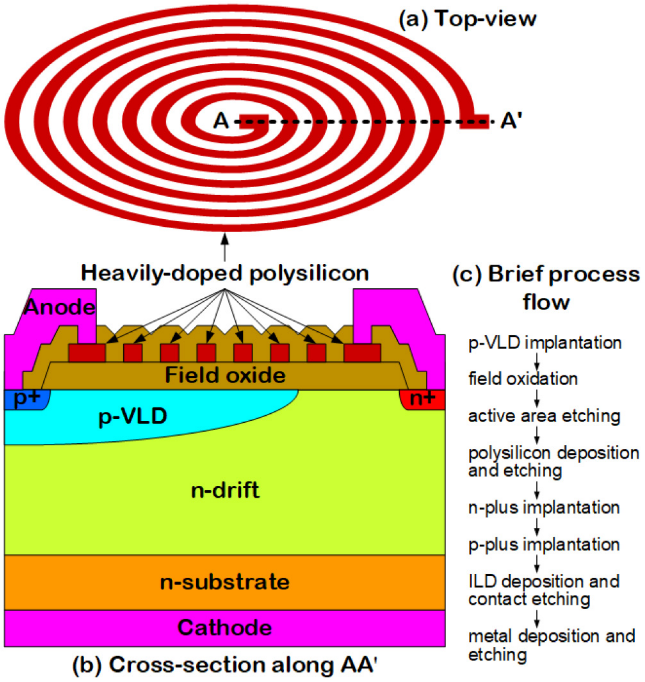

FIGURE 1. (a) Schematic layout of the spiral polysilicon resistive field plate (PRFP) layer. (b) Schematic cross-section of the proposed hybrid junction termination along AA'. The spiral PRFP layer is connect to the p^+ diffusion of the p-VLD region at point A and the n^+ channel stopper at point A', respectively, both by metals. (c) Brief process flow.

consists of a p-type variation lateral doping region and a spiral polysilicon resistive field plate. The dosage of the p-type layer varies laterally and decreases from the p^+ diffusion side. The spiral PRFP layer covers the entire junction termination. Its inside end is connected to the p^+ diffusion of the p-VLD region by the anode metal. Its outside end is connected to the n^+ channel stopper by a floating metal. Since the n^+ channel stopper lies outside the maximum depletion region, it has the same potential as the cathode electrode. Then, the spiral PRFP is connected between the anode electrode and the cathode electrode. And the external voltage applied on the cathode electrode is uniformly undertaken by the polysilicon layer.

In a 2D cross-section view, as shown in Fig. 1(b), the external voltage can also be considered as being uniformly undertaken by polysilicon field plates. The potential of each field plate increases gradually from the p^+ diffusion side to the n^+ diffusion side. Electric flux lines originate from these field plates, terminate on the silicon surface and modulate surface electric fields. The p-VLD later is depleted both by the n-drift layer and polysilicon field plates. Therefore, its dosage is larger than that of a conventional p-VLD termination. To combine the VLD and PRFP structures, some challenges must be overcome. First, their processes must be compatible. Second, their electrical characteristics must be matching. In the proposed hybrid termination, the polysilicon layer is heavily doped. It can also be used as the gate material in power devices with a MOS gate structure. So, no extra masks or process steps are added. The brief process flow is listed in Fig. 1(c). It is compatible with the standard process flow of high-voltage power devices with a MOS gate structure. Further, a thick field oxide layer is used to match electrical characteristics of the VLD and PRFP structures. Its effect will be verified by static and dynamic testing in the next section.

III. RESULTS AND DISCUSSION

The proposed junction termination is studied with the help of numerical simulators Taurus™ TSUPREM-4 [12] and Medici [13]. Mobility models related to impurity concentration, parallel electric fields, surface scattering, and the impact ionization model are included. The length of the region between the p^+ diffusion and the n^+ channel stopper is 110 μm. 52 polysilicon field plates uniformly distribute on the field oxide layer whose thickness is 1.7 μm. Each one has a width of 1 μm. The spacing of adjacent field plates is also 1 μm. The sheet resistance of the polysilicon layer is 6.6 $\Omega/\square$. In subsequent 2D electrical simulations, a resistor is connected between adjacent field plates. Its resistance will not affect the breakdown voltage of the termination. No matter what resistance is used, the external voltage is uniformly undertaken by field plates. The surface impurity concentration and the junction depth of p-VLD are respectively 8×10^{15} cm^{-3} and 7 μm. For comparison, a conventional p-VLD termination with the same size is also included.

Fig. 2 shows simulated distribution of electric fields in the junction termination with and without PRFPs at 700 V. They both have uniform and high electric fields along the p-VLD/n-drift junction. The zigzags in Fig. 2(c) and (d) come from the discontinuity implantation of the variation lateral doping region. It is obvious that the surface electric field of the hybrid termination is modulated by PRFPs. The surface electric field of the conventional p-VLD termination is low while that of the hybrid termination is high. Since there are no longitudinal electric fluxes on top of the p-VLD region, only transverse electric fields exits in the conventional p-VLD termination. They cumulate gradually along the transverse direction and result in peaks at the end of the p-VLD region. On the other hand, longitudinal electric fields are introduced by PRFPs and are superimposed on the original transverse electric fields caused by the p-VLD region. Therefore, the total surface electric fields are raised, as shown in Fig. 2(d). Since PRFPs are uniformly placed on the field oxide, surface electric fields also distribute more uniformly.

As is well known, the breakdown voltage of the VLD termination is sensitive to the deviation of the VLD dosage. Too many or too few impurities will reduce the breakdown voltage. Fig. 3 compares the change of the breakdown voltage with the deviation of the p-VLD dosage of two structures. The references are the samples with the highest breakdown voltages. For the conventional p-VLD termination, its breakdown voltage keeps above 90% of the maximum value when the deviation of the VLD dosage ranges from -20% - $+20\%$.

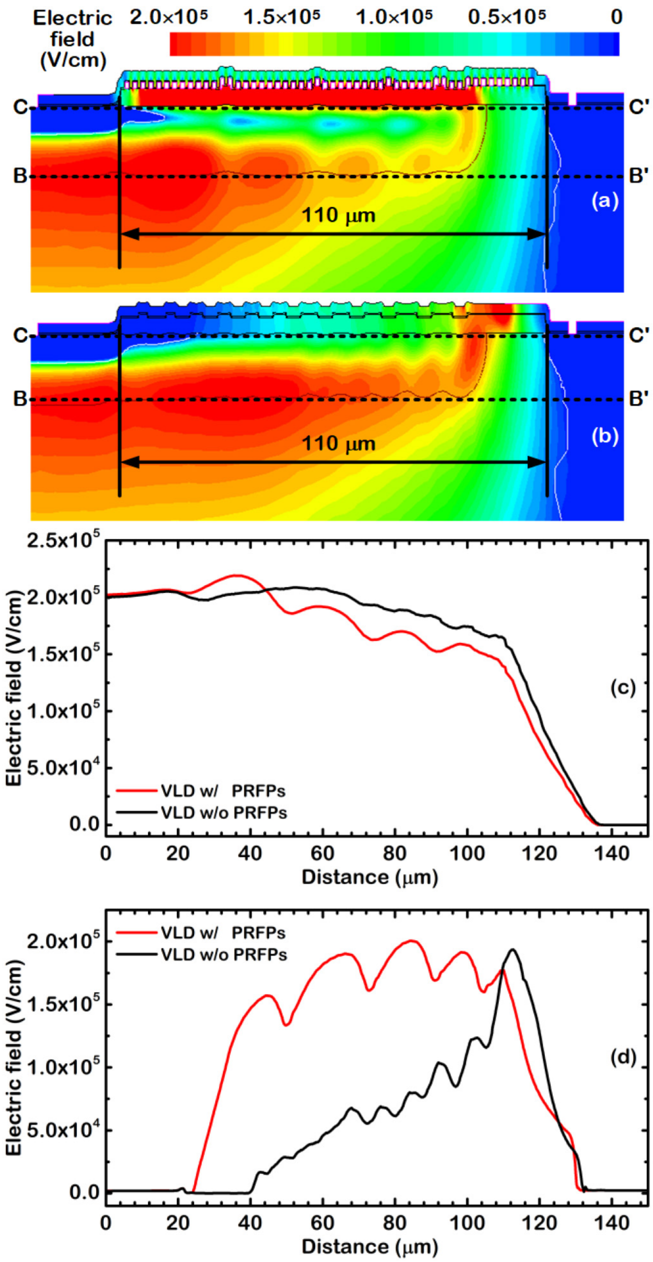

FIGURE 2. **Distribution of electric fields in the junction termination (a) with and (b) without PRFPs at 700 V. Comparison of the surface electric field profile in the junction termination area along (c) BB′ and (d) CC′.**

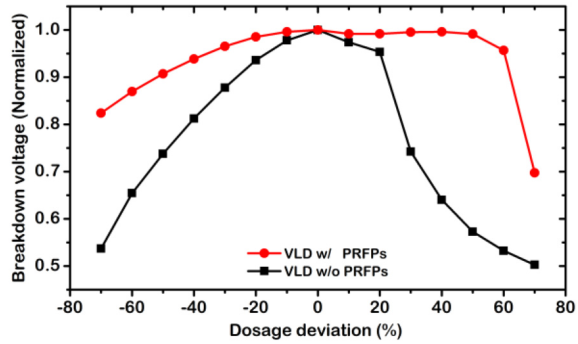

FIGURE 3. **Comparison of the normalized breakdown voltage as a function of the deviation of the p-VLD dosage. The references are the samples with the highest breakdown voltages.**

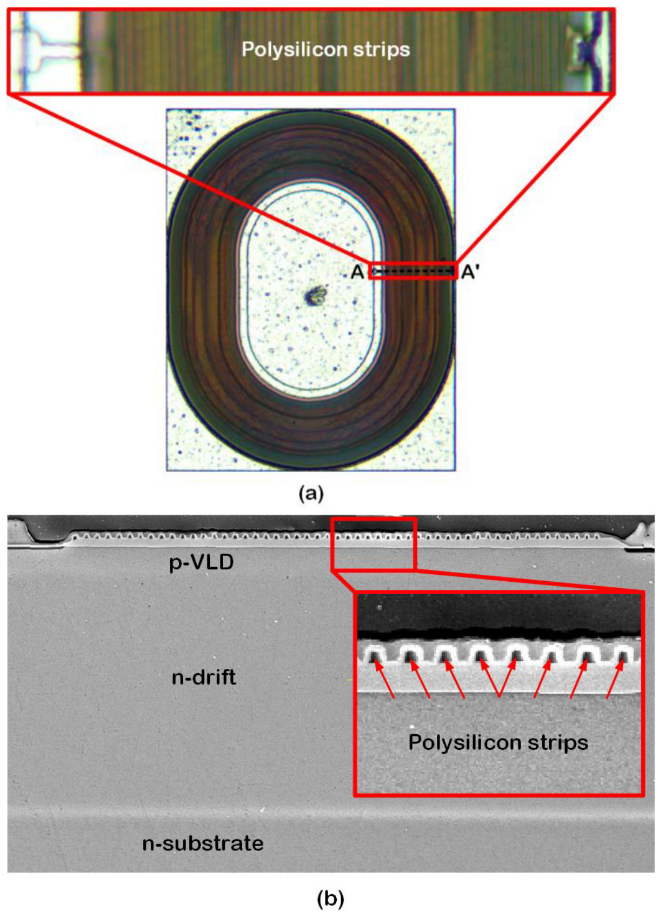

FIGURE 4. **(a) Microphotograph of a fabricated diode using the proposed hybrid junction termination. (b) Scanning electron microscope picture of the cross-section of the termination.**

Whereas, for the hybrid termination, this deviation ranges from −50% - +60%. Thus, the hybrid structure is more immune to the deviation of the VLD dosage than the conventional one. The reason is that surface electric fields are modulated by PRFPs. In a conventional VLD termination structure, when the p-VLD dosage decreases, electric fields gather near the anode side. They are distributed in triangles and lower the breakdown voltage. The PRFPs raise electric fields near the channel stopper side and increase the breakdown voltage. On the other hand, when the p-VLD dosage increases, electric fields tend to gather near the channel stopper side in a conventional VLD termination structure. The PRFPs raise electric fields near the anode side and also increase the breakdown voltage.

Fig. 4 shows the microphotograph of a fabricated diode using the proposed hybrid junction termination and the scanning electron microscope picture of its cross-section. The

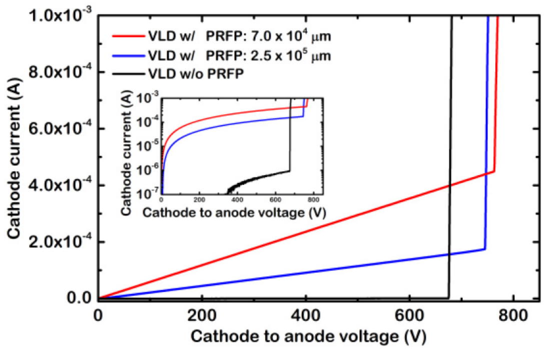

FIGURE 5. Measured blocking IV curves of fabricated junction terminations. All junction terminations have the same length of 110 μm. The inset shows the semilogarithmic coordinate.

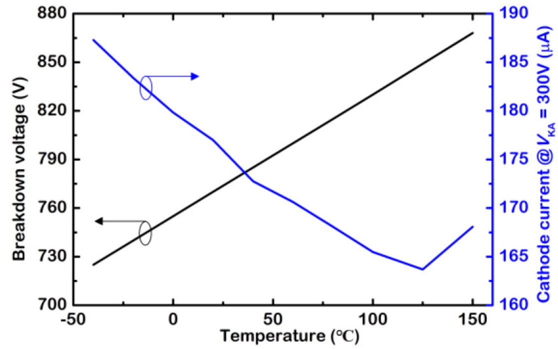

FIGURE 6. Measured temperature dependence of the breakdown voltage and the leakage current at $V_{KA} = 300$ V of the fabricated diode using the hybrid termination.

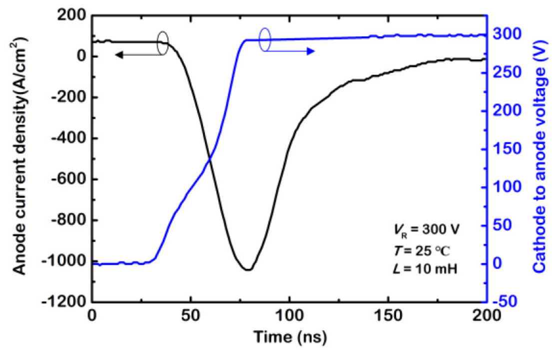

FIGURE 7. Measured reverse recovery waveform of the fabricated diode using the hybrid termination.

enlarged illustration shows the polysilicon strips. Fig. 5 compares the measured blocking IV curves of fabricated junction terminations. All samples have the same length of 110 μm. The breakdown voltage of the conventional p-VLD junction termination is 675 V. It increases to 763 V when the spiral PRFP is employed. The increasement is 11%.

Before breakdown, the hybrid junction termination behaves as a linear resistor, which is corresponding to the spiral PRFP. Its leakage current is three orders of magnitude larger than that of the conventional termination. There are two leakage paths. One is the reverse biased p-VLD/n-drift junction, the other is the spiral poly resistor. And the latter is the main path. So, the leakage current is mainly determined by the length and the sheet resistance of the spiral PRFP. Since the leakage current increases the off-state power of devices, it should be kept as small as possible. It can be reduced by increasing the length of the spiral PRFP. For example, the leakage current of the spiral PRFP is reduced from 177 μA to 68 μA at $V_{DS} = 300$ V, when its length increases from 7.0×10^4 μm to 2.5×10^5 μm. Therefore, the proposed hybrid junction termination is more attractive in large size chips, whose perimeters are long and so do their spiral PRFPs. Of cause, the leakage current can also be simply reduced by increasing the resistivity of the polysilicon layer. Simulated results show that the leakage current can be reduced to the same level as the conventional termination if the sheet resistance of the polysilicon layer increases to 66 kΩ/□. Specially, a SIPOS layer [7] can be used to implement the spiral PRFP.

Fig. 6 shows the temperature dependence of the breakdown voltage and the leakage current of the fabricated diode using the hybrid termination. The temperature range is −40 - 150 °C. The leakage current is extracted when the diode is reversed biased to 300 V. Just like a conventional diode, as temperature rises, its breakdown voltage increases. The increment exceeds 100 V in the measured range. On the other hand, the V-shaped leakage current changes very slowly with temperature. Below 125 °C, the spiral poly resistor dominates. As temperature rises, its resistance increases. Then, the leakage current decreases. Above 125 °C, the leakage current of the PN junction becomes noticeable. As temperature rises, it increases, and so does the total leakage current.

Fig. 7 shows the reverse recovery waveform of the fabricated diode using the hybrid termination. The forward current density and the supply voltage are respectively 70 A/cm^2 and 300 V. The peak reverse recovery current density and the reverse recovery time are respectively −1040 A/cm^2 and 135 ns when the commutation velocity is 345 A/μs. This implies that the hybrid termination is not detrimental to the switching characteristic of the device. Transient characteristics of the spatial PRFP and the p-VLD are well matched. The hybrid termination can be switched safely.

IV. CONCLUSION

This brief verifies that the breakdown voltage of the p-VLD junction termination can be increased, and its immunity to the deviation of the VLD dosage can be enhanced, by inserting a spiral polysilicon resistive field plate over it. No matter the VLD dosage decreases or increases, the PRFP layer modulates surface electric fields and makes them more uniform. The deviation range of the VLD dosage increase from −20% - +20% to −50% - +60% when the breakdown voltage keeps above 90% of the maximum value. The measured breakdown voltage increases by 11%, from 675 V to 763 V, when the spiral PRFP layer is employed. The breakdown voltage still has a positive temperature coefficient. And, the leakage current changes very little from −40 to 150 °C. No extra masks or process steps are needed to implement the hybrid junction termination in power devices with a MOS gate structure, because the PRFP layer can also be used as the gate material. The leakage current caused by the PRFP layer can be reduced by increasing the length of the spiral PRFP or using a high-resistance polysilicon layer. At last, the hybrid termination is not detrimental to the switching characteristic of the device.

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