Charge Balance Effects on UIS Performance of Trench MOSFETs

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Abstract

The Unclamped Inductive Switching (UIS) test is a widely used technique for evaluating the robustness of power MOSFETs under avalanche conditions. The aim of this paper is to optimize the charge balance condition for active and termination cells for optimal UIS performance, characterized by a higher and tighter avalanche current (I_{av} or I_{pk}) distribution across the wafer, resulting in a minimum loss in UIS yield during production. The paper investigates the design layout of active and edge termination cells to ensure that avalanche failures occur in the active cell area rather than in the edge termination cell area, which has a weaker UIS capability.

Approach

The shielded-gate trench FET is a charge balanced structure (Fig. 1) that requires a delicate balance of charge across the die layout (Fig. 2), that includes active cells, transition from active to termination cells, and the edge termination cells to achieve the best tradeoff between breakdown voltage, BV, and on-resistance, $R_{DS(ON)}$.

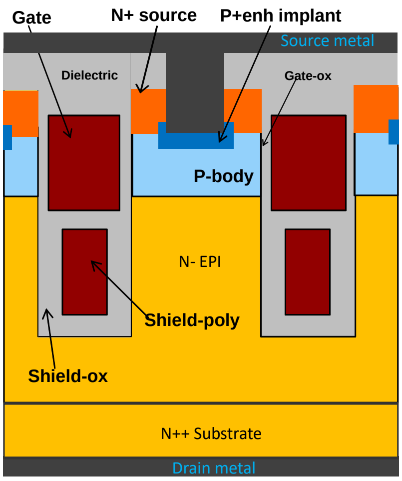

Fig. 1 Shielded-gate Trench MOSFET.

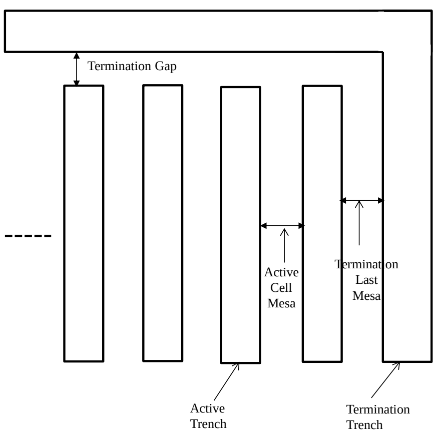

Fig. 2 Power MOSFET top view layout.

While a balanced charge across the die has the best tradeoff in terms of higher breakdown voltage and lower on-resistance, it unfortunately comes with the penalty of poor UIS performance [1]. The UIS robustness or the die's ability to handle the higher UIS energy depends on which portion of the die breaks down first and whether that specific portion of the die can withstand the high current and voltage during the avalanche time. If the termination edge cells or the transition cells break down earlier or at a lower voltage than active cells, peak current, I_{pk} or the UIS energy will be lower as termination or transition cells usually have smaller area than active area with little or no body contacts to absorb all the UIS energy. The purpose of a robust design is to make sure that breakdown occurs at the active cell region, which is loaded with source/body contacts to absorb all the currents during an UIS event.

It is also crucial that both active and edge termination cells have a good breakdown voltage margin before the BV falls off the cliff on the charge balance curve (Fig. 3) and fails to meet the minimum BV requirement. In most cases, the breakdown voltage of active and termination cells is designed to stay on the left-hand side of the charge balance curve (under-charge region, labeled in Fig. 3) with active cells having a lower BV (Point-A) than the termination or transition cells BV (Point-B). It is not desirable to design the active and termination cells' breakdown voltage on the other side of the charge balance curve (Point-C, over-charge region, labeled in Fig. 3) as the BV and UIS robustness become more sensitive to process variation or prolonged field use.

Experimental results have shown that a small amount of charge imbalance between active cell and termination edge cell can lead to higher and tighter avalanche current (I_{av} or I_{pk}). Hence, the active cells are deliberately designed more under-charged than the edge termination cells (termination last mesa and termination gap cells) by making the active cell mesa narrower than the edge termination cells. In other words, the active cell mesa has a lower charge (Q=width*doping conc) than the termination last mesa charge and the termination gap charge, pushing the termination last mesa and the termination gap BV (Point-B in Fig. 3) higher than the active cell BV (Point-A in Fig. 3).

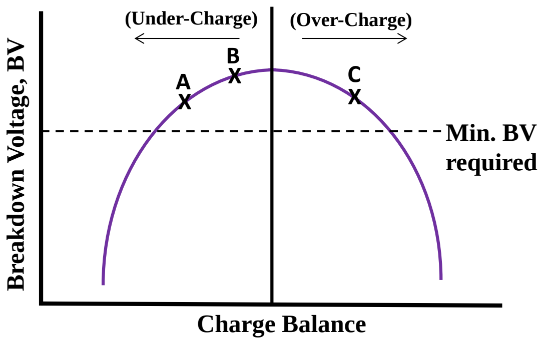

Fig.3 Charge balance curve.

Results and Significance

Figs. 4a, 4b, and 4c illustrate the distribution of peak or maximum avalanche current with respect to design, trench depth, and PHV body dose for a 60V product.

Fig. 4a shows that a higher I_{pk} and tighter distribution is achieved when the termination last mesa is wider than the active mesa. This results in the lowest UIS related yield loss across trench depth and PHV body dose variations.

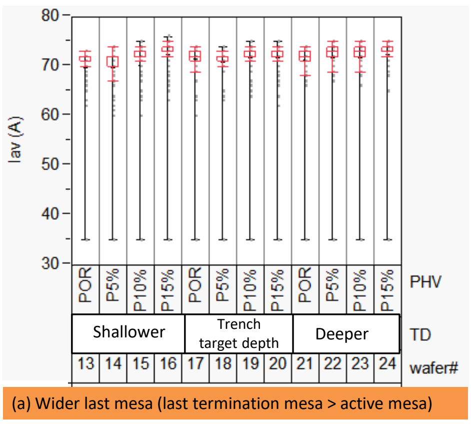

Fig. 4a Peak avalanche current (Ipk or Iav) distribution – last mesa wider than active mesa.

Fig. 4b shows that a lower and widely distributed I_{pk} is observed when the width of the termination last mesa is narrower than the active mesa, leading to significant UIS yield loss. A deeper trench improves the I_{pk} value, but the distribution is still significantly wider for manufacturing.

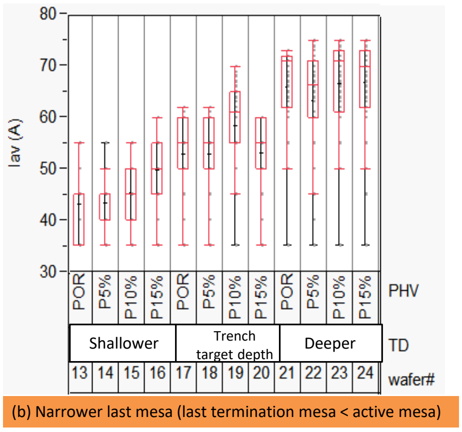

Fig. 4b Peak avalanche current (Ipk or Iav) distribution – last mesa narrower than active mesa.

Fig 4c shows that the I_{pk} distribution is better than that in condition (4b) with equal active and termination last mesa widths, but the I_{pk} distribution is still not as good as that in condition (4a) when last mesa is wider than the active mesa.

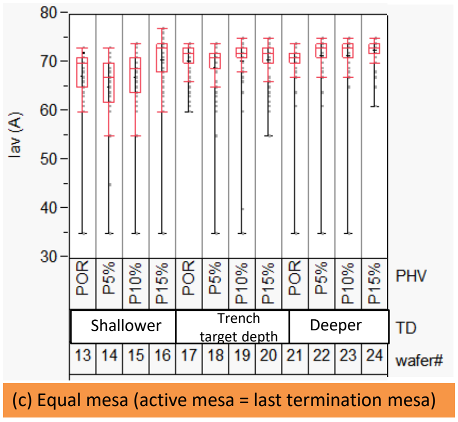

Fig. 4c Peak avalanche current (Ipk or Iav) distribution – last mesa equal to active mesa.

Trench depth and PHV dose has little or no impact on UIS distribution based on Figs. 4a-4c, hence, trench depth and PHV conditions are chosen for the best tradeoffs for BV, threshold voltage, and on-resistance.

Fig. 5 shows the BV_{DSS} distribution with respect to trench depth, PHV body dose, and mesa variations. Narrower mesa and the shallower trench have lower BV_{DSS} comparatively.

Fig. 6 illustrates the TCAD impact ionization rates [2] for three different mesa conditions – impact ionization rates move from the last mesa towards the active cells, as the last termination mesa width moves from narrower mesa width to equal mesa width, and then to wider mesa width. This TCAD impact ionization study validates the experimental findings that the wider last mesa shifts the impact ionization rates from the termination cells towards the active cell region, resulting in improved UIS performance.

Fig. 7 shows the typical burnt marks after UIS failure. For the case with a wider termination last mesa, the failure burnt marks are in the active cell area as desired. And, for the case with a narrower termination last mesa, the failure burnt marks are always at the die edge or at termination last mesa, which is not desired.

Conclusions

The paper presents that a small amount of charge imbalance between active cell and termination cell can lead to higher and tighter UIS energy capability. This charge imbalance is achieved by designing the last termination mesa wider than the active cell mesa in the die layout, considering a specific doping condition. The experimental findings are further validated by a TCAD study.

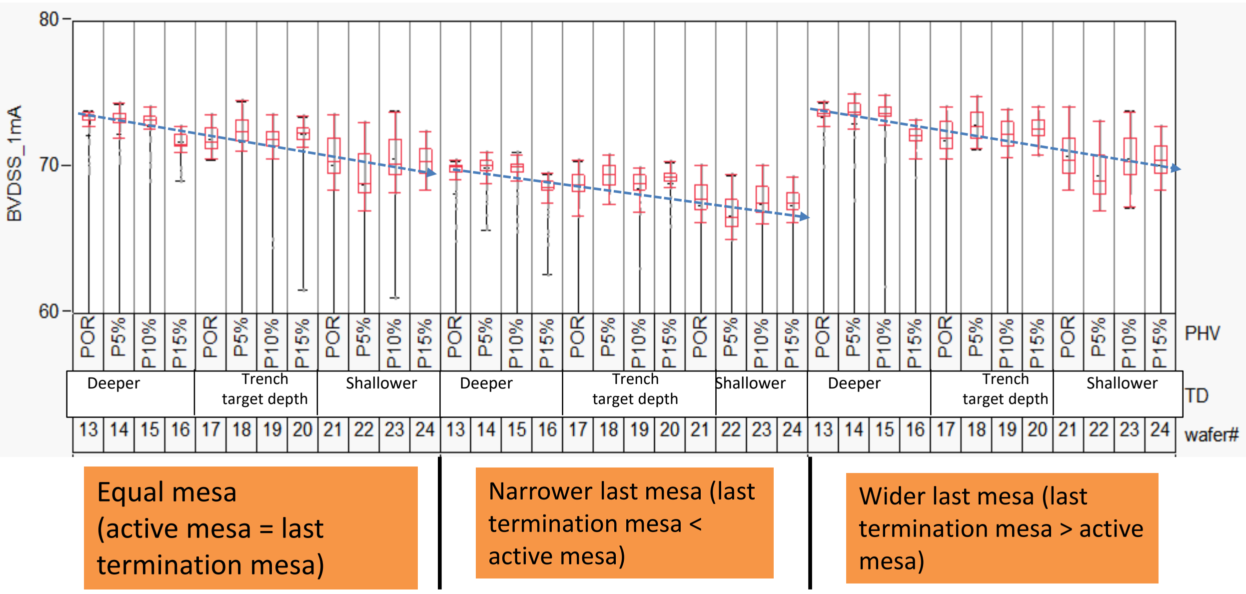

Fig. 5 BVdss with trench depth and body PHV dose variations for equal mesa, narrower mesa, and wider last mesa designs.

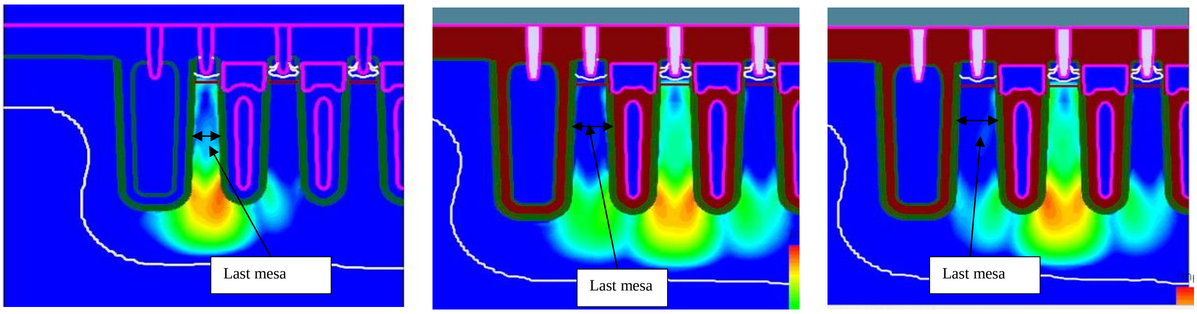

Fig. 6 Impact Ionization rates at breakdown. Left: narrower last mesa; Center: equal active and termination mesa; Right: wider last mesa.

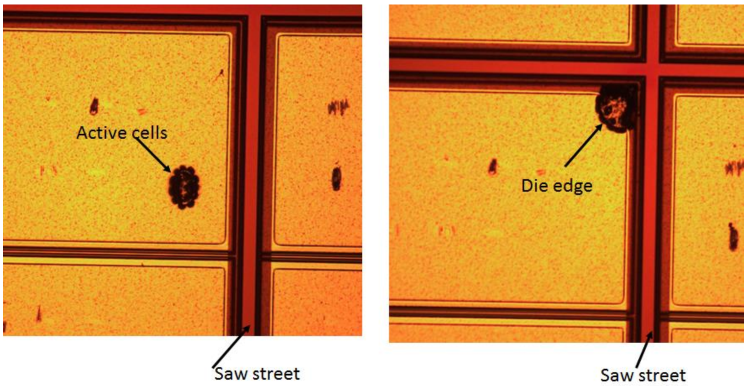

Fig. 7 Burnt marks after UIS failures; Left: wider termination last mesa, usually seen in the active cell area (preferred case); Right: narrower termination last mesa, usually seen in the die edge corner (worst case).

Acknowledgment

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References

[1] Insulated gate semiconductor device having trench termination structure and method – Patent Application No. 16/134,598.
[2] Sentaurus TCAD Process/Device Simulation Tools – SPROCESS, SDEVICE.