Characterization of Trench Schottky Diode with Trench Bottom Oxide (TBO) Process

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***Abstract*- A new Schottky diode structure namely as TBO Trench Schottky diode is proposed. Introduction of TBO process to the trench Schottky diode has shown better device characteristics. In this study, the trench bottom oxide (TBO) process was developed in order to increased reverse blocking voltage of Schottky diode. As a result from the study, an improved reverse blocking voltage has been achieved. TBO layer in trench structure can reduce the electric field crowding at the corner of trench bottom then increased the breakdown voltage as shown in Fig. 1 and Fig. 4. From experimental results, breakdown voltage for Schottky diode structure with TBO is about -64.50V whereas the Schottky diode structure without TBO is around -60.50V. There is about 4V difference of breakdown voltage due to TBO effect. Another important factor that also determines the breakdown voltage of Schottky diode is gate oxide thickness. Thicker gate oxide demonstrating higher breakdown voltage.**

Keywords-Trench Bottom Oxide (TBO), trench Schottky diode, Electric field

I. Introduction

Schottky diode is a rectifying device which electrically non-linear contact between metal and the N-type semiconductor [7]. It is well known that a Schottky diode has an attractive capabilities but it has significant limitation that making them not useable in some applications [1]. In Schottky diode, the main significant limitations are lower reverse voltage and higher reverse leakage current [1-2]. Moreover, the capability of Schottky diode is having a lower forward voltage which offers the fast switching speed mode. It has been widely used in power supply circuits with low operating voltages due to the availability of outstanding devices based upon the silicon technology [7].

In 1995, the trench MOS barrier (TMBS) structure was proposed to overcome the limitation of Schottky diode [5]. The concept in TMBS structure is different with conventional Schottky diode where the trench structure is introduced. In this device, the trench structure was designed in the N^- drift region. Then, the MOS structure is formed at the sidewalls and on the trench bottom. The top surface is used to form the Schottky contact [5]. By making this development structure, the reverse blocking capability can be improved. The lower on state voltage can be realized due to the charge coupling between N^- drift region and metal on the trench side walls [5]. Hence, it is demonstrated that the electric field is reduced at the Schottky interface. Accordingly, it causes the reverse leakage current decreases through the reduction of Schottky barrier height lowering [5].

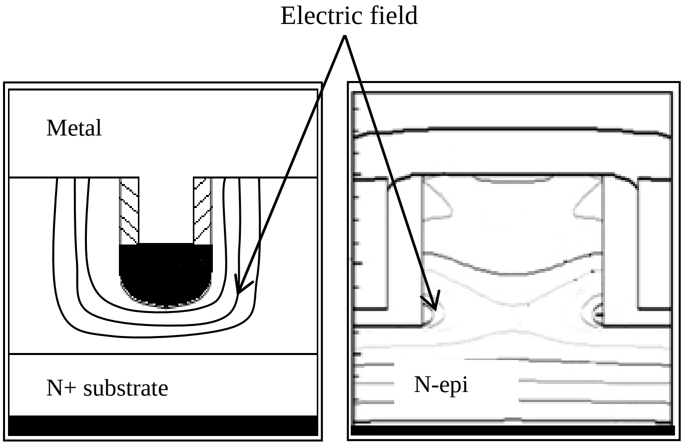
In TMBS structure, when the trench depth increases, the electric field at the trench corner will also increase. However, the electric field exhibits two peaks placed at the metal-semiconductor interface and at the trench bottom of region [8]. The modifications from the TMBS with the form of graded doping TMBS (GD-TMBS) [3], is then proposed to overcome the limitation of the TMBS. The GD-TMBS described as a non-uniformly doped drift region to enhance breakdown capability while maintaining a very low forward voltage drop [3].

Miin-Huang Juang, *et al.,* proposed another technique which is the Trench MOS barrier Schottky rectifier (TMBS) with a counter-doped trench bottom implantation. It was proposed to further enhance the blocking voltage capability of the conventional TMBS rectifiers [8]. In this research, the peak electric field is reduced near the trench corner by implementing a counter doped implantation region. The region is created in the epitaxial layer below trench bottom [8]. On the other hand, Q. Zhang, *et al.*, proposed a variation of the TMBS diode structure. It consist of a large number of MOS on Schottky region integrated without the need for complicated trench etching steps called planar MOS Schottky diode (MOSSD) [9]. By using MOSSD structure, the reverse leakage current has been reduced by one order of magnitude. In fact, the reverse breakdown characteristic is improved from soft breakdown to abrupt breakdown.

In this study, a TBO Trench Schottky diode structure has been proposed. In this concept, this comes up with utilize a metal-oxide-semiconductor (MOS) structure incorporated within trenches etched around the Schottky contact. In the MOS trench of bottom, the thickness of TBO layer is created using high density plasma (HDP) deposition. By rounded structure at the trench bottom of corner, the high electric field at the corner of trench can be extensively reduced through an experimentally deposited of 0.15 µm oxide. In this research, the oxide thickness of TBO plays an important role in an improving the performance of trench Schottky diode. It be able to enhanced the reverse blocking voltage and reduces the leakage current performance without effecting the lower forward voltage characteristic.

II. Device Concept

The basic structure of TBO trench Schottky rectifier is shown in Fig.1 (a). The device structure is similar to other techniques such as TMBS. In this device, a MOS structure is formed at the sidewalls whereas the 0.15 µm of TBO layer is formed in the trench bottom. The electrode in the trench area is filled with polysilicon and the top of mesa surface is used to form the Schottky contact.



(a) (b)

Fig. 1. (a) The schematic device structure of the Trench Schottky Diode with TBO and (b) Trench MOS Barrier Schottky (TMBS)

III. Design and Fabrication

Schottky diode with trench MOS structure is designed and fabricated on N-type epi wafer. The N-type epi layer is grown on 0.6 Ω cm N^+ substrate. The epi doping profile is 8.45 x $10^{15}cm^{-3}$ with a thickness of 6 µm. It has capability to hold up 60 V reverse voltage. The silicon trench structure is formed by reactive ion etching (RIE) process. Then followed by gate oxidation, poly deposition and etch back process to create the trench. Multi-trench single diode structure device design is used in this study. A thicker oxide is designed at the trench bottom structure as shown in Fig 1(a).

The baseline trench depth of 1.5 µm, mesa width of 0.6 µm, trench width of 0.4 µm, trench gate oxide thickness of 800 Å and thick trench bottom oxide (TBO) of 0.15 µm are chosen for 60 V device. Then 4000 Å of oxide layer is grown on the surface of the silicon wafer. Tetraethylorthosilicate (TEOS) layer is used as a hard mask. This structure is then patterned and etched using photoresist as a mask, followed by the silicon etch process. The photoresist is then removed by plasma resist strip process.

The trenches structures were etched by reactive ion etching (RIE) process. All oxide in the trench is removed followed by sacrificial oxidation process to repair damaged along the sidewalls. The trenches with smooth vertical sidewalls and round surface at the bottom are obtained. It is an advantageous to have the trench bottom rounded off than a sharp corner since it helps to reduce the electric field crowding at the corner. The 0.15 µm of thicker oxide is then deposited in the trench bottom using high density plasma (HDP) deposition process. Next step is TBO resist strip process to remove oxide along the sidewalls and leave the thick oxide in the trench bottom. Then, 800 Å gate oxides is grown in the furnace at 950ºC.

This is then followed by polysilicon deposition to refill the trenches. The polysilicon is doped with phosphorous. It is then etched back to planarize the structure and followed by pre-metal deposition process. The pre-metal dielectric (PMD) was then stripped off to expose the silicon to form the contact area. Titanium (Ti) and titanium tungsten (TiN) is patterned using sputtering process to create the Schottky barrier metal contact. Finally, the backside metallization using AlCu. The process flow is summarized in the Fig 2.

Once fabricated, the devices are tested for both characteristic forward and reverse voltage with 4145B Semiconductor Parameter Analyzer (Agilent Technologies) and Micromanipulator Prober. Moreover, the Semi-auto Micro-Manipulator prober and DC voltage source (Keithley 236 SMU) are also used for characterization.

Process flow	Structure
1.Oxide mask 2.Trench pattern 3.Trench Si etch	
4. Wet oxide etch 5. Sac oxidation	
6.Oxide deposition and etch back for TBO 7.Gate oxidation	
8.Poly deposition and etch back 9.PMD deposition	

10.Contct pattern and etch 11.Barrier deposition and RTA	
12. Metal pattern and etch	

Fig. 2. The process flow of Trench Schottky Diode with TBO process

I. EXPERIMENTAL RESULTS

A. Forward voltage characteristic

Under forward bias condition, the potential Schottky barrier will reduced and allow current to flow across the metal-semiconductor junction (schottky contact). The current flows from metal (anode) through the drift region between the trenches to the substrate (cathode). Electrons are the majority carriers for this Schottky diode. Forward voltage is the voltage drop across the schottky contact. In the case of power Schottky rectifiers, a thick lightly doped drift region must be located below the schottky contact to allow supporting the reverse blocking voltage. Very little depletion of the space between the trenches is observed with the MOS structure during on-state current flow.

Based on result, TBO structure with drift region thickness of 6 µm and doping concentration of 8.45 x 10^{15} cm^{-3} are shown in Fig. 3 and 4. The *I-V* characteristics for forward voltage drop in trench Schottky diode with different thickness of TBO process are observed in Fig. 3 and 4. The forward voltage drop with deposition of 0.15 µm TBO is 0.65 V similar to the trench Schottky diode without TBO as shown in Fig. 3. This experiment is examined for the same gate oxide thickness which is 800 Å. The depth trench of 1.5 µm, 0.6 µm mesa width and 0.4 µm trench width is used to analyze the effect in the forward voltage characteristic. As a result, no significant forward voltage difference between Trench Schottky diode with and without TBO process for TBO thickness of 0.15 µm.

Fig. 4 shows the *I-V* curve for 0.3 µm of TBO. It was observed that, TBO process with 0.3 µm thick bottom oxide significantly increased the forward voltage by 0.12 V higher than the 0.15 µm of TBO. It is because of the resistance increased at the drift region. Due to TBO process, the electric field will increase at the gate oxide and bothered the resistance at the drift region area. The resistance will become decreased and forward voltage is higher.

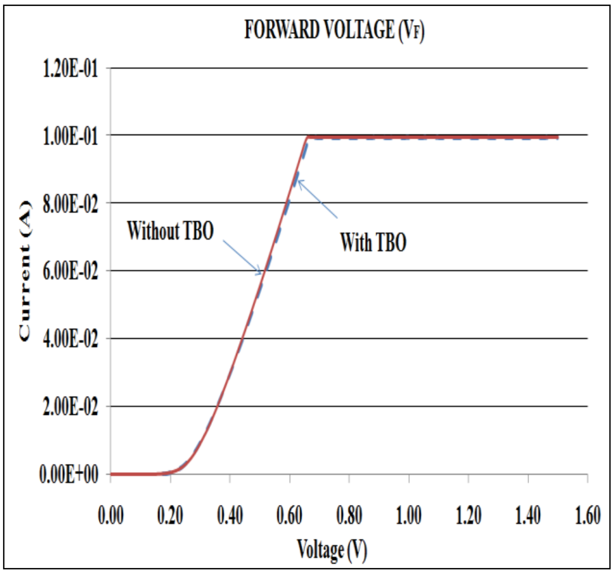


Fig. 3. The forward *I-V* characteristic for Trench Schottky diode with TBO and without TBO where the thickness of TBO is 0.15µm

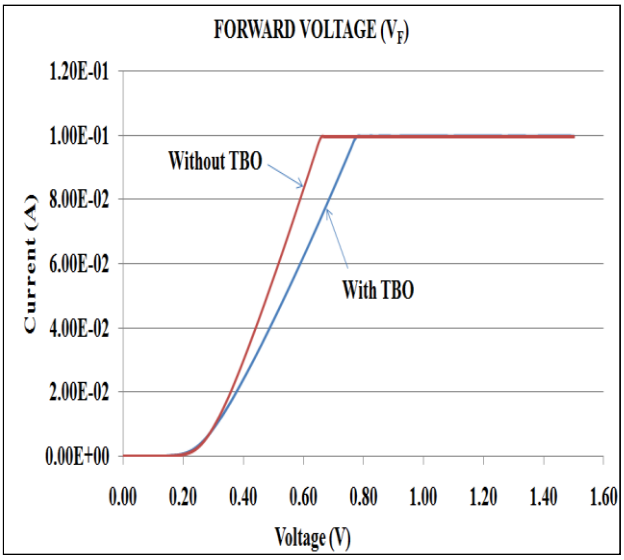


Fig. 4. The forward *I-V* characteristic for Trench Schottky diode with TBO and without TBO where the thickness of TBO is 0.30um

B. Reverse voltage characteristic

The reverse blocking capability of 60 V trench Schottky diode with different thickness of TBO are shown in Fig. 5 and 6. Under reverse bias condition, the negative bias is applied to the metal. Due to that, the voltage is supported across the drift region with the maximum electric field located at the metal-semiconductor contact since no voltage can be supported within the metal. When a reverse bias is applied, deep-depletion regions form at the MOS structure along the vertical sidewalls of the trenches. The potential barrier is formed below the Schottky contact by the extension of a depletion region from the MOS interface [7]. This suppresses the electric field at the Schottky contact preventing the large increase in the leakage current with reverse bias observed in the normal Schottky rectifier structure. The rounded off corner is chosen to reduce the electric field at the trench bottom as shown in Fig. 1 (a). The trench bottom oxide thickness is varied from 0.15 µm to 0.30 µm. The wafer is examined for the same gate oxide thickness which is 800 Å. The trench Schottky diode with TBO is demonstrated an increasing in reverse voltage as compared to the trench Schottky diode without TBO as shown in Fig. 5.

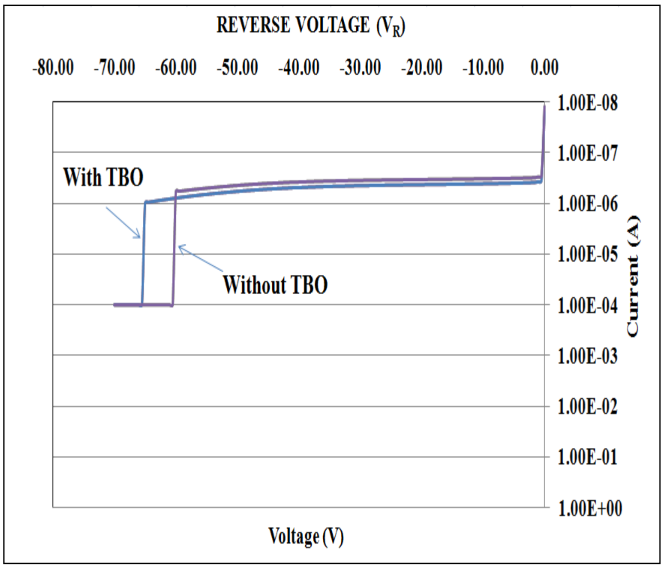


Fig. 5. The reverse *I-V* characteristic for Trench Schottky diode with TBO and without TBO where the thickness of TBO is 0.15um

The breakdown voltage for with TBO is -64.50V whereas without TBO is -60.50V**.** There is about 4 V difference of breakdown voltage due to TBO effect. As can see in Fig. 5, by comparing both results with TBO and without TBO, there is slightly difference in the leakage current. Besides that, the leakage current is reducing with a larger Schottky barrier height in the blocking state [7]. Since that, the electric fields at the Schottky interface can be reduced [3]. Due to TBO effect, it is clearly illustrated that the breakdown capability is enhanced and reverse leakage current is decreased compared to the without TBO. But, there are only little changes to the leakage current due to TBO process. In the other words, TBO process is compatible in reverse leakage current.

Fig. 6 shows the effect of 0.30 µm of TBO where there is improvement in leakage current for without TBO. Therefore, without TBO is slightly better in term of leakage current and reverse voltage. However, there is only 0.5 V difference in breakdown voltage for both with TBO and without TBO. It is demonstrate very little changes for both characteristic in 0.3 µm of TBO. As a result, it can be concluded that the 0.15 µm is more suitable for improvement in reverse blocking mode comparing to the 0.3 µm.

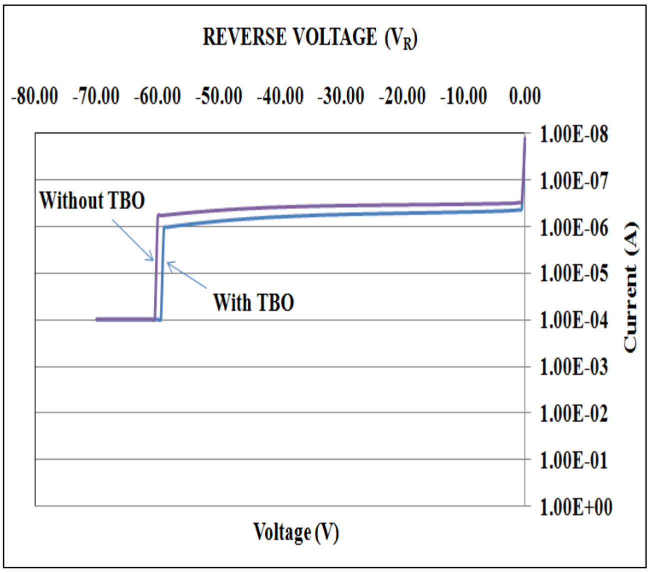


Fig. 6. The reverse *I-V* characteristic for Trench Schottky diode with TBO and without TBO TBO where the thickness of TBO is 0.30um

For the conventional of TMBS structure as shown in Fig. 1(b), a large peak electric field is generate near the corner of trench bottom [8]. Due to that, the thickness of TBO is used in order to reduce the electric field from crowding at the trench corner. In this experiment, silicon oxide with tetraethylorthosilicate (TEOS) is used as oxide. Silicon dioxide acts as insulating dielectrics and passivation layer. The SiO_2 layer of devices has to be capable in reducing the parasitic capacitance and trench filling [10]. The thicker gate oxide is another factor in order to determine the higher breakdown voltage due to the increasing of the electric field at the gate oxide.

By implementing the TBO process, the distribution of electric field is very important in order to enhance the breakdown characteristic which the increasing of electric field acts as a function of higher breakdown voltage. The 0.15 µm of TBO can be applied to improve the performance of trench Schottky diode compared to the 0.3 µm of TBO. The reverse voltage for 0.15 µm exhibits 4 V higher than the 0.3 µm of TBO. It shows that the 0.3 µm of TBO is not suitable to use in trench Schottky diode. It can be concluded that the reverse voltage of trench Schottky diode structure can be significantly enhanced with implementing the 0.15 µm of TBO.

IV. Conclusion

In this study, the trench Schottky diode with trench bottom oxide (TBO) process is designed and has been characterized. The selected thickness of TBO plays a main role in order to improve the breakdown voltage. The forward and reverse characteristic of trench Schottky diode devices with TBO process are studied and characterized in order to get a better result of reverse blocking voltage.

By proposing the trench Schotttky diode with TBO process, the electric field can be reduced at the trench bottom while increasing the reverse blocking voltage with 0.15 μm TBO. Hence, these devices exhibit a significant improvement in reverse voltage while maintaining the forward voltage characteristic and the objective from this research is achieved.

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