Simulation and Characterization of a High Voltage Trench MOS Barrier Schottky Diode

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Abstract - A diode structure which called High Voltage Trench MOS Barrier Schottky Diode has been designed and described in this paper. This type of diode has high voltage blocking capability that suitable to be used for rectifier circuits in various applications such as solar cells, reverse battery protection, switching power supply, dc-to-dc converter and many more. This Schottky diode has low forward voltage and high reverse voltage characteristics. In this study, deep trench MOS structures were introduced to the conventional Schottky diode which then increased the reverse voltage blocking capability. It was confirmed by simulation results which the trench structure has reduced the electric field at silicon surface and distribute it into the silicon bulk hence increasing the breakdown voltage. The device is capable to hold higher breakdown voltage (>45V) with lower leakage current. Same electrical characterization has been performed on fabricated sample to support the simulation result. Another critical parameter, gate oxide thickness is also can directly affect the device characteristic. It was experimentally studied and verified which thicker oxide has higher reverse breakdown voltage.

Keywords: Trench Schottky diode, numerical simulation, Schottky barrier, electric field.

I. INTRODUCTION

In many applications, such as in power supply circuit with low operating voltage, it is desirable to have a device with very low forward voltage drop and have small reverse leakage current in order to reduce the power dissipation by the diode. Low power dissipation will give rise to highly efficient power electronic system [1]. Due to the availability of excellent devices, Schottky diode offers attractive applications such as low on-state voltage drop and fast switching behavior. Schottky diode is a unipolar device, where the current transport is mainly due to the majority carriers and therefore it does not suffer from the charge storage effect that can limit the switching speed [2]. Moreover, other than having a lower forward voltage drop, it also has high frequency capability and low capacitive effect [3]. Unfortunately, there is trade-off between breakdown voltage and forward voltage of Schottky Diode and it is limited by resistance of drift region. The resistance of the drift region increases rapidly with increasing blocking voltage which cause the forward voltage drop to increase [4, 5]. Besides that, another factor that influenced the premature breakdown of a conventional Schottky diode is due to metal electrode sharp edge effect in metal to silicon contact hole [6, 7]. Many efforts have been done to improve the breakdown voltage characteristics. One of the efforts is the implementation of trench MOS structure in conventional Schottky diode that also called Trench MOS Barrier Schottky Diode. This trench device structure can improve the trade-off characteristics between blocking voltage and forward voltage drop which results in lower on-state voltage drop, decreased reverse leakage current and improved reverse breakdown voltage [8]. This paper will discuss the simulation results of Schottky diode with deep trench structure that can produce high reverse breakdown voltage. In order to support the simulation results, some electrical characterizations on similar device fabricated in FAB have been done.

II. DEVICE STRUCTURE

The structures of the conventional and trench MOS barrier Schottky diode are shown in Fig. 1 and Fig. 2. From these figures, it can be seen that the difference between these two structures are the trench structure in the Fig. 2. Oxide layer was deposited at the bottom and sidewall of the trench followed by metal (or polysilicon) deposition for gate electrode in the trench region. By the existence of the oxide layer between the metal and semiconductor at the trench region has produce the metal oxide semiconductor (MOS) structure. Schottky contact is formed along the metal and semiconductor contact for the conventional Schottky diode whereas for the trench Schottky diode, the top surface of the mesa region will act as a Schottky contact.

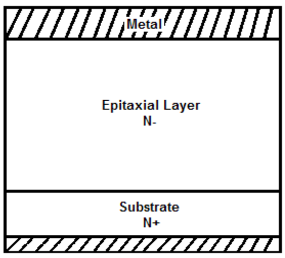

Fig.1: Cross section of the conventional Schottky Diode

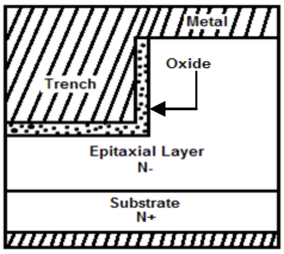

Fig.2: Cross section of the trench MOS barrier Schottky Diode. The oxide is place at the bottom and sidewalls of the trench and the trench is filled with the polysilicon.

III. DEVICE SIMULATION

A. Device preparation

The trench MOS Barrier Schottky diode device was designed and analyzed using two-dimensional SENTAURUS device simulator software. All the characterizations which are forward and reverse characterization were performing by using structure in the Fig. 2 above. In designing the trench Schottky diode device, the basic parameters that were used are shown in Table 1 below. In addition, one of the device parameters which are the oxide thickness has been varying in order to see the impact of this parameter to the device performance. The values that were used for the varying oxide thickness were 0.06µm, 0.08µm and 0.09µm.

Fig.3 shows the process flow in designing the device in the simulator software. Firstly, the intersection of the device was set. The value of the parameters that were set is show on the Table 1 below. 4000 Å oxide layer is deposited on an N-type silicon followed by patterning and etching process to remove some oxide layer. The remaining oxide layer will become a hardmask for the substrate. After that, the uncovered silicon substrate will be etched about 13300 Å depth to make the trench. The oxide hardmask is then removed. Next, another oxide layer which about 600 Å thicknesses is deposited into the sidewall and bottom of a trench and followed by the deposition of undoped polysilicon in the trench. The thickness of the undoped polysilicon is about 5000 Å. Next, the phosphorus is implanted into the polysilicon with a $1e^{16}$ cm^{-2} concentration and 80 keV of energy. After that, the anneal process is performed to restructure the phosphorus dopant in the polysilicon. The time, temperature and the pressure that are used for annealing process are 60 min, 950 ºC and 1 atm. Then, the polysilicon and the oxide on the surface of the device are etched away. Finally for the metal part, Aluminum is deposited around 1400 Å thickness into the structure and patterned as per device requirement. Then, some of the Aluminium is etched away.

TABLE1

SENTAURUS SIMULATOR PARAMETERSFOR THE TRENCH SCHOTTKY DIODE

Parameters	Value
Epi width	0.60 µm
Trench depth	1.27 µm
Trench width	0.55 µm
Oxide thickness	0.06 µm
Metal thickness	0.14 µm

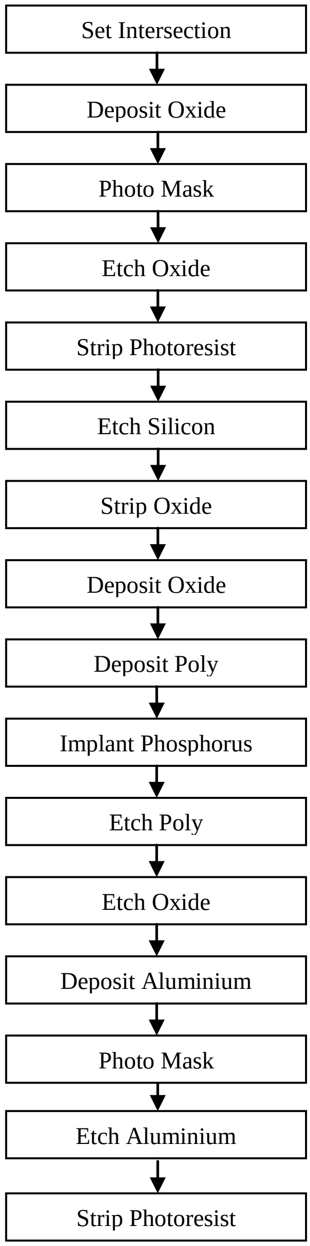

Fig. 3: Process flow of the simulation design

B. *Forward Characteristics*

The trench structure actually does not give big changes on the forward characteristics. The conventional Schottky diode device is already has a lower forward voltage drop and the value of the forward voltage drop for the trench device is said to be same with the conventional Schottky diode device. The deep trench device implementation is actually to improve the performance of the device in the reverse biasing. Schottky diode is a metal-semiconductor device, where when the positive biasing is applied to the metal of the device, carriers will flow toward the junction and decreasing the barrier height and also barrier voltage [9].

The forward voltage drop for Schottky diode increases in proportion to the magnitude of the Schottky barrier height. So that, by reducing the Schottky barrier height, it enables the device to have a low forward voltage drop compare to the pn junction diode. Moreover, since the Schottky diode device is a majority carrier device, it does not suffer from the charge storage effect that can limit the switching speed of the device [7].

C. *Reverse Breakdown Characteristics*

In order to see the improvement of the device characteristics by implementing the deep trench structure into the device, the important things that need to be understand is the distribution of the electric field on the device structure. By studying the distribution of the electric field in the device structure, it is easily to understand the characteristics of the device in the simulation software. By providing the trench MOS structure in the Schottky diode, it changed and reduced the electric fields that are placed in the Schottky interface and distribute it into the silicon bulk. Due to the reducing a peak of electric field in the Schottky interface, a wide Schottky barrier will be produced thus reduced the leakage current and also allow the device to support large breakdown voltage. Compare with the conventional Schottky diode structure, it will distribute an electric field at the Schottky interface that can conduct higher Schottky barrier lowering effect which the Schottky barrier will be narrowed [8]. Due to this effect, it will lead the device to have a large leakage current and allow the premature breakdown to occur where the value of the breakdown will be smaller than the breakdown voltage of a pn junction diode.

When the negative biasing is applied to the device, the carriers will flow away from the junction area thus extending the depletion region and increase the voltage across it [9]. From this two theories, the similarity and significant in the characteristics of the devices performance is observed.

IV. Experimental Result

A. *Structural Properties*

Fig. 4 shows the result for the simulation structure. The trench MOS can be seen in the figure below where the trench bottom and sidewalls is made by an oxide layer and filled with the polysilicon. The above and bottom layer of the structure are deposited with the aluminium metal layer.

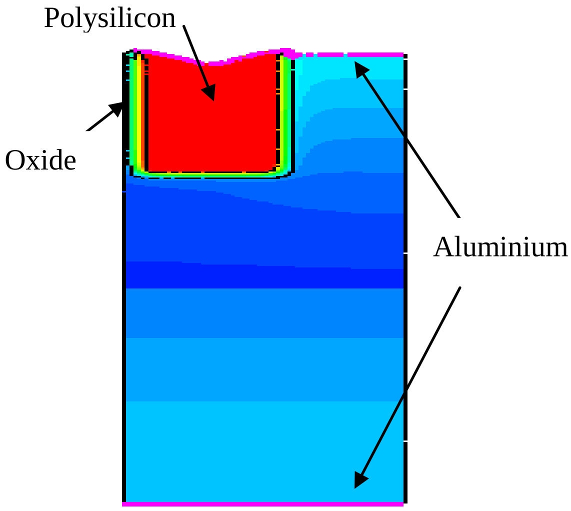

Fig. 4: Cross section of Trench MOS Barrier Schottky Diode in simulator software

B. *IV Characteristics for device simulation.*

Fig. 5 and Fig. 6 show the simulated IV characteristics of the trench MOS barrier Schottky diode. From Fig. 5, the device shows an identical low forward voltage drop which is 0.50 V while Fig. 6 shows the reverse breakdown voltage for the device which can achieved up to 49 V. The high value for the reverse breakdown voltage is due to the coupling between the charge in the epitaxial layer region and the metal on the trench sidewalls has altering electric field distribution in the device structure [8, 10]. By reducing the electric field in the Schottky interface, reverse leakage current can be reduced due to the increasing Schottky barrier height phenomenon and this effect become stronger with the increased in trench depth [10]. From these simulation results, it can be said that, by implementing the deep trench MOS structure, the device will have high breakdown voltage while maintaining the low forward voltage drop. Trench structure does not give any effect to the forward characteristics of the device since the MOS region does not play any role in forward characteristics [8]. Thus, the forward voltage drop for this trench Schottky device was approximately same with the conventional Schottky device.

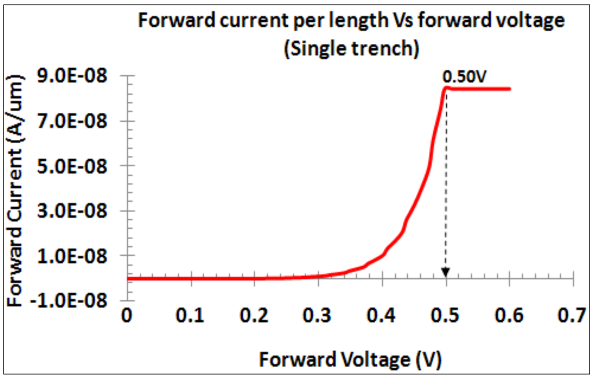

Fig. 5: Forward voltage drop for the trench MOS barrier Schottky diode. The forward voltage drop is 0.50 V.

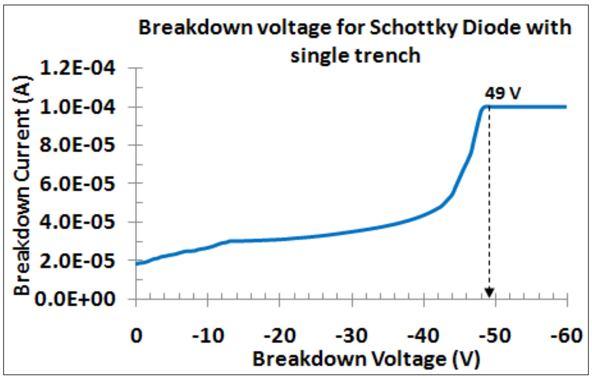

Fig. 6: Breakdown voltage for the trench MOS barrier Schottky diode. The reverse breakdown voltage is about 49 V.

C. IV Characteristics for device fabrication

The fabricated device with the same parameters is also being characterized in order to see the significant of the simulation result with the fabrication result. Fig. 7 and Fig. 8 were shows the forward and reverse characteristics of the fabricated device. From the Fig. 7, the measured forward voltage drop is approximately 0.61 V while Fig. 8 shows that the breakdown voltage for the device is about 50V. Value for the reverse breakdown voltage achieved by the device is depends on the device specification which is could be 45 to 60V. From the Fig 7, the forward voltage is seen to have a large value. This is due to the thicker wafer. The thicker wafer has large series resistance in the device compare to the thinner wafer and this resistance can cause higher forward voltage. The final product will have a thinner substrate after the back grinding process is performed and the forward drop will be reducing in value. There are some important things that need to be considered in order to compare the simulation and fabrication result such as there will be a difference in IV characteristic result between these two kind of experiments which are due to some limitation in the parameters on the simulator software, sheet resistance on the fabricated device and also the shunt resistance in the measuring equipment that were used.

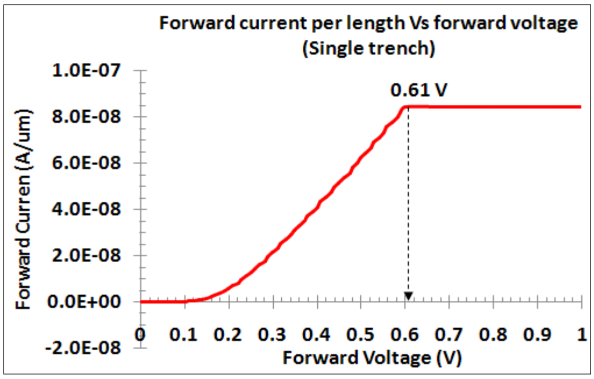

Fig. 7: Forward voltage drop for fabricated Trench MOS Barrier Schottky diode device. The forward voltage drop is 0.61 V.

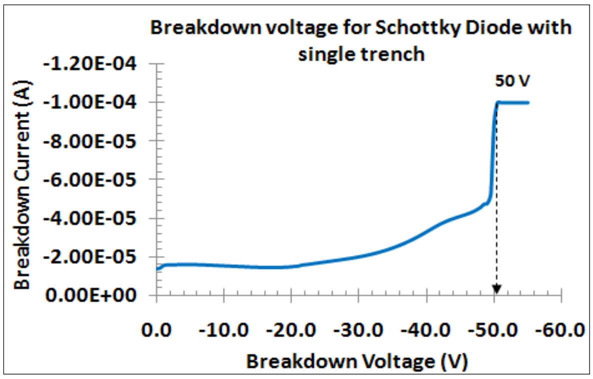

Fig. 8: Breakdown voltage for fabricated Trench MOS Barrier Schottky diode device. The forward voltage drop is 50 V.

D. IV Characteristics for different oxide thickness

The value of an oxide thickness is being varied into 0.06 µm, 0.08 µm and 0.09 µm to see the impact of the parameters on the device performance and the result were shows in the Fig. 9 and Fig.10 below. From Fig 9, it can be said that the oxide thickness have not bring any effects on the forward voltage. The forward voltage drop has shown the same value for a different oxide thickness. However, the value of oxide thickness has effected on the reverse breakdown voltage of the device where the increasing of the oxide thickness will cause an increasing in the reverse breakdown voltage. This can be seen through the Fig. 10 below. The small oxide thickness will reduce the reverse voltage handling capability due to an electric field that crowding at the edges of the trench sidewalls [8, 9]. This means that thicker oxide will provide an improvement to the reverse breakdown voltage. However, if the oxide thickness was too thick, it is not applicable to the structure because it will result in loss of charge coupling between the epitaxial layer region and the metal on the trench sidewalls.

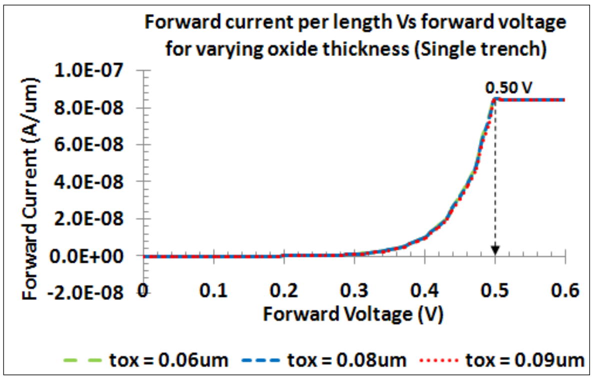

Figure 9: Forward voltage for the varying oxide thickness: tox = 0.06µm, 0.08µm and 0.09µm. All oxide thickness has gives the same forward voltage which is 0.50 V.

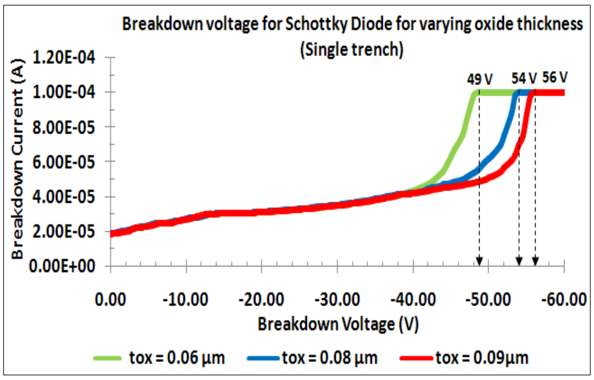

Fig. 10: Breakdown voltage for the varying oxide thickness: tox = 0.06µm, 0.08µm and 0.09µm. Breakdown voltage has increase from 49 V to 54 V and to 56 V due to the thicker oxide thickness.

From the Fig. 11, it shows more detail about the relationship between the reverse breakdown voltage and the oxide thickness of the device where an increasing in the oxide thickness will increase the reverse breakdown voltage.

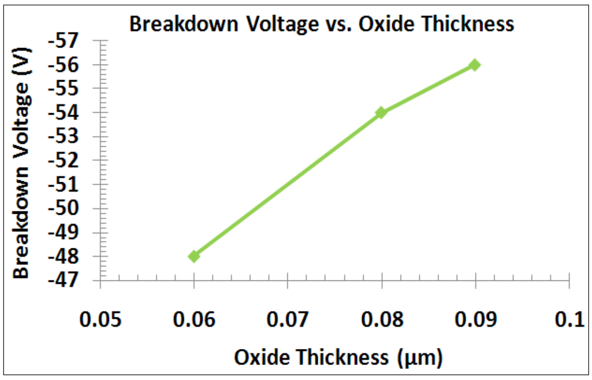

Fig. 11: Breakdown voltage vs. Oxide thickness

V. Conclusion

In this paper, a diode structure which called Trench MOS Barrier Schottky Diode is proved to have better trade-off characteristics which has a low forward voltage drop, low leakage current and also has high voltage blocking capability. By using a two dimensional (2D) simulator software, the device has demonstrated to have high breakdown voltage which is 50 V by improving the electric field distribution in the structure. The trench MOS structure has reduced the electric field at the Schottky interface thus providing a large Schottky barrier to the device to support large reverse breakdown voltage. From the IV curves of a forward and reverse breakdown voltage it is seen that the trench MOS barrier Schottky diode device has proved to have trade-off characteristics. In addition, by the simulation, it has demonstrated the relationship between the oxide thickness and the breakdown voltage. The increasing in oxide thickness will significantly increase the breakdown voltage.

As a recommendation for the next development of the Schottky diode device, the structure of trench bottom oxide (TBO) can be applied. This structure has believed to improve the distribution of the electric field where it will minimize the electric field that crowding in the trench structure.

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