A New 4H-SiC Lateral Merged Double Schottky (LMDS) Rectifier With Excellent Forward and Reverse Characteristics

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***Abstract*—The novel characteristics of a new Schottky rectifier structure, known as the lateral merged double Schottky (LMDS) rectifier, on 4H-SiC are explored theoretically and compared with those of the compatible conventional 4H-SiC Schottky rectifiers. The anode of the proposed lateral device utilizes the trenches filled with a high barrier Schottky (HBS) metal to pinch off a low barrier Schottky (LBS) contact during reverse bias. Numerical simulation of any such SiC structure is complicated by the fact that the thermionic emission theory predicts the reverse leakage current to be orders of magnitude smaller than the measured data. We, therefore, first propose a simple empirical model for barrier height lowering to accurately estimate the reverse leakage current in a SiC Schottky contact. The accuracy of the empirical model is verified by comparing the simulated reverse leakage current with the reported experimental results on different SiC Schottky structures. Using the proposed empirical model, the two-dimensional (2-D) numerical simulations reveal that the new LMDS rectifier demonstrates about three orders of magnitude reduction in the reverse leakage current and two times higher reverse breakdown voltage when compared to the conventional lateral low barrier Schottky (LLBS) rectifier while keeping the forward voltage drop comparable to that of the conventional LLBS rectifier. A unique feature of the 4H-SiC LMDS rectifier is that it exhibits a very sharp PiN diode-like reverse blocking characteristic in spite of the fact that only Schottky junctions are used in the structure. The reasons for the improved performance of the LMDS rectifier are analyzed and design tradeoff between the forward voltage drop and the reverse leakage current is provided by varying the device parameters. Finally, this work demonstrates a simple way of achieving excellent Schottky characteristics on 4H-SiC and provides the incentive for experimental exploration.**

***Index Terms*—Silicon carbide, numerical simulation, lateral Schottky, barrier lowering.**

I. INTRODUCTION

SILICON carbide is an attractive wide bandgap semiconductor material for high-power, high-frequency, and high-temperature devices because of its excellent electrical and physical properties [1]. Therefore, SiC Schottky rectifiers offer substantial advantages over Si and GaAs rectifiers. In general, the Schottky rectifiers are of interest because they are majority carrier devices and consequently have very fast switching speed with no reverse recovery current. However, one has to make a tradeoff between the forward voltage drop (V_F) and the reverse leakage current (J_R) while selecting a metal for the Schottky contact since both these parameters influence the power dissipated by a Schottky rectifier. A low barrier Schottky (LBS) metal gives small forward voltage drop but results in large reverse leakage current. Conversely, a high barrier Schottky (HBS) metal provides large forward voltage drop and a small reverse leakage current. Furthermore, the reverse leakage current of a conventional Schottky rectifier increases very rapidly with applied reverse bias due to the barrier lowering effect and the device shows a relatively low and soft reverse breakdown due to the presence of a large peak electric field at the Schottky contact. Therefore, it is desirable to have a rectifier whose forward characteristic is close to that of an LBS contact and the reverse characteristic close to that of an HBS contact with a high and sharp reverse breakdown similar to that of a PiN diode.

In the past, several vertical Schottky rectifier structures on SiC have been reported [2]–[5] with improved reverse characteristics due to the suppression of the barrier lowering effect which is the primary cause of the increased reverse leakage current in the SiC Schottky rectifiers. However, lateral Schottky rectifiers are increasingly becoming important because of their application in power ICs. Recently, Singh and Kumar [6], for the first time, proposed a lateral merged double Schottky (LMDS) rectifier on silicon utilizing metals with two different barrier heights to achieve low forward voltage drop and small reverse leakage current. However, an interesting question which so far has not received any serious attention is the study of lateral Schottky rectifiers on SiC. To the best of our knowledge, such a structure has not been studied in literature. This is primarily because the numerical simulation of these structures is complicated by the fact that the standard thermionic emission theory including the image-force induced barrier lowering predicts the reverse leakage current to be orders of magnitude smaller than the measured data [7], [8] on SiC Schottky rectifiers. This is because the fabrication process, surface conditioning, and material defects play more than a significant role in determining the reverse leakage current in SiC Schottky contacts. It is difficult to incorporate these effects in a general theoretical model due to lack of a good understanding of the fundamental physics that takes place at a SiC Schottky contact.

The objective of this paper is therefore twofold:

1) to propose a simple empirical model for barrier height lowering for accurately predicting the reverse leakage

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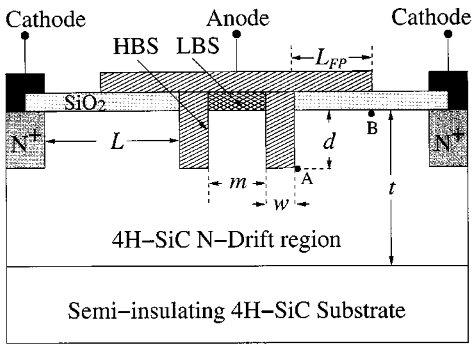

Fig. 1. Schematic cross-sectional view of the 4H-SiC LMDS rectifier.

current in the SiC Schottky contacts and compare its accuracy with the measured reverse leakage current data;

2) to explore for the first time, an LMDS rectifier on 4H-SiC utilizing the trenches filled with a HBS metal to pinch off the LBS region during the reverse bias.

Using a two-dimensional (2-D) device simulator (MEDICI) [9], the unique features of the proposed double Schottky structure are analyzed by comparing its characteristics with that of the compatible conventional lateral low barrier Schottky (LLBS) and conventional lateral high barrier Schottky (LHBS) rectifiers.

Based on our simulation results, we demonstrate that the proposed LMDS rectifier provides about three orders of magnitude reduction in the reverse leakage current when compared to the conventional LLBS rectifier while the forward bias characteristic remains close to that of the LLBS rectifier. An important feature of the proposed LMDS rectifier is that its reverse breakdown voltage is not only two times higher than that of a conventional device but also its reverse characteristic is as sharp as that of a PiN diode.

II. Device Structure and Parameters

A cross-sectional view of the 4H-SiC LMDS rectifier implemented in MEDICI [9] is shown in Fig. 1. The anode of the unit cell consists of an LBS surface contact between the two trenches filled with an HBS metal. We have used Titanium (Ti) and Nickel (Ni) for the LBS ($\phi_{\rm BL} = 0.85$ V) and the HBS ($\phi_{\rm BH} = 1.5$ V) contacts, respectively, since they are more commonly used in SiC Schottky rectifiers [10]. The ohmic cathode contact is taken from the N^+ region and is placed symmetrically on both sides of the anode to increase the active area of the device which results in a reduced ON resistance. A simple metal field-plate termination is used to reduce the electric field crowding at the trench edges. The device parameters used in the simulation are given in Table I. The following parameters were varied in order to study their impact on device performance: drift region thickness (t), trench-depth (d), trench-width (w), and mesa-width (m).

III. Model for Barrier Height Lowering

According to the thermionic emission theory, the reverse leakage current density (J_R) of a Schottky rectifier can be written as [11]

TABLE I
MEDICI Input Parameters for LMDS Rectifier

Parameter	Value
N^+ doping for ohmic contact	10^{20} cm^{-3}
Drift region doping, N_d	5x10^{16} cm^{-3}
Drift region length, L	7 μm
Drift region thickness, t	1.5 - 2.75 μm
Field oxide thickness	0.75 μm
Field-plate length, L_{FP}	5 μm
Trench depth, d	0.5 - 1.50 μm
Trench width, w	0.2 - 1.00 μm
Mesa width, m	0.2 - 2.00 μm
Low Schottky barrier height (Ti), ϕ_{BL}	0.85 V
High Schottky barrier height (Ni), ϕ_{BH}	1.50 V
Richardson constant	140 A/cm^{2}K^{-2}

$$J_R = A^{**}T^2 \exp\left[\frac{-q}{kT}(\phi_B - \Delta\phi_B)\right] \tag{1}$$

where

A^{**} Richardson's constant;

ϕ_B Schottky barrier height;

$\Delta\phi_B$ barrier height lowering.

The image-force induced barrier height lowering can be expressed in terms of the reverse bias electric field E_m at the Schottky contact as follows [11]:

$$\Delta\phi_B = \left[\frac{qE_m}{4\pi\epsilon_s}\right]^{\frac{1}{2}} \tag{2}$$

The measured reverse leakage current of the SiC Schottky rectifiers has been reported [7], [8], [10] to be orders of magnitude higher than that predicted by (1) and shows a stronger voltage dependence than given by (2). This is because in addition to the thermionic emission and the image-force induced barrier lowering, the reverse leakage current in the SiC Schottky rectifiers is influenced by many other parameters such as surface inhomogeneities [7], depletion region generation [10], barrier height fluctuations, and the carrier tunneling [8], [12]. Including all of these current leakage mechanisms in the thermionic emission model is very complex. Therefore, we propose a simple empirical model for the barrier height lowering $\Delta\phi_B$ in (1) for an accurate prediction of the reverse leakage current in the SiC Schottky contacts as follows:

$$\Delta\phi_B = a[E_{\rm av}]^{\frac{1}{2}} + b \tag{3}$$

where $E_{\rm av}$ is the average electric field (V/cm) at the Schottky contact, and a, b are constants. These constants are evaluated by iterating (3) in MEDICI until the simulated reverse leakage current matches the measured data. Based on the experimental results reported by Schoen *et al.* [5], these constants are found to be $a = 3.63 \times 10^{-4}$ V$^{1/2}$cm$^{1/2}$ and $b = -0.034$ V for Ti

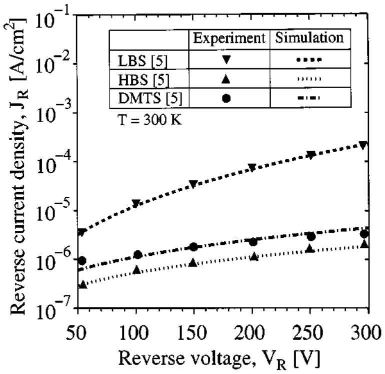

Fig. 2. Comparison of simulated and experimental reverse leakage current densities for the vertical 4H-SiC LBS (Ti), HBS (Ni), and DMTS rectifiers. Experimental results are from [5].

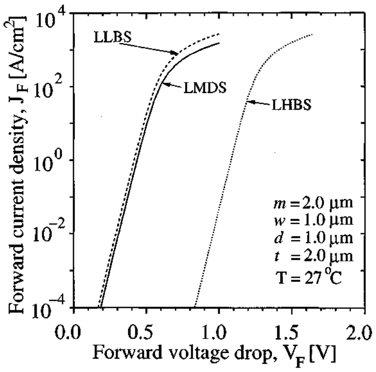

Fig. 3. Simulated forward conduction characteristics of the 4H-SiC LMDS rectifier compared to those of the conventional LLBS and LHBS rectifiers.

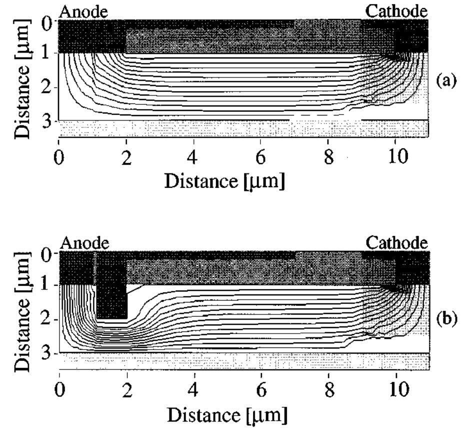

Fig. 4. Current flow lines in the (a) conventional Schottky (LLBS and LHBS) and (b) LMDS rectifiers at a current density of 100 A/cm^2.

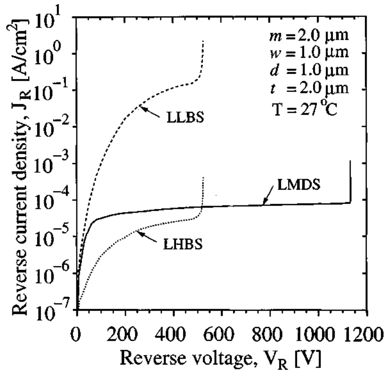

Fig. 5. Simulated reverse blocking characteristics of the 4H-SiC LMDS rectifier compared to those of the conventional LLBS and LHBS rectifiers.

and $a = 1.54 \times 10^{-4}$ V$^{1/2}$cm$^{1/2}$ and $b = 0.638$ V for Ni, the metals used in our study. While the parameters a and b in the above barrier lowering model for both Ti and Ni work very well when compared to the experimental data of [5], it may also be noted that the actual values of a and b have to be found carefully since the measured barrier heights of most metals on SiC can have a wide range of values depending on the process and the quality of SiC wafers used in the fabrication. Fig. 2 shows the simulated reverse characteristics and the experimental data for both the vertical planar LBS (Ti) and HBS (Ni) as well as the dual metal trench (DMT) Schottky rectifiers [5] on 4H-SiC. It can be seen that the simulated results using the proposed empirical model show an excellent agreement with the measured data. It is, therefore, now possible to explore the unique features of the proposed 4H-SiC LMDS rectifier by utilizing the proposed empirical model for barrier height lowering in our 2-D numerical simulation as discussed below.

IV. Simulated I–V Characteristics

A. Forward Characteristics

The simulated forward conduction characteristics of the 4H-SiC conventional LLBS, conventional LHBS, and the LMDS rectifiers are shown in Fig. 3. As can be seen, the conventional LHBS rectifier shows a larger voltage drop due to its higher barrier height as compared to the conventional LLBS rectifier. The forward characteristic of the LMDS rectifier is comparable to that of the conventional LLBS rectifier which shows a low forward voltage drop. For example, the forward voltage drop of the LLBS, LMDS, and LHBS rectifiers is 0.56, 0.59, and 1.22 V, respectively, at a current density of 100 A/cm^2. The low forward voltage drop in the case of LMDS rectifier can be understood from the current flow lines shown in Fig. 4 for both the conventional LLBS & LHBS and the LMDS rectifiers at a current density of 100 A/cm^2. It can be seen that in the case of the LMDS rectifier, the LBS contact plays a key role in facilitating the current flow and hence results in a low forward voltage drop.

B. Reverse Characteristics

Fig. 5 shows a comparison of the simulated reverse blocking characteristics of the 4H-SiC conventional LLBS, conventional LHBS and the LMDS rectifiers. It can be seen that the reverse leakage current density of the conventional LLBS rectifier is highest and that of the conventional LHBS rectifier is lowest due to the fact that the reverse leakage current strongly depends upon the metal-semiconductor barrier height. Furthermore, in the case of both the conventional Schottky devices, the reverse leakage current increases very rapidly with increasing reverse bias due to the increased barrier lowering effect at the Schottky contact. On the other hand, for the LMDS rectifier, the reverse

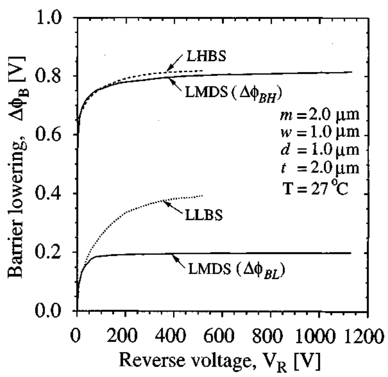

Fig. 6. Barrier height lowering as a function of the reverse bias voltage.

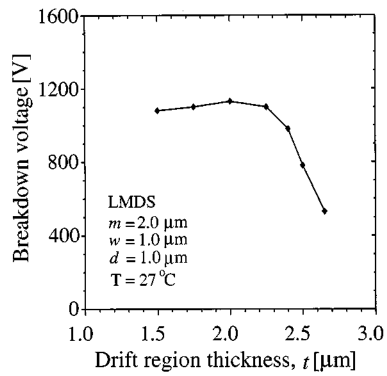

Fig. 7. Breakdown voltage as a function of the drift region thickness for the 4H-SiC LMDS rectifier.

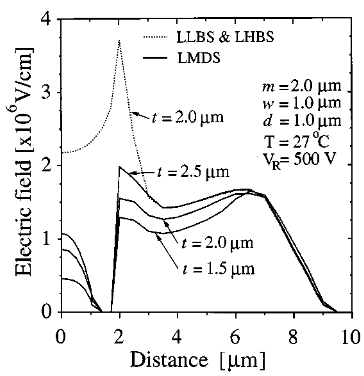

Fig. 8. Electric field variation along the horizontal line near the SiO_2-SiC interface for the right half portion from the center of the structure at a reverse bias of 500 V.

leakage current increases only by a factor of 2–3 as the reverse bias is increased from 100 V to 1000 V and is about three orders of magnitude lower as compared to the conventional LLBS rectifier. It is interesting to note that both the conventional devices exhibit a soft reverse breakdown at 525 V (defined as the reverse bias voltage at $J_R = 1$ A/cm^2) whereas the proposed LMDS rectifier, in spite of using only Schottky contacts, shows a sharp breakdown at 1130 V which is about two times higher than that of the conventional devices. This remarkable improvement in the breakdown voltage of the proposed device is due to the reduced electric field at the Schottky contact and the avalanche breakdown takes place in the drift region below the edge of the field-plate, as discussed in Section V.

C. Barrier Lowering Effect

In order to see the effect of the barrier lowering on the reverse leakage current, the maximum barrier lowering $(\Delta\phi_B)$ as a function of the reverse bias is shown in Fig. 6 for the LMDS rectifier and the conventional devices. It can be observed that for the conventional LLBS rectifier, the barrier lowering increases very fast with increasing reverse bias voltage resulting in a large reverse leakage current. It should also be noted that although the barrier lowering $(\Delta\phi_B)$ for the conventional LHBS rectifier is higher than the conventional LLBS rectifier, the actual Schottky barrier height in the case of the LHBS rectifier is more than that of the LLBS rectifier and hence the reverse leakage current of the LHBS rectifier is lower than that of the LLBS rectifier. In the case of the LMDS rectifier, the rise in barrier lowering at the LBS $(\Delta\phi_{\rm BL})$ and the HBS $(\Delta\phi_{\rm BH})$ contact is 12 mV and 56 mV, respectively, as the reverse bias is increased from 100 V to 1000 V. This increases the reverse leakage current of the LMDS rectifier by a factor of 2–3 as the reverse bias is increased from 100 V to 1000 V. Compared to the conventional LLBS, the reduced barrier lowering at the LBS contact $(\Delta\phi_{\rm BL})$ results in a large reduction in the reverse leakage current of the LMDS rectifier. This is because the SiC region between the two trenches is pinched off during the reverse bias resulting in a reduced electric field at the LBS contact.

V. Breakdown Analysis

Fig. 7 shows the simulated breakdown voltage as a function of the drift region thickness (t) for the LMDS rectifier. It can be seen that the breakdown voltage improves with decreasing drift region thickness and approximately remains constant below a drift region thickness of 2.25 μm. In order to analyze the breakdown phenomenon in the device, it is important to see the electric field distribution inside the device. Fig. 8 shows the electric field variation along the horizontal line near the SiO_2-SiC interface for the right half portion from the center of the LMDS rectifier and the conventional devices. The electric field variation in both the conventional Schottky rectifiers is found to be similar and hence they show identical breakdown at 525 V. Furthermore, in the case of conventional devices, the avalanche breakdown takes place at the Schottky contact due to presence of peak electric field at this point. On the other hand, in the case of LMDS rectifier, the peak electric field at the Schottky contact is much lower as compared to the conventional Schottky rectifier. This reduced peak electric field results in a large improvement in the breakdown voltage of the proposed device. However, the peak electric field at the Schottky contact in LMDS structure increases with increasing drift region thickness and lowers the device breakdown voltage. This can be better understood from Fig. 9 which shows the electric field variation at points A and B (i.e., at the bottom edge of the trench and below the edge of the field-plate, as shown in Fig. 1) as a function of the reverse bias voltage for the LMDS rectifier. It can be observed that for a drift region thickness of 2.6 μm, the electric field at point A is much higher

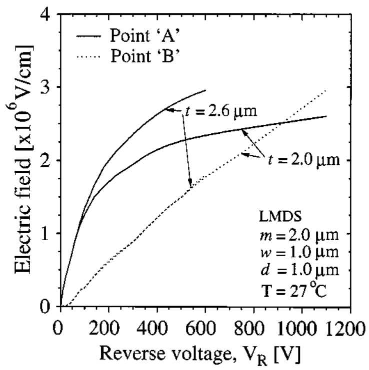

Fig. 9. Electric field at point A (bottom edge of the trench) and point B (below the edge of the field-plate) as a function of the reverse bias voltage for the 4H-SiC LMDS rectifier.

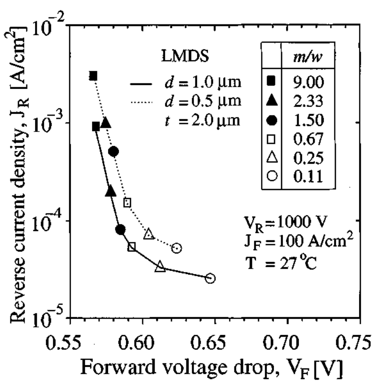

Fig. 10. Tradeoff between the forward voltage drop and the reverse leakage current density for different mesa-width/trench-width (m/w) ratios and a fixed surface anode width ($m + 2w = 4\ \mu$m) for the 4H-SiC LMDS rectifier.

than that at point B resulting in a large reverse leakage current due to increased barrier lowering at the high-barrier Schottky contact. This causes a relatively low and soft breakdown of the LMDS rectifier for a drift region thickness of 2.6 μm. On the other hand, as the drift region thickness is decreased to 2 μm, the electric field at point B becomes higher than the electric field at point A near breakdown. This makes the device to breakdown at point B (away from the Schottky contact) and results in a higher and sharp breakdown voltage.

VI. Design Tradeoff Between V_F and J_R

It is desirable to minimize the forward voltage drop and the reverse leakage current to reduce the power dissipated by a Schottky rectifier. However, one has to make a tradeoff since both these parameters depend upon the mesa-width (m), trench-width (w), and trench-depth (d) of the LMDS rectifier. Fig. 10 shows a tradeoff between the forward voltage drop and the reverse leakage current density for the LMDS rectifier which is obtained by varying the mesa-width to trench-width (m/w) ratio for the trench depths of 0.5 and 1.0 μm. The variation in m/w ratio is obtained for a fixed anode width of 4 μm ($m + 2w = 4\ \mu$m). As can be seen, for a given trench depth, a decrease in the m/w ratio decreases the reverse leakage current density because of a better pinchoff of the SiC region between the two trenches but increases the forward voltage drop due to the reduced LBS area.

VII. Conclusion

We have proposed a simple empirical formula for barrier height lowering in SiC Schottky contacts. The accuracy of the proposed model is verified by comparing the calculated reverse leakage current with the reported experimental results on a variety of SiC Schottky rectifiers. Implementing the above empirical model in our 2-D numerical simulation, we have proposed a 4H-SiC LMDS rectifier having an HBS metal filled within a trench region by the side of an LBS metal. Based on our simulation results, we have demonstrated that the proposed device suppresses the reverse leakage current by three orders of magnitude when compared to the conventional LLBS rectifier. However, the forward voltage drop of the LMDS rectifier is found to be close to that of the conventional LLBS rectifier. Furthermore, the breakdown voltage of the proposed LMDS rectifier has been found to be two times higher than that of the conventional Schottky devices. It is also very significant to note that the reverse breakdown of the LMDS rectifier is very sharp, similar to that of a PiN diode, in spite of the fact only Schottky junctions are used in the proposed structure. The combined low forward voltage drop, excellent reverse blocking capability, and a simple fabrication process make the proposed LMDS rectifier attractive for use in low-loss, high-voltage, high-speed power IC applications.

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