Novel lateral merged double Schottky (LMDS) rectifier: proposal and design

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Abstract: The authors report a new Schottky structure, called the lateral merged double Schottky (LMDS) rectifier, which utilises the trenches filled with a high barrier metal to pinch off a low barrier Schottky contact during the reverse bias. Two-dimensional numerical simulation is used to evaluate and compare the performance of the LMDS rectifier with the conventional Schottky and the recently reported lateral merged PiN Schottky (LMPS) rectifier. The authors show that the proposed device provides an order of magnitude reduction in the reverse leakage current and three times higher reverse breakdown voltage when compared to the conventional Schottky rectifier. A significant feature of the LMDS rectifier is that, in spite of having only Schottky junctions, it gives an extremely sharp breakdown similar to that of a PiN diode. It is demonstrated that for forward current densities up to $400\,A/cm^2$, the LMDS rectifier can provide twice the current that can be realised using the LMPS rectifier for a given forward voltage drop. Furthermore, it is shown that even up to an operating temperature of 80°C, power losses in the LMDS rectifier are smaller than those found in the LMPS rectifier. The reasons for the improved performance of the LMDS rectifier are analysed, and design tradeoffs between the forward voltage drop and the reverse leakage current are presented.

1 Introduction

Low barrier Schottky rectifiers are widely used in applications requiring low power dissipation and fast switching speed. The designer has to make a tradeoff between the forward voltage drop and the reverse leakage current while selecting a particular metal for the Schottky contact since both these parameters influence the power dissipated by a Schottky rectifier. A low barrier metal gives small forward voltage drop but results in a large reverse leakage current. Conversely, a high barrier metal provides large forward voltage drop and 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 peak electric field at the Schottky contact. Therefore, it is desirable to have a rectifier for which the forward characteristic is close to that of a low barrier metal and the reverse characteristic close to that of a high barrier metal with a sharp reverse breakdown. In the past several vertical Schottky rectifiers have been reported [1–7] in which the reverse characteristics are improved by suppressing the barrier lowering effect. However, with the increasing usage of power ICs in many applications [8–12], the need to develop lateral Schottky rectifiers has gained importance because they can be easily integrated in power ICs. Only recently, Sunkavalli *et al.* [13] proposed a lateral merged PiN Schottky (LMPS) rectifier using a deep p^+-region to electrically shield the Schottky region during the reverse bias and minimise the barrier lowering effect. Although the LMPS rectifier is a promising device for power ICs, the difficulty in realising deep p^+-regions by ion implantation and dopant activation by annealing may limit the device designer's choice. Further, the p^+-region acts as a dead zone when the applied forward voltage is $< 0.6\,V$ resulting in a higher power dissipation. An interesting topic of investigation which so far has not received any serious attention is the application of a high barrier metal filled within a trench region by the side of a low barrier metal for making lateral Schottky rectifiers on silicon.

The objective of the present work is therefore to propose and design, for the first time, a lateral merged double Schottky (LMDS) rectifier utilising the trenches filled with a high barrier metal to pinch off the low barrier Schottky region during the reverse bias. To the best of our knowledge, such a structure has not been studied and compared with another lateral structure in the literature. Using a two-dimensional device simulator (MEDICI) [14], the performance of the proposed double Schottky structure is analysed in detail by comparing its characteristics with those of the lateral merged PiN Schottky (LMPS) [13], 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 has a superior performance compared to that of the LMPS rectifier for forward current densities up to $400\,A/cm^2$. At a forward voltage drop of $0.6\,V$, the forward current density in the LMDS rectifier is found to be twice that can be realised using the LMPS rectifier. In addition, up to an operating temperature of 80°C, the power losses in the LMDS rectifier are shown to be smaller than those found in the LMPS rectifier. Unlike

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in the conventional Schottky rectifiers, which have a soft reverse breakdown, an important aspect of our proposed structure is that its reverse breakdown is very sharp and is as large as that realisable using the LMPS rectifier in spite of the fact that our structure uses only Schottky contacts. The reasons for the improved performance of the LMDS rectifier are analysed, and design tradeoffs between the forward voltage drop and the reverse leakage current are presented.

2 Device structure and parameters

A cross-sectional view of a unit cell of the LMDS rectifier implemented on SOI in MEDICI is shown in Fig. 1. The anode of the unit cell consists of a low barrier surface Schottky contact between the two trenches filled with a high barrier metal. 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 for both the LMDS and LMPS are given in Table 1. The only difference between these two rectifiers is that the trench region of the LMDS rectifier is replaced by a p^+-region in the case of the LMPS rectifier. The following device parameters were varied in order to study their impact on device performance: trench depth (d), trench width (w), mesa width (m) and temperature. We have used the well studied metals, namely nickel (Ni) and tungsten (W) for the low barrier Schottky (0.57 eV) and the high barrier Schottky (0.67 eV) contacts, respectively [15].

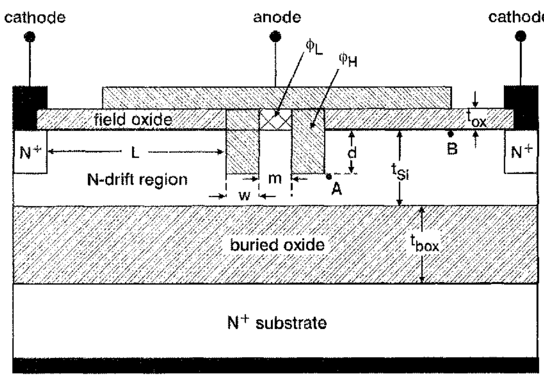

Fig. 1 *Schematic cross-sectional view of LMDS rectifier*

Table 1: MEDICI input parameters for LMDS and LMPS structures

Parameter	Value
N^+ doping for ohmic contact	10^{19} cm^{-3}
Drift region doping N_d	10^{16} cm^{-3}
Drift region length L	12 μm
Drift region thickness t_{Si}	2 μm
Buried oxide thickness t_{box}	3 μm
Field oxide thickness t_{ox}	0.50 μm
Trench depth d	0.0–1.75 μm
Trench width w	0.2–1.00 μm
Mesa width m	0.2–1.00 μm
Low Schottky barrier height (Ni), ϕ_L (for both LMDS and LMPS)	0.57 eV
High Schottky barrier height (W), ϕ_H (for LMDS only)	0.67 eV
P^+ doping (for LMPS only)	10^{19} cm^{-3}
Richardson constant	110 A/cm^{2}K^{-2}
Barrier height lowering coefficient	2×10^{-7} cm
Minority carrier lifetime	10 μs

3 Device simulation

3.1 Forward characteristics

The simulated forward conduction characteristics of the conventional LLBS, conventional LHBS, LMPS and LMDS rectifiers are shown in Fig. 2. As can be seen, the characteristic of the LMDS rectifier lies between that of the conventional LLBS and the conventional LHBS rectifiers. At a low forward bias ($V_F < 0.3$ V), the characteristic of the LMDS rectifier is closer to that of the conventional LLBS rectifier because most of the current flows through the low barrier Schottky region in the LMDS rectifier. It may be noted that, at a higher forward bias, most of the current in the LMDS rectifier is carried by the high barrier Schottky contact and hence the characteristic of the LMDS rectifier becomes closer to that of the conventional LHBS rectifier. As can be seen from Fig. 2, at a given forward voltage drop, the LMDS rectifier carries higher current as compared to the LMPS rectifier within the given forward bias range and the difference between the two forward current densities increases with increasing forward bias. At a forward voltage of 0.6 V, the forward current in the LMDS rectifier becomes twice that of the LMPS rectifier. This can be understood from the current flow lines shown in Fig. 3. When $V_F = 0.3$ V, in both the LMPS and LMDS rectifiers, current flows only through the low barrier Schottky contact. However, at a higher forward bias (e.g. $V_F = 0.6$ V), the entire current in the LMPS rectifier still flows through the Schottky contact with the p^+-region acting as a dead zone while the current in the LMDS rectifier flows through both the low barrier and high barrier Schottky contacts. These results show that the LMDS rectifier has better area efficiency as compared to the LMPS rectifier. For example, the surface area required for the LMDS and LMPS rectifiers is 0.0025 cm^2 and 0.005 cm^2, respectively, to carry a forward current of 1 A. This shows the cost advantage of the proposed device over the LMPS rectifier.

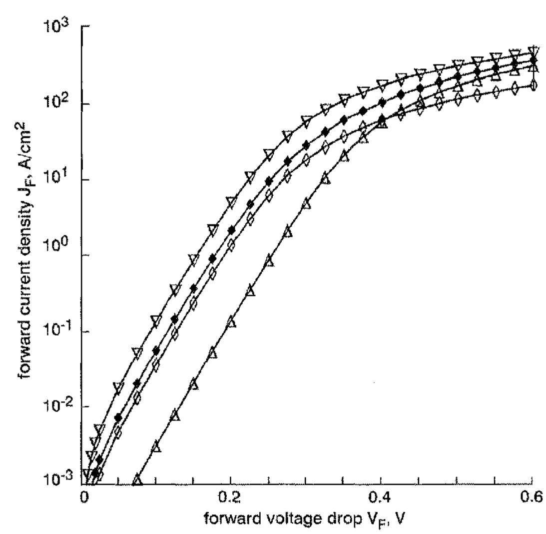

Fig. 2 *Forward conduction characteristics of LMDS rectifier compared to those of LMPS, conventional LLBS and conventional LHBS rectifiers*
—▽— conv. LLBS
—◇— LMPS
—△— conv. LHBS
—◆— LMDS
$m = 1.0$ μm, $w = 1.0$ μm, $d = 1.5$ μm, $T = 27$°C

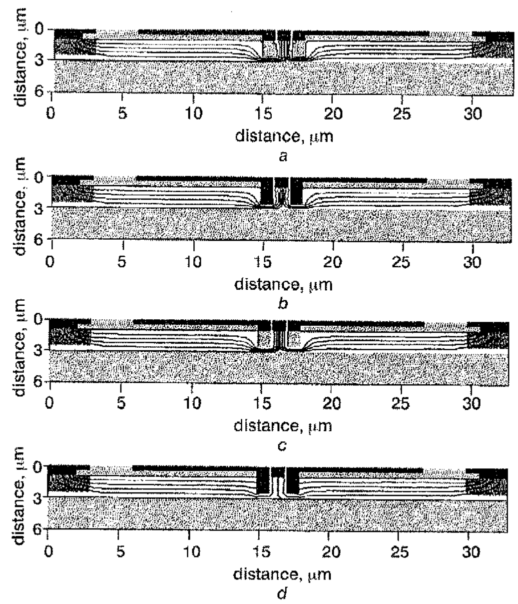

Fig. 3 *Current flow lines in LMPS and LMDS rectifiers for forward voltage drops of 0.3 and 0.6 V*
a LMPS, V_F = 0.3 V
b LMDS, V_F = 0.3 V
c LMPS, V_F = 0.6 V
d LMDS, V_F = 0.6 V

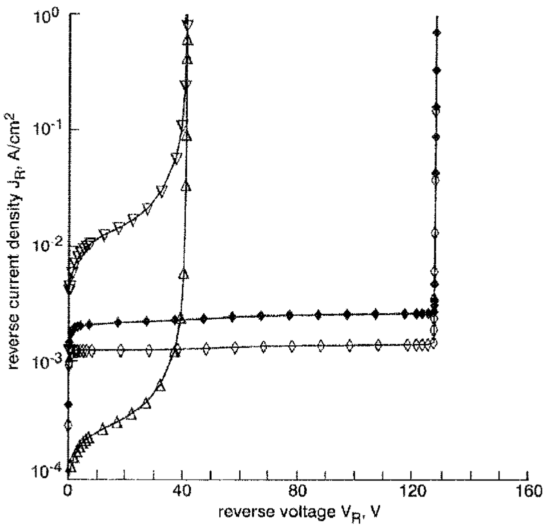

Fig. 4 *Comparison of reverse blocking characteristics of LMDS rectifier with LMPS, conventional LLBS and conventional LHBS rectifiers*
—▽— conv. LLBS
—◇— LMPS
—△— conv. LHBS
—◆— LMDS
m = 1.0μm, w = 1.0μm, d = 1.5μm, T = 27°C

3.2 Reverse characteristics

Fig. 4 shows a comparison of the simulated reverse characteristics of the conventional LLBS, conventional LHBS, LMPS and LMDS rectifiers. It is 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 on the metal-semiconductor barrier height. Furthermore, in both the conventional Schottky devices, the reverse leakage current increases very rapidly with increasing reverse bias, resulting in an extremely soft breakdown at 41 V (defined as the reverse bias voltage at $J_R = 10^{-1}$ A/cm^2). On the other hand, both the LMPS and LMDS rectifiers show an order of magnitude reduction in reverse leakage current as compared to the conventional LLBS rectifier. It is also interesting to note that the proposed LMDS rectifier, in spite of using only Schottky contacts, shows a remarkably sharp breakdown at 127 V which is as good as that can be obtained with the LMPS rectifier. This can be better understood from Fig. 5. It is observed that, for both the structures, the spreading of the depletion region is identical. However, as can be seen, the entire reverse leakage current in the LMPS rectifier flows through the Schottky contact while, in the case of the LMDS rectifier, in addition to the current flowing through the low barrier Schottky contact, a small part of the current also flows through the high barrier Schottky contact. This gives a slight increase in the reverse leakage current of the proposed device as compared to that of the LMPS rectifier.

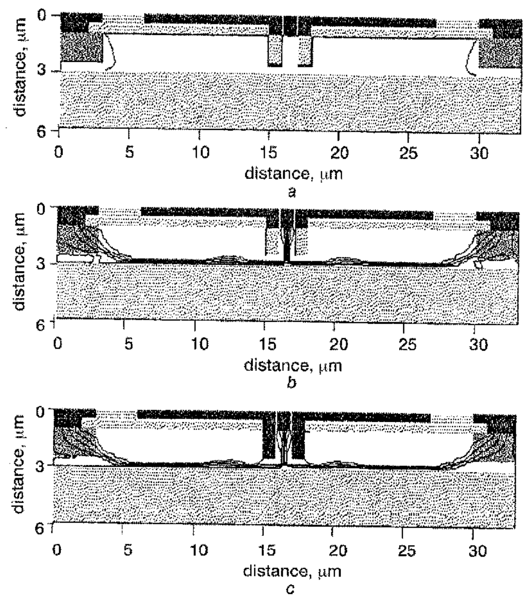

Fig. 5 *Depletion region and current flow lines in LMPS and current flow lines in LMDS rectifiers for a reverse bias of 120 V*
V_R = 120 V
a LMPS and LMDS
b LMPS
c LMDS

3.3 Barrier lowering effect

To see the effect of the barrier lowering on the reverse characteristics, the maximum barrier lowering ($\Delta\phi$) corresponding to the maximum electric field (E) at the Schottky contact is extracted using the following expression [14]

$$\Delta\phi = \left[\frac{qE}{4\pi\epsilon_s}\right]^{\frac{1}{2}} + \alpha E \quad (1)$$

where ε_s is the permittivity (F/cm) of silicon and α is the barrier lowering coefficient given in Table 1. Fig. 6 shows the extracted maximum barrier lowering at the Schottky contacts as a function of reverse bias. It is observed that for both the conventional devices the barrier lowering is identical and increases very fast with the increasing reverse bias, resulting in a large reverse leakage current. In the case of both the LMPS and the LMDS rectifiers, the barrier lowering at the low barrier Schottky ($\Delta\phi_L$) remains almost constant with increasing reverse bias. This is because the silicon region between the two trenches is pinched off during the reverse bias, resulting in a reduced electric field at the low barrier contact. The reduced barrier lowering effect in the LMPS and LMDS rectifiers results in a large reduction in the reverse leakage current. Further, the barrier lowering at the high barrier Schottky ($\Delta\phi_H$) in the LMDS rectifier causes a small part of the reverse leakage current to flow through the high barrier Schottky contact and results in a slight increase in the reverse leakage current of the proposed device as compared to that of the LMPS rectifier.

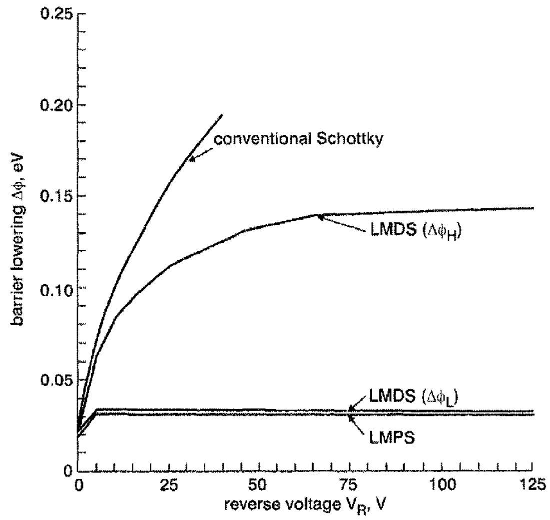

Fig. 6 *Barrier lowering as a function of reverse bias voltage*
$m = 1.0\mu m$, $w = 1.0\mu m$, $d = 1.5\mu m$

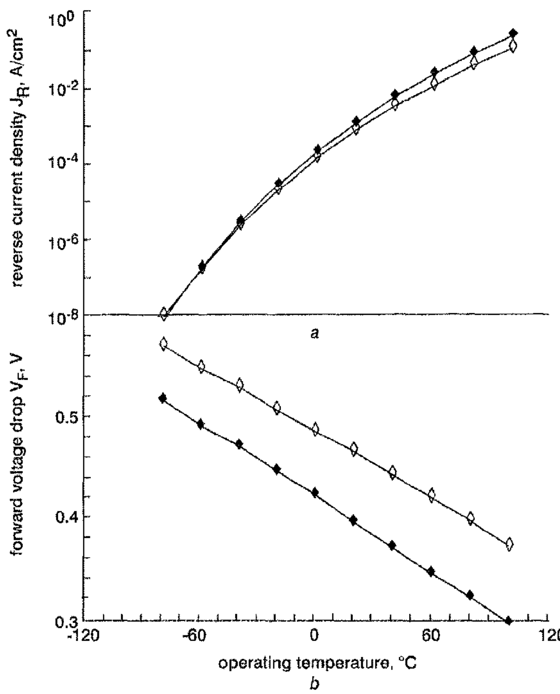

Fig. 7 *Forward voltage drop and reverse leakage current density as a function of operating temperature for LMPS and LMDS rectifiers*
—◇— LMPS
—◆— LMDS
$m = 1.0\mu m$, $w = 1.0\mu m$, $d = 1.5\mu m$
a $V_R = 120V$
b $J_F = 100 A/cm^2$

4 Temperature behaviour

The power loss in a rectifier depends on the operating temperature due to the variation in the forward and reverse leakage characteristics with temperature. Fig. 7 shows the dependence of V_F and J_R on temperature at a forward current density of $100 A/cm^2$ and a reverse bias of 120V for the LMPS and LMDS rectifiers. It can be observed that the forward voltage drop of both the devices decreases with increasing temperature. As can be seen, the LMDS rectifier gives a lower forward voltage drop in comparison to the LMPS rectifier in the temperature range shown. In both the devices, the reverse leakage current increases with increasing temperature. From the results in Fig. 7, a simple calculation of static power dissipation for a 50% duty cycle shows that the proposed LMDS rectifier dissipates less power as compared to the LMPS rectifier even up to 80°C.

5 Breakdown analysis of LMDS rectifier

Fig. 8 shows the simulated breakdown voltage and the electric field near breakdown (at points A and B in the device structure shown in Fig. 1) as a function of the trench depth for the LMDS rectifier. It can be seen that the breakdown voltage improves with increasing trench depth and saturates beyond a trench depth of 0.75µm. Below a trench depth of 0.75µm, the peak electric field at point A is higher than at point B, resulting in a large reverse leakage current due to the barrier lowering effect and makes the device break down at point A. On the other hand, when the trench depth is increased beyond 0.75µm, the peak electric field at point B becomes higher than that at point A and causes the device to break down at point B. This can be better understood from the two-dimensional electric field distribution near breakdown shown in Fig. 9. For zero trench depth, i.e. the conventional Schottky rectifier, the peak electric field occurs at the Schottky contacts, which results in a large reverse leakage current and causes an early breakdown of the device. As the trench depth is increased to 1.5µm, the peak electric field shifts away from the Schottky contact and results in a higher and sharp breakdown of the LMDS rectifier.

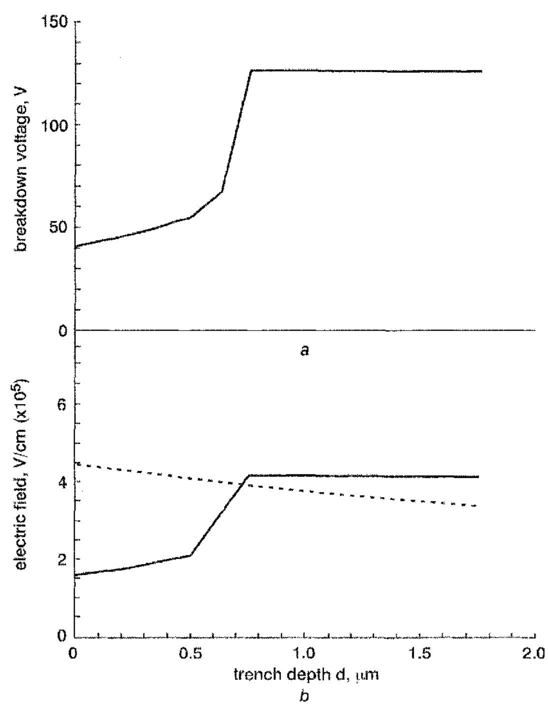

Fig. 8 *Breakdown voltage and electric field near breakdown at point A (bottom of trench) and point B (edge of field plate) as a function of trench depth for LMDS rectifier*
$m = 1.0\mu m$, $w = 1.0\mu m$, $T = 27°C$
.... point A
——— point B
a Breakdown voltage
b Electric field

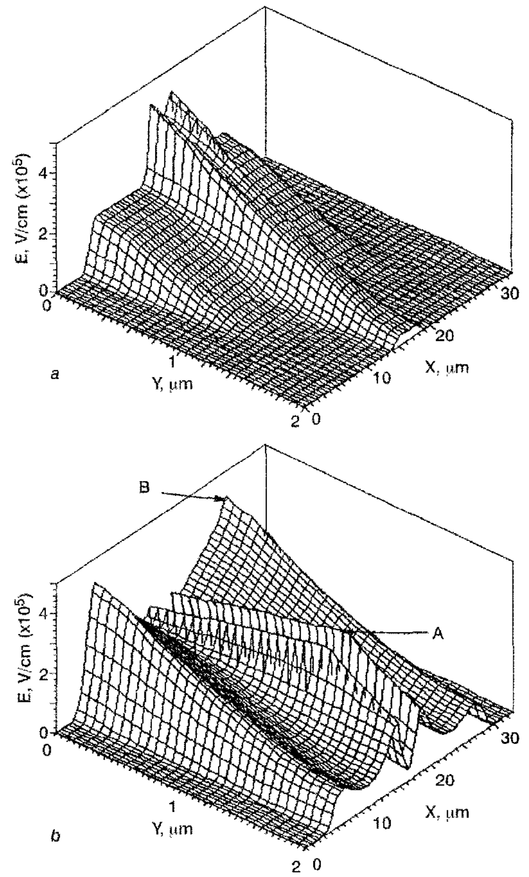

Fig. 9 *Two-dimensional electric field distribution in drift region of LMDS rectifier*
a Trench depth = 0, reverse bias = 40 V
b Trench depth = 1.5 μm, reverse bias = 125 V

6 Forward voltage and reverse current tradeoffs for LMDS rectifier

The tradeoff between the forward voltage drop and the reverse leakage current density for different values of trench depth (d), trench width (w) and mesa width (m) is shown in Fig. 10 for the LMDS rectifier. Fig. 10*a* shows the reverse leakage current density at 120 V reverse bias as a function of the mesa-width to trench-width (m/w) ratio for the trench depths of 1.0 and 1.5 μm. The variation in m/w ratio is obtained for a fixed anode width of 3 μm ($m + 2w = 3$ μm). As can be seen, an increase in the trench depth decreases the reverse leakage current due to the reduced barrier lowering at the low barrier Schottky contact. On the other hand, for a given trench depth, an increase in the m/w ratio increases the reverse leakage current density because of a poor pinch-off of the silicon region between the two trenches. The forward voltage drop as a function of the m/w ratio is plotted in Fig. 10*b* corresponding to a current density of 100 A/cm^2 for the trench depths of 1.0 and 1.5 μm. It can be seen from this figure that the forward voltage drop increases with increasing trench depth because the current flowing through the low barrier Schottky region faces an increased resistance in the drift region present between the bottom of the trench and the buried oxide. For a given trench depth, an increase in m/w ratio causes the forward voltage drop to decrease due to an increase in the forward current through the low barrier Schottky contact.

The forward voltage drop and the reverse leakage current of the LMDS rectifier depend on the barrier height (ϕ_H) of the high barrier Schottky junction. In the analysis of the LMDS rectifier, we have used $\phi_H = 0.67$ eV, which corresponds to a realistic standard metal (tungsten). This barrier height can be adjusted using the barrier height controlling mechanism [16]. The effect of variation of ϕ_H on the forward voltage drop and the reverse leakage current is shown in Fig. 11 corresponding to the forward

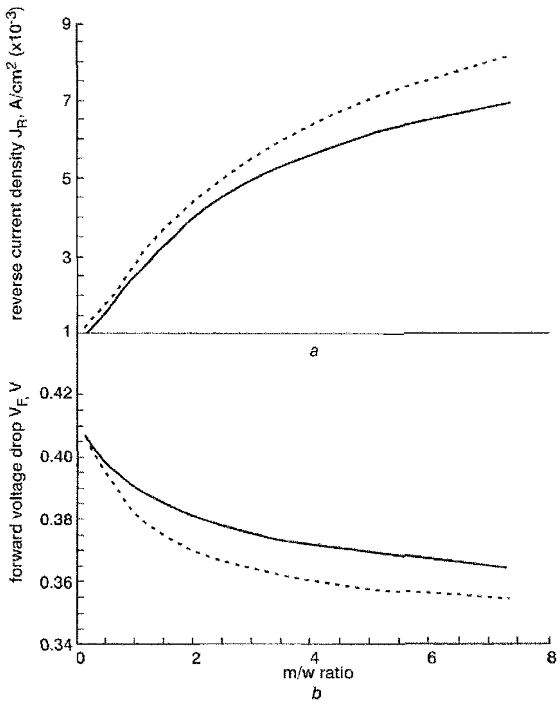

Fig. 10 *Reverse leakage current density and forward voltage drop as a function of mesa-width/trench-width (m/w) ratio for a fixed surface anode width (m + 2w = 3 μm) for LMDS rectifier*
.... d = 1.0 μm
——— d = 1.5 μm
a V_R = 120 V
b J_F = 100 A/cm^2

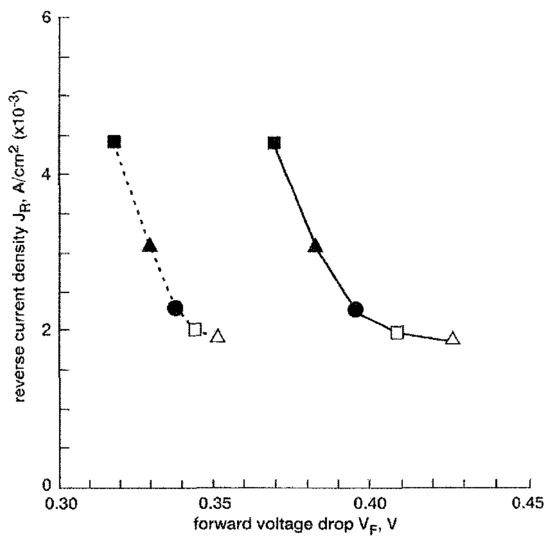

Fig. 11 *Tradeoff relationship between forward voltage drop and reverse leakage current density with variation in barrier height (ϕ_H) of high barrier Schottky contact for LMDS rectifier*
.... J_F = 50 A/cm^2
——— J_F = 100 A/cm^2
ϕ_H (eV) values:
■ 0.64
▲ 0.66
● 0.68
□ 0.70
△ 0.74
m = 1.0 μm, w = 1.0 μm, d = 1.5 μm, V_R = 120 V, ϕ_L = 0.57 eV

current densities of 50 and $100\,A/cm^2$ and the reverse bias of 120V. It can be seen that, for a given forward current density, an increase in the barrier height increases the forward voltage drop and reduces the reverse leakage current. Hence, the designer has to make a tradeoff between the forward voltage drop and the reverse leakage current while selecting a metal for the high barrier contact. Further, as can be seen, when the barrier height is increased beyond 0.7eV, the reverse leakage current saturates to its minimum value while the forward voltage drop increases significantly. This indicates that a metal with $\phi_H > 0.7\,eV$ will increase the power losses significantly without reducing the reverse leakage current. Therefore, it can be observed from Fig. 11 that tungsten is a suitable choice for the high barrier metal with $\phi_H = 0.67\,eV$ since an optimum forward voltage drop and reverse leakage current can be realised for the LMDS rectifier.

7 Conclusions

A novel lateral merged double Schottky (LMDS) rectifier having a high barrier metal filled within a trench region by the side of a low barrier metal has been presented. Based on our simulation results, we have demonstrated that the proposed device suppresses the reverse leakage current by an order of magnitude when compared to the conventional LLBS rectifier. This is due to the reduced barrier lowering effect at the low barrier Schottky contact. Unlike in the conventional Schottky devices, the breakdown of the proposed device has been found to be very sharp and as large as that realisable using the recently reported LMPS rectifier. Our simulation results have shown that the LMDS rectifier is superior in performance to the LMPS rectifier up to the forward voltage drop of 0.6V. The power losses in the LMDS rectifier are shown to be less than those of the LMPS rectifier even up to an operating temperature of 80°C. The design tradeoffs between the forward voltage drop and the reverse leakage current for the proposed device have been obtained by varying the trench depth, mesa width, trench width and barrier height (ϕ_H) The combined low forward voltage drop, excellent reverse blocking capability, reduced power dissipation and a simple fabrication process devoid of any deep diffusions, make the proposed LMDS rectifier attractive for use in low-loss high-speed smart power IC applications.

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