Chapter 4

Trench Schottky Barrier Controlled Schottky Rectifiers

As discussed in the previous chapter, the leakage current for silicon and silicon carbide Schottky rectifiers can be greatly reduced at high reverse bias voltages by shielding the metal contact from the high electric field generated within the semiconductor. The approach utilized in the previous chapter is based up on creating P-N junctions located under the Schottky contact with carefully chosen spacing between them to create a potential barrier under the metal contact during the reverse blocking mode. One of the short-comings of this approach is the need to anneal the ion implanted P-type regions at very high temperatures in order to activate the dopant and remove the lattice damage. At these high temperatures, some dissociation can occur at the semiconductor surface which degrades the quality of the metal-semiconductor junction that must be subsequently formed. Although an issue for silicon devices, this problem is particularly severe for silicon carbide due to the very high (~1600 ^{o}C) annealing temperature for activation of ion implanted regions.

Consequently, a second method has been proposed to ameliorate the barrier lowering effect in vertical silicon Schottky rectifiers by shielding the Schottky contact utilizing a second Schottky contact with a larger barrier height[1,2]. The basic concept was to create a potential barrier to shield the main current carrying low barrier height Schottky contact against high electric fields generated in the semiconductor by using closely spaced Schottky contacts with a large barrier height. In order to produce a strong potential barrier under the main Schottky contact, it is preferable to locate the second high barrier Schottky metal within a vertically walled trench. This device was therefore named the *'Trench-Schottky-Barrier controlled Schottky (TSBS) rectifier' structure*.

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In the TSBS rectifier structure, the on-state current is designed to flow in the un-depleted gaps between the trenches when the diode is forward biased. When a reverse bias is applied, a potential barrier forms under the main Schottky contact which suppresses the electric field at this contact. This prevents a large increase in the leakage current with reverse bias and keeps the leakage current low even if the barrier height of the main contact is small. However, a high electric field is produced at the second Schottky contact located in the trenches. This produces a rapid increase in the leakage current with reverse bias at this contact. However, by using a large Schottky barrier height for this second contact, the absolute value for the leakage current at large reverse bias voltages can be kept much smaller than at the main low barrier height Schottky contact.

This chapter provides analytical models for the TSBS rectifier structure. The physics of operation of these structures is also elucidated by using two-dimensional numerical analysis. It is demonstrated that the TSBS concept improves the performance of silicon and silicon carbide devices[3]. These device structures can be fabricated without the need for high temperature process steps that can degrade the silicon carbide surface so that the quality of the Schottky contact is improved.

4.1 Trench Schottky Barrier controlled Schottky (TSBS) Rectifier Structure

The Trench Schottky Barrier controlled Schottky (TSBS) rectifier structure is illustrated in Fig. 4.1. It consists of a high barrier height metal placed in a trench region to generate a potential barrier that can shield the main low barrier height Schottky contact (at location B) in the reverse blocking mode. The magnitude of

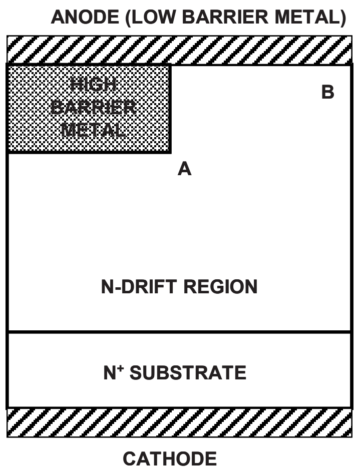

Fig. 4.1 Trench Schottky Barrier controlled Schottky (TSBS) Rectifier Structure.

the potential barrier depends upon the separation between the trenches and the trench depth. A smaller separation and larger trench depth favors an increase in the magnitude of the potential barrier leading to a greater reduction of the electric field at the Schottky contact. A reduction of the electric field at the Schottky contact produces a smaller barrier lowering and field emission effect, which is beneficial for reducing the leakage current at high reverse bias voltages. However, a high electric field can be generated at the sharp corner of the metal in the trenches leading to degradation in the blocking voltage within the device cell structure. Proper optimization of the cell structure can maintain a cell breakdown voltage above that at the edge termination.

The space between the trenches is also chosen so that there is an undepleted region below the main low barrier height Schottky contact during on-state operation to enable unipolar conduction with a low on-state voltage drop. In the TSBS rectifier, the current flow through the metal in the trenches is relatively small due to its large barrier height. Due to small band gap for silicon, it is difficult to make the difference in barrier heights between the main contact and the metal in the trench more than 0.3 eV. The larger band gap for silicon carbide provides the opportunity to utilize a greater difference between the barrier heights of the main contact and the metal in the trench. Consequently, the TSBS concept is well suited for development of silicon carbide structures with very high breakdown voltages.

The TSBS structure can be fabricated by first depositing the main low barrier height metal on a pristine semiconductor surface to obtain a high quality interface. The metal layer is then patterned to open windows where the trenches are formed. The metal layer can serve as a barrier during the etching of the semiconductor to form self-aligned trenches if the appropriate reactive-ion-etching chemistry is used. The second high barrier height metal can then be evaporated to fill the trenches and cover the first metal layer to complete the cell structure. The second metal layer must of course be patterned to terminate the device at the edges. The same device structure, shown in Fig. 4.1, can be produced for both silicon and silicon carbide devices. Consequently, a single basic model can be created for TSBS rectifiers made from both these semiconductors. However, the difference in the Schottky barrier heights that are appropriate for silicon and 4H-SiC result in some differences during device optimization as discussed below.

In silicon JBS rectifiers, the P-N junction is formed with an annealing cycle that creates a planar junction with its extension in the lateral direction as shown in Fig. 3.1. The additional area consumed by the lateral diffusion degrades the on-state characteristics. In addition, the cylindrical shape of the junction allows encroachment of the cathode potential towards the Schottky contact producing an enhancement of the electric field at the contact with increasing reverse bias voltage. The rectangular shape for the metal contact in the trenches in the TSBS rectifier structure produces superior on-state and reverse blocking characteristics when compared with the silicon JBS rectifier structure.

As in the case of the JBS rectifier structure, it will be assumed that the breakdown voltage is reduced to about 80 percent of the ideal parallel-plane value due to the edge termination. The doping concentration for the drift region must be computed after accounting for this reduction in the breakdown voltage:

$$N_D = \left(\frac{5.34x10^{13}}{BV_{PP}} \right)^{4/3} \quad \textbf{[4.1]}$$

where BV_{PP} is the breakdown voltage for the parallel-plane case after accounting for the edge termination. The maximum depletion width in the TSBS structure is limited to that associated with the breakdown voltage (BV) of the structure, as given by:

$$t = W_D(BV) = \sqrt{\frac{2\varepsilon_S BV}{qN_D}} \quad \textbf{[4.2]}$$

The thickness of the drift region required below the bottom of the trenches is therefore less than the depletion width for the ideal parallel-plane junction with the above doping concentration. The resistance of the drift region below the low barrier height main Schottky contact is consequently enhanced above that for the ideal parallel-plane case due to current transport between the trenches and the lower doping concentration of the drift region.

4.2 Forward Conduction Model

Analysis of the on-state voltage drop of the TSBS rectifier requires taking into consideration the current constriction at the main low barrier height Schottky contact due to the presence of the trenches and the enhanced resistance of the drift region due to current spreading from the main Schottky contact to the N^+ substrate. Several models were developed for the spreading resistance for the JBS rectifier structure in the previous chapter. It was found that model C with a 45 degree current spreading angle from the bottom of the P-N junction is the most suitable. In addition, this model was applied to the silicon carbide JBS rectifier by assuming a rectangular shape for the junction. It is therefore appropriate to utilize this model for the on-state current flow in both silicon and silicon carbide TSBS rectifier structures.

The current flow pattern in the forward conduction mode for the TSBS rectifier is illustrated in Fig. 4.2 with the shaded area. The model takes into account the increase in current density at the main Schottky contact due to the space taken up by the trenches and the presence of a depletion layer at the large barrier height metal. The current through the main Schottky contact flows only within the un-depleted portion (with dimension ‘d’) of the drift region at the top surface. Consequently, the current density at the main Schottky contact (J_{FS}) is related to the cell (or cathode) current density (J_{FC}) by:

$$J_{FS} = \left(\frac{p}{d}\right) J_{FC} \quad \textbf{[4.3]}$$

where p is the cell pitch. The dimension 'd' is determined by the cell pitch (p), the size of the window (2s) for etching the trenches, and the on-state depletion width ($W_{D,ON}$):

$$d = p - s - W_{D,ON} \quad \textbf{[4.4]}$$

Depending up on the lithography used for device fabrication to minimize the space (dimension 's') taken up by the trenches, the current density at the main Schottky contact can be enhanced by a factor of two or more. This must be taken into account when computing the voltage drop across the Schottky contact given by:

$$V_{FS} = \phi_B + \frac{kT}{q} \ln\left(\frac{J_{FS}}{AT^2}\right) \quad \textbf{[4.5]}$$

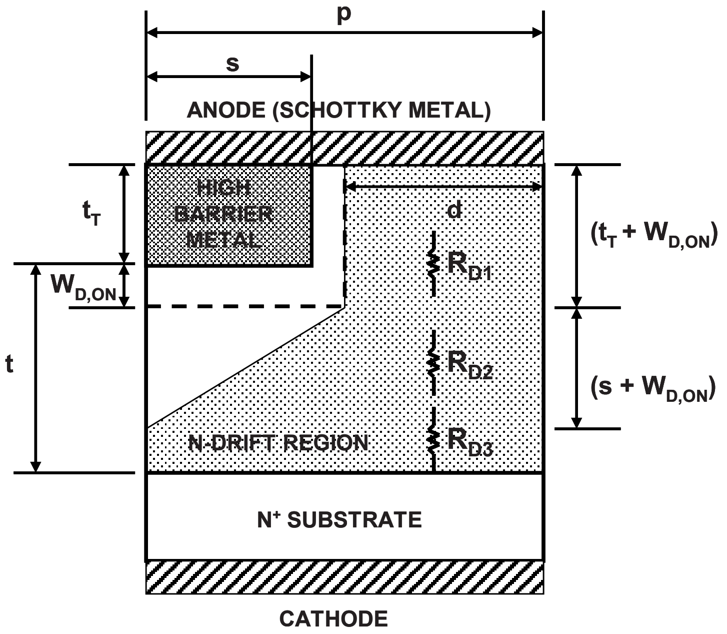

Fig. 4.2 Current Flow Pattern in the TSBS Rectifier Structure during Operation in the On-State.

After flowing across the main Schottky contact, the current flows through the un-depleted portion of the drift region. In the model, it is assumed that the current flows through a region with a uniform width 'd' until it reaches the bottom of the depletion region and then spreads to the entire cell pitch (p) at a 45 degree spreading angle. The current paths overlap at a distance ($s + W_{D,ON}$) from the bottom of the depletion region. The current then flows through a uniform cross-sectional area.

The net resistance to current flow can be calculated by adding the resistance of the three segments. The resistance of the first segment of uniform width 'd' is given by:

$$R_{D1} = \frac{\rho_D.(t_T + W_{D,ON})}{d.Z} \quad \textbf{[4.6]}$$

The resistance of the second segment can be derived by using the same approach used for Model C for the silicon JBS rectifier:

$$R_{D2} = \frac{\rho_D}{Z} \ln\left(\frac{p}{d}\right) \quad \textbf{[4.7]}$$

The resistance of the third segment with a uniform cross-section of width p is given by:

$$R_{D3} = \frac{\rho_D.(t - s - 2W_{D,ON})}{p.Z} \quad \textbf{[4.8]}$$

The specific resistance for the drift region can be calculated by multiplying the cell resistance ($R_{D1} + R_{D2} + R_{D3}$) by the cell-area (p.Z):

$$R_{sp,drift} = \frac{\rho_D.p.(t_T + W_{D,ON})}{d} + \rho_D.p.\ln\left(\frac{p}{d}\right) + \rho_D.(t - s - 2W_{D,ON}) \quad \textbf{[4.9]}$$

In addition, it is important to include the resistance associated with the thick, highly doped N^+ substrate. In the case of silicon devices, the contribution from the substrate is typically 2 x 10^{-5} Ω-cm^2. For 4H-SiC, the specific resistance contributed by the N^+ substrate is typically 4 x 10^{-4} Ω-cm^2.

The on-state voltage drop for the TSBS rectifier at a forward cell current density J_{FC}, after including the substrate contribution, is given by:

$$V_F = \phi_B + \frac{kT}{q} \ln\left(\frac{J_{FS}}{AT^2}\right) + (R_{sp,drift} + R_{sp,subs}).J_{FC} \quad \textbf{[4.10]}$$

The on-state depletion layer width for the silicon and silicon carbide structures is determined by the contact potential for the metal in the trenches and the on-state voltage drop. The contact potential for a metal-semiconductor junction is given by[4]:

$$qV_C = \phi_M - (\chi_S + E_C - E_{FS}) \quad \textbf{[4.11]}$$

where ϕ_M is the work function of the metal in the trenches, χ_S is the electron affinity of the semiconductor, E_C is the conduction band energy, and E_{FS} is the

Fermi level energy in the semiconductor. The Fermi level position in the semiconductor can be computed by using:

$$E_{FS} = E_i + \frac{kT}{q}\ln\left(\frac{n_0}{n_i}\right) \quad \textbf{[4.12]}$$

where E_i is the intrinsic energy level, k is Boltzmann's constant, T is the absolute temperature, q is the charge of the electron, n_0 is the equilibrium concentration for electrons and n_i is the intrinsic carrier concentration. For simplicity, the equilibrium concentration of electrons in the semiconductor can be assumed to be equal to the doping concentration for the analysis of TSBS rectifiers.

When computing the on-state voltage drop using the above equations, it is satisfactory to make the approximation that the depletion layer width can be computed by subtracting an on-state voltage drop from the contact potential:

$$W_{D,ON} = \sqrt{\frac{2\varepsilon_S\left(V_C - V_{ON}\right)}{qN_D}} \quad \textbf{[4.13]}$$

Due to the abrupt junctions formed with the metal-semiconductor contacts, it is appropriate to assume that the entire depletion occurs in the semiconductor for the TSBS rectifier structure.

4.2.1 Silicon TSBS Rectifier: Example

In order to understand the operation of the silicon TSBS rectifier structure, it is instructive to consider a specific example of a device with breakdown voltage of 50 volts. If the edge termination limits the breakdown to 80 percent of the ideal value, the parallel-plane breakdown voltage is 62.5 volts. This voltage can be supported by a depletion region width of 2.85 microns in the drift region with doping concentration of 8×10^{15} cm^{-3}. For this example, it will be assumed that the barrier height for the main Schottky contact is 0.60 eV while that for the metal in the trenches is 0.85 eV. These values are representative of using a low barrier height metal such as Chromium for the main Schottky contact and Platinum as the metal in the trenches.

The contact potential at the metal in the trenches in this case is found to be 0.639 volts. Using this value and an on-state voltage drop of 0.45 volts, the depletion region width in the N-drift region at the metal in the trenches is 0.17 microns. If the TSBS structure has a cell pitch (p) of 1.00 microns, and the trenches are created using a window (2s) of 0.5 microns, the dimension ‘d’ is found to be 0.58 microns. Consequently, the current density at the main Schottky contact region where the current is transported is enhanced by a factor about 2 times when compared with the cathode (or average cell) current density. This enhancement in current density is smaller than that for the silicon JBS rectifier structure because extra space is consumed in the silicon JBS rectifier structure by the lateral diffusion of the junction.

The impact of changing the cell pitch (p) on the on-state characteristics can be predicted by using the above model for the TSBS rectifier structure. The results obtained for the case of a trench depth of 0.5 microns are shown in Fig. 4.3. The *i-v* characteristic of a normal Schottky rectifier with the same drift region parameters is included for comparison. The impact on the on-state voltage drop is small as long as the pitch is more than 1.00 microns. The on-state voltage drop of the TSBS rectifier structure at an on-state current density of 100 A/cm^2 is 0.343 volts compared with 0.322 volts for the normal Schottky rectifier structure with the same barrier height as the main Schottky contact. The ability to obtain a low on-state voltage drop in the silicon TSBS structure with a smaller pitch than for the JBS rectifier structure produces superior on-state characteristics.

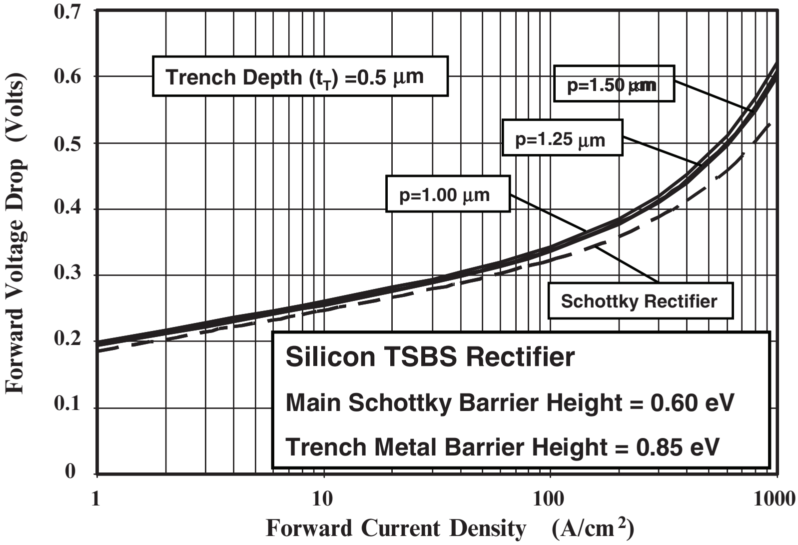

Fig. 4.3 Forward Characteristics of 50V Silicon TSBS Rectifier Structures.

The degree of shielding of the main Schottky contact in the TSBS rectifier structure against the high electric fields generated in the drift region during the reverse blocking mode depends upon the depth of the trenches. A deeper trench improves the *aspect ratio* of the region between the metal in the trenches. As discussed in the previous chapter, a larger aspect ratio has been found to provide greater shielding in the case of the vertical junction field effect transistor leading to a larger blocking gain[5]. However, the resistance of the first segment in the model for the drift region resistance increases with trench depth leading to a larger on-state voltage drop. This is illustrated for the TSBS rectifier structure with a fixed cell pitch of 1 micron in Fig. 4.4 where the analytically calculated forward *i-v* characteristics are shown for various trench depths. Increasing the trench depth from 0.5 to 1 micron increases the on-state voltage drop by a small amount from 0.343 to 0.348 volts. In this figure, the case of a structure with zero depth for the trench is also included. In this case, the on-state voltage for the TSBS rectifier structure is reduced to 0.338 volts. This is still larger than the on-state voltage drop of 0.322 volts for the normal Schottky rectifier because of the space consumed by the large barrier height metal which enhances the current density at the main Schottky contact.

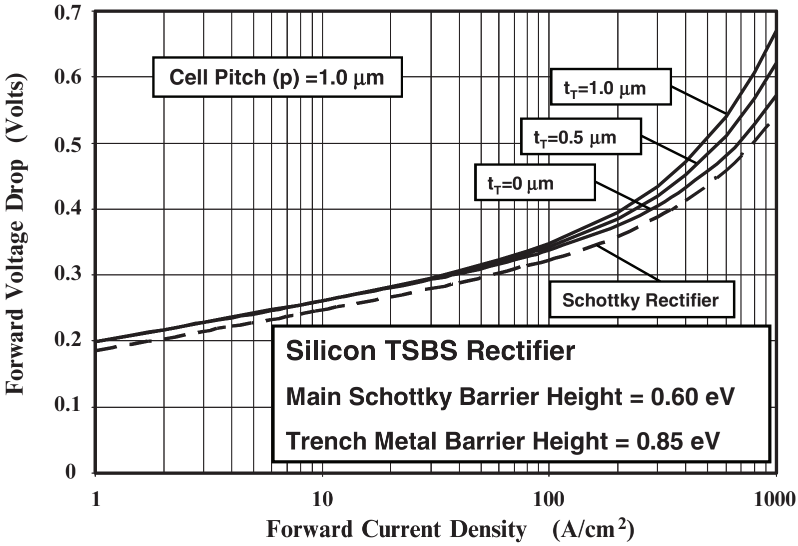

Fig. 4.4 Forward Characteristics of 50V Silicon TSBS Rectifier Structures.

Simulation Example

In order to validate the above model for the on-state characteristics of the silicon TSBS rectifier, the results of two-dimensional numerical simulations of a 50 V structure are described here. All the devices had a drift region thickness of 3 microns with a doping concentration of 8 x 10^{15} cm^{-3}. For all the TSBS rectifier structures, a work function of 4.80 eV was used for the main Schottky contact and 5.05 eV for the metal in the trenches. In all cases, the window for etching the trenches (twice the dimension ‘s’ in Fig. 4.2) was kept at 0.5 microns.

The on-state *i-v* characteristic for the TSBS rectifier with a cell pitch ‘p’ of 1.00 microns and a trench depth of 0.5 microns is shown in Fig. 4.1E. This plot includes the total current (cathode current) flowing through the structure together with the current flowing through the main Schottky contact (dotted line) and the metal in the trenches (dashed line). It can be observed that the current flowing through the metal in the trenches is 3 orders of magnitude smaller than the current through the main Schottky contact because of its larger barrier height. This justifies using an analytical model for the TSBS rectifier with only the current flow through the main low barrier height Schottky contact. At an on-state current density of 100 A/cm^2, the on-state voltage drop obtained from the numerical simulations for this structure is 0.35 volts. The value obtained from the numerical simulations is in good agreement with the value obtained by using in the analytical model for this structure with a barrier height of 0.6 eV for the main Schottky contact (see Fig. 4.3). The saturation current density for the main Schottky contact can be determined to be 8 x 10^{-4} A/cm^2 by extrapolation of the linear portion of the *i-v* characteristics obtained from the numerical simulations (see Fig. 4.1E). In computing this saturation current density, it is important to recognize that the area of the main Schottky contact is only half the cell area. Using this value for the saturation current density, the effective Schottky barrier height for the main Schottky contact in the simulations is found to be 0.60 eV, which is the same value used for the analytical models.

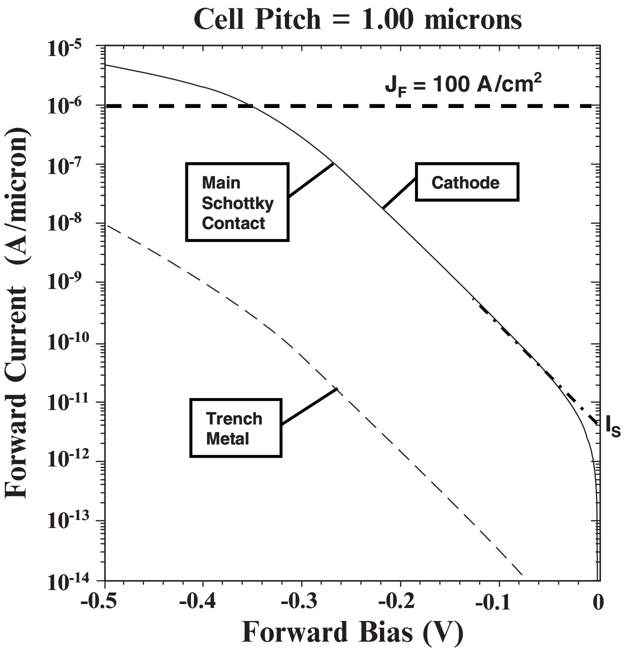

Fig. 4.1E On-State Characteristics for a 50V Silicon TSBS Rectifier.

The current flow-lines for the above TSBS rectifier structure with cell pitch (p) of 1 micron and trench depth of 0.5 microns are shown in Fig. 4.2E at an on-state voltage drop of 0.4 volts. It can be seen that all the current flow-lines converge to the main Schottky contact located on the upper right-hand-side of the structure demonstrating that very little current flows through the metal contact in the trenches. The current flow pattern is consistent with pattern used to develop the analytical model with an approximately uniform cross-section between the trenches followed by a spreading of the current at an angle of about 45 degrees (see Fig. 4.2). The current then becomes uniformly distributed below a depth of 1.5 microns from the surface. This justifies the use of a three region analytical model for the series resistance of the drift region with no current flow through the metal electrode located in the trenches.

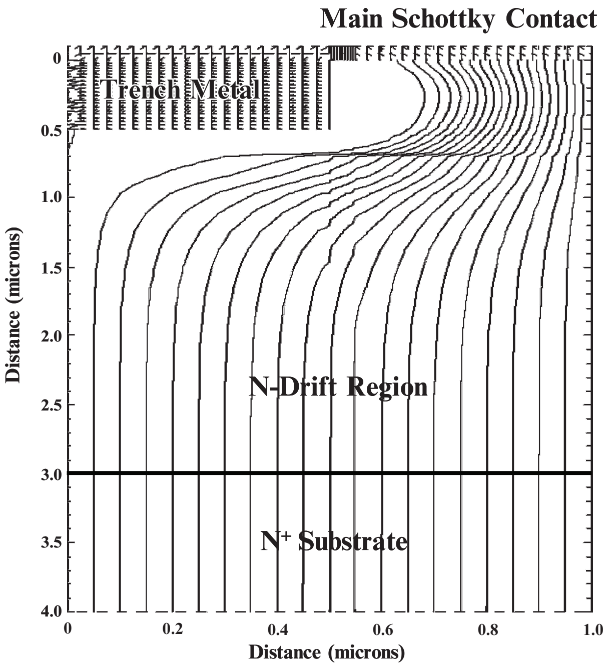

Fig. 4.2E On-State Current Distribution in a 50V Silicon TSBS Rectifier.

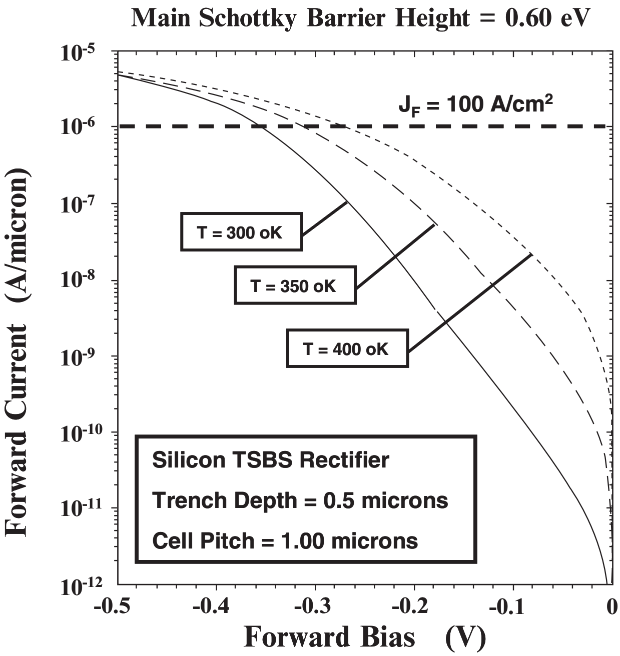

Fig. 4.3E On-State Characteristics for a Typical 50V Silicon TSBS Rectifier.

The on-state characteristics for the silicon TSBS rectifier have the same temperature behavior as the normal Schottky rectifier. The on-state voltage drop decreases with increasing temperature[4] as shown in Fig. 4.3E. This produces a reduction in the on-state power losses as the temperature increases. The reverse blocking power loss becomes dominant at high temperatures because the leakage current density increases rapidly with increasing temperature. The power loss exhibits a minima at a temperature beyond which the device can undergo thermal runaway.

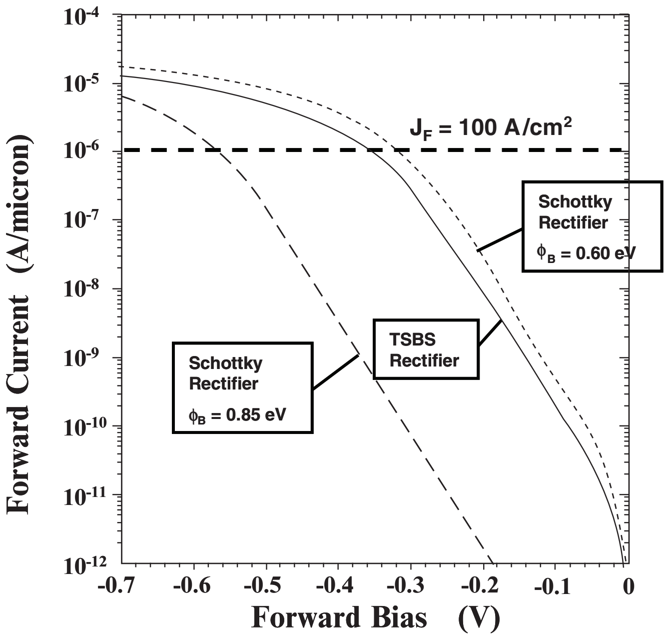

Fig. 4.4E Comparison of the On-State Characteristics for a Typical 50V Silicon TSBS Rectifier with Schottky Rectifiers.

In the TSBS rectifier structure, the area for the main Schottky contact must be sacrificed to introduce the second Schottky contact for providing the shielding during reverse bias operation. This produces an increase in current density at the main Schottky contact and a larger spreading resistance of the drift region. Both of these phenomena can be expected to increase the on-state voltage drop of the TSBS rectifier structure when compared with the normal Schottky rectifier. This impact on the on-state characteristics can be illustrated by using the *i-v* characteristics of the typical TSBS rectifier structure as an example. The *i-v* characteristics of the typical TSBS rectifier with a cell pitch of 1 micron and a trench depth of 0.5 microns are compared with the normal Schottky rectifier with a cell pitch of 1 micron in Fig. 4.4E. It can be observed that the on-state voltage drop for the TSBS rectifier structure is 0.03 volts larger than for the normal Schottky rectifier with same barrier height of 0.60 eV as the main Schottky contact in the TSBS rectifier. For completeness, the i-v characteristics for the normal Schottky rectifier with the same barrier height of 0.85 eV as the metal in the trenches of the TSBS rectifier are also displayed in the figure. The on-state voltage drop for this normal Schottky rectifier is 0.21 volts larger than that of the TSBS rectifier structure.

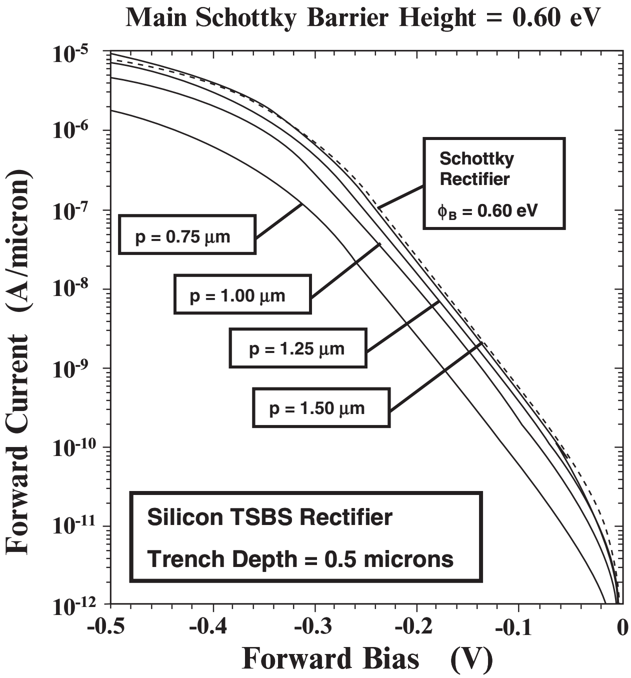

Fig. 4.5E On-State Characteristics for 50V Silicon TSBS Rectifiers.

The on-state characteristics of 50 V TSBS rectifiers with a cell pitch of 0.75, 1.00, 1.25 and 1.50 microns are compared with that of the TSBS rectifier and a normal Schottky rectifier with cell pitch of 1.00 microns in Fig. 4.5E. All the structures had a main Schottky contact with barrier height of 0.60 eV. In the TSBS rectifiers, the trench had a width (2s) of 1 micron and a depth of 0.5 microns. From the graph, the on-state voltage drop may appear to be reducing with increasing cell pitch. However, after accounting for the difference in the areas of the structures, the on-state voltage drop at an on-state current density of 100 A/cm^2 is found to be approximately equal for all the TSBS rectifier structures with cell pitch greater than 1 micron. These results are consistent with those predicted by the analytical model (see Fig. 4.3) confirming its utility for analysis of the JBS rectifier structure in the on-state. However, when the pitch is reduced to 0.75 microns, the on-state voltage drop increases to 0.41 volts compared with 0.35 volts for the other TSBS rectifier structures. Based upon these results, it is better to use a cell pitch of 1 micron for the TSBS rectifier in order to suppress the electric field at the main Schottky contact to a greater degree while obtained a low on-state voltage drop.

In the TSBS rectifier structure, an increase in the trench depth improves the shielding of the main Schottky contact. However, this also increases the resistance of the current path from the Schottky contact to the cathode. The impact of increasing the trench depth from 0 to 1.0 micron in the TSBS rectifier structure can be demonstrated using numerical simulations for the case of a cell pitch of 1 micron. The on-state *i-v* characteristics for these structures are compared with the normal Schottky rectifier in Fig. 4.6E. The i-v characteristics of the structures nearly coincide for the cases of a trench depth of 0.25 and 0.50 microns. The on-state voltage drop at a current density of 100 A/cm^2 increases slightly for the cases of deeper trench regions. These results are in good agreement with the predictions of the analytical model (see Fig. 4.4). The case of zero trench depth is also shown in the figure by the *i-v* characteristics with the dashed line. The on-state voltage drop for this case is still larger than that of the normal Schottky rectifier due to the space consumed by the metal with the larger barrier height.

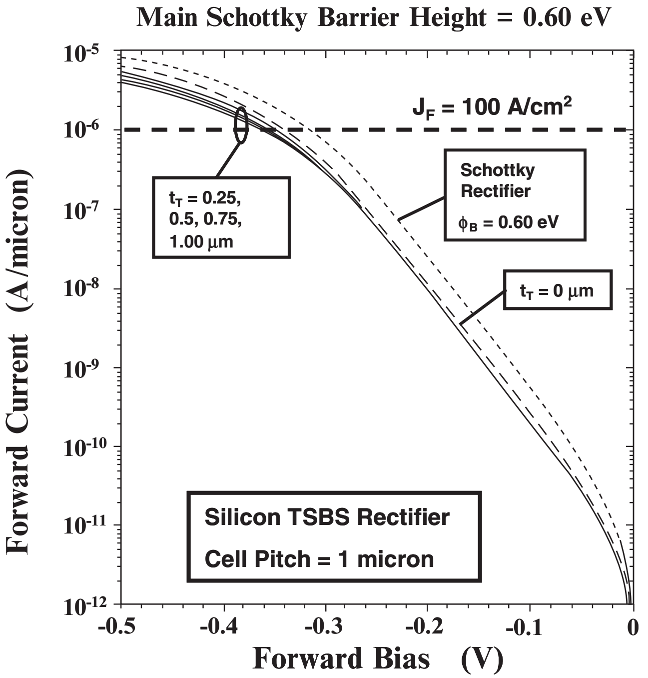

Fig. 4.6E On-State Characteristics for 50V Silicon TSBS Rectifiers.

4.2.2 Silicon Carbide TSBS Rectifier: Example

As mentioned earlier, the same on-state model can be used for the silicon carbide TSBS rectifier and the silicon structure because the cell structure is identical. However, in the case of silicon carbide devices, it is possible to utilize metal layers with larger Schottky barrier heights because of its larger energy band gap than silicon. Although this produces a larger zero bias depletion width at the metal in the trenches, the depletion width under on-state current flow is similar to the silicon structure because the silicon carbide device is operated at a larger on-state voltage drop. One significant difference between the silicon and silicon carbide structures is that the trench depth is a smaller fraction of the total drift region thickness for the case of high voltage silicon carbide rectifiers. This reduces the impact of current spreading within the silicon carbide cell structure. However, it is important to include the resistance associated with the thick, highly doped N^+ substrate because this is substantially larger than for silicon devices. The specific resistance of the N^+ substrate can be determined by taking the product of its resistivity and thickness. For 4H-SiC, the lowest available resistivity for N^+ substrates is 20 mΩ-cm. If the thickness of the substrate is 200 microns, the specific resistance contributed by the N^+ substrate is 4×10^{-4} Ω-cm^2.

The on-state voltage drop for the TSBS rectifier at a forward cell current density J_{FC}, including the substrate contribution, is given by Eq. (4.10). The Richardson's constant for 4H-SiC is 146 A^{o}K^{-2}cm^{-2}. As an example, 4H-SiC TSBS rectifiers with a blocking voltage capability of 3000 volts will be analyzed in this section. This reverse blocking capability can be obtained by using a drift region with a doping concentration of 8.5×10^{15} cm^{-3} and thickness of 20 microns after accounting for loss in voltage at the edge termination. A typical 4H-SiC TSBS rectifier structure has a cell pitch of 1 micron, a trench width (2s) of 1 micron, and a trench depth of 0.5 microns.

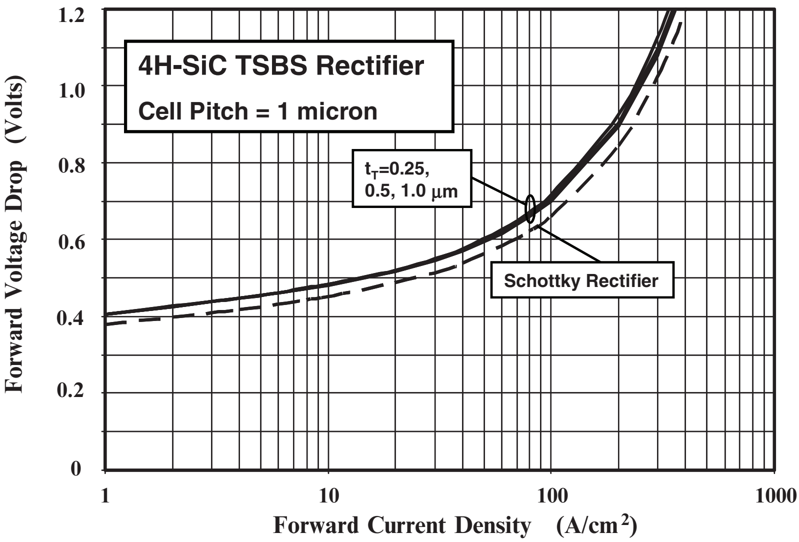

Fig. 4.5 Forward Characteristics of 3kV 4H-SiC TSBS Rectifiers.

The forward characteristics of 3kV TSBS rectifiers, calculated using the analytical model with a barrier height of 0.8 eV for the main Schottky contact, are shown in Fig. 4.5 with the trench depth as a parameter. It can be observed that the on-state characteristics are not strongly affected by the trench depth. This is due to the relatively small trench depth when compared with the total thickness of 20 microns for drift region. The current spreading in these high voltage silicon carbide

TSBS rectifier structures occurs within the top 2 microns making the contribution from the rest of the drift region nearly equal for all the cases. The trench depth can therefore be selected for sufficiently reducing the electric field at the main Schottky contact during the reverse blocking mode.

It is worth pointing out that the area for the main Schottky contact is reduced in half by the presence of the trenches in the TSBS rectifier structures. This results in an increase in the current density at the main Schottky contact which produces the observed shift in the *i-v* characteristics to larger voltages when compared with the normal Schottky rectifier. In comparison with the Schottky rectifier characteristics (shown by the dashed line in the figure), the increase in on-state voltage drop at a forward current density of 100 A/cm^2 is small (0.04 volts) for these TSBS rectifier structures.

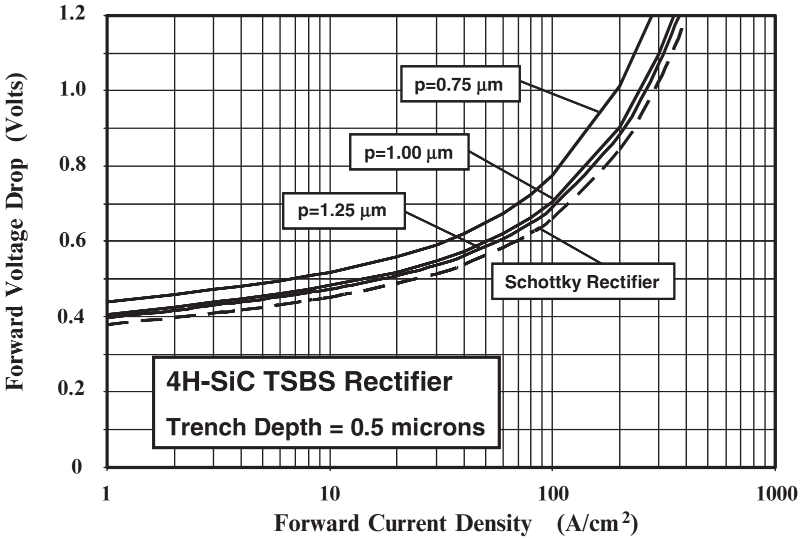

Fig. 4.6 Forward Characteristics of 3kV 4H-SiC TSBS Rectifiers.

The impact of changing the cell pitch on the on-state characteristics of the 4H-SiC TSBS rectifier is illustrated in Fig. 4.6. In this case, the trench depth was kept at the same value of 0.5 microns for the structures. It can be observed that increasing the cell pitch from 1.00 to 1.25 microns produces only a small improvement in the on-state voltage drop. In contrast, reducing the cell pitch to 0.75 microns produces a significant increase in the on-state voltage drop. It is therefore necessary to maintain a cell pitch of at least 1 micron to obtain a low on-state voltage drop. This value is sufficient to suppress the electric field at the main Schottky contact as shown later in the chapter.

Simulation Example

In order to validate the above model for the on-state characteristics of the silicon carbide TSBS rectifier, the results of two-dimensional numerical simulations on a 3000 V structure are described here. The structure had a drift region thickness of 20 microns with a doping concentration of 8.5×10^{15} cm^{-3}. The trench region had a depth of 0.5 microns with an etching window (dimension 2s in Fig. 4.2) of 1.0 microns. A work-function of 4.5 eV was used for the main Schottky contact and 5.0 eV for the metal in the trenches. This corresponds to a Schottky barrier height of about 0.8 eV for the main Schottky metal and 1.3 eV for the metal in the trenches based upon an electron affinity of 3.7 eV for 4H-SiC.

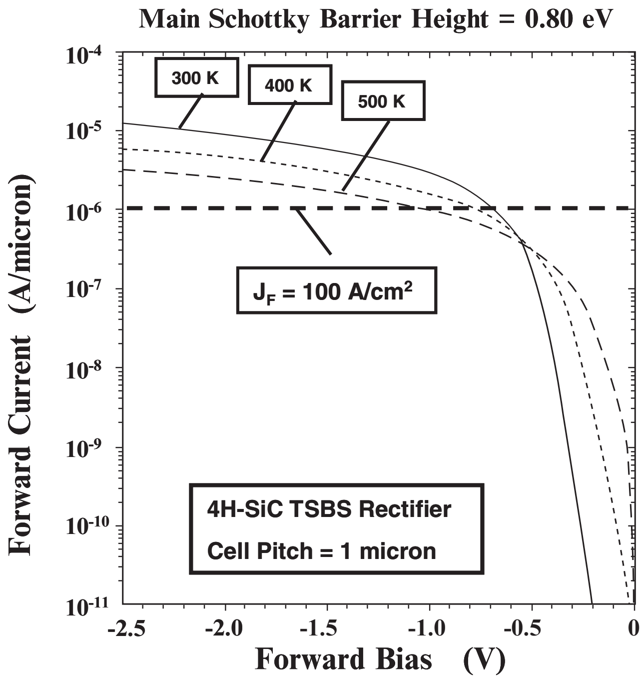

Fig. 4.7E Forward Characteristics of a Typical 3 kV 4H-SiC TSBS Rectifier.

The forward *i-v* characteristics of the typical 3000 V 4H-SiC TSBS rectifier obtained from the numerical simulations are shown in Fig. 4.7E for the case of a cell pitch of 1 micron and a trench depth of 0.5 microns. The on-state voltage drop at a current density of 100 A/cm^2 is 0.7 volts at 300 ^{o}K which is identical to the value obtained by using the analytical model providing validation for the model. This 4H-SiC rectifier exhibits the desirable positive temperature coefficient for the on-state voltage drop because of the substantial contribution from the drift region resistance. The drift region resistance increases with temperature due to a reduction of the mobility for electrons.

In the TSBS structure, the analytical model for the on-state characteristics is based upon the assumption that the current through the metal in the trenches can be neglected. The current flow at the high barrier metal in the trenches in the typical TSBS structure can be observed in Fig. 4.8E for the case of a cell pitch of 1 micron. The current through the high barrier metal is about 7 orders of magnitude less than that through the low barrier metal at the on-state operating point. This validates the assumptions used when developing the analytical model for the 4H-SiC TSBS rectifier and demonstrates that the on-state voltage drop for the silicon carbide TSBS rectifier is controlled by current transported through the main Schottky contact metal.

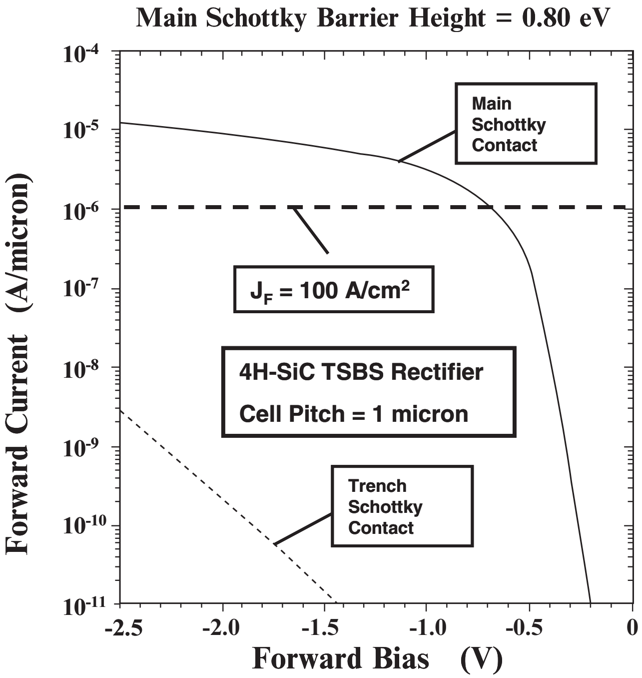

Fig. 4.8E Forward Characteristics of a Typical 3 kV 4H-SiC TSBS Rectifier.

With the analytical model for the silicon carbide TSBS structure, it was found that the on-state voltage drop is not strongly dependent on the depth of the trenches but is sensitive to the cell pitch. The influence of the cell pitch can be demonstrated by performing numerical simulations of the TSBS structure with the same trench depth. It was found that the on-state voltage drop increases substantially when the cell pitch is reduced to 0.75 microns as shown in Fig. 4.9E. The on-state voltage drop increases from 0.7 volts at a cell pitch of 1 micron to 0.9 volts at a cell pitch of 0.75 microns. This increase is similar to the results obtained by using the analytical model (see Fig. 4.6). The reason for the increase in the on-state voltage drop is the greater constriction of the current at the Schottky contact for the smaller cell pitch because the dimension 'd' is reduced from 0.32 microns at a cell pitch of 1 micron to only 0.07 microns for the pitch of 0.75 microns. It will be shown later in this chapter that a cell pitch of 1 micron is adequate to suppress the electric field at the main Schottky contact in the reverse blocking mode.

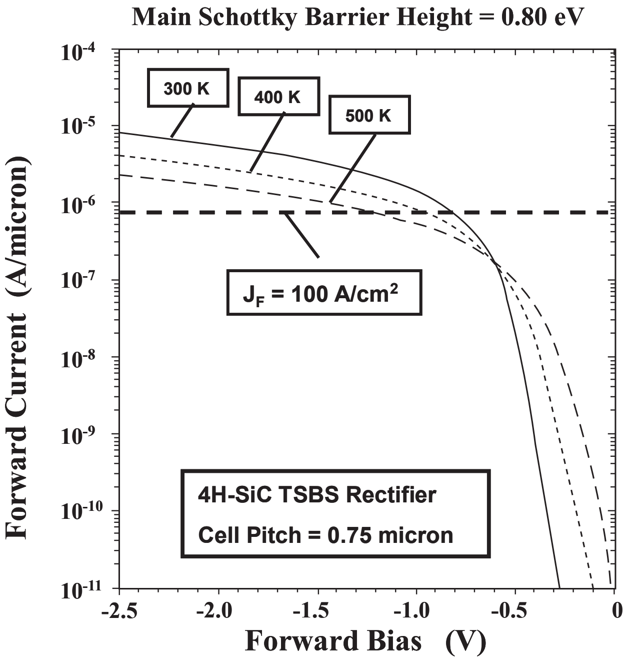

Fig. 4.9E Forward Characteristics of a 3 kV 4H-SiC TSBS Rectifier.

4.3 TSBS Rectifier Structure: Reverse Leakage Model

The reverse leakage current in the TSBS rectifier is reduced when compared with the Schottky rectifier due to the smaller electric field at the metal-semiconductor interface at the main Schottky contact. In addition, the area of the main Schottky contact is a fraction of the total cell area resulting in a smaller reverse current contribution. In the case of the silicon TSBS rectifier, the reduced electric field at the Schottky contact suppresses the barrier lowering effect. In the case of the silicon carbide TSBS rectifier, the reduced electric field not only decreases the barrier lowering but also mitigates the influence of thermionic field emission. The impact of the reduction of the electric field at the Schottky contact in the TSBS rectifier structure on the leakage current is analyzed in this section.

4.3.1 Silicon TSBS Rectifier: Reverse Leakage Model

As in the case of the JBS rectifier structure, the leakage current model for the TSBS rectifier must take into account the smaller main Schottky contact area within the cell and the influence of the smaller electric field generated at the Schottky contact due to the shielding effect. The leakage current contribution from the main Schottky contact in the silicon TSBS rectifier can be obtained by using:

$$J_L = \left(\frac{p-s}{p}\right) AT^2 \exp\left(-\frac{q\phi_b}{kT}\right).\exp\left(\frac{q\beta\Delta\phi_{bTSBS}}{kT}\right) \qquad \textbf{[4.14]}$$

where β is a constant to account for a smaller barrier lowering closer to the trenches as discussed previously for the JBS rectifier structure. In the previous chapter on Schottky rectifiers, it was demonstrated that the high electric field at the Schottky contact produces a reduction of the effective barrier height due to the image force lowering phenomenon. In contrast with the Schottky rectifier, the barrier lowering for the TSBS rectifier is determined by the reduced electric field E_{TSBS} at the main Schottky contact:

$$\Delta\phi_{bTSBS} = \sqrt{\frac{qE_{TSBS}}{4\pi\varepsilon_S}} \qquad \textbf{[4.15]}$$

In the TSBS rectifier structure, the electric field at the Schottky contact varies with distance away from the trenches. The highest electric field is observed at the middle of the main Schottky contact with a progressively smaller value closer to the trenches. In an analytical model with a worst case scenario, it is prudent to use the electric field at the middle of the main Schottky contact to compute the leakage current. Until the depletion regions from the adjacent trenches produce a potential barrier under the main Schottky contact, the electric field at the metal-semiconductor interface in the middle of the contact increases with the applied reverse bias voltage as in the case of the normal Schottky rectifier. A potential barrier is established by the trenches after depletion of the drift region below the main Schottky contact. The voltage at which the depletion regions from the adjacent trenches intersect under the main Schottky contact is referred to as the *pinch-off voltage*. The pinch-off voltage (V_P) can be obtained from the device cell parameters:

$$V_P = \frac{qN_D}{2\varepsilon_S}(p-s)^2 - V_{CT} \qquad \textbf{[4.16]}$$

where V_{CT} is the contact potential for the metal in the trenches.

Although a potential barrier begins to form after the reverse bias exceeds the pinch-off voltage, the electric field continues to rise at the main Schottky contact due to encroachment of the potential to the main Schottky contact. In order to analyze the impact of this on the reverse leakage current, the electric field E_{TSBS} can be related to the reverse bias voltage by:

$$E_{TSBS} = \sqrt{\frac{2qN_D}{\varepsilon_S}(\alpha V_R + V_{CM})} \qquad \textbf{[4.17]}$$

where α is a coefficient used to account for the build up in the electric field after pinch-off and V_{CM} is the contact potential for the main Schottky contact.

The above analysis for the electric field at the main Schottky contact is identical to that for the silicon and silicon carbide JBS rectifiers developed in the previous chapter. Consequently, the same graph relation the electric field to the reverse bias for various values of alpha shown in Fig. 3.11 is also applicable to the TSBS structure. The value for alpha for the silicon TSBS rectifier structure is different from that for the silicon JBS rectifier structure because the rectangular shape of the trenches in the TSBS structure produces a greater suppression of the electric field.

The impact of the reduction of the electric field at the Schottky contact on the Schottky barrier lowering in the silicon TSBS rectifier structure is also the same as that shown in Fig. 3.12. Without the shielding by the metal in the trenches, a barrier lowering of 0.07 eV occurs in the normal silicon Schottky rectifier. The barrier lowering is reduced to 0.05 eV with an alpha of 0.2 in the TSBS rectifier structure. Although this may appear to be a small change, it has a large impact on the reverse leakage current as was already shown in Fig. 3.13.

The analysis of the leakage current for the TSBS rectifier structure requires inclusion of the contribution from the trench metal contact. The leakage current flowing through this contact can in principle be made much smaller than that flowing through the main contact metal by making the barrier height for the trench contact large. For silicon devices, the largest practical value for the Schottky barrier height is only 0.85 volts by using platinum silicide. The leakage current flowing through the trench contact metal increases rapidly with increasing reverse bias voltage because of the Schottky barrier lowering phenomenon. This increase is exacerbated by the larger electric field generated at the trench corners in the TSBS rectifier structure.

The leakage current contribution from the trench contact in the silicon TSBS rectifier can be modeled by using the planar Schottky barrier theory:

$$J_{LTS} = \left(\frac{s}{p}\right) AT^2 \exp\left(-\frac{q\phi_{bTS}}{kT}\right).\exp\left(\frac{q\Delta\phi_{bTS}}{kT}\right) \qquad \textbf{[4.18]}$$

The barrier lowering for the trench contact in the TSBS rectifier is determined by the electric field E_{TS} at this contact:

$$\Delta\phi_{bTS} = \sqrt{\frac{qE_{TS}}{4\pi\varepsilon_S}} \qquad \textbf{[4.19]}$$

where the electric field (E_{TS}) at the trench contact can be computed using parallel-plane analysis. However, this methodology produces a leakage current contribution from the trench metal contact that is much smaller than actually prevalent in the TSBS rectifier structure. The leakage current contribution from the trench metal contact is significantly enhanced by the high electric field generated at the sharp corners of the trenches. The larger electric field at the trench corners aggravates the Schottky barrier lowering phenomenon producing a very rapid increase in leakage current at high reverse bias voltages. Since the electric field at the trench corners is determined by two-dimensional effects, it is not amenable to simple analytical modeling.

Simulation Example

In order to validate the above model for the reverse characteristics of the silicon TSBS rectifier, the results of two-dimensional numerical simulations on a 50 V structure are described here. The structure had a drift region with a doping concentration of 8.5 x 10^{15} cm^{-3} and a thickness of 3 microns. The typical silicon TSBS rectifier structure had a trench depth of 0.5 microns with trench etching window (dimension 2s in Fig. 4.2) of 1 micron. The work function of the main Schottky metal was chosen to obtain a barrier height of 0.60 eV and that for the trench metal was chosen to obtain a barrier height of 0.85 eV.

A three dimensional view of the electric field distribution in the typical TSBS rectifier cell is shown in Fig. 4.10E. The main Schottky contact is located on the lower right-hand-side in the figure with the trench region located at the top of the figure. A high electric field (4 x 10^5 V/cm) is observed at the metal interface at the bottom of the trench. However, the electric field at the middle of the main Schottky contact is greatly reduced (1.5 x 10^5 V/cm). It can also be seen that the electric field becomes smaller when proceeding towards the P-N junction. Consequently, a worst case analysis of the leakage current can be performed by using the electric field at the middle of the main Schottky contact. It is worth pointing out that a large electric field (6 x 10^5 V/cm) is generated at the sharp corner of the trench. This can degrade the breakdown voltage within the cell. A reduction of this electric field can be achieved by rounding the bottom of the trenches.

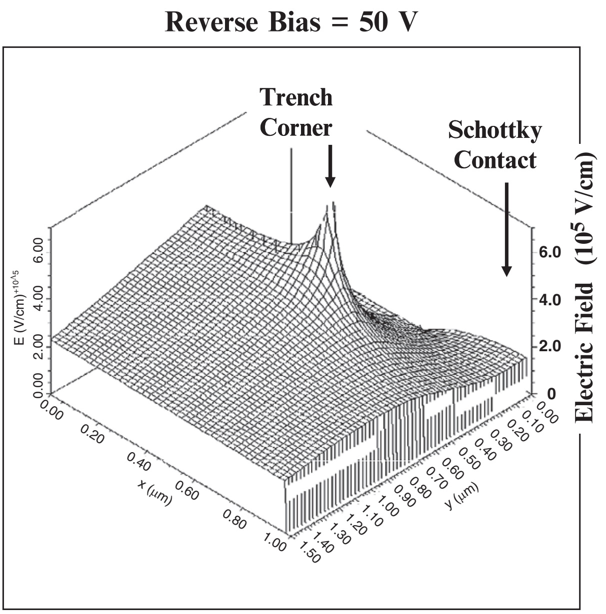

Fig. 4.10E Electric Field Distribution in a Typical 50 V Silicon TSBS Rectifier.

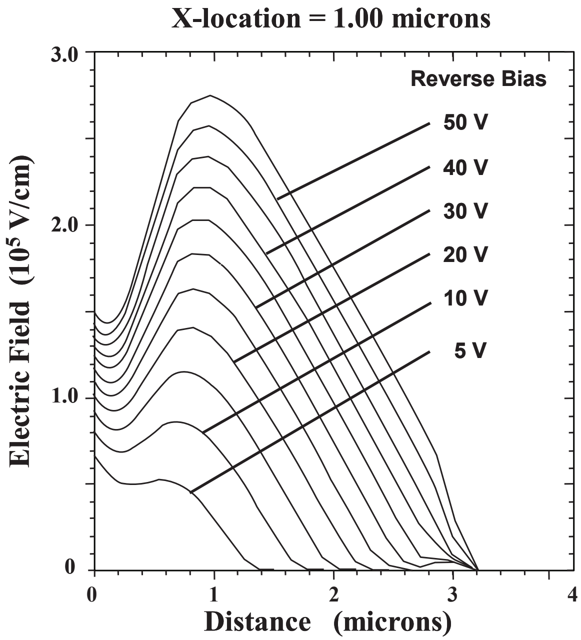

Fig. 4.11E Growth of the Electric Field at the Middle of the main Schottky Contact in a Typical 50 V Silicon TSBS Rectifier.

The growth in the electric field at the middle of the main Schottky contact with increasing reverse bias voltage for the typical TSBS rectifier structure with cell pitch of 1.00 microns is shown in Fig. 4.11E. In comparison with the growth of the electric field for the normal Schottky rectifier previously shown in Fig. 3.10E, it is apparent that the electric field at the main Schottky contact is suppressed in the TSBS rectifier. Although the potential barrier in this TSBS rectifier structure occurs at a depth of about 0.5 microns, the peak electric field occurs at a depth of about 1 micron. Consequently, a sufficient thickness for the drift region is required below the bottom of the trenches to prevent punch-through of the electric field to the N^+ substrate at high reverse bias voltages.

An even greater suppression of the electric field at the main Schottky contact can be obtained by either increasing the trench depth or reducing the cell pitch in the TSBS rectifier structure. The improvement obtained with a trench depth of 0.75 microns is shown in Fig. 4.12E for a TSBS rectifier structure with cell pitch of 1.00 microns. The electric field at the center of the main Schottky contact is now reduced to 0.9 x 10^5 V/cm compared with 1.5 x 10^5 V/cm for the typical TSBS rectifier structure with trench depth of 0.5 microns. The location of the peak electric also shifts to a greater depth for the structure with the deeper trench resulting in strong punch-through of the electric field profile to the N^+ substrate at reverse bias voltages above 40 volts. These simulations are intended to illustrate the impact of changing the trench depth while maintaining the same total thickness for the drift region. In practice, it is preferable to increase the total thickness of the drift region when the trench depth is increased to avoid the punch-through of the electric field to the N^+ substrate.

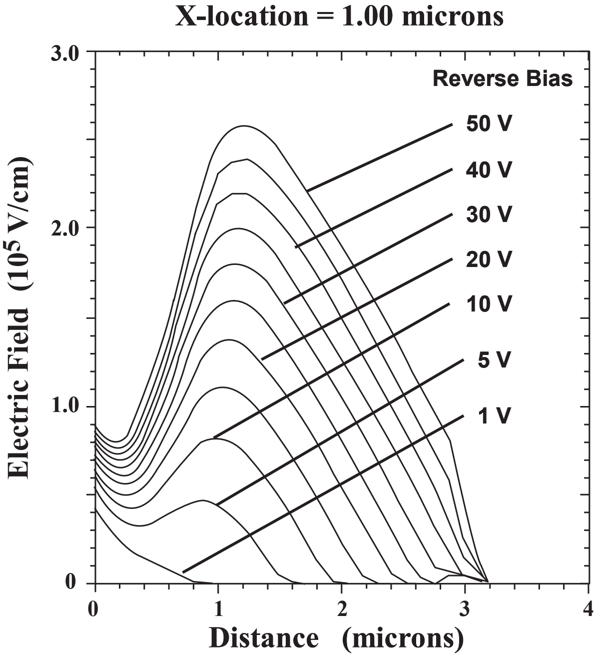

Fig. 4.12E Growth of the Electric Field at the Middle of the main Schottky Contact in a 50 V Silicon TSBS Rectifier.

The greater reduction of the electric field at the main Schottky contact obtained by reducing the cell pitch is illustrated in Fig. 4.13E for the a TSBS rectifier structure with cell pitch of 0.75 microns and trench depth of 0.5 microns. The electric field at the center of the main Schottky contact is now reduced to only 0.35×10^5 V/cm compared with 1.5×10^5 V/cm for the typical TSBS rectifier structure with trench depth of 0.5 microns. However, as pointed out earlier, the increase in the on-state voltage drop does not warrant such a drastic reduction of the electric field at the main Schottky contact.

The electric field generated at the corners of the trenches is also dependent up on the space between the trenches. On the one hand, when the trenches are located close together, the depletion of the space between them occurs at a small reverse bias voltage. The electric field at the trench corners is not significantly enhanced in this case. However, the area of the main Schottky contact is reduced when the space between the trenches is reduced producing a larger on-state voltage drop. On the other hand, if the space between the trenches is enlarged, the electric field enhancement at the trench corners becomes severe.

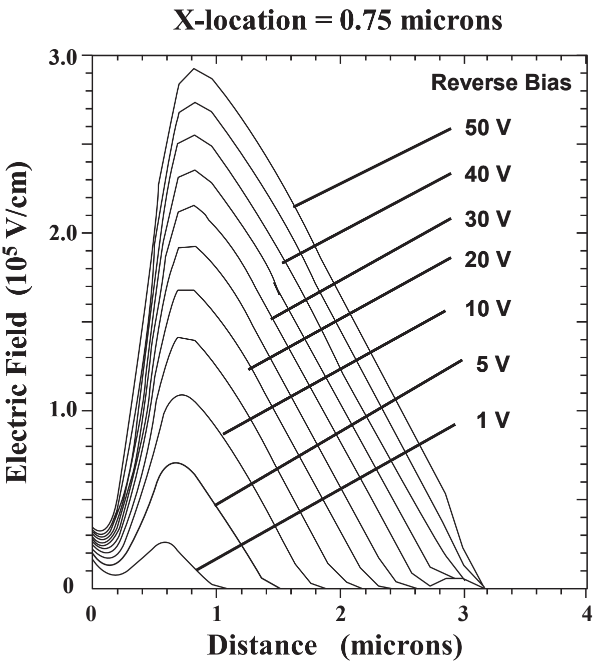

Fig. 4.13E Growth of the Electric Field at the Middle of the main Schottky Contact in a 50 V Silicon TSBS Rectifier.

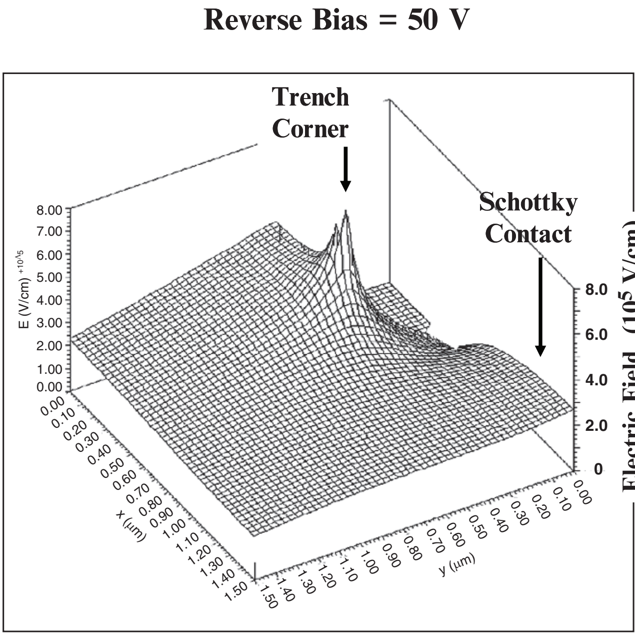

Fig. 4.14E Electric Field Distribution in a 50 V Silicon TSBS Rectifier.

This can be observed in the three-dimensional view of the electric field for a TSBS rectifier structure with a cell pitch of 1.5 microns and a trench depth of 0.5 microns shown in Fig. 4.14E. The electric field at the corner of the trenches has increased to 8 x 10^5 V/cm at a reverse bias of 50 volts when compared with 6.0 x 10^5 V/cm for the typical TSBS rectifier structure with a cell pitch of 1 micron. The enhanced electric field at the trench corners can reduce the breakdown voltage of the TSBS rectifier within the cell. It is important to maintain this breakdown voltage above the breakdown voltage at the edge termination. It is also worth pointing out that the larger space between the trenches results in a larger electric field at the main Schottky contact (compare Fig. 4.14E with Fig. 4.10E).

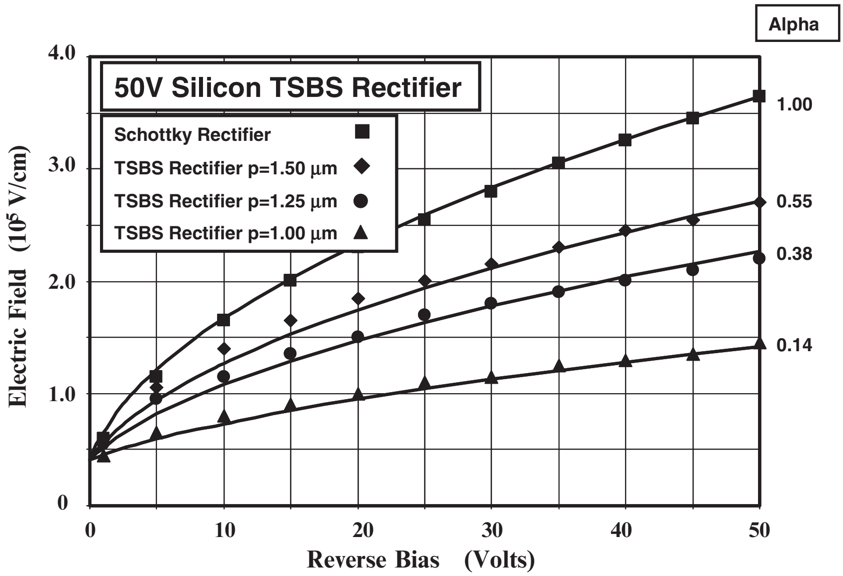

Fig. 4.15E Growth of the Electric Field at the Middle of the Schottky Contact for Silicon 50V TSBS Rectifiers.

The coefficient alpha, that governs the rate at which the electric field increases at the middle of the main Schottky contact in the analytical model for the TSBS rectifier structure, can be extracted from the results of the two-dimensional numerical simulations. The increase in the electric field at the middle of the main Schottky contact, obtained from the numerical simulations, is shown in Fig. 4.15E for the TSBS rectifiers with cell pitch (p) ranging from 1.00 to 1.50 microns by the symbols. The results of calculations based upon using the analytical Eq. [4.17] are shown by the solid lines with the values fro alpha adjusted to fit the results of the numerical simulations. The case with alpha of unity fits the Schottky rectifier quite well as expected. The value for alpha for the TSBS rectifier with pitch of 1.00 microns is found to be 0.14. It increases to 0.38 for a cell pitch of 1.25 microns while the alpha for a pitch of 1.50 microns is 0.55. With these values of alpha, the analytical model accurately predicts the behavior of the electric field at the middle of the Schottky contact. It can therefore be used to compute the Schottky barrier lowering and leakage current in TSBS rectifiers.

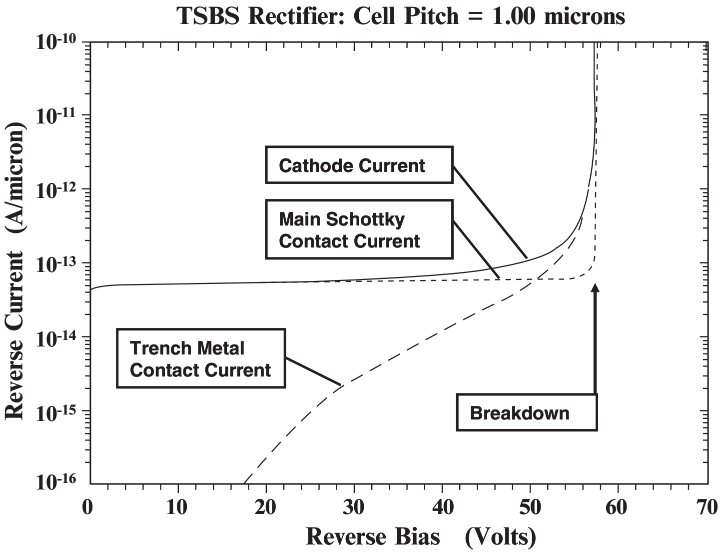

Fig. 4.16E Reverse Blocking Characteristics for a Silicon 50V TSBS Rectifier.

The numerical simulations provide insight into the current flow within the TSBS rectifier structure during the reverse blocking mode. The total reverse current flowing through the cathode electrode is compared with the currents flowing through the main Schottky contact and the trench metal contact in Fig. 4.16E. At reverse bias voltages below 30 volts, the cathode current is equal to the current flowing through the main Schottky contact. The current flow through the main Schottky contact remains essentially constant with increasing voltage due to suppression of growth in the electric field at the main Schottky contact. However, the current flowing through the trench metal contact increases rapidly when the reverse voltage exceeds 30 volts and becomes comparable to the current in the main Schottky contact at reverse bias voltages above 50 volts. It is necessary to use a sufficiently large barrier height for the trench metal contact to reduce this contribution. The leakage current from the trench contact can also be reduced by rounding the bottom of the trenches to reduce the electric field at the corners. It is worth pointing out that the breakdown occurs due to a very rapid increase in the current flowing through both the contacts.

The reverse *i-v* characteristic of the 50 V Silicon TSBS rectifier with a cell pitch of 1.00 microns obtained from the numerical simulations is shown in Fig. 4.17E together with that for the Schottky rectifiers using barrier heights corresponding to the main contact metal (0.60 eV) and the metal in the trenches (0.85 eV). All the devices had a cross-sectional width (cell pitch) of 1 micron. The breakdown voltage for the TSBS rectifier cell is observed to be 57 volts. This is consistent with an edge termination limited breakdown voltage of 50 volts at 80 percent of the parallel-plane breakdown voltage. The leakage current at small reverse bias voltages is 2x times smaller in the TSBS rectifier structure than for the Schottky rectifier with a barrier height of 0.60 eV. This is consistent with the reduction of the Schottky contact area by a factor of 2x in this TSBS rectifier structure. The leakage current for the Schottky rectifier increases by a factor of 7x when the reverse voltage increases to 50 volts. In contrast, the reverse leakage current for this TSBS rectifier increases by a factor of only 2x when the reverse voltage is increased to 50 volts. This increase is consistent with predictions of the analytical model. The leakage current contributed by a planar Schottky rectifier with a barrier height of 0.85 eV, corresponding to the trench contact, is also shown in the figure. This contribution remains well below that for the other devices. From this observation, it can be concluded that the enhancement of the electric field at the trench corners has a significant adverse impact on the leakage current contributed by the trench metal in the TSBS rectifier structure.

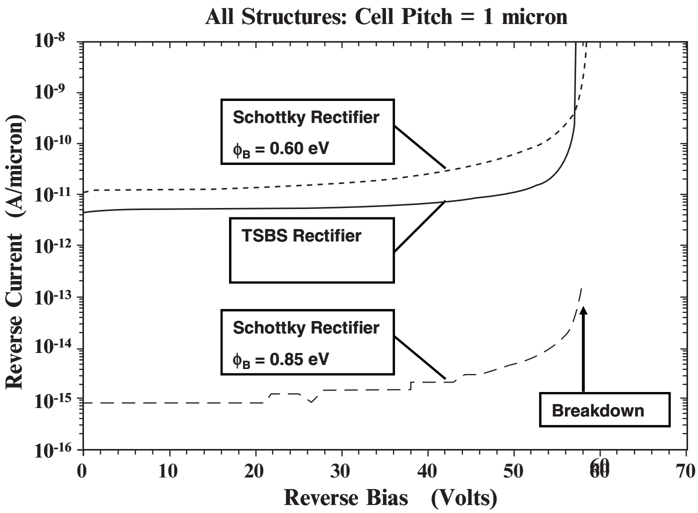

Fig. 4.17E Reverse Blocking Characteristics for a Typical Silicon 50V TSBS Rectifier compared with Schottky Rectifiers.

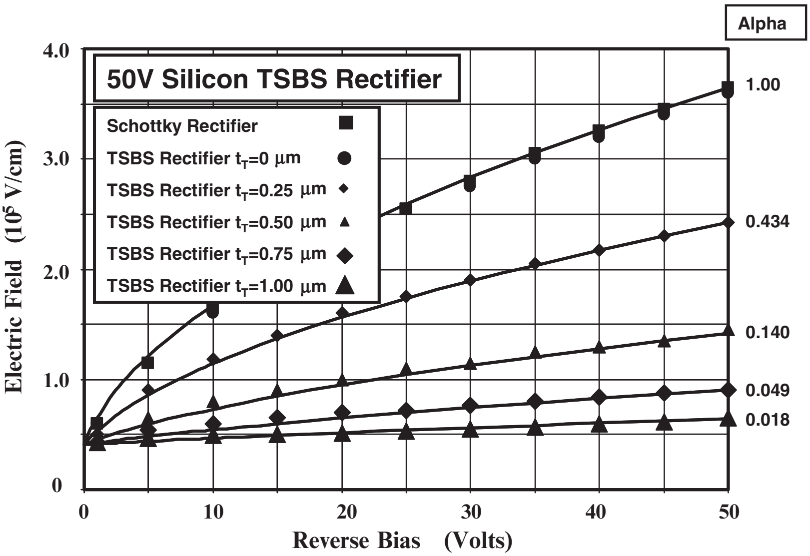

Fig. 4.18E Growth of the Electric Field at the Middle of the Schottky Contact for Silicon 50V TSBS Rectifiers.

The growth of the electric field with reverse bias voltage for the TSBS rectifier structures with the different trench depths is compared in Fig. 4.18E. In this figure, the value for alpha in the analytical model was adjusted to match the simulation data. It can be seen that the alpha is reduced from 1.00 to 0.018 with the increasing trench depth due to the larger channel aspect ratio. This is beneficial for suppressing the Schottky barrier lowering and decreasing the leakage current.

4.3.2 Silicon Carbide TSBS Rectifier: Reverse Leakage Model

The leakage current in the silicon carbide TSBS rectifier can be calculated using the same approach as for the silicon TSBS rectifier structure. Firstly, it is important to account for the smaller main Schottky contact area in the TSBS rectifier cell. Secondly, it is necessary to include Schottky barrier lowering while accounting for the smaller electric field at the main Schottky contact due to shielding by the trench metal electrode. Third, the thermionic field emission current must be included while accounting for the smaller electric field at the main Schottky contact due to shielding by the trench metal contact. After making these adjustments, the leakage current for the silicon carbide TSBS rectifier can be calculated by using:

$$J_L = \left(\frac{p-s}{p}\right) AT^2 \exp\left(-\frac{q\phi_b}{kT}\right).\exp\left(\frac{q\Delta\phi_{bTSBS}}{kT}\right).\exp\left(C_T E_{TSBS}^2\right) \qquad \textbf{[4.20]}$$

where C_T is a tunneling coefficient (8×10^{-13} cm^2/V^2 for 4H-SiC). In contrast to the Schottky rectifier, the barrier lowering for the TSBS rectifier is determined by the reduced electric field E_{TSBS} at the contact:

$$\Delta\phi_{bTSBS} = \sqrt{\frac{qE_{TSBS}}{4\pi\varepsilon_S}} \qquad \textbf{[4.21]}$$

As in the case of the silicon TSBS structure, the electric field at the main Schottky contact varies with distance away from the trenches. The highest electric field is observed at the middle of the main Schottky contact with a progressively smaller value closer to the trenches. When developing an analytical model with a worst case scenario, it is prudent to use the electric field at the middle of the main Schottky contact to compute the leakage current.

Until the depletion regions from the adjacent trenches produce a potential barrier under the main Schottky contact, the electric field at the metal-semiconductor interface in the middle of the main Schottky contact increases with the applied reverse bias voltage as in the case of the normal Schottky rectifier. A potential barrier is established by the trench metal contacts after depletion of the drift region below the Schottky contact. As in the case of the silicon TSBS rectifier structure, the pinch-off voltage (V_P) can be obtained from the device cell parameters:

$$V_P = \frac{qN_D}{2\varepsilon_S}(p-s)^2 - V_{CT} \qquad \textbf{[4.22]}$$

where V_{CT} the contact potential for the metal in the trenches. It is worth pointing out that the contact potential for 4H-SiC is larger than for silicon because it is advantageous to utilize a larger barrier height for the metal in the trenches. Although the potential barrier begins to form after the reverse bias exceeds the pinch-off voltage, the electric field continues to rise at the main Schottky contact due to encroachment of the potential to the main Schottky contact. In order to analyze the impact of this on the reverse leakage current, the electric field E_{TSBS} can be related to the reverse bias voltage by:

$$E_{TSBS} = \sqrt{\frac{2qN_D}{\varepsilon_S}(\alpha V_R + V_{CT})} \quad \textbf{[4.22]}$$

where α is a coefficient used to account for the build up in the electric field after pinch-off.

Since the TSBS structure in silicon carbide has the same rectangular shape for the trenches as the P-N junction in the silicon carbide JBS structure, the plots provided in Chapter 3 are also applicable to the TSBS rectifier structure. The reader can refer to Fig. 3.14 for the reduction of electric field at the main Schottky contact for various values of alpha; Fig. 3.15 for the reduction of Schottky barrier lowering at the main Schottky contact for various values of alpha; and Fig. 3.16 for the reduction of leakage current at the main Schottky contact for various values of alpha. However, the values for alpha extracted from the simulations of TSBS rectifier structures must be utilized for the analysis of specific TSBS rectifier structures.

Simulation Example

In order to validate the above model for the reverse leakage characteristics of the silicon carbide TSBS rectifier, the results of two-dimensional numerical simulations on a 3000 V structure are described here. The structure had a drift region thickness of 20 microns with a doping concentration of 8.5×10^{15} cm^{-3}. The trench region had a depth of 0.5 microns with an etching window (dimension 2s in Fig. 4.2) of 1.0 microns. A work-function of 4.5 eV was used for the main Schottky contact and 5.0 eV for the metal in the trenches. This corresponds to a Schottky barrier height of about 0.8 eV for the main Schottky metal and 1.3 eV for the metal in the trenches based upon an electron affinity of 3.7 eV for 4H-SiC.

The reverse blocking characteristics of the TSBS structure were also studied by using two-dimensional numerical simulations. The breakdown voltage of the TSBS structure was found to be the same (~ 3000 volts) as that for the Schottky rectifiers for the same drift region parameters. The currents flowing through the main Schottky contact and trench metal are shown in Fig. 4.19E as a function of the reverse bias voltage. It can be seen that the leakage current contribution from the main Schottky contact dominates at reverse bias voltages up to 2500 volts due to its low barrier height. However, the exponential increase in leakage current with reverse bias on the unprotected trench metal contact allows its leakage current to catch-up and then exceed the leakage current of the main contact at a reverse bias of 2900 volts.

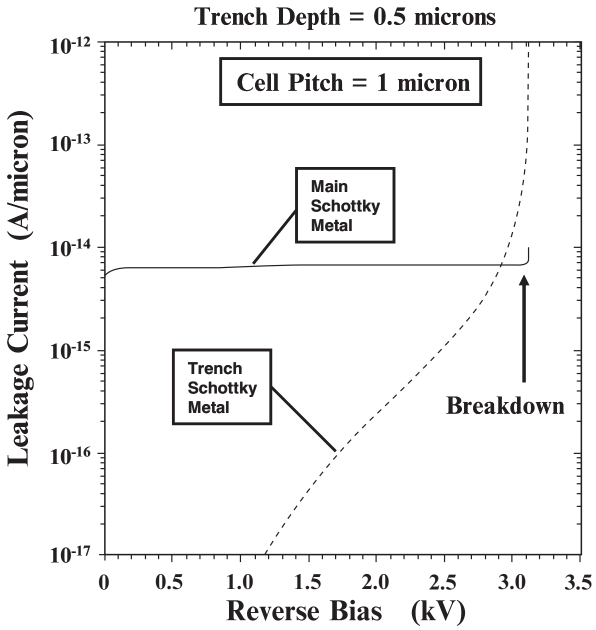

Fig. 4.19E Reverse Blocking Characteristics of a 3 kV 4H-SiC TSBS Rectifier.

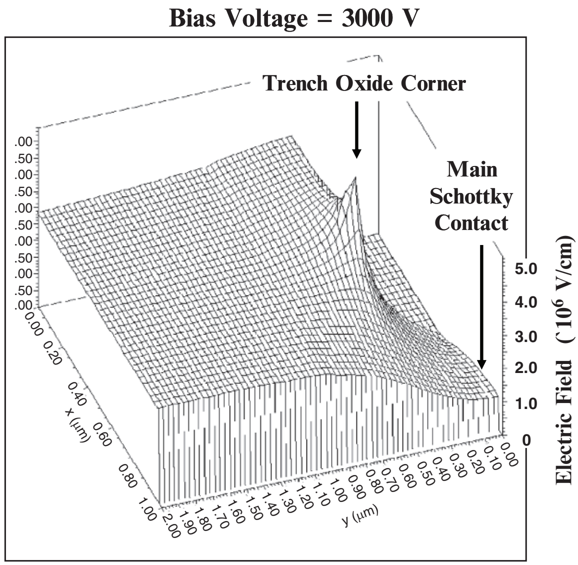

Fig. 4.20E Electric Field distribution in a 4H-SiC TSBS Rectifier.

The increase in the leakage current from the trench contact metal is exacerbated by the enhanced electric field generated at the sharp corners of the trenches. This enhanced electric field can be observed in the three-dimensional view of the electric field in a TSBS structure with cell pitch of 1.00 micron shown in Fig. 4.20E at a reverse bias of 3000 volts (just prior to breakdown). This graph also shows the expected reduction of the electric field at the main Schottky contact by the potential barrier created using the high Schottky barrier metal located in the trenches. As in the case of the JBS rectifier, the maximum electric field at the main Schottky contact occurs at the location furthest away from the trench (at x = 1.00 micron for the structure in Fig. 4.20E). Consequently, the largest barrier lowering and tunneling components will occur at this location. For this reason, the highest electric field at the Schottky contact will be used to analyze the reverse leakage characteristics for the TSBS rectifiers. The degree of field reduction is dependent on the spacing between the trench regions as well as the depth of the trench.

The electric field profile at the center of the main Schottky contact is shown in Fig. 4.21E for the case of a cell pitch of 1 micron. It can be seen that the electric field at the surface under the main Schottky contact is significantly reduced when compared the peak electric field in the bulk. The peak of the electric field occurs at a depth of about 1 micron. At a reverse bias of 3000 volts, the electric field at the Schottky contact is only 1 x 10^6 V/cm compared with 2.85 x 10^6 V/cm at the maxima in the bulk. An even greater reduction of the electric field at the main Schottky contact can be achieved by reducing the cell pitch. This is illustrated in Fig. 4.22E for the case of a cell pitch of 0.75 microns. Here, the electric field at the Schottky contact is only 2 x 10^5 V/cm compared with 2.85 x 10^6 V/cm at the maxima in the bulk.

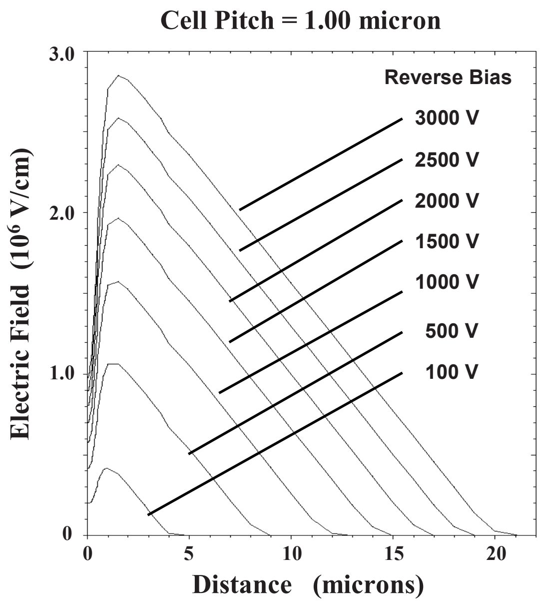

Fig. 4.21E Electric Field variation with Reverse Voltage in a 4H-SiC TSBS Rectifier.

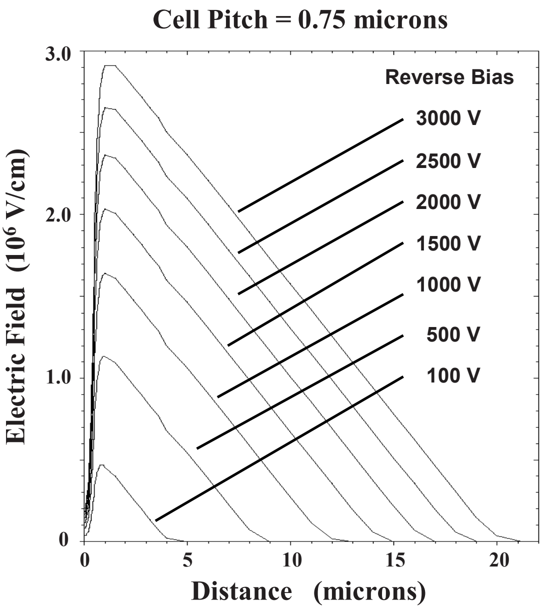

Fig. 4.22E Electric Field variation with Reverse Voltage in a 4H-SiC TSBS Rectifier.

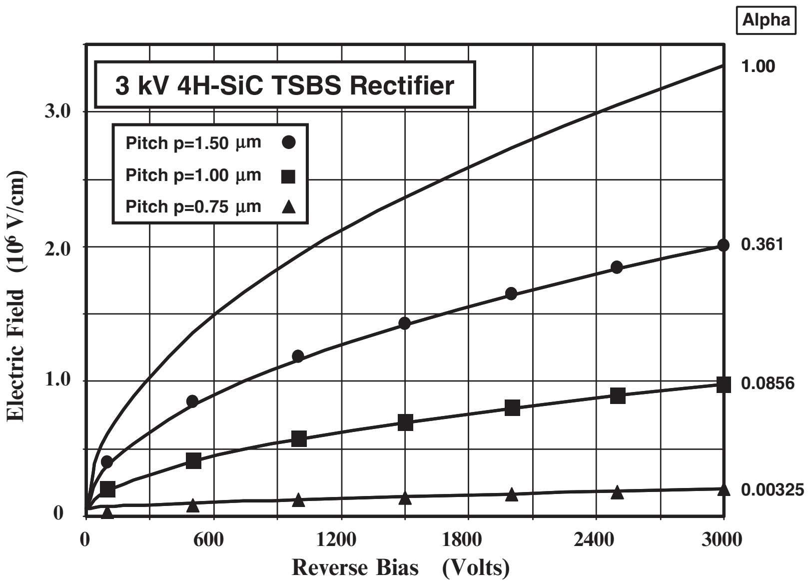

Fig. 4.23E Electric Field variation with Reverse Voltage in 4H-SiC TSBS Rectifiers.

The increase in the electric field at the main Schottky contact in the TSBS rectifier structure with increasing reverse bias voltage is charted in Fig. 4.23E for various cases of the cell pitch with the trench depth held constant at 0.5 microns. The electric field at the middle of the main Schottky contact becomes significantly less than for a normal Schottky rectifier when the cell pitch is made less than 2 microns. A greater suppression of the electric field is apparent as the cell pitch is reduced. In order to extract the alpha coefficient for the silicon carbide TSBS structure, the data obtained from the numerical simulations is shown by the symbols in Fig. 4.23E while the analytically calculated electric field using various alpha values are shown by the solid lines. Thus, the benefits of using the TSBS concept to suppress the electric field at the main Schottky contact can be obtained only with carefully optimized spacing which is slightly smaller than for the silicon carbide JBS rectifier[6]. With proper spacing, the reduction of the electric field provides significant benefits due to reducing the Schottky barrier lowering and tunneling currents.

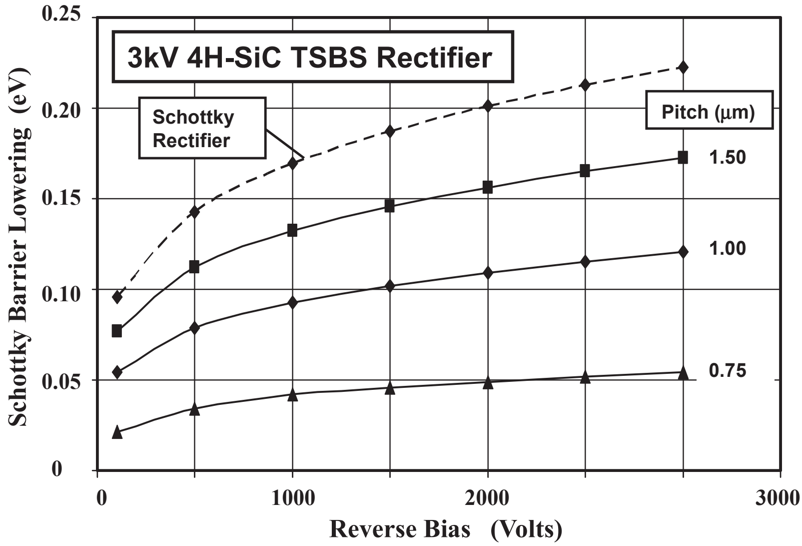

Fig. 4.24E Schottky Barrier Lowering in 4H-SiC TSBS Rectifiers.

The protection of the main Schottky contact against barrier lowering is quantified in Fig. 4.24E, where the values were determined using the analytical formulae with the electric field extracted from the simulations. With a pitch of 1 micron, the Schottky barrier lowering is reduced from 0.22 eV to 0.12 eV. The impact of ameliorating the Schottky barrier lowering phenomenon on the leakage current is quite dramatic for silicon carbide Schottky rectifiers because of the strong dependence of the tunneling component on the electric field. Even for a cell pitch of 1 micron, a reduction in the leakage current by five orders of magnitude is observed at high reverse bias voltages, as shown in Fig. 4.25E, demonstrating the advantage of utilizing the potential barrier to suppress the leakage current from the main contact. (Note that the leakage current from the trench metal was neglected in these plots.) An even greater reduction of the leakage current is possible by shrinking the cell pitch to 0.75 microns but this is accompanied by an increase in the on-state voltage drop. The TSBS structure is therefore very effective for improving the reverse blocking characteristics of high voltage silicon carbide rectifiers.

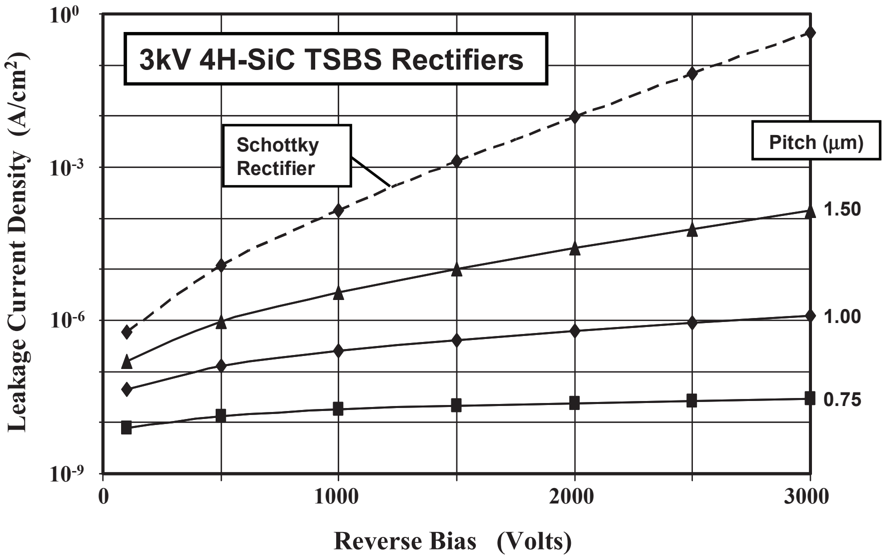

Fig. 4.25E Leakage Current in 4H-SiC TSBS Rectifiers.

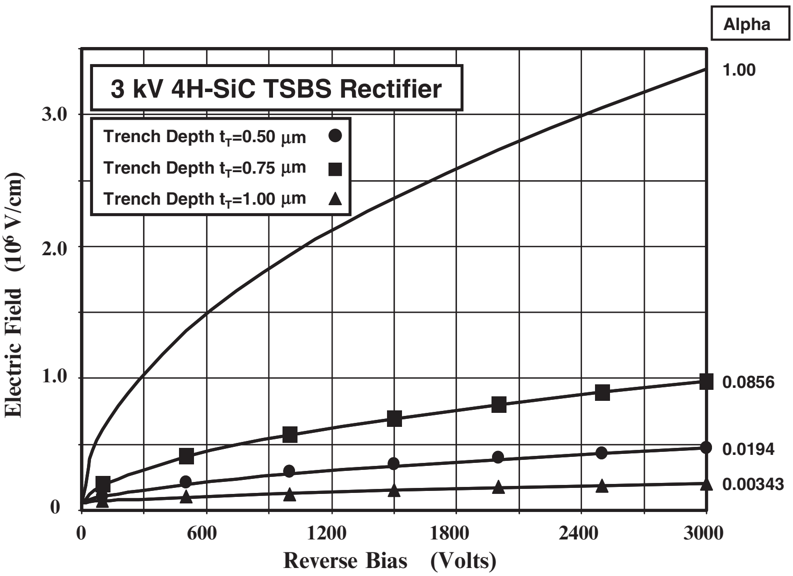

Fig. 4.26E Electric Field variation with Reverse Voltage in 4H-SiC TSBS Rectifiers.

The electric field at the main Schottky contact for the different trench depths is compared in Fig. 4.26E for the case of a fixed cell pitch of 1 micron. The electric field is reduced by a factor of about 3x when a trench depth of 0.5 microns is utilized. An even greater reduction of the electric field by a factor of 5x occurs for a trench depth of 1 micron. In order to extract the alpha coefficient for the silicon carbide TSBS structure, the data obtained from the numerical simulations is shown by the symbols in Fig. 4.26E while the analytically calculated electric field using various alpha values are shown by the solid lines.

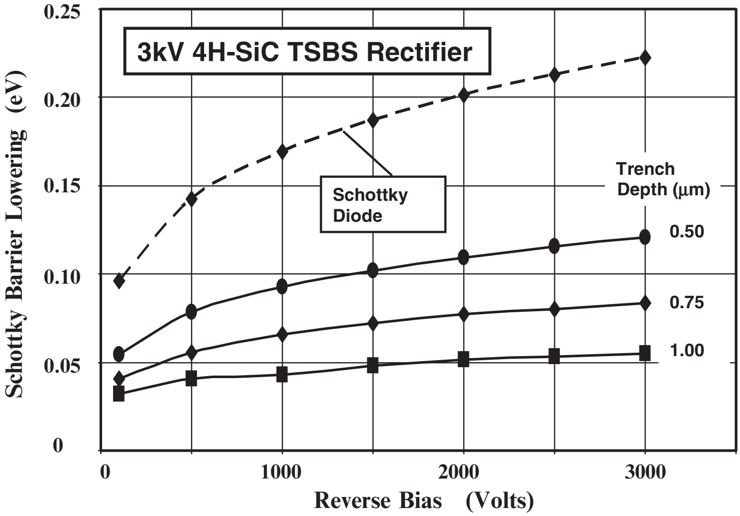

Fig. 4.27E Schottky Barrier Lowering in 4H-SiC TSBS Rectifiers.

The impact of the reduction of the electric field at the main Schottky contact on the Schottky barrier lowering is quantified in Fig. 4.27E. With a trench depth of 0.5 microns, the barrier lowering is reduced from 0.22 eV for a normal silicon carbide Schottky rectifier to 0.125 eV. When the trench depth is increased to 0.75 microns, the barrier lowering is reduced to only 0.08 eV while it becomes only 0.055 eV for a trench depth of 1.00 microns.

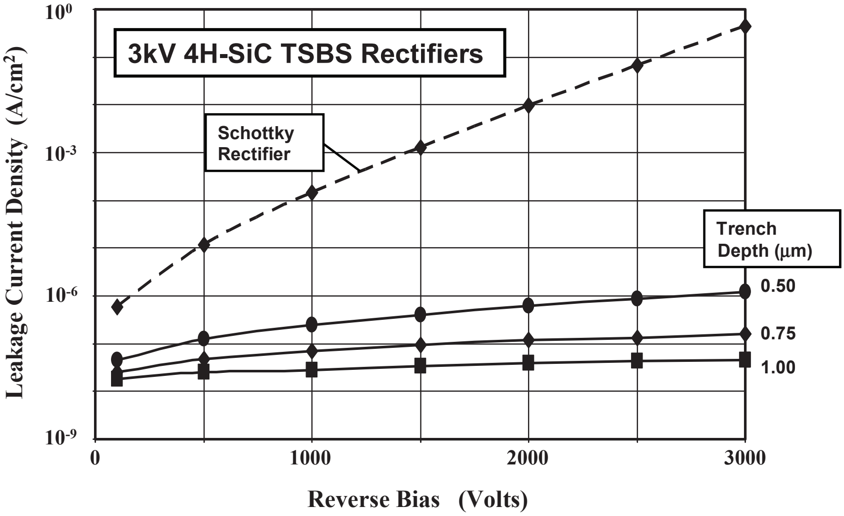

Fig. 4.28E Leakage Current in 4H-SiC TSBS Rectifiers.

This reduction in the Schottky barrier lowering reduces the leakage current in the silicon carbide TSBS Schottky rectifier structure as demonstrated in Fig. 4.28E. The reduction of the tunneling current in silicon carbide Schottky contacts was included when computing the leakage current during the analysis. It can be observed that the leakage current is reduced by 5 orders of magnitude for a trench depth of 0.5 microns. Further increase in the trench depth reduces the leakage current only by another order of magnitude. Consequently, it is sufficient to utilize a trench depth of 0.5 microns for the silicon carbide TSBS rectifier structure to suppress the leakage current.

The aspect ratio of the current conduction region located below the main Schottky contact in the TSBS rectifier has a strong influence on the suppression of the electric field at the contact, which is quantified by the coefficient alpha (α) in Eq. (4.17) and Eq. (4.22). The aspect ratio for both the silicon and silicon carbide TSBS rectifier structures can be computed by dividing the trench depth by the space between the trenches:

$$AR = \frac{t_T}{2(p-s)} \qquad [4.23]$$

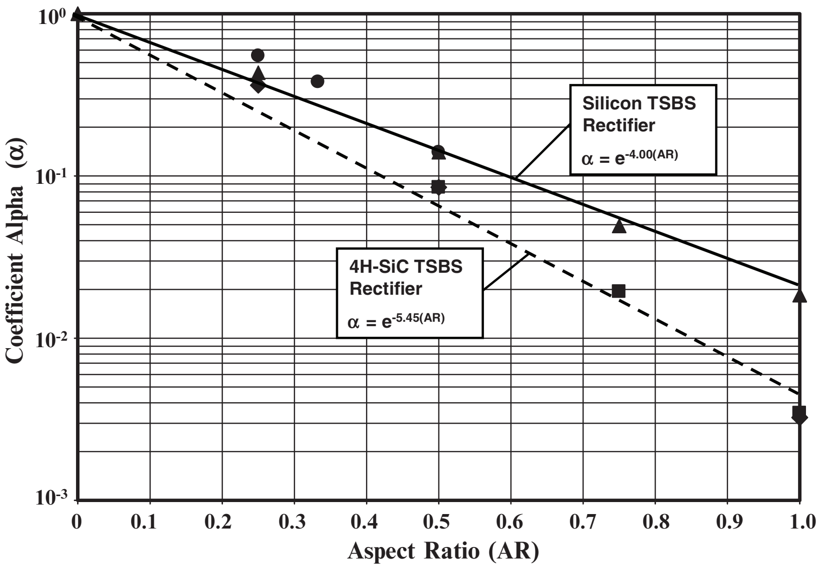

Fig. 4.29E Impact of Aspect Ratio on Alpha for TSBS Rectifiers.

The variation of the coefficient alpha (α) with aspect ratio, obtained from the numerical simulations, is shown in Fig. 4.29E for silicon and silicon carbide TSBS rectifiers. It can be observed that the coefficient alpha (α) varies exponentially with the aspect ratio. A single line fits the data obtained for silicon devices (and another single line fits the data for 4H-SiC devices) with different trench depths and cell pitches demonstrating that the aspect ratio is determining the alpha. It is smaller for the case of silicon carbide devices when compared with silicon devices with the same aspect ratio indicating that the electric field is not suppressed to the same degree in silicon devices. The TSBS structure is therefore particularly well suited for improving the performance of silicon carbide Schottky rectifiers.

4.4 Trade-Off Curve

In the textbook[4], it is demonstrated that the power dissipation can be minimized for a particular duty cycle and operating temperature by varying the Schottky barrier height during optimization of the Schottky rectifier structure. A smaller barrier height decreases the on-state voltage drop reducing conduction power losses while a large barrier height decreases the leakage current reducing reverse blocking power losses. Depending upon the duty cycle and the temperature, minimum power loss occurs at an optimum barrier height. A fundamental trade-off curve between on-state voltage drop and the leakage current was developed in the textbook based upon these considerations which does not depend upon the semiconductor material. However, the fundamental trade-off curve excludes the impact of the series resistance on the on-state voltage drop. More significantly, it excludes the strong influence of Schottky barrier lowering and pre-avalanche multiplication on the increase in leakage current for silicon Schottky rectifiers.

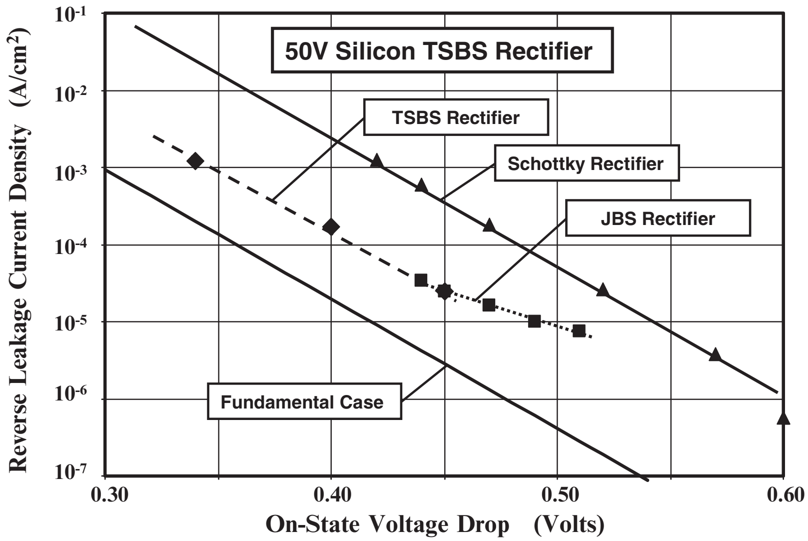

Fig. 4.7 Trade-Off Curve for the 50 V Silicon TSBS Rectifier compared with that for a Schottky Rectifier.

When the voltage drop in the drift region is included for computing the on-state voltage drop of the silicon Schottky rectifier and the influence of Schottky barrier lowering and pre-breakdown multiplication are factored into the calculation of its leakage current, the trade-off curve degrades substantially as shown in Fig.

4.7 by the solid line corresponding to the triangular data points. In this figure, the trade-off curve for the silicon Schottky rectifier was generated by varying the Schottky barrier height. For an on-state voltage drop of 0.45 volts, the leakage current for the Schottky rectifier increases by two-orders of magnitude when compared with the fundamental trade-off curve.

In the silicon TSBS rectifier, the Schottky barrier lowering effect is ameliorated by the reduced electric field at the main Schottky contact. In addition, the pre-breakdown multiplication of the current flowing through the main Schottky contact is suppressed by the much lower electric field at this contact. The trade-off curve obtained from the numerical simulations of the TSBS rectifier structure with a cell pitch of 1 micron and trench depth of 0.5 microns is also shown in Fig. 4.7 by the dashed line corresponding to the diamond data points. For these silicon TSBS rectifier structures, the barrier height for the main Schottky contact was varied while maintaining the same device structure. For an on-state voltage drop of 0.40 volts, the leakage current for the TSBS rectifier is reduced by an order of magnitude when compared with the normal Schottky rectifier. It is worth pointing out that the TSBS rectifier has the same leakage current as the JBS rectifier at an on-state voltage drop of 0.45 volts indicating that both structures are equally effective in reducing the leakage current.

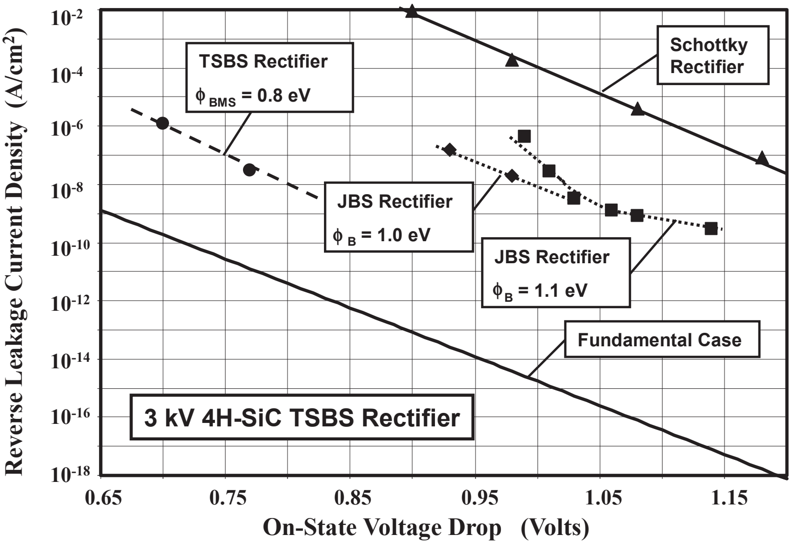

Fig. 4.8 Trade-Off Curve for the 3 kV 4H-SiC TSBS Rectifier compared with that for a Schottky Rectifier.

A similar analysis can be performed for the silicon carbide TSBS rectifier. In this case, a major improvement in reverse blocking characteristics occurs due to suppression of the Schottky barrier lowering and the thermionic field emission current due to the reduced electric field at the main Schottky contact. When these phenomena are included in the analysis of the leakage current for the 4H-SiC Schottky rectifier, the trade-off curve for the case of devices designed to support 3000 volts obtained by varying the Schottky barrier height degrades significantly as shown in Fig. 4.8 by the solid line corresponding to the triangular data points. It can be observed that the leakage current increases by more than 10 orders of magnitude when compared with the fundamental curve.

For the silicon carbide TSBS rectifier structure, the Schottky barrier lowering and thermionic field emission phenomena are suppressed producing greatly reduced leakage currents at large reverse bias voltages. The trade-off curves obtained for these structures by varying the cell pitch is shown in the Fig. 4.8 by the dashed line. It can be observed that the leakage current is seven orders of magnitude smaller than for the Schottky rectifier for the same on-state voltage drop. For the same leakage current density of 1×10^{-8} A/cm^2, the TSBS rectifier structure has a 0.2 V lower on-state voltage drop when compared with the JBS rectifier structure. This difference can be attributed to the larger depletion width under on-state operation in the JBS rectifier structure in silicon carbide because the built-in potential for the P-N junction in 4H-SiC is much larger than the contact potential for the metal is the trenches of the TSBS rectifier structure.

4.5 Summary

In this chapter, it has been demonstrated that a significant improvement in the leakage current of Schottky rectifiers can be achieved by incorporation of a trench region with high barrier contact metal to shield the main current carrying Schottky contact against high electric fields generated in the semiconductor. In the case of silicon devices, the reduction of the electric field at the contact suppresses the Schottky barrier lowering and pre-breakdown multiplication phenomena. This reduces the leakage current by an order of magnitude while the increase in on-state voltage due to loss of Schottky contact area is small. In the case of silicon carbide devices, the reduction of the electric field at the Schottky contact suppresses the Schottky barrier lowering and the thermionic field emission current leading to a reduction of leakage current by seven orders of magnitude. In addition, the TSBS rectifier structure does not require the high temperature annealing process required for formation of the P-N junctions in the JBS rectifier structure. This circumvents the degradation of the silicon carbide surface allowing formation of superior main Schottky contacts.

The application of the TSBS rectifier concept to silicon carbide devices was first explored at PSRC[2] for 1000 volt devices. Subsequently, experimental results were reported on 4H-SiC devices fabricated with blocking voltages of 300 volts using titanium as the main Schottky contact and nickel as the metal in the trenches[7]. A reduction of the leakage current by two-orders of magnitude was observed. A reduction in the leakage current by three-orders of magnitude has also been reported for 6H-SiC devices with blocking voltage of 100 volts[8].

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