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ANALYSIS OF JUNCTION-BARRIER-CONTROLLED SCHOTTKY (JBS) RECTIFIER CHARACTERISTICS

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Abstract—This paper provides analytical solutions for the forward conduction and reverse leakage characteristics of junction-barrier-controlled Schottky (JBS) rectifiers. Good agreement between the calculated output characteristics using these solutions and experimental measurements on devices fabricated with different junction depths and Schottky barrier heights is observed. These equations are valuable for the analysis and design of JBS power rectifiers.

INTRODUCTION

The junction barrier controlled Schottky (JBS) rectifier is a recently developed concept for the suppression of leakage current in Schottky barrier rectifiers [1]. A cross-section of the device structure is shown in Fig. 1. The device consists of a Schottky rectifier with a junction grid incorporated into the drift region. During forward bias across the rectifier, the junction depletion layer shrinks. This allows current to flow between the anode and cathode terminals via the channels between the junctions. During reverse bias across the rectifier, the junction depletion layer expands. This produces a potential barrier for electrons under the Schottky barrier after the depletion layers of adjacent junctions intersect. This phenomenon is similar to that used to achieve forward blocking capability in vertical-channel junction field effect transistors, field-controlled thyristors, and static-induction transistors [2]. Thus, once the depletion layers merge the Schottky barrier is shielded from the cathode voltage. This prevents the Schottky barrier lowering which normally occurs during reverse bias applied to conventional Schottky rectifiers. The severe increase in the reverse leakage current normally observed in Schottky rectifiers at high reverse voltages is thus avoided in the JBS rectifiers.

In this paper, analytical, closed-form solutions to the forward conduction and reverse leakage characteristics of JBS rectifiers are presented. These solutions have been verified by using measured data obtained from JBS rectifiers fabricated with various Schottky barrier heights. These results are useful for the analysis and design of these devices.

DEVICE ANALYSIS

Forward conduction

The forward-conduction characteristics of the JBS rectifier can be derived by using Schottky barrier theory based upon thermionic emission to model the current flow across the metal–semiconductor barrier, and then accounting for the series resistance of the epitaxial layer including the effect of spreading resistance due to the presence of the junction grid. The geometrical parameters used to perform this analysis are defined in Fig. 1. Here s is the diffusion window opening and m is the size of the diffusion mask. A stripe geometry of unit length is assumed here. Other geometries can be similarly modeled. The p^+ junctions used for creating the potential barrier during reverse blocking have a depth x_j. The lateral diffusion, which together with m defines the current flow path ($2d$), is assumed to be 85 percent of the vertical depth [3]. During forward conduction, the junction depletion layer w is given by

$$w = \sqrt{\frac{2\epsilon_s}{qN} \cdot (V_{bi} - V_F)}\,, \qquad (1)$$

where ϵ_s is the dielectric constant, q is the electron charge, N is the epitaxial layer doping, V_{bi} is the junction built-in potential, and V_F is the forward voltage applied across the junction. The Schottky barrier area across which the forward current flows is then given by $A = 2d = (m - 2w - 1.7x_j)$. Based upon the thermionic emission model [4] and neglecting minority carrier injection, the forward voltage drop across the Schottky barrier at any given forward current density J_{FS} is then given by

$$V_{FS} = \phi_B + \frac{kT}{q} \cdot \ln\left(\frac{J_{FS}}{A^* T^2}\right), \qquad (2)$$

where ϕ_B is the barrier height, k is Boltzmann's constant, T is the absolute temperature, and A^* is Richardson's constant. For purposes of device analysis, it is important to deal with the cell current density, J_{FC}. This current density accounts for the dead space created by the presence of the P^+ diffused regions and is useful for computation of device size required to achieve a given current rating. For the stripe geometry considered in Fig. 1, $J_{FS} = ((m$

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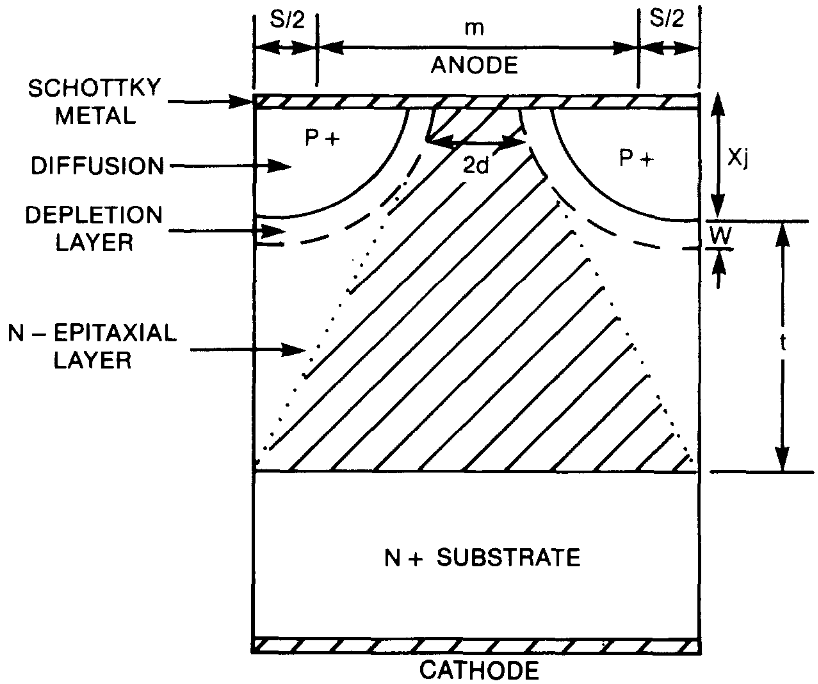

Fig. 1. Unit cell of JBS rectifier with geometrical parameters defined.

$+ s)/2d)J_{FC}$. Using this in eqn (2), the forward voltage drop contributed by the Schottky barrier is given by

$$V_{FS} = \phi_B + \frac{kT}{q} \cdot \ln\left[\left(\frac{m+s}{2d}\right) \cdot \frac{J_{FC}}{A^*T^2}\right]. \quad (3)$$

The contribution to the forward voltage drop from the epitaxial layer resistance must be calculated by taking current spreading into account. Modelling of current flow in high-voltage, vertical-channel JFETs [5] shows that the series resistance of the epitaxial layer can be obtained using

$$R_{epi} = \rho \cdot \frac{(x_j + t)(m+s)}{(m+s-2d)} \cdot \ln\frac{(m+s)}{2d}, \quad (4)$$

where t is the depletion layer thickness required to obtain the desired breakdown voltage in the JBS rectifier. Since the voltage drop across the epitaxial layer appears in series with the voltage drop across the Schottky barrier, the forward drop of the JBS rectifier can now be calculated using

$$V_F = \phi_B + \frac{kT}{q} \cdot \ln\left[\frac{(m+s)}{2d} \cdot \frac{J_{FC}}{A^*T^2}\right] + \rho \cdot \frac{(x_j + t)(m+s)}{(m+s-2d)} \cdot \ln\left(\frac{m+s}{2d}\right) \cdot J_{FC}. \quad (5)$$

As it stands, this equation does not allow closed-form analytical solution of the forward characteristics because of the dependence of $2d$ upon V_F (see eqn (1)). However, the JBS rectifier is intended for operation at relatively low forward bias (less than 0.4 V). Under these conditions, the variation in $2d$ with increasing V_F is small and can be neglected. This simplification allows the calculation of the forward I–V characteristics directly from eqn (5).

Reverse characteristics

The reverse leakage current in the JBS rectifier arises from two components. The first component is due to injection of carriers across the Schottky barrier. This occurs at low reverse-bias voltages prior to the formation of the junction potential barrier. This leakage current is a strong function of the metal–semiconductor barrier height ϕ_B, and is also affected by the electric field across the barrier [4]. After taking into account the area of the Schottky barrier, the Schottky barrier leakage current at a reverse bias V_R is given by

$$J_{LS} = \left(\frac{2d}{m+s}\right) A^* \cdot T^2 \cdot \exp\left(\frac{-q\phi_B}{kT}\right) \cdot \exp\left(q\frac{\sqrt{q\xi/4\pi\epsilon_s}}{kT}\right), \quad (6)$$

where ξ is the electric field across the barrier:

$$\xi = \sqrt{\frac{2qN}{\epsilon_s} \cdot \left(V_R - V_{bi} - \frac{kT}{q}\right)}. \quad (7)$$

The latter term accounts for the barrier height lowering observed in Schottky rectifiers due to the applied reverse voltage[4, 6]. In the case of the JBS rectifier, the electric field across the Schottky barrier remains constant after the junction potential barrier is established. The leakage current contributed by the Schottky barrier can then be assumed to remain independent of the reverse bias voltage beyond this point.

The second component of the leakage current arises from the space charge generation and diffusion currents as commonly observed in all power rectifiers. This component is dependent upon the minority carrier lifetime and is given by

$$J_{LD} = q\sqrt{\frac{D}{\tau}} \cdot \frac{n_i^2}{N} + \frac{qn_i w}{\tau}, \qquad (8)$$

where D is the diffusion coefficient, τ is the lifetime, n_i is the intrinsic carrier concentration and w is the depletion layer width given by

$$w = \sqrt{\frac{2\epsilon_s(V_R + V_{bi})}{qN}}. \qquad (9)$$

This component of the leakage current must be included to obtain proper dependence of the leakage current upon the reverse voltage across the rectifier.

EXPERIMENTAL RESULTS

Experimental devices having the stripe cell geometry were fabricated with an active area of 0.01 cm^2. These devices had a oxide diffusion window s = 5 μm with a repeat spacing of $(m + s) = 10$ μm. The rectifiers were fabricated using 0.5 ohm-cm, n-type epitaxial layers, 6 μm in thickness, grown on highly doped N^+ substrates. Devices were fabricated using p^+ junction depths of 1 and 2 μm to examine its effect on forward conduction and reverse leakage. Aluminum was used as the Schottky barrier metal. The barrier height was varied by using shallow N^+ implants[7]. To achieve this, antimony implants at 5 keV were used at various doses as provided in the table in Fig. 2. The barrier height ϕ_B was determined from the forward conduction characteristics of Schottky rectifiers simultaneously fabricated on the same wafers. In addition, the minority carrier lifetime in the epitaxial layer was measured by the reverse recovery technique to be about 10 μs.

All device characteristics reported in this paper were measured at 80°C. The forward conduction characteristics of JBS rectifiers fabricated with 1 μm p^+ junction depth are shown in Fig. 2. The table incorporated in Fig. 2 provides the antimony implant dose and the corresponding measured barrier height from Schottky rectifiers. The lines in Fig. 2 were

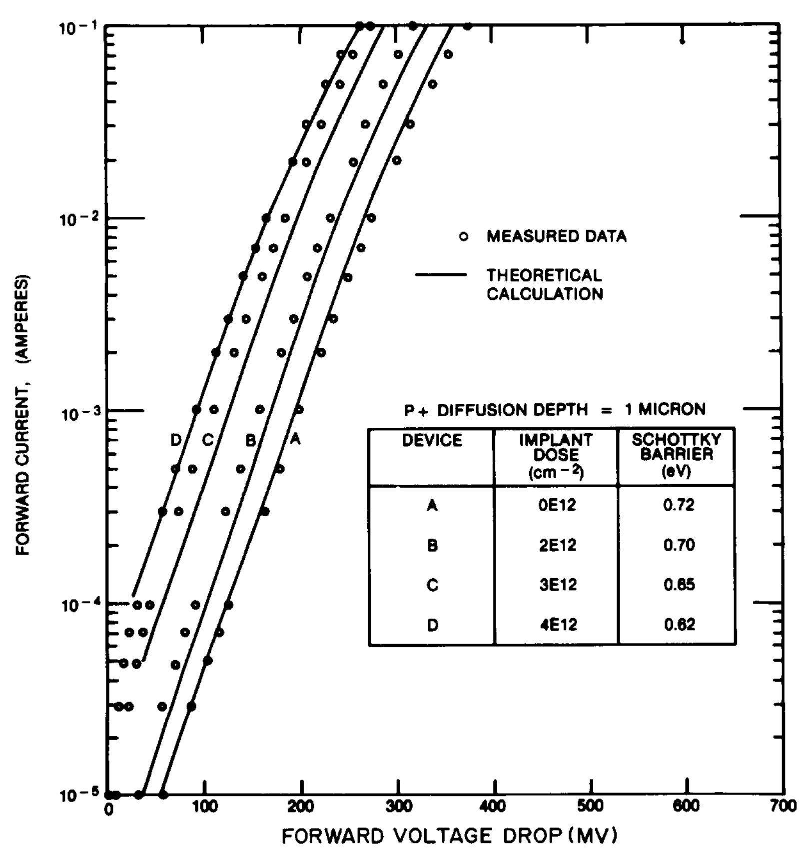

Fig. 2. Forward conduction characteristics of JBS rectifiers fabricated with 1 μm p^+ junction depth. The horizontal scale is in millivolts.

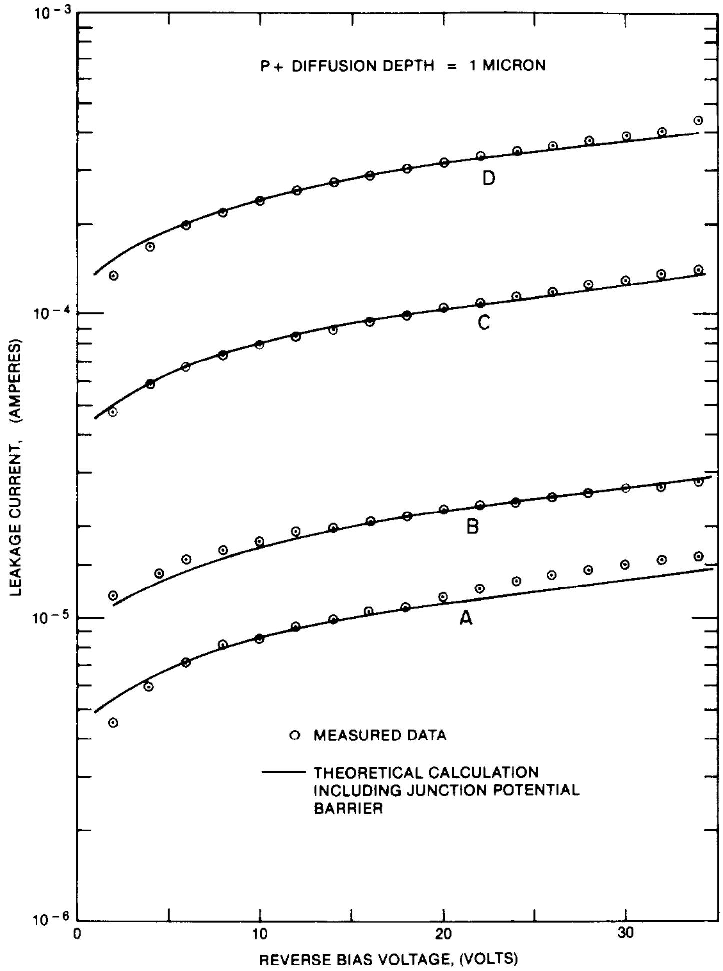

Fig. 3. Reverse leakage current of JBS rectifiers fabricated with (a) 1 μm p^+ junction depth and (b) 2 μm p^+ junction depth.

calculated using eqn (5) with the above device parameters. No curve fitting was performed. It can be seen that there is reasonably good agreement between the analytical solution for the forward characteristics and the measured data. Similar results were observed for devices fabricated with the 2 μm p^+ junction depths.

The reverse leakage characteristics of the JBS rectifiers are shown in Fig. 3. For the case of a junction depth of 1 μm, using the device dimensions given above, it can be shown that the junction potential barrier forms at a reverse bias of about 20 V, while for a junction depth of 2 μm, this occurs at a reverse bias of only 4 V. The impact of this upon the leakage current can best be illustrated by calculating the reverse leakage current with and without taking into account the formation of the junction potential barrier. This has been done for devices with 2 μm p^+ diffusion depth and indicated by the solid and dashed lines in Fig. 3(b). Comparison of the dashed and solid lines clearly shows the benefit of the junction potential barrier. It is worth noting that the leakage current calculations were all done using the same barrier heights given in Fig. 2 as obtained from the forward conduction characteristics of Schottky diodes. The good agreement observed between the calculated leakage current and the measured values for both the 1 μm and 2 μm p^+ diffusion cases indicates that the current flow equations developed in this paper can be used to analyse JBS rectifiers.

CONCLUSIONS

Analytical, closed-form solutions for the forward and reverse characteristics of JBS rectifiers have been developed. These solutions have been experimentally verified using devices fabricated with two junction depths for a variety of Schottky barrier heights. These analytical solutions provide a simple and rapid design aid for JBS rectifiers. For example, they allow performance of the analysis of device geometry upon

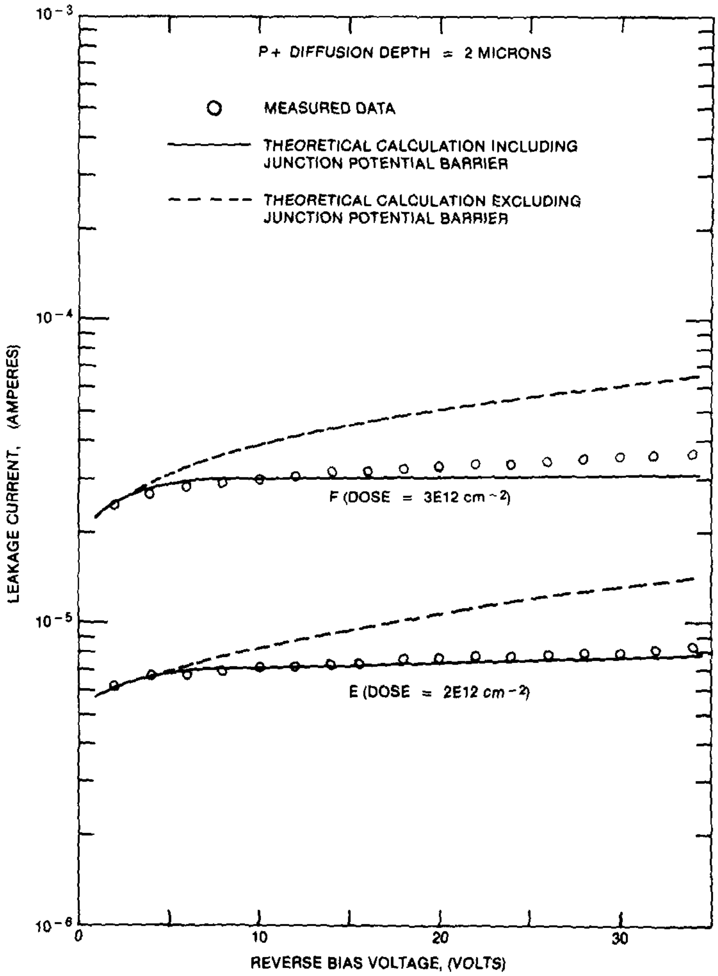

Fig. 3. Continued.

the output characteristics. They are also useful for analysis of the tradeoff between the forward voltage drop and reverse leakage current in these devices. The JBS rectifier has been experimentally shown to be capable of operating at a forward drop of 0.4 V compared with 0.6 V typically observed in Schottky rectifiers[1]. The analytical solutions provided in this paper have allowed further refinement of these devices and indicate that JBS rectifiers with forward voltage drops of 0.3 V may be feasible. These devices are now under development.

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