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Full Paper

A method to calculate the voltage-current characteristics of 4H SiC Schottky barrier diode

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Abstract: The voltage-current characteristics of the Schottky barrier diode defined by the diode equation can be obtained by using iteration method and a C++ program. The diode equation is split into two functions and the current density for a specified forward voltage is evaluated at a point where the equality of these two functions is seen to hold. A set of values of current and voltage are generated using the C++ program. The device parameters, i.e. area, barrier height and doping level, were obtained from published work. These are found to tally well with experimental results. The analysis has been made using 4H silicon carbide diodes with contacts of nickel, titanium and gold.

Keywords: Schottky barrier diode, 4H silicon carbide (4H-SiC), barrier height, specific on-resistance

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Introduction

The voltage-current relationships of the Schottky barrier diodes have been obtained by Bethe [1], Schottky [2] and Crowell and Sze [3]. These have been experimentally verified by Chang and Sze [4] with devices having pre-determined parameters and dimensions. However, it is sometimes useful to obtain a solution for the current density J_F in terms of forward drop directly from the diode equation for specific values of forward voltage V_F. Since the diode equation cannot be solved directly, in this paper a C++ program has been used which can give by iteration the equality of two functions into which the

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diode equation is split. The set of values of J_F and V_F obtained using the C++ program are found to tally well with experimental results by Saxena and Steckl [5] and Sochacki [6] for nickel metal contact, by Itoh et al. [7] for titanium metal contact, and by Itoh et al.[8] for gold metal contact.

Theory

The basic device structure using a partial metal overlap over the Schottky contact by Itoh et al. [7] is shown in Figure 1. The device is made using an n-type 4H SiC substrate on top of which an n-type epilayer is grown. The thickness of the epilayer is 'h' and boron implant from the top of the epilayer is made with a gap in the centre over which a metal contact with finite diameter 'd' is made. The diameter of the Schottky contact is 'a'.

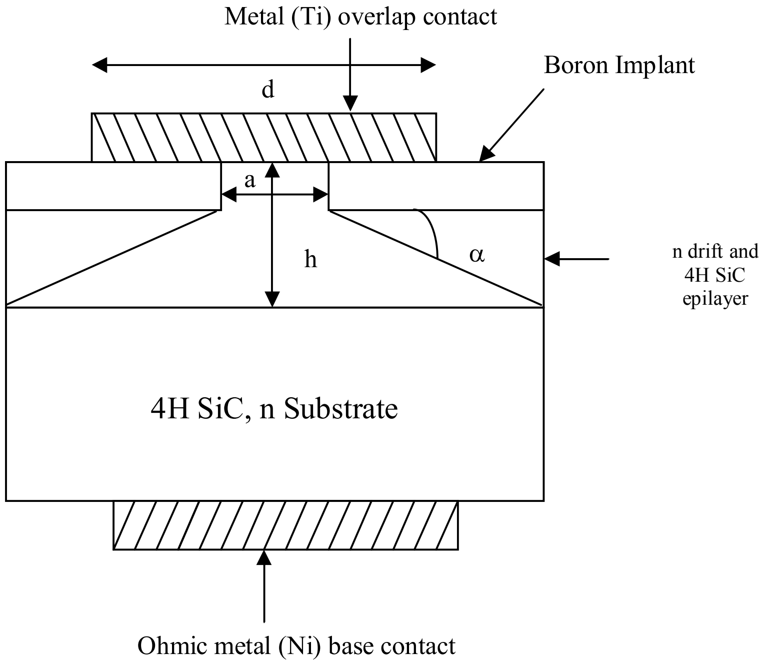

Figure 1. The basic 4H silicon carbide device structure [7]

The voltage-current (V-I) equation of the Schottky diode using thermionic emission theory is given by Saxena et al. [5]. This can be quoted as:

$$J_F = J_S\left[\exp\left(\frac{qV_D}{\eta KT}\right) - 1\right], \qquad (1)$$

where

$$J_S = A^* T^2 \exp\left(-\frac{q\phi_B}{\eta KT}\right), \qquad (2)$$

and V_D is the voltage drop across the diode, i.e. at the Schottky contact, K is the Boltzman's constant (CV/K), q is the electronic charge in coulomb, A^* is the effective Richardson's constant in $\left[\frac{A}{cm^2}K^2\right]$, and ϕ_B is the Schottky barrier height in volt.

The Schottky barrier diode is shown in Figure 2. It has the series resistance, namely the specific on-resistance R_{on-sp}, which is due to the resistance of the drift region R_D, the substrate R_{sub} and the contacts. R_{on-sp} may be approximated at low and medium current levels to the resistance of the drift layer of thickness 'h'.

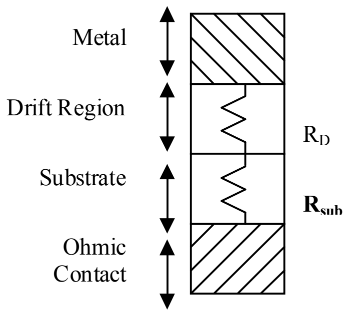

Figure 2. Equivalent circuit model of 4H-SiC Schottky barrier diode of Figure 1

The basic voltage-current equation for such a diode has been derived by Baliga [9] and Bhatnagar et al. [10]. The forward drop VF of the diode can be expressed as :

$$V_F = V_D + J_F R_{on-sp} \qquad (3)$$

Combining equation (3) with (1) and (2) above,

$$V_F = \frac{\eta KT}{q}\ln\left(\frac{J_F}{A^* T^2}\right) + \phi_B + J_F R_{on-sp} \qquad (4)$$

The specific on-resistance, R_{on-sp}, can be calculated using the trapezoidal current flow model as mentioned by Baliga [9]. This is shown to be the same as in Figure 1. The ohmic contact at the base is grounded and the top metal contact is given a negative bias. The current flow in the device starts from the Schottky contact at the top and spreads out to form a trapezoid and α is the angle made by the inclined side of the trapezoid and the horizontal level . The specific on-resistance of the device can be expressed as [9]:

$$R_{on-sp} = \rho_D \frac{L_G}{\tan\alpha}\ln\left[1 + \frac{2h}{a}\tan\alpha\right], \qquad (5)$$

where α = 26° .

The equation (4) can be rewritten as

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$$-\frac{\eta KT}{q}\ln\left(\frac{J_F}{A^* T^2}\right) = -V_F + \phi_B + J_F R_{on-sp} \quad (6)$$

The above equation can be divided into two functions. Let the left hand side be represented by function F_1 and that on the right hand side denoted by function F_2. The equation above can then be written as $F_1 = F_2$.

A C++ program was then developed and run for a fixed value of V_F with known values of other parameters for a given range of values of J_F. The value of J_F at which ($F_1 - F_2$) tends to zero or a minimum value is the required value of J_F for a fixed value of V_F. This process was repeated for other values of V_F and a set of values of 'J_F versus V_F' was obtained. This was performed in the case of nickel, titanium and gold metal contacts for 4H SiC. The results obtained were compared with those obtained experimentally [5-8] for the 4H SiC diodes. The comparisons are shown in Figures 3-5.

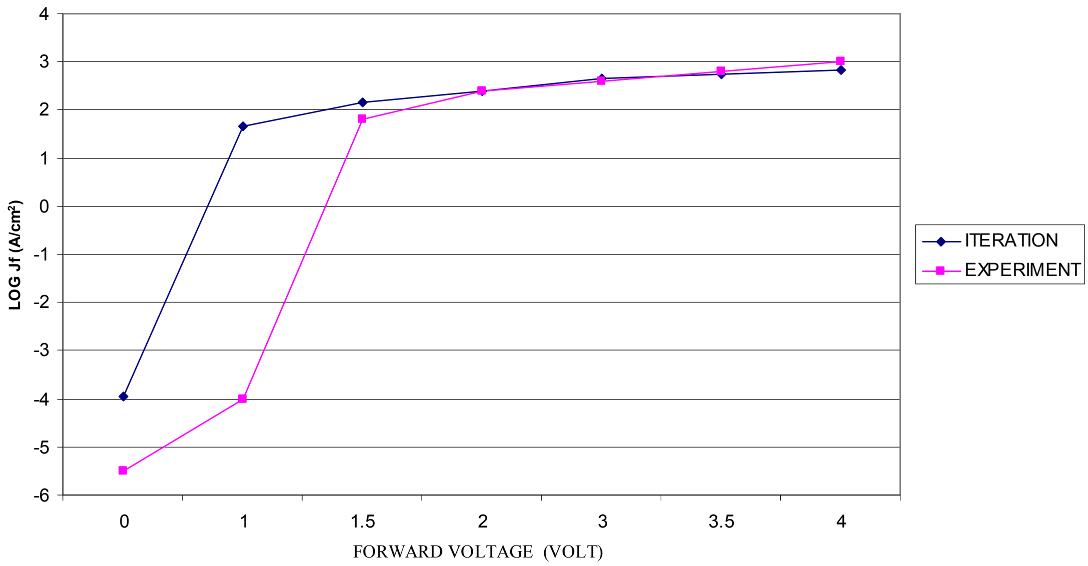

Figure 3. V_F-log J_F plot of 4H SiC with nickel metal contact

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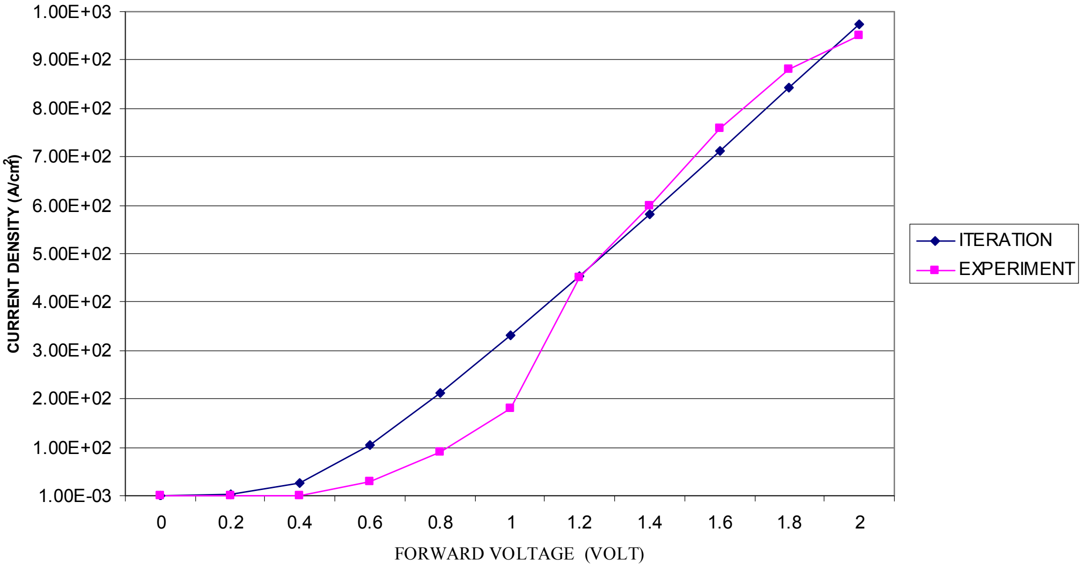

Figure 4. V_F-J_F plot of 4H SiC with titanium metal contact

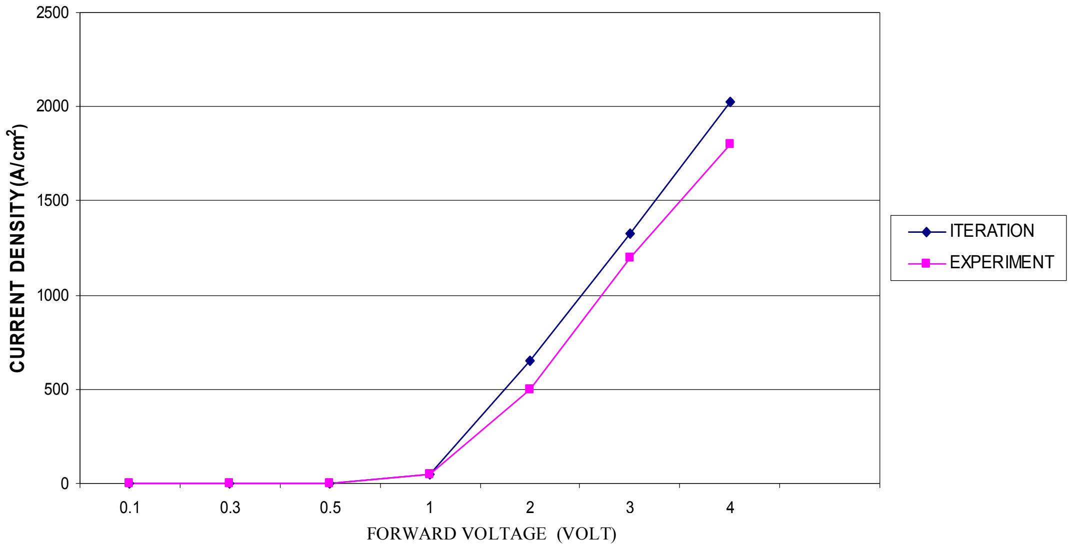

Figure 5. V_F-J_F plot of 4H SiC with gold metal contact

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The C++ program used is given below:

```
#include<iostream.h>
#include<conio.h>
#include<math.h>
void main()
{
clrscr();
long double q,rsp,n,k,t,bh,fv;
float jf=.001;
long double f1,f2;
int a=146;
q=1.602e-19 ;
t=300;
k=1.38e-23;
n=1.7;
rsp=34.94;
bh=1.55;
cout<<"enter the value of Ideality factor:";
cin>>n;
cout<<"enter the value of specific on resistance:";
cin>>Rsp;
cout<<"enter the value of barrier height:";
cin>>fv;
cout<<"enter the value of forward voltage:";
cin>>fv;
cout<<"difference is="<<bh-fv;
for(int i=1;jf<=.07;i++,jf=jf+.001)
{  f1=((n*k*t)/q)*(2.303*log((jf)/a*t*t)));

f2=(bh-fv)+jf*rsp;
cout<<"For value of Jf="<<jf<<endl;
        {
        cout<<(f1-f2)<<endl;
                if(i%10==0)
                        {
                                i=0;
                                getch();
                        }
                }
        }
}
```

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Discussion

The V_F-J_F plots of the 4H SiC diodes obtained by the C++ program tally well in the case of metal contacts of nickel, titanium and gold for some finite range of the forward drop V_F. In the case of nickel (Figure 3) the comparison between the result from the C++ program and the experiment obtained by Saxena et al. [5] shows a deviation in the low voltage region at V_F below about 1.5 V, but the curves tally with each other at higher values of V_F. Similarly, deviation exists for the titanium contact up to 1.2 V; at higher voltages the graphs match. This is shown in Figure 4, in which the result obtained using C++ programming is compared to that obtained by Itoh et al. [7]. The best match of the results can be seen in Figure 5 for gold contact metal, in which marginal deviation of the iterated curve exists at voltages exceeding 1.2 V and both curves merge with each other at V_F values below 1 V. The calculated result shown in Figure 5 is plotted alongside that experimentally obtained by Itoh et al. [8].

The discrepancy in the characteristic curves for nickel contact shown in Figure 3 is primarily because of the low value of Richardson's coefficient used in the experiment [5], the effective Richardson's coefficient A^* being found to be much lower than 146 $A/cm^2/K^2$. This results in a higher value of V_F for a specified value of J_F.

The experimental result for titanium contact shown in Figure 4 [7] have a large deviation from the result obtained by the C++ program in the low voltage region with V_F less than 1.2 V. However, the barrier height for titanium contact metal has been found to depend on the polarity of the crystalline phase, i.e. ϕ_B = 1.17 V for the C face and 1.1 V for the SiC face. Such variation in ϕ_B may be responsible for the voltage drop at the contact at high and low current levels. The present work has not taken into account such variation in ϕ_B.

The result of the C++ program for the gold metal contact shown in Figure 5 seems to tally well with experimental result of Itoh et al. [8] for all ranges of voltage. In this case, the effective Richardson's coefficient A^* of 146 $A/cm^2/K^2$ was taken for both theory and experimentation.

Conclusions

A method was devised to draw the voltage-current characteristics of the 4H-SiC Schottky barrier diode. The method would be useful in generating such characteristics where experimental facilities do not exist, which may help in analysing the differences that may arise between theoretical and experimental results so that a better theoretical model can be developed.

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