Electrical properties of 4H-SiC based Schottky diode

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Abstract - Schottky diodes realized on 4H-SiC n-type wafers with an epitaxial layer and a metal-oxide overlap for electric field termination were studied. The oxide was grown by Plasma Enhanced Chemical Vapor Deposition (PECVD) and the Schottky barriers were formed by thermal evaporation of Titanium or Nickel. Diodes, with voltage breakdown as high as 600V and ideality factor as low as 1.05, were obtained and characterized after packaging in standard commercial package (TO220).

The electrical properties such as ideality factor, height barrier, the resistance, were deduced by current-voltage (I-V) analysis using the Least Mean Square (LMS) method. The effect of temperature on break voltage, and saturation current was studied. A model based on two parallel Schottky diodes with different barrier heights is presented. It is shown that the excess current at low voltage can be explained by a lowering of the Schottky barrier in localized regions. We use the two series RC components electrical model in order to study the dynamic behaviour of the Schottky diode in low frequency.

I. INTRODUCTION

Silicon carbide is considered as the semiconductor material that will enable the transition of traditional silicon power electronics into smart power. Silicon carbide has material properties that allow devices with higher voltage rating and higher operating temperatures compared to traditional silicon, which translates into smaller and less expensive components.

The physical properties make SiC a semiconductor of choice for electronic applications in which high temperature, high voltage, high frequency and/or high power are involved. Devices made by silicon carbide were realized like power Schottky diodes or power MOSFET's[1,2].

The present paper reports on Schottky diodes realized on 4H-SiC n-type wafers with an epitaxial layer and a metal-oxide overlap for electric field termination. The oxide was grown by Plasma Enhanced Chemical Vapor Deposition (PECVD) and the Schottky barriers were formed by thermal evaporation of Titanium or Nickel. The main electrical properties (such as ideality factor, height barrier and so on) were extracted by current / voltage (I-V) analysis using a least mean square method. The dynamic properties were studied by capacitance measurements and correlated to the properties of schottky diode.

II. EXPERIMENTAL DETAILS

Schottky diodes were realized from SiC wafers with a 7-μm thick lightly doped (10^15 cm^-3) n-type epi-layer grown on highly doped (10^19 cm^-3) Si-face 4H-SiC substrate, commercially available from Cree. A thin film of silicon oxide was grown on epitayer by standard 13.56 MHz Plasma Enhanced Chemical Vapor Deposition (PECVD) by a mixture of O2, SiH4 and H2. The growth conditions and the post deposition treatment have been chosen so as to optimize SiC properties [3]. After silicon dioxide growth, a guard ring was realized by standard lithography processes. Schottky barrier formation on 4H-SiC epilayer was obtained by thermal evaporation. We have used Titanium or Nickel, with or without thermal annealing in controlled atmosphere (under N2 flow). For Titanium the annealing temperature was 400°C, for Nickel 350°C. A metal-oxide overlap for electric field termination was realized. Ohmic contact formation was made on the back of the wafer by a sequential evaporation of Titanium, Nickel and Silver for all the samples.

The electrical properties were extracted from I-V analysis, performed in the cryogenic system by an electrometer Keithly 6517A, in temperature range varying from 10 K to 460K. The dynamic properties were studied by the capacitance variation versus frequency and voltage bias measured by using HP 4274A (100Hz-10kHz) LCR meter and HP 4192(1kHz-1MHz) impedance analyser.

III. RESULTS AND DISCUSSION

Schottky diodes in the structure given by fig.1 were realized on analyzed wafers electrically and structurally characterized [4]. Forward I-V analysis has lead to the determination of the characteristic parameters of the devices, such as the Schottky barrier height (Φbs), the ideality factor (n) and the on-resistance (Ron).

Figure 2 reports typical electrical characteristics of a schottky diode with barrier in titanium annealed at 400°C at different temperature varying from 10K to 460K. In low temperature the density of current decreases and the built in voltage increases. In the contrary, at high temperature the current density increases and the built in voltage decreases. A small variation of ideality factor n gives the evidence that current is not dominated by recombination current[5].
Reverse I-V measurements were utilized to obtain the breakdown voltage (the value of reverse voltage at 1 mA of reverse current).

We use the Least Mean Square method (LMS) to extract the parameters of schottky diodes by using the predetermined analytic function describing the experimental data\(^6\).

\[ I = I_s \exp \left( \frac{q(V - RI_s)}{nkT} \right) \]  

\[ \ln I = \ln I_s + \frac{q}{nkT} V \]  

\[ \frac{\partial Q_{lms}}{\partial I_s} = 0; \quad \frac{\partial Q_{lms}}{\partial n} = 0 \]  

In practice, we consider the model, used in diode junction p-n, and gives the current I versus voltage polarisation V:

\[ I = I_s \left[ \exp \left( \frac{V - RI_s}{nkT} \right) - 1 \right] \]  

Where \( I_s \) is the reverse saturation current, \( n \) the ideality factor, \( R_s \) the series resistance.

The LMS method consists on the minimisation of the relative or absolute difference average between N measures point \( I_n(V_i) \) and the results described by \( I(V) \) model from (1). The object is to minimize the function:

\[ Q_{lms} = \frac{1}{N} \sum_{n=1}^{N} \left( \frac{\ln(I(V_i)) - \ln(I(V))}{\ln(I(V))} \right)^2 \]

In the low voltage bias, the term \( R_s I \ll V \), \( I_s \) and \( n \) will be calculated using the least square method. From (3) and where \( (R_s I = 0) \) we can deduce:

\[ \ln I = \ln I_s + \frac{q}{nkT} V \]  

In the high voltage bias, the term \( R_s I \ll V \), \( I_s \) and \( n \) will be calculated using the least square method. From (3) and where \( (R_s I = 0) \) we can deduce:

\[ \ln I = \ln I_s + \frac{q}{nkT} V \]

The calculi of \( R_s \) was deduced in non linear part from the curve \( \ln(I) = f(V) \). In this condition the first model is not respected and we introduce the built-in voltage \( V_{bi} \). This method was noted \( M_1 \) in Table I. The potential difference \( V - R_s I \) gives the value of \( V_{bi} \). The variation of \( I \) can be written:

\[ I = \frac{V - V_{bi}}{R_s} \]

The approximations used in determining parameters \( n, I_s \) and \( R_s \) gives the numeric imprecision's, we consider the method used by Lee et al.\(^7\).

This method noted \( M_2 \) consists to define from the measured values I-V and the arbitrary voltage \( V_a \) an auxiliary function \( F_a(V_a) \):

\[ F_a(V) = V - V_a \ln I \]

\[ V = V(I) \]

The decomposition of system (7) gives

\[ F(I) = V(I) - V_a \ln I \]

From (3) we can write:

\[ I = IR_s + \frac{nkT}{q} (\ln I - \ln I_s) \]
The parameters $I_s$, $L$, and $n$ are considered constants at given temperature.

The (11) represents the linear behaviour of the current $I_{sat}$ versus voltage $V_p$. The $R_s$ and $n$ values were deduced by LMS method. The saturation current $I_s$ determined by the value of $c$ by:

$$I_s = \exp \left( \frac{c q}{n k T} \right)$$

In the thermoionic emission process theory[8], the current-voltage relationship of a Schottky barrier neglected the series and shunt resistances.

The barrier height is most commonly calculated from the current $I_s$:

$$\phi_B = \frac{k T}{q} \ln \left( \frac{AA^*T^2}{I_s} \right)$$

$\phi_B$ is the effective barrier height. In 4H-SiC, the published value of $A^* = 145$ A/cm$^2$K$^2$[9] and the area of schottky contact $A=1 \text{mm}^2$.

The parameters $n$, $I_s$, and $R_{sat}$ were deduced by the LMS method. $Q_{bar}$ term in Table I represents relative difference between experimental and theoretic characteristics. In general we can notice that $Q_{bar}$ term in method M1 is higher than methods M2 and M3 due to the important number of considering points. When this value is important we propose to use the method M1 and M2. The values of $\phi_B$ and $n$ obtained by the M1 and M2 were similar but the difference is observable between M2 and M3 in calculating series resistance probably due to the lower values of $R_{sat}$.

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Results for different types of diodes with Ti or Ni barrier with or without thermal treatment are summarized in Table I. As it can be seen, diodes with Schottky barrier in Titanium evidenced an important improvement in barrier height after thermal annealing at 400°C.

On the contrary the influence of annealing for diodes with Nickel barrier is not relevant. The improvement of barrier height gives also a significant improvement in values of voltage breakdown. Some devices with Ti barrier show breakdown voltage up to 600V and the real not reversible breakdown was found at 850 V. Thermal annealing gives also an improvement in values of on-resistance. In fact, for optimal device performances, $R_{on}$ has to be as low as possible to have high current at low forward voltage.

An interesting feature has been found for some devices which present a current-voltage characteristic reported in figure 3. A fit of this characteristic has been performed by using the two linear regions of the plot.

This behaviour can be schematized with the electrical equivalent circuit reported in fig.4-a consisting of two parallel Schottky barrier. It can be due to different phenomena. One of the most important problems in industrial application of SiC is the low quality of the material compared to classical semiconductors such as silicon. The presence of defects, as micropipes, dislocations, comets with the inclusions of different polytypes in the epitaxial layers, can give effects on devices performances or failures[10]. Various phenomena have been considered to be responsible for Schottky Barrier height inhomogeneities. For example, difference in the
crystal symmetry of the metal with respect to the semiconductor or variation in the orientation at the metal-semiconductor interface, due to localized faceting of the interface has been observed. Doping inhomogeneity, dopant clustering, contaminations are other features which can lead to Schottky barrier inhomogeneities[11]. A clear relation between these defects and barrier inhomogeneities can not be asserted and the effect of Schottky contact will be probably responsible for this effect.

Fig. 4.

(a) Electric model of two barrier height of Schottky diode  
(b) the equivalent dynamic circuit of studied Schottky diode.

Fig. 5(a) reports the measured capacity at low frequency without bias voltage. The capacitance tends to a constant value at high frequency as given elsewhere[12] depending on voltage bias. In order to know this behaviour we simulate using Matlab program, the capacity in the frequency range 100-10000Hz and propose an equivalent circuit inset fig.5-b of the Schottky diode. R₁ is the bulk series resistance and C₁ its associated capacitance, R₂ and C₂ are the resistance and capacitance, respectively of the Schottky barrier. Rₘ and Cₘ the equivalent measured parallel resistance and capacity.

A simple equivalent circuit analysis shows that:

\[
R_s = \frac{X^2 + \alpha^2 Y^2}{X} 
\]

And

\[
C_2 = \frac{Y}{X^2 + \alpha^2 Y^2} \tag{15}
\]

Where

\[
X = \frac{R_m}{1 + \alpha^2 C_m R_m} - \frac{R_s}{1 + \alpha^2 R_s^2 C_1} \tag{16}
\]

R₁ was obtained at the frequency of measurements by measuring the current in phase with the applied ac voltage when the diode is biased into far forward bias. For C₁, we have taken the geometrical capacitance as measured at high frequency. We use the (14), (15) and the Matlab program to simulate the capacitance as shown in fig.4(b). A good agreement between experimental and simulated values was found at low frequency range.

For some devices having two Schottky barrier at room temperature, we observe a higher value of R₂ and C₂ compared to the one having only one barrier showing the effect of defects probably in schottky contact. The improvement of barrier height with annealing gives also a significant improvement in values of voltage breakdown as it can be seen in Table I. From fig. 6, we can deduce that breakdown voltage decreases with increasing temperature it passes from 875 V at 70 K to 489 V at 460 K. Two slopes of breakdown voltage were found. Devices
with barrier in Titanium show breakdown voltage up to 600V and the non reversible breakdown voltage 850V was found. The slope variation of breakdown voltage changes from small temperature range between 70-250K and high range 270-460 K.

Thermal annealing gives also an improvement of the series resistances and on-resistance. In fact, for optimal device performances, $R_{on}$ has to be the lower, so to have high current at low forward voltage.

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### Fig. 6: Variation of reverse breakdown voltage versus temperature of diode Shottky with Ti.anneal.400.(TO220).

#### IV. CONCLUSION

Schottky diodes made by SiC were realized using different metal (Ti or Ni) and different temperature of annealing for the Schottky barrier. Using LMS method, the electrical measurements show that diodes with barrier in Titanium annealed at 400°C have higher $\phi_j$ values with a significant improvement of reverse voltage and on resistance value. In this device, the slope variation of breakdown voltage changes from small temperature range between 70-250 K and high range 270-460 K.

An interesting feature has been found for some devices which present a current-voltage characteristic represented by two barrier height model due probably to the defects in the bulk or to the Schottky contacts.

The capacity behaviour at low frequency exhibits the possibility to describe the Schottky diode by dynamic electric model consisting of two RC components. The simulation using Matlab program confirms the experimental results. The parameters values of the RC components relative to the Schottky barrier were higher in case of device having two Schottky barrier height due probably to the effect of barrier inhomogeneities.

### REFERENCES


