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Improvement of Ni/4H-SiC/Ti Schottky Diode Characteristic Post Annealing Process

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Abstract

The 4H-SiC semiconductor has been used to create Schottky diodes, with Ni and Ti metals serving as Schottky and Ohmic contacts, respectively. One of the samples underwent a 30-minute annealing treatment at 500°C after the metal contacts were created using the DC sputtering process. The quality of the Ni/4H-SiC/Ti Schottky diode has been enhanced by annealing treatment under these conditions. The improvement was marked by the decrease in saturation current from 3.27×10^{-9} A/cm^2 to 2.78×10^{-9} A/cm^2. Another parameter that improving was its series resistance that decreased from 44.88 kΩ to 13.86 kΩ based on calculation using function F1 and 38.87 kΩ into 12.79 kΩ based on calculation using function F2. The difference in values between calculation using function F1 and F2 is only about 13%. Schottky Barrier Height and diode ideality factor also improved. The value of Schottky Barrier Height and diode ideality factor that have been calculated using I-V curve and Cheung's method only vary slightly at about 13%. Hence it can be concluded that both calculation methods have produced consistent results across the data range and annealing process at 500°C for 30 minutes was proven to enhance the diode quality.

Keywords: 4H-SiC; Annealing; Nickel contact; Schottky contact; Schottky diode; Series resistance

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1. Introduction

Metal-semiconductor junction is one of the simplest semiconductor device structures that could be applied as radiation detector [1], [2], [3]. This type of junction is known as Schottky junction or Schottky contact [4], [5]. One of the semiconductors that is commonly used in Schottky junction is silicon carbide (SiC). There are three types of SiC that are commercially produced namely 3C-SiH, 4H-SiC, and 6H-SiC, each is different in their respective crystal structure [6]. 4H-SiC silicon carbide has hexagonal crystal structure and is the most frequently used because it has advantages than the other types of silicon carbide based on its bandgap energy, electron mobility, breakdown electric field, and thermal resistance [7].

Contact formation is one of the important steps in semiconductor device fabrication because this contact will act as connector between the device and the external circuit. Contact in Schottky diode is extremely important since it directly affects the diode characteristic such as barrier height, series resistance, and saturation current [8], [9].

One of the most common used metal contacts is nickel (Ni) [10], [11], [12], molybdenum (Mo) [13], [14], and titanium (Ti) [12], [15], [16]. Performance of Schottky diode could be enhanced by applying heat treatment process or annealing [17], [18], [19]. In many cases most of the experiments have been focused on silicon carbide that has epitaxial layer [20], [21], [22], [23] and less on bare silicon carbide without epitaxial layer despite it is cheaper and easier to produce.

Nickel has unique characteristics when it comes to its interaction with silicon or silicon carbide. Nickel is capable of producing alloy in the form of Ni_xSi_y that affects electrical characteristics of the diode. Previous study showed that the formation of nickel silicide (Ni_xSi_y) is observed when annealing temperature was higher than 700°C [24]. Another study showed that at 620°C the contact between SiC and Ni still behaves as Schottky contact while at higher temperatures the resistance becomes even smaller, and it changes the character of junction from Schottky junction into linear (or Ohmic junction) [25]. Furthermore, nickel silicide in the form of Ni_2Si also formed when annealing was performed between 600 and 950°C and it has smallest series resistance when annealing temperature was 950°C [26].

These studies indicate that the formation of nickel silicide begins at approximately 600°C [25], [26]. When nickel silicide was formed, the series resistance also decreased. This situation presents challenges when addressing series resistance problems. Too small series resistance will change the behavior of metal-semiconductor junction into Ohmic contact, hence loses its rectifying properties. In order to produce Schottky contact as intended in this experiment, series resistance value should be sufficient to keep its rectifying properties. However, too high series resistance value also poses risk in terms of power loss when Schottky diode is intended to be applied as sensor.

In the case of Ni/4H-SiC/Ti Schottky diodes, additional effect could be observed due to longer annealing time. An increase in annealing time theoretically will produce more nickel silicide (Ni_xSi_y) and reduce its series resistance. If the series resistance is kept at a certain level to maintain its rectifying properties, then shorter annealing time is preferable rather than the longer one.

In order to ascertain its performance, this study set out to investigate the behavior of Ni Schottky contacts on bare silicon carbide and how they alter following a 30-minute annealing process at 500°C. Because it may result in a sufficiently lower series resistance while maintaining its rectifying behavior, the annealing temperature of 500°C was selected for this study, which is lower than that which has been previously investigated [26]. The choice of annealing time for 30 minutes in this research could be based on previous research [25]. So far, no studies has been found on the exploration of the impact of annealing time alone on electrical behavior of Schottky diode. However, an increase in annealing time could produce deeper penetration of metal contact into semiconductor due to diffusion process. In this case, the metal contact will be very close to the depletion region. If in a certain circumstance the metal contact touches the depletion region, an effect similar to shunting effect will happen and the diode will be in short circuit condition. In order to avoid these circumstances, usually there is a rule of thumb that higher annealing temperature should be applied using shorter annealing time.

2. Experimental Procedure

Schottky diodes were made from n-type 4H-SiC chips that have thickness of 350 μm and a square area of 1.5×1.5 cm^2. Schottky contact was fabricated using stainless steel (SS) mask that has a two-circle pattern with a diameter of 0.5 cm and Ohmic contact was made with square pattern of 1×1 cm^2.

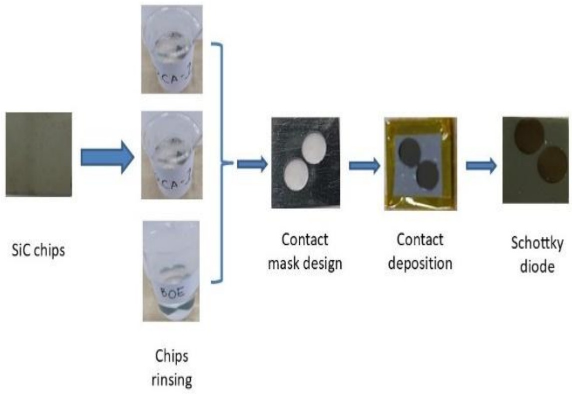


Figure 1. Ni/4H-SiC/Ti Schottky Diode Fabrication Process.

The next step was rinsing the SS mask using methanol and isopropil alcohol and drying the mask. Before contact formation, SiC chips were rinsed using RCA1, RCA2, and BOE solutions to clean the ionic, organic, and native oxide contaminants.

After cleaning process, SS masks were attached onto the SiC chips both on the front and rear surface. The contact formation was ready to be performed. The next step was Schottky contact formation through DC sputtering methods using DC voltage of 5 kV, current of 10 mA for 5 minutes in argon (Ar) plasma. Figure 1 shows the process that has been done to produce Schottky diode from 4H-SiC chips.

Targets that were used for Schottky contact formation were NiCr and for Ohmic contact formation was Ti. Both contacts were made with a thickness of about 80 nm. Argon plasma was used to produce inert atmosphere to ensure no unwanted insulator layer such oxide might present after the process. On the other hand, in oxygen atmosphere, nickel could react with oxygen to produce nickel oxide when annealing temperature is high enough [27]. Titanium also has probability to react with oxygen to form titanium oxide [28], [29], [30]. Most of these papers explain oxide formation on titanium layer at high temperature. There are two conditions that have always been mentioned in the articles. First condition is the high temperature during the process, and the other is the presence of oxygen in the air. If one of these conditions is not met, oxide formation will not occur.

In the application of Schottky diode as radiation sensor, one of the important features that should be met is the capability of radiation particle to penetrate into the diode through metal contact layer and the other is the ability of electric charges to move from diode interior into external circuit through the metal contact. In general, lower metal thickness is preferable because radiation particles are easier to penetrate into the diode through the metal contact. However, after electric charges had been produced, smaller resistance is needed to reduce the power loss during charge transfer from interior of the diode into the external circuit. To realize the condition for smaller resistance, thicker metal contact should be produced.

The condition for penetrability of radiation particle and lower resistance for metal contact seems contradictory to each other. In this case the thickness that we were chosing was thin enough to pass radiation particle while still has sufficient resistivity to maintain its electrical properties as Schottky contact.

2.1 *Diode Annealing Process*

The schematic structure of the fabricated Schottky diode after contact deposition is given in Figure 2.

After contact formation has been finished, there are two types of samples that are available. The first sample was measured as it is, and no thermal treatment (annealing process) was performed for this sample because it was used as control sample.The second sample was heated (annealed) at 500°C for 30 minutes to test if annealing process has impact on Schottky diode's quality.

2.2 *Diode Characterization*

After Schotcky diode fabrication, the characterization was performed by measuring current-voltage (I-V) of the Schottky diodes before and after annealing using Keithley 4200A-SCS semiconductor parameter analyzer. The voltage was varied from 0 up to 8 V and the current was measured.

3. Result and Discussion

Current-Voltage (I-V) curves for sample before and after annealing process is shown in Figure 3.

In Figure 3 I-V curves for both diodes has shown exponential pattern, hence it can be concluded that Ni/4H- SiC/Ti Schottky diodes have been successfully developed. Further examination from I-V curve showed that both diodes have turn-on voltage around 2.9 V. This value is four times higher than Ni-based Schottky diodes that have turn-on voltage around 0.6-0.8 V. This result indicates that the schottky diodes in this experiment still have high series resistance. However, by comparing the I-V curves from sample before and after annealing diode with annealing treatment produced lower series resistance.

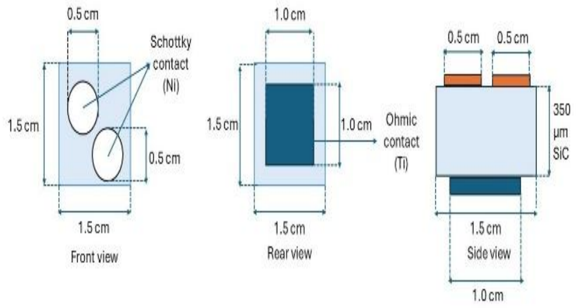


Figure 2. Ni/4H-SiC/Ti Schottky Diode Structure.

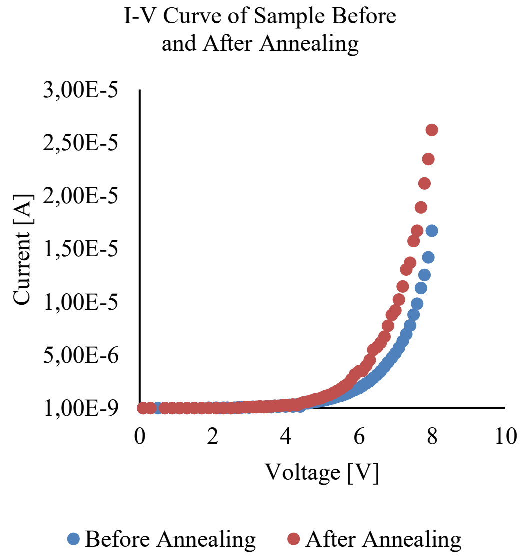


Figure 3. I-V Curve of Sample Before and After Annealing Process

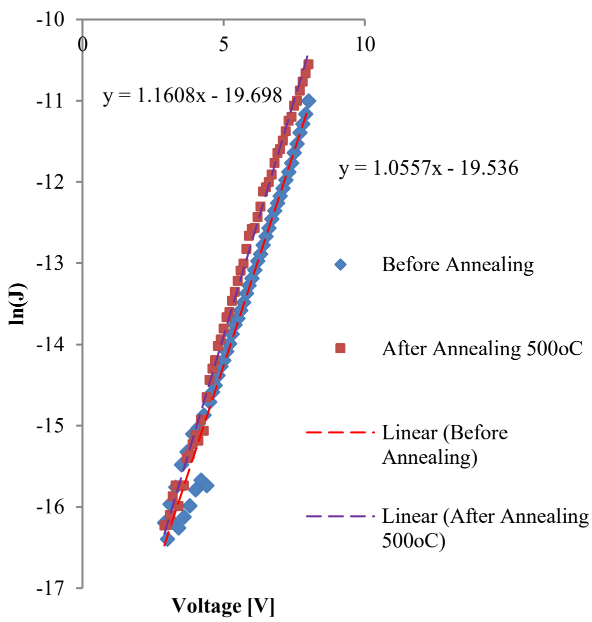


Figure 4. Linear Curve of ln(J) Against Voltage and Its Regression Curve

Table 1. Diode Parameters Before and After Annealing Process

Parameter	Before annealing	After annealing 500°C, 30 minutes
Saturation current (A)	3.27×10^{-9}	2.78×10^{-9}
Ideality factor	36.64	33.32
Schottky Barrier Heigh (V)	0.91	0.92

3.1 *Diode parameter calculation*

The value of Schottky Barrier Height (ϕ_B) and saturation current density (J_S) could be calculated using Equations 1 and 2 as follows.

$$J=J_s\left[\exp\left(\frac{qV}{nkT}\right)\right] \quad (1)$$

$$J_s=A^*T^2\exp\left(-\frac{q\phi_B}{kT}\right) \quad (2)$$

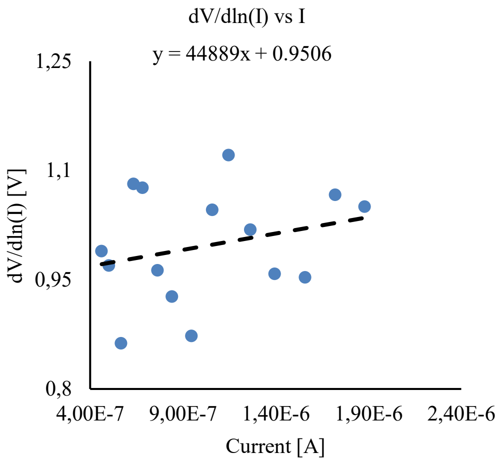
In Equation 1 and 2, q, V, n, k, T, and A^* referred to electron's charge, applied voltage, diode's ideality factor, Boltzmann's constant, operating temperature and Richardson's constant, respectively. Linear form of Equation 1 could be given in Equation 3 as follows.

$$\ln J=\ln J_s+\frac{qV}{nkT} \quad (3)$$

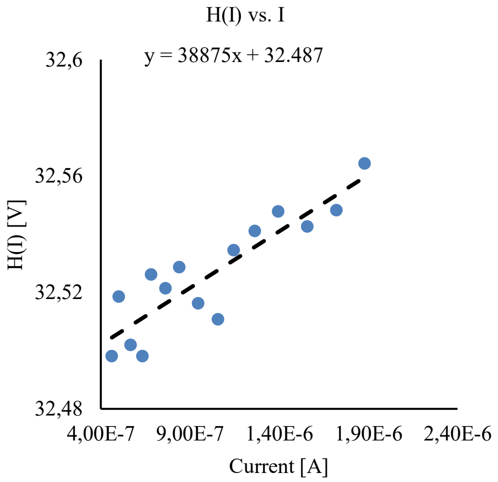
Data from I-V measurement could be used to calculate saturation current density. Plot of $\ln J$ against V could be shown is Figure 4. Linear regression of these curves could be used to infer both saturation current density and diode ideality factor values from their slope and intercept.

After J_s value was extracted using regression curve value, the value of ϕ_B could be determined using Equation 2 by setting operating temperature of diodes at 300 K and using Richardson's constant for 4H-SiC at 146 A/(cm^2.K^2). The values of saturation current density, diode ideality factor, and Schottky Barrier Heigh could be summarized in Table 1.

According to data in Table 1, the value of saturation current density, J_S for both diodes are 3.27×10^{-9} A/cm^2 for diode without annealing treatment and 2.78×10^{-9} A/cm^2 for diode with annealing treatment at 500°C for 30 minutes. These results show that annealing process has enhanced diodes quality. The value of Schottky Barrier Height (ϕ_B) also shows improvement because it increases from 0.91 V before annealing to 0.92 V after annealing treatment.



Plot F1 Before Annealing



Plot F2 Before Annealing

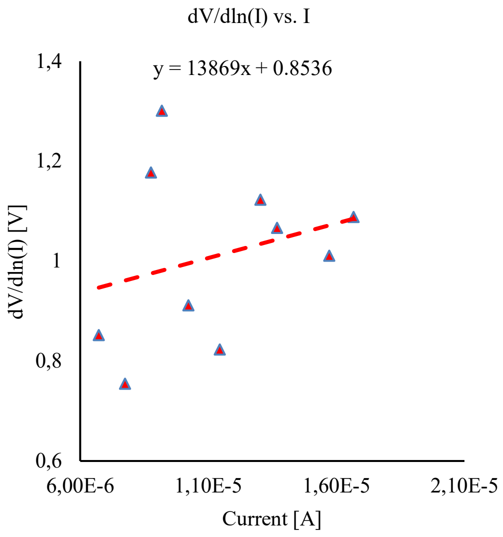
Figure 5. Plot F1 and F2 for Sample Before Annealing

3.2 *Series resistance calculation*

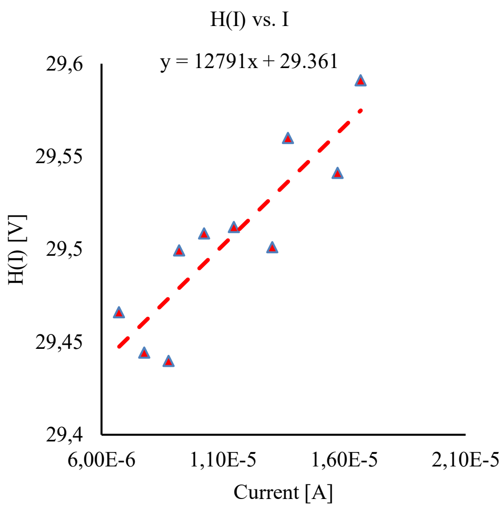
One of junction quality parameter that could be determined through I-V measurement is its series resistance value (R_s). Lower series resistance resulted from better diode. However, Equation 1 to 3 could not be used to extract series resistance value from I-V measurement. Hence a different approach is needed. Cheung[] proposed the method to calculate series resistance from I-V measurement. Using Cheung's method series resistance could be calculated using two function F1 and F2 as follows.

$$F1\equiv\frac{dV}{d(\ln I)}=IR_S+n\left(\frac{kT}{q}\right) \quad (4)$$

$$F2\equiv H(I)=IR_S+n\phi_B \quad (5)$$



Plot F1 After Annealing



Plot F2 After Annealing

Figure 6. Plot F1 and F2 for Sample After Annealing 500°C, 30 minutes

Table 2. Comparation of Pre dan Post Annealing Behavior of Ni/4H-SiC Schottky diode

Diode Treatment	Before Annealing		After Annealing	
Parameter	F1	F2	F1	F2
R_s (kΩ)	44.88	38.87	13.86	12.79
n	36.84	-	33.08	-
Φ_B (V)	-	0.88	-	0.89

Table 3. Data of series resistance calculation for F1 and F2

Data	Series resistance before annealing (kΩ)		Series resistance after annealing (kΩ)	
	F1	F2	F1	F2
1	44.88	38.87	13.86	12.79
2	45.05	31.27	10.32	11.05
3	44.5	36.76	10.32	11.05

Data plot for function F2 could be produced by using I-V data and calculating H(I) using Equation 6 as follows.

$$H(I)=V-n\left(\frac{kT}{q}\right)\ln\left(\frac{J}{A^{*}T^{2}}\right) \qquad (6)$$

Equation 4 and 5 both could be used to calculate series resistance. Hence the value of series resistance calculated from Equation 4 should be consistent with the calculation from Equation 5. The diode ideality factor could be calculated from Equation 4 and the result could be used to calculate Schottky Barrier Height from Equation 5 and 6.

Plot functions F1 and F2 for diode before and after annealing process were shown in Figure 5 and Figure 6, respectively.

The calculation of series resistance, diode's ideality factor and Schottky Barrier Height using function F1 and F2 could be summarized in Table 2.

Based on the value in Table 2, it can be concluded that annealing process is beneficial in enhancing diode's quality because all diode parameters showed improvement after annealing process.

Series resistance calculation using function F1 and F2 shows consistent trend and varied slightly at about 13%. In order to validate this statement, additional measurements were carried out to find the values of F1 and F2. Now there are three sets of data for series resistance calculation before and after annealing process. These data could be summarized in Table 3.

Data in Table 3 was used to perform t-test for paired value of series resistance in F1 and F2 to find if F1 and F2 is significantly different. Using confident level $\alpha = 0.05$ and degree of freedom = 2 , the t-test showed that both F1 and F2 was not significantly different in series resistance calculation for sample before annealing. The same procedure was repeated for sample after annealing. The conclusion was that F1 and F2 calculation for sample after annealing produce similar result.

Statistical test using t-test that has been performed for both sample reached the same conclusion, that series resistance value that was extracted using F1 and F2 have consistently produced similar results.

4. Conclusions

The quality of the Ni/4H-SiC/Ti Schottky diode has been enhanced by annealing it for 30 minutes at 500°C. Saturation current dropped from 3.27×10^{-9} A/cm^2 to 2.78×10^{-9} A/cm^2, indicating the improvement. Its series resistance also improved, going from 44.88 kΩ to 13.86 kΩ based on function F1 and from 38.87 kΩ to 12.79 kΩ based on function F2. The difference between these values is only roughly 13%. Additionally, the diode ideality factor and Schottky Barrier Height increased. There was no significant difference between the diode ideality factor and Schottky Barrier Height values determined using Cheung's method and the I-V curve. Additional measurements and t-tests confirmed the consistency of both calculation methods across the data range.

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