

Ohmic Contact Formation on N-Type 6H-SiC Using Poly-Si and Silicides.

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Abstract - Silicon Carbide with its wide bandgap, high thermal conductivity, and high breakdown electric field is an attractive material to be used for applications in high power, and high temperature semiconductor devices. For such applications, it is extremely important to be able to form stable ohmic contacts. Various metals have been attempted to form ohmic contacts on SiC such as Ni, Ti, and Al. However it has been observed that these metallization schemes have degraded performance due to carbon accumulation by forming carbides at the interface. In this study, polycide (poly Si + silicide) based metallizations have been investigated, using NiSi_2 and TiSi_2 . Silicides of Ni and Ti have been synthesized employing a layer of heavily doped polysilicon to prevent any form of reaction between the metal and the carbon at the SiC interface. Using a 0.5cm^2 n-type 6H-SiC samples with various doping concentrations ($1.3 \times 10^{18} \text{ cm}^{-3}$ and $1.7 \times 10^{18} \text{ cm}^{-3}$), the electrical and structural properties of NiSi_2 and TiSi_2 have been examined by fabricating linear transmission line model (TLM) structures. I-V characterization have been carried out to determine the specific contact resistivity, ρ_c . Samples were processed at various annealing temperatures to determine conditions for the best ohmic contact resistivity.

1. INTRODUCTION

For high temperature applications, Silicon Carbide is an attractive material because of the wide band gap (3eV for 6H-SiC) and high thermal conductivity (4.5W/K cm) SiC possesses over Silicon. To fabricate and duplicate the optimum condition for a device, thermodynamically stable ohmic contacts with low specific resistances are required[4]. In most cases, parasitic resistances in the contacts degrade the performance of an electronic device. This paper studies various types of conductive material for contacts, which are processed at different conditions to determine which chemical activity between the metal and the Poly-Si interface would yield the lowest ohmic contact resistivity.

Generally on an n-type substrate, nickel(Ni) would be the preferred choice to form the silicide(NiSi_2) by

annealing in a vacuum at 900°C to 1100°C . The reaction between the Si in SiC with Ni yields a second substance aside from NiSi_2 , which is Carbon. There have been studies showing that Carbon hampers the ability to attain low resistance[2]. Therefore this study would look into alternative methods in arriving at low thermally stable ohmic contacts.

One possibility is joining metals such as Ti, and Ni to a deposited layer of doped poly-Si to react and form a silicide without the removal of any carbon from the SiC interface. The added Si thin film layer would arrest the residual Carbon atom in the electrode layer. Samples will be processed at various annealing temperatures to monitor which setting yields the best ohmic contact resistivity, ρ_c . In general, ρ_c cannot be measured directly because the current density and voltage distribution under the contact are not consistent. Therefore, the Transmission Line Model (TLM) will be used to indirectly determine the specific ohmic resistivity.

2. TLM MEASUREMENTS

The TLM method is based on a simple resistor network to model the ohmic contacts assuming one-dimensional current flow pattern. Three identical contacts are added to the diffused or ion-implanted sheet with contact spacing d_1 and d_2 . The TLM structure consists of test structures of several rectangular contact pads of length L , and width W .

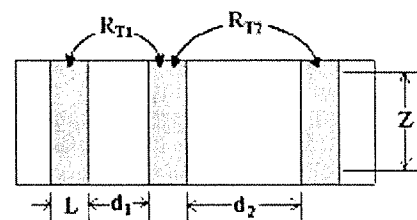


FIG. 1. TLM Structure, showing Schokley pads 1 through 3; dark area is contacts, light area is 6H-SiC.

The total resistance between two contacts in dependence of the different spacings d_i between the contacts can be described by:

$$R_{Ti} = 2R_C + \frac{R_{SH}d_i}{Z} \quad (1)$$

where R_C represents the contact resistance and R_{SH} is the sheet resistance of the semiconductor layer outside the contact region[4]. By solving for R_C , the ohmic resistance can be calculated by taking the difference between the two pairs of contacts. Similar to solving for two equations and two unknowns, contacts resistance can be written as

$$R_C = \frac{(R_{T2}d_1 - R_{T1}d_2)}{2(d_1 - d_2)} \quad (2)$$

Another critical element for solving the specific contact resistivity is the transfer length, L_T . The transfer length can be thought of as the length where the voltage due to the current transferring from the semiconductor to the metal or from the metal to the semiconductor has dropped to $1/e$ of its maximum value. In the case where the contact length (L) is greater than or equal to $1.5L_T$, specific contact resistivity can be written as

$$\rho_c \approx (L_T)(Z)(R_C) \quad (3)$$

The value of ρ_c was calculated from equation 3.0. The value of L_T is half of d at $R_T=0$ [4]. The value of R_C is half of R_T at $d=0$ [4].

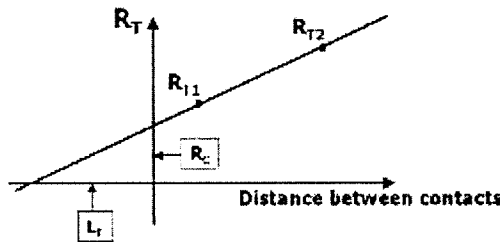


FIG. 2. Theoretical representation of R_T vs. d measurement for each pad spacing.

Essentially TLM modeling can be looked at as a three terminal contact resistance method. By moving away from two terminal structures, TLM modeling removes the ambiguity that existed with the two terminal method by not including the bulk resistance and the layer sheet resistance from the specific contact resistivity calculation. TLM modeling also incorporates the transfer length to consider the effect of current crowding on specific contact resistivity. However, specific resistivity values measured with the TLM model may be subject to systematic error due to the TLM is based on a simplified model of the metal-semiconductor contact[4]. The model assumes identical contact resistances for all three or more contacts, which is questionable but reasonable for a sample that is

not too large. In addition, the contact resistance is obtained by taking the difference of two large numbers, which introduces significant error, especially in the case when the contact resistance is very low. To reduce the amount of error, and increase the amount of confidence in the result, multiple measurements of R_T is obtained to determine ρ_c .

3. EXPERIMENTAL

The devices were fabricated entirely at the RIT facility starting from bare SiC to operating TLM structures. The substrate used in this project were (0001)-oriented p-type 6H-SiC substrate, which were provided by Cree Research Inc., consisting of a $4\mu\text{m}$ thick nitrogen doped n-type ($1.3 \times 10^{18} / \text{cm}^3$ and $1.7 \times 10^{18} / \text{cm}^3$) epitaxial layer. The goal was to process a TLM contact structure using TiSi_2 , and NiSi_2 on both types of net doping concentrations. The TLM contact structures were spaced apart unevenly ($d=15\mu\text{m}$, $25\mu\text{m}$, $45\mu\text{m}$, $85\mu\text{m}$, $170\mu\text{m}$, and $335\mu\text{m}$) with a line widths of $60\mu\text{m}$. As a prelude to this project, one more sample was processed with TiSi_2 , to observe the change in specific ohmic contact resistivity at a different annealing temperature.

A. Poly-Si

After running all the samples through a standard RCA clean (HPM + APM), approximately 400nm of poly-Si was deposited using LPCVD with SiH_4 as a reactive agent. The poly-Si is then doped with N250 Phosphorous spin on dopant and diffused in N_2 at an annealing temperature of 1000°C for 15min. soak drive-in.

B. Nickel Silicide (NiSi_2)

One sample from each dopant concentration was set aside for NiSi_2 contacts. An RF-sputter-system (base pressure 8×10^{-6} Pa) equipped with a 4" Ni compound target was used to deposit 95nm of Ni onto the samples. The thickness of Ni and Poly-Si were calculated so that after an annealing process, the thin films would form a stoichiometric NiSi_2 alloy, assuming that the density of the deposited material is identical to that of the bulk[1]. A first level lithography step was performed to create the lines for the TLM structures, which acts as a masking layer for metal etch and poly-Si etch. The Ni is etched isotropically in a wet etch solution. The poly-Si is anisotropically dry etched with 85% anisotropy, using the DRYTEK QUAD. To isolate the TLM structures into individual n-type wells, an ISOMET low speed saw was utilized to cut $10\mu\text{m}$ into the 6H-SiC substrate, assuring to cut well past the underlying epilayers. The samples were annealed at 950°C for 1min. in Ar flow. The annealing of the samples were carried out using a HEATPULSE 410 RTP oven with a quartz base to support the samples. The

composition of the formed alloy was investigated using X-ray Diffraction (XRD) analysis. The HP 4144 analyzer was used to measure the specific ohmic contact resistivity within each TLM contact structures.

C. Titanium Silicide (TiSi_2)

One sample from $1.3 \times 10^{18} / \text{cm}^3$ dopant concentration and two from $1.7 \times 10^{18} / \text{cm}^3$ dopant concentration was set aside for TiSi_2 contacts. An RF-sputter-system (base pressure 7×10^{-6} Pa) equipped with a 4" Ti compound target was used to deposit 175nm of Ti onto the samples. The thickness of Ti and Poly-Si were calculated so that after an annealing process, the thin films would form a stoichiometric TiSi_2 alloy, assuming that the density of the deposited material is identical to that of the bulk[1]. A first level lithography step was performed to create the lines for the TLM structures, which acts as a masking layer for metal etch and poly-Si etch. The Ti is etched isotropically in a wet etch solution. The poly-Si is anisotropically dry etched with 85% anisotropy, using the DRYTEK QUAD. To isolate the TLM structures into individual n-type wells, an ISOMET low speed saw was utilized to cut $10\mu\text{m}$ into the 6H-SiC substrate, assuring to cut well past the underlying epilayers. One sample from each dopant concentration was annealed at 1000°C for 90s in Ar flow. The additional sample that was processed to observe the change in specific ohmic contact resistivity at a different annealing temperature, was annealed at 1150°C for 90s in Ar flow. The annealing of the samples were carried out using a HEATPULSE 410 RTP oven with a quartz base to support the samples. The composition of the formed alloy was investigated using X-ray Diffraction (XRD) analysis. The HP 4144 analyzer was used to measure the specific ohmic contact resistivity within each TLM contact structures.

4. ANTICIPATED RESULTS

- ◆ *Silicide contact to be preferred over single metal contact*
Having the poly silicon layer adjacent to SiC would restrict the accumulation of carbon atoms at the interface and in the contact layer. The intentional deposition of poly-Si would change the character of the diffusion process, leading to better ohmic contacts.
- ◆ *Increasing the temperature on the RTA will improve the specific ohmic contact resistivity*
Annealing at high temperatures would reduce the voltage necessary to have current flow through the contacts. The contacts would form linear IV characteristics.
- ◆ *Certain metals will exhibit better characteristics for resistivity in contact*

When sputtering/annealing metals to form a silicide, thin film resistivity depends on the metals position (Orthogonal, Hexagonal, Tetragonal, and Cubic). Titanium would exhibit a large variation, from $20 \mu\Omega\text{-cm}$ to $120+ \mu\Omega\text{-cm}$. On the other hand Ni is a very stable thin film but is subject to thermal grooving when the silicide develops small individual pockets, which leads to an increase in the electrical resistance. Depending on how the wafers are processed, it would be hard to determine which metal would favor a low ohmic resistivity.

5. RESULTS AND DISCUSSION

A. Electrical characterization

Before processing the samples through an RTP step to form a silicide, the contact resistivity measurements with no heat treatment was recorded. $1.7 \times 10^{18} / \text{cm}^2$ n-type dopant concentration yielded a specific contact resistivity of $5.4 \times 10^{-5} \Omega\text{-cm}^2$ and $5.8 \times 10^{-5} \Omega\text{-cm}^2$ for the poly-Si contact resistivity. $1.3 \times 10^{18} / \text{cm}^2$ n-type dopant concentration yielded a specific ohmic contact resistivity of $4.12 \times 10^{-5} \Omega\text{-cm}^2$.

The effect of temperature on the TiSi_2 contacts during the RTP process is illustrated in the figure below.

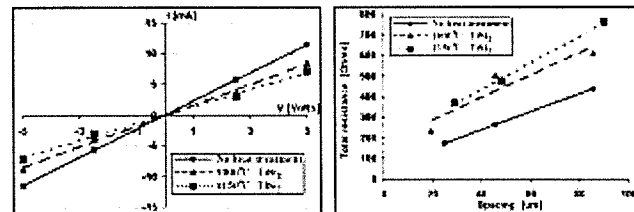


FIG. 3. (a) I-V characterization for TiSi_2 samples annealed at 1000°C and 1150°C for 90s respectively. (b) Total resistance vs. Distance between each contacts on TLM.

The results did not correlate to the expected relationship annealing temperature may have on ohmic resistivity. It is widely understood that by annealing the contacts, specific contact resistivity for TiSi_2 is expected to improve. There was a rise in total resistance, when the temperature was altered from 1000°C to 1150°C . This increase in resistance can be attributed to the oxidation that must have taken place from the time the titanium was sputtered, to the moment the contacts were ready for anneal. If this were the case, by annealing an oxidized film, there is a possibility of forming a parasitic contact in place of an ohmic contact. This parasitic contact layer would inhibit the current from flowing through the contacts, which would increase the amount of voltage required to obtain a measurement. Ohms law states under these conditions, the total resistance would increase

linearly. Despite the increase in total resistance, measurements performed on $1.7 \times 10^{18} / \text{cm}^2$ dopant concentration for specific contact resistivity showed an improvement in value as the annealing temperature was increased. A 1000°C anneal for TiSi_2 provided a specific contact resistivity value of $9.858 \times 10^{-4} \Omega\text{-cm}^2$. A 1150°C anneal for TiSi_2 provided a specific contact resistivity value of $6.678 \times 10^{-4} \Omega\text{-cm}^2$. Unfortunately measurements for $1.3 \times 10^{18} / \text{cm}^2$ dopant concentration was not obtained.

For NiSi_2 , measurements performed on $1.3 \times 10^{18} / \text{cm}^2$ dopant concentration yielded a specific contact resistivity value of $4.058 \times 10^{-3} \Omega\text{-cm}^2$. Once again, the increase in specific resistivity from no heat treatment to 950°C anneal for NiSi_2 can be attributed to the oxidation that must have taken place from the time the nickel was sputtered, to the moment the contacts were ready for anneal. Unfortunately measurements for $1.7 \times 10^{18} / \text{cm}^2$ dopant concentration was also not obtained.

B. Thin film analysis

XRD has been used to examine the reaction within the polycide film by determining the metal position of the particular silicide formed. The composition for TiSi_2 was determined to be orthogonal, and the composition for NiSi_2 was determined to be cubic.

XSEM was employed to determine the rate and amount of consumption for poly-Si during RTP. This chart below serves as a guide to anticipate how thick each film stack should be to process the desired amount of silicide, and the desired amount of poly-Si left behind after an RTP step.

Amount of Silicon Required to Form Silicide				
Metal	Atomic Volume [Å ³]	Silicide	Å of silicon Per Å of metal	Å of Resulting Silicide thickness per Å of metal
Ti	10.60	TiSi_2	2.27	2.51
Ni	6.60	NiSi_2	3.65	3.63

TABLE 1. A conversion table to calculate optimal remaining poly-Si thickness and silicide thickness after an RTP step.

For Instance, if 100nm of titanium is reacted with poly-Si to form TiSi_2 , a minimum of 227nm of poly-Si is required. In addition, the 100nm of titanium would result in a TiSi_2 thickness of 251nm.

Two samples with similar doped poly-Si thickness and titanium thickness were processed to demonstrate and produce a difference in consumption rate for poly-Si. The annealing temperature to form TiSi_2 was altered for both samples. One sample underwent an RTP processing step of 850°C , while the other sample was processed at 1300°C .

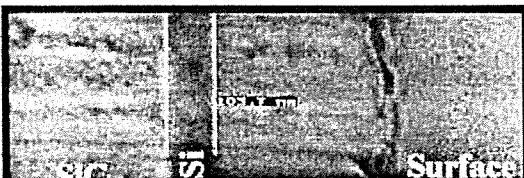


FIG. 4. TiSi_2 for 850°C RTP anneal.

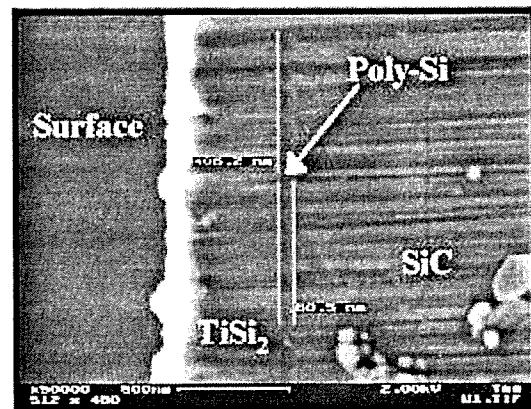
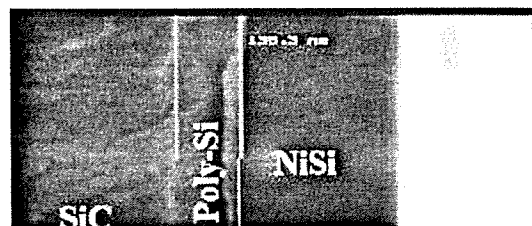


FIG. 5. TiSi_2 for 1300°C RTP anneal.

The results indicate a large amount of poly-Si reacted with the refractory metal to form TiSi_2 at elevated temperatures. Using the values in Table 1, assuming all of the poly-Si is reacted with the metal, the expected TiSi_2 thickness is 4910\AA . The anneal of 850°C resulted in a TiSi_2 thickness of 3565\AA , which is shy of the targeting thickness. This is attributed to the remaining poly-Si of 1037\AA that went unreacted. On the other hand the anneal of 1300°C resulted in a TiSi_2 thickness of 4062\AA , which is also shy of the targeting thickness, due to a smaller amount of poly-Si that did not react with the refractory metal.

In the case of nickel silicide, two more samples with similar doped poly-Si thickness and nickel thickness were processed to demonstrate and illustrate the consumption rate of poly-Si is in fact a function of annealing temperature. The annealing temperature to form NiSi_2 was altered for both samples. One sample underwent an RTP processing step of 850°C , while the other sample was processed at 950°C .



RTP temperature was raised from 1000°C to 1150 °C. In addition, an age test at 545°C for 50h showed significant improvement in specific contact resistivity and sheet resistance for both types of silicides.

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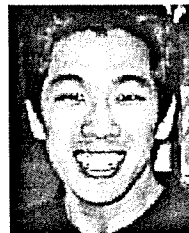
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2001.

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FIG. 6. NiSi₂ for 850°C RTP anneal.

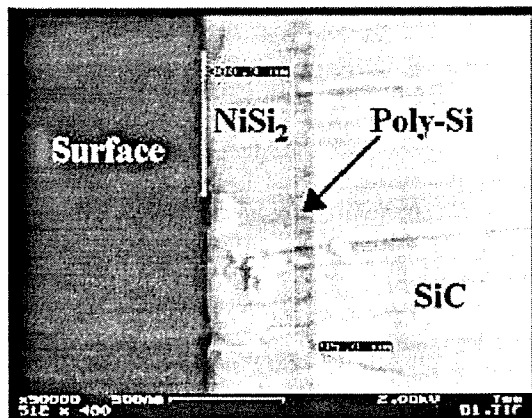


FIG. 7. NiSi₂ for 950°C RTP anneal.

The results indicate a large amount of poly-Si reacted with the refractory metal to form NiSi₂ at elevated temperatures. Using the values in Table 1, assuming all of the poly-Si is reacted with the metal, the expected NiSi₂ thickness was 3993Å. The anneal of 850°C resulted in a NiSi₂ thickness of 3457Å, which is shy of the targeting thickness. This is attributed to the remaining poly-Si of 1383Å that went unreacted. On the other hand the anneal of 950°C resulted in a NiSi₂ thickness of 3803Å, which is also shy of the targeting thickness, due to a smaller amount of poly-Si that did not react with the refractory metal.

6. Conclusions

The average poly-Si specific contact resistivity measured on $1.7 \times 10^{18} \text{ cm}^{-3}$ net doping concentration was approximately $5 \times 10^{-5} \Omega\text{-cm}^2$. As silicides were formed onto the TLM structure, the increase in specific contact resistivity can be attributed to the oxidation that must have taken place from the time the metal was sputtered, to the moment the contacts were ready for anneal. Perhaps a metal capping layer is necessary before silicidation to avoid forming a parasitic layer on the TLM structures. Despite the increase in resistance, a drop in resistance was observed when the