Low Specific Contact Resistivity Nickel to Silicon Carbide Determined Using a Two Contact Circular Test Structure

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Abstract—we present the experimentally determined specific contact resistivity of as deposited nickel to highly doped n-type 3-C silicon carbide using a novel test structure. The specific contact resistivity, extracted using this test structure and the corresponding methodology, is $(0.8-5.7) \times 10^{-6} \Omega \cdot \text{cm}^2$.

Keywords—specific contact resistivity; contact resistance; silicon carbide; circular transmission line model

I. INTRODUCTION

The compound semiconductor silicon carbide (SiC) is widely used in high voltage device applications due to its high breakdown field and high thermal conductivity. High power devices require low resistance ohmic contacts and specific contact resistivity (ρ_c [$\Omega \cdot \text{cm}^2$]) is an important parameter to quantify the electrical interface between a metal and a semiconductor. Here we report on a low value of specific contact resistivity between nickel (Ni) and highly doped n-type 3-C SiC epitaxially formed on <100> silicon substrates. Silicon carbide is difficult to etch and using a test structure that does not require a mesa structure is therefore more convenient. Using a novel test structure, the theory of which was published recently by the authors [1], we report here, the experimentally determined specific contact resistivity of as-deposited Ni to n+ 3-C SiC to be $(0.8-5.7) \times 10^{-6} \Omega \cdot \text{cm}^2$. The sheet resistance (R_{sh} , [$\Omega/\text{sq.}$]) is also determined by the novel test structure and is consistently determined to be 28.94 $\Omega/\text{sq.}$ for the SiC layer which is 293 nm thick.

A number of techniques have been used to determine the specific contact resistivity between metal and SiC [2]-[8]. One commonly used method uses the circular transmission line model (CTLTM) [9]. There is no mesa isolation required in the CTLTM, but the requirement for an equipotential on the central annular ring electrode cannot always be assumed. In this paper, a Ni ohmic contact to highly doped ($>10^{19} \text{ cm}^{-3}$) n type 3-C SiC was investigated. The novel structure used has only two electrodes and the uncertainty with regard to electrodes being at equipotentials is significantly reduced compared to the

conventional three-contact circular transmission line model. CTLM structures were formed and tested on the same samples but results could not be conclusive from the measurements obtained. The test structure reported in this paper, uses three pairs of circular metal contacts, each pair being concentric. Analytical equations and finite element models describing the Ni to SiC contact test structures are presented and the high level of agreement between these and the experimental results is discussed. The sheet resistance of the epitaxial SiC was also determined using the van der Pauw technique [10] and results were consistent with the results from the novel two-electrode structure reported.

II. THE MODEL

A. Test Pattern

The two contact circular test structure for determining ρ_c is shown in Fig. 1. Metal electrodes which are each assumed to be equipotentials (practical radii and thickness of the electrodes allow this assumption) are patterned on the epitaxial semiconductor layer. The radius of the central dot is r_0 and the inner and outer radii of the outer ring contact are r_1 and r'_1 respectively. Total resistance R_T is measured between the central dot and outer ring contact.

Fig. 1. Isotropic view of schematic of the two contact circular test structure. The radius of the central dot is r_0 and the inner and outer radii of the outer ring contact is r_1 and r'_1 respectively. Total resistance R_T is measured between the two electrodes.

Fig. 2 is a schematic which further describes the resistances shown in the model in Fig. 1. These definitions of resistances and radii are used in the analysis technique.

Fig. 2. Schematic of a section of the two-contact circular test structure. Total resistance R_T consists of R_{C0} , R_P and R_{C1} .

As shown in (1), the total resistance R_T between the two electrodes consists of the central dot contact resistance R_{C0} , the parasitic resistance from the surrounding semiconductor ring R_P and the outer ring contact resistance R_{C1} .

$$R_T = R_{C0} + R_P + R_{C1} \quad (1)$$

B. Analytical Equations

For determining ρ_c , three different two-contact circular test patterns which have different radii of the central dot r_{01} , r_{02} and r_{03} and the same inner and outer radii of the outer ring contact r_1 and r'_1 are used. After measuring the total resistance between the two electrodes of these three different two-contact circular test patterns individually, we get measurement values for the following:

$$R_{T1} = R_{C01} + R_{P1} + R_{C1} \quad (2)$$

$$R_{T2} = R_{C02} + R_{P2} + R_{C1} \quad (3)$$

$$R_{T3} = R_{C03} + R_{P3} + R_{C1} \quad (4)$$

The analytical equations for R_{C0} , R_P and R_{C1} are reported by Reeves [9]. By substituting these equations into (2)-(4), we can get

$$R_{T1} - R_{T2} = \frac{R_{sh}}{2\pi} (F + \ln x) \quad (5)$$

$$\text{where } F = \frac{I_0(\alpha r_{01})}{\alpha r_{01} I_1(\alpha r_{01})} - \frac{I_0(\alpha r_{02})}{\alpha r_{02} I_1(\alpha r_{02})} \quad (6)$$

$$x = \frac{r_{02}}{r_{01}} \quad (7)$$

$$R_{T1} - R_{T3} = \frac{R_{sh}}{2\pi} (F' + \ln y) \quad (8)$$

$$\text{where } F' = \frac{I_0(\alpha r_{01})}{\alpha r_{01} I_1(\alpha r_{01})} - \frac{I_0(\alpha r_{03})}{\alpha r_{03} I_1(\alpha r_{03})} \quad (9)$$

$$y = \frac{r_{03}}{r_{01}} \quad (10)$$

Then using (5) and (8), we can get

$$K = \frac{R_{T1} - R_{T3}}{R_{T1} - R_{T2}} = \frac{F' + \ln y}{F + \ln x} \quad (11)$$

Note that in (6) and (9), I_0 and I_1 are the zero and first order modified Bessel functions of the first kind respectively and α is the inverse of the transfer length L_t which is defined as

$$\alpha^2 = \frac{R_{sh}}{\rho_c} \quad (12)$$

With fixed x and y (in this paper, $x=1.5$ and $y=3.5$), we can plot K as a function of αr_{01} by using (6), (7), (9), (10) and (11). In Fig. 3, point A marks the location of an example data value. Using experimentally determined K , we can pick up a value of αr_{01} . Points A' and A'' in Fig. 4 correspond with point A in Fig. 3. Using the value obtained from Fig. 3 in Fig. 4, we can get either F or F' by selecting the related solid curve. Then R_{sh} can be calculated using either (5) or (8). With known R_{sh} and α , ρ_c can be found immediately using (12).

Fig. 3. Ratio K versus αr_{01} for given ratios of radii ($x=1.5$, $y=3.5$). Point A is an example data point.

Fig. 4. Factor F and F' versus ar_{01} for given ratios (γ) of radii ($x=1.5$, $y=3.5$). Point A' and A'' represent point A in Fig. 3.

C. Finite Element Modeling

The test structure and the corresponding method for determining ρ_c was modeled and analyzed using NASTRAN finite element program developed by NASA [1]. With known inputs for contact structure geometry, the conductivity of each layer in the structure and the specific contact resistivity of each interface in the structure, the electrical behavior of ohmic contacts between a metal and a semiconductor can be accurately modeled. There is excellent agreement between results from corresponding analytical equations and finite element modeling results for the proposed test structure [1].

III. EXPERIMENTAL

A number of two contact circular test patterns were prepared on a highly doped n-type 3-C SiC epitaxial wafer with a silicon substrate. The radii of the central dots vary from $r_{01}=6\mu\text{m}$, $r_{02}=9\mu\text{m}$ and $r_{03}=21\mu\text{m}$ to $r_{01}=9\mu\text{m}$, $r_{02}=13.5\mu\text{m}$ and $r_{03}=31.5\mu\text{m}$. Fig. 5 shows an optical micrograph of an example pattern fabricated with $r_{01}=6\mu\text{m}$, $r_{02}=9\mu\text{m}$ and $r_{03}=21\mu\text{m}$.

Fig. 5. Optical micrograph of a two-contact circular test structure fabricated on epitaxial SiC. The radii of the central dots from left to right are $r_{01}=6\mu\text{m}$, $r_{02}=9\mu\text{m}$ and $r_{03}=21\mu\text{m}$.

The contacts are Ni and prepared in the following way. The n-type 3-C SiC was deposited to a thickness of 293 nm on a silicon substrate. The wafers were then diced into squares

with dimensions of $10\times 10\text{ mm}^2$ and cleaned in AZ 100 solvent at 80°C for 40 minutes followed by acetone, isopropyl alcohol and deionized water and dried in nitrogen gas. A Ni film with 200 nm thickness was then deposited on the SiC layer by electron beam evaporation. AZ 1512 was then spin coated on the surface of the wafers followed by soft baking at 90°C for 90 seconds. After removing the edge bead of the photoresist, the wafers were exposed to UV light for 8 seconds and developed in 1:4 DI water: AZ 400 for 12 seconds. The Ni electrodes patterns were formed by wet etching using Ni etchant at room temperature for 30 seconds. Finally, the wafers were cleaned in acetone and blow dried using nitrogen gas.

IV. RESULTS

Measurements were taken for ten different dimensions of the test patterns described above. A probing station with $0.6\mu\text{m}$ radius tips, a multi meter and a current supply were used in the measurements. The current/voltage characteristic of each two-contact circular pattern indicates that ohmic contacts were generated between as-deposited Ni and SiC. The values of ar_{01} ranged from 1.93 to 4.35 with an average value of 3.41. The values of ρ_c were then calculated and varied from $0.83\times 10^{-6}\Omega\cdot\text{cm}^2$ to $5.67\times 10^{-6}\Omega\cdot\text{cm}^2$ with an average value of $2.41\times 10^{-6}\Omega\cdot\text{cm}^2$. R_{sh} was determined with an average value of $28.94\Omega/\text{sq.}$ and it was also determined using the van der Pauw technique and the results were consistent with the proposed novel test structure.

TABLE I. EXPERIMENTAL RESULTS FOR DETERMINING SPECIFIC CONTACT RESISTIVITY FOR AS-DEPOSITED NICKEL TO SILICON CARBIDE CONTACTS

Pattern No.	ar_{01} (no unit)	R_{sh} ($\Omega/\text{sq.}$)	ρ_c ($\Omega\cdot\text{cm}^2$)
1	3.02	28.17	2.37×10^{-6}
2	4.35	30.35	1.23×10^{-6}
3	4.22	29.37	1.26×10^{-6}
4	3.63	29.80	2.37×10^{-6}
5	2.46	28.30	3.59×10^{-6}
6	3.09	28.49	1.16×10^{-6}
7	3.72	29.25	0.83×10^{-6}
8	4.08	28.44	2.41×10^{-6}
9	1.93	27.51	5.67×10^{-6}
10	3.60	29.71	3.24×10^{-6}

V. CONCLUSION

Low specific contact resistivity for as-deposited Ni ohmic contacts to highly doped n-type 3-C SiC were obtained using a two-contact circular test structure. The specific contact resistivity ρ_c and sheet resistance R_{sh} with average values of $2.41\times 10^{-6}\Omega\cdot\text{cm}^2$ and $28.94\Omega/\text{sq.}$ were reported respectively. The analytical equations for this test structure were verified by using finite element modeling and the experiment results show that for appropriate geometries, this structure can be used to

accurately and conveniently determine ρ_c and no mesa etch and correction factor are required.

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