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USING A TWO-CONTACT CIRCULAR TEST STRUCTURE TO DETERMINE THE SPECIFIC CONTACT RESISTIVITY OF CONTACTS TO BULK SEMICONDUCTORS

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Abstract. *We present a numerical method to extract specific contact resistivity (SCR) for three-dimensional (3-D) contact structures using a two-electrode test structure. This method was developed using Finite Element Modeling (FEM). Experimental measurements were performed for contacts of 200 nm nickel (Ni) to* p^+*-type germanium (Ge) substrates and 200 nm of Titanium (Ti) on 4H-Silicon Carbide (SiC). The SCR obtained was (2.3-27)* $\times 10^{-6}$ $\Omega\cdot cm^2$ *for the Ni-Ge contacts and (1.3-2.4)* $\times 10^{-3}$ $\Omega\cdot cm^2$ *for the Ti-SiC.*

Key words: *Specific contact resistivity, test structures, ohmic contact.*

1. INTRODUCTION

Specific contact resistivity (ρ_c, [$\Omega\cdot$cm^2]) is one of the most important parameters in studying metal-semiconductor interfacial properties. This parameter is useful to determine the quality of a contact between two materials, due to specific contact resistance being geometry independent. Therefore methods of testing this parameter can be seen to be of great use to reliability simulations. In measuring the specific contact resistivity, several test structures and methods have been reported [1-6]. Among them, the transmission line model (TLM) and circular transmission line models (CTLM) are commonly used [7] due to their long standing reliability in testing methods. Analysis using the TLM and CTLM is based on a two-dimensional (2-D) model which assumes no voltage drop in the semiconductor layer in the vertical direction. However, due to the reducing size of semiconductor devices and decreased ρ_c, this vertical voltage drop in the semiconductor layer could lead to errors in derivation of specific contact resistivity using either TLM or CTLM. Furthermore, the prevalence of MEMS semiconductor devices suggests the need for a 3-D test structure for determining ρ_c of contacts to such devices. Correction factors are commonly used to increase the accuracy of derived specific contact resistivity in 3-D circumstances [8], but not in the technique used in this paper.

In this paper, we present a numerical method to extract specific contact resistivity for 3-D contact structures using a two-electrode circular test structure derived from investigation of the conventional three-electrode CTLM [9]. The method was developed using Finite

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Element Modeling (FEM) of ohmic contacts between a metal layer and a semiconductor substrate and the scaling behavior of this method was also determined and discussed in this paper. This method presents its most useful application in areas where the lateral dimensions are far greater than the vertical. Experimental measurements using the proposed test structure were performed for contacts of 200 nm Ni to p-type Ge substrates and contacts for 200 nm Ti to 4H-SiC and the specific contact resistivity was determined to be (2.3-27)×10^{-6} $\Omega\cdot\text{cm}^2$ and (1.3-2.4)×10^{-3} $\Omega\cdot\text{cm}^2$ respectively.

2. THE STRUCTURE

As defined by Berger [10], the parameter η is used to determine whether a metal and a semiconductor ohmic contact is in 3-D circumstance or not. In (1), when $\eta \leq 1$, we have a 3-D contact, otherwise it is a 2-D contact. Note that ρ_b and t are the resistivity and the thickness of the semiconductor layer respectively.

$$\eta = \frac{\rho_c}{\rho_b \cdot t} \tag{1}$$

To create a pure 3-D situation, the test structure is assumed to be fabricated on a semiconductor substrate which has a relatively large thickness to make sure $\eta \leq 1$. The test pattern for determining ρ_c in such a 3-D circumstance is shown in Fig. 1 and consists of a central dot contact and a ring contact. The radius of the central dot is r_0 and the inner and outer radii of the outer electrode are r_1 and r_2 respectively. Mesa isolation is not needed, as is the case for all CTLM type test structures.

In this paper, r_0, r_1, r_2, ρ_b and ρ_c are all the information which determine the total resistance R_T that is measured between the two electrodes. It can be written in the following form which is useful in the study of the scaling behavior of this method (discuss later).

$$R_T = R_T\{r_0, r_1, r_2, \rho_b, \rho_c\} \tag{2}$$

By measuring R_T, ρ_c can be found with the resistivity of the semiconductor layer ρ_b and the geometry sizes known.

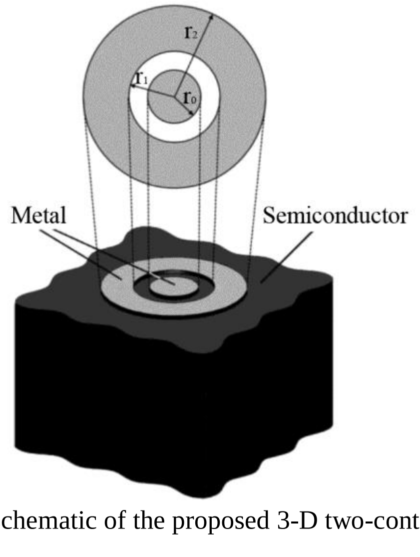

Fig. 1 Isotropic view of schematic of the proposed 3-D two-contact circular test structure.

3. THE METHOD

The analytical solutions to the current-voltage relationship of the proposed test structure were deemed to be too difficult or impossible to obtain. Therefore, we present a numerical method to determine ρ_c which is developed using Finite Element Modeling (FEM) of ohmic contacts between a metal layer and a semiconductor substrate [11].

A. Finite Element Modeling

FEM can be used to accurately model the electrical behavior of ohmic contacts between a metal and a semiconductor. Creating a model requires the following information: (*i*) test structure geometry, (*ii*) conductivity of each layer in the structure and (*iii*) specific contact resistivity ρ_c of each interface in the structure. MSC Nastran is a finite element program developed by NASA for electrical analysis while MSC Patran is used for creating models and meshing.

Fig. 2 shows a section of the FEM model used to develop solutions for the 3-D ohmic contact test structure. It consists of three layers which are metal layer on the top, bulk semiconductor on the bottom and the very thin interfacial layer between them. Only a 45° sector is modeled to reduce the time taken for analysis to run. The current is injected at

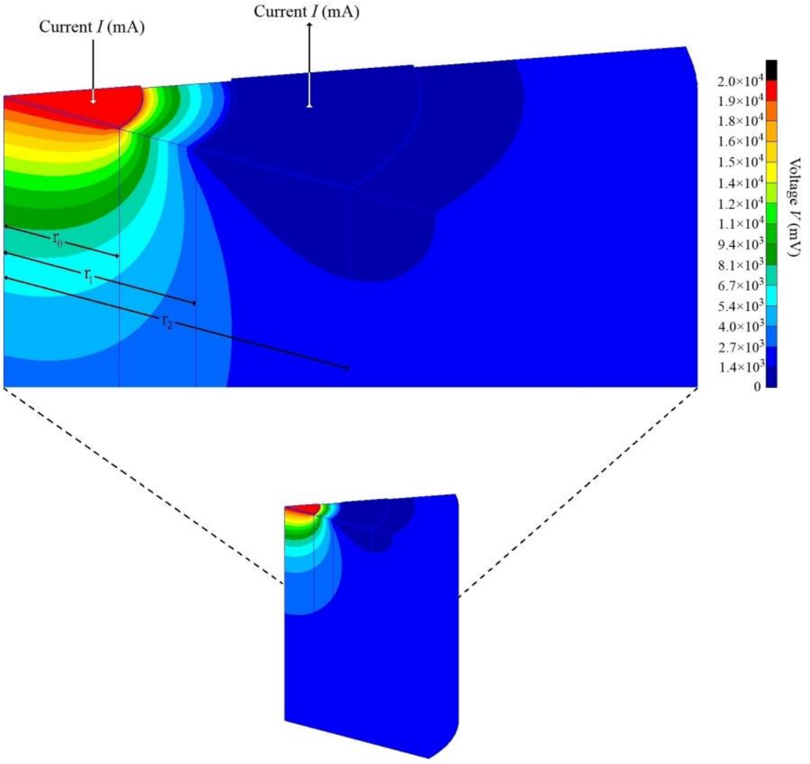

Fig. 2 Equipotentials (in millivolts) in the semiconductor layer in a 3-D situation for the finite-element modeling example where $r_0 = 3$ µm, $r_1 = 5$ µm, and $r_2 = 9$ µm. (a 45° sector of the test structure is presented).

the center electrode and the equipotential of the outer electrode is set to zero. The voltage contours in Fig. 2 shows that when the thickness of the semiconductor layer t is beyond a certain value t', little current goes through the bottom of the semiconductor substrate. What is mean by this is that when metal contacts to the substrate directly, the thickness of the semiconductor layer t can be considered as infinite beyond this t' (relatively small compare to typical substrate thickness).

A number of models are analyzed using FEM with ρ_b and ρ_c varying from 0.0001 Ω·cm to 0.001 Ω·cm and 1×10^{-9} Ω·cm^2 to 1×10^{-4} Ω·cm^2 respectively. The geometry size is fixed and the thickness of the semiconductor layer is set to be large enough to make sure the model is 3-D and little current goes through the bottom of the substrate. By doing this, we can get a constant R_T with different combinations of ρ_b and ρ_c. Plotting R_T as a function of ρ_c with variable ρ_b, we can get Fig. 3.

From Fig. 3, we can pick up the right curve with known semiconductor resistivity ρ_b and find out the value of ρ_c using the experimentally determined total resistance R_T.

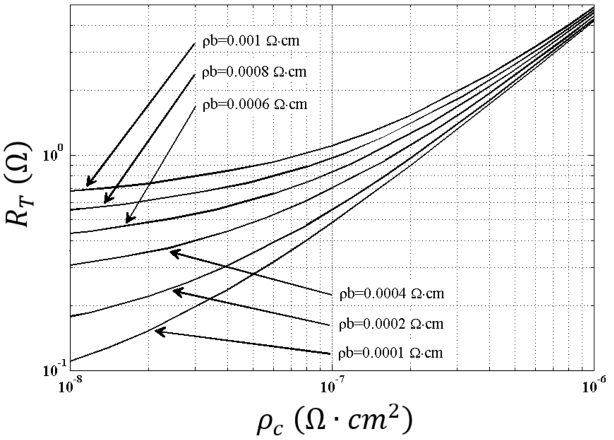

Fig. 3 FEM analysis results for total resistance R_T between the two electrodes as a function of ρ_c with ρ_b varying from 0.0001 Ω·cm - 0.001 Ω·cm. Geometry is fixed. $r_0 = 3$ μm, $r_1 = 5$ μm, and $r_2 = 9$ μm.

B. Scaling Behavior

The scaling behavior of this method is shown in (3)

$$R_T\{mr_0, mr_1, mr_2, mn\rho_b, m^2n\rho_c\} = nR_T\{r_0, r_1, r_2, \rho_b, \rho_c\} \tag{3}$$

Using (3), the plots in Fig. 3 will be the same with ρ_c, R_T and ρ_b scaled by factors of m^2n, n and mn respectively. Thus, the structure is universal and applicable for ohmic contacts where the resistive effects of the semiconductor and the contact can be described by ρ_b and the geometry of the electrodes. For example, when $m = 1$ and $n = 10$, we get Fig. 4 which has the same shape of plots in Fig. 3 but for a new set of ρ_b.

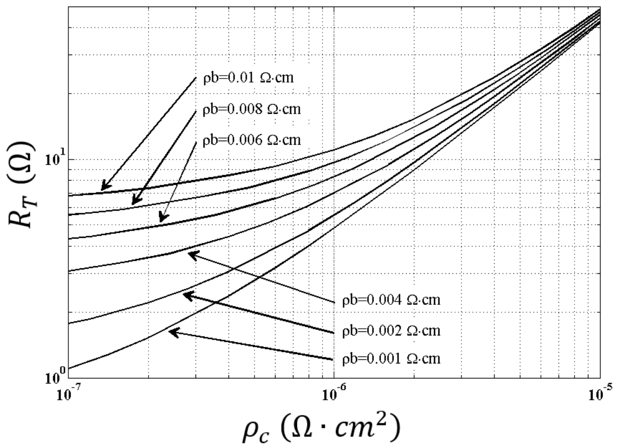

Fig. 4 FEM analysis results for total resistance R_T between the two electrodes as a function of ρ_c with ρ_b varying from 0.001 Ω·cm - 0.01 Ω·cm. Geometry is fixed. $r_0 = 3$ μm, $r_1 = 5$ μm, and $r_2 = 9$ μm. Note that this figure can be scaled using (3).

4. EXPERIMENTAL AND RESULTS

Experimental measurements using the proposed test structure were performed for contacts of 200 nm Ni to Ge substrates. A number of two-contact circular test patterns were prepared on p-type germanium substrate. The geometries vary from $r_0 = 6$ μm, $r_1 = 10$ μm and $r_2 = 18$ μm to $r_0 = 24$ μm, $r_1 = 40$ μm and $r_2 = 72$ μm. Fig. 5 shows an optical micrograph of an example pattern fabricated with $r_0 = 15$ μm, $r_1 = 25$ μm and $r_2 = 45$ μm.

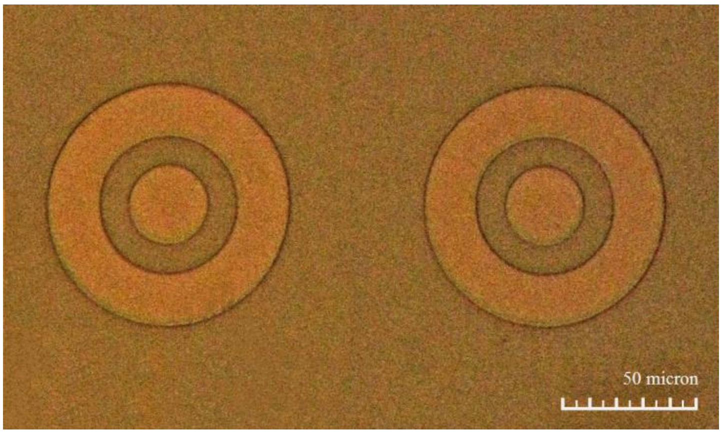

Fig. 5 Optical micrograph of a two-contact circular test structure fabricated on p-type Ge. The geometry size is $r_0 = 15$ μm, $r_1 = 25$ μm and $r_2 = 45$ μm.

The contacts are prepared in the following way. The p-type 3 inch germanium wafer with a thickness of 220 μm was diced into squares with dimensions of 1×1 cm^2 and cleaned in AZ 100 solvent at 80 ºC for 15 minutes followed by acetone, isopropal alcohol and deionized water and dried in nitrogen gas. AZ 1512 was then spin coated on the surface of the wafers followed by soft baking at 90 ºC for 90 seconds. After removing the edge bead of the photoresist, the wafers were exposed to UV light for 8 seconds, soaked in chlorobenzene for 60 seconds and developed in 1:4 DI water: AZ 400K for 25 seconds. After deposit 200 nm Ni on the Ge substrate by electron beam evaporation and soaked in acetone, the Ni electrodes patterns were formed by lift off technique using ultra sound equipment at 90º C for 30 minutes. Finally, the wafers were cleaned in deionized water and dried using nitrogen gas.

The same process was conducted in order to prepare the SiC substrates with Ti deposited to a thickness of 200 nm. In addition to the photolithographic steps as discussed the SiC samples were heat treated at 1100 ºC for 30 minutes in an Argon environment. It is known that Ti and SiC will produce a Schottky contact when deposited with no treatment applied. Therefore this extra step was taken to ensure that the Ti contacted the SiC uniformly and to create an ohmic contact.

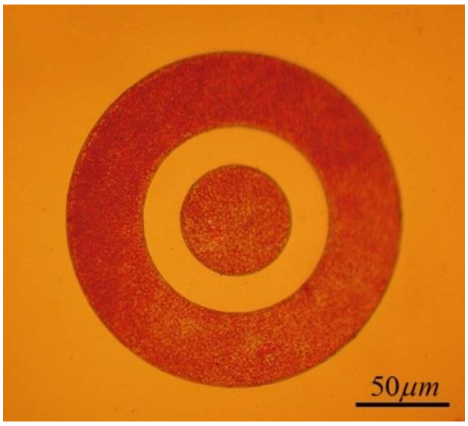

Fig. 6 Optical micrograph of a two-contact circular test structure fabricated on n-type 4H-SiC. The geometry size is: $r_0 = 30$ μm, $r_1 = 50$ μm and $r_2 = 90$ μm.

Resistivity for Ge substrate was determined before the wafer was diced using four point probe technique and it was determined to be 0.035 Ω·cm. Measurements were taken for ten different dimensions of the test patterns described above. A probing station with 0.6 μm 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 Ge. The measured total resistance R_T ranged from 4.78 Ω to 17.23 Ω with different dimensions of patterns. The values of ρ_c were then determined using Fig. 4 and (3) and varied from 2.3×10^{-6} Ω·cm^2 to 2.7×10^{-5} Ω·cm^2. This can be seen in Table 1.

Table 1 Experimental results for determining specific contact resistivity for as-deposited nickel to germanium substrate contacts

Pattern	Gem.	R_T (Ω)	ρ_c (Ω·cm^2)
1	A	15.68	3.7×10^{-6}
2	A	17.23	6.5×10^{-6}
3	A	14.77	2.3×10^{-6}
4	B	6.98	1.3×10^{-5}
5	B	6.48	1.1×10^{-5}
6	B	5.93	7.9×10^{-6}
7	B	5.54	5.3×10^{-6}
8	B	6.06	8.8×10^{-6}
9	C	4.43	2.1×10^{-5}
10	C	4.78	2.7×10^{-5}

A: $r_0 = 6$ µm, $r_1 = 10$ µm, $r_2 = 18$ µm. B: $r_0 = 15$ µm, $r_1 = 25$ µm, $r_2 = 45$ µm.
C: $r_0 = 24$ µm, $r_1 = 40$ µm, $r_2 = 72$ µm.

Table 2 Experimental results for determining specific contact resistivity for heat treated titanium to silicon carbide substrate contacts

Pattern	Gem.	R_T (Ω)	ρ_c (Ω·cm^2)
1	C	140	2.4×10^{-3}
2	C	125	1.8×10^{-3}
3	C	129	1.9×10^{-3}
4	C	137	2.1×10^{-3}
5	C	150	2.4×10^{-3}
6	D	70	1.5×10^{-3}
7	D	63	1.3×10^{-3}
8	D	96	2.1×10^{-3}
9	D	103	2.4×10^{-3}
10	D	98	2.1×10^{-3}

C: $r_0 = 24$ µm, $r_1 = 40$ µm, $r_2 = 72$ µm. D: $r_0 = 30$ µm, $r_1 = 50$ µm, $r_2 = 90$ µm.

Similarly to the Ge substrate, the SiC samples had the sheet resistance measured before fabrication using the four-point probe method. From this measurement the sheet resistance was determined to be 0.01 Ω cm. Using ten different patterns of two differing sizes, measurements were taken as per the described method. The resistance measurements taken from the patterns ranged between 70 Ω to 150 Ω as the patterns became smaller in size. With these measurements taken from the SiC samples, ρ_c was determined to be between 1.3×10^{-3} Ω·cm^2 and 2.4×10^{-3} Ω·cm^2. The full results can be viewed in Table 2.

5. CONCLUSION

A numerical method for determining specific contact resistivity between a metal and a semiconductor ohmic contact in 3-D circumstance using a two-contact circular test structure was presented. It was developed using Finite Element Modeling program. Specific contact resistivity for as-deposited Ni contacts to p-type Ge substrates were obtained by using the proposed test structure and it was determined to be (2.3-27) × 10^{-6} $\Omega\cdot cm^2$ using presented method. In addition the process was conducted a second time on heat treated Ti contacts on SiC to provide a second independent set of results. The specific contact resistivity was determined to be (1.3-2.4) ×10^{-3} $\Omega\cdot cm^2$. The results show that with known semiconductor substrate resistivity ρ_b and a fixed geometry, using a scaling equation, ρ_c can be determined conveniently by picking up data points from the reported figures.

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