Thermal Variation of Specific Contact Resistance

A thesis submitted for the degree of

Doctor of Philosophy

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“For those who have supported this work”
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Aaron M. Collins

August 2015
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Abstract

Test structures for the determination of specific contact resistance are an area of continual research and improvement. It is always important to achieve reliable and accurate results in the extraction of any parameter. Several test structures achieve these conditions, of reliability and accuracy, including the Transmission Line Model, the Circular Transmission Line Model and the newer Single Dot test structure. This work seeks to improve the techniques used to extract specific contact resistance with a focus on the Circular Transmission Model and its equations. As such, the mathematical solutions to the Circular Transmission Line model have been reduced such that they are simpler and therefore faster to solve with no loss of accuracy.

3C-SiC is used as a semiconductor example in developing the work presented. 3C-SiC is not easily etched and is a good example of a semiconductor where circular transmission line model test structures are appropriate. Results presented in this report demonstrated how the improved analysis process increases the accuracy of measurements for determining specific contact resistance.

The effects of temperature on specific contact resistance are discussed and analytical models developed. Since the pioneering research in this area and the extensive reports that were produced in the 1960s and 1970s, there has been relatively little work reported on investigating and testing of specific contact resistance with regard to changes in temperature. In this thesis similar experimental work is reported but with a unified analytical model for specific contact resistance due to different electron transport mechanisms.

This work proposes a solution to determining specific contact resistance at all temperature ranges and doping concentrations with the use of one equation, therefore simplifying the process and $\rho_c$ determination. In addition the proposal is made that when reporting specific contact resistance it should include the temperature that it has been determined at, such that a more complete understanding can be obtained of the parameter.
List of Figures

Figure 1.1  Band diagrams for metal-semiconductor junctions at different levels of doping. (a) shows a lightly doped semiconductor exhibiting thermionic emission. (b) shows a moderately doped semiconductor with thermionic-field mission. Finally (c) shows a highly doped semiconductor that is exhibiting field emission.

Figure 2.1  Schematic of contact region in the TLM with its transmission line resistor network model.

Figure 2.2  Planar view of the TLM structure with dimensions labelled.

Figure 2.3  Resistor network model of the CTLM showing the radius, \( x \), of a contact

Figure 2.4  Planar view of the Circular Transmission Line Model with all geometry parameters labelled.

Figure 2.5  Schematic diagram depicting the resistance between contacts and the contributions of each resistance in the CTLM test structure. Here it is \( R_{c0}, R'_{c1}, R_{c1} \) and \( R_{c2} \) that are the specific contact resistances between metal and semiconductor. Also \( R_A \) and \( R_B \) are the resistances contributed by the sheet resistance of the semiconductor and are defined as the parasitic resistances.

Figure 2.6  Plot of \( \phi \) vs \( \alpha r_0 \) for a CTLM test pattern where \( r_0 = 20\mu m \), \( r'_1 = 40\mu m \), \( r_1 = 60\mu m \), \( r'_2 = 80\mu m \) and \( r_2 = 100\mu m \). Here, \( R_1 = 300\Omega \), \( R_2 = 110\Omega \) and \( R_E = 1\Omega \). These are theoretical values that correspond with \( R_{SH} = 100\Omega/cm^2 \) and \( \alpha r_0 = 5 \). The red line represents equation 2.27 while the blue curve is equation 2.28.

Figure 2.7  Plot of \( \Delta \) vs \( \alpha r_0 \) for a CTLM test pattern where \( r_0 = 20\mu m \), \( r'_1 = 40\mu m \), \( r_1 = 60\mu m \), \( r'_2 = 80\mu m \) and \( r_2 = 100\mu m \). Here, \( R_1 = \)
300Ω, \( R_2 = 110Ω \) and \( R_E = 1Ω \). These are theoretical values that correspond with \( R_{SH} = 100Ω/□ \) and \( \alpha r_0 = 5 \).

**Figure 2.8** Plot of \( \rho_c \) vs \( \alpha r_0 \) for a CTLM test pattern where \( r_0 = 20\mu m, r'_1 = 40\mu m, r_1 = 60\mu m, r'_2 = 80\mu m \) and \( r_2 = 100\mu m \). Here, \( R_1 = 300Ω, R_2 = 110Ω \) and \( R_E = 1Ω \). These are theoretical values that correspond with \( R_{SH} = 100Ω/□ \) and \( \alpha r_0 = 5 \).

**Figure 2.9** Planar view of Single Dot Test Structure showing geometries and Isometric view of Single Dot Test Structure showing the probes used to measure \( R_{T1}, R_{T2} \) and \( R_{T3} \).

**Figure 2.10** Schematic diagram of the Single Dot Test Structure showing resistance components between the metal and semiconductor labelled as \( R_{c0} \) and \( R_{c1} \) which are the specific contact resistances at the edge of the contacts. The resistance contributed by the sheet resistance of the semiconductor is labelled as \( R_p \) which is defined as the parasitic resistance between contacts.

**Figure 2.11** Plot of \( \alpha r_0 \) vs \( K \) for the determination of specific contact resistance with the single dot test structure. By evaluating the ratio of \( K \) it is possible to determine a unique value for \( \alpha r_0 \). Here, \( A \) relates a particular value for \( K \) which is derived from equation 2.43 to a unique value of \( \alpha r_0 \).

**Figure 2.12** Plot of \( \alpha r_0 \) vs \( F \) and \( F' \) for the determination of specific contact resistance with the single dot test structure. By evaluating the ratios of \( F \) and \( F' \) it is possible to determine a unique value for \( \alpha r_0 \). Here \( A' \) and \( A'' \) relate specific values of \( F' \) and \( F \) which are determined from equations 2.39 and 2.41 to \( \alpha r_0 \) respectively.

**Figure 3.1** Isometric view of the CTLM pattern with contact geometry listed

**Figure 3.2** Schematic depicting measurement of \( R_E \) with current being pushed between the annular ring and centre dot contacts.
Figure 3.3  Plot of Current vs Voltage for the determination of $R_E$. Here the sheet resistance is listed and the specific contact resistance is a theoretical value of $1 \times 10^{-6} \Omega cm^2$. Geometry is $r'_1 = 2 \mu m$ and $r_1 = 4 \mu m$. $R_E$ is given when $I = 0$ as defined in equations 3.6 and 3.7.

Figure 3.4  Plot of Current vs Voltage for the determination of $R_E$. Here the sheet resistance is listed and the specific contact resistance is a theoretical value of $1 \times 10^{-7} \Omega cm^2$. Geometry is $r'_1 = 2 \mu m$ and $r_1 = 4 \mu m$. $R_E$ is given when $I = 0$ as defined in equations 3.6 and 3.7.

Figure 3.5  Plot of Current vs Voltage for the determination of $R_E$. Here the sheet resistance is listed and the specific contact resistance is a theoretical value of $1 \times 10^{-8} \Omega cm^2$. Geometry is $r'_1 = 2 \mu m$ and $r_1 = 4 \mu m$. $R_E$ is given when $I = 0$ as defined in equations 3.6 and 3.7.

Figure 3.6  Figure displaying $R_E$ vs $\alpha$ for different values of $R_{SH}$ derived from equation 3.10. The geometry is where $r_0 = 20 \mu m$, $r'_1 = 40 \mu m$, $r_1 = 60 \mu m$, $r'_2 = 80 \mu m$ and $r_2 = 100 \mu m$. By knowing the value of $R_E$ and $R_{SH}$, $\alpha r_0$ can be either calculated using equation (3.8) or drawn directly here for an approximation.

Figure 3.7  Figure displaying $\rho_c$ vs $\alpha$ for different values of $R_{SH}$ derived from equation 3.11. The geometry where $r_0 = 20 \mu m$, $r'_1 = 40 \mu m$, $r_1 = 60 \mu m$, $r'_2 = 80 \mu m$ and $r_2 = 100 \mu m$. By knowing the value of $\alpha$ and $R_{SH}$ then $\rho_c$ can be either calculated using equation (3.9) or drawn directly here for an approximation.

Figure 3.8  FEM modelling showing a CTLM pattern with geometries of $r_0 = 15 \mu m$, $r'_1 = 37.5 \mu m$, $r_1 = 56.25 \mu m$, $r'_2 = 93.75 \mu m$ and $r_2 = 130 \mu m$ with $235.6 mA$ of current being pushed from the central dot to the annular ring and voltage contours shown. Figure shows a model with an $R_{SH}$ of 30 $\Omega/\square$ and $\rho_c$ of $1 \times 10^{-5} \Omega cm^2$. Using this model it is possible to
determine the value of $R_E$ by measuring the voltage between the annular and outer ring contacts.

**Figure 3.9** FEM modelling showing a CTLM pattern with geometries of $r_0 = 15\mu m$, $r'_1 = 37.5\mu m$, $r_1 = 56.25\mu m$, $r'_2 = 93.75\mu m$ and $r_2 = 130\mu m$ with 235.6mA of current being pushed from the central dot to the annular ring and voltage contours shown. Left Figure shows a model with an $R_{SH}$ of $30 \Omega/\square$ and $\rho_C$ of $1 \times 10^{-6} \Omega \text{ cm}^2$ while the right Figure shows $R_{SH}$ of $30 \Omega/\square$ and $\rho_C$ of $1 \times 10^{-7} \Omega \text{ cm}^2$. It can be seen that the voltage contours under the edge of the contacts are altered by $\rho_C$.

**Figure 3.10** Equipotential contours within a CTLM using only one probe to draw current from the annular ring. Shaded areas are the metal contacts. Dimensions of the CTLM shown here are $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. Scale ranges from 0 to 9mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from one probe.

**Figure 3.11** Schematic diagram detailing position of probes used to push and draw current from the CTLM. Here the current is being pushed into the central dot and drawn from the annular ring. Only one probe is used to draw the current from the annular ring.

**Figure 3.12** Equipotential contours within a CTLM using only one probe to push current into the central dot and two shorted probes to create an equipotential on the annular ring. Dimensions of the CTLM shown here are $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. Scale ranges from 0 to 5mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from two probes.

**Figure 3.13** Schematic diagram detailing position of probes used to push and draw current from the CTLM. Here the current is being pushed into the central
dot and drawn from the annular ring. Two probes are used to draw the current from the annular ring and are placed at the maximum distance from each other.

**Figure 3.14** Equipotential contours within a CTLM using one probe to push current into the central dot and three shorted probes to help create an equipotential on the annular ring. Dimensions of the CTLM shown here are \( r_0 = 20\mu m, r'_1 = 40\mu m, r_1 = 60\mu m, r'_2 = 80\mu m \) and \( r_2 = 100\mu m \). Scale ranges from 0 to 5mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from three probes.

**Figure 3.15** Equipotential contours within a CTLM using one probe to push current into the central dot and four shorted probes to help create an equipotential on the annular ring. Dimensions of the CTLM shown here are \( r_0 = 20\mu m, r'_1 = 40\mu m, r_1 = 60\mu m, r'_2 = 80\mu m \) and \( r_2 = 100\mu m \). Scale ranges from 0 to 5mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from four probes.

**Figure 3.16** Figure representing the change seen in pc versus the change in \( R_E \) over the range of 1Ω to 10Ω. Different values of \( \alpha r_0 \) are represented showing that as \( \alpha r_0 \) increases then the difference in pc begins to rapidly increase with smaller variation of \( R_E \). CTLM pattern geometry values are \( r_0 = 20\mu m, r'_1 = 40\mu m, r_1 = 60\mu m, r'_2 = 80\mu m \) and \( r_2 = 100\mu m \).

**Figure 4.1** Plot of \( \rho_c \) vs Temperature for thermionic emission with energy barriers \( (\phi_B) \) as stated. Here, \( A^* \) is equal to 194.1\((m^*/m) A/cm^2K^2\). Plots derived from equation (4.1)

**Figure 4.2** Plot of \( \rho_c \) vs Energy Barrier \( (\phi_B) \) for thermionic emission with Temperature (K) as stated. Here, \( A^* \) is equal to 194.1\((m^*/m) A/cm^2K^2\). Plots derived from equation (4.1)
Figure 4.3  Plot of $\rho_c$ vs Doping Concentration with Barrier Heights as stated. Temperature used is 300K. $A^*$ is 194.1 and $m^*$ is 0.25$m_0$. Figure plotted with Equation 4.2.

Figure 4.4  Theoretical values of $E_{00}$, $E_{00}$ and $kT$ for SiC plotted over doping concentration. Temperature used is 300K.

Figure 4.5  Theoretical values of $E_0$, $E_{00}$ and $kT$ for SiC plotted over doping concentration. Here it can be seen from equation (4.3) that $E_{00}$ has no dependence on temperature whereas $kT$ will change with temperature and not doping. $E_0$ therefore will be dependent on both doping and temperature relative to the ratio of $kT/E_{00}$.

Figure 4.6  Theoretical values of $\rho_c$ versus Temperature for SiC. $A^*$ is 194.1($m^*/m$) A/cm$^2$K$^2$ and $m^*$ is 0.25$m_0$. Doping levels are as stated. Figure derived from equation (4.4). For this equation $cFE$ was chosen for $c$ because $kT/E_{00} > 1$.

Figure 5.1  Mask design used in the process of wet etching for the fabrication of metal contacts for the Single Dot test structure onto semiconductor samples. The black regions are the chromium on the mask and the white regions are the quartz glass which is transparent. Numbers on the mask is the radius of $r_{01}$. Three enlarged test structures are shown at the bottom of the figure.

Figure 5.2  Mask design used in the process of lift off for the fabrication of metal contacts for the Single Dot test structure onto semiconductor samples. The black regions are the chromium on the mask and the white regions are the quartz glass which is transparent. Numbers on the mask is the radius of $r_{01}$, see figure 2.7. Three enlarged test structures are shown at the bottom of the figure.

Figure 5.3  Simplified procedure for (a) wet etching using a positive photoresist and (b) lift off etching using a positive photoresist.
Figure 5.4 Optical micrograph of the two-contact circular test structures fabricated on epitaxial 3C-SiC using wet etching technique, the metal layer is Ni and the radii of the central electrodes shown are 10 µm, 15 µm and 35 µm respectively.

Figure 5.5 Optical micrograph of the two-contact circular test structures fabricated on epitaxial 3C-SiC using the wet etching technique, the metal layer is Ti and the radii of the central electrodes shown are 9 µm, 13.5 µm and 31.5 µm respectively.

Figure 5.6 TRIM simulation of P and C ion concentrations after implantation into SiC at 5 keV at a dose of $1 \times 10^{15}$ ions/cm$^2$.

Figure 5.7 TRIM simulation of P and C distribution of energy deposition after implantation into SiC at 5 keV at a dose of $1 \times 10^{15}$ ions/cm$^2$.

Figure 5.8 Optical micrograph of the two-contact circular test structures fabricated on epitaxial 3C-SiC using the lift off technique, the metal layer is Au/Ni/Ti and the radii of the central electrodes shown are 14 µm, 21 µm and 49 µm respectively.

Figure 6.1 Top - Test pattern schematic of dot and ring used to determine specific contact resistance. Various gap sizes as detailed in Table 1 were used for testing. Bottom – Photograph of fabricated samples on 3C SiC

Figure 6.2 Equipment setup for the two-contact circular test structure to determine the total resistance between the two electrodes.

Figure 6.3 Specific contact resistances vs. temperature at measured values with expected analytical curves for the 3C SiC sample with low doping and Ti contacts. Shown here is a theoretical curve for a $q\phi_B$ value of 0.42eV and a doping concentration of less than $1 \times 10^{16} cm^{-2}$. Theoretical curve has been plotted with Equation 4.4 using thermionic emission.
**Figure 6.4** Specific Contact resistances vs. temperature at measured values with expected analytical curves for the 3C SiC sample with low doping and Ti contacts. Shown here is a theoretical curve for a $q\phi_B$ value of 0.72eV and a doping concentration of $1 \times 10^{20} cm^{-3}$. Theoretical curve has been plotted with Equation 4.4 using field emission.

**Figure 6.5** Specific Contact resistance vs. temperature at measured values with expected analytical curve for the sample implanted with Phosphorus with a $q\phi_B$ value shown of 0.28eV and a doping concentration of $1 \times 10^{19} cm^2$. Theoretical curve has been plotted with Equation 4.4 using field emission.

**Figure 6.6** Specific Contact resistance vs. temperature at measured values with expected analytical curve for the sample implanted with Carbon with a $q\phi_B$ value shown of 0.3eV and a doping concentration of less than $1 \times 10^{16} cm^2$. Theoretical curve have been plotted with Equation 4.4 using thermal emission.
List of Tables

Table 3.1  FEM results taken from CTLM pattern of geometry $r_0 = 15\mu m$, $r'_1 = 37.5\mu m$, $r_1 = 56.25\mu m$, $r'_2 = 93.75\mu m$ and $r_2 = 130\mu m$. $R_{SH}$ and $\rho_C$ were set and voltage contours simulated with a current of 235.6ma between the central dot and annular ring contacts. Voltage measurements have been taken from annular ring to outer ring contact. With geometry and $R_{SH}$ given and $R_E$ calculated, $\rho_C$ has been determined from equations 3.11 and 3.12.

Table 3.2  Calculated values of $R_E$ compared to simulated values of $R_E$. With the use of FEM analysis. Geometry used was $r_0 = 15\mu m$, $r'_1 = 37.5\mu m$, $r_1 = 56.25\mu m$, $r'_2 = 93.75\mu m$ and $r_2 = 130\mu m$ with 235.6ma of current being pushed from the central dot to the annular ring. Calculated values of $R_E$ were determined from equation 3.10.

Table 3.3  Ratio of adjacent contact radii to ensure that $R_A < R_{c0} + R'_{c1}$ and $R_B < R_{c1} + R'_{c2}$. The ratio will change with variations in $\alpha r_0$.

Table 3.4  FEM results showing voltage differences around the annular ring contact for an input current of 1ma and using one probe on the annular ring. The difference in voltage is determined from the maximum and minimum voltages measured on the annular ring.

Table 3.5  Voltage difference measured on annular ring versus the number of shorted probes used to maintain an equipotential for the structures shown in Figures 3.11, 3.13, 3.15 and 3.16. An input current of 1ma pushed into the central dot was used in all cases. Total voltage from central dot to ring was 5mv. Dimensions of the annular ring detailed here are $r'_1 = 40\mu m$ and $r_1 = 60\mu m$.

Table 5.1  Electron beam evaporator conditions used for depositing Ni on 3C-SiC.
**Table 5.2**  Electron beam evaporator conditions for Ti on 3C-SiC.

**Table 5.3**  Electron beam evaporator conditions for Ti/Ni/Au on 3C-SiC.

**Table 6.1**  Geometry of the single dot test structure used in experimentally determined specific contact resistance for all sample types.

**Table 6.2**  Experimental results for $\rho_C$ Using the two-contact circular test structure for as-deposited Ti to 3C-SiC. The Ti layer and the 3C-SiC layer have thicknesses of 400 nm and 1.1 µm respectively. The 3C-SiC layer was lightly doped.

**Table 6.3**  Experimental results for $\rho_C$ Using the two-contact circular test structure for as-deposited Ni to epitaxial 3C-SiC. The Ni layer and the 3C-SiC layer have thicknesses of 200 nm and 1.1 µm respectively. The 3C-SiC layer was very heavily doped with an N type doping concentration of $1 \times 10^{20}$ cm$^{-3}$.

**Table 6.4**  Experimental results for $\rho_C$ Using the two-contact circular test structure for as-deposited Ni/Ti/Au contacts to 3C-SiC that has been ion implanted with Phosphorous. The Au, Ni and Ti layers have the same thickness of 50 µm and the 3C-SiC layer and Si substrate have thicknesses of 1.1 µm and 300 µm respectively. The 3C-SiC layer was implanted with phosphorous as detailed in chapter 5.

**Table 6.5**  Experimental results for $\rho_C$ Using the two-contact circular test structure for as-deposited Ni/Ti/Au contacts to 3C-SiC that has been ion implanted with Carbon. The Au, Ni and Ti layers have the same thickness of 50 µm and the 3C-SiC layer and Si substrate have thicknesses of 1.1 µm and 300 µm respectively. The 3C-SiC layer was implanted with carbon as detailed in chapter 5.
Nomenclature

Roman

\( A^* \)  Effective Richardson’s Constant.
\( d \)  The distance between each two contact in the transmission line model (in micrometers).
\( F \)  Factor used to extract \( \rho_c \) in the two-contact circular test structure (no unit).
\( F' \)  Factor used to extract \( \rho_c \) in the two-contact circular test structure (no unit).
\( \hbar \)  The modified Planck constant.
\( I \)  Current through the contacts (in milliamperes)
\( J \)  Current density (in milliamperes per square micrometers)
\( k \)  The Boltzmann constant.
\( K \)  Ratio of \( RT_1 \) - \( RT_3 \) and \( RT_1 \) - \( RT_2 \) in the two-contact circular test structure (no unit).
\( L \)  Contact length in the transmission line model (in micrometers).
\( m^* \)  Effective mass of tunnelling electron (in kilogrammes).
\( N \)  Doping concentration (in cm\(^{-3}\)).
\( q \)  Electrical charge (in coulomb).
\( T \)  Temperature (in Kelvin degrees).
\( V \) Measured voltage drop between two electrodes (in millivolts).

\( W \) Contact width in the transmission line model (in micrometers).

\( W' \) The width of the diffusion area in the transmission line model (in micrometers).

**Greek symbols**

\( \alpha \) Attenuation constant, the inverse of the transfer length (\( L_T \)) in transmission line models (per micrometer).

\( \Delta \) Factor used to extract \( \rho_c \) when using the circular transmission line model (no unit).

\( \phi \) Factor used to extract \( \rho_c \) when using the circular transmission line model (no unit).

**Other symbols**

\( E_0 \) Reference Energy related to electron transport (in keV).

\( E_{00} \) Reference energy related to the probability of tunnelling (in keV).

\( \varepsilon_s \) Semiconductor permittivity (no unit).

\( I_0 \) Zeroth order modified Bessel function of the first kind.

\( I_1 \) First order modified Bessel function of the first kind.

\( K_0 \) Zeroth order modified Bessel function of the second kind.

\( K_1 \) First order modified Bessel function of the second kind.
$L_T$ Transfer length (in micrometers).

$\phi_B$ Potential barrier (in eV).

$\rho_c$ Specific contact resistivity (in ohms square centimeter).

$r_0$ Radius of the central dot electrode in both the two-contact circular test structure and the circular transmission line model (in micrometers).

$R_1$ Measured resistance between the left two contacts in Figure 2.2 (in ohms); Measured resistance between the inner two contacts in the circular transmission line model (in ohms).

$r_1$ Inner radius of the middle ring contact in the circular transmission line model (in micrometers); Inner radius of the outer contact in the two contact circular test structure (in micrometers).

$r'_1$ Outer radius of the middle ring contact in the circular transmission line model (in micrometers); Outer radius of the outer contact in the two contact circular test structure (in micrometers).

$R_2$ Measured resistance between the right two contacts in Figure 2.2 (in ohms); Measured resistance between the outer two contacts in the circular transmission line model (in ohms).

$r_2$ The inner radius of the outer ring contact in the circular transmission line model (in micrometers).

$r'_2$ The outer radius of the outer ring contact in the circular transmission line model (in micrometers).

$R_A$ The bulk semiconductor resistance between the inner two contacts in the circular transmission line model (in ohms)

$R_B$ The bulk semiconductor resistance between the outer two contacts in the circular transmission line model (in ohms)

$R_C$ Contact resistance (in ohms).
\( R_{C0} \) Central dot contact resistance in both the two-contact circular test structure and the circular transmission line model (in ohms).

\( R_{C1} \) Middle ring contact resistance when current is forced between the middle ring contact and the outer ring contact in the circular transmission line model (in ohms); Outer electrode contact resistance in the Single Dot circular test structure (in ohms).

\( R'_{C1} \) Middle ring contact resistance when current is forced between the central dot contact and the middle ring contact in the circular transmission line model (in ohms).

\( R_{C2} \) Outer ring contact resistance in the circular transmission line model in (in ohms).

\( R_E \) Contact end resistance (in ohms).

\( R_{SH} \) Sheet resistance (in ohms per square).

\( R_{SK} \) Sheet resistance beneath the contact (in ohms per square).

\( R_T \) Measured total resistance between two electrodes (in ohms).

\( u_F \) Fermi energy with respect to the energy band edge.

\( V_{bo} \) Built-in potential (in millivolts).

### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CTLM</td>
<td>Circular Transmission Line Model</td>
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<tr>
<td>FE</td>
<td>Field Emission</td>
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<tr>
<td>FEM</td>
<td>Finite Element Modelling</td>
</tr>
<tr>
<td>HMDS</td>
<td>Hexamethyldisilazane</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>---------</td>
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<tr>
<td>IPA</td>
<td>Isopropyl Alcohol</td>
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<tr>
<td>SCR</td>
<td>Specific Contact Resistance</td>
</tr>
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<td>TE</td>
<td>Thermionic Emission</td>
</tr>
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<td>Thermionic Field Emission</td>
</tr>
<tr>
<td>TLM</td>
<td>Transmission Line Model</td>
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<td>TRIM</td>
<td>Transport and Range of Ions in Matter</td>
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Chapter 1

Introduction

1.1 Ohmic Contacts

Metal to semiconductor contacts can be broadly placed into two groups that are referred to as Ohmic (non-rectifying) or Schottky (rectifying) contacts [Sze, 1981]. Semiconductors that have a low doping concentration tend to exhibit Schottky contacts and are commonly used as diodes. These contacts have an electron transport mechanism known as Thermal Emission (TE). This type of electron transport requires that electrons gain enough energy to pass over the energy barrier caused by Fermi level differences in order to pass from the metal into the semiconductor.

On the other hand, semiconductors that have a high doping concentration are more likely to form Ohmic contacts. These contacts exhibit electron transport known as Field Emission (FE) which occurs when the energy barrier becomes thin enough that electrons may ‘tunnel’ through the energy barrier in order to pass through to the semiconductor [Streetman and Banerjee, 2000] or from the semiconductor to the metal.
Figure 1.1 Band diagrams for metal-semiconductor junctions at different levels of doping. (a) shows a lightly doped semiconductor exhibiting thermionic emission. (b) shows a moderately doped semiconductor with thermionic-field mission. Finally (c) shows a highly doped semiconductor that is exhibiting field emission. (adapted from [Yu, 1970]).

Figure 1.1 (a) is for a lightly doped semiconductor and its energy band diagram. It indicates that an electron must pass over the energy barrier in order to flow from one material into the other. At any given barrier height, this process (thermal emission) occurs only for electrons that have enough thermal energy to pass over the barrier [Yu, 1970]. Figure 1.1 (c) shows a highly doped semiconductor and how an electron will
tunnel through the barrier due to its relative narrow width. This indicates Field Emission, as occurs in an ohmic contact. Tunnelling occurs due to the electron being considered as a plane wave that meets an energy barrier higher than the electrons energy. Solutions to Schrodinger’s equation for the step energy barrier of a metal semiconductor contact, gives the probability of transmission at the bottom of the barrier (i.e. without the electron in the semiconductor increasing its energy level above the conduction band minimum). Figure 1.1 (b) shows the case of a metal-semiconductor junction undergoing thermionic field emission when the semiconductor is only moderately doped. Here an electron is thermally excited to an energy level (where the barrier is sufficiently thin) and it may tunnel through the energy barrier.

An ideal metal-semiconductor Ohmic junction is where the Current-Voltage curve is linear through the origin and useful currents (for devices) are an extension (linear over large voltage range) of this curve [Sze 1981]. Note that both Ohmic and Schottky contacts will have a liner current-voltage (I-V) relationship close to the origin. For practical ohmic contacts it is important for there to be little to no contact resistance such that this relationship is observed, however realistic contacts will have a measureable resistance.

1.2 Specific Contact Resistance

Specific Contact Resistance (SCR) ($\Omega \cdot cm^2$) is an important parameter in the operation of metal-semiconductor contacts. It relates to the resistance of the metal to semiconductor junction and is defined as the derivative of voltage with respect to current density when V=0 [Chang et al., 1971]. A good ohmic contact should have a low value of specific contact resistance to ensure that a linear I-V relationship is observed for useful values of current density.
\[ \rho_c = \left( \frac{dV}{df} \right)_{V=0} \quad (1.1) \]

As is evident from equation (1.1) the derivative should be evaluated where \( V=0 \). This derivative is possible to obtain for ideal ohmic contacts but more difficult for Schottky contacts. The equation can be applied to both types of contacts as it considers only the differential at a point. For Schottky contacts a very small current about the origin would be required and this is difficult to realise experimentally. The author suggests that the second differential (or curvature) is also worth considering as a measure of the ohmic or Schottky behaviour of the contact but this is not the focus of this thesis.

### 1.3 Temperature Variation of Specific Contact Resistance

Specific contact resistance has been known to vary with temperature since [Padovani and Stratton, 1966]. [Chang et al., 1971] derived equations to describe the transport of electrons over or through an energy barrier with a dependence on temperature. When dealing with the temperature variation of specific contact resistance it is possible that the transport mechanism determining specific contact resistance may change between thermionic emission, thermionic-field emission and field emission.

Since the paper by [Chang et al.1971] was published there have been a few research groups who have presented similar numerical solutions when investigating the effects of temperature on specific contact resistance, attempting to simplify the transport equations into a simpler theory. [Varahramyan and Verret, 1996] have presented similar equations to [Chang et al., 1971] to accomplish this and its final form is described as follows

\[ \rho_c = \frac{k}{qA^*T} \bar{e}^{\frac{a\phi_B}{e_0}} \quad (1.2) \]
where \( k \) is Boltzmann’s constant, \( q \) is the charge on an electron, \( A^* \) is the effective Richardson’s constant and \( \phi_B \) is the barrier height between the metal and semiconductor. This equation and its derivations and solutions are discussed in detail during Chapter 4.

1.4 Thesis Outline

This thesis discusses ohmic contacts and test structures to investigate the parameter of specific contact resistance of metal-semiconductor junctions. Following this will be an investigation of established models for use in specific contact resistance measurement and improvements in the design and calculation of the structure. Lastly, it will discuss the effect that temperature has on specific contact resistance and how it is calculated. These models will be used to investigate the variation of specific contact resistance of metal contacts to Silicon Carbide using contacts of titanium, nickel and titanium/nickel/gold.

Chapter 2 will discuss and compare relevant established models used in the determination of specific contact resistance and how to derive a solution. Advantages and disadvantages of each model will be discussed.

Chapter 3 will take one of the established models and present a series of rules and recommendations in order to simplify the model. Analytical expressions are presented with solutions and instructions on accurate measurement. Possible sources of error have been identified and recommendations are made to reduce these errors.
Chapter 4 discusses the transport of electrons across a metal-semiconductor barrier and how this varies with temperature. These transport equations are used to determine the specific contact resistance of particular combinations of metal and semiconductor. Solutions to analytical expressions are derived with respect to Silicon Carbide (3C-SiC) and the theoretically expected values are given.

Chapter 5 details the design and fabrication of test structures used to determine specific contact resistance. A number of different metals were used to produce test structures on 3C-SiC.

Chapter 6 presents the results of electrical testing and comparison to theoretical data. The electrical testing is detailed and was performed on the contact test structures developed in Chapter 5. Comparison with the theoretical results calculated in Chapter 4 is performed and discussed.

Chapter 7 discusses the results in a broader research context and recommends areas of further research.

Appendix A-E detail further mathematical expressions used in the derivation of the test structures in Chapter 2 and Chapter 3. Lastly it presents MatLab code used for solving equations presented throughout the thesis.
1.5 Original Scientific Contributions

1. Improved derivation of specific contact resistance from the circular transmission line model test structure. This includes recommendations for design and measurement in order to simplify analysis without reducing precision and also remove potential sources of error.

2. Derivation of theoretical data for the calculation of specific contact resistance on 3C Silicon Carbide.

3. Experimental results of specific contact resistance on 3C Silicon Carbide over a range of temperature in order to show the variation expected.

4. Existing models on electron transport are refined and unified to include all doping regimes and temperature ranges and hence having a universal equation for specific contact resistance of thermionic, field and thermionic-field emission.
Chapter 2

Metal-Semiconductor Contact Test Structures

In order to measure the value of specific contact resistance (SCR) for any combination of metal and semiconductor, it will be necessary to construct a test structure. The reason for this is that the total resistance contribution to specific contact resistance for a large contact is likely to be too small to determine by probing a large contact and the other components of the contact resistances and the parasitic resistances of the test equipment may be significantly larger. In the same way if the contact is very small then it would become increasingly difficult or practically impossible to probe. For these reasons several different test structures that were developed to determine SCR; these structures are detailed in this chapter. It is important to note however that using several different test structures under the same conditions may result in several different measurements for $\rho_c$. This can be caused by the design of the test structure itself including its fabrication methods as well as the testing conditions and experimental errors. Here, a number of the most common test structures that are relevant to this work are discussed.
2.1 Transmission Line Model Test Structure

The Transmission Line Model (TLM) was one of the first test structures to be theorized and developed to determine specific contact resistance. This model was theorized and proposed by [Shockley, 1964]. It is one of the simplest models to test however difficult to fabricate as will be discussed. [Murrmann and Widmann, 1969] reported a theoretical investigation of the TLM, including sheet resistance and contact resistance enabling a solution for SCR.

Figure 2.1 shows a cross section and schematic of a typical ohmic contact. For a contact of length \( L \), current \( I \) is pushed into the diffusion (active) region and will pass into the metal contact. The equations for voltage and current were determined by [Berger, 1969] and are as follows

\[
V(x) = V(0) \cosh \alpha x - I \cdot Z \sinh \alpha x
\]  

\[
I(x) = I \cosh \alpha x - \frac{V(0)}{Z \sinh \alpha x}
\]

where \( x \) is the distance from the contact and \( Z \) is the characteristic line resistance

\[
Z \sqrt{\frac{R_{SH}}{W} \cdot \rho_c} = \frac{1}{W} \sqrt{R_{SH} \cdot \rho_c}
\]

where \( W \) is the width, \( R_{SH} \) is the sheet resistance and \( \rho_c \) is the specific contact resistance. Here also \( \alpha \) is defined as the attenuation constant and is the inverse of the transfer length \( L_T \)
\[ \alpha = \frac{1}{L_T} = \frac{R_{SH}}{\rho_c} \] (2.4)

Figure 2.1 Schematic of contact region in the TLM with its transmission line resistor network model.
In practice it will be difficult to ensure that the contact width, $W$ will be as wide as the diffusion area, $W'$. For the TLM to provide an accurate answer then $W = W'$ is required. However this may not always be the case. For this reason there have been error corrections techniques developed by [Berger 1972] and [Reeves and Harrison, 1982]. The theory of the TLM ohmic contact test structure was created with the assumption of $W = W'$, and solving for $R_1$ gives

$$R_1 = \frac{R_{SH} \cdot d_1}{W'} + 2R_C \quad (2.5)$$

where

$$R_C = \frac{V(0)}{I} \quad (2.6)$$

Substituting equation 2 with $I(L) = 0$, this becomes
\[ R_c = Z \coth \alpha L = \frac{\sqrt{R_{SH} \cdot \rho_c}}{W'} \coth \alpha L \]  

(2.7)

Repeating this with \( R_2 \) gives

\[ R_2 = \frac{R_{SH} \cdot d_2}{W'} + 2R_c \]  

(2.8)

By subtracting \( R_1 \) from \( R_2 \), \( R_{SH} \) can be determined to be

\[ R_{SH} = \frac{W' \cdot (R_2 - R_1)}{d_2 - d_1} \]  

(2.9)

Finally, by removing \( R_{SH} \) from equation (2.5) and equation (2.8), \( R_c \) is shown to be

\[ R_c = \frac{R_1 \cdot d_2 - R_2 \cdot d_1}{2(d_2 - d_1)} \]  

(2.10)

This will allow \( \rho_c \) to be determined from either equation 2.4 or equation 2.7

As mentioned earlier, it is difficult to ensure that \( W = W' \) and therefore some error will be introduced to the calculations. The effect of this contact width approximation has been discussed by [Chang, 1970], [Ting and Chen, 1971] and [Berger, 1972]. For samples where the active area is large (e.g. large diffusion doped area or an epitaxially grown film), in order to achieve \( W \approx W' \), a mesa etch is performed around the TLM pattern so that the contact edges are aligned as close as possible with the semiconductor active area boundary. Unfortunately, depending on the type of semiconductor used, it may be very difficult to etch, which would make this test pattern unsuitable.
2.2 Circular Transmission Line Model Test Structure

The Circular Transmission Line Model (CTLM) for the determination of specific contact resistance was published by [Reeves, 1980] and is an extension of the TLM and in some ways, an improvement (e.g. no active area definition by mesa etch or otherwise is required). The schematic diagram for the CTLM is shown in Figure 2.3. The CTLM pattern is defined by the radii of the electrodes that are used to construct it. These are labelled $r_0$, $r_1'$, $r_1$, $r_2'$ and $r_2$ as can be seen in Figure 2.4. It is important to note that the sheet resistance under the contacts $R_{SK}$ may not always be the same as the sheet resistance of the semiconductor $R_{SH}$ [Kellner, 1975].

![Resistor network model of the CTLM showing the radius, $x$, of a contact](image)

*Figure 2.3* Resistor network model of the CTLM showing the radius, $x$, of a contact
The basic circular transmission line model, seen in Figure 2.4, for a contact of radius \( x \) and width \( dx \) is given as

\[
\frac{dV}{dx} = \frac{i(x) R_{SK}}{2\pi x}
\]  

(2.11)
\[ \frac{d}{dx} = \frac{V(x)2\pi x}{\rho_c} \]  

(2.12)

Where \( x \) is the distance from the centre of the CTLM pattern. \( V(x) \) and \( i(x) \) are the voltage and current seen at the interface at \( x \).

Substituting equation 2.12 into equation 2.11 and eliminating \( i(x) \) will give

\[ \frac{d^2V}{dx^2} + \frac{1}{x} \frac{dV}{dx} - \alpha^2V = 0 \]  

(2.13)

where \( \alpha \) is the attenuation constant shown in equation 2.4

The solution to this, as shown in [Commerce, 1972] is

\[ V(x) = a I_0(ax) + b K_0(ax) \]  

(2.14)

Here \( I_0 \) and \( K_0 \) are zeroth order modified Bessel functions of the first and second kind respectively and \( a \) and \( b \) are constants. In considering the test pattern it is possible to evaluate the value of the contact resistance at the edge of each contact by using different boundary conditions. Considering first the contact resistance of the central dot contact \( R_{c0} \), the resistance can be written as

\[ R_{c0} = \frac{R_{sk}}{2\pi\alpha r_0} E(r_0) \]  

(2.15)

Likewise the contact resistance of the outer ring, \( R_{c2} \), can be defined as
\[ R_{c2} = \frac{R_{SK} \ B(r'_2, r_2)}{2\pi\alpha r'_2 \ C(r_2, r'_2)} \]  

(2.16)

The functions, \( B, C, E \) as well as \( A \) and \( D \), mentioned below, are defined in Appendix A.

The contact resistance of the annular ring is dependent upon the direction of current flow into and out of it. As such, when the current is flowing between the annular ring and the outer ring contact the contact resistance can be written as

\[ R_{c1} = \frac{R_{SK} \ B(r_1, r'_1)}{2\pi\alpha r_1 \ C(r'_1, r_1)} \]  

(2.17)

When the current is flowing in the opposite direction, from the annular ring to the central dot contact, then the contact resistance can be written as

\[ R'_{c1} = \frac{R_{SK} \ B(r'_1, r_1)}{2\pi\alpha r'_1 \ C(r_1, r'_1)} \]  

(2.18)

As such the total resistance between the central dot contact and the annular ring contact, \( R_1 \), and the total resistance between the annular ring contact and the outer ring contact, \( R_2 \), can be written as

\[ R_1 = R_A + (R_{c0} + R'_{c1}) \]  

(2.19)

\[ R_2 = R_B + (R_{c1} + R_{c2}) \]  

(2.20)
Figure 2.5 Schematic diagram depicting the resistance between contacts and the contributions of each resistance in the CTLM test structure. Here it is \( R_{c0}, R'_{c1}, R_{c1} \) and \( R_{c2} \) that are the specific contact resistances between metal and semiconductor. Also \( R_A \) and \( R_B \) are the resistances contributed by the sheet resistance of the semiconductor and are defined as the parasitic resistances.

As shown in Figure 2.5. The last two resistance components \( R_A \) and \( R_B \) are the resistance between the contacts through the semiconductor layer. Here \( R_A \) is the resistance from the central dot to the annular ring and \( R_B \) is the resistance from the annular ring to the outer ring and are defined as follows

\[
R_A = \frac{R_{SH}}{2\pi} \ln \left( \frac{r'_1}{r_0} \right) \tag{2.21}
\]

and
\[ R_B = \frac{R_{SH}}{2\pi} \ln \left( \frac{r_2'}{r_1} \right) \]  

(2.22)

Using equations 2.19 and 2.20 it is possible to eliminate \( R_{SH} \) as follows

\[
\ln \left( \frac{r_2'}{r_1} \right) R_1 - \ln \left( \frac{r_1'}{r_0} \right) R_2
\]  

(2.23)

\[
= \ln \left( \frac{r_2'}{r_1} \right) (R_{c0} + R'_c) - \ln \left( \frac{r_1'}{r_0} \right) (R_{c1} - R_{c2})
\]

The contact end resistance is defined as

\[ R_E = \frac{V(r_1')}{I(r_1')} \bigg|_{i(r_1')=0} \]  

(2.24)

or

\[ R_E = \frac{V(r_1)}{I(r_1')} \bigg|_{i(r_1)=0} \]  

(2.25)

As given by [Reeves 1980] this equation will reduce to

\[ R_E = \frac{R_{SK}}{2\pi} \left[ A(r_1, r_1') \frac{B(r_1, r_1')}{C(r_1, r_1')} + D(r_1, r_1') \right] \]  

(2.26)
It is now possible remove $R_{SK}/2\pi$ from equation 2.26 with equation 2.23 which will then be split into two equations labelled $\phi$ such that

$$\frac{\ln \left( \frac{r_2'}{r_1} \right) R_1 - \ln \left( \frac{r_1'}{r_0} \right) R_2}{R_E} = \phi \tag{2.27}$$

and

$$\phi = \left\{ \begin{array}{l}
\ln \left( \frac{r_2'}{r_1} \right) \left[ \frac{E(r_0)}{ar_0} + \frac{1}{ar_1'} A(r_1, r_1') \right] - \\
\ln \left( \frac{r_1'}{r_1} \right) \left[ \frac{1}{ar_1 C(r_1, r_1')} + \frac{1}{ar_2 C(r_1, r_1')} A(r_1, r_1') \right]
\end{array} \right\} \left[ A(r_1, r_1') \frac{B(r_1, r_1')}{C(r_1, r_1')} + D(r_1, r_1') \right] \tag{2.28}$$

By utilizing the LHS of this equation, which is detailed as equation 2.27, and experimentally measuring values of $R_1$, $R_2$ and $R_E$ it will be possible to determine $\phi$ and use this to determine $\alpha$ either graphically or mathematically by using the RHS of $\phi$ defined in equation 2.28.

Once $\alpha$ has been determined, from the intersection of equations 2.27 and 2.28 in Figure 2.5, and the resistance values of $R_1$ and $R_2$ are known it is possible to calculate $\rho_c$ as follows

$$\rho_c = \ln \left( \frac{r_2'}{r_1} \right) R_1 - \ln \left( \frac{r_1'}{r_0} \right) R_2 \cdot r_0^2 \Delta \tag{2.29}$$

where $\Delta$ is
\[ \Delta = \frac{\left( \frac{2\pi}{(\alpha r_0)^2} \phi \right)}{A(r_1, r'_1) B(r_1, r'_1) + C(r_1, r'_1) + D(r_1, r'_1)} \]  

(2.30)

The solutions to these equations can be seen graphically in Figures 2.6 - 2.8 for a particular geometry. See [Reeves, 1980] for the complete solution.

**Figure 2.6** Plot of \( \phi \) vs \( \alpha r_0 \) for a CTLM test pattern where \( r_0 = 20\mu m, r'_1 = 40\mu m, r_1 = 60\mu m, r'_2 = 80\mu m \) and \( r_2 = 100\mu m \). Here, \( R_1 = 300\Omega, R_2 = 110\Omega \) and \( R_E = 1\Omega \). These are theoretical values that correspond with \( R_{SH} = 100\Omega/cm^2 \) and \( \alpha r_0 = 5 \). The red line represents equation 2.27 while the blue curve is equation 2.28.
Figure 2.7  Plot of $\Delta$ vs $\alpha r_0$ for a CTLM test pattern where $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. Here, $R_1 = 300\Omega$, $R_2 = 110\Omega$ and $R_E = 1\Omega$. These are theoretical values that correspond with $R_{SH} = 100\Omega/\Box$ and $\alpha r_0 = 5$.

The primary benefit of using the CTLM over the TLM is the simplified process of fabrication. Where the TLM requires a mesa etch around the edge of the pattern to contain the current flow the CTLM does not. Due to the circular nature of the pattern all current is contained within the pattern and as such the CTLM can be placed directly onto a semiconductor without any further concern. However the equations required to solve the CTLM are comparatively more complex than the TLM and prone to greater errors in calculation due to experimental measurement error. Reducing this error is an area of investigation in this thesis. Several researchers have proposed simplifications to the CTLM by either removing the Bessel functions [Hewett et al., 1995], [C. Xu et al., 2006], [Rechid and Heime, 2000] or by assuming that $R_{SH} = R_{SK}$.
Figure 2.8 Plot of $\rho_c$ vs $\alpha r_0$ for a CTLM test pattern where $r_0 = 20\mu m, r_1 = 40\mu m, r_1 = 60\mu m, r_2 = 80\mu m$ and $r_2 = 100\mu m$. Here, $R_1 = 300\Omega, R_2 = 110\Omega$ and $R_E = 1\Omega$. These are theoretical values that correspond with $R_{SH} = 100\Omega/\square$ and $\alpha r_0 = 5$.

2.3 Single Dot Contact Test Structure

The Single Dot Contact Structure as developed by [Pan and Collins et al, 2013] is a novel test structure for the determination of Specific Contact Resistance. It is an extension of the Circular Transmission Line Model work completed by [Marlow and Das, 1982]. This test structure uses three sets of circular contacts to determine the specific contact resistance by comparing the differences measured on each individual pattern.
Figure 2.9 Planar view of Single Dot Test Structure showing geometries and isometric view of this structure and the probes used to measure $R_{T1}$, $R_{T2}$ and $R_{T3}$
Figure 2.10 Schematic diagram of the Single Dot Test Structure showing resistance components between the metal and semiconductor labelled as $R_{c0}$ and $R_{c1}$ which are the specific contact resistances at the edge of the contacts. The resistance contributed by the sheet resistance of the semiconductor is labelled as $R_p$ which is defined as the parasitic resistance between contacts.

From the schematic shown in Figure 2.10 it can be seen that the resistance between contacts is made from three components as follows
\[ R_T = R_{c0} + R_p + R_{c1} \]  \hspace{1cm} (2.31)

where

\[ R_{c0} = \frac{R_{SH} \frac{l_0(\alpha r_0)}{2\pi \alpha r_0} l_1(\alpha r_0)}{2\pi \alpha r_0} \]  \hspace{1cm} (2.32)

\[ R_p = \frac{R_{SH} \ln \left( \frac{r_1}{r_0} \right)}{2\pi} \]  \hspace{1cm} (2.33)

\[ R_{c1} = \frac{R_{SH} \left[ l_1(\alpha r_1) K_0(\alpha r_1) + l_0(\alpha r_1) K_1(\alpha r_1) \right]}{2\pi \alpha r_0 \left[ l_1(\alpha r_1') K_0(\alpha r_1') - l_1(\alpha r_1) K_1(\alpha r_1') \right]} \]  \hspace{1cm} (2.34)

Therefore with three different patterns there will be three different resistance measurements which are listed as follows

\[ R_{T1} = R_{c01} + R_{p1} + R_{c1} \]  \hspace{1cm} (2.35)

\[ R_{T2} = R_{c02} + R_{p2} + R_{c1} \]  \hspace{1cm} (2.36)

\[ R_{T3} = R_{c02} + R_{p2} + R_{c1} \]  \hspace{1cm} (2.37)

Note that \( R_{c1} \) exists in each equation due to the fact that the outer radius of the gap does not change between the three patterns and as such is the same value for all three.

Substituting equations 2.32 – 2.34 into 2.31 yields
\[ R_{T1} - R_{T2} = \frac{R_{SH}}{2\pi} (F + \ln x) \]  
(2.38)

where \( x = \frac{r_{02}}{r_{01}} \) and

\[ F = \frac{I_0(\alpha r_{01})}{\alpha r_{01} I_1(\alpha r_{01})} - \frac{I_0(\alpha r_{02})}{\alpha r_{02} I_1(\alpha r_{02})} \]  
(2.39)

Also the substitution of equations 2.32 – 2.34 into 2.31 yields

\[ R_{T1} - R_{T3} = \frac{R_{SH}}{2\pi} (F' + y) \]  
(2.40)

where \( y = \frac{r_{03}}{r_{01}} \) and

\[ F' = \frac{I_0(\alpha r_{01})}{\alpha r_{01} I_1(\alpha r_{01})} - \frac{I_0(\alpha r_{03})}{\alpha r_{03} I_1(\alpha r_{03})} \]  
(2.41)

Given attenuation is defined as

\[ \alpha = \sqrt{\frac{R_{SH}}{\rho_c}} \]  
(2.42)

the relationship of \( K \) can be obtained from

\[ K = \frac{R_{T1} - R_{T3}}{R_{T1} - R_{T2}} = \frac{F' + \ln y}{F + \ln x} \]  
(2.43)
Here, $K$ can be determined experimentally by measuring the resistances between the contacts while $x$ and $y$ can be determined by selecting appropriate values for $r_{01}$, $r_{02}$ and $r_{03}$. With this information it is possible to plot $K$ as a function of $\alpha r_{01}$ using equation 2.43. In the same way it is possible to use equations 2.39 or 2.41 to plot $F$ or $F'$ respectively as a function of $\alpha r_{01}$. With this information it is possible to use equations 2.38 or 2.40 to determine the sheet resistance and then a final calculation to determine the specific contact resistance.

Graphical Solutions to equations 2.39 – 2.43 are displayed in Figures 2.11 and 2.12.

**Figure 2.11** Plot of $\alpha r_{0}$ vs $K$ for the determination of specific contact resistance with the single dot test structure. By evaluating the ratio of $K$ it is possible to determine a unique value for $\alpha r_{0}$. Here, $A$ relates a particular value for $K$ which is derived from equation 2.43 to a unique value of $\alpha r_{0}$ where $x = 1.5$ and $y = 3.5$. 
Figure 2.12 Plot of $\alpha_{r0}$ vs F and F’ for the determination of specific contact resistance with the single dot test structure. By evaluating the ratios of F and F’ it is possible to determine a unique value for $\alpha_{r0}$. Here A’ and A” relate specific values of F’ and F, which are determined from equations 2.39 and 2.41 respectively, to $\alpha_{r01}$ where $x = 1.5$ and $y = 3.5$.

This test pattern is of great use because it is possible to experimentally determine the sheet resistance of the semiconductor layer from the resistance measurements. This therefore has a significant advantage over the TLM and CTLM due to the ease of fabrication and versatility in measurements. Another advantage to this is that an experiment can be constructed in which several CTLM test patterns are designed such that they contain this test structure inside. This would allow two different series of calculations to be performed on the same set of data to achieve the same result and
improve confidence in reported measurements. Lastly it must be mentioned that from hands on experience in this project, the discussed above test structure has advantages over the CTLM because the contact end resistance is not required. This is a very small value and is used in CTLM analysis and requires small CTLM electrode geometries. For the same SCR and sheet resistance the electrodes of the test structure developed by [Pan and Collins et al., 2013] can be large and hence easier to probe and give easier to determine resistance values. The CTLM however has advantages in that it can be used to determine smaller SCR values though requiring more sophisticated fabricating and electrical probing processes and tools.

2.4 Summary

Two of the most commonly used test structures have been detailed and compared. In addition to this a novel test structure developed in recent years has been reviewed and compared to established methods. The first method being the TLM has a very simple solution when compared to the CTLM and Single Dot test structures. However, the fabrication of this structure poses difficulties with regard to correct alignment of the metal contacts and the mesa etch around the desired test structure. This will also make it unsuitable for semiconductors that are difficult to etch.

The CTLM removes the need for a mesa etch and is therefore applicable to many more semiconductors that are difficult to etch properly. This will lead to an increase in the difficulty of the equations required to solve the test structure. Likewise, the Single Dot test structure presents an attractive alternative to the CTLM. The Single Dot test structure does not require a mesa etch to be effective and can be placed on any semiconductor. The Single Dot test structure however requires three separate structures to be created and measurements to be compared whilst the CTLM is self-contained in one structure.
Chapter 3

Circular Transmission Line Model - Investigating optimum design, analytical modelling and operation.

The Circular Transmission Line Model (CTLM) [Reeves, 1981] method for calculating specific contact resistance involves the fabrication of concentric electrodes. By measuring the resistance between these electrodes the specific contact resistance can be derived. The benefit of this method is that it is simpler to construct than other established methods for the determination of specific contact resistance and can be realised with little or no error correction requirement. It can also be used in a wider variety of circumstances. However this comes at the cost of the mathematical solution being relatively complex.

The CTLM pattern is defined by the radii of the electrodes that are used to construct it. These are labelled $r_0, r_1', r_1, r_2'$ and $r_2$ as can be seen in Figure 3.1. Each contact contributes a unique resistance due to the specific contact resistance between the metal and semiconductor layers, the circumference of the contact and the sheet resistance under the metal contact, $R_{SK}$. It is impossible to measure $R_{SK}$ directly and as such is commonly assumed to be equal to the sheet resistance, $R_{SH}$, of the semiconductor layer away from the contact structure. This however is not always the case and therefore a way to derive the specific contact resistance without needing to measure $R_{SK}$ or $R_{SH}$ was developed by [Reeves, 1980]. Further analysis into the CTLM has shown that assuming $R_{SK}$ is equal to $R_{SH}$ will introduce little to no error if care is taken in the design of the structure [Hewett et al., 1995].
3.1 Analytical Model

By assuming that $R_{SH}$ and $R_{SK}$ are equal it can be shown that the equations necessary for the calculation of specific contact resistance will be greatly reduced. As defined in [Reeves, 1980] the voltage and current in the CTLM pattern are stated in equations 2.11 – 2.13

Solving these two equations for $V(r)$ and $I(r)$ will result in
\[ V = zk_0(x) \frac{zI_0(ax)K_1(ar)}{I_1(ar)} \]  

(3.1)

\[ I = \frac{2\pi rI_0(ax)K_1(ar)}{\alpha \rho \rho_c I_1(ar)} - \frac{2\pi rzK_0(ax)}{\alpha \rho_c} \]  

(3.2)

Where \( \alpha \) is the attenuation defined as

\[ \alpha = \sqrt{\frac{R_{SH}}{\rho_c}} \]  

(3.3)

and \( x \) and \( r \) are the distances from the centre of the pattern as shown in Figure 3.1 and \( z \) is a constant dependent upon the input voltage and current supplied. Here \( I_0 \) and \( I_1 \) are modified Bessel functions of the first kind to the zeroth and first order. In the same way \( K_0 \) and \( K_1 \) are modified Bessel functions of the second kind to the zeroth and first order. The constant \( z \) can be removed when solving for the specific contact resistance. For \( \alpha \) to be determined the contact end resistance, \( R_E \) will first need to determined. \( R_E \) is defined as the output voltage over the input current where the output current is zero. The following two equations define \( R_E \).

\[ R_E = \left. \frac{V(r')}{{I(r_1)}} \right|_{I(r')=0} \]  

(3.4)

and
These are dependent on where the voltage is applied on the pattern. Equation 3.4 requires that the current is pushed from the centre dot contact to the annular ring while the voltage is measured from the annular ring to the outer ring as described in Figure 3.2. Conversely Equation 3.5 requires that current is pushed between the annular ring and the outer ring while the voltage is measured between the centre dot and the annular ring.

**Figure 3.2** Schematic depicting measurement of $R_E$ with current being pushed between the annular ring and centre dot contacts.
In mathematical terms, $R_E$ is determined by evaluating the limit of equations 3.4 and 3.5. This solution will be dependent upon the specific contact resistance of the junction and the sheet resistance of the semiconductor. Figures 3.3 – 3.5 describe this relationship graphically. It can be seen that a higher doping and sheet resistance will lead to a lower value of $R_E$.

To determine $R_E$ experimentally it is necessary to push current from one contact to the adjacent contact (ie. Centre dot to annular ring or annular ring to outer ring). While this is occurring the voltage is measured from between the remaining contact and the annular ring as can be seen in Figure 3.6.

**Figure 3.3** Plot of Current vs Voltage for the determination of $R_E$. Here the sheet resistance is listed and the specific contact resistance is a theoretical value of $1 \times 10^{-6}\Omega cm^2$. Geometry is $r'_{1} = 2\mu m$ and $r_{1} = 4\mu m$. $R_E$ is given when $I = 0$ as defined in equations 3.6 and 3.7.
Figure 3.4 Plot of Current vs Voltage for the determination of $R_E$. Here the sheet resistance is listed and the specific contact resistance is a theoretical value of $1 \times 10^{-7} \Omega \text{cm}^2$. Geometry is $r' = 2 \mu m$ and $r_1 = 4 \mu m$. $R_E$ is given when $I = 0$ as defined in equations 3.6 and 3.7.

It is important to note that in Figures 3.3 – 3.5 the I-V curves representing $R_E$ are not linear which is a direct result of the Bessel functions required to solve current and voltage in a circular test structure. As such, in order to evaluate $R_E$ the solution should be taken as $I$ reaches zero.
Figure 3.5 Plot of Current vs Voltage for the determination of \( R_E \). Here the sheet resistance is listed and the specific contact resistance is a theoretical value of \( 1 \times 10^{-8} \Omega \text{cm}^2 \). Geometry is \( r' = 2 \mu m \) and \( r = 4 \mu m \). \( R_E \) is given when \( I = 0 \) as defined in equations 3.6 and 3.7.

The original equations developed by Reeves, as shown in Chapter 2 with equations 2.27 – 2.30, have been further developed and simplified here. Both of these equations will resolve to the same value for \( R_E \) as shown by [Reeves 1980] and are solved with equation 3.4 or 3.5 by substituting equation 3.1 and 3.2 and hence will give

\[
R_E = \frac{zK_0(r'_{1})zI_0(\alpha r'_{1})K_1(\alpha r_{1})}{I_1(\alpha r_{1})} \left( \frac{2\pi r I_0(\alpha r'_{1})K_1(\alpha r_{1})}{\alpha \rho_c I_1(\alpha r_{1})} - \frac{2\pi z r K_0(\alpha r'_{1})}{\alpha \rho_c} \right)
\] (3.6)

which will reduce to
Equation 3.7 has been further reduced with the use of MatLab as shown in Appendix B to give the following

\[
R_E = \frac{\alpha \rho_c I_1(\alpha r'_1)K_0(\alpha r_1) + I_0(\alpha r_1)K_1(\alpha r'_1)}{2\pi r_1 I_1(\alpha r'_1)K_1(\alpha r_1) - I_1(\alpha r_1)K_1(\alpha r'_1)}
\]  

(3.7)

For this equation to provide a solution, \(R_E\) and \(R_{SH}\) are determined experimentally, and the only unknown is \(\alpha\) For particular CTLM test structure geometry. Using equation 3.8, \(R_E\) can be plotted as shown in Figure 3.6

From here it is a simple matter to determine the value of \(\alpha\) to be used knowing \(r_0\) and having determined \(R_E\). With \(\rho_c\) defined from equation 3.5 as

\[
\rho_c = \frac{R_{SH}}{\alpha^2}
\]  

(3.9)

This equation is plotted in Figure 3.7 with different values of \(R_{SH}\) shown for a particular geometry.
Figure 3.6 Figure displaying $R_E$ vs $\alpha$ for different values of $R_{SH}$ derived from equation 3.10. The geometry is where $r_0 = 20\mu m, r'_1 = 40\mu m, r_1 = 60\mu m, r'_2 = 80\mu m$ and $r_2 = 100\mu m$. By knowing the value of $R_E$ and $R_{SH}$, $\alpha r_0$ can be either calculated using equation (3.8) or drawn directly here for an approximation.

Utilizing Finite Element Method (FEM) software NASTRAN to simulate the solution to $R_E$ and $\rho_C$ yields an accurate representation of current flow and voltage contours. Nastran accomplishes this by solving for the voltage with a current applied and drained from an appropriate mesh. This is shown in Figure 3.8. Table 3.1 displays the FEM results alongside results from equation 3.8 and 3.9. The FEM model was constructed with geometries of $r_0=15\mu m, r'_1=37.5\mu m, r_1=56.25\mu m, r'_2=93.75\mu m$ and $r_2=130\mu m$ and 235.6mA of current pushed from the central dot contact to the annular ring. From here the voltage difference from the annular ring to the outer ring contacts was determined and $R_E$ calculated from equation 3.5.
Figure 3.7 Figure displaying $\rho_c$ vs $\alpha$ for different values of $R_{SH}$ derived from equation 3.11. The geometry where $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. By knowing the value of $\alpha$ and $R_{SH}$ then $\rho_c$ can be either calculated using equation (3.9) or drawn directly here for an approximation.

Table 3.2 shows the expected values of $R_E$ compared to the value of $R_E$ given by the FEM simulations. It can be seen that the results have good agreement and result in the solutions for $\rho_c$. Two examples of the FEM models used are shown in Figures 3.8 and 3.9.
Table 3.1 FEM results taken from CTLM pattern of geometry \( r_0=15\mu m, r'_1=37.5\mu m, r_1=56.25\mu m, r'_2=93.75\mu m \) and \( r_2=130\mu m \). \( R_{SH} \) and \( \rho_C \) were set and voltage contours simulated with a current of 235.6mA between the central dot and annular ring contacts. Voltage difference values (\( \Delta V \)) have been taken from the annular ring to outer ring contact. With geometry and \( R_{SH} \) given and \( R_E \) calculated, \( \rho_C \) has been determined from equations 3.8 and 3.9.

<table>
<thead>
<tr>
<th>( R_{SH} ) (( \Omega/\square ))</th>
<th>( \rho_C ) (( \Omega ) cm(^2))</th>
<th>( \Delta V ) (Volts)</th>
<th>FEM ( R_E ) (( \Omega ))</th>
<th>Calculated ( R_E ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.00( \times 10^{-4} )</td>
<td>3.61( \times 10^{-1} )</td>
<td>1.53</td>
<td>1.00( \times 10^{-4} )</td>
</tr>
<tr>
<td>30</td>
<td>1.00( \times 10^{-5} )</td>
<td>1.13( \times 10^{-2} )</td>
<td>4.80( \times 10^{-2} )</td>
<td>1.02( \times 10^{-5} )</td>
</tr>
<tr>
<td>300</td>
<td>1.00( \times 10^{-4} )</td>
<td>1.09( \times 10^{-1} )</td>
<td>4.63( \times 10^{-1} )</td>
<td>1.01( \times 10^{-4} )</td>
</tr>
<tr>
<td>300</td>
<td>1.00( \times 10^{-5} )</td>
<td>1.96( \times 10^{-4} )</td>
<td>8.32( \times 10^{-4} )</td>
<td>1.42( \times 10^{-5} )</td>
</tr>
<tr>
<td>3000</td>
<td>1.00( \times 10^{-4} )</td>
<td>4.71( \times 10^{-4} )</td>
<td>2.00( \times 10^{-3} )</td>
<td>1.08( \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Table 3.2 Calculated values of \( R_E \) compared to simulated values of \( R_E \) with the use of FEM analysis. Geometry used was \( r_0=15\mu m, r'_1=37.5\mu m, r_1=56.25\mu m, r'_2=93.75\mu m \) and \( r_2=130\mu m \) with 235.6mA of current being pushed from the central dot to the annular ring. Calculated values of \( R_E \) were determined from equation 3.8.

<table>
<thead>
<tr>
<th>( R_{SH} ) ( \Omega/\square )</th>
<th>( \rho_C ) ( \Omega ) cm(^2)</th>
<th>FEM ( R_E ) ( \Omega )</th>
<th>Calculated ( R_E ) ( \Omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.00( \times 10^{-4} )</td>
<td>1.53</td>
<td>1.527</td>
</tr>
<tr>
<td>30</td>
<td>1.00( \times 10^{-5} )</td>
<td>4.80( \times 10^{-2} )</td>
<td>4.612( \times 10^{-2} )</td>
</tr>
<tr>
<td>300</td>
<td>1.00( \times 10^{-4} )</td>
<td>4.63( \times 10^{-1} )</td>
<td>4.612( \times 10^{-1} )</td>
</tr>
<tr>
<td>300</td>
<td>1.00( \times 10^{-5} )</td>
<td>8.32( \times 10^{-4} )</td>
<td>1.310( \times 10^{-4} )</td>
</tr>
<tr>
<td>3000</td>
<td>1.00( \times 10^{-4} )</td>
<td>2.00( \times 10^{-4} )</td>
<td>1.308( \times 10^{-4} )</td>
</tr>
</tbody>
</table>
**Figure 3.8** FEM modelling showing voltage contours in a CTLM pattern with geometries of $r_0=15\mu$m, $r'_1=37.5\mu$m, $r_1=56.25\mu$m, $r'_2=93.75\mu$m and $r_2=130\mu$m with 235.6mA of current being pushed from the central dot to the annular ring and voltage contours shown. Figure shows a model with an $R_{SH}$ of 30 $\Omega/\square$ and $\rho_C$ of $1 \times 10^{-5} \ \Omega \ cm^2$. Using this model it is possible to determine the value of $R_E$ by measuring the voltage between the annular and outer ring contacts.
Figure 3.9 FEM modelling showing voltage contours in a section of a CTLM pattern with geometries of \( r_0 = 15\mu\text{m}, r'_1 = 37.5\mu\text{m}, r_1 = 56.25\mu\text{m}, r'_2 = 93.75\mu\text{m} \) and \( r_2 = 130\mu\text{m} \) with 235.6mA of current being pushed from the central dot to the annular ring and voltage contours shown. Left Figure shows a model with an \( R_{SH} \) of 30 \( \Omega/\Box \) and \( \rho_C \) of \( 1 \times 10^{-6} \) \( \Omega \text{ cm}^2 \) while the right Figure shows \( R_{SH} \) of 30 \( \Omega/\Box \) and \( \rho_C \) of \( 1 \times 10^{-7} \) \( \Omega \text{ cm}^2 \). It can be seen that the voltage contours under the edge of the contacts are altered by \( \rho_C \).

### 3.2 Parasitic Resistance

Parasitic Resistance between the contacts and any error in determining it will have an effect upon the extraction of \( \rho_C \) from the test pattern. For this reason it is necessary to ensure that the contact resistance of contacts is the dominant factor. In general a test pattern should be designed such that the resistance between contacts through the semiconductor is less than the contact resistance under the contacts such that

\[
R_A < R_{c0} + R'_{c1} \quad \text{and} \quad R_B < R_{c1} + R'_{c2}
\]

By ensuring that the contribution of the contact resistance is larger than the contribution of the resistance between contacts the test pattern would become less susceptible to measurement errors. For this reason it is important to calculate the contribution of each resistance component as seen in Figure 2.4 and the equations for these are developed here as follows.
Considering first the innermost dot contact, the effect of $R_{c0}$ can be calculated in the same way as $R_E$ with

$$R_{c0} = \frac{V(r_0)}{I(r_0)}$$  \hspace{1cm} (3.10)

Substituting equation 3.3 and 3.4 will result in

$$R_{c0} = \frac{zK_0(r_0)zI_0(\alpha r_0)K_1(\alpha r)}{I_1(\alpha r)} - \frac{2\pi rK_0(\alpha r_0)}{2\pi r\rho_c I_1(\alpha r)}$$  \hspace{1cm} (3.11)

Because the central dot has only one radii associated with it, $r$ can be assumed to be 0 as it is at the centre of the centre dot contact, which will simplify the equation to

$$R_{c0} = \frac{R_S H L_0(\alpha r_0)}{2\pi \alpha r_0 I_1(\alpha r_0)}$$  \hspace{1cm} (3.12)

Following the same procedure will result in the resistance components of $R'_{c1}, R_{c1}$ and $R_{c2}$ being as follows

$$R'_{c1} = \frac{zK_0(r'_1)zI_0(\alpha r'_1)K_1(\alpha r)}{I_1(\alpha r)} - \frac{2\pi rK_0(\alpha r'_1)}{2\pi r\rho_c I_1(\alpha r)}$$  \hspace{1cm} (3.13)

In the case of $R'_{c1}$ it is assumed that $r$ is distant from $r'_1$ such that it can be said that $r$ is equal to $\infty$. What this means is that the opposite side of the annular ring contact is such a distance that it has no effect on the calculation of $R'_{c1}$. This effect occurs whenever $\alpha r_0$ is less than 1. As such, equation 3.13 can be reduced to
\[ R'_{c1} = \frac{R_{SH} K_0(\alpha r'_1)}{2\pi \alpha r'_1 K_1(\alpha r'_1)} \]  

(3.14)

Considering next the solution to \( R_{c1} \) yields

\[ R_{c1} = \frac{zK_0(r_1) zI_0(\alpha r_1)K_1(\alpha r)}{2\pi rI_0(\alpha r_1)K_1(\alpha r)} - \frac{2\pi zr K_0(\alpha r_1)}{\alpha \rho_c I_1(\alpha r)} \]

(3.15)

Following this solution, a similar assumption to the one made for \( R'_{c1} \) can be made with regards to \( r \) in comparison to \( r_1 \). In this case it can be said that \( r \) is equal to 0 which will reduce equation 3.15 to

\[ R_{c1} = \frac{R_{SH}}{2\pi \alpha r_1} \frac{l_0(\alpha r_1)}{I_1(\alpha r_1)} \]

(3.16)

Considering the solution to \( R_{c2} \) the equations for \( V(r) \) and \( I(r) \) will results in

\[ R_{c2} = \frac{zK_0(r_2) zI_0(\alpha r_2)K_1(\alpha r)}{2\pi rI_0(\alpha r_2)K_1(\alpha r)} - \frac{2\pi zr K_0(\alpha r_2)}{\alpha \rho_c I_1(\alpha r)} \]

(3.17)

And assuming that the other side of the outer ring contact extends to \( \infty \) the following is obtained

\[ R_{c2} = \frac{R_{SH} K_0(\alpha r_2)}{2\pi \alpha r_2 K_1(\alpha r_2)} \]

(3.18)
It is important to note here that following from this calculation it is apparent that the outer ring contact can in fact stretch out as far as possible with no adverse effects presenting in the calculations of the CTLM pattern. It must be noted however that the outer ring contact cannot be shorter than three transfer lengths of the CTLM pattern in order to use the analytical technique of the CTLM.

\[ L_T = \sqrt{\frac{\rho_C}{R_{SH}}} \]  

(3.19)

Where \( L_T \) is the transfer length of a semiconductor. Because \( \rho_C \) is unknown when designing the CTLM geometries it would be necessary to make \( r_2 \) relatively large compared to \( r'_2 \).

The last two resistance components are the parasitic resistance between contacts and are defined as \( R_A \) and \( R_B \) which are defined in chapter 2 and are included for convenience as follows

\[ R_A = \frac{R_{SH}}{2\pi \log_e \left( \frac{r'_1}{r_0} \right)} \]  

(3.20)

and

\[ R_B = \frac{R_{SH}}{2\pi \log_e \left( \frac{r'_2}{r_1} \right)} \]  

(3.21)

By adding the different resistance components together it is possible to obtain the total resistance between the contacts such that
\[ R_1 = R_A + (R_{c0} + R'_{c1}) \]  

(3.22)

\[ R_2 = R_B + (R_{c1} + R_{c2}) \]  

(3.23)

When \( R_{SH} \) is equal to \( R_{SK} \) there are two simple rules that can be followed to ensure that the following two conditions are satisfied.

\[ R_A < R_{c0} + R'_{c1} \quad \text{and} \quad R_B < R_{c1} + R'_{c2} \]

These rules have been determined from theoretical data and concern the ratio between adjacent contact radii. The data were obtained by using theoretical values of \( \rho c \) and \( R_{SH} \) with multiple different geometries to compare the contributions of each resistance component. Table 3.2 shows the ratios of \( r'_{1}/r_0 \) and \( r'_{2}/r_1 \) for the contacts.
Table 3.2 Ratio of adjacent contact radii to ensure that $R_A < R_{c0} + R'_{c1}$ and $R_B < R_{c1} + R'_{c2}$. The ratio will change with variations in $\alpha r_0$.

<table>
<thead>
<tr>
<th>$\alpha r_0$</th>
<th>$r'_1/r_0$</th>
<th>$r'_2/r_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td>3.33</td>
</tr>
<tr>
<td>2</td>
<td>2.42</td>
<td>2.00</td>
</tr>
<tr>
<td>3</td>
<td>1.77</td>
<td>1.58</td>
</tr>
<tr>
<td>4</td>
<td>1.54</td>
<td>1.42</td>
</tr>
<tr>
<td>5</td>
<td>1.41</td>
<td>1.35</td>
</tr>
<tr>
<td>6</td>
<td>1.33</td>
<td>1.28</td>
</tr>
<tr>
<td>7</td>
<td>1.28</td>
<td>1.25</td>
</tr>
<tr>
<td>8</td>
<td>1.25</td>
<td>1.21</td>
</tr>
<tr>
<td>9</td>
<td>1.22</td>
<td>1.18</td>
</tr>
<tr>
<td>10</td>
<td>1.20</td>
<td>1.17</td>
</tr>
</tbody>
</table>

It is obvious that as $\alpha r_0$ is not known at the time of design it would be beneficial to design a test pattern with the worst case in mind. Here the worst case would be where $\alpha r_0$ is equal to or greater than 10 where the ratio reaches an asymptote of approximately 1.2 for $r'_1/r_0$ and 1.7 for $r'_2/r_1$. The reasoning for this is due to the decreasing sensitivity of the CTLM test structure for determining required resistance at this value of $\alpha r_0$. Therefore the maximum allowable ratio between the contacts is as follows

$$\frac{r'_1}{r_0} < 1.2$$

$$\frac{r'_2}{r_1} < 1.17$$
3.3 Equipotential of the annular ring

For the CTLM test structure to be accurate and effective it will be necessary to ensure that an equipotential exists on each individual contact. What this means is that no matter where two probes are placed on a single contact (e.g. one point on an annular ring to another point on the same annular ring), no voltage difference will be measured. Through measurement of the voltage between different points on the annular ring it can be shown that the annular ring may not always be at an equipotential. If the annular ring were at an equipotential then there would be no difference in the voltage measurements between any two points on the ring. This is clearly not the case when the metal contact is not relatively thick or wide, as can be seen by probing the annular ring at various points away from the current source when current is going between this contact and one of the other CTLM contacts.

Theoretical measurements taken with Finite Element Method software have been taken from a CTLM model and analysed. Measurements were taken from one side of the annular ring to the opposite side in order to show this difference and are presented in Table 3.3. It can be seen that as the ring increases in surface area by increasing the distance between $r_1$ and $r_1$, that the voltage difference decreases such that an equipotential is significantly more likely to occur. This is due to the current having a greater ability to flow from one point to another through the contact and hence larger radii for the annular ring will decrease any errors associated with differences in equipotential.

The central dot and annular ring contacts were chosen because it is simpler to ensure that the central dot is at an equipotential with only one probe in the centre as it is a smaller electrode and more likely to have uniform current density and hence be at an equipotential. The outer ring would experience the same problems as the annular ring when attempting to reach an equipotential across the electrode.
Figure 3.10 Equipotential contours within a CTLM using only one probe to draw current from the annular ring. Shaded areas are the metal contacts. Dimensions of the CTLM shown here are $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. Scale ranges from 0 to 9mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from one probe.
Figure 3.11 Schematic diagram detailing position of probes used to push and draw current from the CTLM. Here the current is being pushed into the central dot and drawn from the annular ring. Only one probe is used to draw the current from the annular ring.
Table 3.3 FEM results showing voltage differences around the annular ring contact for an input current of 1mA and using one probe on the annular ring. The difference in voltage is determined from the maximum and minimum voltages measured on the annular ring.

<table>
<thead>
<tr>
<th>Ring radius (inner-outer)</th>
<th>40-60µm</th>
<th>30-60µm</th>
<th>15-60µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆V (mV)</td>
<td>3.5</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
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</tr>
<tr>
<td></td>
<td>3.5</td>
<td>1.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Results in Table 3.3 have been supported by FEM results presented in Figs 3.10, 3.12, 3.14 and 3.15 showing a significant drop in voltage as the number of probes increases and the position of the probes move closer together along the annular ring.
Figure 3.12 Equipotential contours within a CTLM using only one probe to push current into the central dot and two shorted probes to create an equipotential on the annular ring. Shaded areas are the metal contacts. Dimensions of the CTLM shown here $r_0 = 20 \mu m, r'_1 = 40 \mu m, r_1 = 60 \mu m, r'_2 = 80 \mu m$ and $r_2 = 100 \mu m$. Scale ranges from 0 to 9mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from two probes.

Figure 3.12 shows the same FEM model as depicted in Figure 3.10 with two probes on the annular ring and with maximum separation being used to push the current. These two probes have been shorted with each other to help create an equipotential on the annular ring at opposite sides. It can be seen that this method will diminish errors
resulting from the voltage differentials. However it will not completely remove the error from the structure. For this to occur then it would be necessary to significantly increase the number of probes used to push the current from the annular ring to the central dot contact.

**Figure 3.13** Schematic diagram detailing position of probes used to push and draw current from the CTLM. Here the current is being pushed into the central dot and drawn from the annular ring. Two probes are used to draw the current from the annular ring and are placed at the maximum distance from each other.
Following from the FEM results showing voltage contours across the CTLM with probes as described in Figures 3.10 and 3.12 it can be seen in Figure 3.10 and Figure 3.12 that if the number of shorted probes being used to maintain an equipotential is increased then the resulting error will be reduced further. This can be seen in Table 3.4 where the maximum voltage difference on the annular ring is 3.3 mV. Dimensions of the CTLM detailed here are \( r' = 40\mu m \) and \( r = 60\mu m \) from equation 3.10 it can be seen that the only geometries required for a theoretical calculation of \( R_E \) are \( r' \) and \( r \). Different geometries would have different voltage differences and should be taken on an individual basis when concerning errors attributed to the annular ring failing to reach an equipotential.

**Table 3.4** Voltage difference measured on annular ring versus the number of shorted probes used to maintain an equipotential for the structures shown in Figures 3.10, 3.12, 3.14 and 3.15. An input current of 1mA pushed into the central dot was used in all cases. Total voltage from central dot to ring was 5mV. Dimensions of the annular ring detailed here are \( r' = 40\mu m \) and \( r = 60\mu m \).

<table>
<thead>
<tr>
<th>Number of probes pushing current</th>
<th>Difference between maximum and minimum voltage measured on the annular ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3 mV</td>
</tr>
<tr>
<td>2</td>
<td>2.5 mV</td>
</tr>
<tr>
<td>3</td>
<td>1.3 mV</td>
</tr>
<tr>
<td>4</td>
<td>0.8 mV</td>
</tr>
</tbody>
</table>
Figure 3.14 Equipotential contours within a CTLM using one probe to push current into the central dot and three shorted probes to help create an equipotential on the annular ring. Shaded areas are the metal contacts. Dimensions of the CTLM shown here are $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. Scale ranges from 0 to 9mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from three probes.
**Figure 3.15** Equipotential contours within a CTLM using one probe to push current into the central dot and four shorted probes to help create an equipotential on the annular ring. Shaded areas are the metal contacts. Dimensions of the CTLM shown here are $r_0 = 20\mu m$, $r'_1 = 40\mu m$, $r_1 = 60\mu m$, $r'_2 = 80\mu m$ and $r_2 = 100\mu m$. Scale ranges from 0 to 9mV. The input current is 1mA and is being pushed into the central dot whilst being drawn out from the annular ring from four probes.
Figure 3.16 Figure representing the change seen in $\rho_c$ versus the change in $R_E$ over the range of 1$\Omega$ to 10$\Omega$. Different values of $\alpha r_0$ are represented showing that as $\alpha r_0$ increases then the difference in begins to rapidly increase with smaller variation of $R_E$. CTLM pattern geometry values are $r_0=20\mu m$, $r'_1=40\mu m$, $r_1=60\mu m$, $r'_2=80\mu m$ and $r_2=100\mu m$.

Seen here in Figure 3.16 is the effect that $R_E$ measurements will have on the calculation of $\rho_c$ at different values of $\alpha r_0$. It can be shown that for a small difference in the experimentally measured value of $R_E$ the calculated value of specific contact resistance can change dramatically, particularly as $\alpha r_0$ becomes larger. For this reason it becomes far more important to ensure that care is taken in the measurement of $R_E$, particularly at larger values of $\alpha r_0$.

As can be seen in the FEM results presented in Figures 3.10, 3.12, 3.14 and 3.15, the location of testing probes can have an impact on the solutions to the CTLM.
If an equipotential cannot be assured in the structure then any measurements taken should not be considered to be accurate as $\alpha r_0$ increases.

The simplest solution to this problem would be to use several shorted probes placed around the annular ring at an equal distance to draw current from the test structure. This will help to ensure that the entire ring is receiving a uniform supply of current and would remove the differences in electrical potential in the structure that lead to erroneous results. Another solution to this problem is to increase the thickness of the metal layer to ensure that the current is free to move in the metal [Loh et al, 1987]. However for small test structures the lithography and etching required to obtain uniform circular contacts limits the thickness of metal that can be used.

Using a test pattern of comparably larger dimensions would lower the errors introduced by anyequipotential differences. However this would reduce the accuracy of any other measurements on the structure due to previously discussed geometry issues such as the parasitic resistance and equipotential on the annular ring. It is important to note that although the spacing between contacts is constricted by several conditions in order to maintain a useful test structure the dimensions of the annular ring itself does not have a maximum width, however the minimum width should be at least three times larger than the transfer length, and can be designed to eliminate possible errors that may occur from equipotential issues.

### 3.4 Summary

The CTLM test structure has been analysed and simplified such that it requires only one measurement in order to calculate the specific contact resistance of a metal-semiconductor contact. In addition to this a series of recommendations has been made with regard to the planning and design of the CTLM such that results determined are accurate.
Accurate determination of $R_E$ is critical and effective design and use of CTLM for determining $\rho_C$ is the most important issue for CTLM. Considering first the equations for the CTLM as presented by [Reeves 1980] it can be shown that if $R_{SH}$ is known then the calculations become considerably simpler such that only one measurement and two calculations are required to determine a unique result for the specific contact resistance. Following from this the issues that may have arisen due to the parasitic resistance between contacts or the voltage equipotential on the annular ring have been addressed. These problems can both be solved with careful planning in the design of the geometry used to construct the CTLM test structure. Recommendations for the geometries have been presented and discussed.
A semiconductor device typically does not remain at one temperature when operating and hence, parameters such as specific contact resistance ($\rho_c$) and contact resistance will vary. The effects of temperature on specific contact resistance and analytical models developed by [Padovani and Stratton, 1966] to describe these effects are discussed. Other significant publications on this topic were presented by [Chang et al., 1970] and [Varahramyan and Verret, 1996]. In this thesis similar experimental work to that reported by the above researchers is reported with 3C-SiC in place of silicon and utilizing recently developed test structures [Pan and Collins et al., 2013] which give increased accuracy in measurements used to determine $\rho_c$.

As semiconductor devices continue to become smaller it will become increasingly important to be able to predict what effect $\rho_c$ will have on these devices and also how this changes with temperature. In theory it is possible for $\rho_c$ to decrease quite rapidly with very small changes in temperature. This change in $\rho_c$ has the potential to change expected operating parameters in semiconductor devices and possibly when considered with other interconnect resistances will define an optimum operating temperature where the total resistances between components on a chip will be minimised. In recent years it is the contact resistance that is dominating parasitic
resistance on a chip rather than line resistance. Note that temperature change may be caused by the ambient temperature in the operating environment (e.g., desktop computer, deck of a ship in the Antarctic Ocean or the jet engine of an aircraft) or the device itself increasing the temperature due to joule heating.

4.1 Thermionic Emission

Metal to semiconductor junctions where the semiconductor has a relatively low doping will have a specific contact resistance that is controlled by thermionic emission (TE). At low doping concentration $\rho_c$ is controlled primarily by thermionic emission. The equation to describe this was developed by [Chang et al., 1970] and is expressed as follows

$$\rho_c = \frac{k}{qA^*T} e^{\frac{q\phi_B}{kT}}$$

(4.1)

where $k$ is Boltzmann’s constant, $q$ is the charge on an electron, $A^*$ is the effective Richardson’s constant and $\phi_B$ is the barrier height between the metal and semiconductor. It can be seen from this equation that $\rho_c$ will decrease with an increase in temperature.

Figure 4.1 shows $\rho_c$ as it varies with temperature for different barrier heights (using equation 4.1). As the barrier height decreases, so does the value of $\rho_c$ due to electrons requiring less energy to pass over the energy barrier. When comparing the value of $\rho_c$ with temperature it is observed that as more energy is supplied to the electrons, a greater percentage of electrons will pass over the barrier due to their increase in potential energy. Figure 4.1 shows that at 500 °K the specific contact resistance for a barrier height of 0.2 V, is very low and this is independent of doping.
The figures indicate that operating at high temperature is beneficial considering only specific contact resistance.

Figure 4.2 represents the same data set whilst comparing $\rho_c$ to the barrier height. This figure clearly shows the dependence of $\rho_c$ on the barrier height at different temperatures. Therefore, when operating in the thermionic region the value of $\rho_c$ is dependent on both temperature and barrier height, both to a significant degree.

![Figure 4.1](image.png)

**Figure 4.1** Plot of $\rho_c$ vs Temperature for thermionic emission with energy barriers ($\phi_B$) as stated. Here, $A^*$ is equal to 194.1 (m$^2$/m) A/cm$^2$K$^2$ [Byeung 2008]. Plots derived from equation (4.1)
Figure 4.2 Plot of $\rho_c$ vs Energy Barrier ($\phi_B$) for thermionic emission with Temperature ($^\circ$K) as stated. Here, $A^*$ is equal to $194.1(\text{m}^*/\text{m}) \text{ A/cm}^2\text{K}^2$ [Byeung 2008]. Plots derived from equation (4.1)

4.2 Field Emission

For samples that have been doped to a relatively high level, electron transport is controlled by field emission (FE) which occurs when the energy barrier between materials is thin enough such that electrons may ‘tunnel through’ instead of passing over.

The relationship given by [Chang et al., 1970] for the determination of $\rho_c$ as doping increases is
\[ \rho_c \sim \left( \frac{1}{E_{00}} \right) e^{(qV_{bo}/E_{00})} \]  

(4.2)

where \( qV_{bo} \) is the built in potential and the energy level \( E_{00} \) is expressed as

\[ E_{00} = \frac{\hbar}{2} \left( \frac{N}{\varepsilon_s m^*} \right) \]  

(4.3)

where \( \hbar \) is the reduced Planck constant \((\hbar/2\pi)\), \( N \) is the doping concentration of the semiconductor, \( \varepsilon_s \) is the electrical permittivity of the semiconductor and \( m^* \) is the effective mass of the majority carrier.

It should be noted that \( qV_{bo} \) is approximately equal to the energy barrier \( q\phi_B \) when the image lowering is neglected due to its negligible effect on the calculations. It can be seen in this equation that the value of \( \rho_c \) is independent of temperature when in the tunnelling range and is therefore controlled by the amount of doping.

Seen in Figure 4.3 is an example of \( \rho_C \) plotted over a range of doping concentration for various barrier heights. As can be seen, when the doping concentration is below approximately \( 10^{18} \) cm\(^{-3} \), \( \rho_c \) does not change much with doping concentration. This is caused by \( \rho_c \) having a greater dependence on temperature than doping concentration. However, as the doping increases it is seen to have a dramatic effect on the value of \( \rho_c \) as the dependence shifts from temperature to doping where it will become almost entirely dependent on doping regardless of barrier height or temperature. This is evidenced by the different curves shown for the barrier height as each starts with a dramatically different value. As the doping increases and tunnelling becomes the majority transport mechanism, the dependence on the barrier height reduces as a larger percentage of electrons tunnel instead of passing over the energy barrier.
Figure 4.3 Plot of $\rho_c$ vs Doping Concentration with Barrier Heights as stated. Temperature used is 300K. $A^*$ is 194.1 (m*/m) A/cm$^2$K$^2$ [Byeung 2008] and $m^*$ is 0.25$m_0$. Figure plotted with Equation 4.2.

4.3 Thermionic Field Emission

As the doping level increases the relationship between thermionic and field emission becomes more complex as field emission has an increasingly dominant effect. This is described as thermionic-field emission (TFE) where some electrons are thermally excited to an energy level where they can tunnel through the energy barrier (where it gets suitably narrow) without having to passing over.

Further work by [Varahramyan and Verret, 1996] has developed the equations presented by [Chang et al, 1970] into a simpler theory on electron transport across a
metal semiconductor junction. This was accomplished by considering the similarities between the equations for thermionic emission at low doping and field emission at high doping. They have proposed the following equation to calculate $\rho_c$ for TFE and FE mechanisms of electron transport including TFE.

$$\rho_c = \frac{k}{qA^*T} \tilde{e} e^{\frac{a\phi_B}{E_0}}$$  \hspace{1cm} (4.4)

where $\tilde{e}$ is equal to either $c_{TE} (=1)$ for thermal emission, $c_{TFE}$ for thermionic field emission or $c_{FE}$ for field emission.

$$c_{TFE} = \frac{kT}{\sqrt{\pi(q\phi + u_F)E_0}} \cosh \left(\frac{E_0}{kT}\right) \sqrt{\coth \left(\frac{E_0}{kT}\right)} \times e^{\left(\frac{u_F u_F}{E_0}\right)}$$  \hspace{1cm} (4.5)

$$c_{FE} = \left[\frac{\pi}{\sin(\pi bkT)} - e^{-b_\mu_F} \right]^{-1}$$  \hspace{1cm} (4.6)

where $\mu_F$ is the Fermi energy with respect to the energy band edge and the energy level $E_0$ is

$$E_0 = E_{00} \coth \left(\frac{E_{00}}{kT}\right)$$  \hspace{1cm} (4.7)

and $b$ is

$$b = \frac{1}{2E_{00}} \ln \left(\frac{4q\phi_B}{u_F}\right)$$  \hspace{1cm} (4.8)

Equations 4.4 to 4.8 have been presented for thermionic-field and field emission transport mechanisms. In order to determine if the electron transport is defined by FE or TFE the parameter $kT/E_{00}$ is to be evaluated. When $kT/E_{00} \ll 1$ it can be seen that $E_0$ approaches $kT$ and that TE is the primary transport mechanism. When $kT/E_{00} \approx 1$
then TFE would be the dominant effect, otherwise $E_0$ will approach $E_{00}$ and the primary mechanism is determined to be FE. This is evidenced in Figure 4.4 and 4.5.

It should be noted that this equation can also be used to determine specific contact resistivity for the thermal emission region as well. For this to be true then $\bar{c}$ must be equal to $c_{TE} = 1$.

This is true for thermionic emission when $kT/E_{00} \gg 1$ and creates a situation where $E_0 = kT$ such that the equation 4.4 can be used to solve for $\rho_c$ when thermionic emission dominates.

![Calculated values of $E_{00}$, $E_0$ and $kT$ vs Doping Concentration](image)

**Figure 4.4** Theoretical values of $E_{00}$, $E_0$ and $kT$ for SiC plotted over doping concentration. Temperature used is 300 °K and is calculated for 3C-SiC such that $A^*$ is 194.1(m*/m) A/cm²K² [Byeung 2008] and $m^*$ is 0.25$m_0$
Figure 4.5 Theoretical values of $E_0$, $E_{00}$ and $kT$ for SiC plotted over doping concentration. Here it can be seen from equation (4.3) that $E_{00}$ has no dependence on temperature whereas $kT$ will change with temperature and not doping. $E_0$ therefore will be dependent on both doping and temperature relative to the ratio of $kT/E_{00}$.

Equation 4.4 can now be used to calculate all theoretical values for the specific contact resistance on a sample for all three transport mechanisms. This is shown in Figure 4.6 for 3C SiC where both the temperature and doping concentrations are altered to show comparison between the parameters. As can be seen, as the doping concentration increases the sample becomes less dependent on the temperature as the transport mechanism changes from Thermionic emission to Field emission. This is evident when comparing the curves for $10^{20}$ and $10^{21}$ cm$^{-3}$ where little variance with temperature is observed when compared to curves representing the lower doping concentrations. At a doping level of $1 \times 10^{19}$ cm$^{-3}$ the sample would be considered to be
undergoing Thermionic-Field emission and will be influenced by both emission mechanisms.

Figure 4.6 Theoretical values of $\rho_C$ versus Temperature on SiC derived from equation 4.4. $A^*$ is 194.1(m*/m) A/cm$^2$K$^2$ [Byeung 2008] and $m^*$ is 0.25$m_0$. Doping levels are as stated. For this equation $c_{FE}$ was chosen for $c$ because $kT/E_{00} > 1$. Although the lower doping concentrations are controlled by TE, this figure represents the contribution that FE will have at these regions.

As can be seen in Figure 4.5, the calculated values of $E_0$ are highly dependent on both temperature and doping concentration. This reference energy is greatly influenced by temperature when at a low doping region and influenced mainly by doping at a high doping concentration. In practice it would be advisable to solve equation 4.4 with the use of $E_0$ instead of equation 4.1 for all doping concentrations. The reasoning for this measure is due to $E_0$ including the effects of both temperature
and doping concentration. This will effectively be considered TFE and will calculate the contribution of both TE and FE no matter how small the contributions are.

4.4 Summary

Current models for the determination of specific contact resistance and its variance with temperature have been presented and discussed. The most recent model described here has been shown to be universally applicable to all doping concentrations and temperature ranges. As such it will be possible to determine the theoretical and expected values for the specific contact resistance of all metal-semiconductor contacts.

Theoretical solutions for 3C Silicon Carbide undergoing both thermionic and field emission have been presented and discussed. The differences between thermionic and field emission and the interaction between both effects are detailed and discussed. As such it is possible to assume that a sample is operating in the thermionic field emission range of electron transport if it is unknown which electron transport process is in effect.
Chapter 5

Fabrication of Metal-Semiconductor Contact Test Structures

5.1 Mask Design

 Masks for the fabrication test structures were designed using the Cadence Electronic Design Automation (EDA) tool for photolithography in both wet etching and lift off procedures. The layout of these masks can be seen in Figures 5.1 and 5.2. The black regions of the mask represent chromium used to block the UV light used in photolithography techniques while the white section represent the quartz glass which is transparent and will pass the UV light. The relatively smaller features represented on the mask have been placed in the centre to decrease any diffraction errors that may occur through poor contact of the mask during exposure to the UV light.

The two mask designs are identical in geometry however they are inverted with respect to the placement of the chromium so that each may be used in a different patterning technique. The ‘positive’ mask will create contacts where there is no chromium such that the UV light will impact on the section required to create metal contacts through use of a wet-etching technique. The ‘negative’ mask however will block the UV light to where the contacts are to be placed such that it can be used in a lift-off process to create metal contacts.
Figure 5.1 shows the mask designs for the wet-etch procedure. This process involves the use of several liquid chemicals (depending on the number and type of metal layers) to remove metal and finally photoresist from a sample so as to leave behind only the desired contact geometries. After the deposition of metal and photoresist the sample is exposed to UV light that is first passed through the mask which is placed above and in contact with the sample. It is then immersed in several successive chemical solutions to remove the metal(s) and photoresist. Care must be taken to ensure that samples are not left in any chemical bath for too long as due to the nature of the chemicals used to etch it is possible to remove too much material and destroy the metal contacts. The exact procedure undertaken for the fabrication of samples using the wet etch technique is detailed in Section 5.2.

Figure 5.2 presents the mask for use in the lift off technique. This technique was favoured for the experimental work due to its ability to create fabricated patterns with fewer errors due to over etching. For the lift off procedure a sample must first be deposited with photoresist and then exposed with UV light through the mask. Once this has been developed, an inverted image is left behind on the sample. From here metal is deposited over the entire sample to the desired thickness. It is then required to rinse the entire sample in acetone to remove the unexposed photoresist. By removing this photoresist the metal that has been deposited on top will be removed (lifted off) leaving only the metal that is in direct contact with the semiconductor. This process is detailed in Section 5.3.

Simplified diagrams depicting the wet etch and lift off techniques are shown in Figure 5.3.
Figure 5.1 Mask design used in the process of wet etching for the fabrication of metal contacts for the Single Dot test structure onto semiconductor samples. The black regions are the chromium on the mask and the white regions are the quartz glass which is transparent. Numbers on the mask refer to the radius $r_{oi}$ (see Figure 2.7). Three enlarged test structures are shown at the bottom of the figure.
Figure 5.2 Mask design used in the process of lift off for the fabrication of metal contacts for the Single Dot test structure onto semiconductor samples. The black regions are the chromium on the mask and the white regions are the quartz glass which is transparent. Numbers on the mask refer to the radius $r_{01}$ (see Figure 2.7). Three enlarged test structures are shown at the bottom of the figure.
Figure 5.3 Simplified procedure for (a) wet etching using a positive photoresist and (b) lift off etching using a positive photoresist.
A number of metals were evaporated on an epitaxial layer of n-type 3C-SiC which was grown on three inch diameter wafers of p-type Si by low pressure chemical vapor deposition (LPCVD) in a hot wall reactor [Wang et al., 2009]. The film of 3C-SiC was 1.1 µm thick and the p-type Si had a thickness of approximate 300 µm. The two-contact circular test structures were then fabricated using the masks shown in Fig. 5.1 and Fig. 5.2 using either the wet etching or the lift off technique.

5.2 Fabrication of Ni to 3C-SiC Ohmic Contacts

A wafer of 3C-SiC was diced into square pieces to the size of 1×1 cm². In order to ensure that the deposition of metal to the semiconductor is effective without fabrication errors it is necessary to clean the samples of SiC first. This was accomplished with the following procedure.

1. Immerse the sample in AZ100 solvent for 30 minutes at 85°C.

2. Rinse the sample in deionised water for 2 minutes.

3. Immerse the sample in 3% HF for 30 seconds.

4. Rinse the sample in a sequence of acetone, isopropyl alcohol (IPA) and deionised (DI) water.

5. Dry the sample with high purity pressured nitrogen gas.
Once cleaned, the samples were placed into an electron beam evaporation chamber and a layer of nickel was deposited on the 3C-SiC to give a layer of 200nm thickness. The evaporation parameters are shown in Table 5.1. The procedure for patterning using the wet etching technique is as follows:

1. Rinse the sample in a sequence of acetone, IPA and DI water.

2. Bake the sample in an oven for 10 minutes at 110°C for dehydration.

3. Spin on hexamethyldisilazane (HMDS) at 4000 RPM for 10 seconds.

4. Spin on AZ4562 photoresist at 4000 RPM for 15 seconds.

5. Soft bake on the hot plate at 95°C for 90 seconds.

6. Expose the sample using MJB3 mask aligner for 8 seconds.

7. Develop the sample using AZ400K:DI water (1:4) for 10 seconds.

8. Hard bake in an oven at 110°C for 1 minute.

9. Cool the sample down for 5 minutes and etch the sample in Ni etchant (100 ml 70% hydrochloric acid, 50 g (NH₄)₂Ce(NO₃)₆, 150 ml DI water) at room temperature for 30 seconds.

10. Rinse the sample in DI water and dry it using high purity pressured nitrogen gas.
Table 5.1 Electron beam evaporator conditions used for depositing Ni on 3C-SiC.

<table>
<thead>
<tr>
<th>Material</th>
<th>Nickel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>200nm</td>
</tr>
<tr>
<td>Base Pressure</td>
<td>$1.4 \times 10^{-7}$ mbar</td>
</tr>
<tr>
<td>Rate</td>
<td>0.20 nm / sec</td>
</tr>
</tbody>
</table>

Samples were examined under an optical microscope to ensure no defects were present and the patterned photoresist was removed using acetone followed by IPA and DI water. The samples were then dried with compressed nitrogen gas. An initial current-voltage (I-V) test was taken and a linear I-V curve showed that an ohmic contact formed between as deposit Ni and the 3C-SiC film. Fig. 5.5 shows an optical micrograph of sections of the patterns. Note that the 2-D test structure for determining $\rho_c$ and $R_{SH}$ (see Figure 2.7) come as a series of three dot electrodes. In Fig. 5.5 there are eight such patterns, all the same. An optical photograph of the sample is shown in Figure 5.4.
5.3 Fabrication of Ti to 3C-SiC Ohmic Contacts

3C-SiC samples for use with titanium contacts were cleaned and patterned using the same techniques and procedures as the samples used with nickel. The 3C-SiC was similar to that deposited with nickel. The metal deposition conditions are listed in Table 5.2 and the test structure processing details are listed in Section 5.2. An optical photograph of the Ti/3C-SiC test structures is shown in Figure 5.5.
Table 5.2 Electron beam evaporator conditions for Ti on 3C-SiC.

<table>
<thead>
<tr>
<th>Material</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>400nm</td>
</tr>
<tr>
<td>Base Pressure</td>
<td>$1.7 \times 10^{-7}$ mbar</td>
</tr>
<tr>
<td>Rate</td>
<td>0.15 nm / sec</td>
</tr>
</tbody>
</table>

Figure 5.5 Optical micrograph of the two-contact circular test structures fabricated on epitaxial 3C-SiC using the wet etching technique, the metal layer is Ti and the radii of the central electrodes shown are 9 µm, 13.5 µm and 31.5 µm respectively.
5.4 Fabrication of Au/Ni/Ti to Ion Implanted 3C-SiC Ohmic Contacts

Samples of p-type Si with an epitaxial layer of n-type 3C-SiC deposited by low pressure chemical vapor deposition (LPCVD) with the same properties as previous samples were modified by ion implantation and contact test structures were fabricated using the masks designed for the lift off patterning technique.

The n-type 3C-SiC epitaxial layer was 1.1 µm thick with a carrier concentration of $1 \times 10^{20}$ cm$^{-3}$ doped with nitrogen during epitaxial layer formation. The layer of 3C-SiC was implanted with either C or P ions at -196°C using an energy of 5 keV and samples were prepared with doses in the range $10^{13} - 10^{15}$ ions/cm$^2$. These ion species were selected on the basis of calculations using the TRIM (transport and range of ions in matter) software which predicted distinctly different profiles for different energy depositions for P and C ions in SiC. Note that the 3C-SiC epitaxial layer was made n-type during epitaxial growth. The cleaning process is identical to the 3C-SiC samples in the previous section.

Figs. 5.6 and 5.7 show TRIM simulations of the concentration of P and C ions versus depth and the distribution of energy deposition resulting from an implantation at 5 keV into SiC. The TRIM simulation has calculated the cumulative effects of individual ions in their implantation through the substrate. These effects include resulting implanted species concentration profile and damage distribution which is related to energy distribution. In Fig. 5.6, the implanted P ions have been calculated to have a higher level of peak concentration than the C ions. Also, it can be seen that the peak in P concentration in Fig. 5.6 was shown to be at a shallower depth ($4 - 8$ nm) than the peak level of C which was located at $10 - 15$ nm below the surface. Fig. 5.7 shows that the distribution of energy deposition was similar in profile to the ion concentration versus depth in Fig. 5.6. However, the plots in Fig. 5.8 have predicted a slightly shallower depth for the maximum peak than the equivalent peak evident in Fig. 5.6. In Fig. 5.7, the peak in energy deposition was located at 4 nm for P ions and 5 - 10
nm for C. The TRIM simulations have predicted a linear increase in the concentration of implanted P or C ions and the energy deposition with dose. Figs. 5.6 and 5.7 were plotted using a dose of $1 \times 10^{15}$ ions/cm$^2$. It should be noted that the samples have not been heat treated before metal deposition.

**Figure 5.6** TRIM simulation of P and C ion concentrations after implantation into n-type SiC at 5 keV at a dose of $1 \times 10^{15}$ ions/cm$^2$. 
Figure 5.7 TRIM simulation of P and C distribution of energy deposition after implantation into n-type SiC at 5 keV at a dose of $1 \times 10^{15}$ ions/cm$^2$.

The test structures were first cleaned as detailed in section 5.2 and then patterned using the lift off technique as follows:

1. Bake the samples in the oven for 10 minutes at 110°C for dehydration.

2. Spin on AZ1512 photoresist at 3000 RPM for 20 seconds.

3. Soft bake on the hot plate at 95°C for 90 seconds.
4. Expose the samples using MJB3 mask aligner for 8 seconds.

5. Immerse the samples into chlorobenzene for 1 minute.

6. Rinse the samples in DI water for 3 minutes to remove the chlorobenzene.

7. Develop the samples using AZ400K:DI water (1:4) for 25 seconds.

8. Rinse the samples in DI water and dry it using high purity pressured nitrogen gas.

After that, the samples were examined under an optical microscope and loaded into an evaporation chamber and Ti, Ni and Au layers, each of thickness 50 nm were deposited on the SiC layer in sequence by electron beam evaporation. In order to provide a usable contact Ti was chosen because it will reliably form an ohmic contact with SiC [Mochizuki et al., 1994] without any heat treatment. It was decided to add Ni on to the Ti to improve the thermal stability [Chang et al., 2005] of the Ti SiC contacts and finally Au was placed on top to provide protection against oxidation [Alok et al., 1993] to any of the layers below and improve experimental probing.

The evaporation conditions are shown in Table 5.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Gold</th>
<th>Nickel</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>50 nm</td>
<td>50 nm</td>
<td>50 nm</td>
</tr>
<tr>
<td>Base Pressure</td>
<td>4.0×10^{-7} mbar</td>
<td>2.6×10^{-7} mbar</td>
<td>3.9×10^{-7} mbar</td>
</tr>
<tr>
<td>Rate</td>
<td>0.20 nm/sec</td>
<td>0.10 nm/sec</td>
<td>0.10 nm/sec</td>
</tr>
</tbody>
</table>
Lift off was completed by immersing the samples into acetone in an ultrasonic bath for approximately one minute. The samples were then rinsed with acetone, IPA and DI water followed by blowing dry with high purity pressured nitrogen gas. After examining the patterns under an optical microscope, all the samples (ion implanted with doses in the range $10^{13} - 10^{15}$ ions/cm$^2$) were taken for I-V testing. The linear I-V curves showed that ohmic contacts exists on all the samples (for as-deposited Au/Ni/Ti on ion implanted damaged 3C-SiC). An optical photograph of the Au/Ni/Ti contacts on 3C-SiC is shown in Figure 5.9

![Optical micrograph of the two-contact circular test structures fabricated on epitaxial 3C-SiC using the lift off technique, the metal layer is Ti/Ni/Au and the radii of the central electrodes shown are 14 µm, 21 µm and 49 µm respectively.](image)

**Figure 5.9** Optical micrograph of the two-contact circular test structures fabricated on epitaxial 3C-SiC using the lift off technique, the metal layer is Ti/Ni/Au and the radii of the central electrodes shown are 14 µm, 21 µm and 49 µm respectively.
5.5 Summary

Fabrication of test structures was undertaken on n-type epitaxial 3C-SiC using Ti, Ni metal contacts. Further, Ti/Ni/Au metal contacts were fabricated to ion implanted SiC to observe the effects of ion implantation on electron transport characteristics. This has been accomplished using a wet etching or lift off technique. Fabrication details are described in detail as were the masks used in the process. Linear I-V characteristics were observed and the samples have been used for electrical testing as reported in the next chapter.
Chapter 6

Thermal Effects on Electrical Testing

Results and Analysis

For measurements of fabricated samples an experimental environment was setup, consisting of three micro-manipulators with probe tip radius of 0.6 µm, a Keithley 2410 current source which is capable of determining the voltage concurrently with current supply and an optical microscope with a maximum magnification of ×250. As shown in Fig. 6.1, the structure is placed underneath the microscope lens with micro-manipulators placed on the outer edge. 1 µA is supplied by the Keithley 2410 and simultaneously, the voltage difference between the two metal electrodes is shown. From this information the total resistance between the electrodes can be calculated. The current-voltage (I-V) characteristic between the electrodes can be observed on a computer by connecting the Keithley 2410 and using the LabTracer software supplied by Keithley Instruments Inc.

In order to heat the contact test structures, a heating element was placed beneath the sample such that the sample was resting on top in direct contact. A thermistor was placed on the semiconductor directly to measure the temperature and this reading was taken on a FLUKE 287 Multimeter.
Figure 6.1 Equipment setup for the two-contact circular test structure to determine the total resistance between the two electrodes.
Three different sets of test structures were patterned on each sample with geometries as described below in Table 6.1. The radius of the central dot contact of these patterns range from 9 µm to 13 µm in order to gain a wide range of experimental data. Multiple resistance readings were taken from each structure at 25º C, 50º C, 100º C, and 150º C and the resistance measurements were then converted into $\rho_C$ values as detailed by [Pan and Collins et al.,2013].

The samples were first determined to be ohmic by observing that the I-V curves were linear through the origin. The values of $\rho_C$ determined from the resistance measurements taken from test structures on each sample are presented in the following sections.

![Figure 6.2 Top - Test pattern schematic of dot and ring used to determine specific contact resistance. Various gap sizes as detailed in Table 1 were used for testing. Bottom – Photograph of fabricated samples on 3C-SiC](image)

A schematic of the test structure is given in Figure 6.2. It consists of three different two-contact circular patterns which have different radii of the central
dot \( r_{01} \), \( r_{02} \) and \( r_{03} \) and the same inner and outer radii \( r_1 \) and \( r'_1 \) for the outer electrode. The metal electrodes are assumed to be each at equipotentials in the model.

**Table 6.1** Geometry of the Single Dot test structure used to experimentally determined specific contact resistance for all sample types.

<table>
<thead>
<tr>
<th>Structure</th>
<th>( r_{01} )</th>
<th>( r_{02} )</th>
<th>( r_{03} )</th>
<th>( r_1 )</th>
<th>( r'_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure 1</td>
<td>9</td>
<td>14.5</td>
<td>31.5</td>
<td>47.25</td>
<td>315</td>
</tr>
<tr>
<td>Structure 2</td>
<td>12</td>
<td>18</td>
<td>42</td>
<td>63</td>
<td>420</td>
</tr>
<tr>
<td>Structure 3</td>
<td>13</td>
<td>19.5</td>
<td>45.5</td>
<td>68.25</td>
<td>455</td>
</tr>
</tbody>
</table>

**6.1 Ti Contacts – SCR variation with temperature**

Samples of SiC that were deposited with titanium, patterned into an array of single dot test structures, electrically tested and have had the specific contact resistance calculated from results. The test was conducted with 10\(\mu\)A of current passed from the centre electrode to the outer ring. Voltage was then measured from the same two points using the Keithley 2410 and using the LabTracer software to record results. From here the resistance between each set of metal contacts was determined and the results processed to determine \( \rho_C \). These results are seen in Table 6.2.
Table 6.2 Experimental results for $\rho_C$ using the two-contact circular test structure for as-deposited Ti to 3C-SiC. The Ti layer and the 3C-SiC layer have thicknesses of 400 nm and 1.1 µm respectively. The 3C-SiC layer was lightly doped. Current used was 10 µA.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$1.9 \times 10^{-2}$</td>
<td>$1.8 \times 10^{-2}$</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>50</td>
<td>$7.0 \times 10^{-3}$</td>
<td>$6.8 \times 10^{-3}$</td>
<td>$6.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>100</td>
<td>$6.1 \times 10^{-4}$</td>
<td>$6.5 \times 10^{-4}$</td>
<td>$6.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>150</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$1.4 \times 10^{-4}$</td>
<td>$1.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

It can be seen that as the temperature increases the calculated value of specific contact resistance lowers following the theoretical expressions of equation 4.4 using $c_{TFE}$ for $\bar{c}$. The calculated values of $\rho_C$ for the-SiC sample with Ti contacts show average values of $1.9 \times 10^{-2} \, \Omega \, cm^2$ at 30 °C, $6.8 \times 10^{-3} \, \Omega \, cm^2$ at 50 °C, $6.4 \times 10^{-4} \, \Omega \, cm^2$ at 100 °C, and $1.4 \times 10^{-4} \, \Omega \, cm^2$ at 150 °C. From this it has been determined that the contacts are operating in the thermal emission region primarily due to the low doping and high dependence on temperature of the specific contact resistance measured as shown in Figure 6.3. This sample can be seen to have $\rho_c$ varying by two orders of magnitude across the temperature range investigated.
Figure 6.3 - SCR vs. temperature at measured values with expected analytical curves for the 3C-SiC sample with low doping and Ti contacts. Shown here is a theoretical curve for a $q\phi_B$ value of 0.42eV and a doping concentration of approximately $1 \times 10^{16} \text{cm}^{-3}$. The theoretical curve is from equation 4.4 for thermionic emission. Data is also listed in Table 6.2.

6.2 Ni Contacts—Specific Contact Resistance variation with temperature

Samples of-SiC that were deposited with Nickel have been experimentally tested and have had the specific contact resistance calculated from results. The test was conducted with 10µA of current passed from the centre electrode to the outer ring.
Voltage was then measured from the same two points using the Keithley 2410 and using the LabTracer software to record results. From here the resistance between each set of metal contacts was determined and the results calculated for $\rho_C$. The determined values of $\rho_C$ are presented in Table 6.3

**Table 6.3** Experimental results for $\rho_C$ at different temperatures using the two-contact circular test structure for as-deposited Ni to epitaxial 3C-SiC. The Ni layer and the 3C-SiC layer have thicknesses of 200 nm and 1.1 µm respectively. The 3C-SiC layer was very heavily doped with nitrogen to give an n-type doping concentration of $1 \times 10^{20}$ cm$^{-3}$.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 °C</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$1.3 \times 10^{-6}$</td>
<td>$1.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>50 °C</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$1.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>100 °C</td>
<td>$8.1 \times 10^{-7}$</td>
<td>$1.1 \times 10^{-6}$</td>
<td>$9.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>150 °C</td>
<td>$6.0 \times 10^{-7}$</td>
<td>$7.1 \times 10^{-7}$</td>
<td>$8.0 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

As with the titanium contacts it is seen that as the temperature increases the calculated value of specific contact resistance reduces following the theoretical expressions of equation 4.4 using $c_{TFE}$ for $\bar{c}$. The calculated values of $\rho_C$ for the SiC sample with Ni contacts show average values of $1.2 \times 10^{-6}$ Ω cm$^2$ at 30 °C, $1.2 \times 10^{-6}$ Ω cm$^2$ at 50 °C, $9.6 \times 10^{-7}$ Ω cm$^2$ at 100 °C, and $7.0 \times 10^{-7}$ Ω cm$^2$ at 150 °C. From this it has been determined that the contacts are operating in the field emission region primarily due to the high doping and low dependence on temperature of the specific contact resistance measured as shown in Figure 6.4.

Although the barrier height is different in the Nickel and Titanium samples it is evident that the cause of the change from Thermionic emission to Field emission is
caused primarily by the doping concentration of the semiconductor. This observation is in agreement with theoretical data gained from calculating equation 4.4 and Figures 4.3 and 4.6.

Figure 6.4 - SCR vs. temperature at measured values with expected analytical curves for the 3C-SiC sample with low doping and Ti contacts. Shown here is a theoretical curve for a $q\Phi_B$ value of 0.72eV and a doping concentration of $1 \times 10^{20} \text{cm}^{-3}$. The theoretical curve is from equation 4.4 for field emission. Data is also listed in Table 6.3.
6.3 Ni/Ti/Au Contacts to ion implantation damaged-SiC – specific contact resistance variation with temperature

The calculated values of $\rho_C$ for the sample damaged with Phosphorous implantation are listed in Table 6.4 and show average values of $2.0 \times 10^{-4}$ $\Omega$ cm$^2$ at 25 ºC, $1.4 \times 10^{-4}$ $\Omega$ cm$^2$ at 50 ºC, $8.5 \times 10^{-5}$ $\Omega$ cm$^2$ at 100 ºC, and $5.4 \times 10^{-5}$ $\Omega$ cm$^2$ at 150 ºC. This demonstrates a decrease in value of $\rho_C$ by a factor of 3.7 over the 125 ºC range that the experiment was conducted.

Table 6.4 Experimental results for $\rho_C$ using the two-contact circular test structure for as-deposited Ni/Ti/Au contacts to n-type 3C-SiC that has been ion implantation damaged with Phosphorous. The Ti, Ni and Au layers have a thickness of 50nm each and the 3C-SiC layer has a thicknesses of 1.1 µm. The 3C-SiC layer was implanted with phosphorous as detailed in chapter 5.

<table>
<thead>
<tr>
<th>Temp (C)</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 º</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$2.7 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>50 º</td>
<td>$1.4 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>100 º</td>
<td>$7.0 \times 10^{-5}$</td>
<td>$10.1 \times 10^{-5}$</td>
<td>$8.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>150 º</td>
<td>$6.0 \times 10^{-5}$</td>
<td>$5.4 \times 10^{-5}$</td>
<td>$4.9 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

In the same way the average values of specific contact resistance was determined for the sample ion implantation damaged with carbon from data in Table 6.5 are $1.4 \times 10^{-4}$ $\Omega$ cm$^2$ at 25 ºC, $7.0 \times 10^{-5}$ $\Omega$ cm$^2$ at 50 ºC, $1.8 \times 10^{-5}$ $\Omega$ cm$^2$ at 100 ºC and $5.9 \times 10^{-6}$ $\Omega$ cm$^2$ at 150 ºC. There is a decrease by a factor of 23.6 over a range of 125 ºC which shows a dramatic change in the values of $\rho_C$. These results indicate a large shift in the
value of $\rho_C$ when measured at different temperatures. The sample implanted with phosphorous has the potential to be lowered further with increases in temperature, where the carbon sample shows at least two orders of magnitude.

**Table 6.5** Experimental results for $\rho_C$ using the two-contact circular test structure for as-deposited Ni/Ti/Au contacts to n-type 3C-SiC that has been ion implantation damaged with Carbon. The Ti, Ni and Au layers have a thickness of 50nm each and the 3C-SiC layer has a thickness of 1.1 µm. The n-type 3C-SiC layer has been ion implantation damaged with carbon as detailed in chapter 5.

<table>
<thead>
<tr>
<th>Temp (C)</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 °C</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>50 °C</td>
<td>$7.0 \times 10^{-5}$</td>
<td>$5.5 \times 10^{-5}$</td>
<td>$8.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>100 °C</td>
<td>$1.7 \times 10^{-5}$</td>
<td>$2.2 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>150 °C</td>
<td>$6.0 \times 10^{-6}$</td>
<td>$7.4 \times 10^{-6}$</td>
<td>$4.0 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Figures 6.5 and 6.6 graphically represent the decreasing trend of $\rho_C$ in relation to temperature for the samples implanted with phosphorous and carbon respectively. Metal contacts for each as detailed previously. Experimental data points are plotted against theoretical data for the sample that was implanted with carbon. The theoretical data was calculated from equation 4.4 with $A^*$ being referenced as 194.1 A/cm² K² [Byeung 2008]. From this it is possible to match $q\phi_B$ as a curve of best fit to the experimental data.

It is observed from these results that the sample implanted with phosphorous exhibited a field emission type relationship with regards to $\rho_C$ while the carbon implanted sample shows a thermionic emission type relationship. A possible
explanation for this is suggested by Figures 5.6 and 5.7 detailing the implantation depth and concentrations for each sample. The sample implanted with phosphorous shows a peak concentration at 4 – 8 nm while the carbon is at 10 – 15 nm. Likewise the phosphorous sample has a peak concentration of $1.3 \times 10^{21} \text{cm}^{-3}$ and the carbon sample at $6.0 \times 10^{20} \text{cm}^{-3}$. For these reasons it is thought that the phosphorus is exhibiting a narrow depletion region that is very close to the surface and as such allowing electrons to tunnel through. The carbon samples however, with its deeper implant peak region, likely requires electrons to be thermally emitted over the contact energy barrier.

Figure 6.5 - SCR vs. temperature at measured values with expected analytical curve for metal contacts of Ti/Ni/Au to the sample implanted with Phosphorus with a $q\phi_B$ value shown of 0.28eV and a doping concentration of $1 \times 10^{20} \text{cm}^{-3}$. Theoretical curve has been plotted with Equation 4.4 using field emission.
Figure 6.6 - SCR vs. temperature at measured values with expected analytical curve for metal contacts of Ti/Ni/Au to the sample implanted with Carbon with a $q\phi_B$ value shown of 0.3eV and a doping concentration of approximately $1 \times 10^{16}cm^{-3}$. Theoretical curve have been plotted with Equation 4.4 using thermal emission.

As is clearly observed from the results any changes in the operating temperature of a semiconductor device may have a large effect on the $\rho_C$ value for the metal-semiconductor contact. This effect will be easily apparent as devices change from room temperature operation. For this reason it is clear that $\rho_C$ should be reported with the temperature (or preferably variation of specific contact resistance determined over a practical temperature range) that it was measured at in order to effectively design and simulate new devices and their operating characteristics.
6.4 Summary

This chapter has presented electrical testing results for specific contact resistance of samples with different metal contacts to 3C-SiC at different temperatures. These results clearly show the relationship that specific contact resistance has with temperature for both thermionic emission and field emission. The results show good agreement with theoretical expectations.

The values of $\rho_C$ for Ni to 3C-SiC (with heavy doping at a concentration of $1 \times 10^{20}$ cm$^{-3}$ and a thickness of 1.1 µm) ohmic contacts were determined to be $1.9 \times 10^{-2}$ Ω cm$^2$ at 30 °C and $1.4 \times 10^{-4}$ Ω cm$^2$ at 150 °C. Values of $\rho_C$ for Ti to 3C-SiC (with light doping and a thickness of 1.1 µm) ohmic contacts were determined to be $1.2 \times 10^{-2}$ Ω cm$^2$ at 30 °C and $7.0 \times 10^{-7}$ Ω cm$^2$ at 150 °C. The effect that low energy implantation damage with P or C ions to 3C-SiC (doped at a concentration of $1 \times 10^{20}$ cm$^{-3}$ and has thickness of 1.1 µm) on the properties of Ti/Ni/Au contacts has been examined for doses in the range $10^{13} - 10^{15}$ ions/cm$^2$. These samples displayed thermionic emission for the sample implanted with C and field emission for P. The explanation for this difference is possibly the effect of the effective depth of the high carrier concentration region being relatively deeper for the C ion implanted sample and smaller for the P ion implanted sample such that the transport mechanism of electrons changes from thermal emission to field emission due to a narrower energy barrier for charge-transport across the metal–semiconductor junction.
Chapter 7

Conclusion and future research

7.1 Conclusion

This thesis has presented a new solution to an established test structure, the circular transmission line model, used to determine the specific contact resistance of a metal-semiconductor junction. Concerns regarding sources of error in the structure have been addressed and theoretical solutions to these errors are presented.

In addition to this a complete series of equations are presented for the calculation of specific contact resistance for all electron transport mechanisms. These equations have been solved for several metal-semiconductor junctions on 3C-SiC.

1. Reduction of the existing CTLM equations

The established equations for the CTLM has been analysed from first principles of metal-semiconductor junctions and solved to a similar yet compact state. The most noticeable difference is that the CTLM now requires only one measurement, that of $R_g$, to determine a unique value of specific contact resistance. The equations introduce no new errors and are experimentally robust when utilized within normal operating parameters.
2. CTLM corrections

Potential sources of error within the CTLM structure have been identified and mitigated through careful planning and design as well as experimental testing procedures.

3. Temperature equations

Electron transport across metal-semiconductor equations have been presented in a complete form containing all possible doping regimes across all temperature ranges. The equations have been solved theoretically regarding 3C-SiC for all electron transport mechanisms.

4. Temperature effects on SiC

The effect of temperature of 3C-SiC has been experimentally investigated using the original equations and simplified equations for the CTLM and the novel single dot test structure. These results have been compared and reported.

5. Concerns about reporting SCR at temperature

Current methods for the reporting of specific contact resistance have been incomplete and as such a new standard is proposed. This standard involves quoting the value determined for specific contact resistance not only for the metal-semiconductor pairings but also for the temperature that the result was determined for.
7.2 Specific Contact Resistance of 3C-SiC

Several results of electron transport over metal-semiconductor junctions on 3C Silicon Carbide have been reported. This data has been fitted to curves representing both thermionic emission and field emission conditions. A good agreement between theoretical and experimental results has been achieved.

Samples of Ti contacts on lightly doped 3C-SiC and Ni/Ti/Au contacts on carbon implanted 3C-SiC exhibited a thermionic relationship when comparing $\rho_C$ to temperature. The samples of Ti ranged from $2.0 \times 10^{-2}$ at 30 ºC to $1.4 \times 10^{-4}$ at 150 ºC which shows a change of two orders of magnitude. The samples implanted with carbon displayed a similar relationship with $\rho_C$ varying from $1.5 \times 10^{-4}$ at 30 ºC to $4.0 \times 10^{-6}$ at 150 ºC which also showed a change of two orders of magnitude.

The samples with Ni contacts on highly doped 3C-SiC and Ni/Ti/Au contacts on phosphorous implanted 3C-SiC displayed a field emission relationship when comparing $\rho_C$ to temperature. The samples of Ni ranged from $1.3 \times 10^{-6}$ at 30 ºC to $6.0 \times 10^{-7}$ at 150 ºC which shows a low dependence on temperature with regards to $\rho_C$. Similarly, the Ni/Ti/Au contacts on phosphorous implanted 3c-SiC ranged from $2.7 \times 10^{-4}$ at 30 ºC to $4.9 \times 10^{-5}$ at 150 ºC displaying a low dependence on temperature for $\rho_C$.

7.3 Future Research

7.3.1 Joule Heating

Although it is possible to calculate the behaviour of specific contact resistance at different temperatures the sources of the temperature change could be unknown. As such it is currently difficult to know if the temperature is being altered by the environmental effects surrounding the contact or if it may be internally caused by joule heating due to the current flow in the contact itself. This can be observed where a device
may be at a higher temperature than the ambient temperature of the room. Therefore it would be beneficial to determine how joule heating does in fact alter the temperature of a device to a degree where the specific contact resistance may be modified. If this does occur then further research should be taken into consideration.

In particular for joule heating it should be noted that when the specific contact resistance is altered then there is the possibility for the current to increase such that Ohm’s Law is satisfied. As such this increase in current may cause an increased heating effect and cause a further variance in specific contact resistance. This phenomenon may at some stage reach a steady state however it is currently unknown if or when this will happen.

7.3.2 Barrier height determination

Current methods for the determination of barrier height between materials are the Current-Voltage relationship of a metal-semiconductor junction and the Capacitance-Voltage relationship. These two methods do not always result in the same value however and as such cannot be assumed to always be correct.

Test structures for the determination of specific contact resistance have the possibility of also determining the barrier height between materials. The electron transport equations include this parameter and it is therefore required to know the barrier height to solve them. However, if the specific contact resistance is determined from an alternate method then it would be possible to calculate the barrier height from these equations.
Appendices

Appendix A

Functions for use in the CTLM test structure

\[ A(r, x) = I_1(ar).K_0(ax) + I_0(ax).K_0(ar) \]

\[ B(r, x) = I_1(ax).K_0(ar) + I_0(ar).K_1(ax) \]

\[ C(r, x) = I_1(ar).K_1(ax) + I_1(ax).K_1(ar) \]

\[ D(r, x) = I_0(ax).K_0(ar) + I_0(ar).K_0(ax) \]

\[ E(r) = I_0(ar)/I_1(ar) \]
Appendix B

MatLab Code for the determination of the CTLM test structure.

clear all  %clears all data for new calculations
smooth=0.01;  %sets the degree of accuracy *smaller is better
ar0=0:smooth:10-smooth;  %sets the window size of ar0 and corrects to nearest 10

% these radii will need to be entered in meters
r0=20e-6;  %Radius of centre dot contact
r1p=40e-6;  %Inner radius of first ring contact
r1=60e-6;  %Outer radius of first ring contact
r2p=80e-6;  %Inner radius of second ring contact
r2=100e-6;  %Outer radius of second ring contact

Re=1;  % User input of contact end resistance
Res1=304.0198;  % User input of first gap resistance
Res2=112.7068;  % User input of second gap resistance

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                       End of User Input                      %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ar1p=r1p/r0*ar0;  %This will create an array of values for alpha x r1p
ar1=r1/r0*ar0;  %This will create an array of values for alpha x r1
ar2p=r2p/r0*ar0;  %This will create an array of values for alpha x r2p
ar2=r2/r0*ar0;  %This will create an array of values for alpha x r2

% the values above are used in Bessel functions. Because alpha is unknown
% it is necessary to calculate these using the difference ratio between
% each radius

% This block will calculate the Bessel functions used in the body
% of the equations. These are calculated for all possible values of
% ar0.
A=besseli(1,ar1).*besselk(0,ar1p)+besseli(0,ar1p).*besselk(1,ar1);
A2=besseli(1,ar2).*besselk(0,ar2p)+besseli(0,ar2p).*besselk(1,ar2);
B=besseli(1,ar1p).*besselk(0,ar1)+besseli(0,ar1).*besselk(1,ar1p);
C=besseli(1,ar1).*besselk(1,ar1p)-besseli(1,ar1p).*besselk(1,ar1);
C2=besseli(1,ar2).*besselk(1,ar2p)-besseli(1,ar2p).*besselk(1,ar2);
D=besseli(0,ar1p).*besselk(0,ar1)-besseli(0,ar1).*besselk(0,ar1p);
E=besseli(0,ar0)./besseli(1,ar0);
% This block will calculate the RHS of phi for all possible alpha values 
% It has been broken up in parts to make it easier to code 
% Uses the Bessel functions created above 
% Is calculated across entire window length 
phi=log(r2p/r1)*((E./ar0)+(1./ar1p).*((A./C)); 
phi=phi-(log(r1p/r0)*((1./ar1).*((B./C)+(1./ar2p).*((A2./C2)))); 
phi=phi./(((A.*B)./C)+D); 

% phid is the LHS of phi. Uses resistance to acquire one value. 
% This value is used in phi to determine alpha and delta 
phid=(log(r2p/r1)*Res1-log(r1p/r0)*Res2)/Re; 

% delta can be calculated here. delta will be used in the calculation 
% of rho. Is calculated across entire window length for graphing purposes 
% phi will be used to give alpha which will give delta a unique value. 
delta=(2*pi)./((ar0.*ar0).*phi); 
delta=delta./(((A.*B)./C)+D); 

figure(1) % First Graph. Phi and Delta 
semilogy(ar0,phi) % plots phi vs ar0 and sets y axis to log scale 
ylim([0 1000]) % sets y axis limits 0 - 1000 
hold all % Allows more graphs on same plot 
plot(ar0,delta) % plots delta vs ar0 
title(’phi / delta vs ar0’);xlabel(’ar0’);ylabel(’phi / delta’); 
grid on % Turns on grid for ease of viewing 

% this line will calculate all possible values of rho 
% across the window length. this is the last graph shown. 
% will also give the final answer for specific contact resistance 
% NOTE THAT THIS IS IN METERS SQUARED 
rhoc=(log(r2p/r1)*Res1-log(r1p/r0)*Res2)*r0*r0.*delta; 

% this loop will give the approximation for alpha 
% this is done by checking when phid and phi are equal across the window 
% length 
% a=2; 
% while phi(a) < phid 
% a=a+1; 
% end 

% a is now alpha. Note that it has been corrected for the window size 

phi=phi(a); % gives value of phi at alpha 
delta=delta(a); % gives value of delta at alpha 

% rhoc is the calculated value of rho (specific contact resistance) 
rhoc=(log(r2p/r1)*Res1-log(r1p/r0)*Res2)*r0*r0.*delta; 
rhoc=rhoc*10^4 % corrected rho value in cm^2 

figure (2) % second plot
hold on  % as before
plot(ar0,rho*1e4)  % plots rho vs ar0 and corrects to cm^-2
title('rho vs ar0');xlabel('ar0');ylabel('rho');
hold off  % ends plotting
Appendix C

Matlab code for reduced equations of CTLM

clear all %clears all data for new calculations
smooth=0.01; %sets the degree of accuracy *smaller is better
ar0=0:smooth:10-smooth; %sets the window size of ar0 and corrects to nearest 10
r0=20e-6; %Radius of centre dot contact
r1p=40e-6; %Inner radius of first ring contact
r1=60e-6; %Outer radius of first ring contact
r2p=80e-6; %Inner radius of second ring contact
r2=100e-6; %Outer radius of second ring contact
Rsh=30; %Sheet resistance of the semiconductor

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                       End of User Input                      %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

alpha=a.r0./r0; %Creates an array for alpha that can be used for determining Re
%Not required if Re is known
ar1p=r1p/r0*ar0; %This will create an array of values for alpha x r1p
ar1=r1/r0*ar0; %This will create an array of values for alpha x r1
ar2p=r2p/r0*ar0; %This will create an array of values for alpha x r2p
ar2=r2/r0*ar0; %This will create an array of values for alpha x r2

% This block will calculate the Bessel functions used in the body % of the equations. These are calculated for all possible values of % ar0.
E1=besseli(0,ar0)./besseli(1,ar0);
E2=besseli(0,ar1)./besseli(1,ar1);
F1=besselk(0,ar1p).besselk(1,ar1p);
F2=besselk(0,ar2p).besselk(1,ar2p);
C=besseli(1,ar1).*besselk(1,ar1p)-bessel(i,ar1p).*besselk(1,ar1);

Re=(Rsh./(2.*pi.*C.*(r1.*r1p).*alpha.*alpha)); %Calculation of all possible Re values for alpha
rho=(Re.*2*pi.*C.*r1*r1p); %Calculation of specific contact resistance for all possible values of Re
Appendix D

Matlab code for the determination of specific contact resistance versus doping concentration.

\[
\begin{align*}
h &= 4.13 \times 10^{-15} \text{ eV} \\
k &= 8.61 \times 10^{-5} \text{ eV} \\
q &= 1.6 \times 10^{-19} \text{ C} \\
m &= 0.25 \times 9.109 \times 10^{-31} \text{ kg} \\
e &= 1.04 \times 10^{-16} \text{ F}
\end{align*}
\]

\[
\begin{align*}
N &= \text{logspace}(16, 21, 100); \\
T &= 300; \\
A &= 194.1; \\
E00 &= \left(\frac{q h}{4 \pi}\right) \sqrt{\frac{N}{e m}}; \\
E0 &= E00 \times \coth\left(\frac{E00}{k T}\right)
\end{align*}
\]

\[
\begin{align*}
c &= 0.02:0.02:1; \\
c &= 1; \\
\phi &= 0.3; \\
Rc &= \left(\frac{k}{A T}\right) \times c \times \exp\left(\frac{\phi}{E0}\right)
\end{align*}
\]

\[
\text{figure(1)} \\
\text{semilogy(N, Rc)}
\]
Appendix E

Matlab code for the determination of specific contact resistance versus temperature

\[
\begin{align*}
\text{h} &= 4.13 \times 10^{-15}; \quad \% \text{ Planck constant eV} \\
\text{k} &= 8.61 \times 10^{-5}; \quad \% \text{ Boltzmann constant eV} \\
\text{q} &= 1.6 \times 10^{-19}; \quad \% \text{ charge on electron} \\
\text{m} &= 0.25 \times 9.109 \times 10^{-31}; \quad \% \text{ mass of carriers} \\
\text{e} &= 1.04 \times 10^{-16}; \quad \% \text{ permittivity} \\
\text{N} &= 1 \times 10^{15}; \quad \% \text{ doping concentration} \\
\text{T} &= 300; \quad \% \text{ Temperature in Kelvin} \\
\text{T} &= (0:1:1000); \quad \% \text{ Creates a window for temperature between 0 and 1000 K} \\
\text{A} &= 194.1; \quad \% \text{ Effective Richardson's constant} \\
\text{E00} &= ((q \times h)/(4 \times \pi)) \times \sqrt{N/(e \times m)}; \quad \% \text{ Energy level of E00 calculation} \\
\text{E0} &= \text{E00} \times \text{coth}(\text{E00}/(k \times T)); \quad \% \text{ Energy level of E0 calculation} \\
\text{c} &= 1; \quad \% \text{ Constant for thermal emission required} \\
\text{phi} &= 0.3; \quad \% \text{ Barrier Height eV} \\
\text{Rc} &= ((k/(A \times T)) \times \text{c} \times \exp((\text{phi})/\text{E0})); \quad \% \text{ Calculation of specific contact resistance} \\
\text{figure(1)} \quad \% \text{ Figure plotting doping versus specific contact resistance} \\
\text{semilogy(T,Rc)}
\end{align*}
\]
List of Publications

1. N.F. Mohd Nasir, A.S. Holland, G.K. Reeves, P.W. Leech, A. Collins and P. Tanner, Specific contact resistance of ohmic contacts to n-type SiC membranes MRS Spring Meeting 2011


5. Y Pan, A M. Collins, A S. Holland, Determining Specific Contact Resistivity of Contacts to Bulk Semiconductor Using a Two-Contact Circular Test Structure Proc. 29th International Conference On Microelectronics 2014


8. A M. Collins, Y Pan, Anthony S. Holland, Thermal variation effects of Specific Contact Resistance in Silicon Carbide, submitted to ESSDERC 2015
References


