Optimization of Transmission Line Measurement (TLM) Structures for Specific Contact Resistivity Determination

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Abstract
Low resistance ohmic contacts are of extreme importance to modern semiconductor devices. As device sizes continue to shrink, it implies a reduction in the specific contact resistance $\rho_c$. There are various methods for the measurement of $\rho_c$, however the Transmission Line Model (TLM) is most popularly used to determine the specific contact resistivity for Integrated Circuits (IC) and Silicon Photovoltaics (PV) applications. Inconsistencies have been observed in literature between IC and PV devices as $\rho_c$ determination may depend on dimensions. Therefore, TLM test geometries need to be optimized in order to minimize error. Optimum values of TLM widths were fabricated and tested and systematic error was compared with that from simulations.

Keywords: Sheet Resistance, Contact Resistance, Transmission Line Model (TLM), Specific Contact Resistivity, Ohmic Contacts, Error Analysis, Optimization

1. Introduction
In the modern semiconductor industry, device performance can be impacted by various means. One of the major factors that effect the performance of devices is the resistance between the contacts and the device itself. This is termed as contact resistance. Accurate determination of this contact resistance is essential in understanding its impact on device performance. Tremendous reduction in device sizes in modern times have require specific contact resistivity ($\rho_c$) improvement to maintain small parasitic resistances with small contact area within acceptable ranges.

These parasitic resistances need to be significantly small for practically all semiconductor applications. Optimum pattern designs for the Transmission Line Model (TLM) that are suggested to achieve minimum measurement uncertainty of the specific contact resistance can be developed for semiconductor applications of varying $\rho_c$ and $R_{SH}$.

The determination of the specific contact resistance and sheet resistance ($R_{SH}$) of a planar ohmic contact structure and the underlying doped layer can be done through the standard Transmission Line Model (TLM) method.[1] The contact current injection in a standard TLM structure is in a lateral channel that makes it result in resistance values commensurate to FET as well as photovoltaic device structures. These device structures have varying $\rho_c$ and $R_{SH}$ values and the contacts differ between being alloyed and non-alloyed metal contacts.

There is no information on the uncertainties of these alloyed and non-alloyed structures and hence one cannot accurately compare data sets. Similar issues arise for different applications employing varying values of $R_{SH}$ and $\rho_c$. Simulations carried out in this paper as well as in Ueng et al [2] suggest optimum values of the widths of these TLM structures that provide the least uncertainty in measurement. A contour map similar to one below can be formulated for optimum TLM contact geometries for various values of $R_{SH}$ and $\rho_c$ yielding to different semiconductor applications.

![Figure 1: Map of optimum widths for different applications 1 and 2.](URL: www.rit.edu)

The above figure shows a map of the different optimum widths of TLM structures for applications 1 and 2 with values of sheet resistances $R_{SH1}$ and $R_{SH2}$, and specific contact resistivities $\rho_c1$ and $\rho_c2$.

Conventional TLM structures do not accurately determine the transfer length $L_T$ of the contact. Lateral contacts that have contact lengths much larger than $L_T$ behave as semi-infinite contacts. As the length of the contacts is decreased, below $L_T$, the resistance of the contact increases sharply. [3]

2. Theory
2.1. Ohmic Contacts and Contact Resistance
All semiconductor devices have contacts and all contacts have contact resistance. Metal-to-Semiconductor con-
contacts have been of increasing importance to the semiconductor industry in order to better performance of devices by reducing this resistance. A large mismatch in the fermi energy between the metal and the semiconductor can result in a high resistance rectifying contact.

Ohmic contacts are preferred for semiconductor applications as they have linear or quasi-linear and symmetric I-V characteristics. The voltage drop at the contact for ohmic contacts is small compared to that of the active regions of the devices. Ohmic contacts do not degrade device performance and do not inject minority carriers. An ohmic contact results if the Shottky barrier height \( \phi_B \) in a metal-semiconductor is zero or negative. Carriers then flow freely in and out of the junction so that there is minimal resistance across the contact. The contact resistance is given as the resistance of the metal-semiconductor junction and the resistance of the semiconductor material. The specific contact resistivity is a figure-of-merit for ohmic contacts. It is defined as the slope of the I-V curve when the voltage equals zero.

\[
\rho_c \equiv \left( \frac{\partial J}{\partial V} \right)_{V=0} \tag{1}
\]

The specific contact resistivity is a function of the barrier height as well as the doping density \( N_D \) as illustrated below.

From figure 2, it can be observed that for \( N_D \geq 10^{19} \text{ cm}^{-3} \), \( \rho_c \) is dominated by the tunneling process and decreases rapidly with increased doping. For \( N_D \leq 10^{17} \text{ cm}^{-3} \), the current is due to thermionic emission and \( \rho_c \) is predominantly independent. In between the two regions, a combination of tunneling and thermionic emission takes place.

The resistive components that add up in the formation of a contact are illustrated in figure 3. The contact resistance of the two contacts are given as \( R_c \) each and the resistance of the semiconductor is given by \( R_{semi} \). The equation governing the total resistance of the system is given in equation (3).

\[
R_T = R_{semi} + 2R_c = R_{semi} + 2\frac{R_{SH} L_T}{W} \tag{4}
\]

The above equation is then used to obtain the plot for the extraction of the various resistive values. A standard TLM test pattern includes a single rectangular doped region that signifies a specific sheet resistance \( R_{SH} \) value. An array of contacts are fabricated with the same width and different pad spacings on that particular doped region. Resistance measurements are then taken on each pair of these contacts that is used to construct the TLM graph from which \( R_{SH} \), \( R_c \), \( L_T \) and \( \rho_c \) can be determined.

2.2 TLM Analysis

The Transmission Line Measurement (TLM) model is effective in obtaining the specific contact resistance between a metal and a semiconductor. The current flow in the semiconductor us uniform but not through the contact. On flowing from the semiconductor to the metal, it encounters specific contact resistivity \( \rho_c \) and sheet resistance \( R_{SH} \). Therefore, it chooses the path of least resistance leading to ”current crowding” causing a drop in current from the edge of the contact. The transfer length \( L_T \) is the average the electron (or hole) travels in the semiconductor beneath the contact before it flows up into the contact. The expression for the transfer length is given by Reeves[1].

\[
L_T = \sqrt{\frac{\rho_c}{R_{SH}}} \tag{2}
\]

The equation for the contact resistance \( R_c \) is given below in equation (2) as the specific contact resistivity can be written as a product of the sheet resistance and transfer length

\[
R_c = R_{SH} L_T \Rightarrow R_c = \frac{\rho_c}{L_T W} = \frac{R_{SH} L_T}{W} \tag{3}
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The total resistance \( R_T \) is the sum of the resistance of the semiconductor below the contact and the resistance of the contact itself.

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R_T = R_{semi} + 2R_c = R_{semi} \frac{L_T}{W} + 2\frac{R_{SH} L_T}{W} \tag{4}
\]
2.3. Specific Contact Resistivity ($\rho_c$) extraction

The general equation to extract the specific contact resistivity $\rho_c$ is given by

$$\rho_c = \frac{(R_CW)^2}{(\coth \frac{L_T}{2})} \times \frac{1}{R_{SH}} \quad (5)$$

$$L_T = \sqrt{\frac{\rho_c}{R_{SH}}} \quad (6)$$

There are two limiting cases due to the use of the cotangent hyperbolic function. First, is the short contact limit where the length of the contact is less than half of the transfer length. In that case the length of the contact is used in the $\rho_c$ calculation. Second, is the long contact limit where the length of the contact is significantly greater than the transfer length. Then the transfer length is used in the extraction.

Two limiting cases

- $L_c < 0.5L_T \rightarrow \csc \left( \frac{L_T}{2} \right) \approx \frac{L_T}{2} \Rightarrow \rho_c = R_cWL$  
  Short Contact Limit

- $L_c > 1.5L_T \rightarrow \csc \left( \frac{L_T}{2} \right) \approx 1 \Rightarrow \rho_c = R_cWL_T$  
  Long Contact Limit

2.4. Error Analysis

There are two categories that are used to classify the error propagation. These are: Random Error and Systematic Error. The difference between a single measurement of a parameter and the mean determined by a large number of trials is the Random Error. The consistent shift of means due to taking larger numbers of data points is the Systematic Error. The uncertainty in measurement of the specific contact resistivity $\rho_c$ is taken into account in this analysis. The equation for the relative uncertainty due to systematic error is given by the equation below.

$$\frac{\delta \rho_c}{\rho_c} = \left( \frac{W}{\sqrt{\rho_c R_{SH}}} \right) \delta R + \left( \frac{4}{W} \right) \delta W \quad (7)$$

Here $\delta R$, $\delta d$, and $\delta W$ are the measurement uncertainties in the resistance, pad spacing and widths of the TLM structures. The values of $W$ that yield minimum uncertainty in $\rho_c$ is found by evaluating the partial derivative of equation (4) and equating it to zero. This gives us the equation for $W_{opt}$.

$$W_{opt} = \frac{4}{\sqrt{\rho_c R_{SH}}} \delta W \quad (8)$$

Different combinations of $\rho_c$ and $R_{SH}$ pertaining to different applications yield particular values of the optimum width $W_{opt}$ that gives us the least uncertainty in measurement. A contour plot for these values of optimum widths can be generated with respect to ranges of $\rho_c$ and $R_{SH}$.

3. Experimental Procedure

The observed inconsistencies in literature were initially attributed to the error in measurements. Upon optimization of the equation for the relative uncertainty due to systematic error, the equation for optimum width ($W_{opt}$) did not depend upon the TLM length (L) or transfer length ($L_T$). Therefore, only TLM widths were varied in the experiment. The process was designed based on specific values of sheet resistance that pertained to PV and IC applications. Contacts with Aluminum and Nickel Silicide (NiSi) were fabricated.

A 3 level mask was designed for Mesa lithography, contact cut and metal etch processes. TLM length was fixed at $10\mu m$ and the widths were varied from $10\mu m$ and $2000\mu m$. There were 4 spacings between he contacts $d_1$, $d_2$, $d_3$ and $d_4$ and they were set at $30\mu m$, $60\mu m$, $120\mu m$ and $240\mu m$ respectively.

The fabrication process consists of 6” bare Si p-type wafers with initial bulk resistivities ranging between 1-30 $\Omega/cm^3$. These wafers are implanted with n+ dopant (Phosphorous, P31) through a 30nm screening oxide and annealed in a nitrogen ambient to activate the dopants. Application specific values of the sheet resistance based
4.1 Optimization Results

Figure 5: Mask design for 100µm width TLM on silicon photovoltaics and the CMOS IC applications were chosen.

- Emitter \( R_{SH} \) in silicon photovoltaics - 50 -200 \( \Omega/\square \).
- CMOS IC \( R_{SH} \) -1000 - 3000 \( \Omega/\square \).

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Dose (cm(^{-3}))</th>
<th>( R_{SH} ) (( \Omega/\square ))</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.5E12</td>
<td>1500</td>
<td>Aluminum</td>
</tr>
<tr>
<td>2</td>
<td>9.5E12</td>
<td>1500</td>
<td>NiSi</td>
</tr>
<tr>
<td>3</td>
<td>2E15</td>
<td>50</td>
<td>Aluminum</td>
</tr>
<tr>
<td>4</td>
<td>2E15</td>
<td>50</td>
<td>NiSi</td>
</tr>
</tbody>
</table>

Table 1: Process design parameters

A dry silicon reactive ion etch process is used to define MESA patterns on the wafers about 2µm deep. The MESA etch is specifically deep in order to go below the junction depth of the implanted dopant to ensure sufficient isolation. TEOS is used as an insulating oxide for the TLM contact pads. Contact cut openings were patterned using i-line lithography and the TEOS was etched using a reactive ion etch process. Metal was then deposited and patterned. For the NiSi wafers, the metal was first annealed in a Rapid Thermal Process (RTP) to form the silicide and the unreacted Ni was removed using a piranha etch. Aluminum was then deposited on top of NiSi, patterned and etched.

4. Results

4.1 Optimization Results

Systematic error optimization of equation (7) gave optimum width values for application specific \( \rho_c \) and \( R_{SH} \).

The contour map as shown in figure (6) is obtained and the values of optimum widths for a range of \( \rho_c \) and \( R_{SH} \) values. The optimum widths obtained for the \( R_{SH} \) applications used in this paper are shown. The high \( R_{SH} \) value gave an optimum width of 900µm and low \( R_{SH} \) gave an optimum width of 150µm.

The TLM’s were fabricated and tested to obtain the specific contact resistivity for each width and the relative systematic error for each TLM measurement was obtained from equation (7). The values of \( \delta L \), \( \delta R \) and \( \delta W \) were set at 0.1µm, 0.2Ω and 1.5µm respectively. TLM’s on Aluminum metal contacts to high sheet resistance were not analyzed due as schottky contact behavior was observed. The relative systematic error was plotted as a function of the optimum width to observe the values of TLM widths that gave the least amount of error. The values obtained for each of the wafers were a relative close match to those obtained via simulation.

Specific contact resistivity (\( \rho_c \)) extracted from the TLM test measurement of the optimum widths were relatively similar to anticipated values.

On measurement of the non-optimum values of the TLM widths, a trend between the TLM width and the extracted transfer length (\( L_T \)) was observed. Due to this dependence, measurement of optimum values of TLM widths can give inconsistent results due to incorrect use of the TLM formula limits.
It can be observed from figure (8) that for a transfer length extracted from a TLM measurement smaller than the length of the contact, the long contact approximation is to be used and the short contact approximation for transfer lengths significantly greater than the length of the contact in order to accurately determine the specific contact resistivity.

The TLM design can have a significant impact on $\rho_c$ determination. The application of the long contact limit has been repeatedly seen in literature without accurate information about the extracted transfer length, which, as we have seen earlier, depends on the width of the TLM structure. Figure(9) shows that there is a large delta observed in the value of $\rho_c$ extracted from the use of the general formula and the long contact limit. Therefore, while using an optimized value of the TLM width in order to obtain the least amount of systematic error in measurement, the transfer length extracted from that width must be carefully compared to the contact length and appropriate formula must be used. An approach is required to accurately determine $\rho_c$ for a given application space.

5. Conclusion

A process is suggested to accurately determine the specific contact resistivity ($\rho_c$) from the TLM method for a given application space.

![Figure 10: Suggested process flow to accurately determine $\rho_c$.](image)

6. Future Work

Further understanding behind the interaction of transfer length and TLM width needs to obtained and the effect of varying TLM lengths on transfer length and $\rho_c$ extraction needs to be investigated. A standardized approach for accurate determination of the specific contact resistivity ($\rho_c$) and simultaneous comparison with universal Cross Bridge Kevin Resistance (CBKR) curves needs to be developed. Different contact metals and/or metallization schemes can also been investigated.
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References


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