A Method for measuring the specific interface resistivity between two semiconductor layers and its application to a heavily doped n-type InP/GaInAs heterostructure

Research Thesis

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Ran Halevy

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Abstract

The emitter contact resistivity is one of the most dominant factors holding back the cutoff frequencies for high speed hetero-junction bipolar transistors (HBTs), and therefore accurate characterization and improvement of this parameter become of great importance.

RF characterizations of devices in current use exhibit a measured resistivity higher than what is usually attained in standard Transfer Length Method measurements (TLM), which are commonly used to characterize contacts. This work comes to address this issue by more closely examining and improving upon the existing contact characterization methods for single layer and dual layer contacts. It specifically aims to examine dual layer hetero-structure based contacts, which are of frequent use, and determine the actual role of the inter-layer interface resistivity in the overall effective contact resistivity.

Previous works regarding the single layer TLM characterization method include a first order analytic error analysis, which is brought here as reference. As for the dual layer structure, a simplistic interface resistivity estimation method, which was originally presented for p-type contacts, is brought and evaluated, and also an analytic model of the full two layer TLM structure is brought as reference.

In order to correctly and gradually address the two layer structure in this study, I first examined the single layer TLM method on all its aspects, and specifically the error analysis it entails. In order to also attain a numeric form of error analysis, which would later benefit the dual layer part of the study, I devised a custom designed numeric Monte Carlo simulation, based on measured and estimated error factors, as done in the single layer analytic error analysis work that is brought as reference. In order to confirm the validity of the numeric error analysis, simulations were compared to results of the analytic error analysis. However, since the analysis performed in previous work was of a first order approximation, a second order correction had to be made within this study for greater accuracy, and indeed agreement numeric simulation results was observed.

Focusing on the dual layer structure, the existing method previously mentioned is examined and shown to be inadequate for our needs. At that juncture a new analytic model is presented, one of a two layer structure in which the upper layer has been etched away between the contacts. Combining the two analytic models, an innovative
numeric extraction method was formed, giving the ability to extract the four structure parameters. The numeric simulation algorithm was then fitted for the dual layer structure, and simulations were performed. Measurements results for all structures are also presented and compared to simulations.

Finally, the average specific interface resistivity attained from these measurements is found to be $1.6 \pm 0.38 \, [\Omega \cdot \mu m^2]$, and the specific contact resistivity is $9.8 \pm 0.51 \, [\Omega \cdot \mu m^2]$. It is concluded that such values of interface resistivity, along with the error margins of both resistivity values, may indeed account for most of the discrepancies in effective resistivity estimations.
List of Acronyms

HBT  Hetero-junction Bipolar Transistor
BE   Base-Emitter
MOMBE Metal-Organic Molecular Beam Epitaxy
SEM  Scanning Electron Microscope
SPA  Semiconductor Parameter Analyzer
FIB  Focused Ion Beam
List of Symbols

- $\rho_c$: Specific contact resistivity
- $\rho_r$: Specific interface resistivity
- $R_{sh}$: Sheet resistance
- $\sigma_R$: Average measurement error (standard deviation)
- $\sigma_{R\text{-before}}$: Measurement error before the wet etch (standard deviation)
- $\sigma_{R\text{-after}}$: Measurement error after the wet etch (standard deviation)
- $\sigma_W$: Geometric contact width error (standard deviation)
- $\sigma_d$: Geometric contact spacing error (standard deviation)
- $\sigma_{d,\text{undercut}}$: Additional geometric uncertainty in spacing due to under-cut (standard deviation)
- $R_c$: Contact resistance
- $R_m$: Metal resistance (of the pads)
List of Symbols
Chapter 1

Introduction

This chapter introduces the background and pre-existing research pertaining to the main aspects of this study. The chapter first gives a general overview of the heterojunction bipolar transistor (HBT) specifically pertaining to the emitter contact resistance. Following that, introductions will be made for the single layer TLM structure and the dual layer TLM structure. For the single layer structure, an overview of the basic TLM method is presented, and an analytic error analysis is briefly presented and discussed. For the dual layer structure, firstly the existing method for measurement of the inter-layer interface resistivity is presented and extensively discussed. The chapter concludes with the presentation of the existing differential analysis for the full dual layer TLM structure as conducted in former studies.
1.1 Heterojunction Bipolar Transistors (HBTs)

This section presents a short overview of the HBT structure based on the InP/GaInAs material system. Specific attention is aimed at the influential role of the emitter contact resistivity in achieving high frequency performance. The small signal model for the HBT is presented, and the procedure for extracting the emitter contact resistivity from small signal measurements is described, along with actual extracted values.

1.1.1 HBT small signal model & cutoff frequency

A structural schematic of an HBT based on the InP/GaInAs material system is illustrated in figure 1.1. This is a general schematic of the HBT structure, and given as a general example. A more accurate description of the specific HBT used for device characterization within this study will be presented further on in Subsection 1.6.

Analyzing this structure for AC performance, the small signal T model was used, as illustrated in figure 1.2[4]. The parameters for the small signal model were extracted using RF measurements and DC characterization ([5, 6]).
When using the device in high speed circuitry, one of the most pertinent parameters is the current gain cut-off frequency. The theoretical expression for the cut-off frequency is presented in eq. 1.1.

\[ f_T = \frac{1}{2\pi \left[ \tau_D + r_e C_{BE} + (r_e + r_{ee} + r_c)C_{BC} \right]} \]  

(1.1)

For the purposes of small signal element analysis, the emitter effectively consists of the base-emitter (BE) junction, modeled by a standard small signal model of a diode (resistor, denoted by \( r_e \), and capacitor, denoted by \( C_{BE} \)), and in addition the neutral bulk of the emitter itself, and the contact to the outside circuitry, which are modeled together as a serially connected ohmic resistor, denoted by \( r_{ee} \). It is important to mention that \( r_{ee} \) is mostly affected by the quality of the contact. All these parameters are extracted using a set of DC and AC measurements of the device.

It is evident from the presented formula that emitter resistances play an important role in determining and potentially limiting the cut-off frequency. Further more, the HBT is usually operated at high current BIAS points, which substantially lowers the dynamic resistance of the BE junction. This leaves the emitter contact resistivity \( (r_{ee}) \) as a limiting factor, and for that reason it is desirable to lower the emitter contact resistivity as much as possible.

In fact, in order to reach cut-off frequencies of around THz, Emitter contact resistivities of the order of \( 1 \, [\Omega \cdot \mu m^2] \) are required. These values are considered extremely low, and therefore an accurate characterization of the emitter contact resistivity is first required.
1.1.2 Emitter resistance extraction from RF device characterization

In order to extract the emitter contact resistivity from DC & AC measurements of the HBT, first the overall emitter resistance is extracted using the following relation:

\[ r_e + r_{ee} = Re\{z_{12}\} \]  

where \( z_{12} \) is attained by conducting AC measurements, extracting S-parameters, and converting them into Y-parameters and then Z-parameters. The dynamic resistance of the BE junction \( r_e \) is directly dependent on the DC current, just like in PN junctions:

\[ r_e = \frac{kT}{qI_E} \]  

where \( k \) is the Boltzmann constant, \( T \) is the temperature, \( q \) is the charge of an electron, and \( I_E \) is the DC current.

Using these two relations, the emitter contact resistivity \( r_{ee} \) is extracted for the device.

Typical values extracted for \( r_{ee} \) from RF measurements conducted in our research group are around 5 [Ω], for a 0.7 [µm] X 5 [µm] emitter, translating to an emitter contact resistivity of about 17.5 [Ω·µm²]. This is a relatively high value compared to the required resistivity, that was just mentioned. This value is also high when compared to results attained from other contact characterization methods, as will be demonstrated later on. This difference was one of the main motivation for this work.
1.2 The TLM method

The transfer length method (TLM) is a well known classical method for measuring the sheet and contact resistances for single layer contacts ([7, 8, 9, 10, 11]). This section describes the background and the theoretical basis of the TLM contact characterization method. An analytic error analysis conducted in previous studies is also presented. It will later be used for comparison with the numeric error estimation method that was custom designed within this study for complex TLM measurements.

1.2.1 The basic TLM theory

The basis of a standard TLM array is a series of contacts of width \( Z \) and length \( L \), unequally spaced \((d_i)\), aligned in an isolated mesa of width \( W \) of the semiconductor layer, all fabricated simultaneously and therefore presumably identical. The structure is illustrated in figure 1.3 ([12],[7]).

\[
|W - Z| \approx 10[\mu m] \text{ while } Z = 100[\mu m].
\]
Chapter 1. Introduction

Figure 1.4: Model for one layer TLM structure: Structure is described as a mesh of contact resistivity and sheet resistance elements.

Equations 1.4 and 1.5 present the differential analysis of the one layer TLM cross section for the area under the contact, while keeping in mind the structure is symmetrical.

\[
dI = (V_0 - V(x)) \cdot \frac{W \cdot dx}{\rho_c} \tag{1.4}
\]

\[
dV = -R_{sh} \cdot I(x) \cdot \frac{dx}{W} \tag{1.5}
\]

\(R_{sh}\) means the semiconductor sheet resistance, and \(\rho_c\) means the specific contact resistivity. \(W\) is the contact width. The conductive layer is assumed to be very thin compared to the lateral dimensions, enabling us to assume negligible thickness and work under a sheet conduction regime (confirmation of this assumption is shown in APPENDIX A).

The general form of the solution for these equations is shown in eq. 1.6

\[
V(x) = a \cdot e^{\eta x} + b \cdot e^{-\eta x} + c \tag{1.6}
\]

After solving the second order differential equation, we learn that:

\[c = V_0\]

and

\[\eta = \sqrt{\frac{R_{sh}}{\rho_c}} = \frac{1}{L_T}\]

Instead of using \(\eta\) we use the notation \(\frac{1}{L_T}\) where \(L_T\) means the transfer length, or in other words, the distance along the contact for which the voltage drops to 1/e of its value.

Similarly, the differential equation for the area between the contacts is

\[
dV = -R_{sh} \cdot I_0 \cdot \frac{dx}{W} \tag{1.7}
\]

As for boundary conditions, we demand symmetry, meaning \(V_0 - V(0) = V(d)\), and continuity for \(V(x)\) and \(I(x)\) at \(x = 0\). In addition we demand that \(I(x = -L) = 0\).
After assigning the boundary conditions, and assuming that $L_T \ll L$, we get a simple expression for the total resistance between the contacts [12]

$$R_T = \frac{V_0}{I_0} = \frac{R_{sh}}{W} \cdot d + 2 \cdot \frac{R_{sh} \cdot L_T}{W} = \left( \frac{R_{sh}}{W} \right) \cdot d + 2 \cdot \left( \frac{\rho_c}{W \cdot L_T} \right)$$

(1.8)

At first glance it is already evident that the total resistance behaves linearly as a function of the spacing between the contacts (the first expression), when the constant part is actually two times the contact resistance, meaning $R_c = \frac{\rho_c}{W \cdot L_T}$. Essentially this means that the actual contact resistance would be calculated over an area of $(W \cdot L_T)$, bringing us back to the concept of transfer length.

In the measurement itself, the total resistance $R_T$ is measured for each pair of adjacent contacts, and plotted as a function of the various spacings $d$, as shown in figure 1.5.

![Figure 1.5: TLM measurement graph with linear approximation](image)

A linear approximation of the measured resistance values is then extrapolated. This yields a linear function $R_T = A + B \cdot d$, $A$ being the intercept at $d = 0$, and $B$ being the

---

2For the parameter values of $R_{sh}$, $\rho_c$ and $L$ used in this work this assumption is very good ($L_T < 2[\mu m]$ while $L \approx 200[\mu m]$).
slope. When fitting the extracted parameters $A, B$ to the two arguments in eq. 1.8, it can be easily seen that:

$$A = 2 \cdot R_c = 2 \cdot \left( \frac{\rho_c}{W \cdot L_T} \right)$$  \hspace{1cm} (1.9)$$

$$B = \frac{R_{sh}}{W}$$  \hspace{1cm} (1.10)$$

and it is also very helpful to calculate the (theoretical) intercept at $R_T = 0$, which is:

$$-\frac{A}{B} = -2 \cdot \left( \frac{\rho_c}{W \cdot L_T} \right) \frac{W}{R_{sh}} = -2L_T$$  \hspace{1cm} (1.11)$$

Using equations 1.10 and 1.11, and the definition of $L_T$, We can easily extract $\rho_c$ and $R_{sh}$:

$$R_{sh} = B \cdot W$$  \hspace{1cm} (1.12)$$

$$\rho_c = R_{sh} \cdot \frac{L_T^2}{4} = R_{sh} \cdot \left( \frac{A}{2B} \right)^2 = \frac{W \cdot A^2}{4B}$$  \hspace{1cm} (1.13)$$

and that is how the TLM measurement provides us with the desired contact characteristics.

### 1.2.2 First order analytic error analysis

The analytic error estimation in the first order approximation is described in full in [13], but is briefly summarized here for review. The basic equations used in the development of this analysis will also be used later when the second order correction is described.

By differentiating 1.13 for first order perturbations, the uncertainty in $\rho_c$ is derived as

$$\Delta \rho_c \simeq \left| \frac{\partial \rho_c}{\partial A} \right| \Delta A + \left| \frac{\partial \rho_c}{\partial B} \right| \Delta B + \left| \frac{\partial \rho_c}{\partial W} \right| \Delta W$$

$$= \left( \frac{WA}{2B} \right) \Delta A + \left( \frac{WA^2}{4B^2} \right) \Delta B + \left( \frac{A^2}{4B} \right) \Delta W$$  \hspace{1cm} (1.14)$$

Therefore, using 1.14 and 1.13 the relative uncertainty of $\rho_c$ is

$$\frac{\Delta \rho_c}{\rho_c} \simeq 2 \left( \frac{\Delta A}{A} \right) + \frac{\Delta B}{B} + \frac{\Delta W}{W}$$  \hspace{1cm} (1.15)$$

The relative uncertainty for $R_{sh}$ is derived in the same manner from 1.12 as

$$\frac{\Delta R_{sh}}{R_{sh}} \simeq \frac{\Delta B}{B} + \frac{\Delta W}{W}$$  \hspace{1cm} (1.16)$$
Now that the general formulas for uncertainties in $\rho_c$ and $R_{sh}$ are presented, we have to estimate the uncertainties in $A$, $B$ and $W$.

These estimations are done according to a standard analysis of the linear regression process\cite{14}, and under certain assumptions\footnote{It is assumed in \cite{13} that $N \gg 1$ so that $(N - 1) \simeq (N - 2)$ (N is the number of contacts in the TLM array), and also that the spacings $d_i$ are uniformly spaced, and that $\Delta d$ and $\Delta R$ are uncorrelated.} they eventually yield

$$
\sigma_B |_{\sigma_d, \sigma_R} = \left( \frac{2\sqrt{3}}{\sqrt{N} d_{\text{max}}} \right) \sqrt{B^2 \sigma_d^2 + \sigma_R^2} \quad (1.17)
$$

$$
\sigma_A |_{\sigma_d, \sigma_R} = \left( \frac{2}{\sqrt{N}} \right) \sqrt{B^2 \sigma_d^2 + \sigma_R^2} \quad (1.18)
$$

A similar derivation is done for the dependency on uncertainties in $W$

$$
\sigma_B |_{\sigma_W} = \frac{1}{\sqrt{N}} \left( \frac{B}{W} \right) \sigma_W \quad (1.19)
$$

$$
\sigma_A |_{\sigma_W} = \frac{1}{\sqrt{N}} \left( \frac{A}{W} \right) \sigma_W \quad (1.20)
$$

Now, by substituting 1.17, 1.18, 1.19 and 1.20 into 1.15, and substituting the parameters $A$ and $B$ (1.9, 1.10), the total relative uncertainty of the specific contact resistivity by random error in first order approximation can be expressed as

$$
\frac{\sigma \rho_c}{\rho_c} \simeq \frac{1}{\sqrt{N}} \left( \frac{2W}{\sqrt{\rho_c R_{sh} d_{\text{max}}}} + \frac{2\sqrt{3}W}{R_{sh} d_{\text{max}}} \right) \cdot \sqrt{\left( \frac{R_{sh}}{W} \right)^2 \sigma_d^2 + \sigma_R^2 + \left( \frac{4}{W} \right) \sigma_W} \quad (1.21)
$$

and by making the same substitutions into 1.16, we get

$$
\frac{\sigma R_{sh}}{R_{sh}} \simeq \frac{1}{\sqrt{N}} \left( \frac{2\sqrt{3}W}{R_{sh} d_{\text{max}}} \right) \cdot \sqrt{\left( \frac{R_{sh}}{W} \right)^2 \sigma_d^2 + \sigma_R^2 + \left( \frac{2}{W} \right) \sigma_W} \quad (1.22)
$$

Equations 1.21 and 1.22 are the main result in \cite{13}, and we will use them later for comparison with the numeric simulation results.
1.3 The dual layer contact

This section addresses the actual contact structure of the HBT emitter as a two layer structure, and provides the initial understanding as to why a closer inspection of the specific interface resistivity between semiconductor layers is required. A short description is brought of the existing method for measuring the specific interface resistivity. This method is reviewed and its validity for our purposes is evaluated. Following that, an analytic model of a full two layer contact structure is brought, as developed in previous relevant studies.

1.3.1 Contact structure of the InP based HBT Emitter

In InP based devices, the contact to the metal is not usually done directly, but through a layer of GaInAs, as demonstrated in the HBT schematic shown in Fig. 1.6. The GaInAs layer has a substantially smaller band gap than the InP, which enables near-ohmic contacts. This is demonstrated more clearly in the band diagram, presented in Fig. 1.7.

Figure 1.6: Schematic of actual layer structure in InP based HBT: Contact to metal is accomplished through a layer of GaInAs
1.3. The dual layer contact

Figure 1.7: Band diagram of the InP based HBT emitter: GaInAs shows smaller band gap, enabling near-ohmic contact

Intuitively, the interface resistivity between the two semiconductor layers should present to be little to none. This usually shifts the attention to the metal-GaInAs contact, which is ordinarily measured separately from the HBT characterizations. Typical results for this contact when fabricated using ex-situ metal deposition and defined by lift-off (as done for this study) are around \(10 \, \Omega \cdot \mu m^2\). It is clear that this typical value is smaller than the emitter contact resistivity extracted from the small signal measurements, as presented in Subsection 1.1.2. This means that the effective contact resistivity of our GaInAs-InP emitter is not merely that of a one layer contact, suggesting that the interface resistivity might not be as negligible as one would hope, and most likely requires further study.

Furthermore, the metal-GaInAs contact has been quite extensively researched by various research group and contact resistivities of around \(1 \, \Omega \cdot \mu m^2\) have already been shown to be attainable using in-situ metal deposition and high temperature annealing. This raises the concern that the interface resistivity might even be substantial when compared to such low contact resistivities, and therefore definitely requires measurement.

1.3.2 Existing estimation technique for the specific interface resistivity

The previous method found for estimating the specific interface resistivity between two semiconductor layers was presented in [1], and was used for p-type heterojunction based contacts. The method was based on two consecutive TLM measurements, one performed on a full two layer TLM structure, as illustrated in figure 1.8 (a) and the other on a similar structure, only with the top layer etched away in the area between
the contacts, (figure 1.8 (b), denoted as the inter-etched structure).

As presented in SubSection 1.2.1, each TLM measurement produces a certain contact resistivity and a sheet resistance. In this method the contact resistivity attained from the first measurement is assumed to be the actual contact resistivity for the semiconductor-metal junction, and the contact resistivity attained from the second measurement is assumed to be the sum of both the specific contact resistivity and the specific interface resistivity. The desired interface resistivity is then extracted by a straightforward subtraction of the two results.

It is worth noticing that the resistivity values dealt with in the described study are fairly substantial, and that the approximate specific interface resistivity, as extracted within that work, is about two orders of magnitude greater than the approximate specific contact resistivity.

Figure 1.8: TLM structures as used in existing interface resistivity extraction method:
(a) Full two layer structure (b) Inter-etched structure

The assumption regarding the contact resistivity extracted from the first structure may be considered a good assumption only for extreme values of the specific interface resistivity. When it is much higher than the specific contact resistivity, it can be considered infinite by comparison and the structure effectively resembles a single layer structure. When it is negligible in comparison, the two layers actually combine together effectively resembling a single layer structure once again. However, for finite non-negligible values of interface resistivity, the assumption is inaccurate, and the actual contact resistivity cannot be specifically extracted from this two layer structure. In order to correctly evaluate the specific contact resistivity for the intended subtraction, it would have to be measured on a separate one layer TLM structure, meaning that the accuracy of the subtracted resistivity would be directly dependent on the standard deviation in the parameter. This means that either option of evaluating the contact resistivity needed for this subtraction entails a certain inherent inaccuracy.
As for the assumption regarding the contact resistivity in the second structure being the sum of the two resistivities, the accuracy of this assumption is dependent on the parameters of the upper layer. The extracted contact resistivity could be construed as the sum of resistivities only when the sheet resistance in the upper layer is high enough so that horizontal current flow is fairly restricted, and only vertical current flow is possible. Ideally, it would have been preferable to use a structure as shown in figure 1.9, in which the upper layer is ultra thin, since the sheet resistance would become much greater.

![Ultra thin top layer (GaInAs)](image)

Figure 1.9: Inter-etched TLM cross section with ultra thin top layer - required for using the existing method

Simple simulations done for arbitrary metal-semiconductor resistivity values ($\rho_C$) and arbitrary interface resistivity values ($\rho_R$) agree with this statement, showing how the contact resistivity extracted from such a TLM structure approaches the serial sum of the actual two resistivities as the top layer thickness goes thinner.

For P-type layers and resistivity values such as the ones presented in [1], even with only a mildly thin top layer, the extracted contact resistivity serves as a sufficient approximation for the sum of the two resistivities. This is demonstrated in Fig. 1.10. Using the full analytic model developed within this study for the inter-etched structure (from figure 1.8 (b)), as described in Subsection 3.1.1, simulations were performed to estimate the contact resistivity and sheet resistance that would be attained if TLM measurements were conducted on this structure and analyzed in the standard fashion. This was done as a function of the upper layer thickness. The contact and interface resistivity values for which the simulation is performed are approximately those discussed in [1]: specific contact resistivity ($\rho_C$) is around $100 \Omega \cdot \mu m^2$, and the specific interface resistivity ($\rho_R$) is around $10^4 \Omega \cdot \mu m^2$. The figure shows the projected “extracted” contact resistivity as a function of the upper layer thickness. It is clearly evident that a top layer thickness of 15 nm would yield a sufficient approximation for the sum of the two actual resistivities (accuracy level of about 99.99%).
Figure 1.10: Exact contact resistivity attained by simulation of the two layer inter-etched TLM structure vs. upper layer thickness (for high resistivity values[1]): See text for full description of the simulation.

However, the contacts discussed in this study are heavily doped N-type hetero-junction based contacts. The specific contact resistivity ($\rho_c$) is relatively low, and, based on the location of the Fermi level as previously mentioned, the specific interface resistivity ($\rho_s$) is much lower than the values presented in [1], and specifically lower than the specific contact resistivity ($\rho_c$). When dealing with such low resistivity values, and heavily doped layers, the layer thickness needed for the assumption to be valid would be ultra-thin. This is demonstrated in figure 1.11. The resistivity values used for the simulation were: specific contact resistivity ($\rho_c$) of about 14 [$\Omega \cdot \mu m^2$] and specific interface resistivity ($\rho_s$) of around 0.1 [$\Omega \cdot \mu m^2$]. The simulation itself was performed exactly like the previous simulation, only with different parameters. It is clear from the presented simulation that a top layer thickness of less than 10 Angstroms would be necessary for an accuracy level of 99% in the estimation of the sum, and since the specific interface resistivity we considered is two orders of magnitude smaller than the specific contact resistivity, it would yield a very substantial error in the extracted interface resistivity, if the calculation can even be attempted. Such an accuracy level in layer thickness resolution is very hard to achieve, and in an MOMBE system it is virtually unattainable. Therefore, the assumption regarding the serial sum of resistivities is inaccurate for our resistivity values and structure parameters.
1.3. The dual layer contact

These in-accurate assumptions make the existing method unsuitable for our purposes. It is now clear that a more accurate analysis of the two layer structure is required.
1.3.3 The analytic model for the two layer TLM structure

This analytic model brought here for the estimation of the total resistance in a full two layer TLM structure was developed and presented in [2]. An earlier version of the model can also be found in [3].

Similarly to the one layer case, analyzing the cross-section of one pair of contacts, we consider the TLM structure to be a web of resistors, both across the metal-semiconductor contact, and along the semiconductor body. In this case, however, the structure consists of two semiconductor layers, and therefore an additional web of resistors is present, to account for the interface resistivity, and the sheet resistance of the second layer.

We again assume that $|W - Z| \ll Z$, since geometrical relations are the same as in the one layer structure, so effectively the cross section is again considered to be constant for the entire width of the contact.

The assumption of thin layers and sheet conduction is still in effect, as was in the one layer model (assumption is verified in APPENDIX A).

![Figure 1.12: Model for standard two layer TLM structure [2, 3]. Model depicts the structure as a mesh of differential resistors, including contact resistivity and interface resistivity elements which we wish to estimate.](image)

Figure 1.12 shows the equivalent resistor mesh presented in [2]. The original model considered the possibility of different parameters underneath and between the contacts in order to account for the possibility of alloying, with the intention of keeping the model as general as possible. In this work, however, it is assumed there is no change in parameters due to alloying, and therefore parameters are considered to be consistent underneath and between the contacts.

As shown in figure 1.12, $\rho_c$ is the contact resistivity ($[\Omega \cdot \mu m^2]$), $\rho_r$ is the interface resistivity ($[\Omega \cdot \mu m^2]$), and $R_{sh1}$, $R_{sh2}$ are the sheet resistances for the upper and lower
1.3. The dual layer contact

layers ([Ω/□]), respectively. The purpose of the full two layer model, as stated in [2], is to find the total resistance between two contact pads as a function of pad separation, and the other geometric and material parameters.

Similarly to the one layer case, the procedure involves solving the differential equations for the areas under the contacts and between the contacts, and invoke continuity in order to attain the overall solution.

Equations 1.23-1.26 present the differential analysis of the full two layer TLM cross section for the area under the contact (−L ≤ x ≤ 0)[15]:

\[ dI_1 = (V_0 - V_1(x)) \cdot \frac{W \cdot dx}{\rho_c} - dI_2 \]  
\[ dI_2 = (V_1(x) - V_2(x)) \cdot \frac{W \cdot dx}{\rho_r} \]  
\[ dV_1 = -R_{sh1} \cdot I_1(x) \cdot \frac{dx}{W} \]  
\[ dV_2 = -R_{sh2} \cdot I_2(x) \cdot \frac{dx}{W} \]

and again, \( V_0 \) is the voltage drop between the contacts, and \( W \) is the contact width.

As described in [2], The general solutions to \( I_1(x) \) and \( I_2(x) \) are obtained by noticing that the solution must be of exponential form, and the coefficients for these exponential arguments are the eigenvalues of the coefficient matrix that corresponds with equations 1.23-1.26. Thus, we attain the general solutions for the region under the contact connected to \( V = V_0 \)

\[ I_1(x) = a_1p e^{\eta_p x} + b_1p e^{-\eta_p x} + a_1n e^{\eta_n x} + b_1n e^{-\eta_n x} \]  
\[ I_2(x) = \lambda_p (a_1p e^{\eta_p x} + b_1p e^{-\eta_p x}) + \lambda_n (a_1n e^{\eta_n x} + b_1n e^{-\eta_n x}) \]  
\[ V_1(x) = -\frac{R_{sh1}}{W \eta_p} (a_1p e^{\eta_p x} - b_1p e^{-\eta_p x}) - \frac{R_{sh1}}{W \eta_n} (a_1n e^{\eta_n x} - b_1n e^{-\eta_n x}) + V_0 \]  
\[ V_2(x) = -\lambda_p \frac{R_{sh2}}{W \eta_p} (a_1p e^{\eta_p x} - b_1p e^{-\eta_p x}) - \lambda_n \frac{R_{sh2}}{W \eta_n} (a_1n e^{\eta_n x} - b_1n e^{-\eta_n x}) + V_0 \]

where

\[ \eta_{p,n} = \frac{1}{\sqrt{2}} \left[ \frac{R_{sh1}}{\rho_c} + \xi_c^2 \pm \sqrt{\left( \frac{R_{sh1}}{\rho_c} + \xi_c^2 \right)^2 - 4 \frac{R_{sh1} \parallel R_{sh2}}{\rho_c} \xi_c^2} \right] \]  
\[ \xi_c \equiv \sqrt{(R_{sh1} + R_{sh2})/\rho_r} \]
\[ \lambda_{p,n} = \frac{\xi^2}{\eta_{p,n}^2} \frac{R_{sh1}}{R_{sh1} + R_{sh2}} - \frac{x^2}{\eta_{p,n}^2} \frac{R_{sh2}}{R_{sh1} + R_{sh2}} \] (1.33)

The subscripts \( p \) and \( n \) in 1.27-1.33 correspond to the positive and negative root choices in 1.31, respectively. The coefficients \( a_1 \) and \( b_1 \) are determined by matching boundary coefficients. The solutions for the region under the contact connected to ground can be obtained through symmetry.

As for the area between the contacts (0 ≤ \( x \) ≤ \( d \)), since it is assumed that no change in parameters due to alloying takes place, equations 1.24-1.26 can still be used in this case, and we simply adjust eq. 1.23, which yields:

\[ dI_1 = -dI_2 \] (1.34)

The general solutions for this set of equations is found through simple integrations. Equations 1.35-1.38 present the general solutions found for the region between the contacts:

\[ I_1(x) = -(d_1e^{\xi_c x} + d_2e^{-\xi_c x}) + \frac{R_{sh2}}{R_{sh1} + R_{sh2}} I_0 \] (1.35)

\[ I_2(x) = d_1e^{\xi_c x} + d_2e^{-\xi_c x} + \frac{R_{sh1}}{R_{sh1} + R_{sh2}} I_0 \] (1.36)

\[ V_1(x) = -\frac{R_{sh1}}{W_\xi_c} (-d_1e^{\xi_c x} + d_2e^{-\xi_c x}) - (R_{sh1} \parallel R_{sh2}) I_0 \frac{x}{W} + d_3 \] (1.37)

\[ V_2(x) = -\frac{R_{sh2}}{W_\xi_c} (d_1e^{\xi_c x} - d_2e^{-\xi_c x}) - (R_{sh1} \parallel R_{sh2}) I_0 \frac{x}{W} + d_4 \] (1.38)

Now that the general solutions for all regions have been determined and presented, the proper boundary conditions need to be imposed in order to attain the desired solution. The pertinent boundary conditions, as presented in [2], are:

1. It is assumed that all contacts are electrically long, meaning that all currents decay to zero at the outer end, i.e. \( I_1(-L) = I_2(-L) = 0 \).

2. \( I_1(0), I_2(0), V_1(0), V_2(0) \) should be continuous over the boundary between region.

3. Due to symmetry, \( I_1(0) = I_1(d), I_2(0) = I_2(d) \)

The formed equations are used to determine the coefficients, and the total resistance \( R_t = V_0/I_0 \). The resulting expression for the total resistance, as shown in [2] is:

\[ R_t = (R_{sh1} \parallel R_{sh2}) \frac{d}{W} + \left[ \frac{2}{(\lambda_p - K)G_p + (\lambda_n - K)G_n} \right] \left[ \frac{R_{sh1} - KR_{sh2}}{R_{sh1} + R_{sh2}} \right] \] (1.39)
1.3. The dual layer contact

where

\[
K(d, L) = \frac{(\lambda_p F_p(L) + \lambda_n F_n(L)) \tanh(\xi_c d/2) + 1}{(F_p(L) + F_n(L)) \tanh(\xi_c d/2) - 1}
\] (1.40)

\[
G_{p,n}(L) = \frac{W \eta_{p,n}}{R_{sh2}} \left( \frac{1}{\lambda_{p,n} - \lambda_{n,p}} \right) \cdot \left( 1 - \lambda_{n,p} \frac{R_{sh2}}{R_{sh1}} \right) \tanh(\eta_{p,n} L)
\] (1.41)

\[
F_{p,n}(L) = \frac{\eta_{p,n}}{\xi_c} \left( \frac{1}{\lambda_{p,n} - \lambda_{n,p}} \right) \cdot (1 + \lambda_{n,p}) \tanh(\eta_{p,n} L)
\] (1.42)

In conclusion of this analytic model of the full two layer structure, the model indeed provides us with the ability to estimate the total resistance for the full two layer structure, essentially making the connection between 2 extracted parameters of a TLM measurement to the 4 structure parameters (contact resistivity, interface resistivity, and sheet resistances of 2 layers). In other words, the model takes the 4 structure parameters, and uses them to provide us with 2 empirical measurement results, which makes it impossible to reversely extract the structure parameters using only these measurements. In order to extract 4 initial structure parameters, one would need to attain 4 actual empirical results.

This brought on the idea of conducting similar measurements on a different structure of the same two layers and contacts. The subject will be further discussed in Chapter 3.
This chapter starts by addressing the technical aspects of the single layer TLM measurements as performed in this study. Following that, a second order correction to the existing analytic error analysis is presented. The chapter then moves on to describe the numeric error analysis method designed within this study. Finally, the chapter concludes by comparing the analytic error analysis with the numeric error analysis, and also presenting single layer TLM measurement results, and analyzing them.
2.1 The single Layer TLM

The theoretical basis of the standard single layer TLM contact characterization method has been presented in Subsection 1.2.1 in the Introduction chapter. This section elaborates on the technical specifics of the TLM array structure and fabrication process as used for measurements in this work.

2.1.1 Single layer TLM pad structure

Basically, the TLM measurements can be taken using a structure as shown in figure 1.3 (Subsection 1.2.1) with a 2 probe measurement method. However, it is well known that 2 probe measurements yield a substantial inherent measurement error due to probe resistance, as will be demonstrated in subsection 2.2. Therefore, the metal contacts of the TLM array, as used in this study, are overlayed with Kelvin structure pads as shown in figure 2.1 in order to enable 4 probe measurements, and thus downsize the measurement error[16, 17]. This will also be demonstrated in subsection 2.2.

Figure 2.1: SEM Image of the TLM array with measurement pads. Specific location of measurement points and current source points is shown.

As illustrated on the pads in figure 2.1, the current source pads are on the opposite sides of the TLM array, and the voltage measurement is performed between two points on the contact area itself, fairly close to the inter contact spacing. In order to correctly account for all resistance factors that might influence the measurement result,
the metal resistance affecting current distribution along the contact has to be modeled, as demonstrated in figure 2.2.

![Figure 2.2: Geometric layout of the TLM pad structure with dominant resistance elements.](image)

The resistance noted by \( R_m \) is the metal resistance of the pad itself along the inter-contact spacing. Using an approximate model of distributed resistors, the pad structure including the current source and measurement points can be represented as:

![Figure 2.3: Resistor model of pad structure. Measurement points and current sources match our specific pad structure](image)
The actual measured resistance for such a structure would be \( R = V / I \). Solving the resistor web presented in figure 2.3, the solution for \( R \) is reached:

\[
R = R_{\text{TLM}} - \frac{R_m}{9} \tag{2.1}
\]

The metal resistance of the pad (\( R_m \)) is predominantly determined by the resistance of the gold layer at the top of the pad, which brings it to a value of around \( 0.1 \, [\Omega] \). This means that the actual measurement includes an under-estimation of about \( 0.01 \, [\Omega] \). Models of greater levels of resistance distribution were also examined and yielded similar results.

However, it is important to mention at this point that the measurements were not all done from the absolute edge of the contact, but from points, which are a bit farther apart, and therefore in actuality a systematic over-estimation was also included. This over-estimation is directly connected to the positioning related measurement error, which is discussed in Section 2.2. Therefore, it is of the same order of magnitude, which is also \( 0.01 \, [\Omega] \).

In conclusion of the pad related issues, it is first important to notice that the over-estimation due to the probe positioning fairly counteracts the under-estimation due to the metal resistance. It is also worth mentioning that nominal measured resistances of a TLM array are about two orders of magnitude greater than these inaccuracy factors. For these reasons, they are considered negligible.
2.1.2 Contact fabrication process

The TLM pattern is fabricated on a 200 nm thick GaInAs layer silicon doped to $3.5 \cdot 10^{19} \text{cm}^{-3}$ grown by metal organic molecular beam epitaxy. Prior to metal deposition the sample is etched in $\text{HCl} : \text{H}_3\text{PO}_4$ 3:1. The TLM metals consist of a 10nm/10nm/200nm Ti/Pt/Au stack, deposited ex-situ by e-beam evaporation in a TEMESCAL system, and defined by the lift off technique. The surrounding GaInAs is wet etched in $\text{H}_2\text{SO}_4 : \text{H}_2\text{O}$ 1:8 for mesa definition. Figure 2.4 shows a schematic cross section of all layers.

![Cross section](image.png)

Figure 2.4: Cross section of the one layer TLM contact: 200 nm thick layer of GaInAs doped to $3.5 \cdot 10^{19} \text{cm}^{-3}$, with a Ti/Pt/Au metal stack.
2.2 Error factors in TLM measurements

As shown in Subsection 1.2.1, The TLM method relies on several geometrically or electrically measured parameters to produce a linear function approximation, from which the desired contact resistivity and sheet resistance are extracted. Therefore these parameters are considered to be the potential sources of uncertainty. We distinguish between geometric error factors and electrical measurement error factors.

2.2.1 Geometric errors

The TLM method requires two geometrically measured sizes: contact width $W$, which in this work is nominally $100 \mu\text{m}$, and inter contact spacings $d$, which in this work range between $2$ and $10 \mu\text{m}$. Geometric errors were estimated by SEM imagery, as shown in figure 2.5.

![SEM image of the 3 $\mu\text{m}$ spacing measurement: Standard deviation of 0.05 $\mu\text{m}$ is observed](image)

Figure 2.5: SEM image of the 3 $\mu\text{m}$ spacing measurement: Standard deviation of 0.05 $\mu\text{m}$ is observed

Averaging on geometric measurement results, the standard deviation for contact width, $\sigma_W$ is 0.05 $\mu\text{m}$, and the standard deviation for inter contact spacing, $\sigma_d$ is also 0.05 $\mu\text{m}$. 
2.2. Error factors in TLM measurements

2.2.2 Measurement errors

Measurements performed within the TLM extraction process are simple resistance measurements between two contacts. Theoretically, in an ideal system, two probes should suffice for such a measurement. However, in any actual system the probes themselves obviously present an inherent resistivity as well. Therefore, the need arises for a 4 probe measurement, thus substantially reducing the measurement error added by the probes.

In order to estimate and demonstrate all standard deviations pertinent to a specific measurement, repeated measurements were performed for the same set of contacts, both using 4 probes and 2 probes, with the probes being repositioned for each measurement. Measurements were also performed repeatedly without repositioning the probes, in order to estimate the internal measurement error of the equipment.

The following histograms show the standard deviations attained for 2 probe measurements, 4 probe measurements, and the internal instrument error for the measurement equipment. As we can clearly see, the internal uncertainty added by the measurement equipment is obviously negligible compared to the actual measurement errors due to repositioning of the probes (almost 20 times smaller than the 4 probe measurement error).

We also observe a smaller measurement error for the 4 probe method compared to the 2 probe. Is it important to note that the 2 probe measurement results include the resistance of the probes themselves, which in this case is around 2.1 $\Omega$, which is in fact larger than the actual resistance we want to measure. Therefore, the 4 probe method was the predominantly used method in this study, and so, an average standard deviation for measurements ($\sigma_R$) of 0.01 $\Omega$ was used as the measurement error for the standard single layer TLM in this study (in this set of results it was 0.013 $\Omega$, but at other instances, values of around 0.007 $\Omega$ were also observed).
Figure 2.6: Histogram of 2 probe measurement results. Measurements taken with repeated repositioning of the probes. Error is fairly substantial.

Figure 2.7: Histogram of 4 probe measurement results. Measurements taken with repeated repositioning of the probes. Error is preferrable to 2 probe measurements.
Figure 2.8: Histogram of measurements taken without repositioning of the probes for estimation of the instrument error. Evidently instrument error is negligible.
2.3 Analytic error analysis

Previous studies have yielded an analytic error estimation of a first order approximation, as presented in Subsection 1.2.2 in the Introduction chapter. This section starts with a general observation into the error estimations attained by that first order approximation in an attempt to identify the dominant error factors at play for the single layer TLM method. The section later moves on to present a second order correction to the analytic model, which was developed within this study, in order to enhance the error estimation accuracy. The benefits of this correction will be more evident in Section 2.4.2 when comparing this analysis to numeric simulation results.

2.3.1 Review of the first order analysis - Identifying dominant error factors

Examining the expressions for the relative error presented in the previous Subsection, it is evident that the relationship between the geometric error in spacing $\sigma_d$ and the measurement error $\sigma_R$ takes place only inside the square root when each of them is squared. The slope of the linear TLM approximation is also squared $\left(\frac{R_{sh}}{W}\right)^2$ and acts as a coefficient for the squared spacing error. Assigning the nominal contact width $W$ to be 100 [µm], and considering a layer thickness of about 200 nm, and a doping level of over $3 \cdot 10^{19}$ [cm$^{-3}$] (matching those used in this work), the extracted sheet resistance for the single layer was around 6 [$\Omega/\square$]. Given an approximate geometric spacing error of about 0.05 [µm], the term $\left(\frac{R_{sh}}{W}\right)^2 \sigma_d^2$ comes to about $9 \cdot 10^{-6}$ [$\Omega^2$] while $\sigma_R^2$ is around $1 \cdot 10^{-4}$ [$\Omega^2$] for a 4 probe measurement error, which is about an order of magnitude smaller. This means that even in 4 probe measurements, the measurement error is fairly dominant in comparison with the geometric spacing error, and for 2 probe measurements that ratio would obviously only become greater.

At this juncture, we move to examine the geometric error in contact width $\sigma_W$. This error element appears in both expressions for relative errors, being divided by the contact width $W$, and multiplied by a factor of 2 or 4. Therefore, if we consider a geometric error of about 0.05 [µm] in contact width, it contributes 0.002 at most to the sum of terms within the brackets. Now, considering the square root and the coefficient attached to it, and assigning the same values we have been using so far, we can see that the geometric error in contact width is more than an order of magnitude smaller. Therefore, it is negligible in comparison, and the measurement error is obviously the dominant error in this case.

2.3.2 Second order correction

First order approximations are fairly effective when accounting only for negligible perturbations, but a second order approximation is sometimes necessary when dealing
2.3. Analytic error analysis

with slightly more substantial perturbations. Since the purpose of this work is to characterize contact resistivity as effectively as possible, it seems prudent to take the second order approximation as our reference point when comparing to numeric data.

The dependency of the random uncertainties in $\sigma_d$, $\sigma_R$ and $\sigma_W$ are still as described in 1.17, 1.18, 1.19 and 1.20, since the linear regression process and the definition of $A$ and $B$ as functions of the contact parameters have not changed. The uncertainty in $\rho_c$, however, will now have to take second order perturbations into account as follows

$$\Delta \rho_c \approx \left| \frac{\partial \rho_c}{\partial A} \right| \Delta A + \left| \frac{\partial \rho_c}{\partial B} \right| \Delta B + \left| \frac{\partial \rho_c}{\partial W} \right| \Delta W$$

$$+ \frac{\partial^2 \rho_c}{\partial A^2} \frac{\Delta A^2}{2} + \frac{\partial^2 \rho_c}{\partial A \partial B} \frac{\Delta A \Delta B}{2} + \frac{\partial^2 \rho_c}{\partial A \partial W} \frac{\Delta A \Delta W}{2}$$

$$+ \frac{\partial^2 \rho_c}{\partial B \partial A} \frac{\Delta B \Delta A}{2} + \frac{\partial^2 \rho_c}{\partial B^2} \frac{\Delta B^2}{2} + \frac{\partial^2 \rho_c}{\partial B \partial W} \frac{\Delta B \Delta W}{2}$$

$$+ \frac{\partial^2 \rho_c}{\partial W \partial A} \frac{\Delta W \Delta A}{2} + \frac{\partial^2 \rho_c}{\partial W \partial B} \frac{\Delta W \Delta B}{2}$$

$$= \left( \frac{WA}{2B} \right) \Delta A + \left( \frac{WA^2}{4B^2} \right) \Delta B + \left( \frac{A^2}{4B} \right) \Delta W$$

$$+ \left( \frac{WA}{2B^2} \right) \Delta A \Delta B + \left( \frac{A}{2B} \right) \Delta A \Delta W + \left( \frac{A^2}{4B^2} \right) \Delta B \Delta W$$

$$+ \left( \frac{W}{2B} \right) \Delta A^2 + \left( \frac{WA^2}{2B^3} \right) \Delta B^2$$

(2.2)

Therefore, using 1.13, the relative uncertainty of $\rho_c$ for a second order approximation is

$$\frac{\Delta \rho_c}{\rho_c} \approx 2 \left( \frac{\Delta A}{A} \right) \frac{\Delta B}{B} + \left( \frac{\Delta A}{A} \right)^2 + \left( \frac{\Delta B}{B} \right)^2$$

$$+ 2 \left( \frac{\Delta A}{A} \right) \left( \frac{\Delta B}{B} \right) + 2 \left( \frac{\Delta A}{A} \right) \left( \frac{\Delta W}{W} \right) + \left( \frac{\Delta W}{W} \right) \left( \frac{\Delta B}{B} \right)$$

(2.3)

Using the same procedure, the relative uncertainty of $R_{sh}$ for a second order approximation is

$$\frac{\Delta R_{sh}}{R_{sh}} \approx \frac{\Delta B}{B} + \frac{\Delta W}{W} + \left( \frac{\Delta W}{W} \right) \left( \frac{\Delta B}{B} \right)$$

(2.4)

Now, by substituting 1.17, 1.18, 1.19 and 1.20 into 2.3, and substituting the parameters $A$ and $B$ (1.9, 1.10), the total relative uncertainty of the specific contact resistivity
by random error in the second order approximation can be expressed as

\[
\frac{\sigma_\rho}{\rho} \simeq \frac{1}{\sqrt{N}} \left( \left( \frac{2W}{\sqrt{\rho_c R_{sh} d_{max}}} + \frac{2\sqrt{3}W}{R_{sh} d_{max}} \right) \cdot \sqrt{\frac{R_{sh}}{W}} \sigma_d^2 + \sigma_R^2 + \left( \frac{4}{W} \right) \sigma_W \right)
\]

\[
+ \frac{1}{N} \left[ \left( \frac{R_{sh}}{W} \right)^2 \sigma_d^2 + \sigma_R^2 \right] \cdot \left( \frac{W^2}{\rho_c R_{sh}} + \frac{12W^2}{R_{sh} d_{max}^2} + \frac{4\sqrt{3}W^2}{R_{sh} d_{max} \sqrt{\rho_c R_{sh}}} \right)
\]

\[
+ \frac{1}{N} \left[ \left( \frac{5\sigma_W}{\sqrt{\rho_c R_{sh}}} + \frac{8\sqrt{3}\sigma_W}{R_{sh} d_{max}} \right) \cdot \sqrt{\frac{R_{sh}}{W}} \sigma_d^2 + \sigma_R^2 + 7 \left( \frac{\sigma_W}{W} \right)^2 \right]
\]  

(2.5)

and by making the same substitutions into 2.4, we get

\[
\frac{\sigma_{R_{sh}}}{R_{sh}} \simeq \frac{1}{\sqrt{N}} \left( \left( \frac{2\sqrt{3}W}{R_{sh} d_{max}} \right) \cdot \sqrt{\frac{R_{sh}}{W}} \sigma_d^2 + \sigma_R^2 + \left( \frac{2}{W} \right) \sigma_W \right)
\]

\[
+ \frac{1}{N} \left[ \left( \frac{2\sqrt{3}\sigma_W}{R_{sh} d_{max}} \right) \cdot \sqrt{\frac{R_{sh}}{W}} \sigma_d^2 + \sigma_R^2 + \left( \frac{\sigma_W}{W} \right)^2 \right]
\]  

(2.6)

Equations 2.5 and 2.6 will also be used later for comparison with the numeric simulation results, and naturally with the first order approximation results as well.

2.4 Numeric error analysis

This section focuses on numeric error estimation for the basic one layer TLM method, using Monte-Carlo simulations (using the TLM method for repeatedly randomized error values, and analyzing the resulting histograms). The application of this additional form of error analysis to the existing single layer TLM method serves as a step in validating the Monte-Carlo method as a viable method for estimating the error in TLM measurements. Finally, the simulation results are presented, and compared to the first order and second order analytic error analysis results as another step in validating the use of the Monte-Carlo method for error analysis in TLM measurements.

2.4.1 Monte Carlo simulation method for TLM

The Monte Carlo method relies on repeated random sampling to compute results for a given function, when it is unfeasible or even impossible to attain exact deterministic results for said function.

During this simulation, uncertainty values for the relevant error factors will be repeatedly randomized under a normal distribution, each according to its standard deviation, and measurement sets of a TLM array will be created accordingly. These results will be analyzed in the normal fashion, yielding a result distribution, which will
enable us to calculate the standard deviation for each extracted parameter, like the ones attained by the analytic method shown in section 2.3.

Figure 2.9: Demonstration of the TLM randomization procedure as part of the Monte Carlo simulation: Error in contact width determines the slope, error in spacing determines the X-axis coordinate and the intersection with the randomized slope, and measurement error determines the specific value. See text for full description.

The general Monte Carlo randomization algorithm for a TLM measurement set goes as follows (visually demonstrated in figure 2.9):

1. \( \rho_c \) and \( R_{sh} \) are given parameters, defining \( L_T \), and by that setting the intercept with the x axis.

2. Width of the contact \( W \) is randomized (the desired \( W \) is the mean, \( \sigma_W \) is the standard deviation), setting the slope of the graph.

3. Each spacing \( d_i \) is randomized (the desired spacing is the mean, \( \sigma_d \) is the standard deviation), setting the intersection between the spacing and the slope line.

4. For each intersection as mentioned above, a measurement error is randomized (zero error is the mean, \( \sigma_R \) is the standard deviation) and added to the intersection value.
The actual MATLAB algorithm implementing this procedure is shortly described in APPENDIX C.

The resulting graph is a randomized measurement set for which a linear extrapolation is now made, and parameters are extracted. A histogram of the results shows the distribution and enables us to extract the standard deviation, as demonstrated in Section 2.4.2.
2.4.2 Simulations

Based on the numeric simulation method described in section 2.4, and using approximate error factor values mentioned in subsection 2.2, we can now present the simulation result histograms, and extract the standard deviations.

![Histogram of contact resistivity](image)

![Histogram of sheet resistance](image)

Figure 2.10: Monte Carlo simulation result histograms for error estimation in single layer TLM. Results are presented for $\rho_c$ (upper) and $R_{sh}$ (lower) with 100,000 samples. Standard deviation of 0.84 [Ω·μm²] is observed in contact resistivity, and 0.08 [Ω/□] in sheet resistance.
Figure 2.10 shows histograms of a Monte Carlo simulation for the results of $\rho_c$ and $R_{sh}$. Base parameters of $\rho_c = 12.6 [\Omega \cdot \mu m^2]$ and $R_{sh} = 6.5 [\Omega / \square]$ were used (in accordance with average values to be shown later in subsection 2.5.1). The simulation was performed for 100,000 random samples. As shown in the histogram, simulations yielded a mean $\rho_c$ value of $12.62 [\Omega \cdot \mu m^2]$ with a standard deviation of $0.84 [\Omega \cdot \mu m^2]$, which translates to a relative uncertainty of about 0.07, and a mean $R_{sh}$ value of $6.5 [\Omega / \square]$ with a standard deviation of $0.08 [\Omega / \square]$, which translates to a relative uncertainty of 0.01.

Now, based on analytic error estimations done in section 2.3, and the numeric simulation results, and again, using approximate error factor values described in subsection 2.2, we can compare the numeric error estimation with the analytic ones. Figure 2.11 (next page) shows the results of the comparison between the numeric Monte Carlo simulation and the calculation result from the analytic approximations (1st and 2nd order).

It can be easily seen in the diagrams that the second order approximation is much closer to the more realistic results of the Monte-Carlo simulations. The remaining difference is probably due to several approximations made during the statistical calculation, specifically the approximation regarding the number of spacings, $N$ (namely, the assumption that $(N - 1) \simeq (N - 2)$).

---

1Effectively, 1000 samples would have sufficed for the calculation of the standard deviations, but the extra samples enable the formation of the Gaussian, showing how the results also exhibit a normal distribution.
Figure 2.11: Relative errors in $\rho_c$ (upper) and $R_{sh}$ (lower) from numeric simulations (full line) vs. analytic simulations (1st order in dashed line, 2nd order in dotted line): Good match is observed between numeric analysis and analytic first order analysis, but better match is observed for second order correction.
2.5 Measurements

TLM Measurements were conducted using an Agilent 4155B Semiconductor Parameter Analyzer (SPA), with 4 probes.

2 sets of measurements were conducted. The first set consisted of single measurements of multiple TLM arrays on the same wafer, so that average parameter estimations across the wafer could be attained. Such measurements obviously take into account all error factors, as described in subsection 2.2, but they also inevitably include a process dependent parameter variance across the wafer. The second set consisted of numerous measurements of a single array, so that only measurement errors could account for uncertainty in results, excluding the possible variance in the desired parameter itself.

It is important to note that the measurements performed on the single array obviously do not account for geometric errors in pad spacings and contact width. However, since measurement errors are the dominant errors in the single layer case, as demonstrated in Section 2.3, the single array measurement still produces a better fit to simulation results than the multiple array measurements, as will be demonstrated shortly.

2.5.1 Measurements of multiple arrays

Single measurements of multiple arrays yielded a mean $\rho_c$ value of 12.58 $[\Omega \cdot \mu m^2]$ with a standard deviation of 1.91 $[\Omega \cdot \mu m^2]$, which translates to a relative uncertainty of 0.15, and a mean $R_{sh}$ value of 6.53 $[\Omega/\square]$ with a standard deviation of 0.22 $[\Omega/\square]$, which translates to a relative uncertainty of 0.03.

Figure 2.12 shows the histograms for the measurement results.

2.5.2 Repeated measurements of a single array

Numerous measurements of a specific array yielded a mean $\rho_c$ value of 11.89 $[\Omega \cdot \mu m^2]$ with a standard deviation of 0.96 $[\Omega \cdot \mu m^2]$, which translates to a relative uncertainty of 0.08, and a mean $R_{sh}$ value of 6.87 $[\Omega/\square]$ with a standard deviation of 0.07 $[\Omega/\square]$, which translates to a relative uncertainty of 0.01.

Figure 2.13 shows the histograms for the measurement results.
Figure 2.12: Histogram of measurement results for multiple 1-layer TLM arrays on the same wafer: Specific contact resistivity $\rho_c$ (upper) and Sheet resistance $R_{sh}$ (lower)
Figure 2.13: Histogram of measurement results for repeated measurements of a single 1-layer TLM array: Specific contact resistivity $\rho_c$ (upper) and Sheet resistance $R_{sh}$ (lower): Error for single array matches numeric simulation results, confirming that measurement error is dominant for the single layer TLM.
2.6 Comparison & Discussion

We have seen the differential analysis of the single layer TLM structure, and the linear extraction method resulting thereof. We have gone over error estimations, both analytic, using first and second order approximations, and numeric, using Monte Carlo simulations.

We have attained measurement results both for repeated measurements of a single array, and for measurements of multiple arrays across the wafer, thus, on one hand, avoiding the issue of possible parameter variance when assessing the accuracy of the extraction method, and, on the other hand, still getting an actual average estimation of the contact parameters.

It can be easily seen that the relative uncertainty extracted from the repeated measurements of the single array is in fairly good agreement with the values suggested by the analytic error model, and the Monte Carlo simulations, since they did not account for variance in the parameters themselves. It should also be noted that the repeated measurements of the single array only take into account the measurement error ($\sigma_R$), and not the uncertainties in contact width ($\sigma_W$) or inter-contact spacings ($\sigma_d$). The obvious agreement shown here between the Monte Carlo simulations and these repeated measurements essentially demonstrates how dominant the measurement error truly is in this case, compared to geometric uncertainties. Therefore, we can safely conclude that given the error factors mentioned in subsection 2.2, the single layer TLM method yields a relative uncertainty of about 7-8% in the specific contact resistivity $\rho_c$ and about 1% in the sheet resistance $R_{sh}$.

Also fairly evident is the rise in relative uncertainties attained from measurements conducted over multiple arrays across the wafer, compared to those from the single array, the cause of which is obviously a non-negligible variance in parameters across the specific wafer. These variations will be further discussed later on.
Chapter 3

The Dual Layer TLM Method

Dual layer contacts is a well known method for attaining near-ohmic contacts in microelectronic devices based on certain material systems, such as HBTs based on the Inp/GaInAs material system. It has been shown that there is a definite need for a more precise characterization of the two layer structure in general, and specifically the interface resistivity, especially when attempting to reach extremely low contact resistivities. This chapter starts by describing the full analytic model for the second two layer structure, as developed within this study, and then the innovative parameter extraction method for the two-layer structure is presented. Following that, the custom designed error analysis is presented. The chapter then moves on to present structure optimizations using the numeric simulations, and concludes with measurement result presentation and discussion.
3.1 The dual layer TLM Model

As mentioned previously in Subsection 1.3.2, the existing estimation method is not sufficiently accurate when dealing with low resistivity values, and it becomes apparent that a different method is required. As discussed in Subsection 1.3.3, measurements performed on the full two layer structure alone would not suffice for extracting the structure parameters. For that reason, the need arose to find a different structure, for which the parameters would be the same, but would yield different measurement. The structure chosen was the inter-etched structure, in which the upper layer has been etched away in the area between the contacts.

In this section the analytic model for the new two layer structure (the inter-etched structure) is presented. This model was developed within this study. Following that, a new numeric extraction method for the desired parameters will be presented, combining the the existing analytic model, as shown in the Subsection 1.3.3 of the Introduction, and the new analytic model described in this section. The section will conclude with a description of the actual layer structure and fabrication process.
3.1.1 The analytic model for the inter-etched two layer TLM structure

The structure discussed in this subsection is the same inter-etched model mentioned in Subsection 1.3.2 and illustrated in figure 1.8(b). It is still assumed the layers are thin enough for the assumption of sheet conduction to still be in effect, but the top layer is not required to be ultra thin as in the existing method discussed in Subsection 1.3.2. The analytic model for this inter-etched TLM structure was developed within this study similarly to the full layer structure.

Figure 3.1: Model for the new “inter-etched” two layer TLM structure: developed within this study. Model depicts the inter-etched structure as a mesh of differential resistors, including: contact resistivity, interface resistivity and sheet resistances.

Figure 3.1 shows the equivalent resistor mesh for the new inter-etched structure, similarly to the full two layer structure shown in Subsection 1.3.3. It is still assumed there is no change in parameters due to alloying, and therefore parameters are considered to be consistent underneath and between the contacts.

Again, as shown in figure 3.1, \( \rho_c \) is the contact resistivity \( ([\Omega \cdot \mu m^2]) \), \( \rho_r \) is the interface resistivity \( ([\Omega \cdot \mu m^2]) \), and \( R_{sh1}, R_{sh2} \) are the sheet resistances for the upper and lower layers \( ([\Omega/\square]) \), respectively.

Similarly to the full two layer structure, the procedure involves solving the differential equations for the areas under the contacts and between the contacts, and invoke continuity and boundary conditions in order to attain the desired solution.

For the region underneath the contact \((-L \leq x \leq 0)\), Equations 1.23-1.26 from the full two layer structure description are still valid, since that region is identical in the full two layer model and in the inter-etched model.

Therefore, the general solutions for the area under the contacts in the inter-etched model are also the ones from the full two layer model, as presented in equations 1.27-1.33.

For the region between the contacts \((0 \leq x \leq d)\), the pertinent differential equation is
Chapter 3. The Dual Layer TLM Method

actually similar to the one layer analysis:

\[ dV_2 = -R_{sh2} \cdot \frac{I_0}{W} \cdot \frac{dx}{W} \]  \hspace{1cm} (3.1)

which yields a general solution:

\[ V_2(x) = c_1 - R_{sh2} \cdot \frac{I_0}{W} \cdot x \]  \hspace{1cm} (3.2)

Now that the general solutions for all regions have been determined and presented, the proper boundary conditions need to be imposed in order to attain the desired solution. The pertinent boundary conditions in this case are:

1. It is assumed that all contacts are electrically long, meaning that all currents decay to zero at the outer end, i.e. \( I_1(-L) = I_2(-L) = 0 \).

2. \( V_2(0) \) should be continuous over the boundary between region.

3. Due to symmetry and etching of the upper layer between the contacts, \( I_1(0) = I_1(d) = 0, I_2(0) = I_2(d) = I_0 \)

4. Due to symmetry, \( V_2(\frac{d}{2}) = \frac{V_0}{2} \)

The formed equations will be used to determine the coefficients, and the total resistance \( R_t = \frac{V_0}{I_0} \). In this case, since it is a solution fully developed within this study, all stages of solution will be described in full, as opposed to the full two layer model solution described in the previous subsection, and detailed in \([2]\).

Essentially, there are 6 coefficients: \( a_{1p,n}, a_{1n}, b_{1p,n}, b_{1n}, c_1 \) and \( I_0 \), and there are 6 relevant boundary conditions.

Imposing the symmetry condition in \( V_2(x) \) gives us the coefficient \( c_1 \) and a more specific solution for the voltage between the contacts:

\[ V_2(x) = \frac{V_0}{2} - R_{sh2} \cdot \frac{I_0}{W} \cdot \left( x - \frac{d}{2} \right) \]  \hspace{1cm} (3.3)

Imposing zero current at the outer end of the contact yields the following relation between \( a_{1p,n} \) and \( b_{1p,n} \):

\[ \left( a_{1p,n} e^{-\eta_{p,n} L} + b_{1p,n} e^{\eta_{p,n} L} \right) (\lambda_p - \lambda_n) = 0 \]  \hspace{1cm} (3.4)

Using the definitions of \( \lambda_{p,n} \) from eq. 1.33, it is obvious that the expression \( (\lambda_p - \lambda_n) \) would only amount to zero if \( \eta_{p,n}^2 = \eta_{p,n}^2 \), and it is easy to see that this equality would never happen. Therefore we are left with the specific relations between \( a_{1p,n} \) and \( b_{1p,n} \):

\[ b_{1p,n} = -a_{1p,n} \cdot e^{-2\eta_{p,n} L} \]  \hspace{1cm} (3.5)
3.1. The dual layer TLM Model

Imposing the continuity (or dis-continuity) in \( I_1(0) \), yields a specific relation between \( a_{1p} \) and \( a_{1n} \):

\[
a_{1p} = -a_{1n} \frac{1 - e^{-2\eta_p L}}{1 - e^{-2\eta_n L}} \tag{3.6}
\]

Imposing the continuity in \( I_2(0) (= I_0) \), yields the specific definitions for these 4 coefficients:

\[
a_{1p,n} = \frac{I_0}{(\lambda_{p,n} - \lambda_{n,p}) (1 - e^{-2\eta_p L})} \tag{3.7}
\]

\[
b_{1p,n} = \frac{I_0}{(\lambda_{p,n} - \lambda_{n,p}) (1 - e^{\eta_p L})} \tag{3.8}
\]

Now that all actual coefficients have been determined, The last condition, of continuity in \( V_2(0) \), can be used to determine the total resistance \( R_t = V_0 / I_0 \):

\[
R_t = R_{sh2} \cdot \frac{d}{W} + \frac{2R_{sh2}}{W \cdot (\lambda_p - \lambda_n)} \left[ \frac{\lambda_p}{\eta_p \tanh(\eta_p L)} - \frac{\lambda_n}{\eta_n \tanh(\eta_n L)} \right] \tag{3.9}
\]

Since we use characteristically long contacts (\( L \approx 200 [\mu m] \)), it can be easily seen using the definitions of \( \eta_{p,n} \) that the hyperbolic tangent is effectively 1, and we get the simplified version of the solution for the inter-etched TLM structure:

\[
R_t = R_{sh2} \cdot \frac{d}{W} + \frac{2R_{sh2}}{W \cdot (\lambda_p - \lambda_n)} \left[ \frac{\lambda_p}{\eta_p} - \frac{\lambda_n}{\eta_n} \right] \tag{3.10}
\]

3.1.2 The Numeric Dual TLM Parameter Extraction Method

Now that two different structures are available, both based on the same 4 parameters, but each with its own separate analytic model, one would be able to extract these parameters using 4 measurement results. It is important to note that the two structures share the same parameters since it is actually the same layer structure before and after etching. The use of the same structure keeps the extraction procedure safe from variance in the parameters themselves, as seen for example in the single layer measurement results, and discussed in Section 2.6.

The 2 results attained from the full two layer structure are the effective contact resistance and the effective sheet resistance for that structure, which we will name \( R_{c,no-etch} \) and \( R_{sh,no-etch} \), respectively. Similarly, the 2 results attained from the inter-etched structure will be named \( R_{c,inter-etch} \) and \( R_{sh,inter-etch} \). By examining the final simplified solutions for both structures, we can easily get the analytic expressions for all 4 results:
Chapter 3. The Dual Layer TLM Method

\[ R_{sh,\text{no-etch}} = (R_{sh1} \ || R_{sh2}) \]  
\[ R_{c,\text{no-etch}} = \left[ \frac{1}{(\lambda_p - K)G_p + (\lambda_n - K)G_n} \right] \left[ \frac{R_{sh1} - KR_{sh2}}{R_{sh1} + R_{sh2}} \right] \]  
\[ R_{sh,\text{inter-etch}} = R_{sh2} \]  
\[ R_{c,\text{inter-etch}} = \frac{R_{sh2}}{W \cdot (\lambda_p - \lambda_n) \left( \frac{\lambda_p}{\eta_p} - \frac{\lambda_n}{\eta_n} \right)} \]  

where \( \lambda_{p,n}, K, G_{p,n} \) are described in 1.33, 1.40, 1.41.

Using the immediate sheet resistance results, the actual sheet resistance for each layer can be easily and directly extracted.

Now two expressions remain for the effective contact resistance of each structure. Mathematically we can describe them as two non-linear functions of the remaining two unknown parameters (two parameters, which are the sheet resistances, are already known at this point).

Using numeric tools for solving a set of 2 non-linear equations, we equate these analytic expression to the values extracted from the TLM measurements, and numerically attain the desired parameters.
3.1.3 Two layer TLM Layer structure & fabrication process

The TLM pattern is fabricated on a hetero-structure consisting of 50 nm thick GaInAs layer silicon doped to $3.5 \cdot 10^{19} \text{ cm}^{-3}$ on top of a 80 nm thick InP layer doped to $3 \cdot 10^{19} \text{ cm}^{-3}$, grown by metal-organic molecular beam epitaxy. The hetero-structure layer thickness was designed according to the optimizations described in Subsection 3.2.5.

Prior to metal deposition the sample is etched in $\text{HCl} : \text{H}_3\text{PO}_4$ 3:1, rinsed in $\text{HCl} : \text{H}_2\text{O}$ 1:25, and loaded into the evaporation chamber. The TLM metals consist of a 10nm/10nm/200nm Ti/Pt/Au stack, deposited ex-situ by TEMESCAL, and defined by lift off technique. The surrounding GaInAs and InP is then wet etched (in $\text{H}_2\text{SO}_4 : \text{H}_2\text{O}$ 1:8) for Mesa definition. The first TLM measurement is performed at this stage. Following that, the upper layer in the area between the contacts is also wet etched (in $\text{H}_2\text{SO}_4 : \text{H}_2\text{O}$ 1:8), thus yielding the desired inter-etched structure, at which point the second TLM measurement can be performed. Figure 3.2 shows a cross section of all layers.

![Cross Section of Layers](image)

**Figure 3.2: Cross section of the two layer TLM contact: 80 nm thick layer of InP doped to $3 \cdot 10^{19} \text{ cm}^{-3}$, 50 nm thick layer of GaInAs doped to $3.5 \cdot 10^{19} \text{ cm}^{-3}$, with a Ti/Pt/Au metal stack**
3.2 Error analysis

This section focuses on the error analysis relevant to the new dual TLM method. First, the additional error factors, which are not present in single layer TLM measurements, are described. Following that we discuss the numeric error estimation for the dual TLM method using Monte-Carlo simulations, and how they are revised to simulate the two consecutive measurements and also incorporate the additional error factors.

Finally, Numeric simulations and optimizations are also presented.

3.2.1 Additional error factor

When performing a standard error analysis for a TLM structure, the geometric uncertainty in the spacings between the contacts is taken under consideration (via the standard deviation $\sigma_d$).

As mentioned in Subsection 3.1.3, preparation of the model for the second TLM measurement entails a wet etch of the upper layer (GaInAs in our case), an etch which ideally would leave a straight edged structure.

However, since the wet etch is an isotropic etch, the edges of the inter-etched area undergo a certain amount of undercut beneath the edges of the contacts, thus effectively making each spacing bigger, as can be seen in Figure 3.3.

Figure 3.3: FIB image and measurement of the wet etch undercut: Undercut leaves the side wall of the upper layer at a substantial slant, thus adding both to the actual inter-contact spacing, and to the geometric uncertainty in the inter-contact spacing
This addition is accounted for when entering the spacings into the analysis for the inter-etched structure. However, as seen in figure 3.3, the undercut leaves the side of the upper layer aslant, so a specific value for this addition could be attained by the FIB measurement alone. In order to reach an actual value that can be used in the analysis, that side wall had to be approximated to be a vertical wall located at some point within the slanted region. For that purpose, the structure was simulated using finite element simulations, and it has been found that a vertical edge located at 60% of the way into the slanted region would serve as a good approximation. This approximation and its validity will be discussed and explained in greater detail in APPENDIX B.

Setting aside this offset in spacing value, the unavoidable standard deviation in this undercut also has to be taken into consideration. This additional standard deviation, which will be named $\sigma_{d,\text{undercut}}$, was estimated using the FIB imagery and will be added to the original standard deviation in spacing when performing the error randomization for the Monte Carlo simulations.

### 3.2.2 Monte Carlo simulation method for two layer TLM

Due to the complexity of the extraction procedure the experimental error in the obtained values for the dual TLM method cannot be estimated analytically as done in the single layer case, and therefore it can only be calculated by numeric Monte Carlo simulations.

The general Monte Carlo randomization algorithm for the dual TLM method is essentially based on the algorithm for the standard single layer single measurement Monte Carlo, as described in Subsection 2.4.1, but with a few adjustments to account for the fact that two different measurements are performed instead of one, and that an additional error factor is at play. The revised algorithm for the dual TLM measurement goes as follows:

1. $\rho_c, \rho_r$ and $R_{sh1,2}$ are given parameters, setting the projected intercept $R_c$ with the $x$ axis for each model, i.e. $R_{c,\text{no-etch}}, R_{c,\text{inter-etch}}$.

2. Width of the contact $W$ is randomized (the desired $W$ is the mean, $\sigma_W$ is the standard deviation), setting the slope of the graph according to the pertinent effective sheet resistance of each structure, and also adjusting $R_{c,\text{no-etch}}$ and $R_{c,\text{inter-etch}}$ accordingly (both are linearly dependent on $W$, so it is a simple matter of multiplying by the nominal value of $W$, and re-dividing by the randomized one).

3. Each standard spacing $d_i$ is randomized once (the original desired spacing is the mean, $\sigma_d$ is the standard deviation), setting the intersection point between the randomized spacing and the slope line for the non-etched structure.

4. The estimated undercut is randomized and added to each spacing (the nominal estimated undercut is the mean, $\sigma_{d,\text{undercut}}$ is the standard deviation. Both are
estimated as described in Subsection 3.2.1), thus setting the intersection point between the randomized spacing and the slope line for the inter-etched structure.

5. For each intersection as mentioned above, a measurement error is randomized (zero error is the mean, \( \sigma_R \) is the standard deviation) and added to the intersection value.

The resulting graphs are a set of two randomized measurements for a specific array for which linear extrapolations are now made, and parameters are extracted using the dual TLM method, as detailed in Subsection 3.1.2.
3.2.3 Simulations

Based on the numeric simulation method described in section 3.2.2, we can now simulate and present the result histograms, so we can extract the standard deviations, as we did for the single layer TLM. Since the measurements before and after the inter-contact wet etch are in actuality separate measurements, the measurement error before and after the etch have also been incorporated separately. This way, the effect of the measurement error before the etch will be independent from the effect of the measurement error after the etch, thus making each and every error factor have a distinct contribution. This subject will be further discussed in Subsection 3.2.4. Table 3.1 summarizes the standard distributions used to simulate every error factor, and the nominal values for each one, estimated as previously described in section 2.2 and subsection 3.2.1.

Figures 3.4 and 3.5 show histograms of the four extracted parameters ($\rho_c$,$\rho_r$,$R_{sh1,2}$) as produced with Monte Carlo simulations. Base parameters of $\rho_c = 9.8[\Omega \cdot \mu m^2]$, $\rho_r = 1.6[\Omega \cdot \mu m^2]$, $R_{sh1} = 31[\Omega/\Box]$, and $R_{sh2} = 35.8[\Omega/\Box]$ were used (in accordance with average values to be shown later in Section 3.3). The simulation was performed for 100,000 random samples. As shown in the histogram, simulations yielded a standard deviation in $\rho_c$ of 1.03 $[\Omega \cdot \mu m^2]$, which translates to a relative uncertainty of about 0.1, a standard deviation in $\rho_r$ of 0.76 $[\Omega \cdot \mu m^2]$, which translates to a relative uncertainty of about 0.45, a standard deviation in $R_{sh1}$ of 0.57 $[\Omega \cdot \mu m^2]$, which translates to a relative uncertainty of about 0.02, and a standard deviation in $R_{sh2}$ of 0.34 $[\Omega/\Box]$, which translates to a relative uncertainty of 0.01.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Nominal Value</th>
<th>Related Error Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_d$</td>
<td>0.05 $[\mu m]$</td>
<td>Uncertainty in inter-contact spacing as fabricated</td>
</tr>
<tr>
<td>$\sigma_{d, undercut}$</td>
<td>0.025 $[\mu m]$</td>
<td>Additional uncertainty in spacing due to under-cut</td>
</tr>
<tr>
<td>$\sigma_W$</td>
<td>0.05 $[\mu m]$</td>
<td>Uncertainty in contact width as fabricated</td>
</tr>
<tr>
<td>$\sigma_{R_{-before}}$</td>
<td>0.011 $[\Omega]$</td>
<td>Error in the measured resistance before the wet etch</td>
</tr>
<tr>
<td>$\sigma_{R_{-after}}$</td>
<td>0.017 $[\Omega]$</td>
<td>Error in the measured resistance after the wet etch</td>
</tr>
</tbody>
</table>

Table 3.1: Error factors used for simulations
Figure 3.4: Monte Carlo simulation result histograms for estimating the error in the dual layer TLM. Simulation results are presented for $\rho_c$ (upper) and $\rho_r$ (lower) with 100,000 samples. Standard deviation of 1.03 $[\Omega \cdot \mu m^2]$ is observed in contact resistivity, and 0.76 $[\Omega \cdot \mu m^2]$ in interface resistivity.
3.2. Error analysis

Figure 3.5: Monte Carlo simulation result histograms for dual layer TLM for $R_{sh1}$ (upper) and $R_{sh2}$ (lower) with 100,000 samples.
3.2.4 Identifying dominant error factors

Since the experimental error for this method can only be estimated using numeric simulations, identification of the dominant error factors for this method would also have to be accomplished numerically. In order to account for the specific effect of every single one of the error factors, Monte Carlo simulations were conducted for every error factor separately. Since the most pertinent experimental errors are the ones in specific contact resistivity $\rho_c$ and specific interface resistivity $\rho_r$, only those are discussed here.

The error factors considered for this simulation and the nominal values used for the standard distributions, are as described in Subsection 3.2.3 and summarized in Table 3.1. Figures 3.6 and 3.7 show the contribution of $\sigma_d$, $\sigma_{d,\text{undercut}}$, $\sigma_W$, $\sigma_{R-\text{before}}$, and $\sigma_{R-\text{after}}$.

First of all, it is clearly evident that, similarly to the one layer TLM, the uncertainty in contact width, represented by $\sigma_W$ contributes very little to the overall error. As for the geometric uncertainty in spacing, it is observed that the extracted specific interface resistivity is fairly sensitive both to the initial spacing error and to the additional spacing error added by the undercut and by roughly the same measure. However, the extracted specific contact resistivity is more sensitive to the initial error in spacing than to the added error in spacing by about an order of magnitude. Moving on to the specific contributions of measurement errors, we notice that the specific interface resistivity is fairly sensitive to measurement errors both before and after the wet etch by roughly the same measure, a little more to the latter. The specific contact resistivity, on the other hand, is very sensitive to measurement errors before the wet etch, and by an order of magnitude more than it is sensitive to measurement errors after the wet etch.

Taking all into account, we derive that in the dual TLM method:

(a) The extracted specific contact resistivity is highly sensitive to the measurement error before the wet etch, and fairly sensitive to the initial spacing error.

(b) The extracted specific interface resistivity is fairly sensitive to all error apart from the error in contact width, with the measurement error after the wet etch being the most dominant.
3.2. Error analysis

Figure 3.6: Specific contributions of geometric error factors. Monte Carlo simulation results for: (a) \( \sigma_d \) (b) \( \sigma_{d,\text{undercut}} \) and (c) \( \sigma_W \). Original spacing error affects both resistivities, additional undercut related spacing error mainly affects interface resistivity, and contact width error is negligible.
Figure 3.7: Specific contributions of measurement error factors. Monte Carlo simulation results for: (a) $\sigma_{R_{\text{before}}}$ and (b) $\sigma_{R_{\text{after}}}$. Measurement error before the wet etch affects both resistivities and measurement error after the wet etch mainly affects interface resistivity.
3.2. Error analysis

3.2.5 Optimizations

In preparation for the actual measurements, layer thickness for both layers had to be determined, and therefore optimizations had to be made in order for the chosen structure to best exhibit the method and yield the smallest possible error in extracted parameters. This subsection describes the simulations performed for optimizing the layer thickness.

For the purpose of the optimization, a scan has been run over possible layer thicknesses for both layers, i.e. over possible sheet resistance values for both layers. A brief Monte Carlo simulation was performed for each set of values, yielding an approximate 3D rendering of the resulting errors in specific contact resistivity ($\rho_c$) and the specific interface resistivity ($\rho_r$).

Figure 3.8: 3D renderings of the errors in $\rho_c$ (upper) and $\rho_r$ (lower) vs. various values of $R_{sh1}$ and $R_{sh2}$: Relatively low sheet resistance values seem less desirable
Figure 3.8 shows the results of the initial scan over $R_{sh1}$ and $R_{sh2}$ values. It clearly shows higher uncertainty levels in both extracted parameters for relatively low values of either sheet resistance. This result meets with preliminary expectations. As previously described in Subsection 3.1.2, the sheet resistance of the upper layer ($R_{sh1}$) is extracted from the measured sheet resistance of both layers in parallel. If it is relatively high in comparison to the lower layer sheet resistance ($R_{sh2}$), the parallel resistance ($R_{sh1} \parallel R_{sh2}$) becomes very close to the lower layer sheet resistance, thus making the reverse extraction of the $R_{sh1}$ very difficult, and extremely prone to measurement error. On the other hand, if the lower layer sheet resistance is significantly low, extracting it could again be problematic due to measurement error.

In order to further demonstrate this point, 3D renderings of the relative errors in extracted sheet resistance values have also been produced, as seen in figure 3.9 (since the sheet resistances serve as variables in this simulation, relative errors are presented).

![3D renderings of the relative errors in $R_{sh1}$ (upper) and $R_{sh2}$ (lower) vs. various values of $R_{sh1}$ and $R_{sh2}$](image)

Figure 3.9: 3D renderings of the relative errors in $R_{sh1}$ (upper) and $R_{sh2}$ (lower) vs. various values of $R_{sh1}$ and $R_{sh2}$
It is worth noticing that the error in specific interface resistivity is even more severe for relatively high values of $R_{sh2}$. This also meets with preliminary expectations, since a relatively high sheet resistance in the lower layer of the structure would divert the majority of current to pass through the upper layer, thus making the transition between layers less noticeable, hence the higher error level.

At this point, after conducting the first stage of optimizations, it was concluded that generally it would be most beneficial to have sheet resistance values of similar magnitudes for both layers, and neither of them too low. Therefore, under the preposition that both layers would be of the same approximate sheet resistance, another scan, of higher resolution, was performed.

Figure 3.10: High resolution scan results for errors in $\rho_c$ (upper) and $\rho_r$ (lower) vs. symmetrical sheet resistance values: High values of sheet resistance for both layers seem preferable

Figure 3.10 shows the results of this high resolution scan. It is evident from these figures that relatively high values of sheet resistance are preferable for minimizing the uncertainty levels in both extracted parameters. More specifically, an approximate sheet resistance of $70[\Omega/\Box]$ would supposedly yield the best results.
In actuality, when performing the optimizations originally, the projected approximate value of the specific interface resistivity was lower than what was eventually measured (values closer to zero were presumed, as mentioned previously in Subsection 1.3.1). In addition, the etch associated undercut was neglected, and the measurement error entered into the simulation was the one measured in the single layer TLM measurements. These assumptions led to somewhat different optimization results, as displayed in figure 3.11.

![Figure 3.11](image)

Figure 3.11: Original high resolution scan results for errors in $\rho_c$ (upper) and $\rho_r$ (lower) vs. symmetrical sheet resistance values. Simulations were conducted under assumptions of negligible interface resistivity and negligible undercut. Sheet resistance of around $30[\Omega/\square]$ originally seemed to be the best choice.

The extraction error for the specific interface resistivity seemed to be somewhat erratic, and the extraction error for the specific contact resistivity seemed to be minimal around a value of $30[\Omega/\square]$. For those reasons, that was the approximate sheet resistance selected for both layers, and given the expected doping level, a specific thickness was selected for each layer: a layer thickness of 80 nm was chosen for the bottom InP layer, for which the projected doping level was $3 \cdot 10^{19}[cm^{-3}]$, and a layer thickness of 50 nm was chosen for the upper GaInAs layer, for which the projected doping level was $3.5 \cdot 10^{19}[cm^{-3}]$. 
3.3 Measurements

TLM Measurements were conducted using an Agilent 4155B Semiconductor Parameter Analyzer (SPA), with 4 probes. Two sets of measurements were conducted. The first set consisted of measurements of multiple TLM arrays on the same wafer, so that average parameter estimations across the wafer could be attained. Such measurements obviously take into account all error factors, as described in subsection 2.2, but they also inevitably include a process dependent parameter variance across the wafer. The second set consisted of repeated measurements of a single array, so as to specifically estimate the measurement errors.

In addition, if we recall the single layer TLM, it was shown that the measurement error is the dominant error in the single layer TLM measurement. This was demonstrated very clearly by the single array measurements, which did not account for geometric errors, but still greatly resembled the simulation results. However, as presented in Subsection 3.2.4, the measurement error is not the sole dominant error in the dual layer TLM method. It should therefore be interesting to examine the similarity between simulation results and the single array measurement results to confirm this claim.

3.3.1 Measurements of multiple arrays

TLM arrays were fabricated across a quarter of a 2" wafer, yielding 31 arrays, which were measured and analyzed. Single measurements of multiple arrays yielded a mean $\rho_c$ value of 9.8 [$\Omega \cdot \mu m^2$] with a standard deviation of 0.68 [$\Omega \cdot \mu m^2$], which translates to a relative uncertainty of 0.07, a mean $\rho_r$ value of 1.6 [$\Omega \cdot \mu m^2$] with a standard deviation of 0.71 [$\Omega \cdot \mu m^2$], which translates to a relative uncertainty of 0.43, a mean $R_{sh1}$ value of 30.66 [$\Omega / \square$] with a standard deviation of 0.81 [$\Omega / \square$], which translates to a relative uncertainty of 0.03, and a mean $R_{sh2}$ value of 36.29 [$\Omega / \square$] with a standard deviation of 1.81 [$\Omega / \square$], which translates to a relative uncertainty of 0.03.

Figures 3.12 and 3.13 show the histograms for the measurement results.

3.3.2 Repeated measurements of a single array

Numerous measurements of a specific array yielded a mean $\rho_c$ value of 9.15 [$\Omega \cdot \mu m^2$] with a standard deviation of 0.47 [$\Omega \cdot \mu m^2$], which translates to a relative uncertainty of 0.05, a mean $\rho_r$ value of 2.38 [$\Omega \cdot \mu m^2$] with a standard deviation of 0.56 [$\Omega \cdot \mu m^2$], which translates to a relative uncertainty of 0.23, a mean $R_{sh1}$ value of 31.03 [$\Omega / \square$] with a standard deviation of 0.39 [$\Omega / \square$], which translates to a relative uncertainty of 0.01, and a mean $R_{sh2}$ value of 35.83 [$\Omega / \square$] with a standard deviation of 0.16 [$\Omega / \square$], which translates to a relative uncertainty of less than 0.01.

Figures 3.14 and 3.15 show the histograms for the measurement results.
Figure 3.12: Histogram of measurement results for multiple two layer TLM arrays on the same wafer: Specific contact resistivity $\rho_c$ (upper) and Specific interface resistivity $\rho_i$ (lower): Average value of specific contact resistivity is 9.8 [$\Omega \cdot \mu m^2$], and average value of specific interface resistivity is 1.6 [$\Omega \cdot \mu m^2$]. Standard deviation in results seems lower than simulated error.
Figure 3.13: Histogram of measurement results for multiple two layer TLM arrays on the same wafer: $R_{sh1}$ (upper) and $R_{sh2}$ (lower)
Figure 3.14: Histogram of measurement results for repeated measurements of a single two layer TLM array: Specific contact resistivity $\rho_c$ (upper) and Specific interface resistivity $\rho_i$ (lower)
Figure 3.15: Histogram of measurement results for repeated measurements of a single two layer TLM array: $R_{sh1}$ (upper) and $R_{sh2}$ (lower)
3.4 Discussion & Conclusions

We have seen the full differential analysis of both dual layer TLM structures (the full two layers and the inter-etched upper layer), and the numeric extraction method resulting thereof. We have gone over relevant error factors, and numeric error estimations using Monte Carlo simulations which were specifically fitted for the dual TLM method. We have also used these simulations to determine the actual effect of each error factor, and specifically ascertain which ones are most dominant for each extracted parameter.

We have received measurement results both for repeated measurements of a single array, and for measurements of multiple arrays across the wafer, for the same benefits as in the single layer case.

As for the accuracy of the method, using the Monte Carlo simulations we have established that the method yielded a specific contact resistivity with an accuracy of $\pm 0.51 \ [\Omega]$ and a specific interface resistivity with an accuracy of $\pm 0.38 \ [\Omega]$, translating to $\pm 5\%$ for the specific contact resistivity in our case, and $\pm 23\%$ for the specific interface resistivity.

When comparing the cross wafer measurement results to the simulation results, it is evident that the standard deviation in parameters extracted from measurements of multiple arrays (Subsection 3.3.1) is within the limits of the standard deviation as estimated by the Monte Carlo simulations (Subsection 3.2.3). If we fit the gaussian error distribution attained from the numeric simulations to the measurement result histograms, as demonstrated in fig. 3.16, this result becomes even more evident. It is noted that the mean values of the fitted error Gaussians are somewhat different from the mean values extracted from measurements ($<\rho_c>\approx 10.1 \ [\Omega \cdot \mu m^2], <\rho_r>\approx 1.55 \ [\Omega \cdot \mu m^2]$), but these differences obviously result from the continuous nature of the large scale simulations as opposed to the discrete nature of small scale measurement sample results.

This means that the variance in extracted parameters across the wafer is to be attributed to the standard error in the extraction process, and the parameters themselves can be considered relatively uniform across the wafer.
3.4. Discussion & Conclusions

Figure 3.16: Histograms of multiple array measurement results outlined by the error distribution obtained from Monte Carlo simulations: Error in extracted parameters falls within measurement error

We have also conducted simulations in the purpose of optimizing the layer thickness as preparation for the wafer fabrication and actual measurements. As previously explained, initial optimizations have been conducted with the assumptions of a specific interface resistivity that is almost zero in value, and when the wet etch associated undercut is neglected. These optimizations led to the selection of a certain thickness for each layer. In retrospect, the measurements have proven otherwise: the extracted specific interface resistivity was higher than expected, the undercut was fairly substantial, and even the measurement error itself came up higher than before. At that stage, theoretical optimizations were performed again, incorporating these new findings into the simulations. The new round of optimizations produced results, which naturally better corresponded with the actual measurements. As it seemed, greater values of sheet resistance for both layer would have produced somewhat lower errors margins, but the difference was neither substantial nor critical enough for a renewed set of fabrication and measurements.
It has also been noticed that contrary to the one layer TLM, we do not observe such a good agreement between numeric simulation results and results from the repeated measurements of a single array. The meaning of this change is that, as expected, the measurement error is not the only dominant error factor in the dual TLM method. As discussed and concluded in Subsection 3.2.4, the extracted specific contact resistivity is indeed very sensitive to the measurement error before the wet etch, but it is an order of magnitude less sensitive to measurement errors after the wet etch. Furthermore, it shows a non-negligible sensitivity to the initial spacing error. As for the the extracted specific interface resistivity, things are even more acute. It shows sensitivity to all error factors apart from the error in contact width, and contrary to the specific contact resistivity, the specific interface resistivity is more sensitive to the measurement error after the wet etch than to the error before.

In conclusion, we observe that the specific contact resistivity is more strongly sensitive to errors associated with the full two layer structure, resembling the simple one layer TLM structure. The specific interface resistivity, on the other hand, is sensitive to errors in both structures and both measurements. These results especially demonstrate why in the presence of a relatively low specific interface resistivity, the specific contact resistivity can usually be estimated to a fair approximation simply by using the full two layer TLM measurement by itself. The quality of this approximation would obviously depend on the ratio between the two resistivities, and the desired accuracy level. In other words, the measure of how negligible the specific interface resistivity is, when compared to the specific contact resistivity, dictates to what degree we can approximate the specific contact resistivity (within a pre-determined acceptable error margin) using just a single measurement and the simple linear TLM extraction method. The same cannot be said regarding the estimation of the specific interface resistivity. As demonstrated, the extraction procedure it requires entails the use of both measurements (before and after wet etch) and a more complex numeric calculation, making it evident, even in retrospect, that the new dual TLM method serves an undeniable purpose.
Chapter 4

Summary & Conclusions

The results of the research and the conclusions derived from it are discussed in this last chapter.
The study originated in results extracted from RF measurements which were compared to straightforward parameters extracted from TLM array measurements, and presented certain contradictions. RF results yielded greater contact resistivity values than those of the TLM measurements, a difference which called for a more detailed analysis of the contact resistivity measurement.

Since the contact in use is based on a highly doped n-type hetero-structure, a more detailed analysis of the specific resistivity for the hetero-structure interface was also called for, as a possible cause for these contradictions.

The initial steps of the study were taken with the distinct intent on gaining a better understanding of the TLM resistivity extraction method. The single layer TLM method has been extensively discussed and measured, and specifically error factors were analyzed and simulated. A first order analytic error analysis had been previously conducted in a separate study, and was brought here as reference. As presented and discussed in this work, the first order analysis has been found to be potentially lacking in accuracy for certain ranges of the nominal error factors, and therefore a second order correction was developed within this study and presented in this work.

A numeric error analysis was also conducted and presented. The analysis consisted of brute-force Monte Carlo simulations, which were designed specifically for the TLM extraction method. The numeric simulation results were compared to the analytic analysis results and an evident agreement was shown between the two analysis methods. It is worth mentioning that a better agreement was observed for the second order analysis.

This agreement between analytic and numeric results effectively served as an affirmation for the validity of these custom designed Monte Carlo simulations, which were to be later utilized for the characterization of the dual-layer structure as well.

Moving on to the dual layer structure, an existing method for estimating the specific interface resistivity was presented and its validity for our case was evaluated. It was found and extensively shown that the existing method is inadequate for measurement of low level resistivity values, specifically when the projected specific interface resistivity is smaller than the specific contact resistivity. These findings called for a more detailed analysis of the dual layer structure, and for an innovative method of measuring said resistivities.

A full analytic model for a full two layer TLM structure had already been developed elsewhere, and brought here in this work as reference.

However, this model only enabled the estimation of the resistance given the material parameters, and not the other way around, it alone did not provide the desired solution. Therefore a different analytic model was developed within this study, one of a two layer structure in which the upper layer has been etched away between the contacts. Combining the two analytic models, a numeric extraction method was formed, giving
the ability to attain the four structure parameters (contact resistivity, interface resistivity, and sheet resistance of each layer) from four measurement results (two sets of two TLM results).

Since this new method entailed numerically solving a set of two non linear equations, an analytic error analysis was not feasible. Therefore, the specifically designed numeric Monte Carlo simulation was utilized for error estimation in the extracted parameters.

It is worth mentioning that for the dual layer structure error analysis, an additional error factor was taken into consideration, and that is the error in undercut under the contacts, which is created by the isotropic wet etch of the upper layer performed between the two consecutive measurements.

Measurements of multiple dual layer TLM arrays were conducted, and compared to error margins attained from simulations. Results have shown a relatively good fit, with a variance in results that is well within the standard error margins.

The average specific interface resistivity attained from these measurements was $1.6 \pm 0.38 \, [\Omega \cdot \mu m^2]$, and the specific contact resistivity was $9.8 \pm 0.51 \, [\Omega \cdot \mu m^2]$.

Going back to the effective contact resistivity issue in the emitter, since the conduction in the emitter as it is structured in our devices is supposedly vertical, the overall contact resistivity observed in actual emitter functionality should be the serial sum of the specific contact resistivity and the specific interface resistivity. Accounting for the average values and standard error margins, the overall resistivity might come to $11.4 \pm 0.89 \, [\Omega \cdot \mu m^2]$.

In addition, given that the average specific contact resistivity has slightly improved over the period of this study, and that at the time of the RF measurements in question, the average value for the specific interface resistivity was around $13 \, [\Omega \cdot \mu m^2]$, it is certainly not unlikely that the serial sum of the resistivities would even reach a value of around $17 \, [\Omega \cdot \mu m^2]$, which would fit RF results.

It is not in my intention to claim that the unexpected interface resistivity independently accounts for all differences between values extracted from high frequency RF measurements and values extracted from various TLM based characterizations. Obviously, some other additional mechanism may also be in effect, but it seems that this non-negligible interface resistivity does indeed play a irrefutable role in creating these discrepancies.

It is also worth mentioning that while the specific contact resistivity presented in this work was around $10 \, [\Omega \cdot \mu m^2]$, which is rather typical for ex-situ fabrication with lift off, smaller values of specific contact resistivity, around $1 \, [\Omega \cdot \mu m^2]$, have been shown to be attainable using other techniques, such as hydrogen cleaning [18] and in-situ fabrication ([19]). Bearing that in mind, this specific interface resistivity is indeed less dominant when accompanied by a substantial specific contact resistivity of $10 \, [\Omega \cdot \mu m^2]$, but it
would certainly become much more significant when compared to a specific contact resistivity of $1 \, \Omega \cdot \mu m^2$.

In conclusion, it has been shown that it is of great importance to be able to estimate the specific interface resistivity. It has been clearly demonstrated that this estimation cannot be performed with existing methods, and can only be accomplished to a satisfactory level of precision with the new dual TLM extraction method presented in this work. It has also been shown that the level of precision obviously depends solely on the error factors in play, and can therefore be minimized.
APPENDIX A - Validity of the Sheet Conduction Assumption

During the differential analysis of both the single layer and the dual layer TLM structures, the assumption is made that the conductive layer is very thin compared to the lateral dimensions, thus enabling us to assume negligible thickness and work under a sheet conduction regime.

This first appendix aims to verify and demonstrate the validity of said assumption.
Single layer sheet conduction approximation

In order to verify the validity of the sheet conduction approximation, a model of the relevant TLM structure has been entered into finite element method physical simulation software, namely COMSOL MULTIPHYSICS (FEMLAB).

Similarly to standard analysis of the TLM structure, the model is analyzed in a 2-D form.

For the single layer structure, the geometry of a simple TLM structure has been entered. A single metal contact layer has been defined, and an thin interface layer has been defined as well to enable representation of the contact resistance.

Conductivities of the interface layer and the semiconductor layer have been entered according to nominal values extracted from measurement results. Figure A.1 presents the geometric structure as entered into the simulation software.

![Figure A.1: Geometric definition cross section of single layer TLM simulation model](image)

After defining the pertinent boundary conditions for the structure, a mesh was created, thus enabling the software to analyze the structure using the finite element method, and produce a complete electro-static analysis of the structure. Following this analysis, cross section lines were defined in numerous points along the structure for examination of current density. The electric potential distribution produced by the electro-static solution along with the cross section lines are shown in figure A.2, and the results are shown in figure A.3. It is evident from these results that for every cross section the current density is uniform for the entire length of the structure, thus confirming the validity of the sheet conduction approximation for this structure.
Figure A.2: Cross section lines for current density examination in single layer TLM model

Figure A.3: Current cross sections for single layer TLM
Dual layer sheet conduction approximation

For the dual layer structure, the geometry of the full two layer TLM structure has been entered. A single metal contact layer has been defined, and thin interface layers have been defined as well to enable representation of the contact resistance, and the interface resistance.

Conductivities of these interface layers and the semiconductor layers have been entered according to nominal values extracted from measurement results. Figure A.4 presents the geometric structure as entered into the simulation software.

![Figure A.4: Geometric definition cross section of dual layer TLM simulation model](image)

Once again, boundary conditions were defined, a mesh was created, and a complete electro-static analysis have been performed. Following this analysis, cross section lines were once again defined in numerous points along the structure exactly as they were in the single layer structure. For comparison, the electric potential distribution is shown in figure A.5, and the results are shown in figure A.6. It is again evident that current densities are uniform for the entire length of the structure, thus confirming the validity of the sheet conduction approximation for this structure as well.
Figure A.5: Electric potential simulation dual layer TLM

Figure A.6: Current cross sections of dual layer TLM
APPENDIX B - Approximation of the effective undercut

As described in detail in Chapter 3, the dual TLM method entails a wet etch of the upper layer in the area between the contacts in between the two consecutive measurements. As stated before, ideally this wet etch would leave a straight edged structure, but since it is an isotropic etch, the edges of the etched area unavoidably suffer from a certain degree of undercut beneath the edges of the contacts, thus effectively making each spacing bigger. This undercut also does not leave the side walls of the etched area in a straight angle, making it slightly more difficult to determine by how much the spacings have actually grown. For purposes of result analysis and simulations, the re-positioned side wall is effectively approximated to be a vertical wall at the middle of the slanted region. This appendix aims to address that approximation and its validity.
As described in Subsection 3.2.1 and specifically shown in figure 3.3, the wet etch required for the dual TLM method is an isotropic etch, and therefore entails a certain amount of undercut, which leaves the upper layer beneath the edges of the contact in a slanted angle. The analytic model itself does not account for the geometric form of the side of the layer, it just works under the assumption of a sheet conduction for the layer, and therefore requires that the edge of the layer be approximated to a straight side wall.

Figure B.1 demonstrates the actual slanted edge of the upper layer as created by the undercut (bold line), and also the effective straight edge approximation (dashed line).

![Figure B.1: Schematic of the effective undercut approximation](image)

In order to determine the location of this effective sidewall for this approximation to be valid, simulations of the physical simulations of the structure had to be conducted. Similarly to the sheet conduction approximation, in order to conduct the simulations, models of the relevant inter-etched TLM structures have been entered into the COMSOL MULTIPHYSICS (FEMLAB) simulation software. Figure B.2 presents the geometric model for the actual undercut as entered into the simulation software.

![Figure B.2: Geometric definition cross section of the simulation model for the actual undercut](image)
An electro-static analysis of the structure was performed, and the total current was sampled (equivalent to measuring the overall resistance). The electric potential distribution along with the current sample are shown in figure B.3. The extracted current was $170.45 \, [\text{mA} \mu\text{m}^2]$.

After the actual undercut structure was simulated, structures with straight edged upper layers were considered, so an effective approximation can be made. For corner examination, straight edged structures were simulated: one in which the straight edge was at the beginning of the slanted area, and one in which the edge was at the end of it. These measurements yield a minimum and maximum current levels of $167.38 \, [\text{mA} \mu\text{m}^2]$ and $172.45 \, [\text{mA} \mu\text{m}^2]$.

Now a location had to be found in which the current, and with it the resistance, would resemble the values fitting the actual undercut structure.

Simulations have shown that an edge located at approximately 60% of the way in the slanted area would produce results that most resemble the desired values (specifically a 58% effective undercut yields a total current of $170.49 \, [\text{mA} \mu\text{m}^2]$), and would therefore serve as the optimal effective approximation.

Figure B.3: Electric potential distribution for actual undercut model (left) and current measurement sample (right)
APPENDIX C - The MATLAB implementation of Monte Carlo for TLM

This appendix sheds some light on the actual implementation of the Monte Carlo method in MATLAB as used in this work for TLM arrays.
The number of arrays to be randomized, \( n \), is given.

A matrix of index columns called \( \text{pure\_index} \) (9 by \( n \)) is prepared and added to a matrix of errors in \( d \) (also 9 by \( n \)) randomized under a normal distribution with a standard deviation \( \sigma_d \). Resulting matrix is named \( \text{index\_mat} \).

A vector of errors in \( W \) called \( \text{Z\_vec} \) (1 by \( n \)) is randomized under a normal distribution with a standard deviation of \( \sigma_W \), and then used to create a matrix of randomized slope columns called \( \text{slope} \), and also a matrix of randomized axis intercept (\( d = 0 \)) columns called \( \text{intercept} \). The matrices \( \text{intercept} \), \( \text{index\_mat} \) and \( \text{slope} \) are then used to create a matrix of projected measurement values called \( \text{pure\_meas} \) (9 by \( n \)), to which we add a matrix of measurement errors randomized under a normal distribution with a standard deviation of \( \sigma_R \), thus creating the final measurement set matrix called \( \text{final\_meas\_sim} \).
Bibliography


Hebrew Section
תקציר

כעת משאוששה תקפותו של אלגוריתם הסימולציה הנומרית, ה משתמשתי בה כדי לשערוך את השגיאה בשיטת השערוך הדו-שכבית الجديدة. יש לציין כי התייחסתי לגורם שגיאה נוסף הוכנסה לאלגוריתם בגרסתו עבור המדע הדו-שכבתי. גורם שגיאה נוסף זה מתיחס לחוסר הודאות במרווחים בין המגעים בתוך מערך ה-TLM. результате הלוגם בין הגורמים, ככל שהמגעים וה المتوسطים בין המגעים בתוך מערך המדידה, התגלה השגיאת שלПетית, ש录用 והפיכהת הכל גורמי השגיאה, בgiesה.

значי התמידה שלבודיד-ה תしょうי, 있고 שמתבצעת את אידאלה הרטוב.

בחלק אפקט פונקציית הפרמטרים למורם שיגיאה, חכת סדרת התמידה של מוערכ
מטיע-ד-שגבתי, התבצעה סדרת אופטימיזציה על עובי השכבות בכדי לנסות למזור
את השגיאה בחלוק תוספי לשפרים.

בהחכמה לתإزאות שפוסטים, מגיע עובי השכבות שלבודיד-ה בומר, סדרת ממידה מודרני שמערכיה-ד-שגבתי, ממידות ועל מכ$h והמתחשס
ומוצרת בעבירה, ונסgunakan התאמות לתﺈוזאת יהודית והשיגיאה שבוצעה.

בלסף, התדירות הסטודית הממוצעת של נכניס ב bụבעה זוג-שגבתי, ממידות
-0.51 [Ω·μm²] 9.8±0.38 [Ω·μm²]
. [Ω·μm²]

אם ימיים כי עץ זה על התדירות הסטודית של נכניס, ייח וATORY שיגיאה
של על התדירות הסטודית של נ韫 פגום, ואל שיגיאת לחום וניה להברר
התאמה בין הדץ ממידה בטטר לטבעה ארורים התדירות של-BMOMBE
-0.38 [Ω·μm²]
. [Ω·μm²]

לעבורה מצפים נוספים והשעון באוותי עיני התוכן סמוליצייל של אופטимальויות של גורמים סופים
של קיבור מוסיפים משועי במנגון וibbean: קיבור חולכים (COMSOL MULTIPHYSICS)
משת indebונים בדוגמה ד-שגבתי ו-שגבתי, ונסgunakan כקיבור הראיל התחלתי wipe.

اقة מייקוש השッグיה של אופטומיטר ומצלמת, בעelleicht כפולה ו-שגבתי
-0.51 [Ω·μm²] 9.8±0.38 [Ω·μm²]
. [Ω·μm²]

אם ימיים כי עץ זהול התדירות הסטודית של נכניס, ייח וATORY שיגיאה
של על התדירות הסטודית של נ韫 פגום, ואל שיגיאת לחום וניה להברר
התאמה בין הדץ ממידה בטטר לטבעה ארורים התדירות של-BMOMBE
-0.38 [Ω·μm²]
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לעבורה מצפים נוספים והשעון באוותי עיני התוכן סמוליצייל של אופטимальויות של גורמים סופים
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משת indebונים בדוגמה ד-שגבתי ו-שגבתי, ונסgunakan כקיבור הראיל התחלתי wipe.
The self-field resistance of the contact itself. Within the framework of the work, it is explicitly demonstrated how and why this method does not meet the needs in the case of contacts with contact resistance N with lower self-field values.

Moreover, some previously mentioned analytical TLM two-layer full structures are analyzed here as well. This analysis allows us to calculate the total resistance measured in the presence of two parameters of contact-two-layer (contact self-field resistance and interlayer resistance and total resistance of each layer), but being a model that produces two measurement results, it does not allow extraction of these parameters given the regular measurement of the structure.

Instead, an additional analytical TLM two-layer structure is analyzed in this work, in which the upper layer goes through a wet oil layer between the contacts. This analysis actually produced an additional contact two-layer structure, which has the four parameters as in the structure mentioned above, but the expected response will differ and will yield two other measurement results.

Based on the combination of the two, a new extraction method was developed, which uses two TLM measurements of a two-layer contact, where between the measurements, a wet oil layer passes.

Based on the four measurement results from the two measurements, a numerical solution of a system of nonlinear equations allows extraction of the four parameters of the two-layer structure.

As a measurement method, it was natural to estimate the accuracy of the parameters extracted, but as a numerical extraction method, it was not possible to estimate the error analytically, and naturally I turned to Monte Carlo simulation. No special algorithm for TLM measurement of two-layer contacts was found, so I planned a specific randomization and simulation algorithm for this work, in order to test the correctness of randomization for TLM measurements of two-layer contacts, so that one could compare the results of the simulation to the analytical error analysis done previously, as mentioned above.

Considering all the errors, it seemed that the analytical error analysis was not sufficiently accurate, being a first-order approximation, and therefore I developed a second-order correction to the analytical error, this correction has already shown much closer to the numerical simulation results.

Some differences were still found in the basis of the analytical analysis that stood in the numbers that are not necessarily accurate.

Multiple measurements of single-layer structures were done, analyzed statistically and presented in the work, and they fit the results of the error analysis performed.

The conclusions of the numerical solution of the system of equations and the analytical error analysis match, but there are still some differences in the numerical values that are not necessarily accurate.
The transition between the high-speed components and the reduced capacitance on the inter-well interface is one of the dominant factors in the effective skin resistance of field-effect transistors in bipolar devices. This phenomenon becomes crucial in high-speed systems and enhances the performance of system parameters.

The objective of the research is to deepen the analysis of the inter-well capacitance characteristics for single and dual-layer structures. In a more detailed manner, the research analyzes the transition between dual-layer structures, commonly used in high-speed transistors, to determine how effective the skin resistance truly is and how it is affected by the capacitance in the end. Previous studies on the TLM method for single-layer capacitance analysis have been presented here, including orders-of-magnitude analysis and comparison for resistive factors. Studies on dual-layer capacitance analysis using simplistic methods for skin resistance have also been presented, with the original method applied to dual-layer capacitance on the P-type, applicable only for high skin resistance cases, especially when the inter-well capacitance is dominant compared to other capacitances.
אני מודה לטכניון ולקרן ויטרבי על התמיכה הכספית הנדיבה בהשתlesaiי. אנוי מודהلطכניון ולкарן ויטרבי על התמיכה הכספית הנדיבהתשתlesaiי.
שיטה להמדידת התחרהנות הסנגלית של פן הבניין בין שני שכבות מ"ל"מ ויישומה עבור צומת מעורב של המסוג N-& הפיק InP/GaInAs

חתום על מחקר

לשם مليולי חלקי של הדרישות לקבלת התואר מ"גיסטר למדעים בהנדסת חשמל

מניטמר למדעים בהנדסת חשמל

ר''ל הלוי

הוגש לסנט הטכניון – מכון טכנולוגי לישראל

תיופת

שנים תשע''א

יוני 2011