An Analytical Model for Alloyed Ohmic Contacts Using a Trilayer Transmission Line Model

Geoffrey K. Reeves and H. Barry Harrison

Abstract—This paper describes a Transmission Line Model approach to the modeling and analysis of alloyed planar ohmic contacts. It briefly reviews the standard Transmission Line Model (TLM) commonly used to characterize a planar ohmic contact. It is shown that in the case of a typical Au-Ge-Ni alloyed ohmic contact, a more realistic model based on the TLM should take into account the presence of the alloyed layer at the metal-semiconductor interface. In this paper, such a model is described. It is based on three layers and the two interfaces between them, thus forming a Tri-Layer Transmission Line Model (TLM). Analytical expressions are derived for the contact resistance $R_c$ and the contact end resistance $R_e$ of this structure, together with a current division factor, $f$. Values for the contact parameters of this TLM model are inferred from experimentally reported values of $R_c$ and $R_e$ for two types of contact. Using the analytical outcomes of the TLM, it is shown that the experimental results obtained using a standard TLM can have considerable discrepancies.

I. INTRODUCTION

IMPROVEMENTS in the reliability and performance of semiconductor devices often require improvements to the quality of their ohmic contacts. The quality of such contacts is measured using various parameters. For the purposes of measuring and comparing the electrical quality of the contact, the specific contact resistance $\rho_c$ is probably the most commonly derived and quoted parameter. Thus much of the research on ohmic contacts is devoted to obtaining values for the specific contact resistance and its subsequent minimization. Ohmic contacts are commonly formed by the evaporation of the appropriate metals followed by an alloying or sintering heat cycle in order to bring about an ohmic characteristic to the contact. The measurement of parameters to obtain $\rho_c$ enables the influence of the metallizations and the alloying cycle on the contact resistance to be monitored, thus allowing an optimization of the contact procedure.

A variety of metallizations and alloying conditions have been utilized for the formation of ohmic contacts particularly for compound semiconductors [1], [2]. The most studied compound semiconductor ohmic contact is undoubtedly the Au-Ge-Ni alloyed ohmic contact on to n-type GaAs. Electrical measurements on this system generally use the Transmission Line Model (TLM) technique to obtain a value of $\rho_c$ for the contact. Additional data on the contact is sometimes reported with the derivation of the parameter $R_{sk}$, referred to as the sheet resistance of the semiconducting layer beneath the contact [3].

In addition to the electrical characterization of alloyed ohmic contacts, a considerable amount of research has been undertaken on the physical nature of the Au-Ge-Ni contact in order to understand the mechanisms of the reactions taking place between the metallizations and the underlying GaAs. Vertical cross sections of the alloyed Au-Ge-Ni contact show that following the alloying cycle, a complex alloyed region is formed between the contact metallization and the unreacted GaAs. This interfacial alloyed layer is generally found to have a thickness $t$ of the order of 0.1-0.2 $\mu$m [3], [4]. In fact from the vertical cross section, the contact structure can reasonably be represented by three distinct layers—the top metallization, the complex alloyed layer (of thickness $t_{\mu m}$) and the underlying but unreacted GaAs. There thus arises a problem in using the standard TLM for the electrical characterization of such a contact as the standard Transmission Line approach models the contact as a two layer structure—the metallization and the underlying semiconductor, with one interface between the two layers. A more realistic electrical model should acknowledge the existence of the alloyed layer.

Various modifications to the standard TLM have been developed in order to more closely model the particular contact system being characterized. Thus an extended TLM was proposed [5] to take into account an additional voltage drop in the semiconductor layer in the contact region, modified TLM's were developed to account for the finite sheet resistivity of the two contacting layers [6], [7], an additional interface was added to account for the AlGaAs layer when modeling HEMT contacts [8] and the current flow in the active layer of MOSFET's was divided into two regions of current flow at fixed depths below the contact [9].

However in the case of alloyed contacts, a more flexible and comprehensive model is needed to accurately represent the observed physical characteristics of this contact1. A Tri-layer Transmission Line Model (TLM) is presented here in order to electrically represent the metal layer, the alloyed region layer and the unreacted semiconductor layer that together make up the contact region. The model allows the Alloyed contact layer and the unreacted semiconductor layer to have separate and identifiable sheet resistances, while the top conducting layer is assumed to have zero sheet resistance. It also allows

1 Shur has briefly discussed the desirability of having a more comprehensive model for characterizing alloyed ohmic contacts in GaAs Devices and Circuits, M. Shur, Plenum Press, NY, 1987, p. 156.
two interfaces—one between the metal and alloyed layer and the second between the alloyed and semiconductor layer—to be individually represented. The effects of current crowding at the leading edge of the contact and its effect on contact current flow and on the contact resistance can also be evaluated.

In Section II of this paper a brief review of the standard TLM is given. This model is commonly used to measure the specific contact resistance of planar ohmic contacts including alloyed ohmic contacts to semiconductors such as GaAs. In Section III, the TLTLM is described in detail and the equations for contact current flow, current division, the contact resistance \( R_c \) and the contact end resistance \( Re \) are given. In Section IV, the effects of the various contact parameters on the current flow beneath the contact and the calculated contact resistance are discussed. The detailed derivation of the equations given in Section III is provided in an appendix.

II. STANDARD TLM NETWORK

The specific contact resistance is a parameter that allows an easy quantitative comparison to be made between contacts independent of their geometry. A wide variety of test structures have been designed in order to provide measurements that extract the specific contact resistance \( \rho_c \) of metal-semiconductor ohmic contacts [5], [10]–[13]. (The specific contact resistance is a normalized value of the contact resistance making it independent of the area of the contact and allowing easy calculation of contact resistances for contacts with differing areas). A brief description of the most commonly used test structure patterns is provided in [14].

It is important to clarify exactly what is being obtained when the contact resistance \( R_c \) is measured from the various test structures. The value of \( R_c \) depends on the type of contact and thus the nature of the current flow in the contact region. The two contact geometries commonly encountered are the planar and the "sandwich" contact which have quite different current flow patterns. In a "sandwich" contact the current flow is normal and uniform in current density to the plane of the contact. The "sandwich" contact is due to the presence of current flow in \( R_{sk} \) while the voltage drop in the vertical direction (perpendicular to the plane of the contact) is due to \( \rho_c \). The contact has a length \( d \) and a width \( w \).

With reference to Fig. 2, \( R_c \) and \( Re \) are defined as

\[
R_c = \frac{V_{BA}}{I_0} \quad \text{and} \quad Re = \frac{V_{CD}}{I_0}. \tag{1}
\]

From these definitions, it may be shown [5] that the following relationships hold for the contact modeled in Fig. 2

\[
Re = \frac{(R_{sk} \cdot \rho_c)^{1/2}}{w} \sinh (\alpha d) \quad \text{and} \quad R_c = \frac{(R_{sk} \cdot \rho_c)^{1/2}}{w} \cdot \coth (\alpha d) \tag{2}
\]

where

\[
\alpha = (R_{sk}/\rho_c)^{1/2}. \tag{3}
\]

The voltage drop across this region is caused by the presence of \( \rho_c \). The voltage drop beneath the contact in the horizontal direction is attributed solely to the current flow in \( R_{sk} \) while the voltage drop in the vertical direction (perpendicular to the plane of the contact) is due to \( \rho_c \). The contact has a length \( d \) and a width \( w \).

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\]

The resistive element \( \rho_c \) represents the narrow carrier depleted region occurring at the metal-semiconductor interface. Hence
decreases close to exponentially in the semiconductor layer. Thus the transfer length $L_0$ is the distance along the contact from the leading edge for the current in the semiconducting layer to fall to $1/e$ of its initial value as it transfers to the metal layer.

III. THE TLTLM NETWORK

Ohmic contacts to n-type GaAs are commonly made by evaporating a combination of Au-Ge-Ni followed by an alloying cycle. This alloying cycle causes Ga from the GaAs to outdiffuse into the contact metallization, creating Ga vacancies which can then be occupied by the Ge. The Ge thus acts as a donor resulting in a highly doped surface region (typically $>10^{19}$ cm$^{-3}$) just below the contact metal. This highly doped region narrows the metal semiconductor barrier allowing tunnelling of carriers to take place. Although this explains in a simple way the observed ohmic behavior, a much more complex process is known to take place. Many detailed studies have been performed on this contact system [4], [15]-[17]. The alloyed layer at the metal-semiconductor interface is generally observed to have the physical microstructure as shown in Fig. 3 [18]. When taken on a microstructure scale, this layer is clearly not one of uniform composition and is more akin to a matrix of various compounds and/or alloys. Thus on a microscale, the concept of a uniform sheet resistance for the alloyed layer is not appropriate. However, when scaled over an area the size of a typical ohmic contact, an average resistivity (and thus sheet resistance) can be ascribed to this layer. (All ohmic contact test patterns which provide data on specific contact regions where the current enters the contact region via this sidewall. Of the total contact current a proportion of the contact current will enter the contact region via this sidewall. Of the total contact current which accounts for the fraction of current entering the sidewall of the alloyed layer. Since the alloyed layer has a depth $t$ which may be a significant fraction of the total epilayer thickness of FET devices. As a result of the alloying process, the combined sheet resistance of the semiconductor-alloy layers under the contact will probably have altered. This change can be represented in the standard TLM by using $R_{sk}$ to represent the magnitude of the sheet resistance of this region, as opposed to assuming that the underlying semiconductor region of the contact still retains its unalloyed value of $R_{sh}$. However the use of a single modified resistance to represent the alloyed layer, the semiconducting layer and the interface between them is unsatisfactory. Physically, no single resistive layer of $R_{sk}$ exists under the contact and there is an additional voltage drop in the vertical direction due to the interface. This additional voltage drop cannot be represented by $R_{sk}$.

This deficiency can be overcome by using a Tri-Layer TLM (TLTLM) in order to electrically model the properties of the alloyed layer. Fig. 4 shows the cross section of the alloyed contact and its corresponding TLTLM electrical network. The voltage drop at the metal to alloyed layer interface occurs across the specific contact resistance element $\rho_{ca}$, while the voltage drop across the alloyed layer to the unreacted GaAs layer occurs across $\rho_{cu}$, the specific contact resistance at this interface. The sheet resistance of the metal layer is taken as zero, while the alloyed layer and the underlying epilayer have sheet resistances $R_{sa}$ and $R_{su}$ respectively. The currents flowing in $R_{sa}$ and $R_{su}$ are taken as $i_1$ and $i_2$ respectively. As noted previously in this section, the alloyed layer is not homogeneous on the microstructure scale. Thus in a contact system where the contact process has resulted in such inhomogeneities, there will naturally be corresponding regions where the current $i_2$ will have local fluctuations from its average value.

The complete TLTLM network is shown in Fig. 5. Current $i_3$ is the current collected by the metal layer of the contact between $x = 0$ (leading edge of the contact) and the point $x$ back from the leading edge. Thus the total contact current $i_0 = i_1(x) + i_2(x) + i_3(x)$, and at $x = d_{1}(d)$ and $i_2(d) = 0$ and $i_3(d) = i_0$. Fig. 5 also includes a contact front edge resistor $R_f$ which accounts for the fraction of current entering the sidewall of the alloyed layer. Since the alloyed layer has a depth $t$ which may be a significant fraction of the total epilayer depth, it is clear that a proportion of the contact current will enter the contact region via this sidewall. Of the total contact
The alloyed layer (width \( w \) and thickness \( t \)) of the sidewall, assuming a uniform current density across the area \( w \times t \), the magnitude of the currents \( i_0 \) and \( i_0(1 - f) \) entering the contact layers.

In the conventional TLM manner—via \( R_{SU} \) under the contact. Since a portion of the current enters the sidewall of the alloyed layer (width \( w \) and thickness \( t \)), then assuming a uniform current density across the area \( w \times t \) of this sidewall, the magnitude of \( R_f \) for the contact is given by

\[
R_f = \frac{\rho_{cu}}{(w \times t)}.
\]

Referring to Fig. 5, \( R_c \) and \( R_e \) are defined in a similar manner as for the standard TLM

\[
R_c = \frac{V_{AC}}{i_0} \quad \text{and} \quad R_e = \frac{V_{XZ}}{f_0}.
\]

The two entry points at the leading edge of the contact for the currents \( i_0 \) and \( i_0(1 - f) \) are taken as being at the same potential. The network of resistive elements in Fig. 5 may be solved to give the current densities \( i_1, i_2 \) and \( i_3 \) as well as calculated values of \( R_c, Re \) and the current division factor, \( f \).

The following equations are thus obtained for \( R_c, R_e \) and \( f \) (see also (8) at the bottom of this page):

\[
R_c = K \cdot \left\{ f \cdot \frac{(R_{SU} - \rho_{cu} \cdot a^2) - (1 - f) \cdot R_{sa}}{b \cdot \tanh(bd)} - \frac{f \cdot (R_{SU} - \rho_{cu} \cdot b^2) - (1 - f) \cdot R_{sa}}{a \cdot \tanh(ad)} \right\}
\]

\[
R_e = K \cdot \left\{ f \cdot \frac{(R_{SU} - \rho_{cu} \cdot a^2) - (1 - f) \cdot R_{sa}}{b \cdot \sinh(bd)} - \frac{f \cdot (R_{SU} - \rho_{cu} \cdot b^2) - (1 - f) \cdot R_{sa}}{a \cdot \sinh(ad)} \right\}
\]

where

\[
a = \sqrt{[(c - (c^2 - 4 \cdot R_{SU} \cdot R_{sa}/(\rho_{cu} \cdot \rho_{cu}))^{1/2}]}/2
\]

\[
b = \sqrt{[(c + (c^2 - 4 \cdot R_{SU} \cdot R_{sa}/(\rho_{cu} \cdot \rho_{cu}))^{1/2}]}/2
\]

\[
c = [(R_{SA} + R_{SU})/\rho_{cu} + (R_{SA}/\rho_{cu})
\]

\[
K = R_{SU}/\rho_{cu} \cdot w \cdot (b^2 - a^2)
\]

\[
N = R_f \cdot w \cdot (b^2 - a^2) \cdot \tanh(bd) \cdot \tanh(ad).
\]

The equations for \( R_c \) and \( R_e \) reduce to the corresponding standard TLM (2) and (3) when all the contact current enters the \( R_{SU} \) layer (take \( f = 1 \)) and the presence of the alloyed layer \( R_{sa} \) is ignored (\( R_{sa} \rightarrow \infty \)). Thus

\[
R_c = [(R_{SU} \cdot (\rho_{cu} + \rho_{cu}))^{1/2}/w] \cdot \sinh(ad)
\]

\[
R_e = [(R_{SU} \cdot (\rho_{cu} + \rho_{cu}))^{1/2}/w] \cdot \coth(ad)
\]

where

\[
\alpha = (R_{SU}/(\rho_{cu} + \rho_{cu}))^{1/2}.
\]

For these conditions the network of Fig. 5 thus has the quantity \( (\rho_{cu} + \rho_{cu}) \) representing \( \rho_{CC} \) and \( R_{SU} \) representing \( R_{SK} \).

IV. DISCUSSION

A. Current Division \( f \)

Equations (A11) and (A12) for \( i_1(x) \) and \( i_2(x) \), as derived in the appendix, may be plotted to illustrate the way in which the currents in \( R_{SU} \) and \( R_{SA} \) are distributed along the contact length. For a contact of \( d = 10 \mu m \) and selecting values of \( R_{SA} \) and \( R_{SU} \) of 100 and 500 \( \Omega \), respectively, and \( \rho_{cu} \) and \( \rho_{cu} \) values of 1 and \( 10 \times 10^{-6} \Omega \cdot cm^2 \), then Fig. 6(a) shows the current distributions for \( f = 1.0 \) and Fig. 6(b) shows the distribution for \( f = 0.25 \). Note that the actual value of \( f \) for a given contact is determined by the contact parameters as defined in (8). These same contact parameters are used in an example to illustrate the influence that \( R_f \) has on the current division factor. Since \( \rho_{cu} \) is kept constant at \( 10 \times 10^{-6} \Omega \cdot cm^2 \) in this example, the variation in \( R_f \) can be taken as being due to a variation in the depth \( t \) of the alloyed layer (4). The dependency of \( f \) on \( R_f \) (or \( t \)) and on the contact length is shown in Fig. 7 where \( f \) is plotted as a function of the contact length for various values of \( R_f \). The corresponding values of \( t \) (for a contact width \( w = 100 \mu m \)) are shown in parentheses. Note that for the same \( R_f \) value, if \( \rho_{cu} \) decreases by a factor of 10, the values of \( t \) also decrease by 10. Only for very short contacts does \( f \) vary with the contact length.

B. Transfer Length \( L_t \)

The concept of contact transfer length for planar ohmic contacts was put forward by Shockley [10]. With reference to the standard TLM, and where the contact length \( d \gg L_t \), the current flow decreases exponentially in the semiconductor layer. Thus the transfer length \( L_t \) is the distance of the contact traversed in order for the current in the semiconductor layer to fall to \( 1/e \) of its initial value as it transfers to the metal layer. In the standard TLM \( L_t \) is given by (3). However it should be noted that in deriving the equation for \( L_t \) an exponential current decay below the contact is assumed. For a TLTLM network contact, the current distribution of \( i_1 + i_2 \) is not

\[
f = \left\{ \frac{N + R_{SA} \cdot [b \cdot \tanh(ad) - a \cdot \tanh(bd)]}{N + (R_{SA} + R_{SU} - \rho_{cu} \cdot a^2) \cdot b \cdot \tanh(ad) - (R_{SA} + R_{SU} - \rho_{cu} \cdot b^2) \cdot a \cdot \tanh(bd)} \right\}
\]
exponential even for a long contact, and thus the use of (3) is not appropriate. For a contact described using the TLTLM network, a more accurate representation of the transfer length $L_t$ can be found from a graph of the current distribution in the contact. By taking a contact where $d \gg L_t$, then $L_t$ can be defined as the distance taken for the combined currents $i_1$ and $i_2$ to fall to $1/e$ of their initial value (or for $i_3$ to reach 63% of its final value). For example, from the current distribution given in Fig. 6(a) and (b), the respective transfer lengths for this contact are 2.0 $\mu$m and 1.2 $\mu$m. Other examples of $L_t$ values for contacts are given in Sections IV-C and IV-D.

C. Analysis Using the TLTLM

Analysis using the standard TLM generally involves the experimental determination of $R_e$ and $R_{sh}$, and then applying the standard TLM (2) and (3), to calculate unique values for $\rho_c$ and $R_{sk}$. However the standard TLM test pattern does not provide sufficient data for a unique determination of the TLTLM parameters $(\rho_{ca}, \rho_{cu}, R_{sa}$ and $R_{su})$. Despite this, a good indication of the magnitude of these parameters may be found by using (6) and (7). A set of possible TLTLM parameters is chosen by noting that (6) and (7) must be satisfied as well as considering TLTLM values which are consistent with the semiconductor material from which the test pattern is fabricated. This particularly applies to the sheet resistance $R_{sa}$ and $R_{su}$. For example, a reasonable estimate for $R_{su}$ can be obtained from the sheet resistance $R_{sh}$ of the active layer of the test pattern structure. The value of $R_{su} \geq R_{sh}$ as some of the original epitaxial layer (sheet resistance $R_{sh}$) is consumed in the alloying process, leaving a thinner unreacted epitaxial layer (sheet resistance $R_{su}$) beneath the contact. The size of the difference is dependent on the value of $t$ resulting from alloying the contact; as previously noted values of $\sim 0.1-0.2 \mu$m are commonly observed. Thus an alloyed ohmic contact with $t = 0.1 \mu$m on a uniformly doped active layer of 0.3 $\mu$m thickness would result in a $R_{sa}$ of $3/2 \times R_{sh}$. The possible range for $R_{sa}$ is also a function of the alloying process. By taking $t = 0.1 \mu$m, and assuming that the alloying process in GaAs produces a highly doped alloyed layer beneath the contact, then $R_{sa}$ could reasonably fall in the range of 10-100 $\Omega$/sq. The range of values for $\rho_{ca}$ and $\rho_{cu}$ will be of the same order as $q_e$, the specific contact resistance derived using the standard TLM analysis. The magnitude of $R_f$ depends primarily on $\rho_{cu}$ (4), with some further variation occurring if the depth, $t$, of the alloyed layer varies.

An example of assigning TLTLM parameters to an alloyed GaAs ohmic contact is shown in Table I where Henry's [20] result for his sample 5-B/8.6 is used. (Henry reported values for $t$ of 0.1-0.125 $\mu$m for his alloyed contacts). For this test pattern ($w = 100 \mu$m), the $R_e$ and $R_{ce}$ values were measured as 1.6 $\Omega$ and 0.144 $\Omega$, respectively, giving $\rho_c = 2.6 \times 10^{-6} \Omega \cdot \text{cm}^2$ and $R_{sk} = 100 \Omega$/sq. using the standard TLM analysis. $R_{sh}$ was measured as 284 $\Omega$/sq. While two possible sets of TLTLM parameters are given in Table I, the possible set values are constrained by the requirement to match the observed values of $R_e$ and $Re$ and by the restrictions placed on $R_{sa}$ as previously noted. The range of $R_{su}$ is $3/2 \times R_{sh}$ as the implant depth was 0.35 $\mu$m [20]. $R_f$ is calculated from (4) using the corresponding $\rho_{cu}$ value in Table I, while the range for $R_{su}$ corresponds to a 40–55% increase in $R_{sh}$, due to the decreased active layer thickness beneath the contact. Table I also shows that for this contact, a significant
part \((1 - f)\) of the contact current enters the sidewall of the alloyed layer. The calculated \(Rc\) and \(Re\) values in Table I are the values calculated using the TLM parameters listed and (6) and (7).

The contact current distributions \(i_1, i_2\) and \(i_3\) for the first set of values in Table I are shown in Fig. 8 as a function of the distance traversed beneath the contact, where the total contact current \(i_0\) is taken as unity. The contact transfer length \(L_t\) can be derived from Fig. 8. The value of \(L_t\) corresponds to the contact distance traversed in order for 63\% of the device current to have transferred to the metal layer. From Fig. 8 this occurs at 2.1 \(\mu\)m. Note that this value is somewhat longer than the transfer length of 1.6 \(\mu\)m which is derived using the standard TLM equation (3).

D. Other Contact Structures

Although the analysis and discussion just given refer to alloyed ohmic contacts on GaAs, the TLTLM can be applied to other contact structures. The \(n^+\) structure is one example, where a highly doped contact layer is grown on an n-type epitaxial layer. This technique allows a non alloyed ohmic contact to be formed [21], [22], as the metal \(n^+\) barrier is narrow enough to allow the charge carriers to readily tunnel through it. A detailed analysis of the current transport mechanisms has been given [23] for the non-alloyed \(n^+\) contact, including a derivation of \(\rho_c\) for an ohmic Al-\(n^+\)GaAs to GaAs contact. The contact geometry here is of the “sandwich” type described in Section II and the subsequent analysis thus differs from the planar contacts considered here.

A similar structure occurs in some nonalloyed heterojunction contacts, where a thin layer of a different (low bandgap) semiconductor material is deposited on the epitaxial device layer. The heterojunction approach is particularly applicable to compound semiconductors where narrow bandgap lattice matched materials can be epitaxially grown on wider bandgap device material. One example is the use of a HgTe layer to contact the wider bandgap HgTe-CdTe (MCT) material [24]. A cross section of the TLM test patterns used to measure \(Rc\) and \(Re\) is shown in Fig. 9. In one test pattern, \(Rc\) was 88.1 \(\Omega\), \(Re = 0.75 \Omega\) resulting in \(Rsk = 481 \Omega/\text{sq.}\) and \(\rho_c = 1.46 \times 10^{-3} \Omega \cdot \text{cm}^2\). Applying the TLTLM to this structure, \(Rsa\) becomes the sheet resistance of the HgTe layer (0.2 \(\mu\)m thick) and \(Rsu\) that of the MCT layer. Since the HgTe is etched away outside the contact region there will be no current entering the sidewall of the HgTe layer (equivalent to the alloyed layer in the alloyed contact). Thus in using the TLTLM to analyse this structure, \(Rf\) will be infinite (i.e., \(f = 1.0\)). Unlike the alloyed contact, it is possible for non-alloyed \(n^+\) and heterojunction contacts to have \(Rf \to 0\) when the \(n^+\) or the HgTe layer (see Fig. 9) has not etched away between the contacts). The sheet resistance of the HgTe layer was measured as 15–16 \(\Omega/\text{sq}\) while the test pattern of Fig. 9 gave \(Rsh\) for the MCT layer \(\sim 500 \Omega/\text{sq.}\). Since the MCT layer is the same outside the contact as under it, the value of \(Rsu\) is taken as 500 \(\Omega/\text{sq.}\). The current distribution for this contact is illustrated in Fig. 10. Compared to the Au-Ge-Ni contact current distribution of Fig. 8, the current \(i_2\) in the MCT layer is somewhat less due largely to the fact that there is no sidewall entry. The value of \(L_t\) for the heterojunction contact is found from Fig. 10 to be 26.3 \(\mu\)m. Table II gives two sets of TLTLM parameters that have been derived for this contact in order to match the experimental values of \(Rc\) and \(Re\), and also taking into account small variations in \(Rsu\).

A point of interest with this contact is the fact that despite all the contact current entering \(Rsu\) \((f = 1.0)\), some horizontal current flow within the \(Rsu\) layer still occurs. Hence the sheet resistance of this layer will still affect the contact properties. However the magnitude and distribution of the current in the \(Rsu\) layer is much reduced for this contact when compared to the alloyed Au-Ge-Ni contact. Thus the influence of the magnitude of \(Rsa\) on the contact and in particular on the value of \(Rsk\) is considerably less than for the Au-Ge-Ni contact. Hence \(Rsk\) for the heterojunction contact 481 (\(\Omega/\text{sq}\))
is only slightly modified from the $R_{sh}$ value (490–500 $\Omega$/sq), despite the presence of a low sheet resistance layer under the contact ($R_{sa} = 15 \Omega$/sq). For the Au-Ge-Ni contact, $R_{sk}$ is 100 $\Omega$/sq, which is a significant reduction on the $R_{sh}$ value of 284 $\Omega$/sq.

### E. Interpretation of Standard TLM Parameters

1) Sheet Resistance Parameter $R_{sk}$: For the example given in Table I, the standard TLM gives a value of $R_{sk}$ of 100 $\Omega$/sq for this contactalthough no single layer of this value is present under the contact. The original epitaxial layer sheet resistance $R_{sh}$, was measured as 284 $\Omega$/sq. The TLTLM analysis shows that standard TLM parameter $R_{sk}$ is the result of a combination of the respective sheet resistances of the alloyed ($R_{sa}$) and unalloyed ($R_{su}$) layers. The exact combination depends on the respective current flows in the two layers and thus depends on $\rho_{cu}$ and $\rho_{cu}$ as well. The influence of the sheet resistance of the alloyed layer $R_{sa}$ will increase as the proportion of contact current in this layer increases.

A more detailed analysis of the magnitude of $R_{sk}$ may be made using the TLTLM network. By assigning values to the TLTLM parameters, the corresponding values of $R_c$ and $R_e$ can be calculated. Then, on using the standard TLM equations, the equivalent TLM parameters of $\rho_c$ and $R_{sk}$ are found. Thus the effect of the various TLTLM parameters on $R_{sk}$ may be predicted. Results of such an analysis [25] show that values of $R_{sk}$ both above and below the sheet resistance $R_{sh}$ of the epitaxial layer outside the contact region can be obtained. This is in line with experimentally reported values where for alloyed contacts $R_{sk}$ often differs from $R_{sh}$. Generally $R_{sk}$ is found to be lower than $R_{sh}$ [4], [12] although measured values above this value of $R_{sh}$ have also been reported [20], [26]. For the TLTLM to predict that $R_{sk} > R_{sh}$, it is necessary to acknowledge that the alloying process will reduce the epilayer thickness causing $R_{su}$ (the sheet resistance of the semiconductor layer under the contact after alloying) to be larger than $R_{sh}$ (the sheet resistance of the semiconductor layer under the contact before the contact is alloyed). The thinner the starting epilayer layer, the greater the increase. Hence the possibility of obtaining $R_{sk} > R_{sh}$ will be more likely for thin epilayer layers.

Fig. 11(a) shows the variation of $R_{sk}$ as a function of $\rho_{cu}$ for various values of $\rho_{cu}$ for a contact 5 $\mu$m long ($R_{sa}$ and $R_{su}$ are taken as 34.4 and 440 $\Omega$/sq, respectively). Point A represents the first set of contact parameters in Table I. The TLTLM also shows that the calculated values of $R_{sk}$ have a dependency on contact length. This is particularly apparent for short contacts as shown in Fig. 11(b). The solid line in this figure shows the variation of $R_{sk}$ as a function of contact length for the contact using the first set of TLTLM parameters from Table I. The experimentally reported value of the sheet resistance outside the contact $R_{sh}$, is marked on the figure. The dashed line shows the $R_{sk}$ variation when the value of $\rho_{cu}$ is increased to $4 \times 10^{-6} \Omega \cdot \text{cm}^2$. Note that even when all the electrical parameters of the contact remain unchanged, then using the standard TLM analysis, a contact of length 3 $\mu$m would have given an $R_{sk}$ value different from that of a 5 $\mu$m long contact. This influence of contact geometry on $R_{sk}$ becomes more marked as $\rho_{cu}$ increases. Had $\rho_{cu}$ been $4 \times 10^{-6} \Omega \cdot \text{cm}^2$ then values of $R_{sk}$ both greater and less than $R_{sh}$ (284 $\Omega$/sq) would have been measured for contacts of say 4 and 10 $\mu$m, respectively.

2) Specific Contact Resistance Parameter $\rho_c$: The TLTLM also describes how the standard TLM parameter $\rho_c$ will vary with the TLTLM parameters and with contact length. Using the same TLTLM parameters as for Fig. 11(a), the value of $\rho_c$ is shown in Fig. 12(a) as a function of $\rho_{cu}$ for various values of $\rho_{cu}$. In Fig. 12(b) the dependence of $\rho_c$ on contact length for two values of $\rho_{cu}$ is shown. The contact of Table I is marked by the position A in both figures. Some analyses based on contact current flow through the separate potential barriers at the metal-alloy and alloy-semiconductor interface infer that the experimental $\rho_c$ is the sum of $\rho_{cu}$ and $\rho_{cu}$ [27]. From Table I it is observed that the sum of $\rho_{cu}$ and $\rho_{cu}$ is not the same as $\rho_c$. This is generally the case, with equality only occurring when there is no horizontal current flow in the alloyed layer ($\rho_{cu} = 0$).

A similar calculation for the HgTe/MCT contact of Table II shows that $\rho_c$ has little dependency on contact length. Using the parameters of Table II and varying the contact length from 1–200 $\mu$m causes the value of $\rho_c$ to increase by only 2.3%. This follows from the fact that since $f = 1.0$, then $\gamma_2$ is very small for this contact. Thus the vertical voltage drop across $\rho_c$ closely approximates the voltage drop across $(\rho_{cu} + \rho_{cu})$, making $\rho_c \approx (\rho_{cu} + \rho_{cu})$ irrespective of the contact length.

<table>
<thead>
<tr>
<th>$R_{sk}$</th>
<th>$R_{su}$</th>
<th>$R_{sa}$</th>
<th>$R_{cu}$</th>
<th>$R_{cu}$</th>
<th>$R_{sh}$</th>
<th>$R_{sh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>284</td>
<td>15.0</td>
<td>4.0</td>
<td>14.0</td>
<td>1.0</td>
<td>34.4</td>
<td>44.0</td>
</tr>
</tbody>
</table>

Fig. 10. Current distribution within the contact layers as a function of contact distance traversed for a Au-In contact on a HgTe/HgCdTe heterojunction structure. $L_t$ marks the value of the contact transfer length.
REEVES AND HARRISON: AN ANALYTICAL MODEL FOR ALLOYED OHMIC CONTACTS USING A TRILAYER TRANSMISSION LINE MODEL

As noted in the previous paragraph, had $\tilde{i}_2$ equaled zero, then $\rho_c$ would equal $(\rho_{ca} + \rho_{cu})$.

The contribution from one of the two interfaces may dominate the measured $\rho_c$. The TLTLM model predicts that for the contact in Table II, most of the relatively large value of $\rho_c$ measured is due to the HgTe-HgCdTe interface ($\rho_{cu}$). For the Au-Ge-Ni contact summarized in Table I, the major contribution to the standard TLM parameter $\rho$ comes from $\rho_{ca}$, although the contribution from the two interfaces is not nearly as unequal as for the heterojunction contact of Table II. It was pointed out in Section IV-E-1 that $R_{sk}$ could be greater or less than $\rho_{ca}$. While the calculated value of $\rho_c$ is generally greater than $(\rho_{ca} + \rho_{cu})$, it is possible for it to be less as well. This occurs for contacts where $\rho_{ca}$ is smaller than $\rho_{cu}$ and where $f$ is small, i.e., a significant portion of the contact current enters the alloyed layer via $R_f$ and thus by-passes the $\rho_{ca}$ interface beneath the contact. However, this tendency is also counteracted by the large $\rho_{cu}$ which in turn increases both $R_f$ and $f$. For example in Fig. 12(a), $\rho_c < (\rho_{ca} + \rho_{cu})$ on the line where $\rho_{ca} = 0.1 \times 10^{-6}$ $\Omega \cdot \text{cm}^2$ provided $\rho_{cu} > 1 \times 10^{-6}$ $\Omega \cdot \text{cm}^2$.

The results of Figs. 11 and 12 indicate that in using the standard TLM to analyze alloyed ohmic contacts, the contact length can affect the values of both $R_{sk}$ and $\rho_c$ even when the contacts are electrically identical.

F. Contact End Resistance

In the standard TLM, the contact end resistance $R_{e}$ is given by (1) as $V_{GD}/i_0$ where, with reference to Fig. 1, $V_{GD}$ is the voltage drop across the contact interface at $CD$ at the far end of the contact. The current $i_0$ is injected into the opposite end of the contact at node $B$. From Fig. 13(a), the voltage $V_{GD}$ is measured by assuming that the third metal contact (contact 3) adjacent to contact 2 is at the same potential as node $C$, and thus $V_{GD}$ is equated to the voltage between contacts 2 and 3 [12].

In the TLTLM, the contact end resistance is similarly defined as the ratio of the vertical voltage drop across the metal-semiconductor interface to the injected current $i_0$ (see Fig. 5 and (5)). However in this model, the existence of two interfaces $\rho_{ca}$ and $\rho_{cu}$ suggests that two end resistance terms can be defined. The first end resistance term is the one that has been defined in (5) and considered up to this point. The second end resistance term $R''_{e}$ is defined as $V_{YZ}/i_0$ (Fig. 13(b)), and following the procedure used for deriving $R_e$ (A17), it may...
be shown that

\[
Re' = \frac{Rsa}{\rho_{cu} \cdot \left( b^2 - a^2 \right) \cdot w} - \frac{\rho_{cu} \cdot a^2 (1 - f) - Ru}{a \cdot \sinh(ad)}. \tag{9}
\]

If the electrical model for the standard TLM is followed, the potential on contact 3 of the test pattern is taken as the same as the potential on node X (equivalent to node C in the standard TLM). However as Fig. 13(b) shows, in the TLTLM, the alloyed layer just beneath the contact (sheet resistance \(Rsa\)) is electrically connected (from node Y) to the semiconductor material outside the contact by a resistance \(Rf\) equivalent to the \(Rf\) present at the leading edge of the contact \((4)\). Thus the potential on contact 3 will probably have a value somewhere between the potential of nodes X and Y. Exactly where between \(Re\) and \(Re'\) the end resistance will lie, will also depend on such factors as the magnitudes of \(Rf\) and \(Rsh\) (since current now flows between X and Y via \(Rf\) and \(Rsh\), as well as through \(\rho_{cu}\)), the distance between contacts 2 and 3 and the thickness of the active semiconductor layer. Note that for the HgTeMCT contact that since \(f = 1.0\) \((RF \rightarrow \infty)\), then no \(Re'\) term exists.

It is useful to compare the ratio of \(Re:Re'\) and thus establish under what conditions \(Re\) differs from \(Re'\). This in turn would indicate if a significant error could arise by taking \(Re\) as the end resistance rather than some average of \(Re\) and \(Re'\). The ratio \(Re:Re'\) is graphed in Fig. 14(a) as a function of \(\rho_{cu}\) for several values of \(\rho_{cu}\). The other contact parameters are the same as for Fig. 13. In Fig. 14(b), the same ratio is graphed as a function of contact length. Depending on the TLTLM parameters, the length can influence the value of \(Re:Re'\).

Generally any variations in \(Re:Re'\) only occur for lengths up to \(\sim 20 \mu m\). Beyond this \(Re:Re'\) tends to a constant value.

**V. CONCLUSION**

A new electrical model based on TLM principles has been proposed in order to more accurately model the known physical structure of an alloyed ohmic contact. The model allows the alloyed layer beneath the contact to be characterized by its own sheet resistance. It is also characterized by two independent specific contact resistances—one for the metal:alloyed layer interface and the second for the alloyed:semiconductor layer interface. In addition, the TLTLM model can account for the current crowding due to current directly entering the sidewall of the alloyed layer at the leading edge of the contact. The model is applicable not only to alloyed ohmic contacts, but to other contact structures such as nonalloyed n+/n and heterojunction contacts. Examples of deriving a set of TLTLM parameters from the experimental values of \(Re\) and \(Re\) of an alloyed GaAs contact and a heterojunction HgTe/HgCdTe are given. The results show that quite plausible values of the TLTLM parameters are derived when the constraint of obtaining agreement with the measured \(Re\) and \(Re\) is applied.
Since \( i_0 = i_1 + i_2 + i_3 \), then on substituting for \( i_2 \) and rearranging
\[
i_3 \cdot R_{sa} = i_0 \cdot R_{sa} + \rho_{cu} \cdot i''_1 - i_1 \cdot R_{s}'
\] (A7)
where \( R_{s}' = R_{sa} + R_{su} \). On differentiating twice
\[
i''_3 = (\rho_{cu} \cdot i''_1 - i''_1 \cdot R_{s}')/R_{sa}.
\] (A8)

Substituting (A8) into (A5) for \( i''_3 \) and substituting (A7) into (A5) for \( i_3 \), then (A5) becomes a fourth-order differential equation in \( i_1 \)
\[
i''_1 - i''_1 (R_{sa}/\rho_{cu} + R_{s}/\rho_{cu})
+ i_1 \cdot R_{sa} \cdot R_{su}/(\rho_{cu} \cdot \rho_{ca}) = 0.
\] (A9)

Equation (A9) may be solved by rewriting and factorizing
\[(D^2 - A)(D^2 - B) \cdot i_1 = 0\]

where the operator \( D \equiv d/dx \) and \( A + B = (R_{sa}/\rho_{cu} + R_{s}/\rho_{cu}) \) and \( A \cdot B = R_{sa} \cdot R_{su}/(\rho_{cu} \cdot \rho_{ca}) \).

The general solution is obtained in the normal way by summing the complementary function and the particular integral. Thus
\[
i_1(x) = (C_1 e^{ax} + C_2 e^{-ax})/(a^2 - b^2) + C_3 e^{bx} + C_4 e^{-bx}.
\] (A10)

where \( a = A^{1/2} \) and \( b = B^{1/2} \). The first term in (A10) represents the particular integral and the last two terms, the complementary function. The constants \( a \) and \( b \) are given by
\[
a = \sqrt{c - (c^2 - 4 \cdot R_{su} \cdot R_{sa}/(\rho_{cu} \cdot \rho_{ca}))^{1/2}}/2
\]
\[
b = \sqrt{c + (c^2 - 4 \cdot R_{su} \cdot R_{sa}/(\rho_{cu} \cdot \rho_{ca}))^{1/2}}/2
\]

where \( c = [R_{s}/\rho_{cu} + R_{sa}/\rho_{ca}] \).

The constants \( C_1 \cdot C_4 \) are determined from the boundary conditions
\[
Atx = 0: i_1(0) = f \cdot i_0 \quad i_2(0) = (1 - f) \cdot i_0 \quad i_3(0) = 0
\]
\[
Atx = d: i_1(d) = 0 \quad i_2(d) = 0 \quad i_3(d) = i_0.
\]

Thus it may be shown that
\[
C_1 = i_0 \cdot [f \cdot (R_{su} - \rho_{cu} \cdot b^2)
- R_{sa}(1 - f)/[\rho_{cu}(1 - e^{2ad})]
\]
\[
C_2 = i_0 \cdot [f \cdot (R_{sa} - \rho_{cu} \cdot a^2)
- R_{sa}(1 - f)/[\rho_{cu}(1 - e^{-2ad})]
\]
\[
C_3 = i_0 \cdot [f \cdot (R_{su} - \rho_{cu} \cdot a^2)
- R_{sa}(1 - f)/[\rho_{cu}(b^2 - a^2) \cdot (1 - e^{2bd})]
\]
\[
C_4 = i_0 \cdot [f \cdot (R_{sa} - \rho_{cu} \cdot a^2)
- R_{sa}(1 - f)/[\rho_{cu}(b^2 - a^2) \cdot (1 - e^{-2bd})].
\]

Thus on substitution into (A10) and simplifying, the equation for \( i_1(x) \) becomes
\[
i_1(x) = \begin{bmatrix}
i_0 \\
\rho_{cu} \cdot (b^2 - a^2) \\
- Q \cdot \sinh(b(d - x))
\end{bmatrix} \cdot \begin{bmatrix}
P \cdot \sinh(b(d - x)) \\
\sinh(bd) \\
\sinh(ad)
\end{bmatrix}
\] (A11)

---

### APPENDIX

#### A. Derivation of Current Flow

Referring to Fig. 15, and summing the potentials around the loop DABC, then
\[
V_1(x) + i_2(x) \cdot R_{sa} - dx/w
= V_1(x + dx) + i_1(x) \cdot R_{su} - dx/w \quad \text{or}
\]
\[
dV_1(x)/dx = (i_2(x) \cdot R_{sa} - i_1(x) \cdot R_{su})/w.
\] (A1)

Likewise from loop AEFB
\[
dV_2(x)/dx = -i_2(x) \cdot R_{sa}/w.
\] (A2)

Across the resistor AD \( (\rho_{cu}/w \cdot dx) \)
\[
V_1(x) = -(\rho_{cu}/w) \cdot di_1/dx
\] (A3)

and across the resistor AE \( (\rho_{ca}/w \cdot dx) \)
\[
V_2(x) = (\rho_{ca}/w) \cdot di_3/dx \quad \text{or}
\]
\[
dV_2(x)/dx = (\rho_{ca}/w) \cdot d^2 i_3/dx^2.
\] (A4)

(Note: the signs in (A3) and (A4) reflect the fact that \( i_2(x) \) decreases as \( x \) increases while \( i_3(x) \) increases as \( x \) increases). Equating (A2) and (A4) and using primes to denote the differentials \( i''_1 = d^2 i_1/dx^2 \)
\[
\rho_{ca} \cdot i''_1 = -i_2 \cdot R_{sa} = -R_{sa} \cdot (i_0 - i_1 - i_3)
\] (A5)

as \( i_0 = i_1 + i_2 + i_3 \).

Equating (A1) and the differential of (A3)
\[
\rho_{cu} \cdot i''_1 = (i_1 \cdot R_{su} - i_2 \cdot R_{sa}).
\] (A6)
where \( P = f \cdot (R_{su} - \rho_{cu} \cdot a^2) - (1 - f) \cdot R_{sa} \) and \( Q = f \cdot (R_{su} - \rho_{cu} \cdot b^2) - (1 - f) \cdot R_{sa} \).

The equation for \( \text{i}_2(x) \) may be found on substitution into (A6) to be

\[
i_2(x) = \left\{ \frac{\text{i}_0}{(b^2 - a^2) \cdot w} \right\} \cdot \left\{ \frac{P \cdot b \cdot \cosh b(d - x)}{\sinh(bd)} - \frac{Q \cdot a \cdot \cosh a(d - x)}{\sinh(\text{ad})} \right\}.
\]

Likewise, expressions for the potentials \( V_1(x) \) and \( V_2(x) \) may be calculated from (A3) and (A2), respectively,

\[
V_1(x) = \left\{ \frac{\text{i}_0}{(b^2 - a^2) \cdot w} \right\} \cdot \left\{ \frac{P \cdot b \cdot \cosh b(d - x)}{\sinh(bd)} - \frac{Q \cdot a \cdot \cosh a(d - x)}{\sinh(\text{ad})} \right\}
\]

\[
V_2(x) = \left\{ \frac{\text{i}_0}{\rho_{cu} \cdot (b^2 - a^2) \cdot w} \right\} \cdot \left\{ \frac{P \cdot (R_{su} - \rho_{cu} \cdot b^2) \cdot \cosh b(d - x)}{b \cdot \sinh(bd)} - \frac{Q \cdot (R_{su} - \rho_{cu} \cdot a^2) \cdot \cosh a(d - x)}{a \cdot \sinh(\text{ad})} \right\}.
\]

B. Derivation of \( R_c \) and \( R_e \)

The total potential \( V(x) \) across both interfaces \( \rho_{cu} \) and \( \rho_{cu} \) is found by summing \( V_1(x) \) and \( V_2(x) \)

\[
V(x) = \left\{ \frac{\text{i}_0 \cdot R_{su} \cdot \rho_{cu} \cdot (b^2 - a^2) \cdot w}{b \cdot \sinh(bd)} - \frac{Q \cdot a \cdot \cosh a(d - x)}{\sinh(\text{ad})} \right\}.
\]

In Fig. 16, points 1 and 2 lie on an equipotential at the front edge of the contact. The device current enters the contact at this equipotential which is \( V(0) \) volts above the potential of the metal layer. Thus \( R_c = V(0)/\text{i}_0 \). On taking \( x = 0 \) and dividing by \( \text{i}_0 \) then \( R_c \) is found to be

\[
R_c = \left\{ \frac{R_{su}}{\rho_{cu} \cdot (b^2 - a^2) \cdot w} \right\} \cdot \left\{ \frac{P}{b \cdot \sinh(bd)} - \frac{Q}{a \cdot \sinh(\text{ad})} \right\}.
\]

The contact end resistance is calculated from the definition \( R_e = V_XZ/\text{i}_0 \) (see Fig. 13(b)). Since \( V_XZ = V(0) \) then using (A15)

\[
R_e = \left\{ \frac{R_{su}}{\rho_{cu} \cdot (b^2 - a^2) \cdot w} \right\} \cdot \left\{ \frac{P}{b \cdot \sinh(bd)} - \frac{Q}{a \cdot \sinh(\text{ad})} \right\}
\]


Geoffrey K. Reeves received the Ph.D. degree in solid-state physics from Monash University, Melbourne, Australia, in 1970. He subsequently held several industrial research and development positions, before joining the Research Laboratories of Telecom Australia. Here he undertook research on compound semiconductor materials and optoelectronic devices, including work on the electrical characterization of ohmic contacts. In 1988, he took up a research position at the Royal Melbourne Institute of Technology, where he continued research on semiconductor materials and the development of fabrication technologies for Microwave Integrated Circuits.

H. Barry Harrison received the B.E. degree in electrical engineering (honors) and the Diploma of Education from the University of Melbourne, Australia, in 1965 and 1967, respectively. He received a graduate degree in communication engineering in the Netherlands in 1972. He has held various academic and industrial positions around the world, such as at Philips Research Laboratory in the Netherlands, and the IBM T. J. Watson Research Laboratories and Bell AT&T in the United States. He served as a Professor at the University of Edinburgh, Scotland and Leuven in Belgium. He is currently Deputy Dean of the Faculty of Science and Technology, and Head of the School of Microelectronic Engineering at Griffith University.