FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 30, N° 3, September 2017, pp. 313 - 326
DOI: 10.2298/FUEE1703313H

CIRCULAR TEST STRUCTURES FOR DETERMINING THE SPECIFIC CONTACT RESISTANCE OF OHMIC CONTACTS

Anthony S. Holland, Yue Pan, Mohammad Saleh N. Alnassar, Stanley Luong

School of Engineering, RMIT University, Melbourne, Victoria, Australia

Abstract. *Though the transport of charge carriers across a metal-semiconductor ohmic interface is a complex process in the realm of electron wave mechanics, such an interface is practically characterised by its specific contact resistance. Error correction has been a major concern in regard to specific contact resistance test structures and investigations by finite element modeling demonstrate that test structures utilising circular contacts can be more reliable than those designed to have square shaped contacts as test contacts become necessarily smaller. Finite element modeling software NASTRAN can be used effectively for designing and modeling ohmic contact test structures and can be used to show that circular contacts are efficient in minimising error in determining specific contact resistance from such test structures. Full semiconductor modeling software is expensive and for ohmic contact investigations is not required when the approach used is to investigate test structures considering the ohmic interface as effectively resistive.*

Key words: *Ohmic contact, Specific contact resistance, Contact Resistance, Test structure, Circular Transmission Line Model, Transmission Line Model.*

1. INTRODUCTION

In practice, ohmic contacts are one of the least complex aspects of semiconductor devices. The modelling of an ohmic contact requires only contact geometry, material resistivities and the specific contact resistances of all contact interfaces in the contact structure. If a contact is ohmic then its current-voltage behaviour is linear. An ohmic contact interface has a finite thickness defined by the alignment of the Fermi levels of the two contacting materials at equilibrium and the thickness is really that of the 'disturbed' region (depletion layer) of the semiconductor. The 'undisturbed' region (undisturbed by the presence of the metal) of the semiconductor behaves resistively as intended due to whatever doping values it was fabricated with. Though the transport of charge carriers across a metal-semiconductor ohmic interface is a complex process, such an interface is practically characterised by a characteristic specific

Received January 23, 2017
Corresponding author: Anthony S. Holland
School of Engineering, RMIT University, Melbourne, Victoria, Australia
(E-mail: anthony.holland@rmit.edu.au)

contact resistance (SCR). The evolution of semiconductor devices required the lowering of values of this parameter for ohmic contacts and the investigation of test structures to determine these small values has been a significant and important area of research. Error correction has been a major concern in regard to SCR test structures and investigations by finite element modelling demonstrate that test structures utilising circular contacts can be more reliable than square shaped contacts which are impractical to realise for small geometries. Circular designed contacts will remain as circles when fabricated and hence their area can be accurately determined. Test structures with circular contacts can be realised with an equipotential always resulting at the contact circumference and mathematical solutions are obtainable. In this paper it is shown that the use of finite element modelling software NASTRAN can be used effectively for designing and modelling ohmic contact test structures and that circular contact are efficient in minimising error in determining SCR from such test structures. NASTRAN software solves for heat flow and gives temperature contour distribution. It has been extensively used for solving problems for the analogous situation of electrical current flow and equipotential distribution. Full semiconductor modelling software is expensive and for ohmic contact investigation is not required when the approach used is to investigate test structures considering the ohmic interface as purely resistive. More complex investigations that consider tunnelling probability and other aspects of charge transport across an interface will require software for full semiconductor physics solutions but this is not necessary when an experimentalist wants to determine the effect of this physics which is an interface's SCR.

There are two ways to look at the parameter specific contact resistance (represented by symbol $\rho_{c,}$ [Ω.cm^2]). First there is the rather academic or theoretical way of describing it as the inverse of the differential of current density versus voltage (J-V at the origin) for uniform current density, so that even a Schottky contact has a SCR value. There is much to be gained from this first approach in understanding the physics of current across a metal-semiconductor junction. Semiconductor software tools are great for this first approach but not real test structures as it is difficult to isolate a contact so that it is the only entity determining a J-V curve and have uniform current density at the same time. However, this approach is worth pursuing with computer modelling (and actual test structures if possible) of appropriate test structures to demonstrate the physics in SCR equations [1]. The second or the more practical investigation is to study SCR in regard to practical ohmic contacts only so that the derivative of a contacts J-V curve is the same at the origin as it is at practical voltage values e.g. J-V being linear from -5V to +5V. This second approach need not consider the physics of current transfer but rather the effective resistance of a contact interface as it contributes to the total resistance of a source or drain contact of a MOSFET for example. In practical ohmic contacts the depletion layer of the metal-semiconductor interface is relatively small and for active layers of a practical contact structure, each layer-to-layer interface can be considered to have a unique SCR value. Having determined SCR values for any layer-to-layer interface should enable accurate modelling of structures of any geometry involving such interfaces. So, the second approach is very much a 'try and see'; where the first enquiry is to determine if a particular contact interface is ohmic and if so what is its SCR value and can this be used to determine the effective resistance of a contact of a particular area. The reverse is also used, where the effective resistance of a two-layer contact can be used to determine the SCR of the interface using appropriate analytical expressions relating SCR and contact resistance. Although the authors are not aware of any report on using computer modelling in this reverse way, it should be possible to use computer modelling in an iterative way to determine what SCR realises a given (e.g. experimentally determined) contact resistance.

The study of SCR requires the use of test structures for measuring the voltage drop across the contact of interest and any parasitic resistance encountered. It is the parasitic resistance that causes most difficulty. Another difficulty is the effect of contact area, unless the area is small enough that uniform current distribution can be assured, otherwise the concept of transfer length has to be considered. It is in regard to area that circular contacts have an advantage (compared to square contacts) in that even though a circular contact realised after fabrication may not have the same diameter as designed, it will still be a circle and its diameter and area can be accurately determined. Square designs have the disadvantage of ending up having rounded corners. Several test structures have been developed using this advantage of circular contact designs [2-5]. The Circular Transmission Line Model (CTLM) ohmic contact test structure [6] was developed not with this advantage of circular contacts always being circular but with the advantage that no mesa etch or active area isolation is required which is a significant advantage compared to Linear Transmission Line Model (TLM) ohmic contacts test structure's [7, 8]. The disadvantages include the active layer isolation process steps and active layer overlap of contacts where in theory there should be none. The Cross Kelvin Resistor (CKR) test structure has the same disadvantages [9].

2. OHMIC CONTACT CHARACTERISATION

Ohmic contacts are fundamentally important: there are at least two contacts in every transistor and there are billions of transistors on the most complex semiconductor chips. Ohmic contact research is crucial for the development of novel nanotechnology devices [1]. It is imperative to have low resistance contacts to these nanoscale devices. Fundamental understanding of ohmic contact structures, materials properties and processing will result in better semiconductor devices performance and enhanced power efficiency. SCR is an extremely important parameter for quantifying a metal to semiconductor ohmic contact. Its theoretical description is defined as the reciprocal of the derivative of current density with respect to voltage at V = 0 [8] (equation 1). A good ohmic contact requires a negligible value of SCR to ensure the linear I-V characteristic (between such two contacts) is mainly due to resistance of the semiconductor

$$\rho_c = \left(\frac{\partial J}{\partial V}\right)_{V=0}^{-1} \tag{1}$$

Note that equation (1) is the definition of SCR which is a theoretical quantity referring to the metal-semiconductor interface only. In practice, a more meaningful definition of the SCR for a real metal-semiconductor ohmic contact is an electrical parameter which is determined from measured contact resistance between a metal and a semiconductor. SCR is a very useful term for characterising ohmic contacts because it is independent of contact area and is a convenient parameter when comparing contacts of various sizes. Though in practice, an experimentalist or device process engineer will want to know how many ohms an ohmic contact presents to current flow, a design engineer can utilise known SCR values to better design and model a contact considering contact layers, interfaces and geometry parameters are all known, including the SCR of each interface. To ensure accurate semiconductor modelling, any SCR determined experimentally and used in contact or device modelling should be in agreement with equation 1, if this is possible to demonstrate.

Ohmic contact characterisation is carried out by using test structures to investigate the electrical behaviour and a suite of materials analysis tools to investigate the materials which make up the ohmic contacts e.g. silicide (metal-silicon reaction product) layer. Characterisation usually aims to attain the outcomes listed below for optimising contact properties.

1. Use test structures to accurately quantify the resistance due to contact interfaces. This resistive property is qualified using SCR and improved efficiency and speed in determining low SCR values for ultra-small contacts is often a goal of particular research in this area.
2. Understand the influence of mechanical, electrical and thermal materials parameters, in particular the influence of defects and stress formation at the contact interface, on SCR values.
3. Optimise test structures and demonstrate new ones to confirm a test structure's suitability for determining processing changes that contribute to reducing the SCRs of metal-silicide-silicon contacts for example.
4. Hybridisation of analytical calculations and numerical computations of ohmic contact architectures to model the electrical behaviour of fabricated test structures.

Item 4 above is an area that could be explored further. Multilayer ohmic contact test structures will of course have an effective resistance to electrical current and the accurate determination of the resistance of such contact structures can be better realised if interfaces have their SCR's included – other parameters being layer resistivities and geometries for ohmic contacts structures only.

SCR is a parameter that has been reduced by several orders of magnitude (due to the introduction of silicides for silicon contacts [17] for example) throughout the semiconductor era. Reported values of SCR for some ohmic contacts are listed in Table 1. In the International Technology Roadmap for Semiconductors (ITRS) the SCR values required for particular technology nodes have been given in many of its publications showing significant reduction in the required value as technology generations progress. In 2017 the target is in the low 10^{-9} Ωcm^2 range. Determining the value of SCR quantifies the interface for a particular processing technology and gives information about the quality of an ohmic contact fabrication process. It also allows for comparison of different two-layer ohmic contacts or for different device processes using the same two layers for contacts. Hence, determining SCR allows for optimisation of the process for forming an ohmic contact. Determining accurate values of SCR will aid in better modelling of contact structures, in order to minimise the contact resistance (R_c). Note that SCR is the biggest contributor to R_c for relatively small contacts. Minimising R_c in turn minimises the net resistance of a circuit, and its overall power consumption; these will result in more power efficient devices and circuits.

Unlike contact resistance R_c, the SCR value should not include contributions from the resistivity of the two contacting layers or topological effects due to the contact geometry design. If a reported value of SCR does include these effects it is regarded as an effective SCR for a particular contact (including geometry) and such a SCR value cannot be used in designing and modelling other geometries with the same contact layers (and processing steps). The units of SCR (Ωcm^2) may be misleading to some researchers who have not specialised in this area. This parameter cannot be used directly to determine the resistance contribution of the interface in a two-layer contact unless one is confident that the current is uniformly distributed in the contact interface. If current can be assumed to be distributed uniformly in the interface of a two-layer contact then for area A (cm^2) the resistance of the interface is simply ρ_c/A (Ω). This assumption does not always hold (unless A is relatively small) because electrical current in most semiconductor devices (which are planar) has to turn 90^o into a contact, and so is not always uniformly distributed across a contact interface. For example, current can flow laterally under the gate region of a transistor and then turn upwards through the drain ohmic contact, similarly for a contact in a test structure. The distribution of current in the drain contact area is dependent on the value of ρ_c, but is also influenced by other parameters such as the resistivity of any silicide used, the interconnect material, and any liner used; and the geometry of these materials. Intuitive understanding in this case can be misleading, and only rigorous analytical and numerical modelling will portray the actual current distribution.

Table 1 Reported values of Specific Contact Resistance (SCR) for some ohmic contacts

Ohmic Contact Layers	SCR Value Ωcm^2	Ref.
Al-Si	1×10^{-6}	[11]
Al-WSi_x-Si	3×10^{-7}	[12]
Al-$TiSi_2$-Si	1×10^{-8}	[13]
Al-$TiSi_2$	4×10^{-9}	[5]
NiSi-Si	5×10^{-9}	[14]
NiGe-Ge	2.3×10^{-9}	[15]
$TiSi_X$-Si	1.3×10^{-9}	[16]

3. Test Structure Modelling

The main test structures used for characterising ohmic contacts and determining SCR in particular are the Transmission Line Model (or Transfer Length Method) (TLM) [7,8], Cross Kelvin Resistor [9], and the Circular Transmission Line Model [6]. More recent test structures are the Multi-Ring CTLM [15], Refined TLM [16] and the two-circle electrode contacts [4]. One of the main issues with test structures based on the transmission line model is that they are essentially 2-D models and do not allow for vertical voltage drops. An estimate as to whether a 3D correction is applicable to a contact can be made by calculating the parameter η where $\eta=\rho_c/\rho_b .t$ and ρ_b is the resistivity of the semiconductor layer. This parameter was first used by Berger [8] to estimate the influence of semiconductor depth and resistivity on the derivation of ρc using Transmission Line Model test structures. The parameter gives an indication of the ratio of the voltage drop across the contact interface to the voltage drop in the vertical direction occurring in the semiconductor material beneath the contact. When $\eta<1$, 3D effects are significant as the voltage drop in the vertical direction in the semiconductor layer is nominally greater than the voltage drop across the contact interface (SCR = ρ_c.) When $\eta>1$ and increasing, the voltage drop in the vertical direction is becoming less important (the contribution of this vertical voltage drop compared to the measured values becomes less significant) and 2D modelling will be sufficiently accurate. Calculation of η requires some knowledge of ρ_c; however an initial upper figure for η can be found using ρ_c determined from a 2D correction.

This will give an indication of whether a 3D correction may be applicable. If $\eta<1$ and the corrections are made using 2D data, then significant errors can be introduced (over-estimation) in the derivation of ρ_c [18].

By using Finite element analysis we can optimise the use of material and geometries of interconnect to minimise ohmic contact and interconnect via resistance [18]. The electrical equation used to describe d.c. electrical conduction (equation. 2) is analogous to that for thermal conduction (equation 3)

$$J = \sigma \partial V / \partial n \tag{2}$$

where J = electrical current density, V = voltage, n = spatial coordinate in the direction of current flow and σ = material electrical conductivity

$$H = k \, \partial T / \partial n \tag{3}$$

where H = heat flux, T = temperature, n = spatial coordinate in the direction of heat flow, and k = material thermal conductivity

Equations 2 and 3 have the same form and therefore can be solved using the same finite element program. NASTRAN is a finite element program developed by NASA for heat transfer analysis (and mechanical structural analysis). Nathan et al. [19] reported on the use of this program for electrical analysis based on the analogy indicated by equations 2 and 3. NASTRAN has been used by the authors to design and model various ohmic contacts test structures as well as interconnect vias [20] as shown in Figure 1.

Figures 2 (a) and (b) show an example of modeling a CKR test structure using NASTRAN. In Figure 2(b) the metal layer has been lifted up to show the equipotentials. The contact layers are typically separated by a thin oxide layer with the contact opening. V_b is the value of the equipotential of the voltage tap of the (top) metal layer of the contact. The voltage measured on the tap (V_a) is used to determine the average voltage at the bottom of the contact interface.

Figure 3 shows an ideal CKR ohmic contact test structure. It can easily be appreciated that such a test structure is not possible to realise, and contact widths smaller than the current and voltage arms are required. (Stavitski et al give an excellent report on using CKR test structures in [21]).This leads to parasitic error which can be studied using software such as NASTRAN. Figure 4 shows a possible test structure for fast turnaround in CKR measurements using the technique described in [5]. Again, the software NASTRAN can be readily used to model such a test structure. The circular contacts used can be as small as possible as long as their diameters can be measured. This contrasts with square contacts which will most likely have rounded corners (Figure 5). Extrapolation of SCR' (SCR plus parasitic resistance effect) for small contacts where the effective SCR' is determined for each d/w value using SCR'=(V_a – V_b) x Area, gives the actual SCR, as shown in [5]. Again the use of circular contacts is more reliable as contact area can be reliably determined using measured diameters. The series of CKR test structures demonstrated in Figure 4 utilises the technique of the CKR and the accuracy of determining area of circular contacts. The benefits of the series of CKR of Figure 4 is that as the contact becomes infinitely small then the contact resistance will dominate the CKR resistance measurement.

The possible problems with TLM test structures can be demonstrated using NASTRAN modelling. Figure 6 shows the effect of vertical voltage drop in the semiconductor layer which occurs when the semiconductor resistance (due to semiconductor resistivity and thickness) below the contact is comparable to that due to the contact interface (SCR effect). Investigation shows the relevance of the parameter η [17]. In Fig 6(a) there is the effect of horizontal and vertical voltage drop and in Fig 6(b) the semiconductor has only the horizontal resistance effect of sheet resistance and the TLM equations can be reliably applied. Figure 7 shows a schematic with the inclusion of this TLM contact section in a test structure and the effect is to increase the value of R_c determined. Similar error contributions occur for the CKR test structure [10].

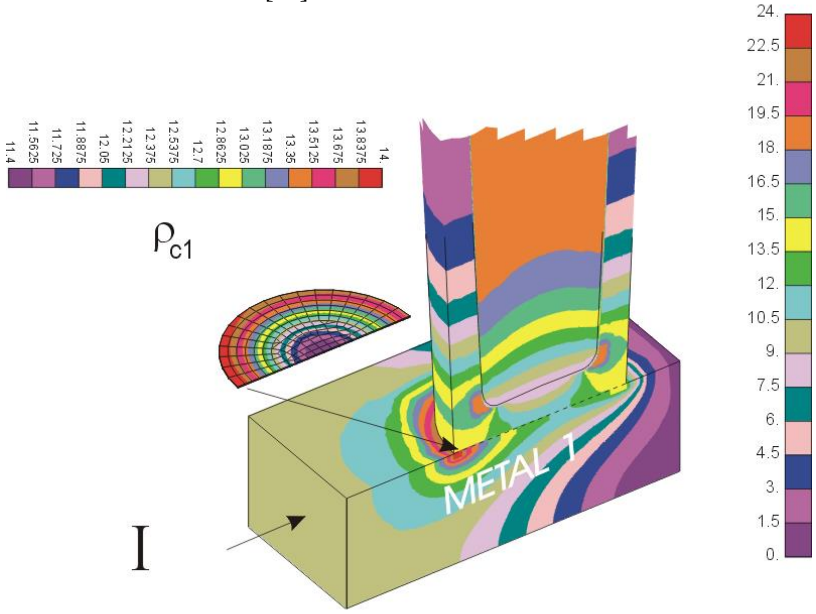
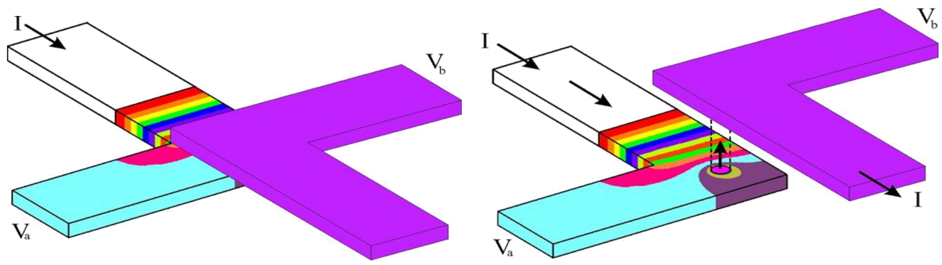


Fig. 1 Example of equipotential distribution in an interconnect via (for input current I) determined using NASTRAN finite element modeler. ρ_{c1} is the specific contact resistance between METAL1 and the via liner material [7].



(a) (b)

Fig. 2 (a) Example of equipotentials in a Cross Kelvin Resistor test structure for ohmic contact characterisation of a semiconductor layer (bottom layer) to a metal layer contact. The distribution of quipotentials in the semiconductor layers current input arm and the voltage (V_a) tap are more clearly shown in (b). The metal layer is shown as having one equipotential (V_b) for the scale used. (Modelled using NASTRAN).

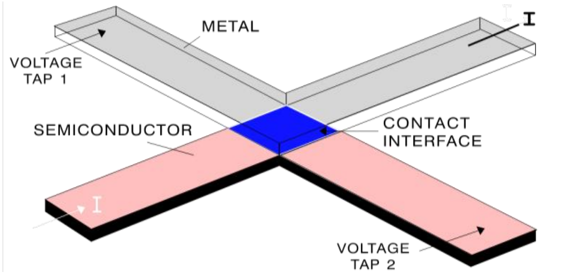


Fig. 3 Ideal CKR test structure, where the square contact area has the same width as the four arms.

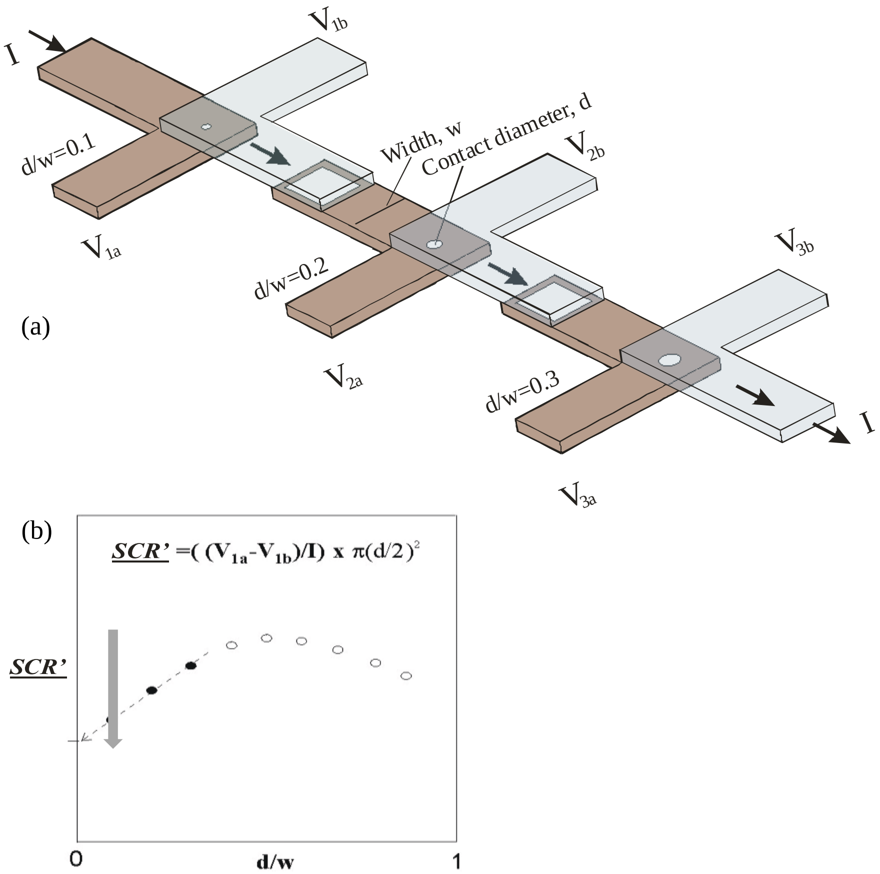


Fig. 4 (a) Schematic of a chain of CKR test structures with varying contact sizes to determine SCR and quick electrical testing. V_{1a} etc. are voltages measured on the respective CKR taps. (b) Expected and observed trend for SCR' determined for varying CKR contact geometry. The actual value of SCR is obtained by extrapolating to d/w = 0. d is the contact diameter and w is the CKR arm width.

Fig. 5 Possible effects of fabrication steps in reducing designed area of contacts of circular and square shapes.

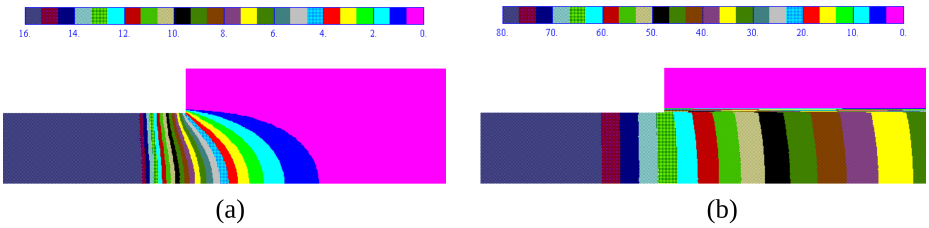


Fig. 6 Examples of equipotentials (Volts) distribution for TLM models of metal to semiconductor contacts. In (a) the structure has η<1 and (b) has η>1, η being the parameter introduced by Berger [17] to quantify the effect of semiconductor layer resistivity on TLM resistance measurements.

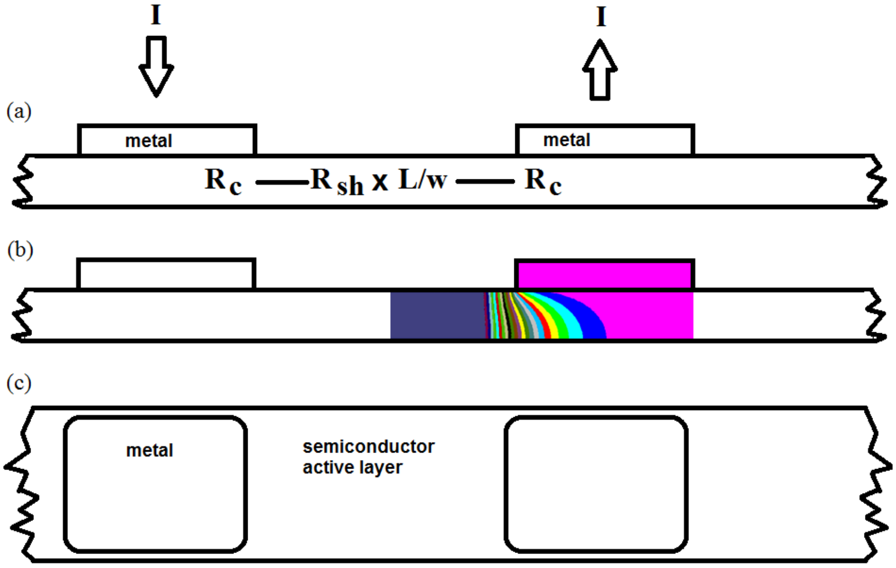


Fig. 7 (a) Schematic of TLM test structure for determining contact resistance (R_c) by measuring resistance between two contacts. (b) shows shows the equipotential distribution where the vertical voltage drop is significant as indicated by the curvature of the equipotentials. The TLM test structure does not include this contribution and measurements will. Hence error results when the measured R_c is used to determine the SCR of the contact. (c) plan view of TLM test structure. (I is input current, R_{sh} is sheet resistance, L is distance between contacts, w is width of active layer).

4. 2D CIRCULAR SPECIFIC CONTACT RESISTANCE TEST STRUCTURE

The Circular Transmission Line Model (CTLM) test structure can be demonstrated using NASTRAN finite element modelling. This test structure completely eliminates alignment error (as there is no alignment) and error is mainly due to the any inaccuracy in sheet resistance and like the TLM and CKR, error due to finite resistivity of the semiconductor layer can cause significant voltage drop in the semiconductor layer under the contact. Yue et al [4] reported a technique using the CTLM test structure shown in Figure 8 (a) and Figure 9. The outer radius r_1' is regarded as infinite in Figure 9. Here we will call this test structure the Yue-2D. It consists of three electrode discs and resistance measurement from these can relatively easily give semiconductor sheet resistance and SCR. The main error that can occur in the Yue-2D will be due to the η factor [17]. Figure 8 (b)-(d) show images from examples of NASTRAN finite modelling of the Yue-2D test structure. The perfect symmetry of each electrode means that only a small 'wedge' of each of the three electrodes (of Fig. 9) needs to be modelled. The equipotentials shown in the semiconductor layer of Figure 8(d) are similar to those in Figure 6(b) where the vertical arrangement of the equipotentials indicates that there is little voltage drop in the vertical direction and hence accurate determination of sheet

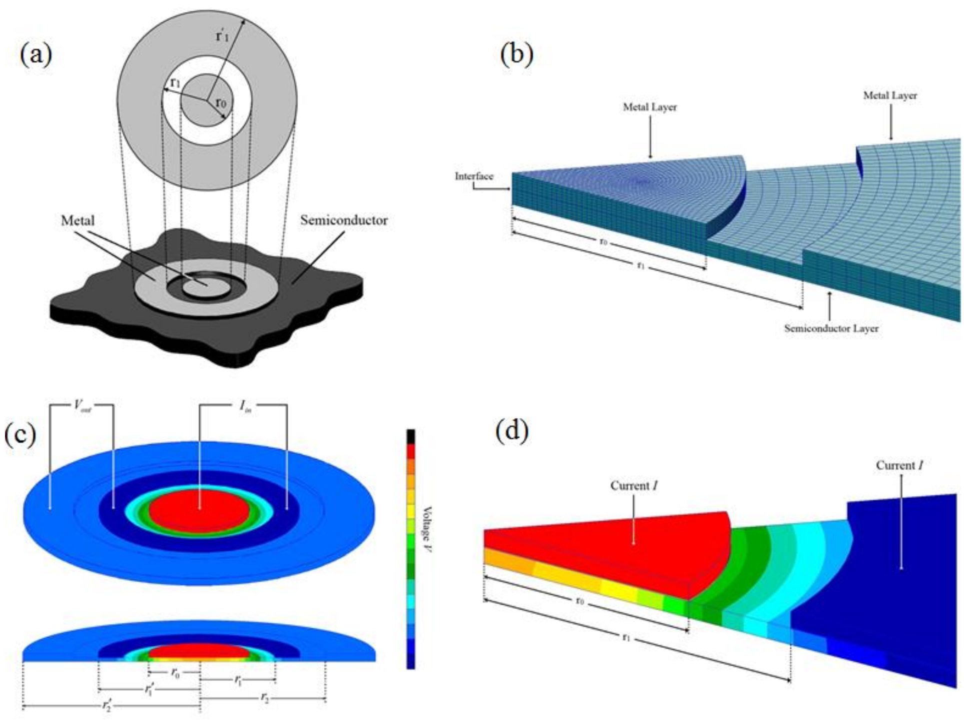


Fig. 8 (a) Schematic of Circular Transmission Line Model (CTLM) test structure using two electrodes, for determining contact resistance (R_c) and SCR, (b) finite element mesh used to model representative section of CTLM, (c) NASTRAN model result showing equipotential distribution for two electrode CTLM and (d) section of CTLM showing equipotentials in semiconductor layer.

resistance and SCR should ensue. Again, an advantage of the circular electrodes is that accurate contact geometry can be measured (the fabricated contacts will be circular) and the actual radii can be used in calculations to determine contact parameters. Extremely small contacts can also be realised when the value of SCR is small and appropriate geometry is described in [4] for this. Such a test structure with extremely small contacts will require more than one metal layer [22] in order to connect a probe to the electrode.

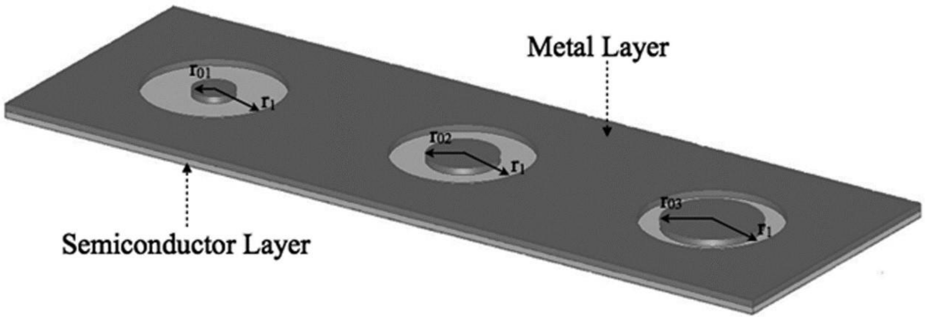


Fig. 9 Schematic of the Yue-2D test structure for determining semiconductor layer sheet resistance and SCR of metal to semiconductor interface [4].

5. 3D Circular Specific Contact Resistance Test Structure

The SCR of metals contacts to bulk semiconductor material is not usually reported, as the main interest for the semiconductor industry is in determining and reducing SCR to shallow active layers. However the authors consider the test structure shown in Figure 10 which shall hereafter be called the Yue-3D, to give the most reliable measurements [3]. However, unlike the test structures reported previously in this paper, there is no analytical solution available relating resistance measurements and SCR. Solutions have to be obtained by computer modelling and resistance measurements plotted as a function of varying semiconductor resistivity, SCR and the two radii (see Figure 11). Unlike the Yue-2D, the Yue-3D only needs one resistance measurement (from one pair of electrodes). Because of its accuracy, this test structure would be very suitable for studies of SCR where a series of substrates are available with varying resistivity and for investigating the effects of surface treatments on varying SCR. The Yue-3D can be used for investigating ohmic contacts to bulk semiconductors where the semiconductor has uniform resistivity to a depth of several times the inner radius (r_1) of the outer electrode shown in Figure 10(a). As in the Yue-2D, the outer radius r_1' can be infinite [2]. A scaling equation can be applied to this test structure similar to that reported by Loh et al. [23] for CKR test structures.

$$R_T(mr_0, mr_1, mr_2, mn\rho_b, m^2 n\rho_c) = nR_T(r_0, r_1, r_2, \rho_b, \rho_c) \qquad (2)$$

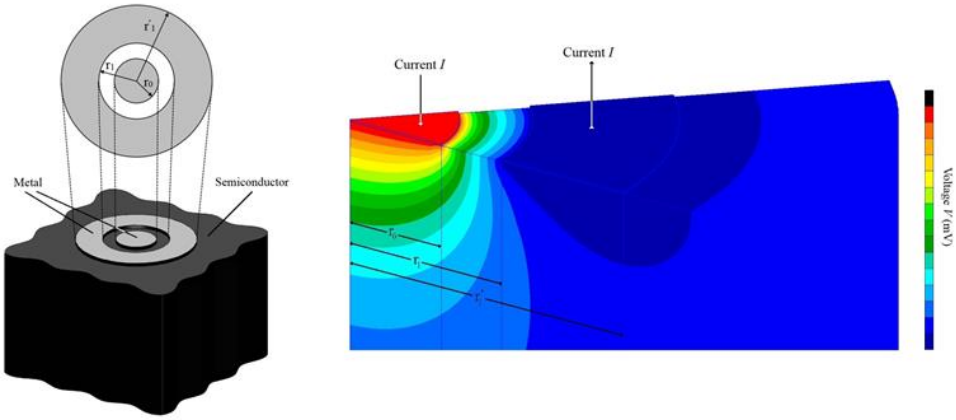


Fig. 10 (a) schematic of the Yue-3D test structure for determining SCR of a metal to semiconductor contact interface for bulk semiconductor [3], (b) example of equipotential distribution in a section of the Yue-3D test structure obtained from FEM modeling using NASTRAN.

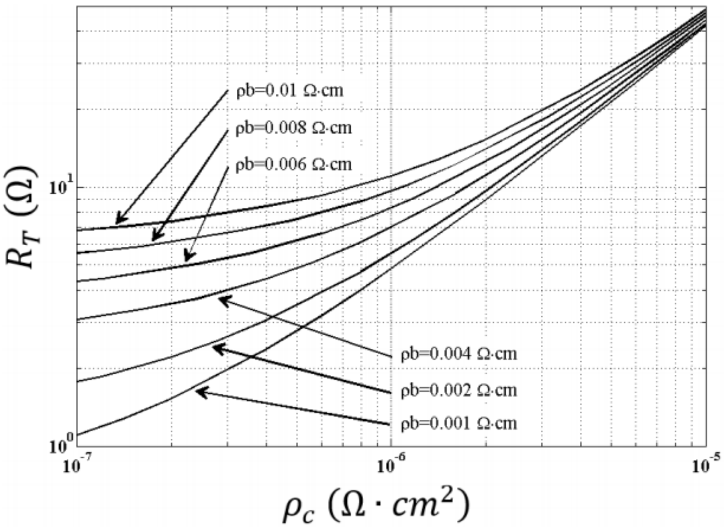


Fig. 11 Example of FEM (NASTRAN) analysis results for total resistance R_T between two electrodes (Fig. 10) as a function of SCR (ρ_c) with resistivity ρ*b* varying from 0.001 Ω·cm -to- 0.01 Ω·cm. Geometry is fixed; r_0 = 3 µm, r_1 = 5 µm, and r_2 = 9 µm. Note that this figure can be scaled using (3). [2]

6. CONCLUSION

This paper has reviewed ohmic contact test structures investigated by the authors for ohmic contact characterisation between a metal and semiconductor in both two dimensional (2-D) and three-dimensional (3-D) circumstances using these test structures. The issues with regards to error correction, difficulty in analysing results and difficulty in fabrication, lead to the development of test structures with circular electrodes. These issues are (i) Active layer definition, (ii) Contact misalignment and overlap, (iii) Equipotential problem, (iv) Complicated analytical expressions and (v) Vertical voltage drop. When the semiconductor layer in a metal-to-semiconductor contact is neither true 2-D nor true 3-D, there will always be some error, and error correction is required. For the test structure presented here, accurate results can be always determined when semiconductor layer can be regarded as truly 2-D or 3-D. In summary, all of the above issues with conventional test structures have been addressed and improved by the novel test structures (Yue-2D and Yue-3D) developed for ohmic contact characterisation in both 2-D and 3-D circumstances. The corresponding methods for determining SCR have also been presented and demonstrated using finite element modeling (FEM). Because of the resistance only effect of ohmic contacts, a full semiconductor physics modelling program is not required. Commercially available FEM software for static thermal analysis, such as NASTRAN can be used for ohmic contact test structure investigation considering the analogous equations for heat and electric current flow. The Yue-2D set of three two-contact circular test structures does not require mesa isolation and correction factors are unnecessary. Furthermore, the analytical expressions are relatively simple compared to the conventional CTLM test structure. A 3D test structure (Yue-3D) was demonstrated that should be most accurate in determining specific contact resistance.

REFERENCES

[1] Hiep N. Tran, Tuan A. Bui, Aaron M. Collins, and Anthony S. Holland, “Consideration of the Effect of Barrier Height on the Variation of Specific Contact Resistance With Temperature”, *IEEE Trans. Electron Devices*, vol. 64, no. 1, pp. 325, 2017.

[2] A. M. Collins, Y. Pan, A. S. Holland, “Using a Two-contact circular test structure to determine the specific contact resistivity of contacts to bulk semiconductors”, *Facta Universitatis, Series Electronics and Energetics*, vol. 28, no. 3, pp. 457 – 464, September 2015.

[3] Y. Pan, A. M. Collins and A. S. Holland, "Determining Specific Contact Resistivity to Bulk Semiconductor Using a Two-Contact Circular Test Structure", In Proceedings of the IEEE International Conference on MIEL, May 2014, pp. 257-260

[4] Y. Pan, G. K. Reeves, P. W. Leech, and A. S. Holland, “Analytical and finite-element modeling of a two-contact circular test structure for specific contact resistivity,” *IEEE Trans. Electron Devices*, vol. 60, no. 3, pp. 1202–1207, Mar. 2013.

[5] A. S. Holland, G. K. Reeves, "New Challenges to the Modelling and Electrical Characterisation of Ohmic Contacts for ULSI Devices", *Microelectronics Reliability*, vol. 40, pp. 965-971, 2000.

[6] G. K. Reeves, “Specific contact resistance using a circular transmission line model,” *Solid State Electron.*, vol. 23, no. 5, pp. 487–490, May 1980.

[7] W. Shockley, “Research and Investigation of inverse epitaxial UHF power transistors”, Air Force Atomic Laboratory, Wright-Patterson Air Force Base, Rep. No. AL-TDR-64-207, Sept. 1964.

[8] H. Berger, “Models for contacts to planar devices,” *Solid State Electronics*, vol. 15, pp. 145-158, 1972.

[9] S. J. Proctor and L. W. Linholm, *IEEE Electron Device Lett.*, EDL-3 (10) 294 (1982).

[10] C. Y. Chang, Y. K. Fang, and S. M. Sze, “Specific contact resistance of metal-semiconductor barriers,” *Solid-State Electron.*, vol. 14, no. 7, pp. 541–550, Jul. 1971.

[11] G. Srinivasan, M. F. Bain, S. Bhattacharyya, P. Baine, B. M. Armstrong, H.S. Gamble, D. W. McNeill, *Mat. Sci. Eng. B*, 114-115, pp.223-227, 2004.

[12] M. Finetti, S. Guerri, P. Negrini, A. Scorzoni, and I. Suni, *Thin Solid Films*, vol. 130, no. 37, 1985.

[13] Majumdar et al, "STLM: A Sidewall TLM Structure for Accurate Extraction of Ultralow Specific Contact Resistivity", *IEEE Trans. Electron Devices*, vol. 34, no. 9, September 2013.

[14] Miyoshi et al, "In-situ Contact Formation for Ultra-low Contact Resistance NiGe Using Carrier Activation Enhancement (CAE) Techniques for Ge CMOS", In Digest of Technical Papers Symposium on VLSI Technology, 2014.

[15] Yu et al, "Titanium Silicide on Si:P With Precontact Amorphization Implantation Treatment: Contact Resistivity Approaching 1×10^{-9} Ohm-cm^{2}", IEEE Trans. Electron Devices, vol. 63, no.12, September 2016.

[16] R. Dormaier and S. E. Mohney, "Factors controlling the resistance of ohmic contacts to *n*-InGaAs," *J. Vac. Sci. Technol. B*, vol. 30, no. 3, pp. 031209-1–031209-10, May/Jun. 2012.

[17] N. Stavitski, M. H. van Dal, A. Lauwers, C. Vrancken, A. Y. Kovalgin, and R. M. Wolters, "Evaluation of transmission line model structures for silicide-to-silicon specific contact resistance extraction," *IEEE Trans. Electron Devices*, vol. 55, no. 5, pp. 1170–1176, May 2008.

[18] Holland A. S. and Reeves G.K., "New Challenges to the Modelling and Electrical Characterisation of Ohmic Contacts for ULSI Devices", In Proc. of the MIEL 2000 Conference, vol. 2, pp.461-464, Nis, May 2000.

[19] M. Nathan, S. Purushothaman and R. Dobrowolski, "Geometrical effects in contact resistance measurements: Finite element modelling and experimental results", *J. Appl. Phys.*, vol. 53, no. 8, pp. 5776-5782, August 1982,

[20] Anthony S. Holland, Geoffrey K. Reeves, Patrick W. Leech, "Finite Element Modelling of Misalignment in Interconnect Vias", pp. 307-310, COMMAD, Brisbane 2004.

[21] N. Stavitski, J. H. Klootwijk, H. W. van Zeijl, A. Y. Kovalgin, and R. A. M. Wolters, "Cross-bridge kelvin resistor structures for reliable measurement of low contact resistances and contact interface characterization," *IEEE Trans. Semicond. Manuf.*, vol. 22, no. 1, pp. 146–152, Feb. 2009.

[22] PhD thesis, "Versatile Circular Test Structure for Ohmic Contact Characterisation" Dr Pan Yue, RMIT University 2015.

[23] W. M. Loh, S. E. Swirhun, T. A. Schreyer, R. M. Swanson, and K. C. Saraswat, "Analysis and scaling of Kelvin resistors for extraction of specific contact resistivity," *IEEE Electron Device Lett.*, vol. EDL-6, pp. 105–108, Mar. 1985.