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A Simplified Method for Extracting Contact Resistivity Using the Circular Transmission Line Model

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Abstract. To ensure maximum device current is supplied through a vertical device having a backside ohmic contact, the specific contact resistivity, ρ_c, must be well characterized as it constitutes a portion of the device resistance. While there are multiple approaches to deduce ρ_c, the transmission line model (TLM) remains a convenient choice because of its simplicity in terms of fabrication, measurement, and analysis. For thick substrates where mesa isolation is impractical, the circular transmission line model (CTLM) is an attractive path. In this study we propose an additional restriction on the CTLM design such that the ρ_c is readily extracted from a simple linear regression just as is the case in a linear TLM. We demonstrate the simplified method by extracting ρ_c of an ohmic contact to the c-face of 4H-SiC substrate.

Introduction

To minimize conduction loss for optimal efficiency in a power semiconductor switch, all resistive components, including ohmic contact resistance for example, need to be characterized and understood. The measure of ohmic contact resistance between a metal and a semiconductor is generally conveyed by specific contact resistivity, ρ_c, which is scale-invariant with respect to contact area. While there are multiple approaches to deduce it [1-5], the transmission line model (TLM) remains a convenient choice because of its simplicity in terms of fabrication, measurement, and analysis. TLM assumes one-dimensional flow of current that can be challenging to satisfy because devices are realized in three-dimensional space with finite sizes, i.e. currents bend at edges and corners, causing deviations away from the one-dimensional model. The issue can be circumvented in part by using circular transmission line model (CTLM) that reduces two (x and y) dimensions into a single radial (r) one by introducing radial symmetry to the metal contact pattern. However, there is a price to pay as CTLM requires more complicated analysis to extract the contact resistivity. This work proposes an additional restriction in the CTLM design such that the specific contact resistivity is readily extracted from a simple linear regression just as is the case in a linear TLM. In addition, we report our finding that the statistical errors of the extracted quantities, such as semiconductor sheet resistance (R_{sh}) and transfer length (L_T), depend on the values of CTLM design parameters. Finally, we demonstrate how we can combine the results of two varying designs – one optimized for extracting R_{sh} and the other optimized for L_T – to arrive at deducing the specific contact resistivity.

Theory

Given a CTLM structure as shown on Fig. 1, the resistance across two metal pads on a semiconductor separated by an annular gap is given by Eq. 1 where r_o and r_i are outer radius and inner radius respectively, and I_0, I_1, K_0, and K_1 are the modified Bessel functions of first and second kinds. Eq. 1 can be simplified to Eq. 2 assuming $r_i \gg 4L_T$ [6].

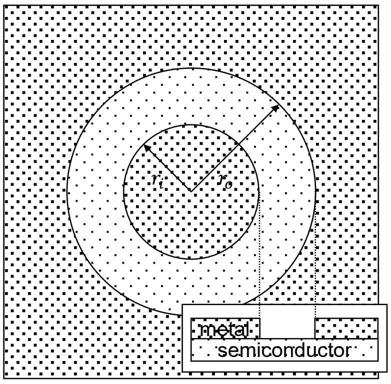

Fig. 1. Circular contact resistance test structure showing the designations of inner and outer radii, r_i and r_o. The inset shows a cross-sectional view.

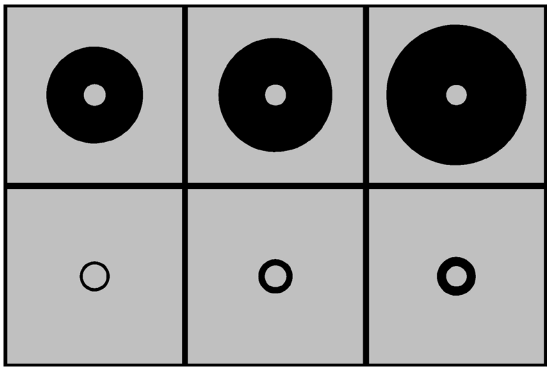

Fig. 2. Schematics of representative CTLM structures with varying gap spacings, representing group A (top) and group B (bottom).

After imposing a design restriction as shown in Eq. 3 so that the reciprocal sum of r_i and r_o is a constant value, $1/r_c$, Eq. 2 can be further simplified to Eq. 4. Note that Eq. 4 has the same linear equation form as linear TLM formulation. A simple linear regression of the resistance R as a function of varying ratio of r_o and r_i allows the extraction of sheet resistance R_{sh} and transfer length L_T from the slope and y-intercept respectively. The specific contact resistivity is obtained from the expression $\rho_c = R_{sh} L_T^2$ in a straightforward manner.

$$R = \frac{R_{sh}}{2\pi}\left[ln\left(\frac{r_o}{r_i}\right) + \frac{L_T}{r_i}\frac{I_0(r_i/L_T)}{I_1(r_i/L_T)} + \frac{L_T}{r_o}\frac{K_0(r_o/L_T)}{K_1(r_o/L_T)}\right] \tag{1}$$

$$R \approx \frac{R_{sh}}{2\pi}\left[ln\left(\frac{r_o}{r_i}\right) + L_T\left(\frac{1}{r_i} + \frac{1}{r_o}\right)\right] \tag{2}$$

$$\frac{1}{r_c} = \frac{1}{r_i} + \frac{1}{r_o} = const. \tag{3}$$

$$R = \frac{R_{sh}}{2\pi} ln\left(\frac{r_o}{r_i}\right) + \frac{R_{sh}}{2\pi}\frac{L_T}{r_c} \tag{4}$$

The choice of r_c must be such that it allows the assumption ($r_i \gg 4L_T$ to use Eq. 2) to hold while managing to yield a reasonable range of gap spacing that satisfies Eq. 3. Given the r_c value of 263 µm, a wide range of annular gap spacing can be chosen as shown in Table 1 below. Table 1 shows CTLM design parameters for the two groups to demonstrate the simplicity of the proposed methodology.

Table I. CTLM design parameters.

r_c (µm)	Group A			Group B		
	r_i (µm)	r_o (µm)	gap (µm)	r_i (µm)	r_o (µm)	gap (µm)
263	330	1300	970	510	544	34
263	320	1480	1160	490	568	78
263	310	1740	1430	470	598	128
263	300	2140	1840	450	634	184

Experimental

Two sets of CTLM structures, groups A and B, were fabricated on the c-face of Wolfspeed 4H-SiC substrates with 4° off-axis cut, using one set of process conditions for ohmic contact formation. Resistance of each CTLM was extracted by fitting a line to the IV curve measured on a typical semiconductor probe station as shown in Fig. 3.

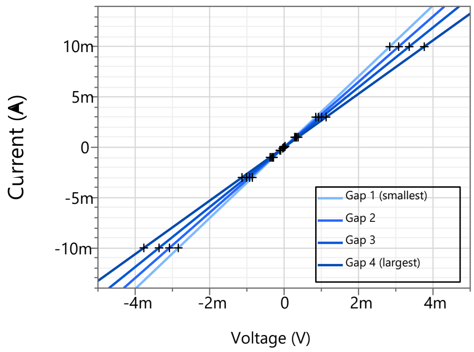

Fig. 3. An example plot of I-V curves at 25 °C for extracting resistance for varying gaps.

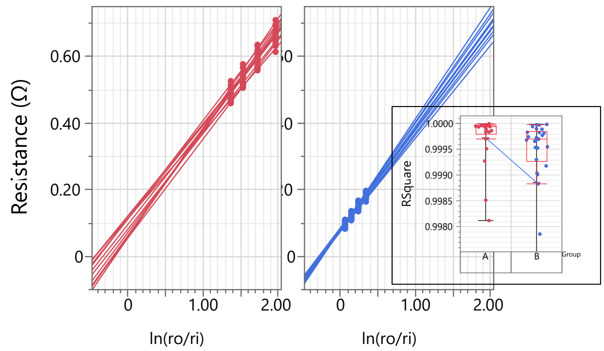

Fig. 4. Resistance versus ln(r_o/r_i) at 25 °C for the groups A (left) and B (right). Inset is showing the R^2 comparison.

Results and Discussion

Figure 3 shows an example of four I-V curves with four gap spacings, each with a specific ratio of r_o/r_i. The collection of the resistances and their corresponding ratios are plotted on Fig. 4 by groups A and B. Group A (red) was designed with CTLM structures with large ratio values, or large gap spacings. Both groups A and B have R^2 values close to unity (see the inset in Fig. 4), indicating the simplified approach to CTLM from Eq. 3 and Eq. 4 are not unreasonable. The slopes and y-intercepts of the fitted lines in Fig. 4 yield the sheet resistance and transfer length respectively using Eq. 4. The fitted lines on Fig. 4 reveal a distinction between groups A and B as the red fitted lines resemble a band of parallel lines while the blue lines cross the y-intercept in a tighter window. In other words, group A, having the larger spacings, owes more of its resistance to the semiconducting film and, therefore, provides more reliable extraction of R_{sh} as indicated by higher values of R^2. Group B, having smaller spacings, is more reliable at extracting L_T as shown by narrower window of y-intercepts.

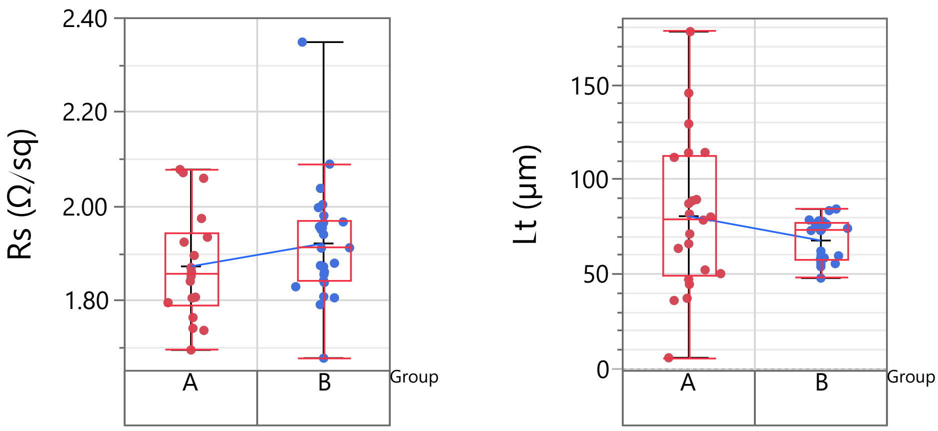

Fig. 5. Extracted sheet resistance R_s (left) and transfer length L_t (right) distributions are compared between groups A and B.

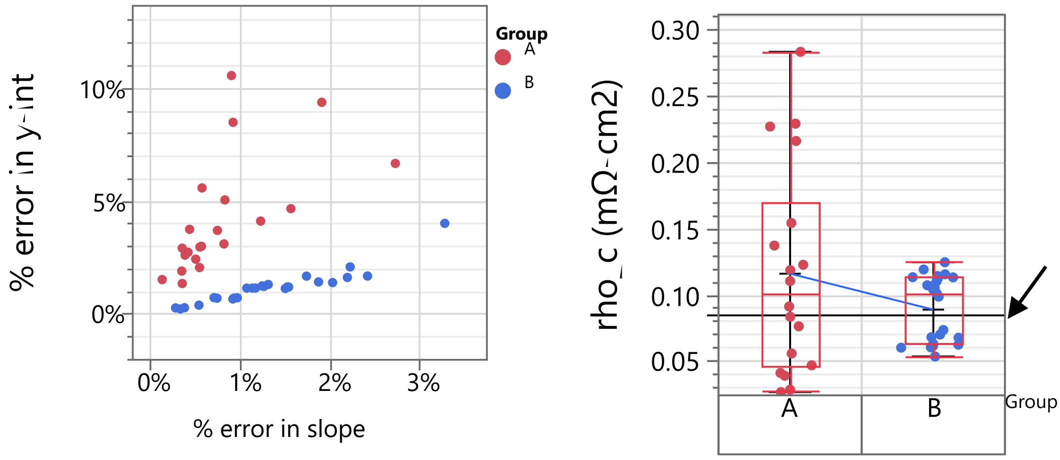

Fig. 6. Standard errors in the extracted values from linear regression are compared between groups A and B (left). Specific contact resistivity distributions (right) are plotted by group. The arrow indicates the best estimate by combining group A and B results.

Figure 5 shows the values of extracted R_{sh} and L_T. We have more confidence in the extracted value of R_{sh} from group A because of the higher R^2 values as shown in the Fig. 4 inset. On the other hand, the extracted values of L_T from group B are more reliable as their statistical distribution is tighter and their percentage errors in y-intercept are lower. Some transfer length values, above 80 µm, from group A violate the assumption $r_i \gg 4L_T$ while that is not an issue with group B. Since there was no way to know the transfer length a priori, this issue would have to be resolved through iteration. It is worth noting that the extracted quantities are generally aligned between the two groups despite their respective shortcomings and even potential violation of the assumption used to extract the relevant quantity.

Figure 6 shows the respective standard errors in y-intercept and slope. It highlights that group A has a large variation in y-intercept that leads to the large variation in the extraction of L_T. This is unexpected because it is typically assumed that higher resistance values yield better measurement sensitivity and the consequent higher R^2 values would increase the confidence in the line fitting. The data suggests the CTLM design should consider a balance of the voltage drop between semiconducting and contact regions. Put another way, high accuracy and high precision measurement may utilize varying CTLM structures aimed at extracting the sheet resistance and the transfer length separately, knowing their statistical errors in both cannot be simultaneously minimized. Good news is that there is only marginal difference between the statistical averages for groups A and B if their errors and assumptions can be ignored. The specific contact resistivity of group A is 1.2×10^{-4} Ω-cm^2 (0.12 mΩ-cm^2) while that of group B, with a tight distribution of L_T, is 8.9×10^{-5} Ω-cm^2 (0.089 mΩ-cm^2) at room temperature. Based on our learnings, it would make sense to combine the R_{sh} of group A and the L_T of group B to yield 8.5×10^{-5} Ω-cm^2 (0.085 mΩ-cm^2).

Summary

We have demonstrated a simple method for the design and analysis of CTLM structures. It yields a straightforward analysis at the expense of upfront design restriction. We found that the gap spacings of CTLM structures yield a trade-off relationship between the standard errors of sheet resistance (slope) and contact resistance (y-intercept) and can marginally skew the extracted value of ρ_c. The conclusion of this study is that methods of ohmic contact evaluation need to be made with close attention to the design of the structures being used.

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