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# The Spreading Resistance Error in the Vertical Kelvin Test Resistor Structure for the Specific Contact Resistivity

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***Abstract*—The spreading resistance error in the vertical Kelvin test resistor (VTR) structure is studied based on an analytic approach. It is found that it is always less than the error existing in the horizontal test structures and can be expressed as $R_s z_j^2 / C$, where $R_s$ and $z_j$ are the sheet resistance and the junction depth of the conductor resistor, respectively, and $C$ is a factor approximately equal to 2.**

## I. Introduction

Presently, the specific contact resistivity for VLSI contacts is in the range of $10^{-6}$–$10^{-7}$ $\Omega \cdot \text{cm}^2$. Many test structures have been proposed and studied to measure the $\rho_c$ value [1]-[9] of this range. Among the proposed test structures, there is a vertical test resistor (VTR) structure [5], for which the driving current is forced to flow "vertically" from the metal contact pad toward the contact substrate. The current crowding effects that are inherent in the horizontal types of test structures are eliminated during measurement. However, for this VTR test structure, there exists an error that is caused by the current spreading within the conduction bar region as the current flows from the metal pad toward the substrate (see Fig. 1(a)). This nonvertical flow makes the potential at the sensing terminal to be not exactly the same as that underneath the contact pad. In this brief, we report the result of a study on the error caused by this spreading effect.

## II. Structure and Model

The test structure for this study is shown in Fig. 1(a). In contrast to the conventional test arms to measure the Kelvin voltage, a circular implanted conduction region is used to surround the contact pad. The vertical current $I$ is forced to flow through the contact pad, and the Kelvin voltage is sensed at the outer metal ring. The whole implanted conduction region is embedded in an isolating region that has an opposite doping and has at its center an opened hole to connect the conduction region with the substrate. When the current flows from the contact pad toward the substrate, it spreads inside the conduction region. For the ideal case, this spreading should be zero. The measured Kelvin voltage $V_k$ gives the contact resistance

$$R_k = R_c = \frac{V_k}{I}.$$

However, due to the presence of spreading, additional voltage drops exist in the horizontal direction, and this produces an additional term in the measured $V_k$. The measured contact resistance contains an additional component $R_{sp}$. If it is assumed that this $R_{sp}$ is linearly independent of $R_c$ [8], then

$$R_k = R_c + R_{sp}.$$

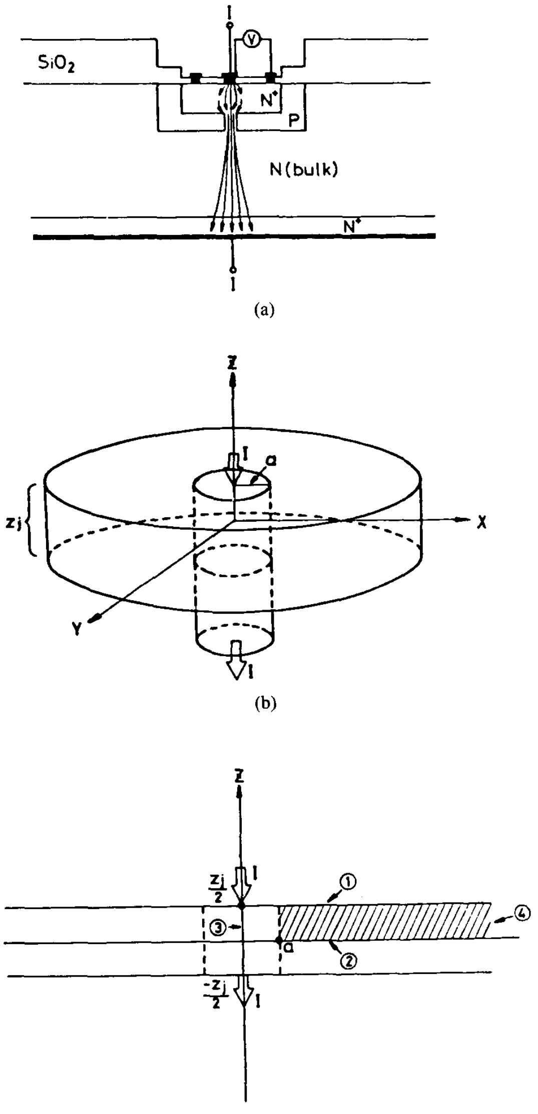

Fig. 1. (a) A cross-sectional view of the circular vertical Kelvin test structure. (b), (c) The analytical model for the circular vertical Kelvin resistor.

In the above, $R_{sp}$ can be approximately calculated by setting $R_c$ to be zero to solve Laplace's equation in the conduction region by placing the appropriate boundary conditions. In the following, this $R_{sp}$ is calculated.

The physical model for calculating $R_{sp}$ is shown in Fig. 1(b), where the conduction region is of the shape of a circular pancake with a thickness of $z_j$ and a radius of $r = \infty$. At the center, there is a circular top contact pad with a radius $r = a$. At the bottom, there is a current conduction channel, also with a radius $r = a$. Since the conduction region is circularly symmetric, the system can be simplified to be a two-dimensional problem as shown in Fig. 1(c), and the first quadrant of the region (the shaded region) needs to be treated. This problem is similar to the one used to calculate the spreading resistance of the two-probe system to measure the

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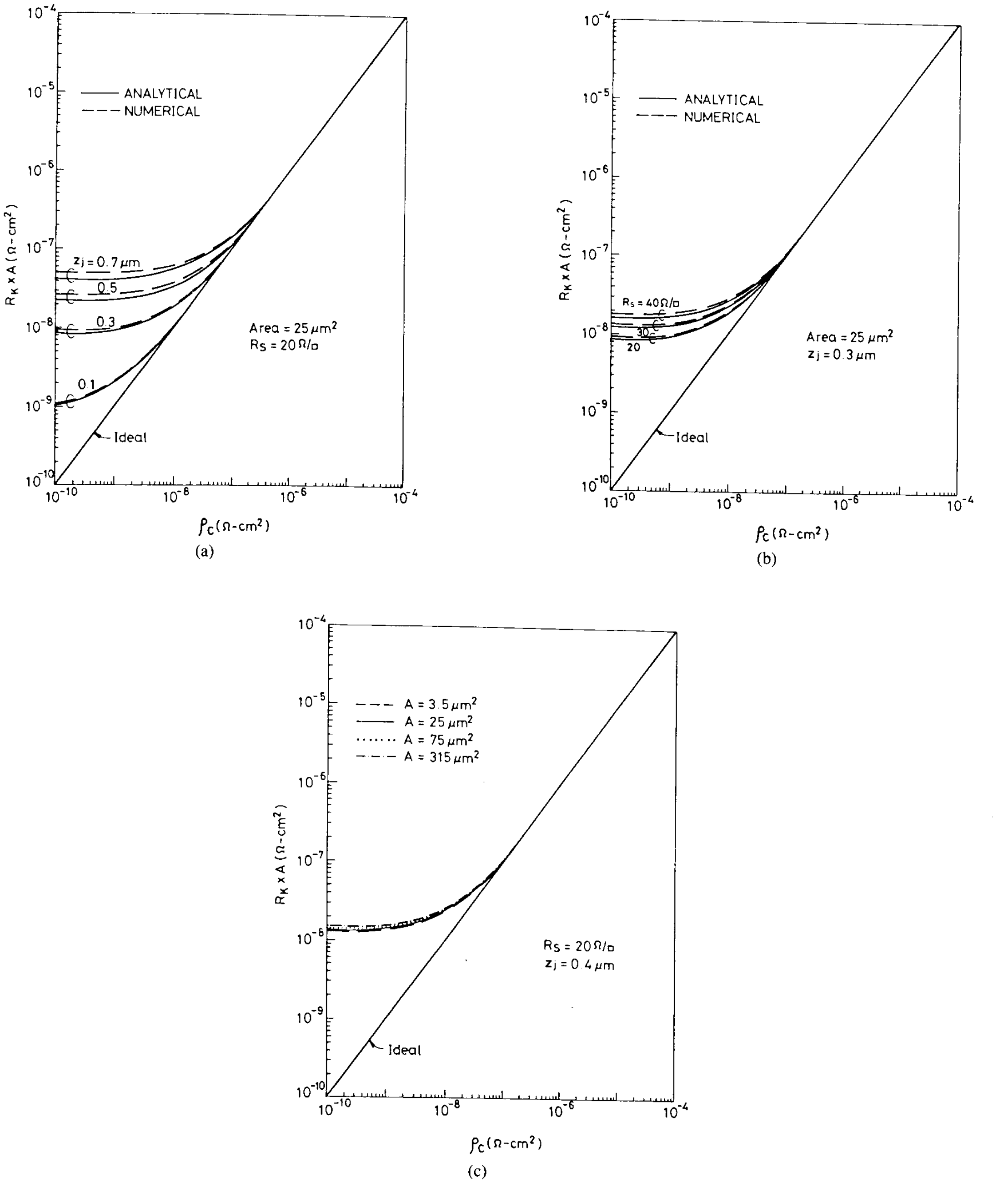

(a)

(b)

(c)

Fig. 2. The measured specific vertical Kelvin resistivity $R_k \times A$ versus the true contact resistivity $\rho_c$: (a) with $A = 25\ \mu\text{m}^2$ and $R_s = 20\ \Omega/\square$ for $z_j = 0.1, 0.3, 0.5$, and $0.7\ \mu\text{m}$; (b) with $A = 25\ \mu\text{m}^2$ and $z_j = 0.3\ \mu\text{m}$ for $R_s = 20, 30$, and $40\ \Omega/\square$; (c) with $z_j = 0.4\ \mu\text{m}$ and $R_s = 20\ \Omega/\square$ for $A = 3.5, 25, 75$, and $315\ \mu\text{m}^2$.

sheet resistance of a semiconductor material [10]. The boundary conditions are

$$\frac{\partial V}{\partial z} = 0, \qquad r > a \qquad \text{for Boundary ①}$$

$$= \frac{I\rho}{2\pi a(a^2 - r^2)^{1/2}}, \qquad r \leq a$$

$$V(r, 0) = 0 \quad \text{for Boundary ②}$$

$$\frac{\partial V(0, z)}{\partial r} = 0 \quad \text{for Boundary ③}$$

$$V(\infty, z) = 0 \quad \text{for Boundary ④}$$

where $\rho$ is the resistivity of the conduction region.

The solution of Laplace's equation with the above boundary conditions is of the following form [11]:

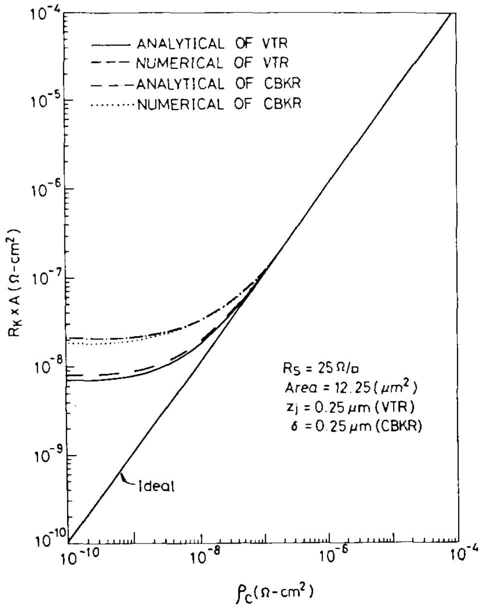

Fig. 3. Comparison of the computed $R_k \times A$ for the VTR and the CBKR for $R_s = 25\ \Omega/\square$; $A = 12.25\ \mu m^2$. For the VTR, $z_j = 0.25\ \mu m$, and for the CBKR, $\delta = 0.25\ \mu m$.

$$V(r, z) = \frac{I\rho}{2\pi a}\int_0^\infty \frac{e^{-\lambda((z_j/2)-z)} - e^{-\lambda((z_j/2)+z)}}{1 + e^{-\lambda z_j}} \cdot \sin(\lambda a)\, J_0(\lambda r)\, \frac{d\lambda}{\lambda} \qquad (1)$$

where $J_0$ is the Bessel function of the zeroeth order, and $\lambda$ is a dummy variable. The measured Kelvin voltage $V_k$ now is the average of the $V(r, z_j/2)$, i.e.

$$V_k = \frac{\int_0^a \int_0^{2\pi} V(r, z_j/2)\, r\, dr\, d\theta}{\int_0^a \int_0^{2\pi} r\, dr\, d\theta}$$

and $R_{sp} = V_k/I$.

Equation (1) can be numerically evaluated, and we have

$$R_{sp} \approx \frac{1}{C}\frac{R_s z_j^2}{A} \qquad (2)$$

where $R_s = \rho/z_j$ is the sheet resistance of the conduction region, $A$ is the contact area, and $C$ is a factor whose value is approximately 2 as $a$ is significantly larger (5 times, for example) than $z_j$, which is usually true in practical cases.

## III. Results and Discussions

The $R_k(=R_c + R_{sp})$ are numerically plotted in Fig. 2(a), (b), and (c) for various $z_j$, $R_s$, and $A$, respectively, with respect to the true specific contact resistivity $\rho_c$. A two-dimensional analysis program based on the numerical analysis has been written to simulate this spreading resistance effect [12] and the results are also included for comparison. In Fig. 2(a) and (b), it is seen that the results obtained by this analytic approach are generally consistent with those obtained through the exact numerical analysis except that, at the low $\rho_c$ range ($10^{-9}\ \Omega \cdot cm^2$), there is approximately a 15 percent error. In the figures, the unity slope line, which represents the ideal case, is also plotted.

Several additional points can be drawn from those figures:

1) The spreading resistance component decreases with $z_j$ and $R_s$.

2) The measured Kelvin specific contact resistance is nearly independent of the contact area $A$.

3) And, as the junction depth of the Kelvin conduction region is 0.3 $\mu$m with $R_s = 40\ \Omega/\square$, $R_{sp}$ is nearly three times of $\rho_c$ for $\rho_c = 10^{-8}\ \Omega \cdot cm^2$.

Fig. 3 shows plots for a $R_s = 25\ \Omega/\square$ and $z_j = 0.25\ \mu m$ case with this vertical test resistor (VTR) and for a horizontal structure with the same $R_s$ but with the alignment tolerance $\delta = 0.25\ \mu m$ [7]. It is seen that the VTR curve is less than a similar curve of the CBKR structure in [8]. It is because, in the VTR structure, $R_{sp}$ is proportional to $z_j^2$, which is usually in the range of 0.1–0.2 $\mu$m, while for a horizontal structure, the $R_{geom}$ is proportional to $\delta^2$ [8], which depends on the photolithographical resolution and is usually in the range of 0.4–0.5 $\mu$m.

## IV. Conclusions

In this brief, the spreading resistance error in the vertical test structure has been studied based on an analytic approach. The spreading resistance component can be expressed in terms of a simple relationship with the sheet resistance and the junction depth of the conduction resistor. To reduce the error caused by this spreading resistivity component, it is desirable to reduce $z_j$ rather than $R_s$. The spreading resistance error in the VTR structure is always less than the error existing in the horizontal structure. Also, it is found that the measured specific Kelvin Resistivity is independent of the area of the contact pad.

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