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THE EFFECTS OF CONTACT SIZE AND NON-ZERO METAL RESISTANCE ON THE DETERMINATION OF SPECIFIC CONTACT RESISTANCE†

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Abstract—This paper presents theoretical and experimental results concerning two sources of error in the determination of specific contact resistance of ohmic contacts to semiconductor device structures that utilize circular test patterns with varying gap length. It is shown that the potential drop vs gap length data cannot be usually represented by a straight line and a non-zero metal overlay sheet resistance can significantly alter the effective contact resistance value.

INTRODUCTION

In many semiconductor devices, the quality of ohmic contacts plays a vital role in determining the performance limitations of the device; hence, the need for a low contact resistance metallization system. For example, in GaAs MESFET's with 1 μm channel length and an active conducting layer sheet resistance (R_s) of 400 Ω/sq., the specific contact resistance (R_c) needs to be lower than 10^{-6} Ω-cm^2. Errors in the determination of such low contact resistance values can become quite large unless proper care is taken to allow for the effect of contact size, as in the case of the circular contact test patterns, and the effect of non-zero sheet resistance of the metallic overlay. These effects are analyzed and the results are compared with experimental data obtained from Au–Ge based ohmic contacts to n–GaAs.

THE EFFECT OF CONTACT GEOMETRY

For the determination of specific contact resistance of ohmic contact systems in semiconductor devices, test patterns of either rectangular or circular geometry (see Fig. 1a and b) are commonly used. By forcing a constant current through the adjacent pairs of rectangular contact pads, with different spacings, d, the voltage drop ΔV across the same pads can be plotted vs d, and this would result in a straight line with slope proportional to the semiconductor sheet resistance (R_s) and an intercept $2L_T$ to the negative d-axis, where L_T is the transfer length (see Fig. 2). The potential distribution $V(x)$ under the pad, for the rectangular geometry, obtained from the transmission line model (TLM) can be expressed in the manner[1],

$$V(x) = i_0 R_s \frac{L_T}{Z} \frac{\cosh(X/L_T)}{\sinh(W/L_T)} \tag{1}$$

where L_T is the transfer length or inverse of attenuation constant given by

$$L_T = \sqrt{\left(\frac{R_c}{R_s}\right)}. \tag{2}$$

When $W \gg L_T$, the voltage drop under one of the contact pads becomes,

$$V(W) \simeq \frac{i_0 R_s L_T}{Z}. \tag{3}$$

As the voltage ΔV drop is measured across both pads it can be written as (see Fig. 2a),

$$\Delta V = i_0 R_s \left[\left(\frac{d}{Z} + \frac{2L_T}{Z}\right)\right]. \tag{4}$$

In the rectangular contacts, the current flow at the contact edge can significantly affect the results of contact resistance measurement unless mesa structures are fabricated in order to eliminate the unwanted current flow patterns. In circular test patterns this complication

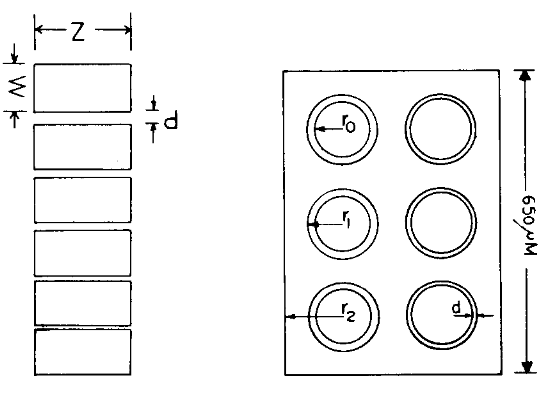

Fig. 1. Test patterns for ohmic contact characterization: (a) rectangular pattern, (b) circular pattern.

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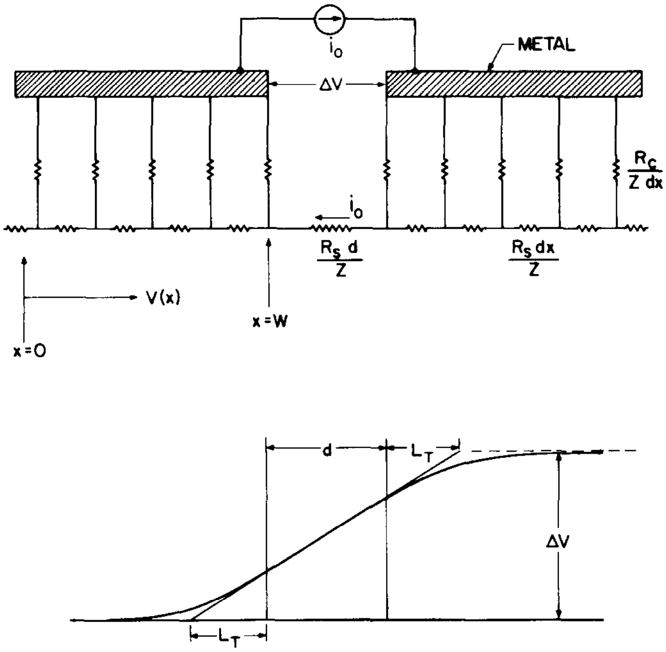

Fig. 2. Transmission line model for rectangular contacts and the significance of transferred length.

can be totally avoided without making mesa structures (see Fig. 1b). However, errors can occur due to finite radii of the contact patterns as may be seen from the following equation[2] for the voltage drop across the separation d:

$$\Delta V = \frac{i_0 R_s}{2\pi}\left[\ln\left(\frac{r_1}{r_0}\right) + \frac{L_T}{r_0}\frac{I_0(r_0/L_T)}{I_1(r_0/L_T)} + \frac{L_T K_0(R_1/L_T)}{r_1 K_1(r_1/L_T)}\right], \quad (5)$$

where I_0, I_1 and K_0 and K_1 are the modified Bessel Functions and r_0 and r_1 are the radii that define the separation d. When r_0 and r_1 are greater than L_T at least by a factor of 4, then both I_0/I_1 and K_0/K_1 approximate to unity[3]. Thus, eqn (5) becomes

$$\Delta V \simeq \frac{i_0 R_s}{2\pi}\left[\ln\left(\frac{r_1}{r_1 - d}\right) + L_T\left(\frac{1}{r_1} + \frac{1}{r_1 - d}\right)\right]. \quad (6)$$

Note that if $r_1 \gg d$ the above reduces to eqn (4) with $2\pi r_1 = z$.

The effect of a linear approximation, in a practical case where r_1 is not infinitely greater than d, is illustrated in Fig. 3. These data were obtained from Ni/Au–Ge ohmic contacts using circular test patterns. The outer radius of the test patterns was 75 μm with gap length values ranging from 4 to 25 μm. The method of least squares was used to obtain straight line plot of the voltage drop vs gap length data and a Texas Instrument SR52 programmable calculator was used for the numerical calculations, based on eqn (6), to obtain least square fit to the experimental data. The latter yielded R_s = 406 ohm/sq., L_T = 5.24 μm and $R_c = 1.11 \times 10^{-4}$ cm^2. The linear least square fit, taking the average radius to the center of the gap, yielded R_s = 444 ohm/sq., L_T = 355 μm and $R_c = 0.560 \times 10^{-4}$ ohm-cm^2. These results clearly indicate that the linear approximation can lead to an underestimation of the contact resistance value. In this example the underestimation is by a factor of two.

THE EFFECT OF NON-ZERO METAL RESISTANCE

In the course of an investigation of the aging process in simple Au–Ge ohmic contacts to n–GaAs, it was found that the sheet resistance of the metallic layer was

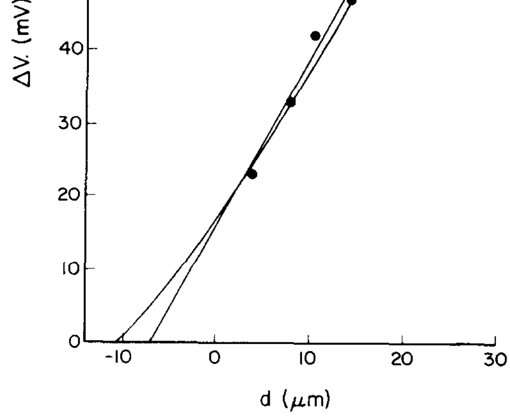

Fig. 3. Actual curved and straight line fits to experimental data obtained from circular contact resistance test patterns.

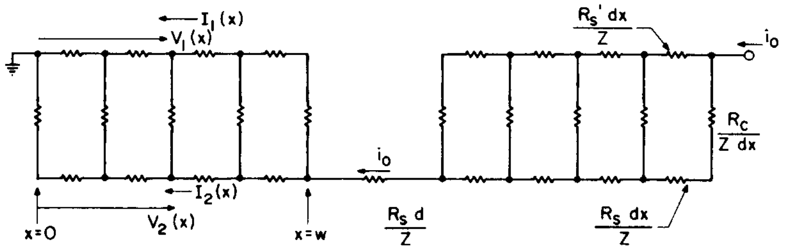

Fig. 4. A modified transmission line model with non-zero metal sheet resistance.

increasing with aging at an elevated temperature (350°C). Thus it was necessary to analyze the effect of the non-zero metal sheet resistance on the determination of the specific contact resistance. For this purpose the transmission line model of the contact, with zero metal sheet resistance, needs to be modified in the manner shown in Fig. 4. This double transmission line can be described in terms of the following differential equations:

$$R_s \frac{\partial^2 I_2(x)}{\partial x^2} - R_s I_2(x) + R_s' I_1(x) = 0$$

$$\frac{\partial I_1(x)}{\partial x} + \frac{\partial I_2(x)}{\partial x} = 0 \tag{7}$$

with the solution:

$$I_1(x) = C_1 \frac{R_s}{R_s'} - C_2 e^{x/a} - C_3 e^{-x/a}$$

and

$$I_2(x) = C_1 + C_2 e^{x/a} + C_3 e^{-x/a} \tag{8}$$

where

$a = \sqrt{(R_c/(R_s + R_s'))}$, $C_1 = i_0 R_s'/(R_s + R_s')$,

$$C_2 = \frac{R_s}{R_s'} C_1 e^{-W/a}$$

and

$$c_3 \simeq -c_1, \left(\text{assuming } \frac{w}{a} \gg 4\right).$$

The following simplifying boundary conditions have been used

$$I_2(o) = 0 \qquad I_1(o) = i_o$$

$$I_2(w) = i_0 \text{ and } I_1(w) = 0.$$

The potential drop across the single rectangular contact structure thus becomes,

$$V_2(w) = \frac{R_c}{Z} \frac{dI_2(x)}{dx}\bigg|_w + \frac{R_s'}{Z}\int_0^w I_1(x)\,dx. \tag{9}$$

Thus the potential drop $\Delta V'$ between two adjacent contacts can be written in a manner similar to that given in eqn (4), yielding,

$$\Delta V' = \frac{i_0 R_s}{Z}(d + 2L_T') \tag{10}$$

where L_T' is the effective transfer length given by,

$$L_T' = \frac{R_c/a + R_s'(w-a) + aR_s'^2/R_s}{(R_s + R_s')}. \tag{11}$$

Note that when $R_s' = 0$, L_T' becomes L_T as given in eqn (1). However, in the case when $R_s' \neq 0$, the specific contact resistance R_c' becomes,

$$R_c' = R_s L_T'^2. \tag{12}$$

Figure 5, depicts a plot of R_c' vs R_s' with typical values of R_c, w, and R_s for the simple Au–Ge contact. From this curve it can be seen that the effective contact resistance would double for a change in metal sheet resistance from 15 to 33 ohm/sq. and this was experimentally observed in simple Au–Ge contacts to n–GaAs.

CONCLUSION

It has been shown that circular contact patterns commonly used for the determination of contact resistance can introduce large error if a linear fit to the voltage drop vs gap length data is assumed. A simple but very good approximation to the exact Bessel function solution is

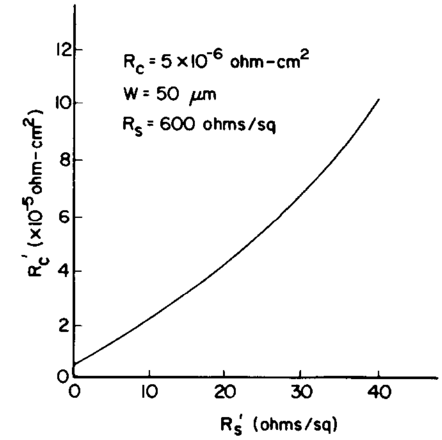

Fig. 5. Dependence of the effective specific contact resistance on the sheet resistance of the metal overlay.

obtained that provides the basis for an accurate determination of the specific contact resistance value. In situations where the metal overlay sheet resistance is finite, rather than zero, significant errors are introduced in the determination of the specific contact resistance. Using the analytical results presented the true contact resistance value can be calculated, however.

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