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OHMIC CONTACT CHARACTERIZATION WITH TRANSMISSION LINE MODEL
(A REVIEW)

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ABSTRACT: *The transmission line model for the ohmic contact characterization is described. Shortcomings of the method are pointed out, and modifications for the measurement technique are presented. The limitations of the technique are discussed. For large geometry semiconductor devices, the transmission line method may be used in the characterization of the ohmic contacts; however, care must be taken for small geometry devices where the contact resistance is small and easily obscured by the other effects.*

KEYWORDS: *Ohmic Contacts, Transmission Line Model, Semiconductor Device Characterization*

TRANSMİSYON HATTI MODELİ İLE OMİK KONTAK İNCELENMESİ
(DERLEME)

ÖZET: *Bu yazıda omik kontakların özelliklerinin araştırılmasında kullanılabilecek transmisyon hattı modeli açıklanmıştır. Modelin eksik yönleri ele alınarak gerekli düzeltmeler sunulmuş, geçerliliği tartışılmıştır. Büyük boyutlu yarıiletken düzenler için, transmisyon hattı yöntemi kullanılabilir; ancak, küçük boyutlu düzenlerde, kontak direnci diğer etkenler tarafından gölgelenebileceğinden, daha dikkatli olmak gerekir.*

ANAHTAR KELİMELER: *Omik Kontaklar, Transmisyon Hattı Modeli, Yarıiletken Düzen Ölçümleri*

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I. INTRODUCTION

No sockets are drilled on semiconductor substrates to insert miniature banana plugs in order to connect the device to the outside circuit; instead, some kind of metallization is used to form contacts by which the device is reached. The wires soldered or welded to these contacts serve as terminals of the device.

A metal-semiconductor contact is a device itself. Depending on the material properties and the metallization process, it can be rectifying or ohmic. The rectifying contact results from the depletion of majority carriers in the semiconductor in the vicinity of the metal. A contact of this kind conducts the current practically in one direction only. The ohmic contacts, on the other hand, result from the accumulation of majority carriers in the semiconductor at the metal-semiconductor interface. An ohmic contact supplies the majority carriers and conducts the current in two directions. A metal on a heavily doped semiconductor may also form an ohmic contact.

Unlike the rectifying contact, the ohmic contact has negligible effects on device performance for the "first order considerations." For the "textbook model" of any semiconductor device, the ohmic contact has no effects at all. This is true for "large" devices with "large" contact areas. For VLSI devices, as the contact size gets smaller and smaller, the contact effects become more and more important because the ohmic contact sustains some voltage and degrades the frequency response of the device, hence, alters the overall device performance.

The ohmic contact has a linear or quasi-linear I-V characteristic; therefore, a contact resistance, $R_C = V/I$, is associated with it. Also, the contact resistivity or specific contact resistance is defined by

$$\rho_C = \left(\frac{dJ}{dV}\right)^{-1}_{V=0} (\Omega.\mathrm{cm}^2) \tag{1}$$

which is independent of the contact area.

Any work to obtain better quality ohmic contacts requires accurate measurements of R_C and ρ_C. The simplest structure for contact resistance determination is given in Fig.1. It consists of a homogeneous piece of semiconductor with two identical contacts. The total resistance of the system

$$R_T = 2R_C + R_B \tag{2}$$

where the semiconductor resistance

$$R_B = \rho_B \frac{L}{A} \tag{3}$$

therefore, the contact resistance

$$R_C = \frac{1}{2}\left(R_T - \rho_B \frac{L}{A}\right) \tag{4}$$

and the specific contact resistance

$$\rho_C = R_C A \tag{5}$$

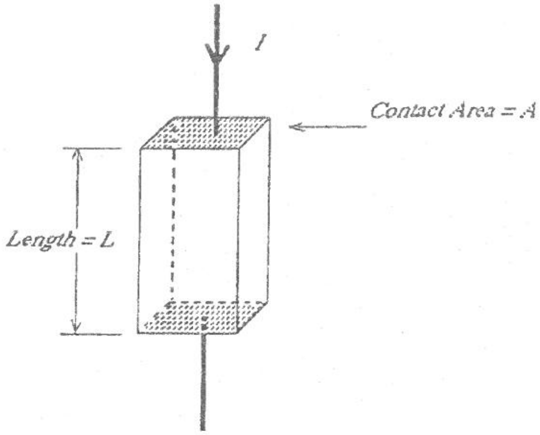

Fig.1. The two-terminal resistor structure.

This model is very unrealistic for planar contacts because the current density beneath such a contact is not uniform. The three-terminal resistor method -- also known as TLM, transmission line method, transfer length method, and Shockley technique -- takes the current crowding effect into consideration [1 - 5]. The transmission line method for the ohmic contact characterization is described and its limitations are pointed out in this paper.

II. THREE-TERMINAL RESISTOR METHOD

The three-terminal resistor method uses three identical planar contacts on a semiconductor bar which is usually a diffused p-tub on an n-substrate or vice versa as shown in Fig.2. Contacts are separated with distances of l_1, l_2. The total resistance between two neighboring contacts

$$R_{Ti} = R_S \frac{l_i}{W} + 2R_c$$

where $i = 1, 2$; W = width of the tub, and R_S = sheet resistance of the tub (Ω/sq).

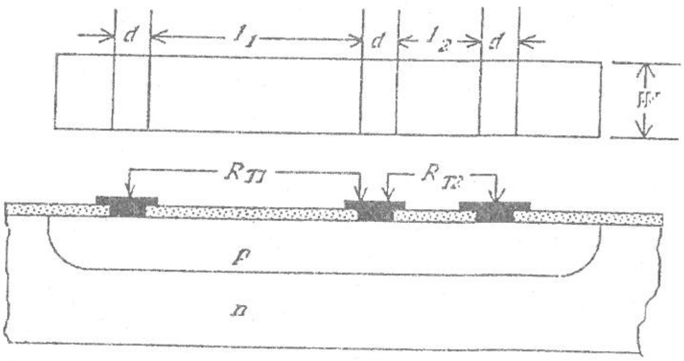

Fig.2. The three-terminal resistor structure.

Then the contact resistance

$$R_C = \frac{(R_{T2}l_1 - R_{T1}l_2)}{2(l_1 - l_2)} \tag{7}$$

As a result of the current crowding beneath the contact edge, for this resistor structure, $\rho_C \neq R_C A$.

The semiconductor region beneath the contact can be modeled as a transmission line as shown in Fig.3 [1]. From the unit cell of the model,

$$dG = \frac{W}{\rho_C} dx \tag{8}$$

$$dR = \frac{R_S}{W}\,dx \tag{9}$$

$$di = i(x+dx) - i(x) = v(x)\,dG \tag{10}$$

$$dv = v(x+dx) - v(x) = i(x)\,dR \tag{11}$$

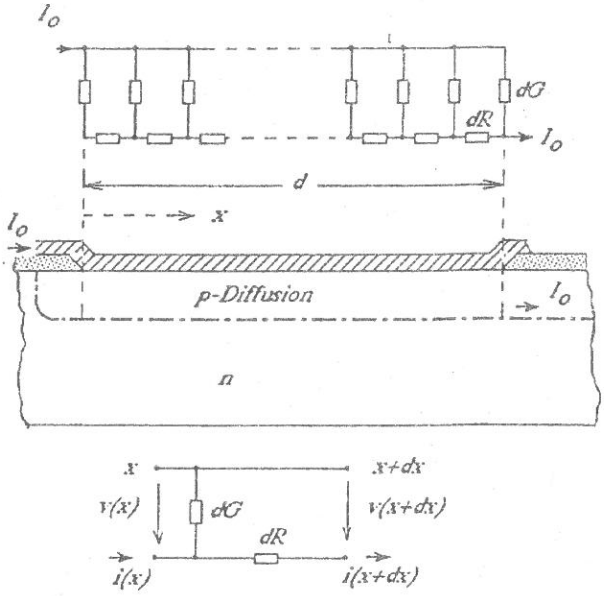

Fig.3. Transmission line model for the planar contact [1].

Substituting (8) and (9) into (10) and (11),

$$\frac{di}{dx} = \frac{W}{\rho_C}\,v \tag{12}$$

$$\frac{dv}{dx} = \frac{R_S}{W}\,i \tag{13}$$

are obtained. Now taking the derivative of (12),

$$\frac{d^2i}{dx^2} = \frac{W}{\rho_c}\frac{dv}{dx} \tag{14}$$

dividing (14) by $\frac{W}{\rho_c}$,

$$\frac{dv}{dx} = \frac{d^2i}{dx^2}\frac{\rho_c}{W} \tag{15}$$

Now from (13) and (15),

$$\frac{d^2i}{dx^2} - \frac{i}{L_T^2} = 0 \tag{16}$$

where

$$L_T^2 = \frac{\rho_c}{R_s} \tag{17}$$

L_T is called the transfer length, i.e. the effective dimension of the contact in the current flow direction. The solution for this homogeneous differential equation with the boundary conditions of $i(0) = 0$, $i(d) = I_o$,

$$i(x) = \frac{I_o sinh\left(\frac{x}{L_T}\right)}{sinh\left(\frac{d}{L_T}\right)} \tag{18}$$

and from (12),

$$v(x) = \frac{\rho_c}{WL_T}\frac{I_o cosh\left(\frac{x}{L_T}\right)}{sinh\left(\frac{d}{L_T}\right)} \tag{19}$$

Thus, the contact resistance,

$$R_c = \frac{v(d)}{i(d)} = \frac{\rho_c}{WL_T} coth\left(\frac{d}{L_T}\right) \tag{20}$$

or

$$R_c = \frac{L_T}{W} R_s \, coth\left(\frac{d}{L_T}\right) \tag{20a}$$

Now the total resistance expression (6) can be rewritten as

$$R_{Ti} = R_S \frac{l_i}{W} + 2 \frac{L_T}{W} R_S \, coth\left(\frac{d}{L_T}\right) \tag{21}$$

This expression holds for $W >> d$ and L_T, and negligible metal resistance.

Two limiting cases can be considered here. For $d \geq 1.5\, L_T$, $coth(d/L_T) \leq 1.1$; therefore, the contact resistance

$$R_C \approx \frac{L_T}{W} R_S \tag{22}$$

It is independent of the contact dimension d; because only a fraction of the contact participates in current transfer from metal to semiconductor. For $d \leq 0.5\, L_T$, $coth(d/L_T) \geq 2.1$; therefore,

$$R_C \approx \frac{\rho_C}{Wd} \tag{23}$$

For this case, the entire contact is used during current transfer.

The contact resistance and the transfer length can be determined graphically from the resistance measurements [5 - 6]. Assuming that $d \geq 1.5\, L_T$,

$$R_{Ti} \approx R_S \frac{l_i}{W} + 2\, R_S \frac{L_T}{W} \tag{24}$$

R_T is plotted as a function of l, as shown in Fig.4. For $l = 0$, $R_T = R' = 2\, R_S\, (L_T/W)$, and for $R_T = 0$, $l = l' = -2\, L_T$.

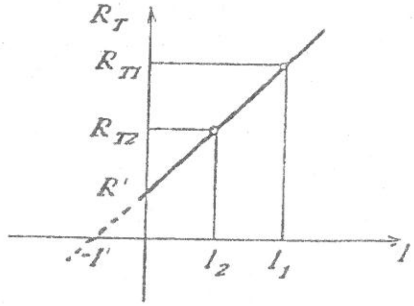

Fig.4. Total resistance as a function of l.

III. MODIFICATIONS TO TLM

The disagreement between the measured data and TLM has led a modification to the transmission line model [7 - 9]. The alloying/sintering process changes the sheet resistance of the region beneath the contact from R_s to R_{sm}. With this modification (24) becomes

$$R_{Ti} \approx R_s \frac{l_i}{W} + 2\, R_{sm} \frac{L_T}{W} \tag{25}$$

L_T, R' and l' are now different from before:

$L_T = \sqrt{\rho_c/R_{sm}}$

$R' = 2R_{sm}\,(L_T/W)$

$l' = -\,2(R_{sm}/R_s)L_T.$

The specific contact resistance

$$\rho_c = R_{sm}L_T^2 \tag{26}$$

can be found by an additional measurement -- the contact end resistance, R_E [5].

R_E is measured as shown in Fig.5, by passing a constant current between two contacts and measuring the potential between one of these contacts and an opposite outside contact pad. The ratio V/I yields R_E.

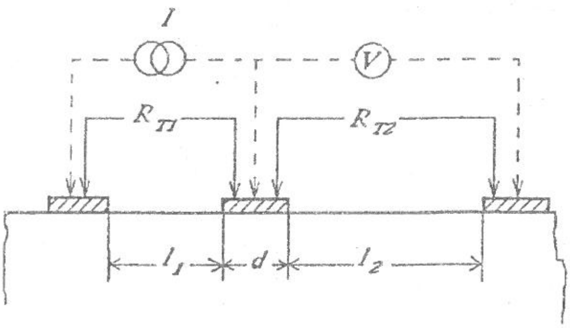

Fig.5. Experimental setup for obtaining total resistance and contact end resistance values [5].

From (19), [$v = v(0)$ and $i = I_o$]

$$R_E = \frac{\rho_C}{L_T W} \frac{1}{sinh\left(\frac{d}{L_T}\right)} \tag{27}$$

from (20) and (27),

$$\frac{R_C}{R_E} = cosh\left(\frac{d}{L_T}\right) \tag{28}$$

thus L_T is obtained readily. ρ_C is determined from (27).

The contact end resistance R_E can also be determined with a simple resistance measurement extension [5]. An equivalent circuit for the contact is given in Fig.6a. For the Fig.6b, R_1, R_2 and R_3, measure

$$R_1 = R_{CO} + R_A + R_C' \tag{29}$$

$$R_2 = R_C + R_B + R_{C2} \tag{30}$$

$$R_3 = R_{CO} + R_A + R_C' - 2R_E + R_c + R_B + R_{C2} \tag{31}$$

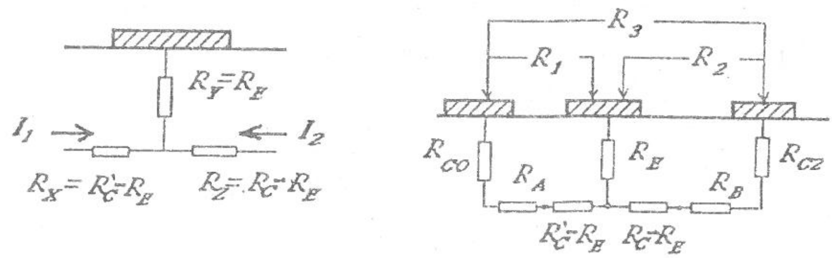

Fig.6. a) Equivalent circuit under the contact. b) Extra resistance measurement to derive contact end resistance [5].

Then,

$$R_E = (R_1 + R_2 - R_3)/2 \tag{32}$$

where R_C' and R_C are contact resistances of contact 1 which are measured when $I_2 = 0$ and $I_1 = 0$, respectively. R_A and R_B represent the semiconductor resistances between the contacts, while R_{CO} and R_{C2} are contact resistances.

This technique is suitable for many contact configurations; however, there exist situations in which more refinements are required. If the contact bar is very thin or resistive so that the sheet resistance of the contact material is not negligible compared to the sheet resistance of the underlying layer, an appreciable voltage drop occurs within the contact bar. This is commonly the case for silicide contacts. A model for such a contact is discussed in [9]. For a test pattern given in Fig.7, when a current I_o passes through the pads A and C, the vol age V_{AB} develops across the contacts A and B:

$$V_{AB} = 2\,n\,I_o \left\{ \frac{R_S}{R_s + R_{sm}} \left[R_{sm}\frac{Z}{W} + R_s\frac{a}{W}\tanh\left(\frac{Z}{a}\right) \right] + R_s''\frac{Z''}{W} \right\} \tag{33}$$

where

R_s = Semiconductor sheet resistance beneath the contact

R_{sm} = Metal sheet resistance

$R_s'' = \frac{W}{D}\frac{V_{BC}}{I_o}$ = Semiconductor sheet resistance

$n-1$ = Number of contact bars between A and B

W = Contact bar length

$2Z$ = Contact bar width

$2Z''$ = Distance between two contact bars

D = Distance between B and C

a = Generalized current transfer length, which is

$$a = \sqrt{\frac{\rho_C}{R_s + R_{sm}}} \tag{34}$$

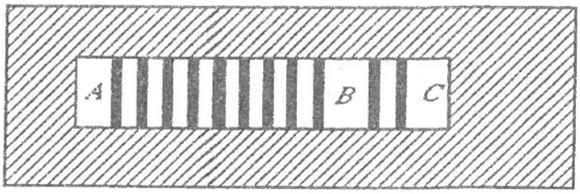

Fig.7. Test pattern for contact resistivity measurement. Dark areas represent bare semiconductor surfaces; cross-hatched area represents a region etched below the p-n junction for isolation [9].

Here, while I_o, n, W, Z, Z'' and D are set experimentally, V_{AB}, V_{BC}, R_s and R_{sm} are measured. The generalized transfer length, a, is solved from (33). From (34), the specific contact resistance is determined as

$$\rho_C = a^2\,(R_s + R_{sm}) \tag{35}$$

Pimbley [10] modified the transmission line model to include two dimensional currents. In the new model, possible currents perpendicular to the contact interface is allowed to flow. Reeves and Harrison [11] further extended the model into a three-layer structure (TLTLM) which is applicable to alloyed planar contacts as well as other contacts. They introduced a current division factor f along with the contact resistance and contact end resistance. Recently Sawdai *et al.* [12] proposed an improved technique to measure the contact transfer length which included. This technique employs isolated thin metal stripes between the contact pads on an isolated mesa stricture. These stripes are have the same width as the contacts, yet they have different lengths of the order of the transfer length.

IV. LIMITATIONS TO TLM

The TLM has limitations. One of the limitations is that R_C is calculated from the difference of two large numbers, namely $R_{T2}l_1$ and $R_{T1}l_2$ in (7). For small R_C values, it can not be determined accurately. Also errors are involved in measuring the resistor lengths l_1, and l_2 which may lead to negative R_C values [7]. Another source of error is the assumption that all three contacts have identical contact resistances. Practically R_C may differ as large as 200% [7]. This questions the practical validity of (7). When the contact length is different from the semiconductor tub width, the lateral current spreading can introduce large errors. Concentric circular patterns can be used to eliminate the current spreading, yet there are difficulties with the formation of the test patterns. Besides, most contacts in integrated circuits are not concentric but rectangular.

For large geometry devices, TLM can be an adequate technique in the characterization of the ohmic contacts; however, care must be taken for small geometry devices where R_C is small and easily obscured by the other effects. As a numerical example, if $\rho_C = 10^{-6}$ $\Omega.cm^2$ and $R_S = 60$ Ω/sq, then $L_T = 1.3$ µm, $Z'' = 50$ µm. The effect of the contact relative to the semiconductor sheet is $2L_T/Z'' = 5\%$. Furthermore, for meaningful results, Z'' must be measured with a precision of $\pm$ 0.5 µm or better. It is clear that TLM begins to lose credibility as the ρ_C falls below 10^{-6} $\Omega.cm^2$. Smaller contact resistivities as low as 10^{-8} $\Omega.cm^2$ can be measured with a four-terminal Kelvin resistor test structure [9], which is not much different from the measurement of the contact end resistance. There is also a six-terminal contact resistance method which allows the measurement of the contact resistance, the specific contact resistance, the end resistance, the front resistance, and the sheet resistance under the contact [13]. It requires special diffusion, contact and metal patterns.

V. CONCLUSION

The TLM remains to be a simple and practical technique in the characterization of the ohmic contacts; however, care must be taken for small geometry devices. It becomes less reliable as the ρ_C falls below 10^{-6} $\Omega.cm^2$. The four-terminal or six-terminal test structures should be used for the measurements of smaller contact resistivities.

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