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# SPECIFIC CONTACT RESISTANCE USING A CIRCULAR TRANSMISSION LINE MODEL

G. K. Reeves
Telecom Australia Research Laboratories, Clayton, Victoria, Australia

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**Abstract**—The measurement of the specific contact resistance of ohmic contacts to semiconductors can be made in a number of ways. One of the methods uses a transmission line model of an ohmic contact on a semiconductor and this paper describes the application of the transmission line model to a contact test pattern of circular symmetry. By using a circular test pattern, the mesa etch step necessary for the standard rectangular test pattern may be omitted, thus simplifying test pattern fabrication.

## 1. INTRODUCTION

The improvements in GaAs device performance in recent years have resulted in part from improved ohmic contact technology[1, 2]. In order to compare the "quality" of ohmic contacts, the parameter $\rho_c$—the specific contact resistance—is generally determined and quoted. The measurement of $\rho_c$ for ohmic contacts to GaAs has been detailed by a number of people who used the transmission line model[3, 4]. This technique requires the deposition of three or more contacts with in-line geometry together with a mesa etch to isolate the contact pattern. With this model, the value of $\rho_c$ for contacts on epitaxial layers on semi-insulating substrates and ion-implanted layers in semi-insulating GaAs can be found.

This paper describes a transmission line contact pattern of circular symmetry which eliminates the necessity for the mesa isolation of the contact pattern, thus simplifying test pattern fabrication.

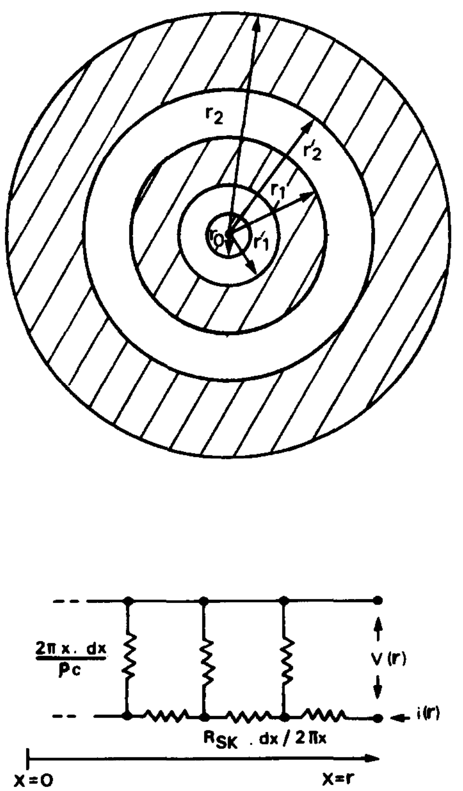


Fig. 1. Circular contact pattern and transmission line model parameters for circular contact.

## 2. THE MODEL

The test pattern for the determination of $\rho_c$ is shown in Fig. 1 and consists of a central dot contact and two concentric ring contacts. The usual resistances and conductances which describe the transmission line model for a rectangular contact have to be modified to account for the circular contact geometry. Following Kellner's[4] work, the sheet resistance of the GaAs beneath the contacts is written as $R_{SK}$ to distinguish it from the normal sheet resistance $R_{SH}$. As shown in Fig. 1, the series resistance element under the contact becomes $(R_{SK}\cdot dx/2\pi x)$ and the conductance element is $2\pi x\cdot dx/\rho_c)$ where $x$ is the radius of a contact element of width d$x$. Thus the basic transmission line equations become

$$\frac{dV}{dx}=\frac{i(x)\cdot R_{SK}}{2\pi x} \text{ and } \frac{di}{dx}=\frac{V(x)\cdot 2\pi x}{\rho_c} \qquad (1)$$

where $i(x)$ and $V(x)$ represent respectively, the current flowing beneath the contact at $x$ and the voltage drop across the contact interface at $x$.

Eliminating $i(x)$ from the eqns in (1) gives the following differential equation for voltage,

$$\frac{d^2V}{dx^2}+\frac{1}{x}\frac{dV}{dx}-\alpha^2V=0 \qquad (2)$$

where

$$\alpha^2=R_{SK}/\rho_c.$$

The solution to this differential equation is (see for example Chapter 6 of Ref. [5]),

$$V(x)=aI_0(\alpha x)+bK_0(\alpha x)$$

where, $I_0$ and $K_0$ are zero order modified Bessel functions of the first and second kind respectively.

Considering first the outer ring contact whose inner and outer radii are $r_2'$ and $r_2$ respectively, then with the following boundary conditions at $x = r_2'$, $V(x) = V(r_2')$ and $i(x) = i(r_2')$, the equation for $V(x)$ is calculated as

$$V(x) = (\alpha r_2')\cdot[V(r_2')\cdot A(r_2', x) - i(r_2')\cdot Z_2'\cdot D(r_2', x)] \quad (3)$$

where $Z_2' = R_{SK}/2\pi\alpha r_2'$ and the functions $A(r_2', x)$, etc. are defined in the appendix.

Likewise, the current distribution for the outer contact is found to be,

$$i(x) = (\alpha x)\cdot\left[i(r_2')\cdot B(r_2', x) + \frac{V(r_2')}{Z_2'}\cdot C(r_2', x)\right]. \quad (4)$$

The contact resistance $R_{c2}$ for the outer contact is defined as $[V(r_2')/i(r_2')]$ and since $i(r_2) = 0$, then using eqn (4),

$$R_{c2} = Z_2'\cdot\frac{B(r_2', r_2)}{C(r_2, r_2')}. \quad (5)$$

Considering next the innermost dot contact of radius $r_0$, the corresponding equations for $V(x)$ and $i(x)$ may be derived and hence the contact resistance for the inner dot contact $R_{c0}$ is found to be

$$R_{c0} = \frac{V(r_0)}{i(r_0)} = Z_0\cdot E(r_0) \quad (6)$$

where

$$Z_0 = R_{SK}/2\pi\alpha r_0.$$

Finally, for the centre ring contact, the voltage and current distributions beneath the contact will depend on whether the voltage is applied between the centre contact and the inner dot or between the centre contact and outer ring contact. Thus in the latter case when current flows between the centre and outer ring contact, the contact resistance of the centre ring (whose inner and outer radii are $r_1'$ and $r_1$ respectively) is $R_{c1}$ where

$$R_{c_1} = \frac{V(r_1)}{i(r_1)} = Z_1\cdot\frac{B(r_1, r_1')}{C(r_1, r_1')} \quad (7)$$

and

$$Z_1 = R_{SK}/2\pi\alpha r_1.$$

When the current flow is between the centre ring and the inner dot contact, the contact resistance is $R_{c_1}'$ where

$$R_{c_1}' = \frac{Z_1'\cdot B(r_1', r_1)}{C(r_1, r_1')} \quad (8)$$

and

$$Z_1' = R_{SK}/2\pi\alpha r_1'.$$

Figure (2) shows a cross section of the contact pattern with the bulk semiconductor resistance between the inner two contacts being $R_A$ and between the outer two contacts being $R_B$. Thus the resistance measured between the inner two contacts is

$$R_1 = R_A + (R_{c0} + R_{c_1}') \quad (9)$$

and between the outer two contacts, $R_2$

$$R_2 = R_B + (R_{c_1} + R_{c2}). \quad (10)$$

Since $R_A = \frac{R_{SH}}{2\pi}\log_e\left(\frac{r_1'}{r_0}\right)$ and $R_B = \frac{R_{SH}}{2\pi}\log_e\left(\frac{r_2'}{r_1}\right)$,

then $R_{SH}$ may be eliminated from eqns (9) and (10) giving

$$\log_e\left(\frac{r_2'}{r_1}\right)\cdot R_1 - \log_e\left(\frac{r_1'}{r_0}\right)\cdot R_2 = \log_e\left(\frac{r_2'}{r_1}\right)\cdot[R_{c0} + R_{c_1}'] - \log_e\left(\frac{r_1'}{r_0}\right)\cdot[R_{c_1} + R_{c2}]. \quad (11)$$

Equation (11) contains two unknowns—$R_{SK}$ and $\alpha$ and by measuring the contact end resistance $R_E$ of the centre contact, $R_{SK}$ can be eliminated. The contact end resistance is defined as the ratio of the contact output voltage to the contact input current when the contact output current is zero.

Thus,

$$R_E = \left.\frac{V(r_1')}{i(r_1)}\right|_{i(r')=0} \quad \text{or} \quad \left.\frac{V(r_1)}{i(r_1')}\right|_{i(r_1)=0}$$

depending on whether the current is between the outer two or inner two contacts. Either way the same expression for $R_E$ is obtained, namely

$$R_E = \frac{R_{SK}}{2\pi}\cdot\left\{A(r_1, r_1')\cdot\frac{B(r_1, r_1')}{C(r_1, r_1')} + D(r_1, r_1')\right\}. \quad (12)$$

On eliminating $R_{SK}/2\pi$ from eqns (11) and (12), then

$$\left\{\log_e\left(\frac{r_2'}{r_1}\right)\cdot R_1 - \log_e\left(\frac{r_1'}{r_0}\right)\cdot R_2\right\}/R_E = \left\{\log_e\left(\frac{r_2'}{r_1}\right)\cdot\left[\frac{E(r_0)}{\alpha r_0} + \frac{1}{\alpha r_1'}\cdot\frac{A(r_1, r_1')}{C(r_1, r_1')}\right]\right.$$

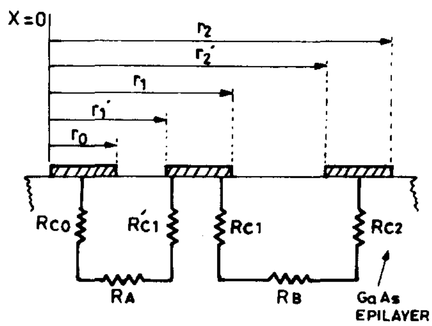


Fig. 2. Crossection of circular transmission line contact pattern.

$$-\log_e\left(\frac{r_1'}{r_1}\right)\cdot\left[\frac{1}{\alpha r_1}\cdot\frac{B(r_1,r_1')}{C(r_1,r_1')}+\frac{1}{\alpha r_2}\cdot\frac{A(r_2,r_2')}{C(r_2,r_2')}\right]\Bigg\}\Bigg/\left\{\frac{A(r_1,r_1')\cdot B(r_1,r_1')}{C(r_1,r_1')}+D(r_1,r_1')\right\} \quad (13)$$

The RHS of eqn (13) is computed and plotted as a function $\phi$ of $(\alpha r_0)$ for a given contact configuration. On determining the LHS of eqn (13) experimentally, the value of $(\alpha r_0)$ and hence $\alpha$ can be found. Figure 3 shows such a plot for a contact pattern with the following dimensions,

$$r_1' = 1.65\, r_0 \quad r_1 = 2.74\, r_0 \quad r_2' = 4.34\, r_0 \quad r_2 = 5.45\, r_0.$$

The specific contact resistance $\rho_c$, can be determined directly without first calculating $\alpha$. Since $\rho_c = [R_{SK}/(\alpha r_0)^2]\cdot(r_0)^2$ and from eqns (12) and (13), on eliminating $R_E$ –

$$\log_e\left(\frac{r_2'}{r_1}\right)\cdot R_1 - \log_e\left(\frac{r_1'}{r_0}\right)\cdot R_2 = \frac{R_{SK}}{2\pi}\cdot\phi\cdot\left\{\frac{A(r_1,r_1')\cdot B(r_1,r_1')}{C(r_1,r_1')}+D(r_1,r_1')\right\}$$

then

$$\rho_c = \left(\log_e\left(\frac{r_2'}{r_1}\right)\cdot R_1 - \log_e\left(\frac{r_1'}{r_0}\right)\cdot R_2\right)\cdot(r_0)^2\cdot\Delta \quad (14)$$

where

$$\Delta = \frac{2\pi}{(\alpha r_0)^2\cdot\phi}\Bigg/\left\{\frac{A(r_1,r_1')\cdot B(r_1,r_1')}{C(r_1,r_1')}+D(r_1,r_1')\right\}.$$

The function $\Delta$ is also shown in Fig. (3).

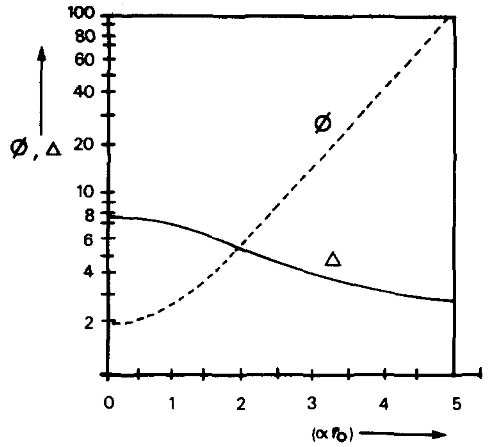


Fig. 3. The dependence of $\phi$ and $\Delta$ on the parameter $(\alpha r_0)$.

## 3. RESULTS

A number of transmission line contact patterns of both circular symmetry and in-line geometry were prepared on a single epitaxial GaAs ($N_d = 1.5\times10^{16}/\mathrm{cm}^3$) wafer with a semi-insulating substrate. The dimensions of the circular pattern are given in the previous section, so that Fig. (3) is applicable to the calculation of $\rho_c$. The value of $r_0$ is 46.5 $\mu$m. The contacts are conventional Au–Ge–Ni and were prepared in the following way. The GaAs wafers were cleaned in hot solvents prior to the application of Shipley AZ1350H photoresist. After exposure and development of the photoresist, the contact openings were briefly etched with a $H_2O_2$:NaOH solution to minimize the thickness of the oxide layer[6]. The contact metals with the ratio of Au:Ge:Ni being 83.6:9.9:6.5 were then evaporated. The thickness of the contact metals was 80 nm. A final Au evaporation brought the total contact thickness up to 200 nm. Following float-off of the unwanted metalization, the sample was alloyed in a continuous flow of $H_2$ gas for 90s at 440°C. The final sample preparation step was the mesa isolation of the in-line geometry transmission line pattern.

Measurements were made on 10 of each type of test pattern. On the circular patterns, the value of $\phi$ ranged from 4.1 to 16.0 with an average of 10.5. The corresponding values of $\Delta$ are obtained from Fig. 3 and $\rho_c$ is calculated from eqn (14) as $(4.1\text{–}8.7)\times10^{-5}\,\Omega\cdot\mathrm{cm}^2$, with an average value of $6.8\times10^{-5}\,\Omega\cdot\mathrm{cm}^2$. Similar measurements on the in-line geometry test pattern gave for $\rho_c$ a range of $(4.7\text{–}9.1)\times10^{-5}\,\Omega\cdot\mathrm{cm}^2$ with an average value of $6.6\times10^{-5}\,\Omega\cdot\mathrm{cm}^2$.

## 4. CONCLUSION

A technique for measuring specific contact resistance using a circular transmission line model has been described. The values obtained are in good agreement with those measured using the more conventional in-line geometry, but by eliminating the mesa etch, the production of a test pattern is simplified. Further, this technique could well be incorporated into the Corbino effect test pattern reported by Poth[7], thus extending the parameters which this test pattern can measure. In his analysis, Poth justified neglecting contact resistance in his samples. There may well arise occasions when contact resistance cannot be neglected and by incorporating a third circular ohmic contact, such a determination may be made.

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*Note added in proof.* Since this paper was prepared for publication, the work of Niskov and Kubetskii [*Sov. Phys.-Semicond.* **4**, 1553 (1971)] on ohmic contact resistance has come to the author's notice. They derived expressions similar to eqns (6)–(8), but for the case where $R_{SK} = R_{SH}$.

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## APPENDIX

To simplify the equations in the text, the following functions are defined;

$$A(r, x) = I_1(\alpha r)\cdot K_0(\alpha x) + I_0(\alpha x)\cdot K_1(\alpha r)$$

$$B(r, x) = I_1(\alpha x)\cdot K_0(\alpha r) + I_0(\alpha r)\cdot K_1(\alpha x)$$

$$C(r, x) = I_1(\alpha r)\cdot K_1(\alpha x) - I_1(\alpha x)\cdot K_1(\alpha r)$$

$$D(r, x) = I_0(\alpha x)\cdot K_0(\alpha r) - I_0(\alpha r)\cdot K_0(\alpha x)$$

$$E(r) = I_0(\alpha r)/I_1(\alpha r)$$

where $I$ and $K$ are modified Bessel functions of the first and second kind respectively.