Contact Resistance with Dissimilar Materials

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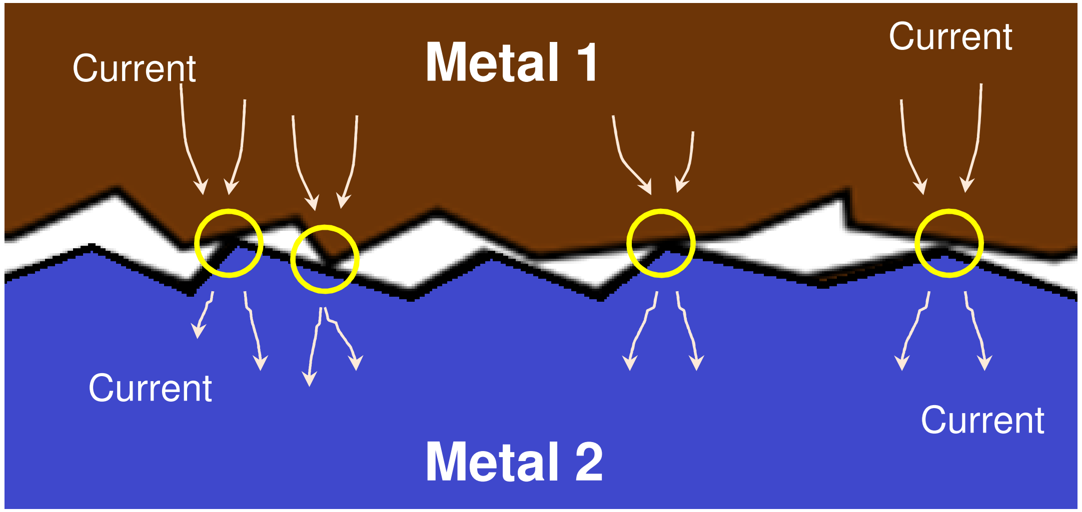
Introduction

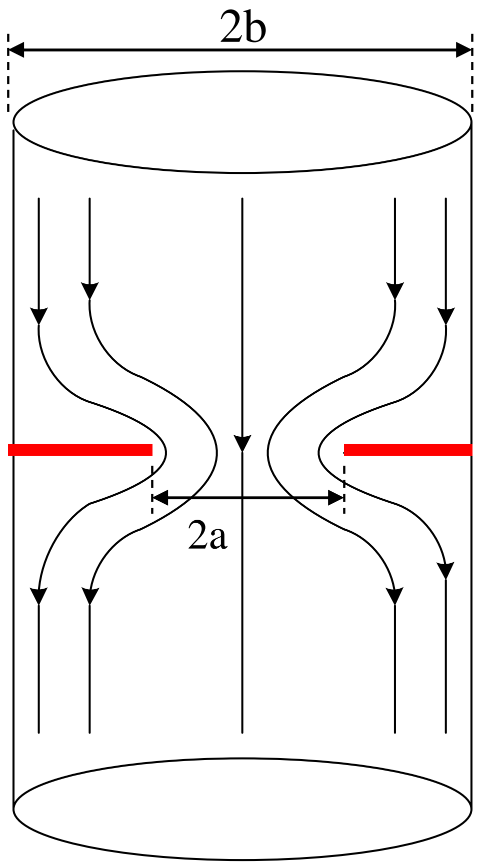
- Electrical contact is important to
  - Thin film devices and integrated circuits
  - Carbon nanotubes based cathodes and interconnects
  - Field emitters
  - Tribology
  - Wire-array Z pinches
  - Metal-insulator-vacuum junctions
  - High power microwave (HPM) sources
  - Faulty electrical contact caused the recent failure of the Large Hadron Collider (LHC), and threatens the International Thermonuclear Experimental Reactor (ITER)
- There is no prior theory of electrical contact with dissimilar materials



: True points of contact => High contact resistance

- Current flows only through the true points of contact
- Contact resistance is highly random, affected by surface roughness, pressure, hardness, residing oxides and contaminates, etc

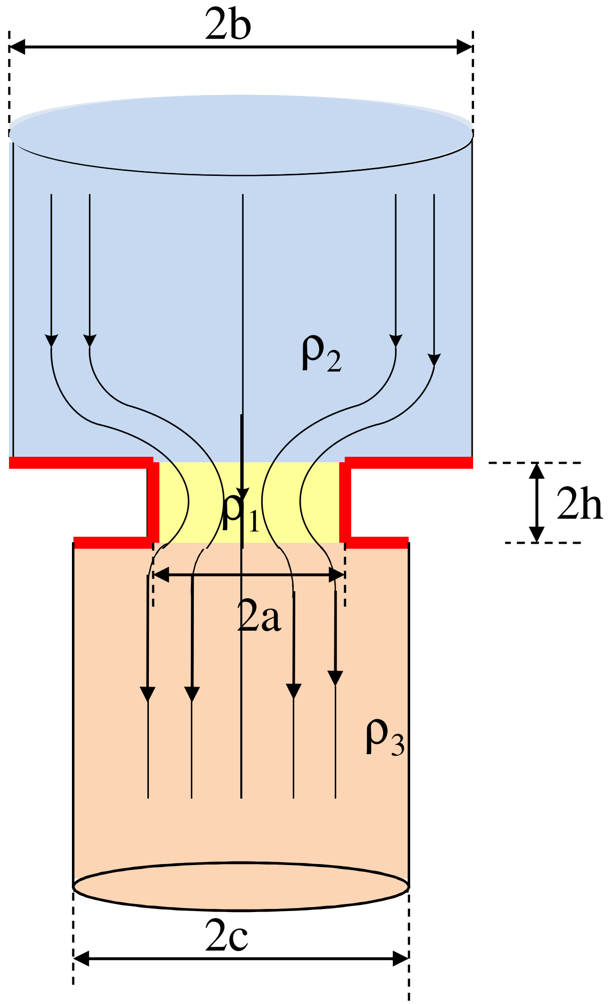
Holm's Model*: h = 0



h = 0

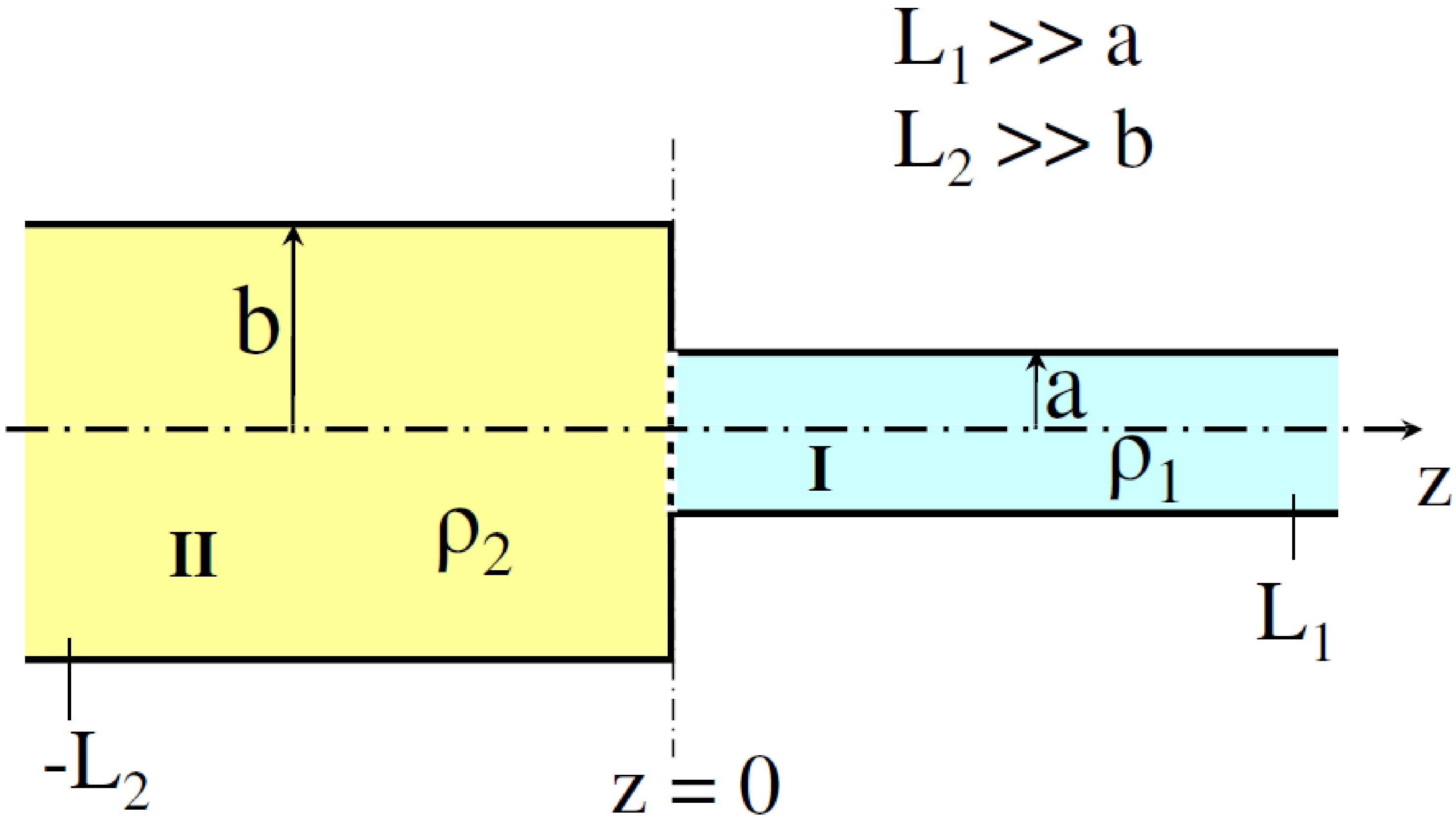
*Holm, *Electric Contacts: Theory and Application*, Springer-Verlag, NY (1967).

Our Model: h > 0



$h > 0$, $a \neq b \neq c$, $\rho_1 \neq \rho_2 \neq \rho_3$

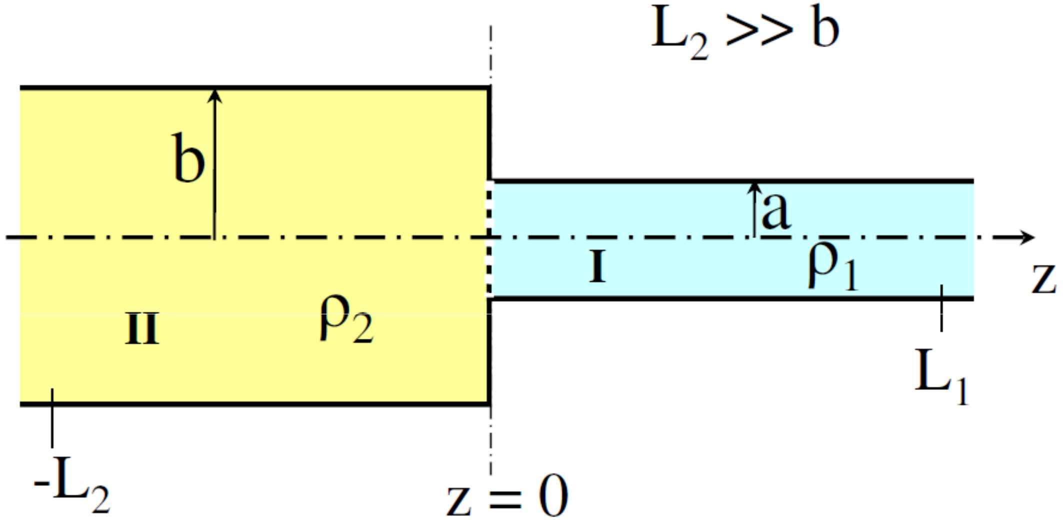
Interface Resistance with Dissimilar Materials



Cylindrical (Cartesian) Semi-infinite Channel

A. Cylindrical semi-infinite channel

$L_1 >> a$
$L_2 >> b$



Boundary conditions

$$\Phi_+ = \Phi_-, \qquad z = 0, r \in (0, a)$$

$$\frac{1}{\rho_1}\frac{\partial \Phi_+}{\partial z} = \frac{1}{\rho_2}\frac{\partial \Phi_-}{\partial z}, \quad z = 0, \; \mathrm{r} \in (0, a)$$

$$\frac{\partial \Phi_-}{\partial z} = 0, \qquad z = 0, \; \mathrm{r} \in (a, b)$$

Laplace's equation

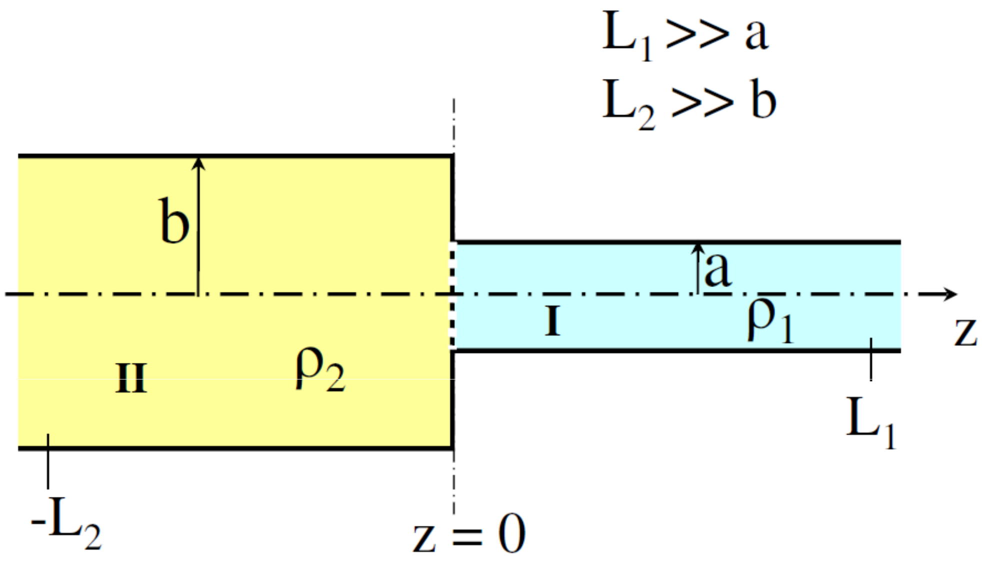
$$\Phi_+(r, z) = A_0 + \sum_{n=1}^{\infty} A_n J_0\left(\alpha_n r\right) e^{-\alpha_n z} - E_{+\infty} z, \qquad z > 0, r \in (0, a);$$

$$\Phi_-(r, z) = \sum_{n=1}^{\infty} B_n J_0\left(\beta_n r\right) e^{+\beta_n z} - E_{-\infty} z, \qquad z < 0, r \in (0, b).$$

A. Cylindrical semi-infinite channel

$$R = \frac{\rho_2 L_2}{\pi b^2} + \frac{\rho_2}{4a}\overline{R}_c\left(\frac{b}{a}, \frac{\rho_1}{\rho_2}\right) + \frac{\rho_1 L_1}{\pi a^2}$$

Bulk — Interface — Bulk

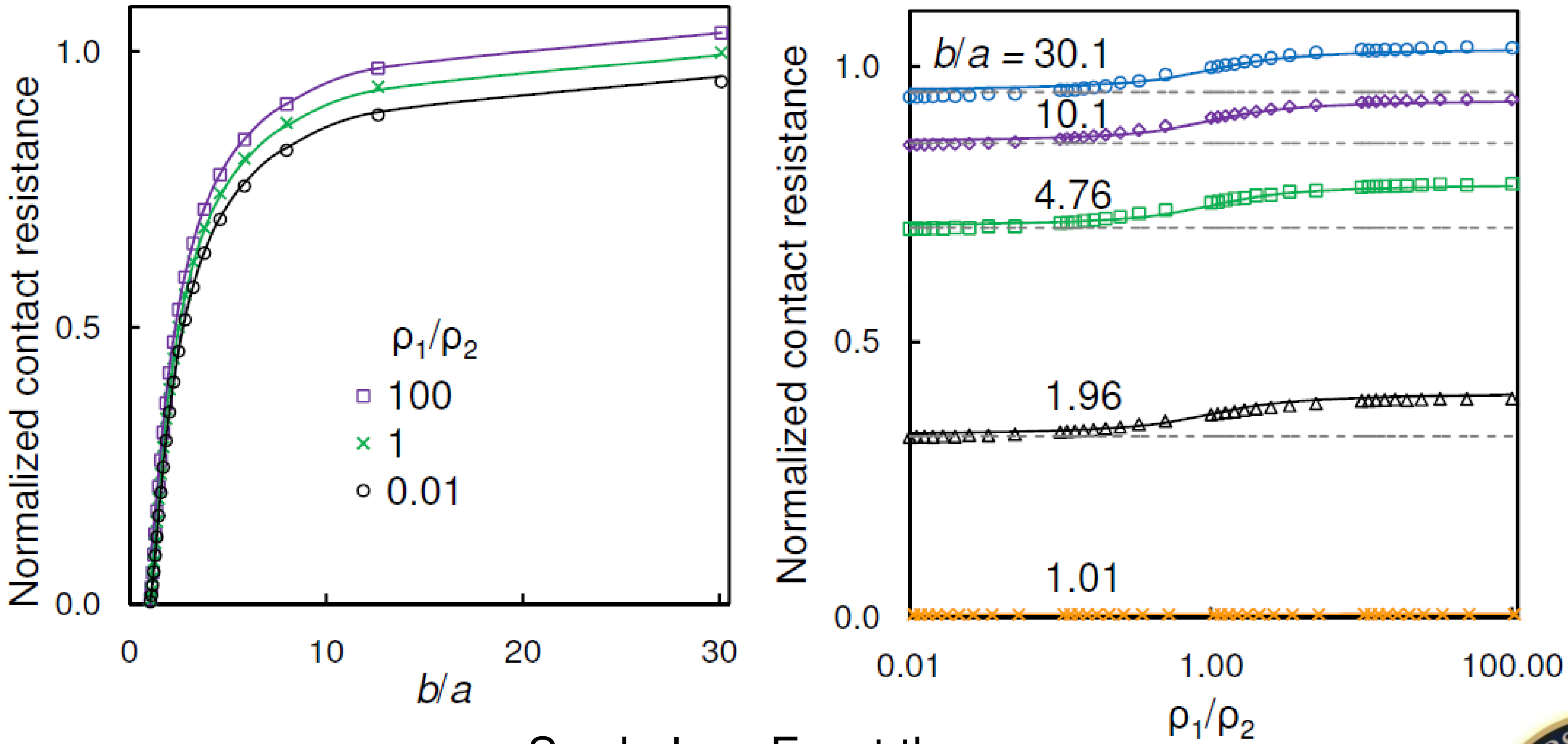


Contact Resistance:

$$R_c = \frac{\rho_2}{4a}\overline{R}_c$$

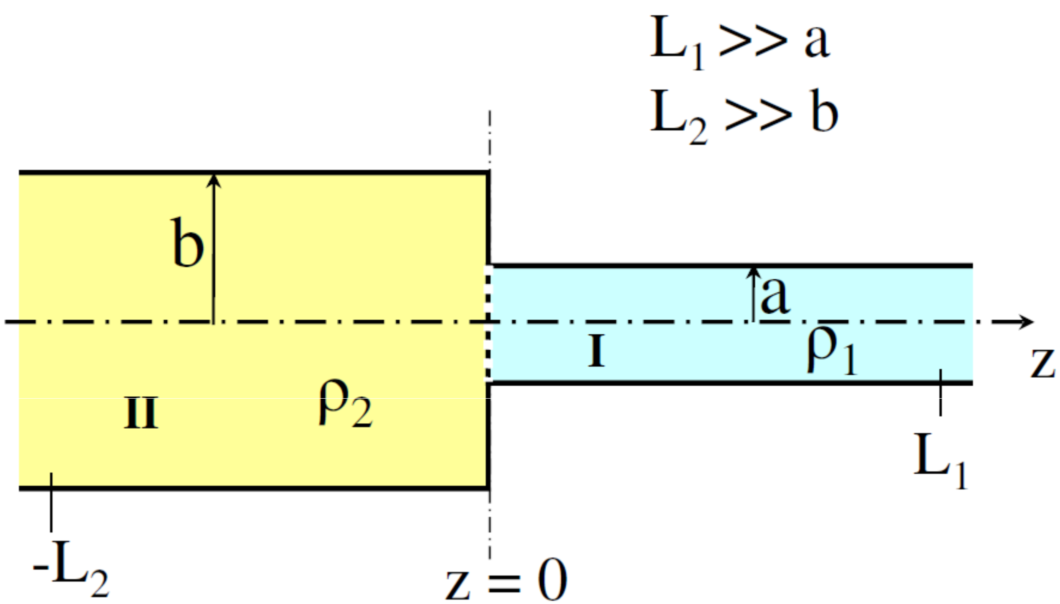
A. Cylindrical semi-infinite channel

Scaling law (Cylindrical):



Symbols: Exact theory
Solid lines: Scaling law
Dashed lines: $\bar{R}_{c0}(b/a)\big|_{Timsit}$

B. Cartesian semi-infinite channel



Boundary conditions

$$\Phi_+ = \Phi_-, \quad z = 0, y \in (0, a)$$

$$\frac{1}{\rho_1}\frac{\partial \Phi_+}{\partial z} = \frac{1}{\rho_2}\frac{\partial \Phi_-}{\partial z}, \quad z = 0, \quad \mathrm{y} \in (0, a)$$

$$\frac{\partial \Phi_-}{\partial z} = 0, \quad z = 0, \quad \mathrm{y} \in (a, b)$$

Laplace's equation

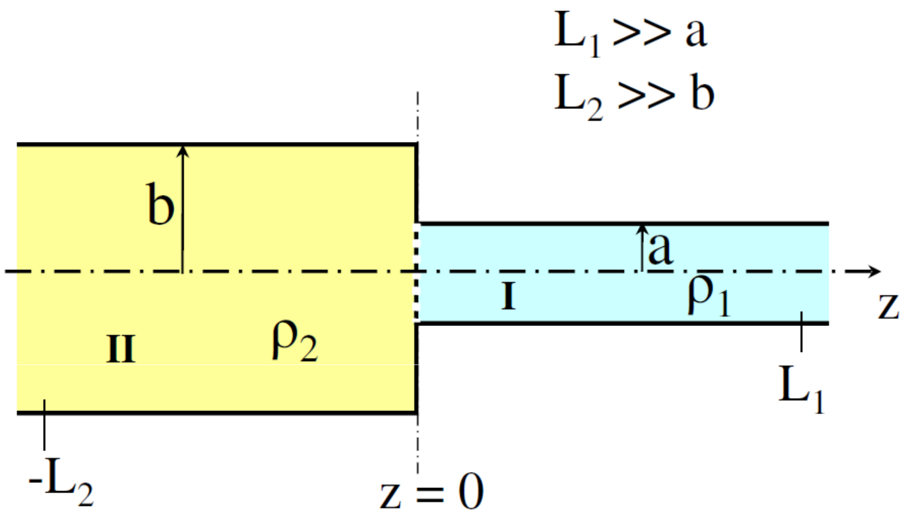
$$\Phi_+(y,z) = \sum_{n=0}^{\infty} A_n \cos\left(\frac{n\pi y}{a}\right) e^{-\frac{n\pi z}{a}} - E_{+\infty} z, \qquad z > 0, y \in (0, a),$$

$$\Phi_-(y,z) = \sum_{n=1}^{\infty} B_n \cos\left(\frac{n\pi y}{b}\right) e^{+\frac{n\pi z}{b}} - E_{-\infty} z, \qquad z < 0, y \in (0, b),$$

B. Cartesian semi-infinite channel

$$R = \frac{\rho_2 L_2}{2b \times W} + \frac{\rho_2}{4\pi W}\overline{R}_c\left(\frac{b}{a}, \frac{\rho_1}{\rho_2}\right) + \frac{\rho_1 L_1}{2a \times W}$$

Bulk — Interface — Bulk

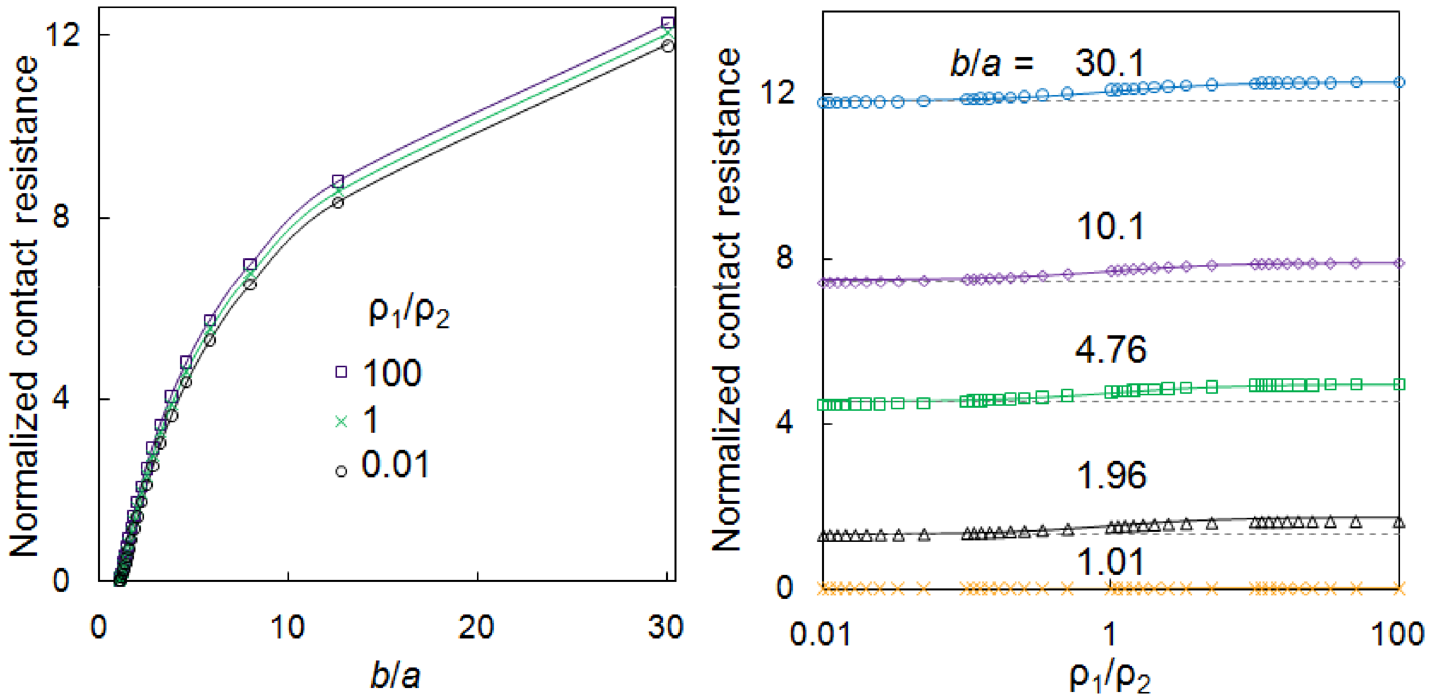


Contact Resistance:

$$R_c = \frac{\rho_2}{4\pi W}\overline{R}_c$$

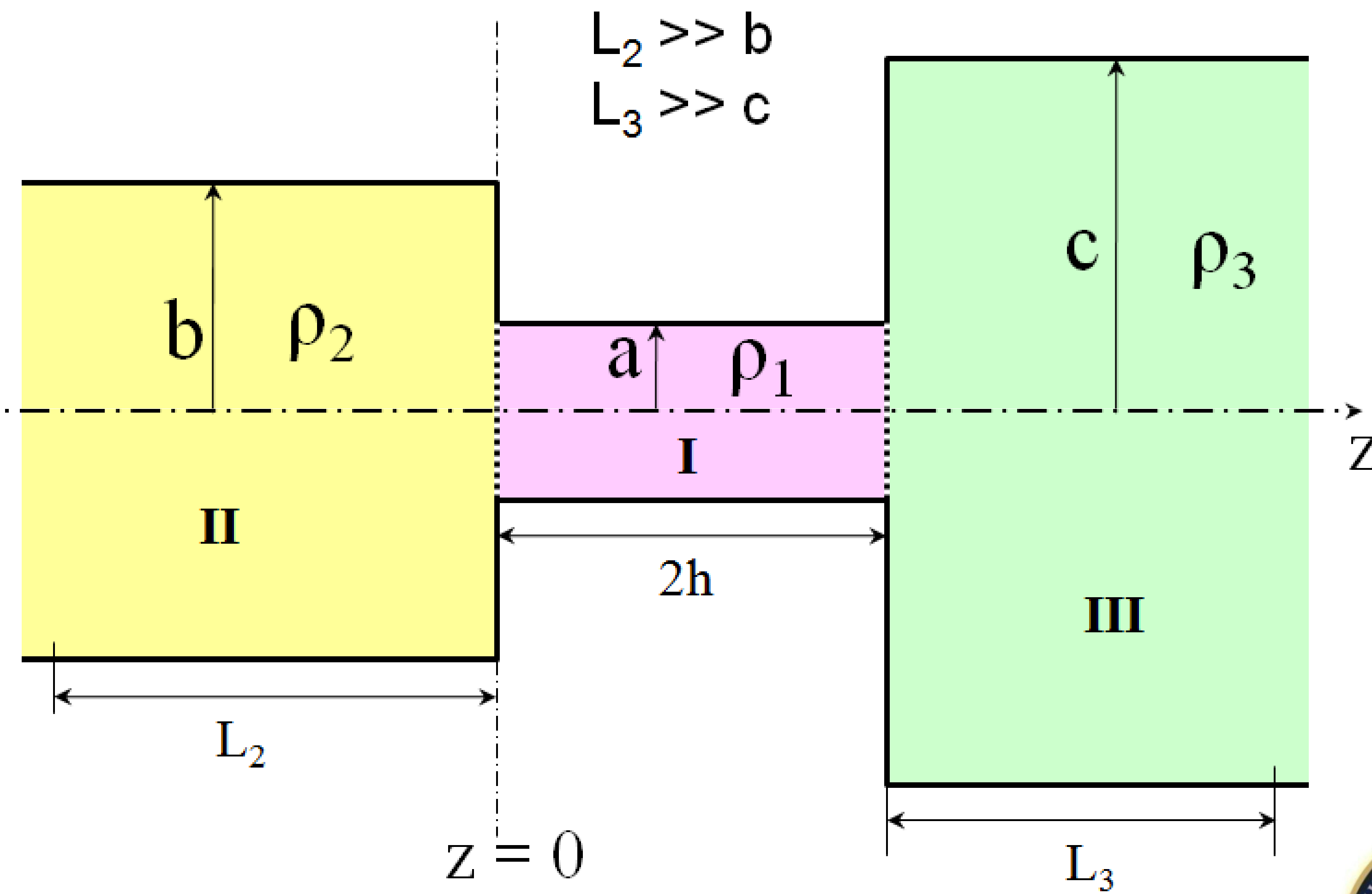
B. Cartesian semi-infinite channel

Scaling law (Cartesian):



Symbols: Exact theory
Solid lines: Scaling law
Dashed lines: $\bar{R}_{c0}(b/a)\big|_{LTZ}$

Total Resistance of Composite Channel



Cylindrical or Cartesian

Total Resistance of Composite Channel

Cylindrical:

$$R = \underbrace{\frac{\rho_2 L_2}{\pi b^2}}_{\text{Bulk}} + \underbrace{\frac{\rho_2}{4a}\overline{R}_c\left(\frac{b}{a}, \frac{\rho_1}{\rho_2}\right)}_{\text{Interface}} + \underbrace{\frac{\rho_1 \times 2h}{\pi a^2}}_{\text{Bulk}} + \underbrace{\frac{\rho_3}{4a}\overline{R}_c\left(\frac{c}{a}, \frac{\rho_1}{\rho_3}\right)}_{\text{Interface}} + \underbrace{\frac{\rho_3 L_3}{\pi c^2}}_{\text{Bulk}}$$

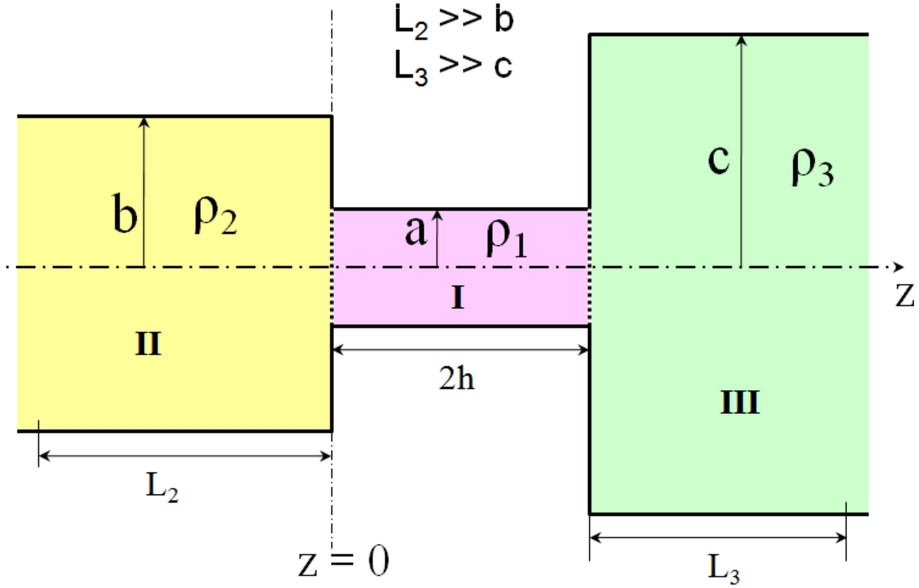
Cartesian:

$$R = \underbrace{\frac{\rho_2 L_2}{2b \times W}}_{\text{Bulk}} + \underbrace{\frac{\rho_2}{4\pi W}\overline{R}_c\left(\frac{b}{a}, \frac{\rho_1}{\rho_2}\right)}_{\text{Interface}} + \underbrace{\frac{\rho_1 \times 2h}{2a \times W}}_{\text{Bulk}} + \underbrace{\frac{\rho_3}{4\pi W}\overline{R}_c\left(\frac{c}{a}, \frac{\rho_1}{\rho_3}\right)}_{\text{Interface}} + \underbrace{\frac{\rho_3 L_3}{2c \times W}}_{\text{Bulk}}$$

Test of Scaling Laws

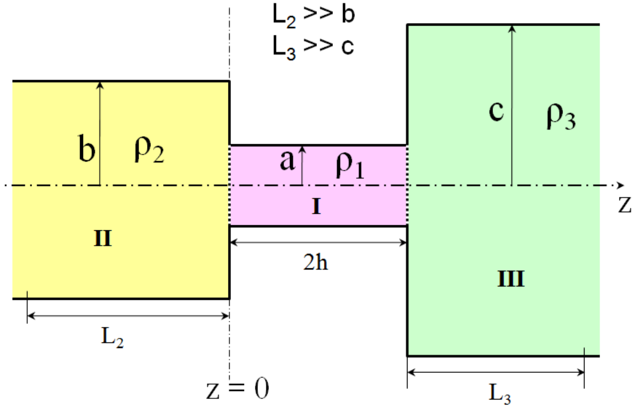
<u>Test A.</u> *h >> a*

- Electrostatic fringe field at one interface has an exponentially small influence on the other interface
- Both interface resistance the same as in the semi-infinite channel



Test B. $h \to 0$

- $h = 0$, $\rho_2 = \rho_3$ and $b = c$ ⟹ *a*-spot
    1. Cylindrical $\left.\overline{R}_{c0}(b/a)\right|_{Timsit}$
    2. Cartesian $\left.\overline{R}_{c0}(b/a)\right|_{LTZ}$

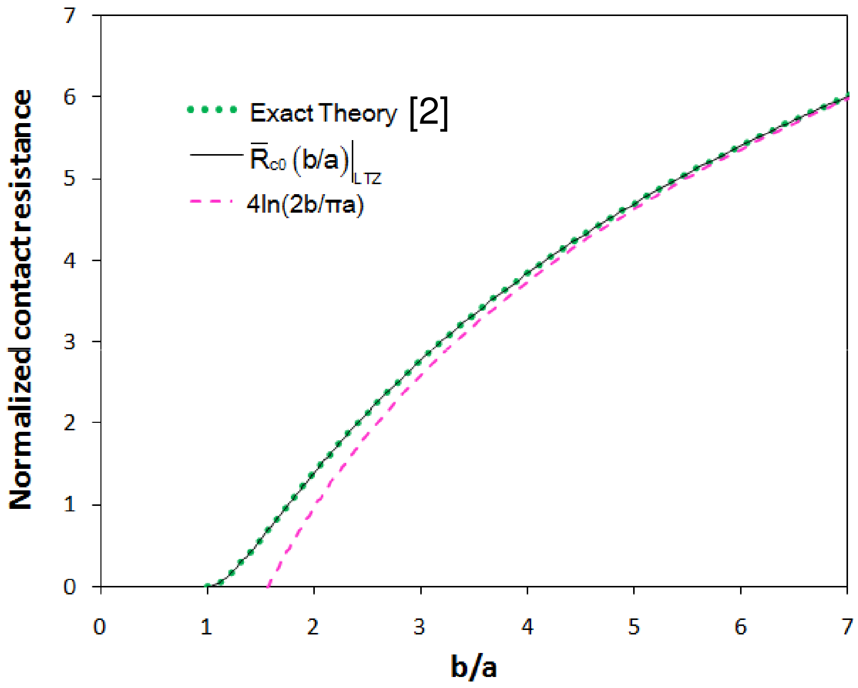


- $\rho_1 \to 0$, Region I is perfectly conducting, contact resistance at each interface equivalent to ½ of the symmetrical *a*-spot

- $b/a \to \infty$, $c/a \to \infty$, but $\rho_2 \neq \rho_3$, the cylindrical scaling laws differs by at most 8% from $(\rho_2 + \rho_3)/4a$

Test C. $\rho_1 = \rho_2 = \rho_3$

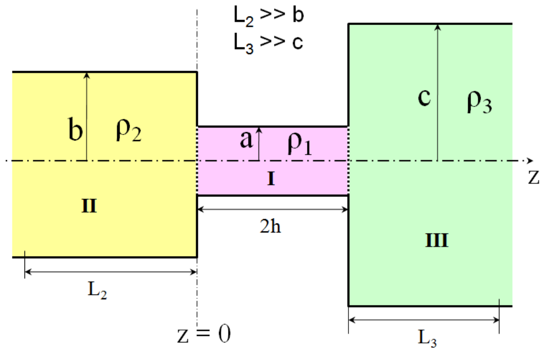
- All channels are made of the same material
- Analyzed in great detail in [2]
- Verified by experiment in [3]



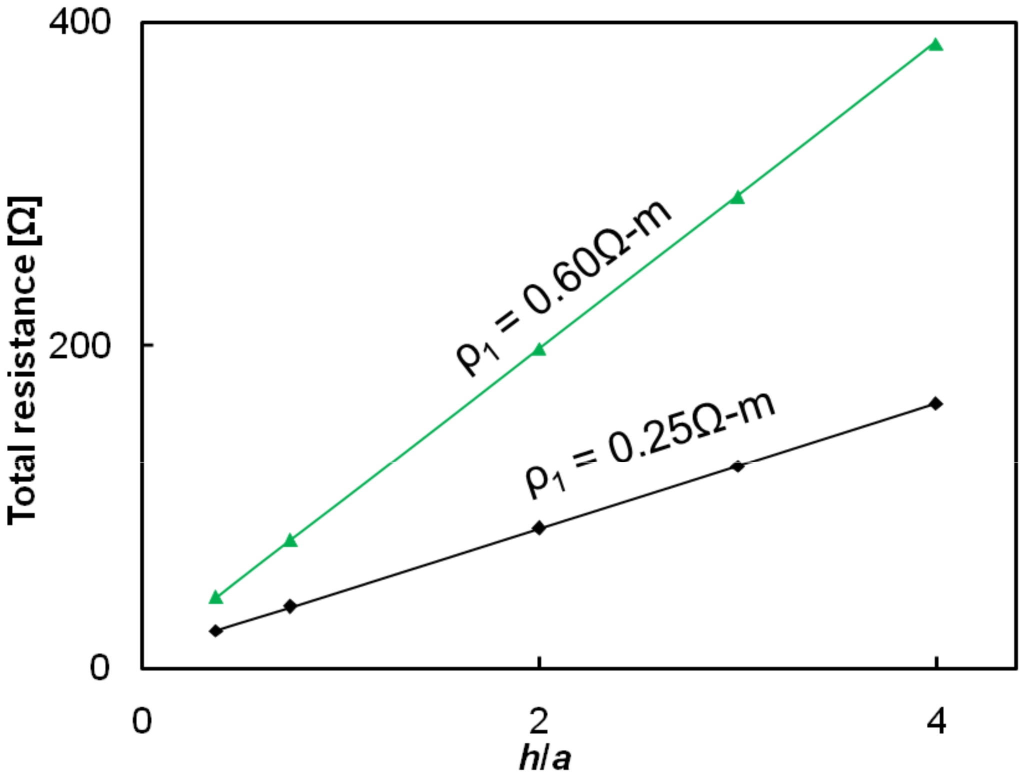
[2] Y. Y. Lau and Wilkin Tang, J. Appl. Phys. **105**, 124902 (2009).

[3] M. R. Gomez et al., Appl. Phys. Lett. **95**, 072103 (2009)

Test D. Comparison of 3D Maxwell code



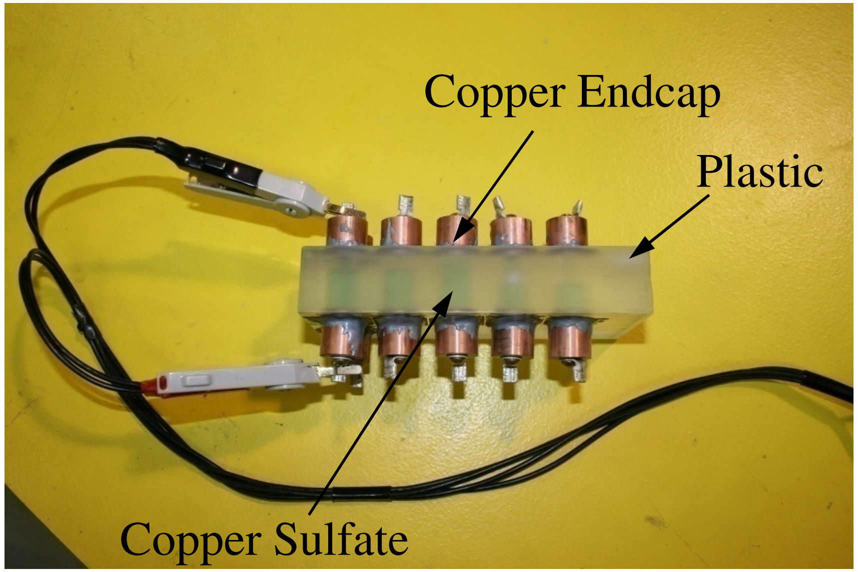
ρ_2 = 0.038Ωm,
ρ_3 = 0.001Ωm,
a = 4mm,
b = 8mm,
c =10 mm,
$L_2 = L_3$,
2h from 1.5 to 16 mm,
L_2 +2h + L_3 = 80 mm,
Excitation voltage = 10V



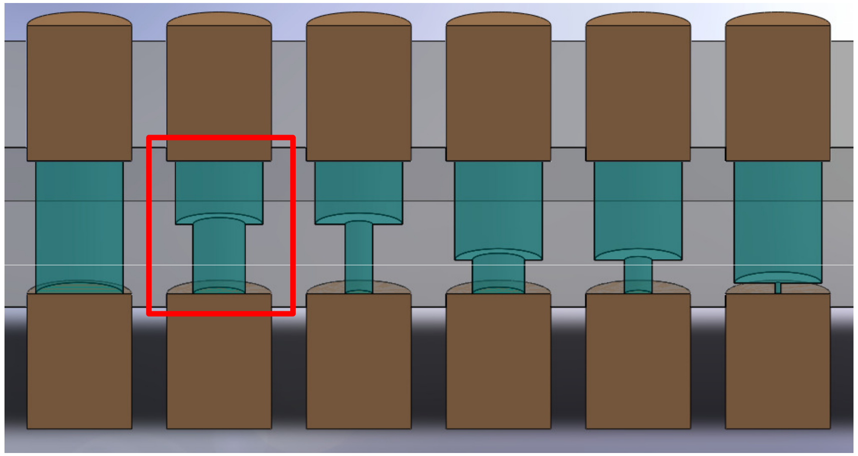
Symbols: Maxwell 3D
Solid lines: Scaling law

Gomez's Experimental Validation of Scaling Law ($\rho_1 = \rho_2 = \rho_3$, $b = c$)

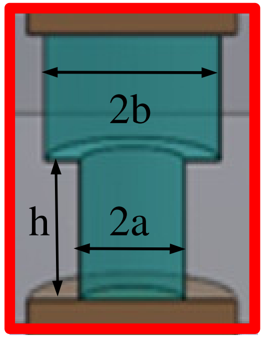
Experimental Configuration



Cross Sectional View



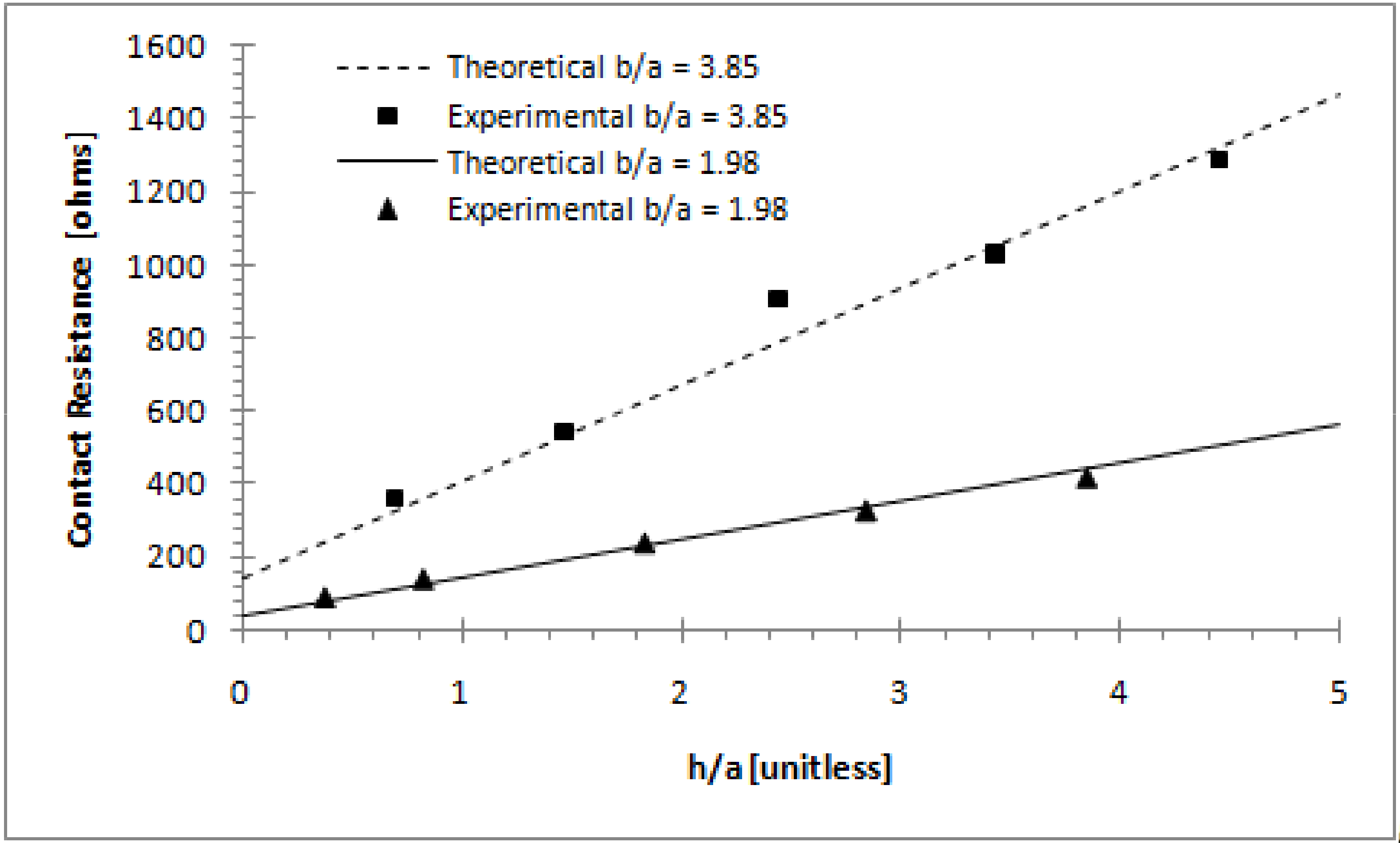
Case: A B C D E



Theoretical contact resistance geometry was mimicked by machining holes of varying diameter in a piece of plastic and filling it with copper sulfate.

[3] M. R. Gomez et al., Appl. Phys. Lett. **95**, 072103 (2009)

Gomez's Experimental Validation
($\rho_1 = \rho_2 = \rho_3$, $b = c$)



A plot comparing the second set of experimental data and the theoretically predicted values [3]

[3] M. R. Gomez et al., Appl. Phys. Lett. **95**, 072103 (2009)

Conclusion

- Simple scaling laws for contact resistance with dissimilar materials are constructed. They have been validated in various tests and simulations, and experiments.
- If the electrical contact is highly resistive ($\rho_1 >> \rho_2$, $\rho_1 >> \rho_3$), bulk resistance dominates over the interface resistance, if $2h$ exceeds a few times $(\rho_2/\rho_1)a$ and $(\rho_3/\rho_1)a$.
- Once the geometry (a,b,c,h) specified, interface resistance depends mainly on resistivity of main channel (ρ_2, ρ_3); insensitive to that of contact region (ρ_1).
- This work vastly generalized Holm's classical theory (1967) of contact resistance to higher dimensions, with dissimilar materials.

Peng Zhang, and Y. Y. Lau, "*Scaling laws for electrical contact resistance with dissimilar materials*", J. Appl. Phys **108**, 044914 (2010).