Contact Resistance

Semiconductor devices II - EE-567

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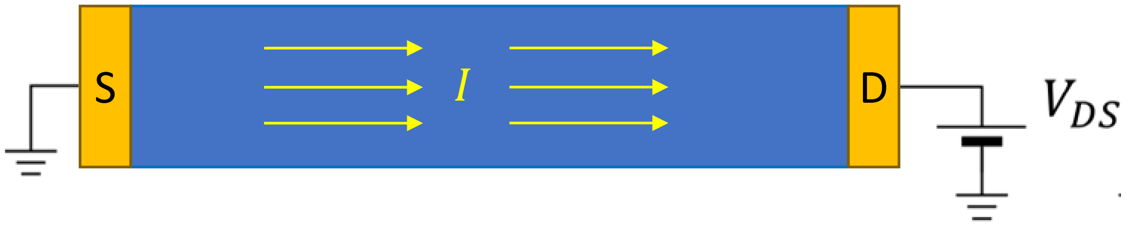
Contacts

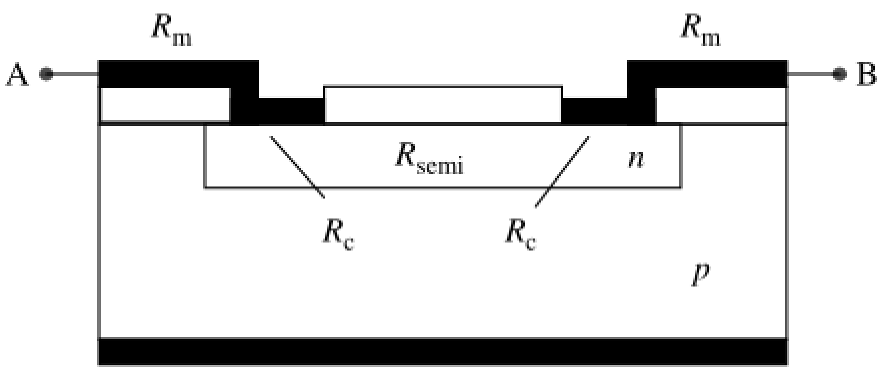
“Horizontal contacts”:
contact area = effective contact area



“Vertical contacts”:
what part of the contact contributes to the conduction?

In general: $R_{TOT} = R_{sc} + 2R_c + 2R_m$

Contact resistance



Semiconductor resistance: $\rho \cdot l/A$

Metal resistance R_m

Contact resistance R_c: involves some part of the metal, some part of the semiconductor, the structure of the interface

One can think of two quantities of interest in contact resistance measurements:

- Total contact resistance (Ω)
- Specific contact resistivity (Ω cm^2)

How to measure it?

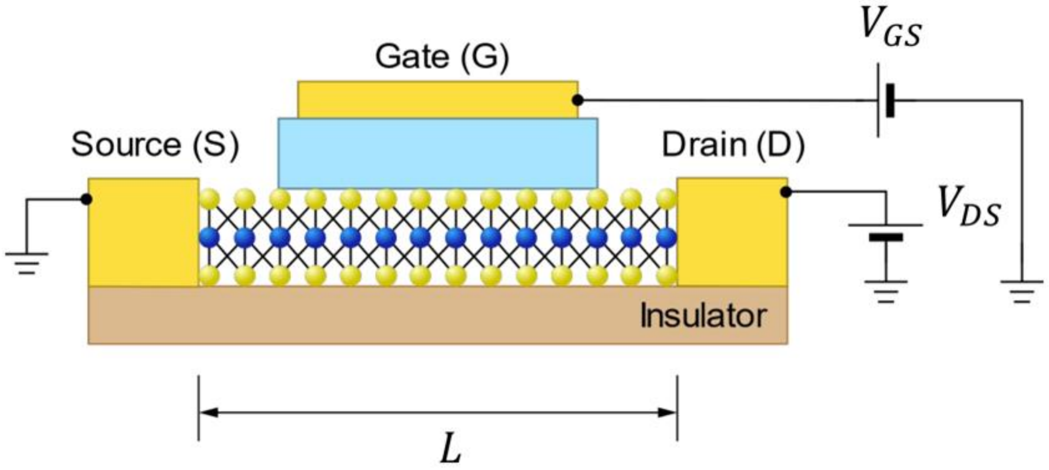
2D Semiconductor

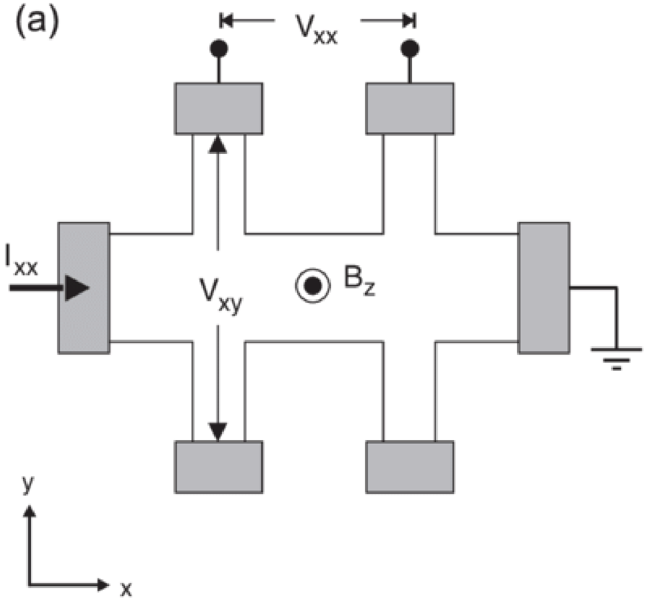
$$R_{2D} = \rho_{2D} \cdot \frac{L}{W}$$

If we can measure ρ_{2D}, then:

$$R_c = \frac{1}{2}\left(R_{TOT} - \rho_{2D}\frac{L}{W}\right)$$

Example: we make 4-terminal measurements and extract the sheet resistivity from the area between the probes



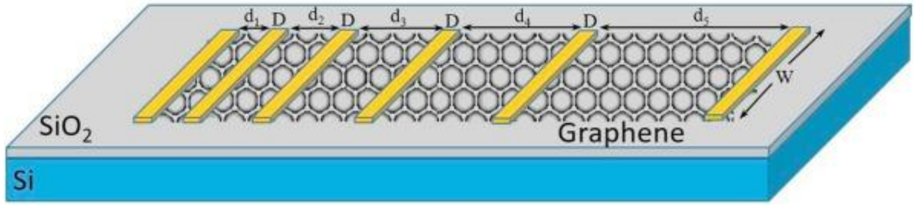


Another method

$R_{Ti} = \rho_{2D}\frac{d_i}{W} + 2R_c$ is the resistance measured between a pair of contacts i, j

We can extract the contact resistance without any knowledge of ρ_{2D}: $R_c = \frac{(R_{Tj}d_i - R_{Ti}d_j)}{2(d_i - d_j)}$

Assumptions:



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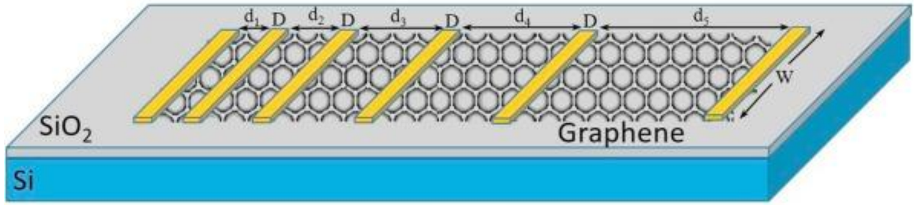
Assumptions:

- All contacts are equal
- Material is homogenous



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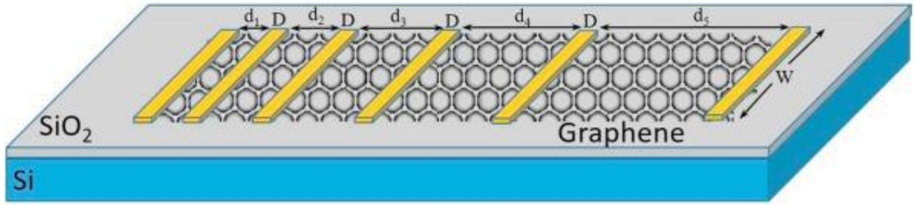
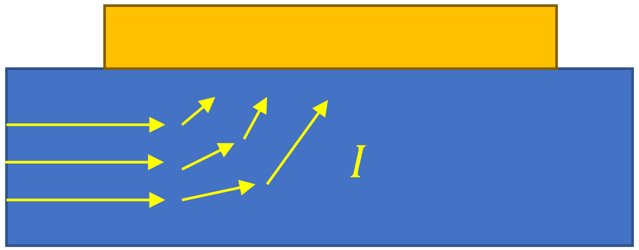


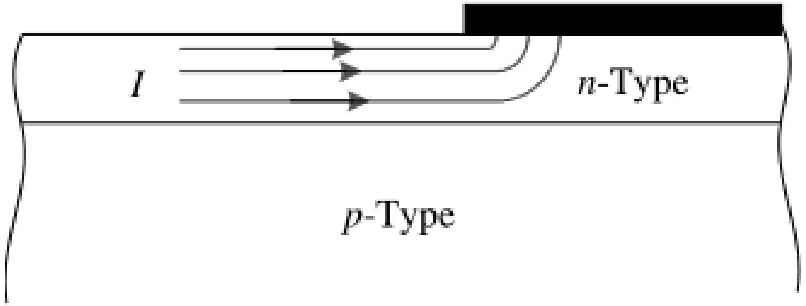
Problem: We can measure the total contact resistance (Ω). It would be more interesting to obtain a quantity that does not depend on the shape and size of the contacts!

Transmission line method

How does the current flow into the contact?



We can describe the contact between metal and the channel as composed of…



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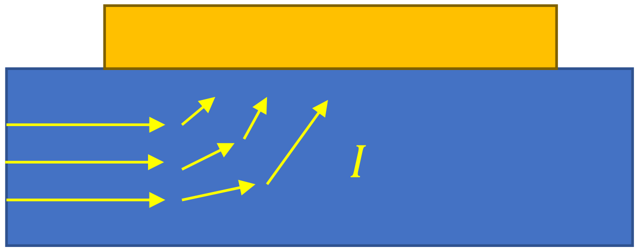


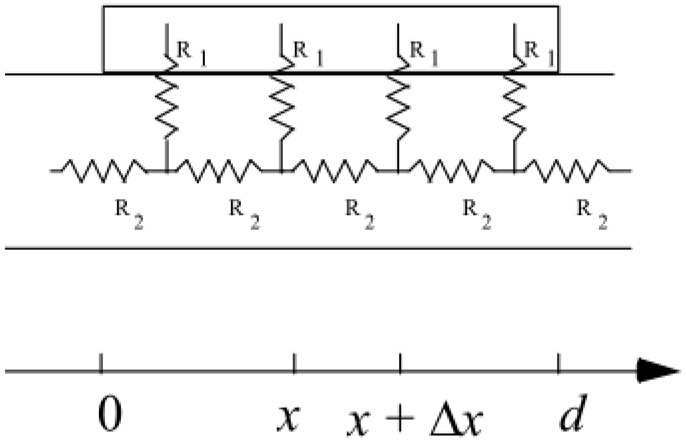
We can describe the contact between metal and the channel as composed of:

Interface resistance for a tiny slice Δx:

$$R_1 = \frac{\rho_c}{W\Delta x}$$

Channel resistance for a tiny slice Δx:

$$R_2 = \rho_s \frac{\Delta x}{W}$$



Transmission line method

Using Kirchoff's laws:

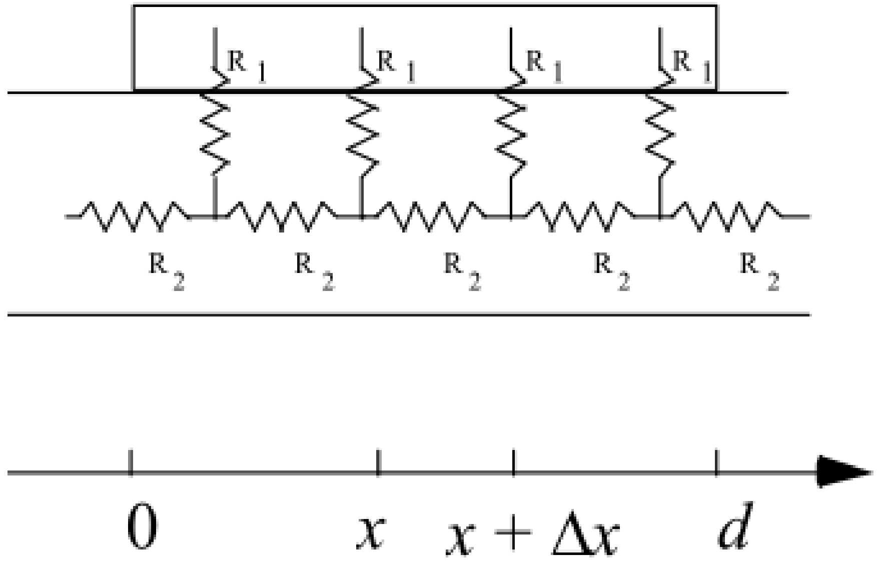
$$V(x + \Delta x) - V(x) = I(x)R_2$$

$$I(x + \Delta x) - I(x) = V(x)/R_1$$

Using the expressions for R_1, R_2:

$$V(x + \Delta x) - V(x) = I(x)\frac{\rho_s}{W}\Delta x$$

$$I(x + \Delta x) - I(x) = V(x)\frac{W}{\rho_c}\Delta x$$



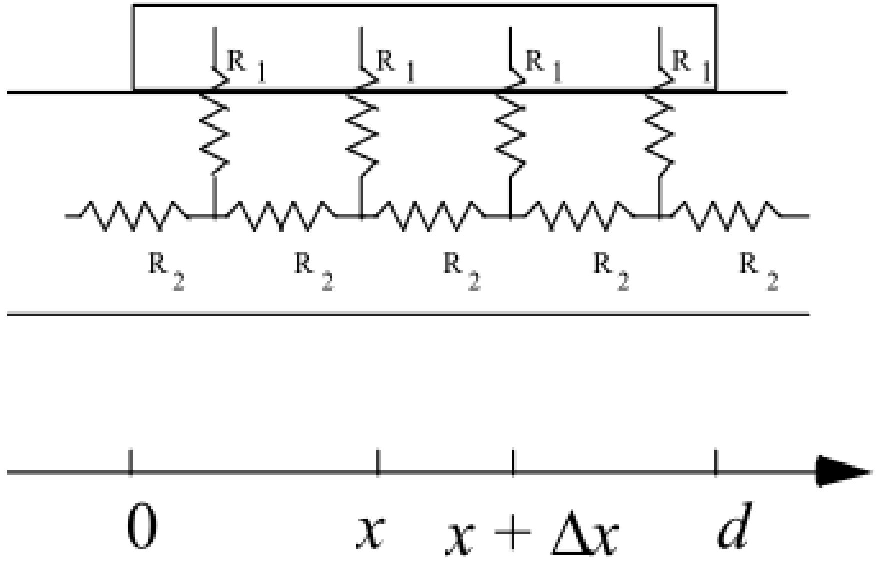
Transmission line method

So now we have:

$$V(x+\Delta x) - V(x) = I(x)\frac{\rho_s}{W}\Delta x$$

$$I(x+\Delta x) - I(x) = V(x)\frac{W}{\rho_c}\Delta x$$

In the limit $\Delta x \to 0$



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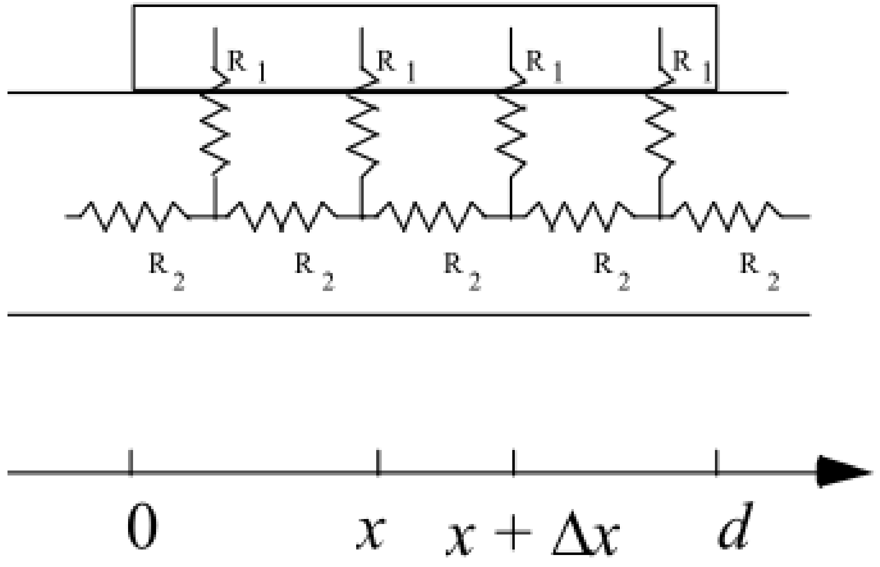


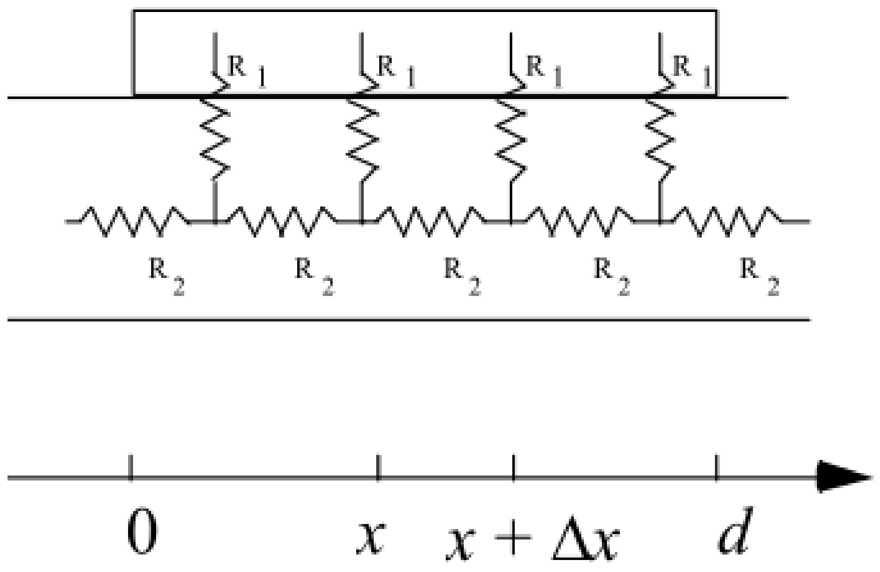
In the limit $\Delta x \to 0$ they become differential equations

$$\frac{dV}{dx} = I(x)\frac{\rho_s}{W}$$

$$\frac{dI}{dx} = V(x)\frac{W}{\rho_c}$$

Transmission line method

We can combine everything into one equation:

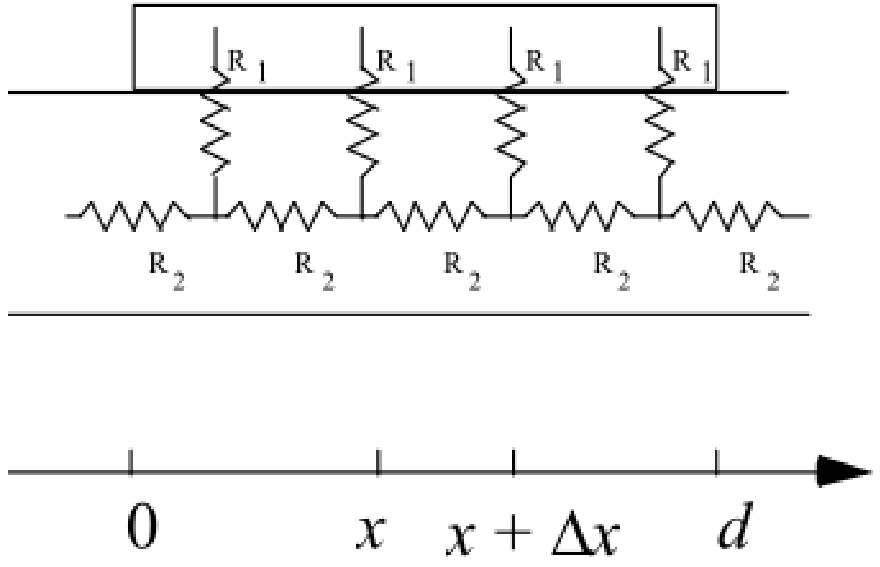


Transmission line method

We can combine everything into one equation:

- Take the derivative of the second equation:

$$\frac{d}{dx}\left(\frac{d}{dx}I(x)\right) = \frac{d}{dx}\left(V(x)\frac{\rho_s}{W}\right)$$
$$\frac{d^2}{dx^2}I(x) = \frac{dV(x)}{dx}\frac{\rho_s}{W}$$



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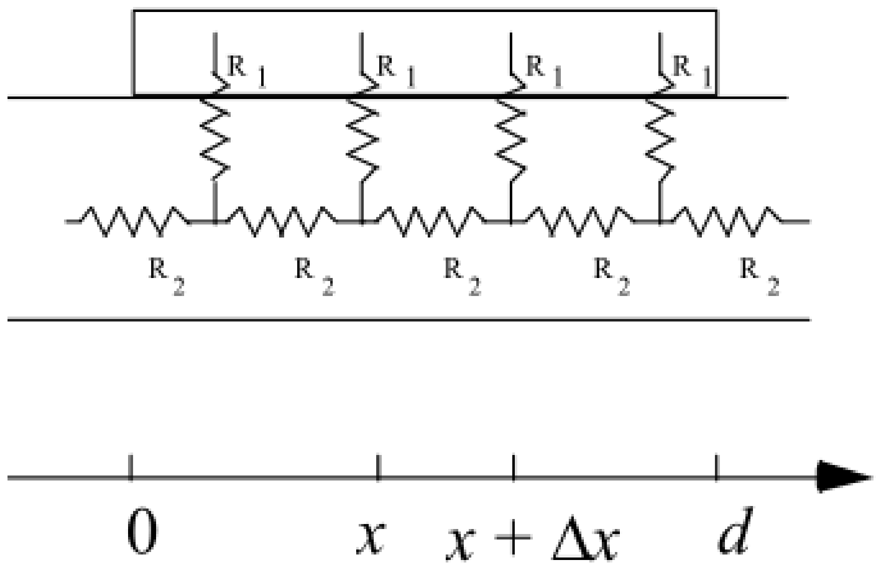
$$\frac{d^2}{dx^2}I(x) = \frac{dV(x)}{dx}\frac{\rho_s}{W}$$

- Insert the first to substitute dI/dx

$$\frac{d^2I(x)}{dx^2} = I(x)\frac{\rho_s}{\rho_c}$$



Transmission line method

We can rewrite this as ($\lambda = \sqrt{\rho_c/\rho_s}$):

$$\frac{d^2 I(x)}{dx^2} = \frac{I(x)}{\lambda^2}$$

General solution: $I(x) = c_1 e^{x/\lambda} + c_2 e^{-x/\lambda}$

$I(0) = I_0$

Which boundary conditions?

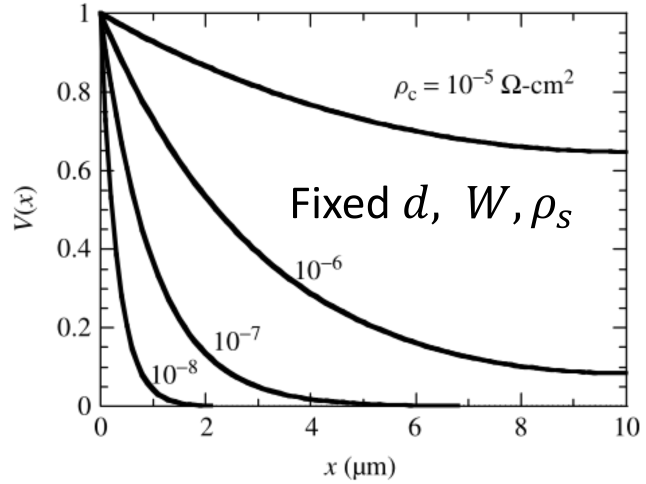
$I(d) = 0$ at the end of the contact - no current can flow

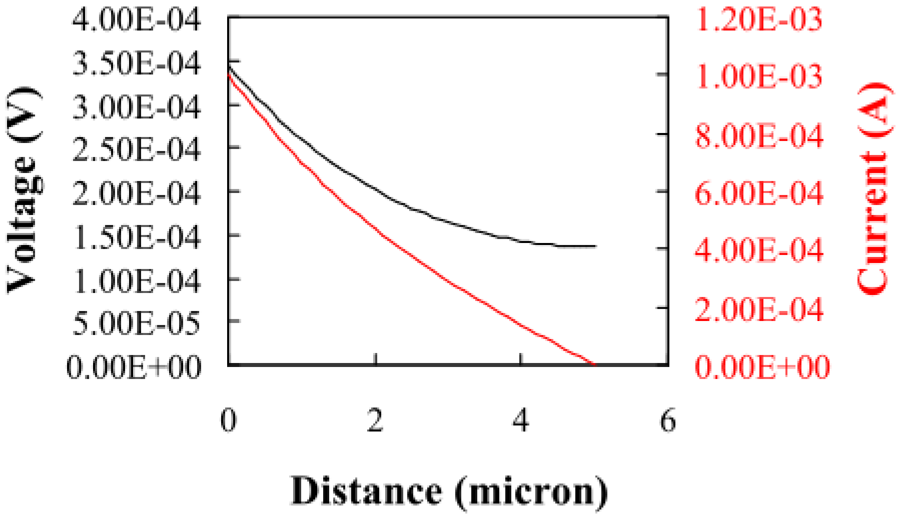
Transmission line method

After some calculations we find:

$$I(x) = I_0 \frac{\sinh\left(\frac{d-x}{\lambda}\right)}{\sinh\left(\frac{d}{\lambda}\right)}$$

$$V(x) = I_0 \frac{\lambda \rho_s}{W} \frac{\cosh\left(\frac{d-x}{\lambda}\right)}{\sinh\left(\frac{d}{\lambda}\right)}$$

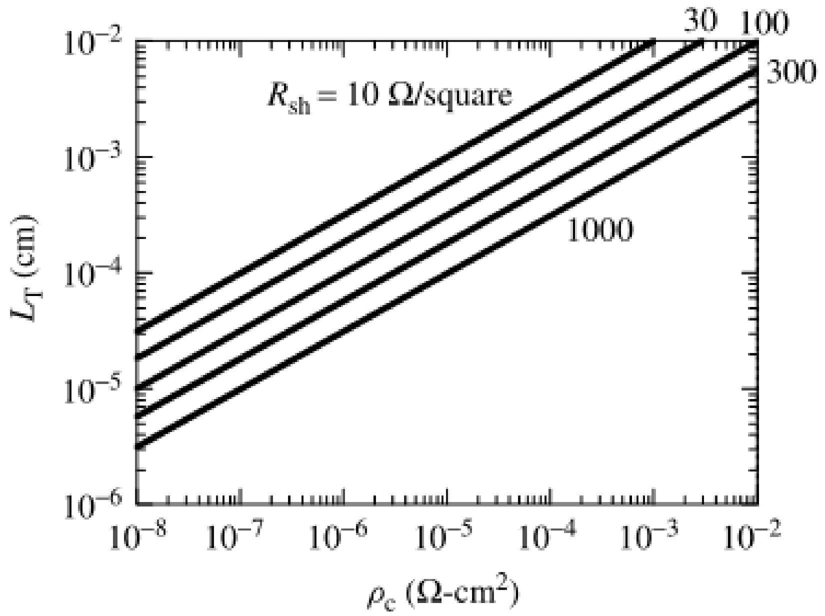




Transmission line method

$$I(x) \sim \sinh\left(\frac{d-x}{\lambda}\right)$$

$$V(x) \sim \cosh\left(\frac{d-x}{\lambda}\right)$$



We define "**transfer length**" the quantity

$$\lambda = \sqrt{\rho_c/\rho_s}$$

The transfer length can be thought of as that distance over which most of the current transfers from the semiconductor into the metal or from the metal into the semiconductor.

Transmission line method

The total contact resistance is

$$R_c = \frac{V(0)}{I(0)} = \frac{\lambda \rho_s}{W} \coth\left(\frac{d}{\lambda}\right)$$

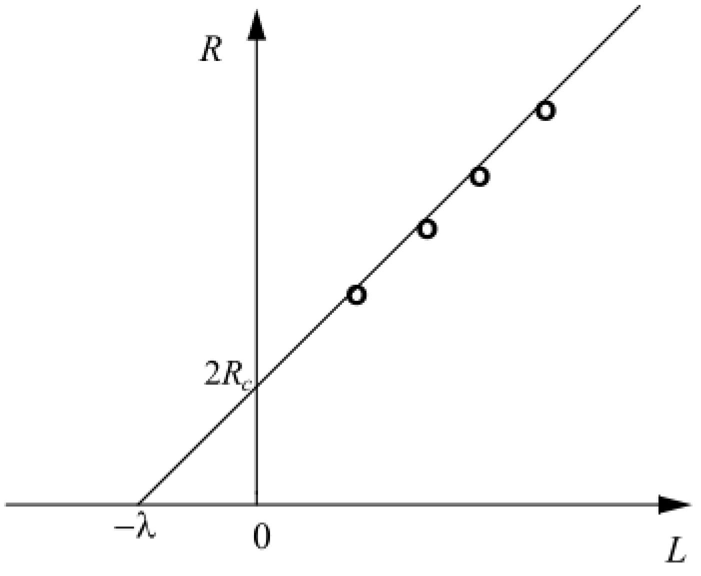
For $d \gg \lambda$ (contact much longer than the transfer length) we have $\coth\left(\frac{d}{\lambda}\right) \sim 1$:

$$R_c \approx \frac{\sqrt{\rho_c \rho_s}}{W}$$

When we measure our device the total resistance will be:

$$R_{TOT} = 2 \cdot \frac{\sqrt{\rho_c \rho_s}}{W} + \rho_s \frac{L}{W}$$

$$\boldsymbol{\lambda = \sqrt{\rho_c / \rho_s}}$$



Transmission line method

The total contact resistance is

$$R_c = \frac{V(0)}{I(0)} = \frac{\lambda \rho_s}{W} \coth\left(\frac{d}{\lambda}\right)$$

For $d \ll \lambda$ (contact much shorter than the transfer length) we have

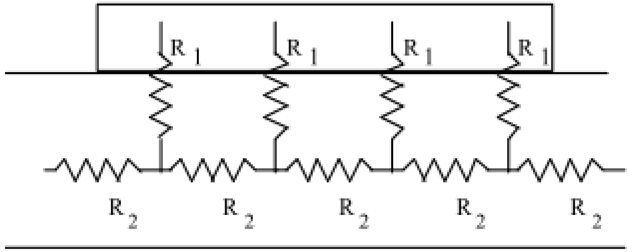
$$\coth\left(\frac{d}{\lambda}\right) \sim \frac{\lambda}{d} + \frac{1}{3}\left(\frac{d}{\lambda}\right) + \cdots$$

$$R_c \approx \frac{\rho_c}{Wd} + \frac{1}{3}\rho_s \frac{d}{W}$$

When we measure our device the total resistance will be:

$$R_{TOT} = 2 \cdot \left(\frac{\rho_c}{Wd} + \frac{1}{3}\rho_s \frac{d}{W}\right) + \rho_s \frac{L}{W}$$

$$\boldsymbol{\lambda = \sqrt{\rho_c/\rho_s}}$$



R_c =
Resistance between metal and channel (parallel connection of all the resistors R_1)
+
1/3 of the channel underneath the metal (series connection of all resistors R_2).