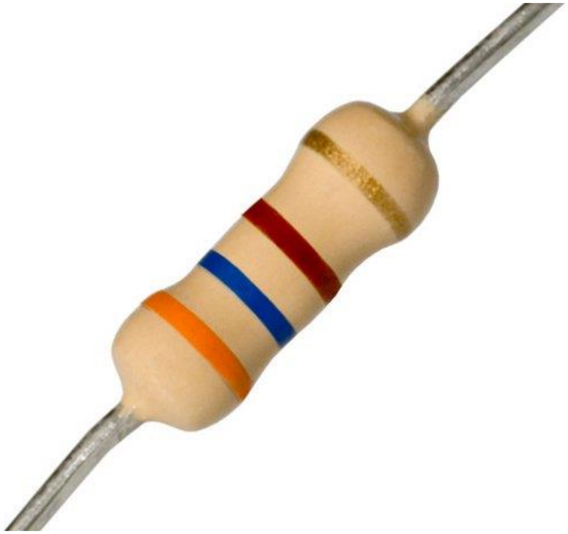
IC RESISTORS

Lecture 1

- IC passive components modeling and fabrication
  - IC resistors
  - IC inductors
  - IC capacitors

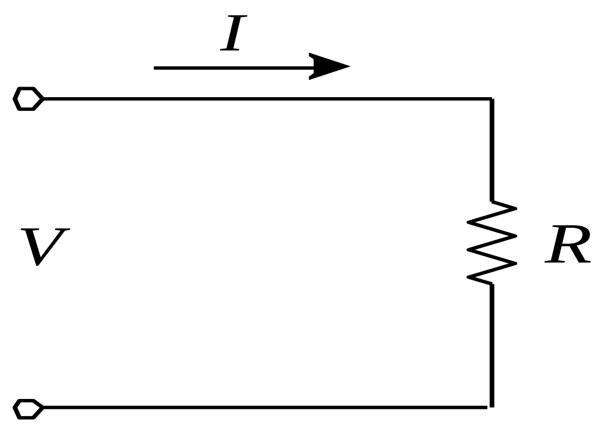
- **Discrete resistors**: are made from wires wounded around a cylinder of carbon film layers.



- **Integrated-circuit resistors**: are made from doped semiconductors, polysilicon film and connected to each other or other part of IC circuit with metallization using good conductors like aluminum.

- Resistors follow **Ohm's law** that states the resistance in ohm Ω of resistors is directly proportional to voltage applied V in volts across the resistor and indirectly proportional to current, I in ampere flows through the resistor.

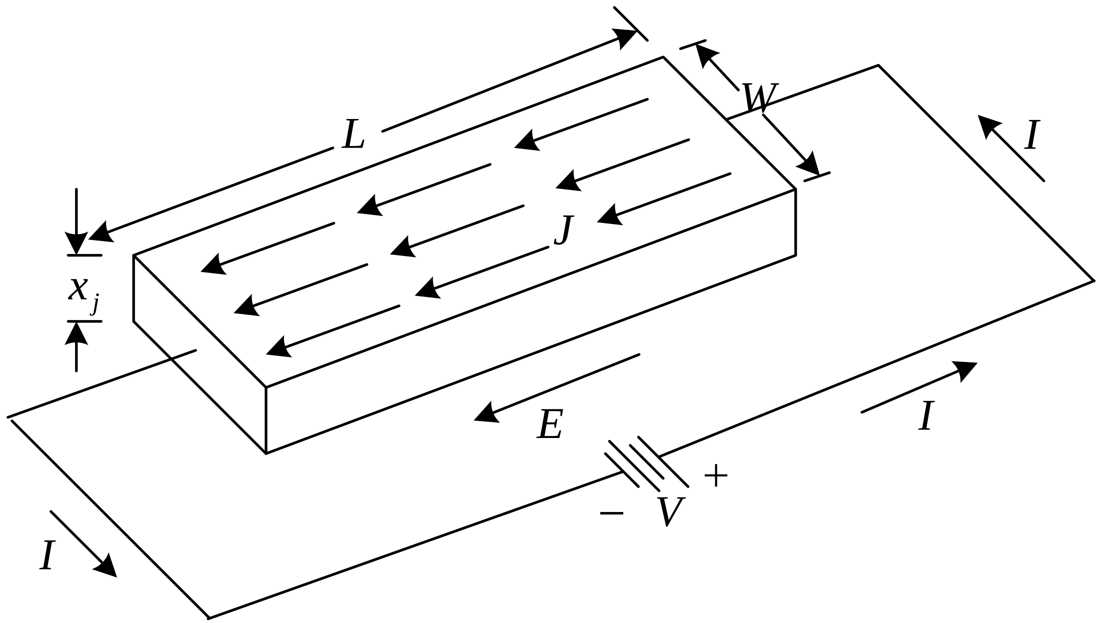
$$R = \frac{V}{I}$$



- Resistance of a resistor is defined as a ratio of voltage across it over current through it.

- The Resistance is also directly related to resistivity ρ in $\Omega - cm$ of the material of which the resistor is made of and its length ,L in cm and indirectly proportional to its cross sectional area $A = x_j W$ in .

$$R = \rho \frac{L}{x_j W}$$

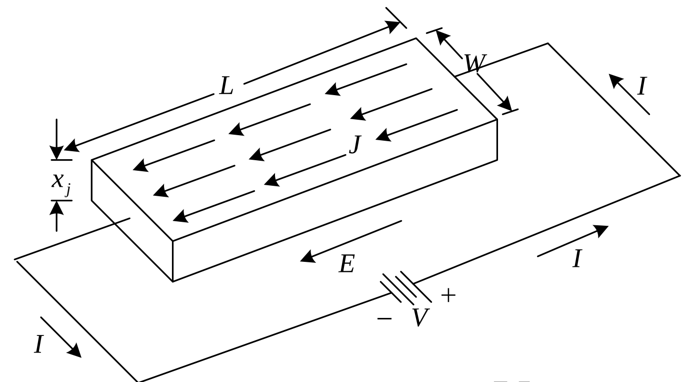


- The resistivity is also inversely proportional to the conductivity.

$$\rho = \frac{1}{\sigma}$$

- The electric field:

$$E = \frac{V}{L}$$



- The drift current density

$$J = J_n(drift) + J_p(drift) = qn\mu_n E + qp\mu_p E = q(n\mu_n + p\mu_p)\frac{V}{L}$$

- The drift current

$$I = J.A = q(n\mu_n + p\mu_p)\frac{V}{L}(Wx_j) = q(n\mu_n + p\mu_p)\frac{Wx_j}{L}V$$

- The resistance can be rewritten in terms of sheet resistance as

$$R = \frac{V}{I} = \frac{1}{q(n\mu_n + p\mu_p)x_j}\frac{L}{W} = R_S\frac{L}{W} = R_S N_S$$

- The resistivity is also inversely proportional to the conductivity.

$$\rho = \frac{1}{\sigma}$$

- The sheet resistance is defined as a ratio of resistivity over junction depth x_j in integrated circuit,

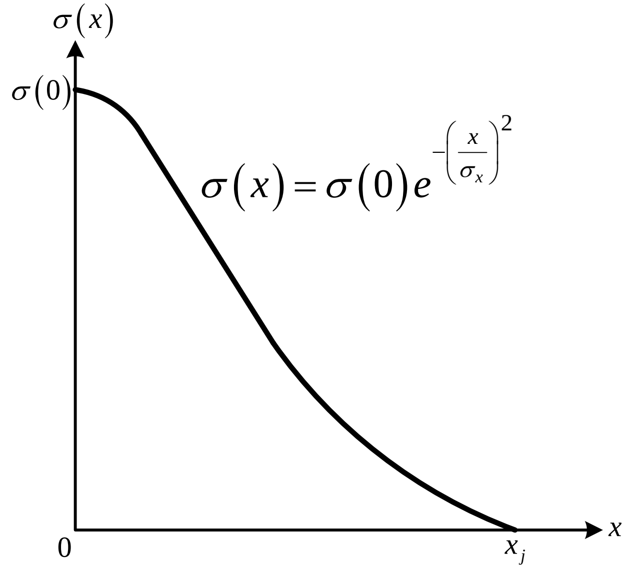
$$R_S = \frac{\rho}{x_j} = \frac{1}{\sigma x_j}$$

- and expressed in $\Omega/\square$.
- Resistance can be rewritten in terms of sheet resistance as

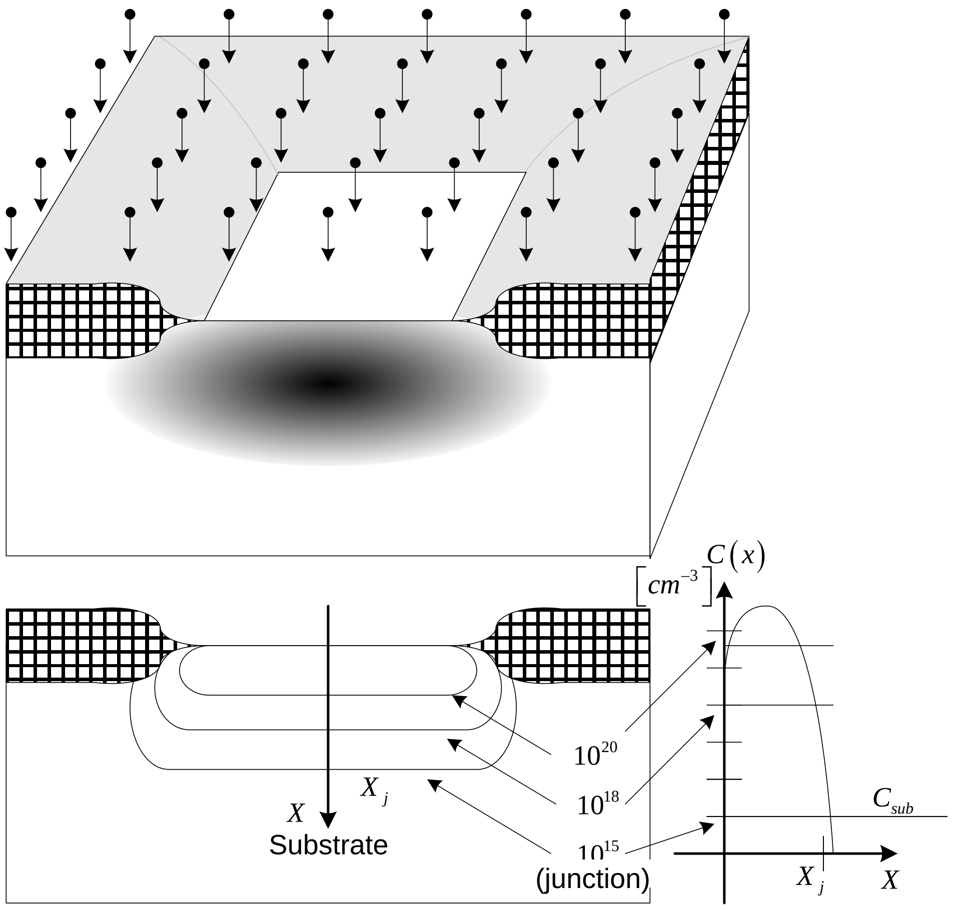
$$R = R_S \frac{L}{W} = R_S N_S$$

- Where $N_S = L/W$ is the length-to-width ratio and is called the number of squares and is unit-less

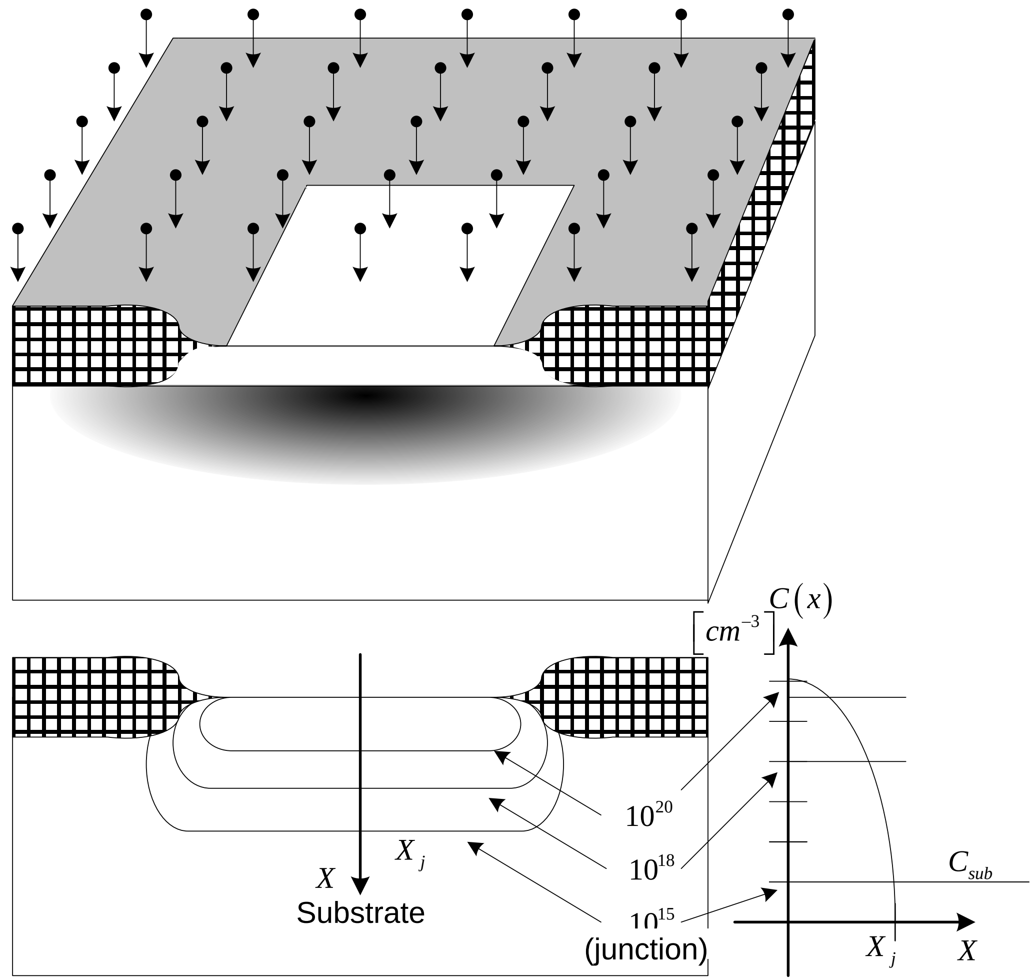
- Distribution models
  - Gaussian
  - Dual Pearson IV
  - Monte Carlo
- Resistivity $\rho(x)$ is not uniform in integrated circuit. Resistivity is smallest at surface, increasing inside the material due to diffusion, or stating in another way, conductivity is highest at surface, reducing inside material.



- Gaussian distribution resulting from ion implantation



- Gaussian distribution resulting from annealing



- Impurity Concentration profile
- Gaussian distribution resulting from ion implantation. The impurity is shown implanted completely below the wafer surface $x = 0$
- The projected range, or expected vale which is function of the ion energy plus mass and atomic number of impurity as well as target material

R_P = Projected range

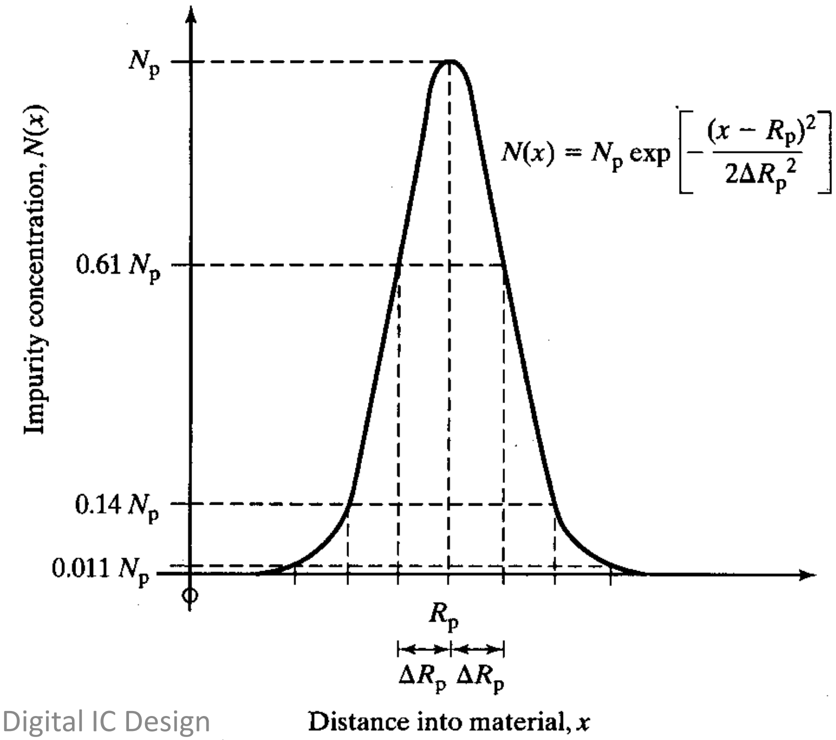
ΔR_p = Straggle = standard deviation

N_P = The peak concentration @ $x = R_p$

$$Q = dose = \int_0^{\infty} N(x)\,dx = \sqrt{2\pi} N_p \Delta R_p$$

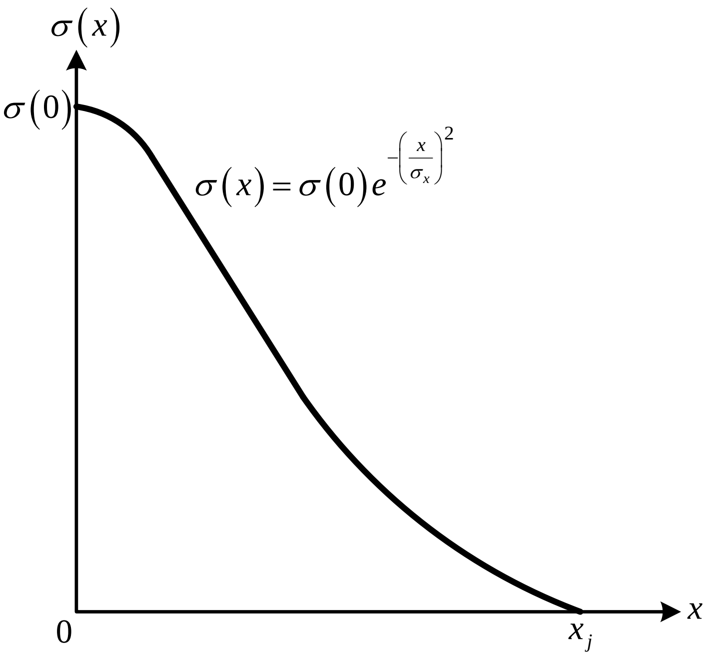
$$N(x) = N_p e^{-\frac{(x-R_P)^2}{2\Delta R_p^2}}$$

$$N_p = \sqrt{2\pi} N_p \Delta R_p$$



- The conductivity profile is a normalized Gaussian distribution resulting from ion implantation.

$$\sigma(x) = \sigma(0) e^{-\left(\frac{x}{\sigma_x}\right)^2}$$



- The expected value is zero
- The standard deviation is

$$\sigma_x = \text{standard deviation}$$

- The peak-value is

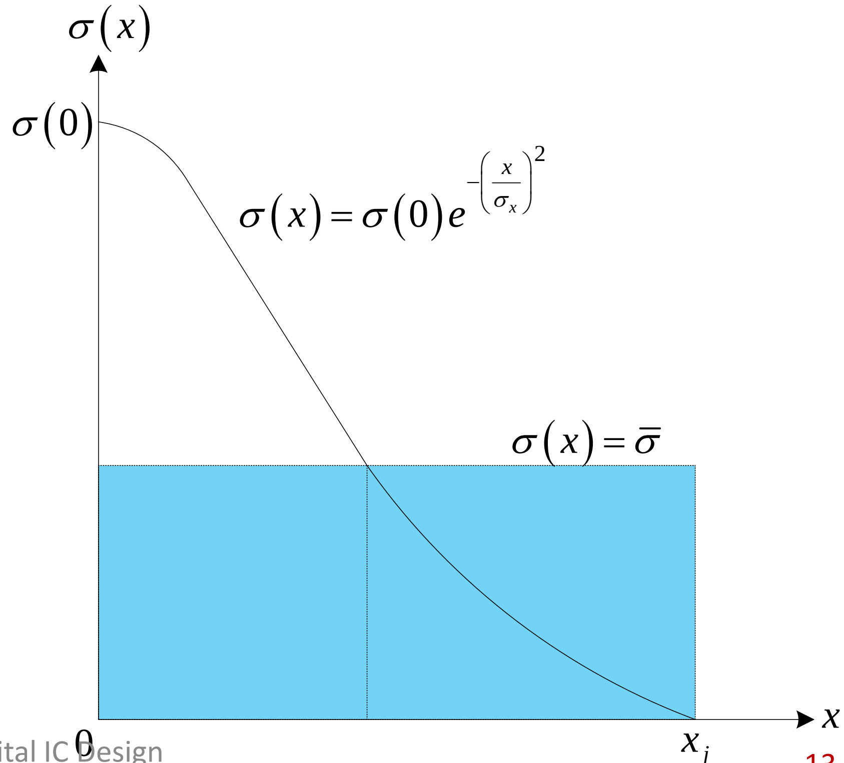
$$\sigma(x) = \text{ the peak conductivity @ x =0}$$

- The average conductivity is a single value for the conductivity that will provide the most suitable uniform conductivity approximation of the real conductivity dependence.
- The average conductivity $\bar{\sigma}$ is shown in dashed line, can be found by equating the rectangular area $\bar{\sigma} x_j$ and enclosed area:

$$\int_0^{x_j} \sigma(x)\,dx \simeq \int_0^{\infty} \sigma(x)\,dx$$

$$\bar{\sigma} \simeq \frac{1}{x_j}\int_0^{\infty} \sigma(x)\,dx$$

$$R_S = R_{\square} = 1/\bar{\sigma} x_j$$



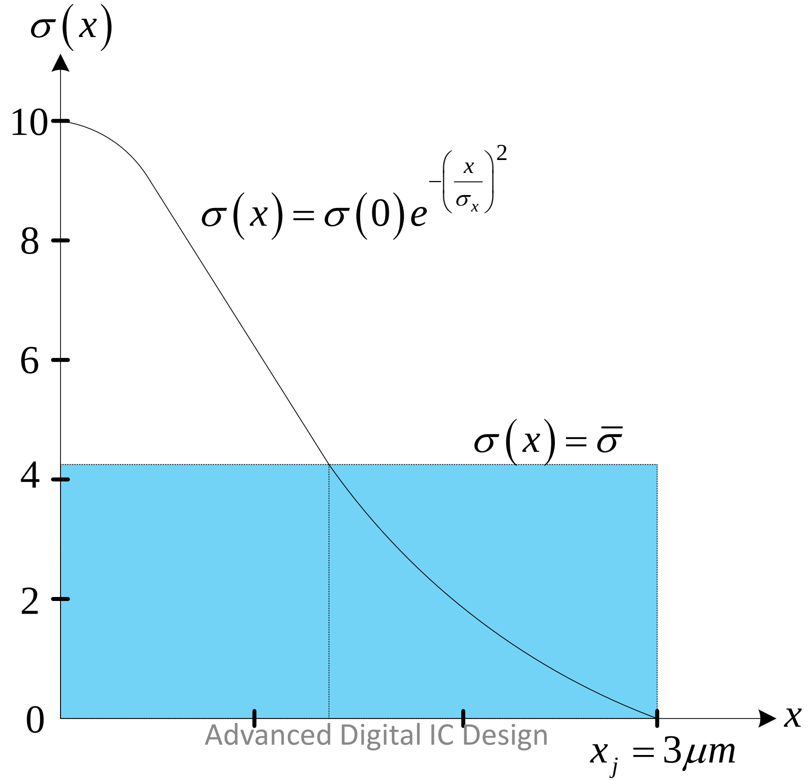
- A single Pearson distribution $P(x)$ is characterized by four parameters position of the peak R_P, the straggle ΔR_P, the skewness which is indicating the tilting of the profile δ, and kurtosis β which indicates the flatness at the top of the profile.
- The concentration

$$n(x) = n(0)\exp[P(x)]$$

- The Pearson type IV

$$P(x) = \frac{1}{2b_2}\ln\left(b_2x^2 + b_1x + b_0\right) - \frac{\dfrac{b_1}{b_2} + 2a_0}{\sqrt{4b_2b_0 - b_1^2}}\arctan\frac{2b_2x + b_1}{\sqrt{4b_2b_0 - b_1^2}}$$

- **Problem:**
  - A) Find the average conductivity for the layer shown in figure, given the standard deviation is $\sqrt{2}$
  - B) Design a $100k\Omega$ resistor using this layer, given the minimum dimension achievable by the particular technology is $1\mu m$.



- **Solution:**
  - A) The average conductivity:

$$\bar{\sigma} = \frac{10(\Omega - cm)^{-1}}{3\mu m}\int_0^{\infty} e^{-\frac{x^2}{2}}dx$$

  - The so called Laplace integral is:

$$\int_0^{\infty} e^{-\frac{x^2}{2}}dx = \sqrt{\frac{\pi}{2}}\mu m$$

  - Then the average conductivity is:

$$\bar{\sigma} = \frac{10(\Omega - cm)^{-1}}{3\mu m}\left(\sqrt{\frac{\pi}{2}}\mu m\right) = 4.18(\Omega - cm)^{-1}$$

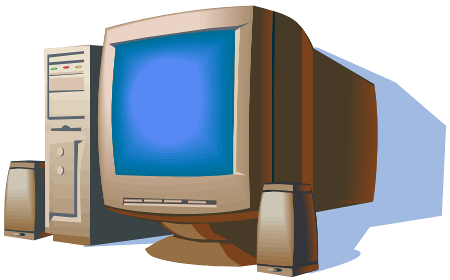
  - B) The sheet resistance:

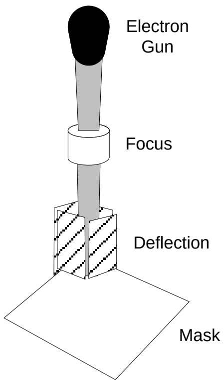
$$R_s = R_\square = \frac{1}{\bar{\sigma}x_j} = \frac{1}{4.18(\Omega - cm)^{-1}\times 3\times 10^{-4}cm} = 797.4\Omega/\square$$

$$\frac{L}{W} = \frac{R}{R_s} = \frac{100{,}000}{797.4} = 125 \quad \Rightarrow L = 125W = 125\mu m$$

- The fundamental unit of IC manufacturing: Silicon wafer.
- The typical wafer diameter: 20 cm in 1990’s, $50.00, 150 chips.
- The maximum wafer diameter: 30 cm in 2014.
- Development of 45 cm wafer is in horizon.
- A lot: A group of around 24 wafers undergoes the same sequence of fabrication process.
- DRAM: 200 steps
- A typical complex IC chip area: 1.5cmX1.5cm
- A typical IC: Several millions electronic devices
- A typical cost of wafer: $2000.00.
- The yield of mature process: how many of the chip work: %90
- A typical IC package: In plastic Dual-in-line (DIP)/ Wire bonds
- A typical IC for cellular phone/laptop package: encapsulated in low-profile surface mount package or mount directly mounted on the circuit board using a flip-chip technique/ Electroplated solder bumps.

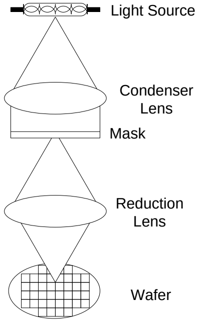
- Photolithography can be divided into three steps:
  - Design using CAD system
    - Layout
    - Simulation
    - Design Rule Verification
  - Mask making





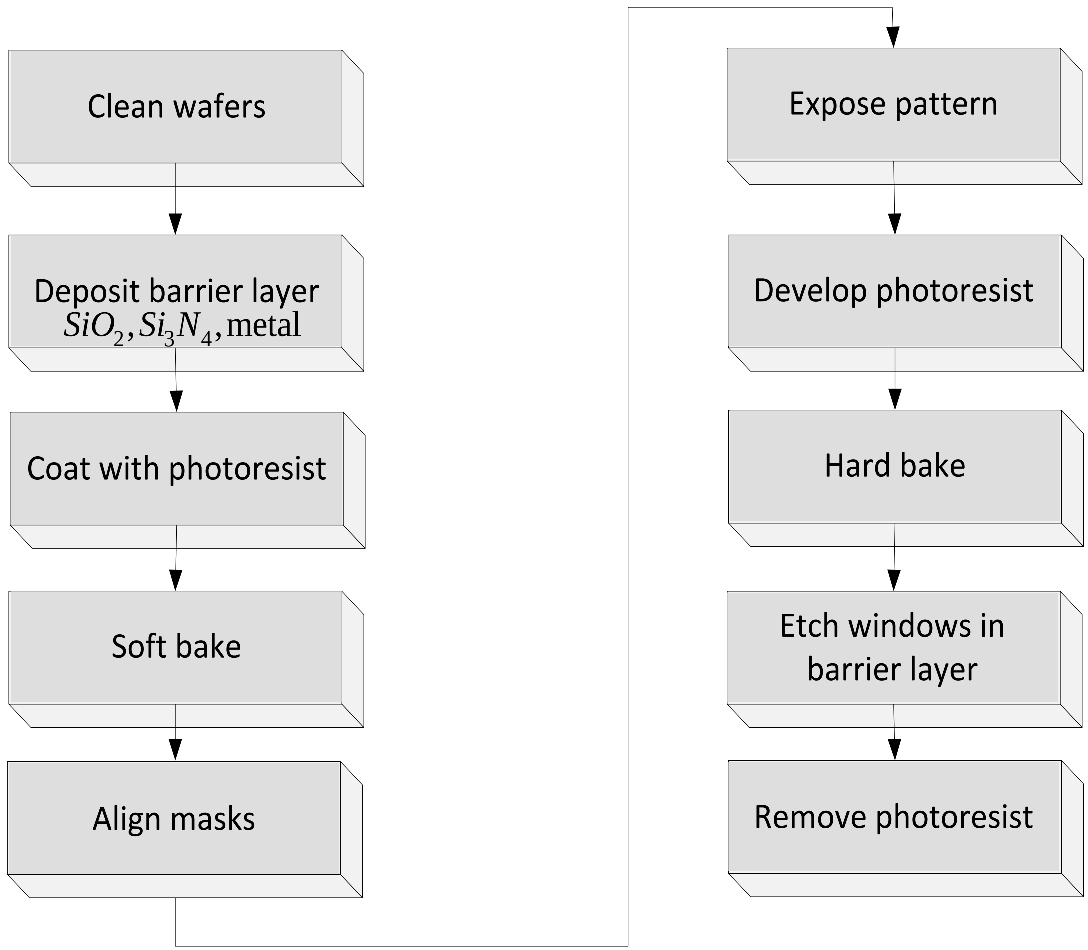
Mask Making

  - Wafer exposure
    - The patterns transfer form mask to photo resist
    - Chemical or plasma etching to transfer the
    - pattern from the photo resist to burrier material
    - on the surface of wafer.



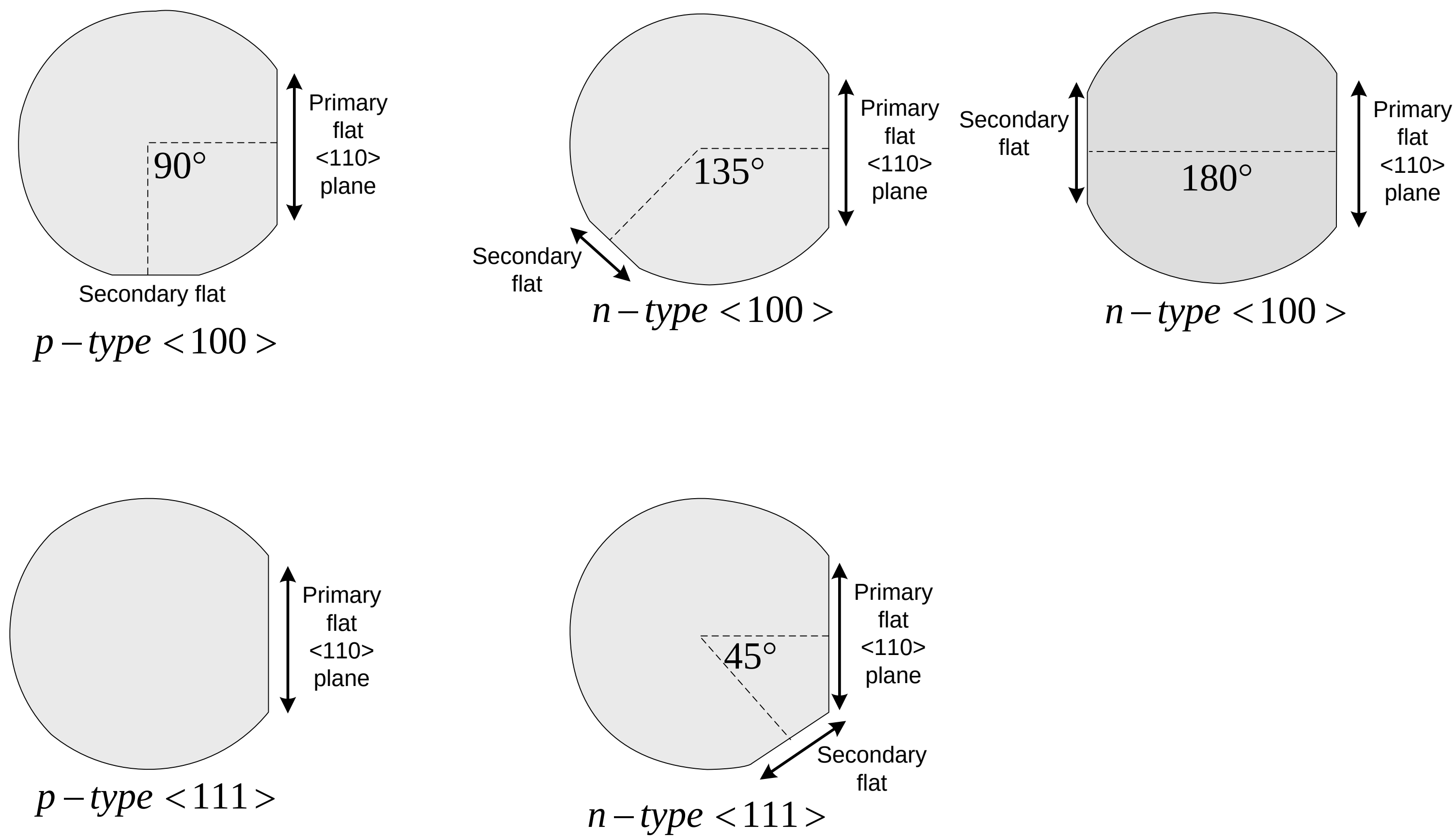
Wafer Exposure

- The various steps of basic photolithographic process



- n or p-type silicon wafer are available with a specified resistively
- Typically the growing crystal is doped with boron, phosphorous or arsenic. Arsenic and antimony is used for low resistively (high concentration) n-type crystal.
- The thickness $250\mu m \le t \le 500\mu m$
- The diameter $200mm(8 \text{ inch}) \le d \le 300mm(12 \text{ inch})$ (wafers with diameter of 1,1.5,2,3,4,5 and 6 inches have been used at various stages in history of solid state devices).
- The diameter of wafer is chosen in order to withstand the mechanical and thermal strain during the process steps. (for example a 6 to 8 inch diameter semiconductor wafer needs to be about $500\mu m$ thick.

- Schematic of a simple lithographic exposure system



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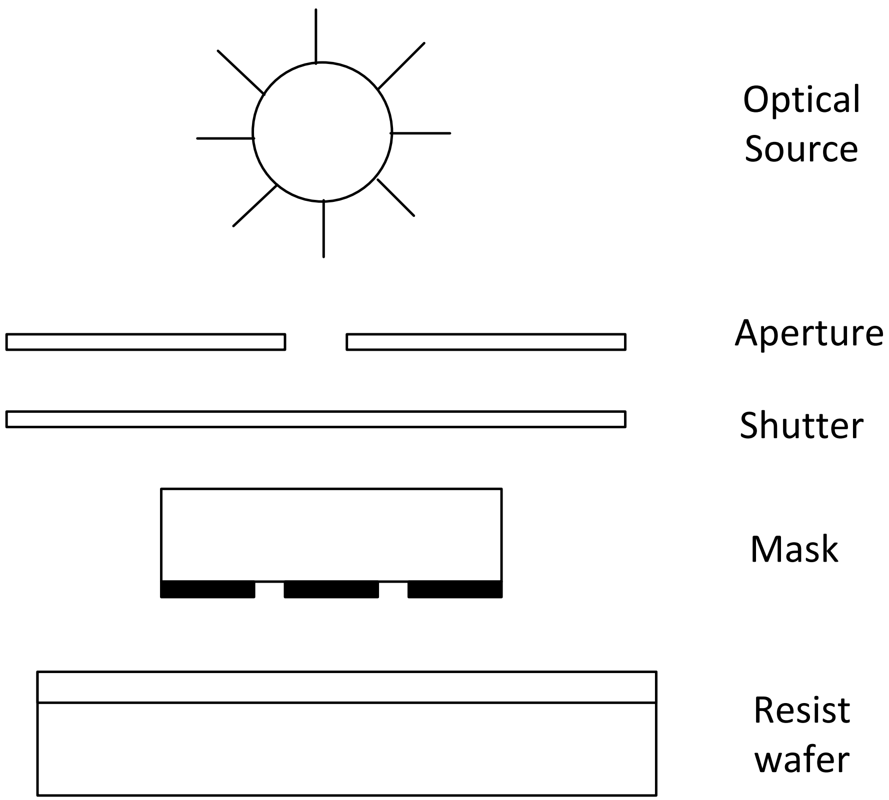
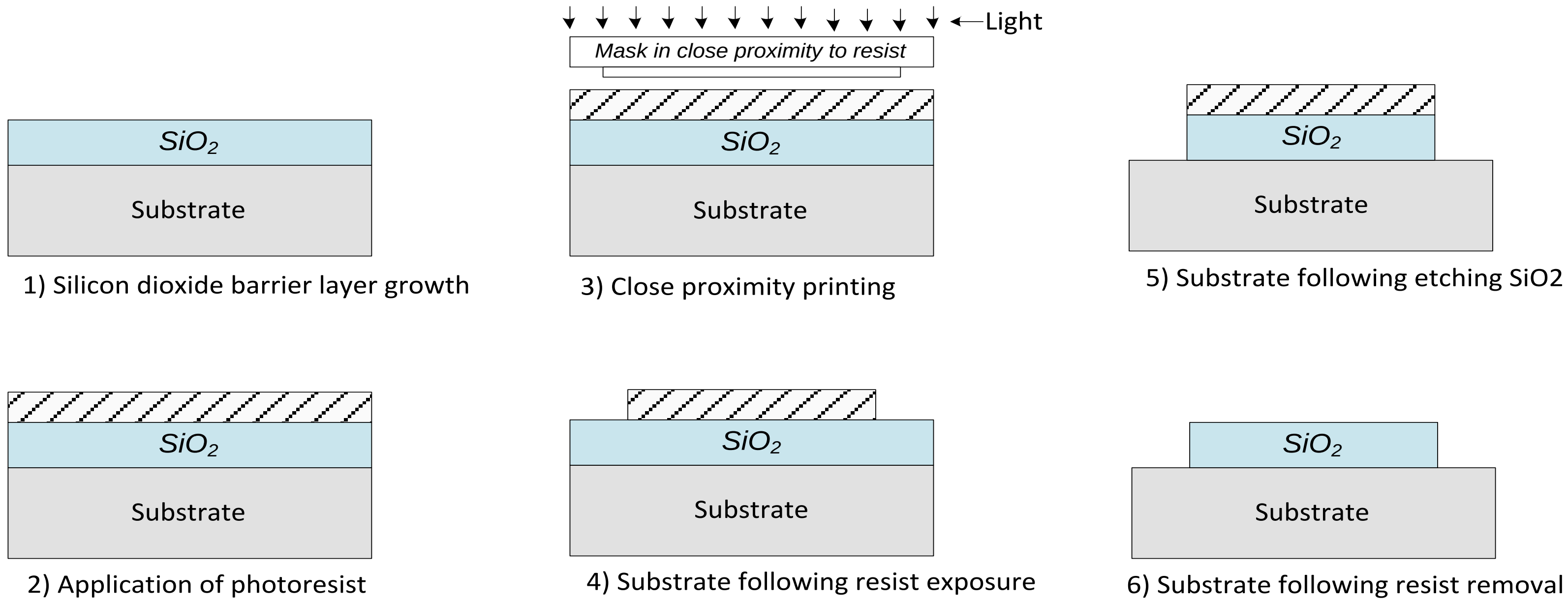
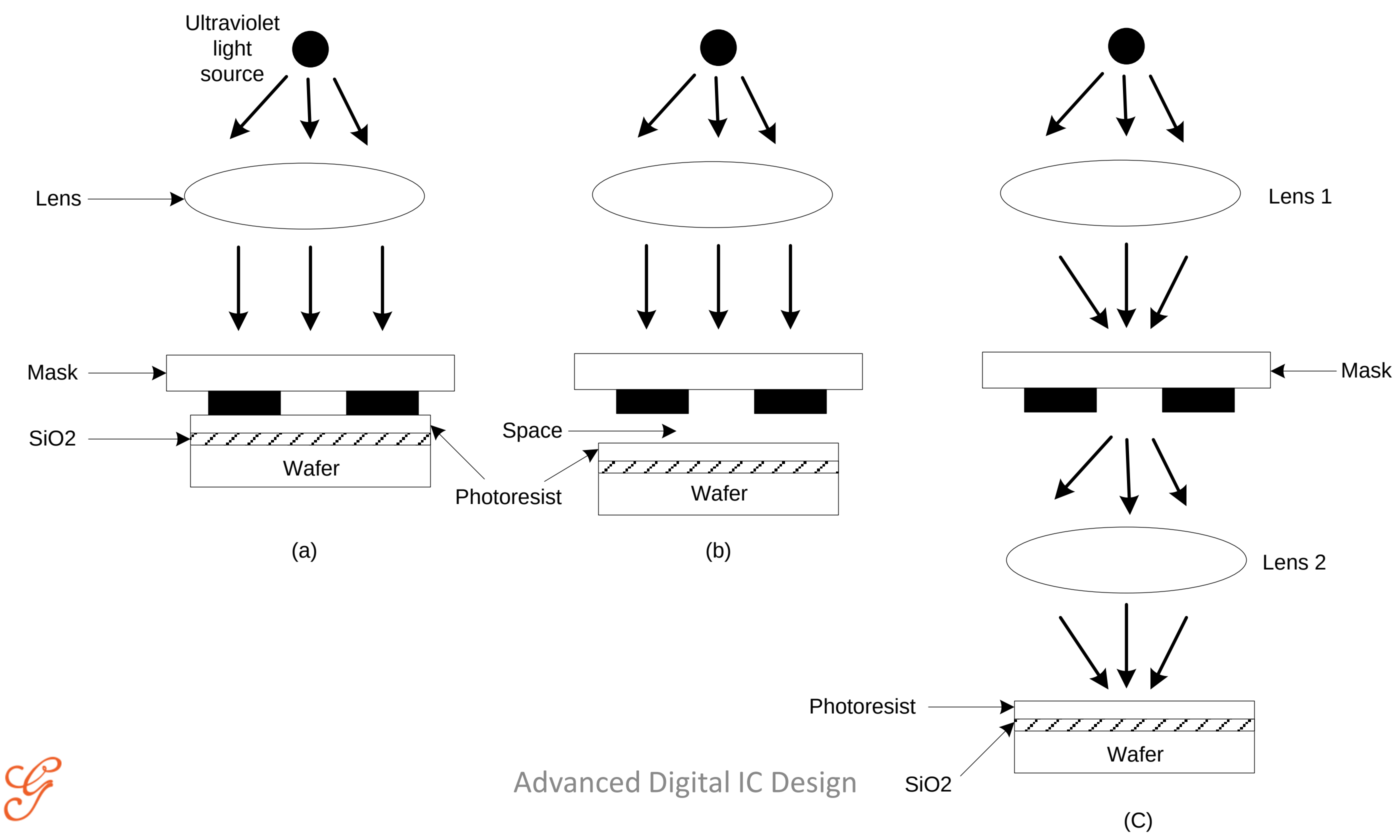


- Schematic of a simple lithographic exposure system



- (a) Contact printing, in which wafer is in intimate contact with mask,
- (b) proximity printing, in which wafer and mask are in close proximity
- (c) projection printing, in which light source is scanned across the mask and focused on the wafer.



- The resistivity is also inversely proportional to the conductivity.

$$\rho = \frac{1}{\sigma}$$

- The sheet resistance is defined as a ratio of resistivity ρ over junction depth x_j in integrated circuit,

$$R_S = \frac{\rho}{x_j} = \frac{1}{\sigma x_j}$$

- and expressed in Ω/cm
- Resistance can be rewritten in terms of sheet resistance as

$$R = R_S \frac{L}{W} = R_S N_S$$

- Where $N_S = L/W$ is the length-to-width ratio and is called the number of squares

- The Sheet resistance for frequently used materials in IC.

MATERIAL	THICKNESS (x_j)	SHEET RESISTANCE
n^+ -Polysilicon	500 nm	$R_S = 20\,\Omega/cm$
Aluminum	1000 nm	$R_S = 0.07\,\Omega/cm$
Silicided polysilicon		$R_S = 5\,\Omega/cm$
Silisided source/drain diffusion		$R_S = 3\,\Omega/cm$

- The Change from run-to-run, chip-to-chip is largely due to ion-implanter.
- The doping concentration N_D can be expressed as:

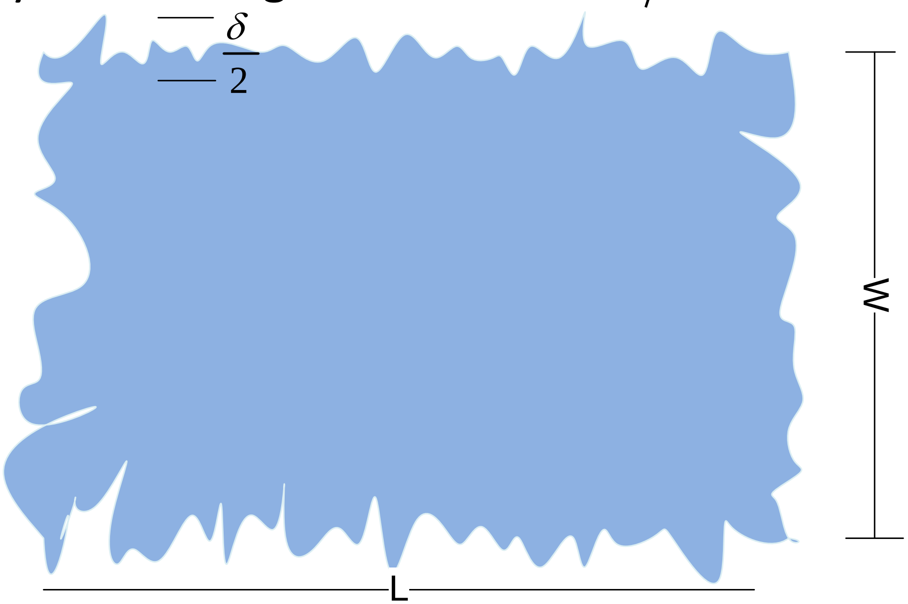
$$N_D = \bar{N}_D\left(1 \pm \varepsilon_{N_D}\right)$$

- Where $\bar{N}_D$ is the average doping and is the normalized uncertainty.
- For example:

  Doping concentration defined by an average of $\bar{N}_D = 10^{17}\,cm^{-3}$
  and normalized uncertainty of $\varepsilon_{ND} = 0.025$ means that

$$Nd = \left(10^{17}\,cm^{-3}\right)\left(1 \pm 0.025\right) = 10^{17} \pm 2.5 \times 10^{15}\,cm^{-3}$$

- Mobility Variation are due to random local variation in Crystal defects
- Ignoring Coupling between doping concentration and mobility variation
- The resistor thickness x_j variation is due to time and local wafer temperature variation during the furnace annealing process
- The lateral dimensions of the resistor are affected by random linewidth variations from the pattern transfer processes.
- The uncertainty on one edge is defined as $\delta/2$



- Sheet Resistance

$$W = \bar{W} \pm \delta/2 \pm \delta/2 = \bar{W} \pm \delta$$

$$L = \bar{L} \pm \delta/2 \pm \delta/2 = \bar{W} \pm \delta$$

- Uncertainty from each edge:

$$W = \bar{W}\left(1 \pm \delta/\bar{W}\right) = \bar{W}\left(1 \pm \varepsilon_W\right)$$

$$L = \bar{L}\left(1 \pm \delta/\bar{L}\right) = \bar{L}\left(1 \pm \varepsilon_L\right)$$

$$E_W = \delta/\bar{W} \qquad E_L = \delta/\bar{L}$$

$$\bar{R} = \frac{1}{q\bar{N}_D\left(1+\varepsilon_{N_D}\right)\bar{\mu}_n\left(1+\varepsilon_{\mu_n}\right)\bar{\chi}_j\left(1+\varepsilon_{x_j}\right)}\left[\frac{\bar{L}\left(1+\varepsilon_L\right)}{\bar{W}\left(1+\varepsilon_W\right)}\right]$$

- Sheet Resistance
- The average resistance

$$\bar{R} = \frac{1}{qN\bar{d}\,\bar{\mu}_n \bar{\chi} j}\left(\frac{\bar{L}}{\bar{W}}\right)$$

- Substitution for each term that is subject to manufacturing is

$$\bar{R} = \frac{1}{q\bar{N}_D\left(1+\varepsilon_{N_D}\right)\bar{\mu}_n\left(1+\varepsilon_{\mu_n}\right)\bar{\chi}_j\left(1+\varepsilon_{x_j}\right)}\left[\frac{\bar{L}\left(1+\varepsilon_L\right)}{\bar{W}\left(1+\varepsilon_W\right)}\right]$$

- The average resistance

$$\varepsilon_R = \sqrt{\varepsilon_{N_D}^2 + \varepsilon_{\mu_n}^2 + \varepsilon_{x_j}^2 + \varepsilon_L^2 + \varepsilon_W^2}$$

- Uncertainty up to 0.1