Resistors

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OUTLINE

Definitions
Resistor I-V Characteristics
The Semiconductor Resistor
  Resistivity
  Carrier Mobility
The Diffused Semiconductor Resistor
Resistor Design and Cross-Sections
Resistor Fabrication Sequence (micrographs)
Resistor Networks, Terminations
DEFINITIONS

**Voltage** - The force applied between two points causing charged particles (and hence current) to flow. Units - Volts, and the symbol used is V. Sometimes called the potential.

**Current** - A measure of the number of charged particles passing a given point per unit time. Units - Amperes or Coulombs per second. The symbol I is usually used to denote a current.

**Resistance** - A measure of the ability of a sample of a material to allow a current to pass through it when an external force or potential is applied. The units are Ohms and the symbol R is used for a resistance.

Ohm’s Law \[ V = I \times R \] or \[ R = \frac{V}{I} \] or \[ I = \frac{V}{R} \]
**MEASURING RESISTOR I-V CHARACTERISTIC**

Variable Voltage Supply  
Ammeter (measures current)

<table>
<thead>
<tr>
<th>Volts</th>
<th>Amperes</th>
<th>Resistance (V/I) in Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>-0.005</td>
<td>1000</td>
</tr>
<tr>
<td>-4</td>
<td>-0.004</td>
<td>1000</td>
</tr>
<tr>
<td>-3</td>
<td>-0.003</td>
<td>1000</td>
</tr>
<tr>
<td>-2</td>
<td>-0.002</td>
<td>1000</td>
</tr>
<tr>
<td>-1</td>
<td>-0.001</td>
<td>1000</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>?</td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>1000</td>
</tr>
</tbody>
</table>
Resistor a two terminal device that exhibits a linear I-V characteristic that goes through the origin. The inverse slope is the value of the resistance.

\[ R = \frac{V}{I} = \frac{1}{\text{slope}} \]
THE SEMICONDUCTOR RESISTOR

Resistance = \( R = \rho \frac{L}{\text{Area}} = \rho_s \frac{L}{w} \) ohms

Resistivity = \( \rho = \frac{1}{(q\mu_n n + q\mu_p p)} \) ohm-cm

Sheet Resistance = \( \rho_s = \frac{1}{\int q \mu(N) N(x) \, dx} \sim \frac{1}{(q\mu \text{ Dose})} \) ohms/square

\( \rho_s = \frac{\rho}{t} \)

Note: sheet resistance is convenient to use when the resistors are made of thin sheet of material, like in integrated circuits.

\( q = 1.6E-19 \) coulombs
RESISTIVITY OF SILICON

Because the carrier mobility, $\mu$ is a function of $N$ and $N$ is the doping, the relationship between resistivity $\rho$ and $N$ is given in the figure shown to the left, or calculated from equations for $\mu$ as a function of $N$ (see next page).

$$\rho = 1/(q\mu N)$$
ELECTRON AND HOLE MOBILITY

Electron and hole mobilities in silicon at 300 K as functions of the total dopant concentration (N). The values plotted on the next page are the results of the curve fitting measurements from several sources. The mobility curves can be generated using the equation below with the following parameter values:

\[
\mu(N) = \mu_{\text{min}} + \frac{\left(\mu_{\text{max}} - \mu_{\text{min}}\right)}{\left\{1 + \left(N/N_{\text{ref}}\right)^{\alpha}\right\}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Arsenic</th>
<th>Phosphorous</th>
<th>Boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_{\text{min}})</td>
<td>52.2</td>
<td>68.5</td>
<td>44.9</td>
</tr>
<tr>
<td>(\mu_{\text{max}})</td>
<td>1417</td>
<td>1414</td>
<td>470.5</td>
</tr>
<tr>
<td>(N_{\text{ref}})</td>
<td>9.68X10^{16}</td>
<td>9.20X10^{16}</td>
<td>2.23X10^{17}</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.680</td>
<td>0.711</td>
<td>0.719</td>
</tr>
</tbody>
</table>
ELECTRON AND HOLE MOBILITY

Carrier Mobilities versus Doping Concentration

Doping Concentration (Na or Nd)

Carrier Mobility (cm²/V·sec)

- μ_n
- μ_p
The n-type wafer is always biased positive with respect to the p-type diffused region. This ensures that the pn junction that is formed is in reverse bias, and there is no current leaking to the substrate. Current will flow through the diffused resistor from one contact to the other. The I-V characteristic follows Ohm’s Law: $I = V/R$
Resistor Fabrication

Layout/Mask Layer 1 - Diffusion (green)

Top View

W

Resistor termination

L

Side View

P type Diffusion

N wafer

The resistance, \( R = \rho \text{ (L/W)} \)

The sheet resistance \( \rho \), is the resistance of each square \( L/W \) is the number of ‘squares’ long the resistor is said to be.

5 squares in this case

If \( \rho \) is 100 ohms per square,
\[ R = 500 \text{ ohms} \]
Resistor Fabrication

Layout/Mask Layer 3 - Contacts (gray)

Top View

W  ➔  10 by 10 microns

Remember, inside the green (diagonally shaded) regions is p type silicon, outside is n type

Side View

contact openings

Oxide

Diffusion

N wafer
Resistor Fabrication

Layout/Mask Layer 4 - Metal (blue)

Top View

- 10 by 10 microns

Side View

- Metal (Aluminum)
- Oxide
- Diffusion
- N wafer

Resistor Symbol
Metal (Aluminum) wiring to the Probe Pads

Rhos for diffusion = 100 Ohms per square

Resistor 10 squares

Rhos for aluminum is 0.01 Ohms per square

R_{total} = 10(100) + (5+5)(0.01) = 1000.1 Ohms, therefore

Metal “wiring” does not add very much to the resistance
Wafer with silicon dioxide, patterned and etched

This end of the resistor loops were cut off in the picture

This resistor is many, many squares long

20µm

Green is oxide (glass)

Gray is bare silicon

Diffusion openings

MASK # 1
After dopants have been diffused in and a new oxide grown

- Purple areas are diffused and pink areas are not (the oxide in this area did not allow the dopant to diffuse into the silicon)
After thin oxide openings have been patterned and etched

- The thin oxide layer is actually part of the transistor fabrication sequence.

MASK # 2

Bare Silicon
After thin oxide growth (part of the transistor process)

1000Å of SiO₂
After the contact openings have been patterned and etched
After Aluminum has been deposited

- Aluminum short circuits everything at this stage, until it is patterned and etched.

Particle on the microscope lens
After aluminum is patterned and etched
RESISTOR NETWORK

Desired resistor network

500 Ω

400

250 Ω

Layout
VARIATIONS ON THE BASIC RESISTOR LAYOUT

\[ R = \rho_s (10+0.5+0.5) \]

Corner squares count ~ 1/2
RESISTOR TERMINATIONS

Field Mapping

~ 0 squares

~ 0.5 squares