

# *Resistors*

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# Resistors

- Important parameters:

- Resistance: achievable resistance values ( $\Omega \dots M\Omega$ )
- Device size (independent of resistance value)
- Linearity: independence of resistance ( $dV/dI$ ) of applied voltage
- Temperature stability: independence of resistance of operation temperature
- Maximum dissipated power
- Maximum applied voltage
- Maximum operating frequency

# Conduction Mechanisms

- Ohmic and non-ohmic conduction
- Temperature and voltage coefficients for different conduction processes
- Tunnel effect through thin dielectric sheets

$$\sigma_t = A e^{-b/V}$$

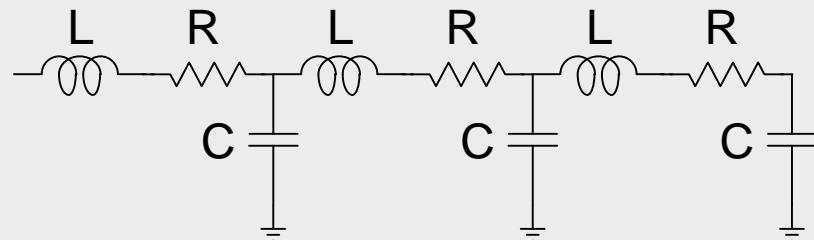
- Schottky effect at the oxide-metal interface

$$\sigma_s = \frac{AT}{V^2} e^{-b\sqrt{V}/KT}$$

# Parameter Dependencies

- Temperature coefficient  $\alpha = \frac{1}{R} \frac{dR}{dT}$  ppm/°C
- Voltage coefficient  $\beta = \frac{1}{R} \frac{dR}{dV}$  ppm/V
- Frequency dependence

Equivalent circuit



$$\omega_{MAX} = \frac{1}{RC}; \frac{R}{L}$$

# Resistors Noise

- Thermal noise is always present  $v_n^2 = 4kTRB$

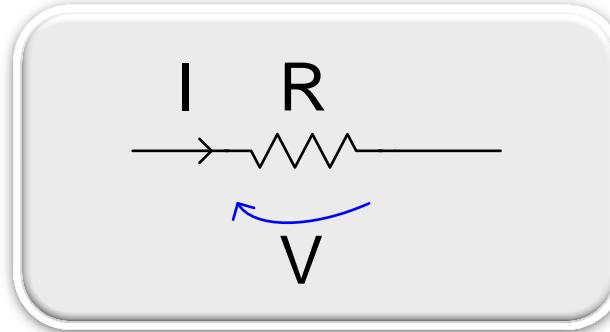
- Flicker (1/f) noise is proportional to *rms* current  $S_n = \frac{dv_n^2}{df} = aRI^2 \frac{1}{f}$

## NOISE INDEX

$$I = \frac{\left( \int_{300Hz}^{3kHz} S_n df \right)^{1/2} [\mu V]}{V [V]}$$

$dB$

# Maximum Dissipated Power



$$P_{DISS} = V^2/R$$

- The maximum dissipated power ( $P_{MAX}$ ) is set by the maximum device temperature ( $T_{MAX}$ ) and by the *thermal resistance* ( $R_{TH}$ )

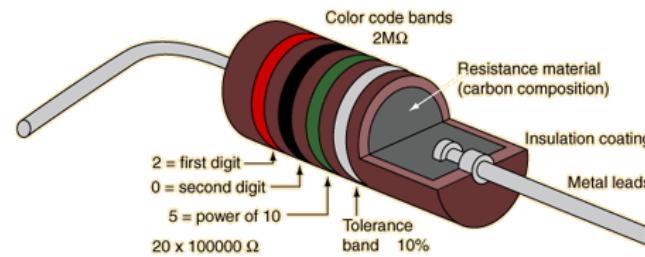
$$T_{RES} = T_A + P_{DISS} R_{TH}$$

# Resistor Types

- Carbon compound
- Cermet
- Carbon/metal film
- Metal wire

# Carbon Resistors

- Implemented as a compound of resistive (carbon) and isolating materials, finely grinded and mixed in a plastic material providing a stable supporting structure.
- Conduction is carried out through a **percolation** process
- Resistivity varies, depending on carbon concentration, from  $10\text{m}\Omega\cdot\text{cm}$  to  $100\text{k}\Omega\cdot\text{cm}$ .
- Resistance value spread is larger for larger resistance values as fewer paths in parallel are formed.
- At high voltages more parallel paths are activated, lowering resistance (**negative voltage coefficient**)



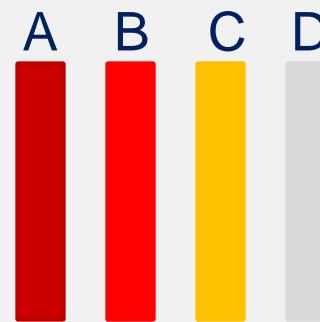
# Color Code

Values

	0
	1
	2
	3
	4
	5
	6
	7
	8
	9
	-1
	-2

Precision

	20%
	10%
	5%
	2%



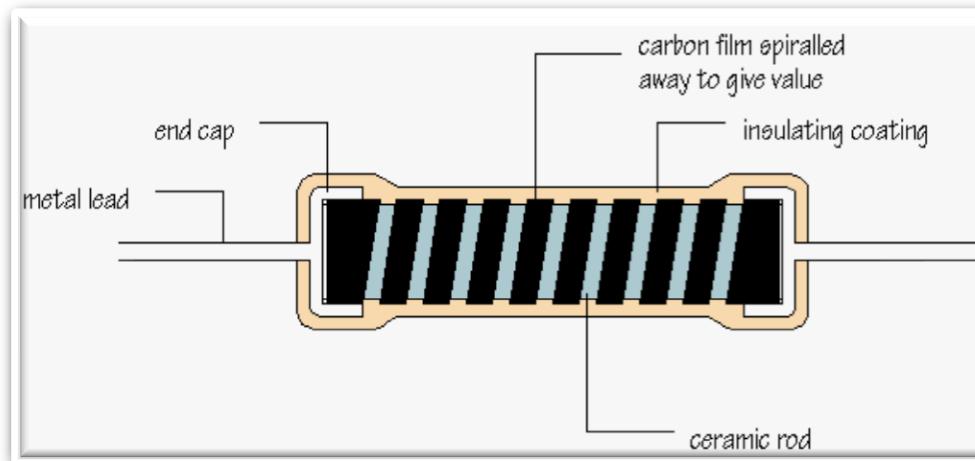
Resistance value: A.B x 10<sup>C</sup>  
Precision: D  
Example: 1.2 kΩ, ± 10%

# Cermet Resistors

- In ceramic-metals (cermet) resistors, a metal (e.g. Ru) is mixed with glass; the compound is deposited over a ceramic cylinder
- Better precision but lower maximum dissipated power compared to carbon resistors

# Film Resistors

- A thin (50nm-5μm) resistive layer (**carbon or metal**) is deposited over a glass/ceramic cylinder through CVD, PVD or sputtering
- Layer thickness determines resistance per square ( $R_{\square}$ )
- Layer is patterned (spiral shaped) to achieve high resistance values (above 10kΩ) using a SiC high pressure stream abrasion
- Precision better than 1% achievable through patterning



# Wire Resistors

- A wire ( $\varnothing \sim 50\mu\text{m}$ ) is coiled on a *steatites* cylinder
- High resistivity, low temperature coefficient composed materials are used:
  - NiCu       $\rho = 50 \mu\Omega\text{cm}$ ,  $\alpha_p = 10 \text{ ppm}/^\circ\text{C}$
  - NiCr       $\rho = 100 \mu\Omega\text{cm}$ ,  $\alpha_p = 100 \text{ ppm}/^\circ\text{C}$
  - CuMn       $\rho = 170 \mu\Omega\text{cm}$ ,  $\alpha_p = \pm 50 \text{ ppm}/^\circ\text{C}$
- High operating temperatures ( $\sim 300^\circ\text{C}$ )
- Low operating frequencies ( $\sim 100\text{kHz}$ ) limited by series inductance

# Summary

- What do you need to know about a resistor beyond its resistance value?
  - Resistance value precision (tolerance)
  - Maximum operating frequency (size, losses)
  - Maximum power, resistance temperature dependence
    - temperature effects
  - Maximum voltage, resistance voltage dependence (linearity)
  - Noise index

# Resistor Types

	<b><i>Carbon</i></b>	<b><i>Carb. Film</i></b>	<b><i>Metal Film</i></b>	<b><i>WiRes</i></b>
R [Ω]	1-10M	10 – 100M	0.1 – 1M	<100k
Tolerance	2-20%	0.5-5%	0.05-2%	0.5 – 5%
P <sub>DISS</sub> [W]	0.125 - 2	0.5-10	0.5-10	1-10k
f <sub>MAX</sub> [Hz]	100M	100M	10M	<200k
α [ppm/° C]	-200 / -500	-20 / -100	5 / 50	20 / 100
β [ppm/V]	-30 / -100	-0.2 / -10	0.2	0.5
I* [dB] *100Ω	-10 / 0	-20	-30	-30