Electrical Prop. of NP

- Ohms Law
  \[ I = \frac{U}{R} = U \cdot G \]
  \[ R_{\text{in}} \in [\Omega, \text{S}] \]

\[ R = \rho \cdot \frac{L}{A} \]

\[ S = \{ \text{semi} \} \rightarrow \text{material property} \]
Electrical Prop. of NP

- Ohm's Law

\[ V = \frac{1}{R} = \frac{A}{l} \]

\[ G = \frac{A}{l} \]

\[ \sigma = \frac{1}{\sigma} \]

\[ \rho = \frac{1}{\rho} \]

\[ \mu = \frac{1}{\mu} \]

\[ S = \frac{1}{S} \]

\( G \) - Conductance; \( \sigma \) - Conductivity

\( \rho \) - Resistance; \( \mu \) - Resistivity
E. P. KPF

- 5, 6, - at macroscale are related to diffuse electron scattering.

ECE 5320

Stanko R. Brankovic
\( E_\text{L P.} \ \text{in} \)

\( \nu_\text{e} - \text{electron speed} \)

\( \lambda - \text{mean free path} \)

\( \tau - \text{time between collisions} \)

\[ \nu_\text{e} = \frac{a}{\Delta t} \quad \lambda = \nu_\text{e} \cdot \Delta t \]

- At nano scale:

\[ L \rightarrow \lambda \]

BECOMES COMPARABLE
\[ E = P \cdot \nu P \]

\[ Q = \text{charge} \quad e^- = 1 \text{e}^- \]

\[ N e^- = Q \]

\[ \Delta t = \frac{2}{\nu e} \eta \frac{L_{\text{em}}}{\nu e} \quad \nu \text{mA} \]

\[ G = \frac{\frac{I}{V}}{\Delta t} = \frac{Q}{\Delta t V} = \frac{N e^- \nu e}{\Delta t V} \]

\[ E = e \cdot V \quad \text{energy of } e^- \]

\[ E = h \cdot \nu = h \cdot \frac{\nu e}{\lambda} \quad (\text{Planck, } h \in \text{B}) \]
\[ E = \frac{N e V e}{V \cdot L} \]
\[ e \cdot v = \frac{h V e}{\lambda} \]
\[ \Rightarrow G = \frac{N e V e}{h V e} \cdot \frac{L}{\lambda \cdot c} \]
\[ G = \frac{N e^2}{h} \cdot \frac{\theta}{L} \]
\[ \theta \approx \frac{m^2}{n^2} \]
\[ L = m^2, n=1, 2, \ldots \]
$E. P. NP$

$m$ - electron wave mode number

$m = 1$ or spin; $N = 2m$

\[ E = \frac{2m \cdot e^2}{h} \quad \frac{1}{m} = \frac{2e^2}{h} \quad \text{[C = 7 \times 10^{-5}]} \]

- Conductive of one mode than non-actve modes.
Figure 7.3 Electrical conductivity of a gold nanowire of 5 nm length, determined at a constant applied voltage of 32 mV. The gold wire was elongated during this experiment in 0.2-nm steps. The conductivity decreases stepwise with increasing elongation, which is equivalent to a reduction of the diameter. The shaded areas show the range of experimental scatter [2].
Figure 7.4 $I-V$ characteristics of a gold nanowire of 9.5 nm length after two different elongations. The non-Ohmic behavior, as indicated by the more than linear increase in current with increasing voltage, is clearly visible \[2\]. At increasing elongation, the cross-section becomes smaller and the wire longer, leading to an increased resistance.

As voltage increases, more ballistic channels are activated.
Figure 7.5 Electrical conductance of an originally 9.5 nm-long gold wire after elongation as a function of the applied voltage. These data were calculated using the values from Figure 7.4. Note the transition of a metallic behavior with voltage-independent conductance, to a semiconductor- or insulator-like behavior, where the conductance increases with the applied voltage.

(This is also semiconductor or insulator behavior.)
Figure 7.6 Current-voltage characteristics of a 50 nm-diameter, 5 μm-long silver nanowire measured at 4.2 K [3]. The current offset in the original data was removed.

\[ j = 10^3 - 10^4 \frac{A}{m^2} \]

\[ A = 25 \times 10^{-17} m^2 \]
E. P. N. P.
CNT

Who drawn them (Dale, et al)

Nanoswirl
Figure 7.8 Experimental set-up to measure the electric conductivity of carbon nanotubes of different length and orientation is fixed onto a sample holder and moved in the direction of a mercury droplet. The lengths of orientations of the carbon nanotubes are characterized by the carbon nanotube bundle.

Figure 7.9 Electrical conductance of multiwall nanotubes determined at a voltage of 100 mV. As characterized by the carbon nanotube bundle shown in Figure 7.8 for this experiment, four multiwall carbon nanotubes were immersed successively into a mercury droplet. The conductance of the carbon nanotube bundle was measured by the conductance meter. The conductance of the carbon nanotube bundle remained independent of the immersion depth.
\[ G = G_0 \left( \alpha + \beta |V| \right) \]

\[ G = G_0 \alpha + \beta G_0 |V| \]
Figure 7.11 Electric conductance of multiwall nanotubes according to Poncharal et al. [5]. For voltages above ca. ±100 mV, the electric conductance follows Equation (7.4); below that limit, the conductivity has a constant value. Graphene layers show a similar behavior [6].
Figure 7.13 Dependency of the electrical resistance of a single-walled nanotube as a function of the applied electric voltage [7]. In contrast to multivalved nanotubes, the resistance increases with increasing applied voltage.

\[ R = R_0 + \frac{1}{I_0} \]

\[ R_0/I_0 \text{ model parameters, relating to contact resistance} \]

\[ I = \frac{V}{R_0 + \frac{1}{I_0}} \]