ISSUES TO ADDRESS...

- How are electrical conductance and resistance characterized?
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, $T$, and deformation?
- For semiconductors, how is conductivity affected by impurities (doping) and $T$?
View of an Integrated Circuit

- Scanning electron microscope images of an IC:
  - A dot map showing location of Si (a semiconductor):
    - Si shows up as light regions.
  - A dot map showing location of Al (a conductor):
    - Al shows up as light regions.

![View of an Integrated Circuit](image_url)
Electrical Conduction

- **Ohm's Law:**
  
  \[ \Delta V = I \cdot R \]
  
  - Voltage drop (volts = J/C)
  - Current (amps = C/s)
  - Resistance (Ohms)

- **Resistivity, \( \rho \) and Conductivity, \( \sigma \):**
  
  - Geometry-independent forms of Ohm's Law
  - Resistivity is a material property & is independent of sample

- **Resistance:**
  
  \[ R = \frac{\rho L}{A} = \frac{L}{A \sigma} \]

- **Resistivity:**
  
  \[ \rho = \frac{\Delta V}{IL} \]

- **Conductivity:**
  
  \[ \sigma = \frac{1}{\rho} \]

- **Electric Field Intensity:**
  
  \[ E = \frac{\Delta V}{L} \]

- **Current Density:**
  
  \[ J = \frac{I}{A} \]
Electrical Properties

• Which will conduct more electricity?

\[ \rho = \frac{RA}{\ell} = \frac{VA}{l\ell} \]

• Analogous to flow of water in a pipe

• So resistance depends on sample geometry, etc.
Definitions

Further definitions

\[ J = \sigma \varepsilon \]

\( J \equiv \text{current density} = \frac{\text{current}}{\text{surface area}} = \frac{I}{A} \)

\( \varepsilon \equiv \text{electric field potential} = \frac{V}{\ell} \) or \( \frac{\Delta V}{\Delta \ell} \)

\[ J = \sigma \left( \frac{\Delta V}{\Delta \ell} \right) \]

Electron flux  conductivity  voltage gradient

Current carriers
- electrons in most solids
- ions can also carry (particularly in liquid solutions)
## Conductivity: Comparison

- Room $T$ values $(\text{Ohm-m})^{-1} = (\Omega \cdot m)^{-1}$

<table>
<thead>
<tr>
<th>METALS</th>
<th>Conductors</th>
<th>CERAMICS</th>
<th>POLYMERS</th>
<th>SEMICONDUCTORS</th>
<th>POLYMERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>$6.8 \times 10^7$</td>
<td>Soda-lime glass</td>
<td>Polystyrene</td>
<td>Silicon</td>
<td>$4 \times 10^{-4}$</td>
</tr>
<tr>
<td>Copper</td>
<td>$6.0 \times 10^7$</td>
<td>Concrete</td>
<td>Polyethylene</td>
<td>Germanium</td>
<td>$2 \times 10^0$</td>
</tr>
<tr>
<td>Iron</td>
<td>$1.0 \times 10^7$</td>
<td>Aluminum oxide</td>
<td></td>
<td>GaAs</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CERAMICS</th>
<th>Insulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soda-lime glass</td>
<td>$10^{-10}$-$10^{-11}$</td>
</tr>
<tr>
<td>Concrete</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>$&lt;10^{-13}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SEMICONDUCTORS</th>
<th>Insulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>$&lt;10^{-14}$</td>
</tr>
<tr>
<td>Germanium</td>
<td>$10^{-15}$-$10^{-17}$</td>
</tr>
<tr>
<td>GaAs</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POLYMERS</th>
<th>Insulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polystyrene</td>
<td>$&lt;10^{-14}$</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>$10^{-15}$-$10^{-17}$</td>
</tr>
</tbody>
</table>
Example: Conductivity Problem

What is the minimum diameter ($D$) of the wire so that $\Delta V < 1.5$ V?

Solve to get $D > 1.87$ mm
Conductivity, $\sigma$

$$\sigma = nq\mu$$

$m^{-3}$ \quad 0.16$\times$10$^{-18}$ C

$(\Omega \cdot m)^{-1}$ \quad m$^2$//(V$\cdot$s)

-1

Drift velocity, m/s

$$\mu = \frac{\bar{v}}{E}$$

Electric field strength, $E = V/l$, V/m

-1
Electronic Band Structures

- 2s Electron energy band (12 states)
- 1s Electron energy band (12 states)

Energy

Individual allowed energy states

Interatomic separation

2s Electron state

1s Electron state
Band Structure

- **Valence band** – filled – highest occupied energy levels
- **Conduction band** – empty – lowest unoccupied energy levels
Conduction & Electron Transport

• Metals (Conductors):
  -- Thermal energy puts many electrons into a higher energy state.

• Energy States:
  -- for metals nearby energy states are accessible by thermal fluctuations.
Energy States: Insulators & Semiconductors

• Insulators:
  -- Higher energy states not accessible due to gap (> 2 eV).

• Semiconductors:
  -- Higher energy states separated by smaller gap (< 2 eV).
Charge Carriers

Two charge carrying mechanisms

Electron – negative charge
Hole – equal & opposite positive charge

• Move at different speeds - drift velocity

Higher temp. promotes more electrons into the conduction band
∴ \( \sigma \uparrow \text{ as } T \uparrow \)

Electrons scattered by impurities, grain boundaries, etc.
Electron mobility

Scattering center: Imperfection in the crystal lattice including impurity atoms, vacancies, interstitial atoms, and thermal vibrations of atoms themselves

$$\mu = \frac{v_d}{E}$$

$v_d$: drift velocity, represents the average electron velocity in the direction of the force imposed by the applied field
Metals: Resistivity vs T

\[ \rho_T = \rho_0 + \alpha T \]

Due to the increase with temperature in thermal vibration and other lattice irregularities (e.g., vacancies), which serve as electron-scattering centers.
Metals: Resistivity vs Impurities

- Imperfections increase resistivity
  - grain boundaries
  - dislocations
  - impurity atoms
  - vacancies

  These act to scatter electrons so that they take a less direct path.

- Resistivity increases with:
  - temperature
  - wt% impurity
  - %CW

\[
\rho = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{deformation}}
\]
Pure Semiconductors: Conductivity vs T

- Data for Pure Silicon:
  - \( \sigma \) increases with \( T \)
  - opposite to metals

Electrical conductivity, \( \sigma \) (Ohm-m)^{-1}

\[
\sigma_{\text{undoped}} \propto e^{-\frac{E_{\text{gap}}}{kT}}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Band Gap (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.11</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
</tr>
<tr>
<td>GaP</td>
<td>2.25</td>
</tr>
<tr>
<td>CdS</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Electrons can cross gap at higher \( T \)
Conduction in Terms of Electron and Hole Migration

• Concept of electrons and holes:
  - valence electron
  - Si atom
  - electron • hole •
  - pair creation
  - no applied electric field
  - applied electric field
  - electron • hole •
  - pair migration

• Electrical Conductivity given by:
  
  \[ \sigma = n e \mu_e + p e \mu_h \]

  # electrons/m^3
  # holes/m^3
  electron mobility
  hole mobility
Intrinsic vs Extrinsic Conduction

- **Intrinsic**: 
  # electrons = # holes \((n = p)\)  
  -- case for pure Si

- **Extrinsic**:  
  \(-n \neq p\)  
  -- occurs when impurities are added with a different  
  # valence electrons than the host (e.g., Si atoms)

- **\(n\)-type Extrinsic**: \((n \gg p)\)  
  - no applied electric field

- **\(p\)-type Extrinsic**: \((p \gg n)\)  
  - no applied electric field

\[
\sigma \approx n|e|\mu_e \\
\sigma \approx p|e|\mu_h
\]
Hall effect

- Determine majority charge carrier type, concentration, and mobility.

\[ V_H = \frac{R_H I_x B_z}{d} \]

where \( R_H \): Hall coefficient

- For metal (CC; electron), \( R_H \) is negative.

\[ R_H = \frac{1}{n|e|} \]

\[ \mu = \frac{\sigma}{n|e|} = |R_H| \sigma \]
Intrinsic Semiconductors

• Pure material semiconductors: e.g., silicon & germanium
  – Group IVA materials

• Compound semiconductors
  – III-V compounds
    • Ex: GaAs & InSb
  – II-VI compounds
    • Ex: CdS & ZnTe
  – The wider the electronegativity difference between the elements the wider the energy gap.
FIGURE 13.40  Arrhenius plot of electrical conductivity for a $p$-type semiconductor over a wide temperature range. This plot is quite similar to the behavior shown in Figure 13.36. The region between intrinsic and extrinsic behavior is termed the saturation range, which corresponds to all acceptor levels being "saturated" or occupied with electrons.
Doped Semiconductor: Conductivity vs. T

- **Data for Doped Silicon:**
  - $\sigma$ increases doping
  - reason: imperfection sites lower the activation energy to produce mobile electrons.

- **Comparison:** intrinsic vs extrinsic conduction...
  - extrinsic doping level: $10^{21}/m^3$ of a $n$-type donor impurity (such as P).
  - for $T < 100$ K: "freeze-out", thermal energy insufficient to excite electrons.
  - for $150$ K $< T < 450$ K: "extrinsic"
  - for $T >> 450$ K: "intrinsic"
Number of Charge Carriers

Intrinsic Conductivity

\[ \sigma = n|e|\mu_e + p|e|\mu_p \]

- for intrinsic semiconductor \( n = p \)
  \[ \therefore \sigma = n|e|(\mu_e + \mu_n) \]

- Ex: GaAs
  \[ n = \frac{\sigma}{|e|(\mu_e + \mu_n)} = \frac{10^{-6}(\Omega \cdot m)^{-1}}{(1.6 \times 10^{-19} \text{C})(0.85 + 0.45 \text{ m}^2/\text{V} \cdot \text{s})} \]

  For GaAs \( n = 4.8 \times 10^{24} \text{ m}^{-3} \)
  For Si \( n = 1.3 \times 10^{16} \text{ m}^{-3} \)
<table>
<thead>
<tr>
<th>Element</th>
<th>Dopant</th>
<th>Periodic table group of dopant</th>
<th>(Maximum solid solubility of dopant atoms/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>B</td>
<td>III A</td>
<td>$600 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>III A</td>
<td>$20 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>Ga</td>
<td>III A</td>
<td>$40 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>V A</td>
<td>$1,000 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>V A</td>
<td>$2,000 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>V A</td>
<td>$70 \times 10^{24}$</td>
</tr>
<tr>
<td>Ge</td>
<td>Al</td>
<td>III A</td>
<td>$400 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>Ga</td>
<td>III A</td>
<td>$500 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>In</td>
<td>III A</td>
<td>$4 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>V A</td>
<td>$80 \times 10^{24}$</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>V A</td>
<td>$10 \times 10^{24}$</td>
</tr>
</tbody>
</table>

### TABLE 13.7

Impurity Energy Levels for Extrinsic Semiconductors

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Dopant</th>
<th>$E_g - E_d$ (eV)</th>
<th>$E_d$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>P</td>
<td>0.044</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>0.049</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>0.039</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Bi</td>
<td>0.069</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>—</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>—</td>
<td>0.057</td>
</tr>
<tr>
<td></td>
<td>Ga</td>
<td>—</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>In</td>
<td>—</td>
<td>0.160</td>
</tr>
<tr>
<td></td>
<td>Tl</td>
<td>—</td>
<td>0.260</td>
</tr>
<tr>
<td>Ge</td>
<td>P</td>
<td>0.012</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>0.013</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>0.096</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>—</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>—</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Ga</td>
<td>—</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>In</td>
<td>—</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>Tl</td>
<td>—</td>
<td>0.010</td>
</tr>
<tr>
<td>GaAs</td>
<td>Se</td>
<td>0.005</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Te</td>
<td>0.003</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Zn</td>
<td>—</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>Cd</td>
<td>—</td>
<td>0.021</td>
</tr>
</tbody>
</table>

### TABLE 13.8

Some Compound Semiconductors

<table>
<thead>
<tr>
<th>Group</th>
<th>Compound</th>
<th>Group</th>
<th>Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>III–V</td>
<td>BP</td>
<td>II–VI</td>
<td>ZnS</td>
</tr>
<tr>
<td></td>
<td>AlSb</td>
<td></td>
<td>ZnSe</td>
</tr>
<tr>
<td></td>
<td>GaP</td>
<td></td>
<td>ZnTe</td>
</tr>
<tr>
<td></td>
<td>GaAs</td>
<td></td>
<td>CdS</td>
</tr>
<tr>
<td></td>
<td>GaSb</td>
<td></td>
<td>CdSe</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td></td>
<td>CdTe</td>
</tr>
<tr>
<td></td>
<td>InAs</td>
<td></td>
<td>HgSe</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td></td>
<td>HgTe</td>
</tr>
<tr>
<td>Group</td>
<td>Semiconductor</td>
<td>$E_g$ (eV)</td>
<td>$\mu_e$ [m$^2$/V·s]</td>
</tr>
<tr>
<td>-------</td>
<td>---------------</td>
<td>------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>III–V</td>
<td>AlSb</td>
<td>1.60</td>
<td>0.090</td>
</tr>
<tr>
<td></td>
<td>GaP</td>
<td>2.25</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>GaAs</td>
<td>1.47</td>
<td>0.720</td>
</tr>
<tr>
<td></td>
<td>GaSb</td>
<td>0.68</td>
<td>0.500</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>1.27</td>
<td>0.460</td>
</tr>
<tr>
<td></td>
<td>InAs</td>
<td>0.36</td>
<td>3.300</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>0.17</td>
<td>8.000</td>
</tr>
<tr>
<td>II–VI</td>
<td>ZnSe</td>
<td>2.67</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>ZnTe</td>
<td>2.26</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>CdS</td>
<td>2.59</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>CdTe</td>
<td>1.50</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>HgTe</td>
<td>0.025</td>
<td>2.200</td>
</tr>
</tbody>
</table>

**p-n Rectifying Junction**

- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.
- Processing: diffuse P into one side of a B-doped crystal.
- Results:
  - No applied potential: no net current flow.
  - Forward bias: carrier flow through $p$-type and $n$-type regions; holes and electrons recombine at $p$-$n$ junction; current flows.
  - Reverse bias: carrier flow away from $p$-$n$ junction; carrier conc. greatly reduced at junction; little current flow.
Properties of Rectifying Junction

(a) Voltage, V vs. Time

(b) Current, I vs. Time
Transistor MOSFET

- MOSFET (metal oxide semiconductor field effect transistor)
Integrated Circuit Devices

- Integrated circuits - state of the art ca. 50 nm line width
  - 1 Mbyte cache on board
  - > 100,000,000 components on chip
  - chip formed layer by layer
    - Al is the “wire”
FIGURE 13.48  Schematic illustration of the lithography process steps for producing vitreous SiO$_2$ patterns on a silicon wafer.  
FIGURE 13.49  Schematic illustration of the lithography process steps for producing metal patterns on a silicon wafer.
FIGURE 13.52  Plot of the electrical conductivity data from Table 13.1. The conductivity ranges correspond to the four fundamental types of engineering materials.
Superconductivity

- $T_c = \text{temperature below which material is superconductive} = \text{critical temperature}$

4.2 K

- Hg
- Copper (normal)
Limits of Superconductivity

• 26 metals + 100’s of alloys & compounds
• Unfortunately, not this simple:
  \[ J_c = \text{critical current density if } J > J_c \text{ not superconducting} \]
  \[ H_c = \text{critical magnetic field if } H > H_c \text{ not superconducting} \]

\[ H_c = H_0 \left(1 - \left(\frac{T}{T_c}\right)^2\right) \]
Advances in Superconductivity

• This research area was stagnant for many years.
  - Everyone assumed $T_{c,\text{max}}$ was about 23 K
  - Many theories said you couldn’t go higher
• 1987—new results published for $T_c > 30$ K
  - ceramics of form $\text{Ba}_1-\text{x} \ K_\text{x} \ \text{BiO}_3-\text{y}$
  - Started enormous race.
    • $\text{Y Ba}_2\text{Cu}_3\text{O}_{7-\text{x}}$ \hspace{1cm} $T_c = 90$ K
    • $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ \hspace{1cm} $T_c = 122$ K
    • tricky to make since oxidation state is quite important
• Values now stabilized at ca. 120 K
Meissner Effect

• Superconductors expel magnetic fields

• This is why a superconductor will float above a magnet
Current Flow in Superconductors

- **Type I**
  - current only in outer skin
  - so amount of current limited

- **Type II**
  - current flows within wire

![Diagram showing current flow in superconductors with magnetic field (H) and magnetization (M) axes.](image)
Superconducting Materials

YBa$_2$Cu$_3$O$_7$

Vacancies (X) provide electron coupling between CuO$_2$ planes.

CuO$_2$ planes

Ba

Y

Ba

linear chains

(001) planes
FIGURE 13.14  Schematic illustration of a thermocouple. The measured voltage, $V_{12}$, is a function of the temperature difference, $T_1 - T_2$. The overall phenomenon is termed the Seebeck effect.
### TABLE 13.3

<table>
<thead>
<tr>
<th>Type</th>
<th>Common name</th>
<th>Positive element</th>
<th>Negative element</th>
<th>Recommended service environment(s)</th>
<th>Maximum service temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Platinum-rhodium/platinum-rhodium</td>
<td>70 Pt–30</td>
<td>94 Pt–6</td>
<td>Oxidizing Vacuum Inert</td>
<td>1,700</td>
</tr>
<tr>
<td>E</td>
<td>Chromel/constantan</td>
<td>90 Ni–9 Cr</td>
<td>44 Ni–55 Cu</td>
<td>Oxidizing</td>
<td>870</td>
</tr>
<tr>
<td>J</td>
<td>Iron/constantan</td>
<td>Fe</td>
<td>44 Ni–55 Cu</td>
<td>Oxidizing Reducing</td>
<td>760</td>
</tr>
<tr>
<td>K</td>
<td>Chromel/alumel</td>
<td>90 Ni–9 Cr</td>
<td>94 Ni–Al, Mn, Fe, Si, Co</td>
<td>Oxidizing</td>
<td>1,260</td>
</tr>
<tr>
<td>R</td>
<td>Platinum/platinum-rhodium</td>
<td>87 Pt–13 Rh</td>
<td>Pt</td>
<td>Oxidizing Inert</td>
<td>1,480</td>
</tr>
<tr>
<td>S</td>
<td>Platinum/platinum-rhodium</td>
<td>90 Pt–10 Rh</td>
<td>Pt</td>
<td>Oxidizing Inert</td>
<td>1,480</td>
</tr>
<tr>
<td>T</td>
<td>Copper/constantan</td>
<td>Cu</td>
<td>44 Ni–55 Cu</td>
<td>Oxidizing Reducing</td>
<td>370</td>
</tr>
</tbody>
</table>

* Alloy compositions expressed as weight percents.

FIGURE 13.15  Plot of thermocouple electromotive force (= $V_{12}$ in Figure 13.14) as a function of temperature for some common thermocouple systems listed in Table 13.3.
Dielectrics

유전체로 채워진 콘덴서의 정전용량을 $Q$라 하면 인가직류전압 $V$와 전극간에 축적된 전하 $Q$간에는 다음 관계가 성립한다.

$$ Q = CV $$ (1)

일반적으로 $C$는 전극의 형상, 크기에 따른 상수 $K$와 유전율 $\varepsilon$의 곱이다.

$$ C = \varepsilon K $$ (2)

유전체를 진공으로 치환한 경우의 정전용량을 $C_0$라고 하면

$$ C_0 = \varepsilon_0 K $$ (3)

여기서 $C_0$를 geometrical capacity(기하용량)이라 하며

$$ \varepsilon_0 = 8.855 \times 10^{-12} \text{ F/m} \quad (4) $$

이이다.

$$ \varepsilon = \frac{\varepsilon_0}{\varepsilon_r} $$ (5)

를 relative dielectric constant (비유전율)라고 한다. 유전체의 비유전율은 항상 1보다 크다.

평행평판 콘덴사를 예를 들어 유전율의 의미를 간단하게 살펴보기로 하자. 전극의 면적을 $A$, 이의 간격을 $d$라 하면 식(2)의 $K$는 다음과 같다.

$$ K = \frac{A}{d} $$ (6)

식 (2)와 (6)을 식(1)에 대입하면

$$ \frac{Q}{A} = \frac{V}{d} \quad (7) $$

전극전하의 표면밀도를 $q$, 전장강도를 $E$라 하면

$$ q = \varepsilon E \quad \text{or} \quad E = \frac{q}{\varepsilon} $$ (8)

이 식은 표면밀도 $q$와 전하에 의해 유전체중에 형성되는 균일한 전기장과 유전율간의 관계를 보이고 있다. 또한 condenser에 축적된 에너지 $W$를 계산하면

$$ W = \frac{1}{2} \varepsilon \frac{A}{d} V^2 = \frac{1}{2} \varepsilon (Ad)E^2 $$

즉 유전율은 단위전장 아래 단위부피중에 축적된 정전에너지의 크기를 나타내는 양으로 이해할 수 있다.
<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric constant, $^a\kappa$</th>
<th>Dielectric strength (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$ (99.9%)</td>
<td>10.1</td>
<td>9.1$^b$</td>
</tr>
<tr>
<td>Al$_2$O$_3$ (99.5%)</td>
<td>9.8</td>
<td>9.5$^b$</td>
</tr>
<tr>
<td>BeO (99.5%)</td>
<td>6.7</td>
<td>10.2$^b$</td>
</tr>
<tr>
<td>Cordierite</td>
<td>4.1–5.3</td>
<td>2.4–7.9$^b$</td>
</tr>
<tr>
<td>Nylon 66-reinforced with 33% glass fibers (dry-as-molded)</td>
<td>3.7</td>
<td>20.5</td>
</tr>
<tr>
<td>Nylon 66-reinforced with 33% glass fibers (50% relative humidity)</td>
<td>7.8</td>
<td>17.3</td>
</tr>
<tr>
<td>Acetal (50% relative humidity)</td>
<td>3.7</td>
<td>19.7</td>
</tr>
<tr>
<td>Polyester</td>
<td>3.6</td>
<td>21.7</td>
</tr>
</tbody>
</table>

$^a$ At $10^3$Hz.

$^b$ Average root-mean-square (RMS) values at 60 Hz.

Source: Data from Ceramic Source '86, American Ceramic Society, Columbus, OH, 1985, and Design Handbook for DuPont Engineering Plastics.
Ferroelectric Ceramics

Ferroelectric Ceramics are dipolar below Curie $T_C = 120^\circ C$

- cooled below $T_c$ in strong electric field - make material with strong dipole moment
On a plot of polarization ($P$) versus applied electrical field strength ($E$), a paraelectric material exhibits only a modest level of polarization with applied fields. In contrast, a ferroelectric material exhibits spontaneous polarization in which domains of similarly oriented unit cells grow under increasing fields of similar orientation.
A ferroelectric hysteresis loop is the result of an alternating electric field. A dashed line indicates the initial spontaneous polarization illustrated in Figure 13.23. Saturation polarization ($P_s$) is the result of maximum domain growth (extrapolated back to zero field). Upon actual field removal, some remanent polarization ($P_r$) remains. A coercive field ($E_c$) is required to reach zero polarization (equal volumes of opposing domains).
Piezoelectric Materials

Piezoelectricity – application of pressure produces current

- at rest
- compression induces voltage
- applied voltage induces expansion
Summary

• Electrical **conductivity** and **resistivity** are:
  -- material parameters.
  -- geometry independent.
• Electrical **resistance** is:
  -- a geometry and material dependent parameter.
• Conductors, semiconductors, and insulators...
  -- differ in accessibility of energy states for conductance electrons.
• For metals, conductivity is increased by
  -- reducing deformation
  -- reducing imperfections
  -- decreasing temperature.
• For pure semiconductors, conductivity is increased by
  -- increasing temperature
  -- doping (e.g., adding B to Si (p-type) or P to Si (n-type)).