# A Constitutive Parameters of Some Common Materials

## A Constitutive Parameters of Some Common Materials

## A.1 Permittivity of Some Common Materials

The values below are relative permittivity $\epsilon_r \triangleq \epsilon/\epsilon_0$ for a few materials that are commonly encountered in electrical engineering applications, and for which permittivity emerges as a consideration. Note that "relative permittivity" is sometimes referred to as *dielectric constant*.

Here we consider only the physical (real-valued) permittivity, which is the real part of the complex permittivity (typically indicated as $\epsilon'$ or $\epsilon_r'$) for materials exhibiting significant loss.

Permittivity varies significantly as a function of frequency. The values below are representative of frequencies from a few kHz to about 1 GHz. The values given are also representative of optical frequencies for materials such as silica that are used in optical applications. Permittivity also varies as a function of temperature. In applications where precision better than about 10% is required, primary references accounting for frequency and temperature should be consulted. The values presented here are gathered from a variety of references, including those indicated in "Additional References."

**Free Space** (vacuum): $\epsilon_r \triangleq 1$

**Solid Dielectrics**:

| Material | $\epsilon_r$ | Common uses |
|---|---|---|
| Styrofoam[1] | 1.1 | |
| Teflon[2] | 2.1 | |
| Polyethylene | 2.3 | coaxial cable |
| Polypropylene | 2.3 | |
| Silica | 2.4 | optical fiber[3] |
| Polystyrene | 2.6 | |
| Polycarbonate | 2.8 | |
| Rogers RO3003 | 3.0 | PCB substrate |
| FR4 (glass epoxy laminate) | 4.5 | PCB substrate |

[1] Properly known as *extruded polystyrene foam* (XPS).
[2] Properly known as *polytetrafluoroethylene* (PTFE).
[3] Typically doped with small amounts of other materials to slightly raise or lower the index of refraction ( $= \sqrt{\epsilon_r}$).

Non-conducting spacing materials used in discrete capacitors exhibit $\epsilon_r$ ranging from about 5 to 50.

**Semiconductors** commonly appearing in electronics – including carbon, silicon, geranium, indium phosphide, and so on – typically exhibit $\epsilon_r$ in the range 5–15.

**Glass** exhibits $\epsilon_r$ in the range 4–10, depending on composition.

**Gasses**, including air, typically exhibit $\epsilon_r \cong 1$ to within a tiny fraction of a percent.

**Liquid water** typically exhibits $\epsilon_r$ in the range 72–81. Distilled water exhibits $\epsilon_r \approx 81$ at room temperature, whereas sea water tends to be at the lower end of the range.

**Other liquids** typically exhibit $\epsilon_r$ in the range 10–90, with considerable variation as a function of temperature and frequency. Animal flesh and blood consists primarily of liquid matter and so also exhibits permittivity in this range.

**Soil** typically exhibits $\epsilon_r$ in the range 2.5–3.5 when dry and higher when wet. The permittivity of soil varies considerably depending on composition.

**Additional Reading:**

- *CRC Handbook of Chemistry and Physics* (http://hbcponline.com).
- "Relative permittivity (https://en.wikipedia.org/wiki/Relative_permittivity)" on Wikipedia.
- "Miscellaneous Dielectric Constants (http://www.microwaves101.com/encyclopedias/miscellaneous-dielectric-constants)" on microwaves101.com (http://www.microwaves101.com).

## A.2 Permeability of Some Common Materials

The values below are relative permeability $\mu_r \triangleq \mu/\mu_0$ for a few materials that are commonly encountered in electrical engineering applications, and for which $\mu_r$ is significantly different from $1$. These materials are predominantly ferromagnetic metals and (in the case of ferrites) materials containing significant ferromagnetic metal content. Nearly all other materials exhibit $\mu_r$ that is not significantly different from that of free space.

The values presented here are gathered from a variety of references, including those indicated in "Additional References" at the end of this section. Be aware that permeability may vary significantly with frequency; values given here are applicable to the frequency ranges for applications in which these

materials are typically used. Also be aware that materials exhibiting high permeability are also typically non-linear; that is, permeability depends on the magnitude of the magnetic field. Again, values reported here are those applicable to applications in which these materials are typically used.

**Free Space** (vacuum): $\mu_r \triangleq 1$.

**Iron** (also referred to by the chemical notation “Fe”) appears as a principal ingredient in many materials and alloys employed in electrical structures and devices. Iron exhibits $\mu_r$ that is very high, but which decreases with decreasing purity. 99.95% pure iron exhibits $\mu_r \sim 200,000$. This decreases to $\sim 5000$ at 99.8% purity and is typically below 100 for purity less than 99%.

**Steel** is an iron alloy that comes in many forms, with a correspondingly broad range of permeabilities. *Electrical steel*, commonly used in electrical machinery and transformers when high permeability is desired, exhibits $\mu_r \sim 4000$. *Stainless steel*, encompassing a broad range of alloys used in mechanical applications, exhibits $\mu_r$ in the range 750–1800. *Carbon steel*, including a broad class of alloys commonly used in structural applications, exhibits $\mu_r$ on the order of 100.

**Ferrites** include a broad range of ceramic materials that are combined with iron and various combinations of other metals and are used as magnets and magnetic devices in various electrical systems. Common ferrites exhibit $\mu_r$ in the range 16–640.

**Additional Reading:**

- *CRC Handbook of Chemistry and Physics* (http://hbcponline.com).
- “Magnetic Materials (https://www.microwaves101.com/encyclopedias/magnetic-materials)” on microwaves101.com (http://www.microwaves101.com).
- “Permeability (electromagnetism) (https://en.wikipedia.org/wiki/Permeability_(electromagnetism))” on Wikipedia.
- “Iron (https://en.wikipedia.org/wiki/Iron)” on Wikipedia.
- “Electrical steel (https://en.wikipedia.org/wiki/Electrical_steel)” on Wikipedia.
- “Ferrite (magnet) (https://en.wikipedia.org/wiki/Ferrite_(magnet))” on Wikipedia.

## A.3 Conductivity of Some Common Materials

The values below are conductivity $\sigma$ for a few materials that are commonly encountered in electrical engineering applications, and for which conductivity emerges as a consideration.

Note that materials in some applications are described instead in terms of *resistivity*, which is simply the reciprocal of conductivity.

Conductivity may vary significantly as a function of frequency. The values below are representative of frequencies from a few kHz to a few GHz. Conductivity also varies as a function of temperature. In applications where precise values are required, primary references accounting for frequency and

temperature should be consulted. The values presented here are gathered from a variety of references, including those indicated in “Additional References” at the end of this section.

**Free Space** (vacuum): $\sigma \triangleq 0$.

**Commonly encountered elements**:

| Material | $\sigma$ (S/m) |
|---|---|
| Copper | $5.8 \times 10^7$ |
| Gold | $4.4 \times 10^7$ |
| Aluminum | $3.7 \times 10^7$ |
| Iron | $1.0 \times 10^7$ |
| Platinum | $0.9 \times 10^7$ |
| Carbon | $1.3 \times 10^5$ |
| Silicon | $4.4 \times 10^{-4}$ |

**Water** exhibits $\sigma$ ranging from about $6$ $\mu$S/m for highly distilled water (thus, a very poor conductor) to about $5$ S/m for seawater (thus, a relatively good conductor), varying also with temperature and pressure. Tap water is typically in the range of 5–50 mS/m, depending on the level of impurities present.

**Soil** typically exhibits $\sigma$ in the range $10^{-4}$ S/m for dry soil to about $10^{-1}$ S/m for wet soil, varying also due to chemical composition.

**Non-conductors**. Most other materials that are not well-described as conductors or semiconductors and are dry exhibit $\sigma < 10^{-12}$ S/m. Most materials that are considered to be *insulators*, including air and common dielectrics, exhibit $\sigma < 10^{-15}$ S/m, often by several orders of magnitude.

**Additional Reading:**

- *CRC Handbook of Chemistry and Physics* (http://hbcponline.com).
- “Conductivity (electrolytic) (https://en.wikipedia.org/wiki/Conductivity_(electrolytic))” on Wikipedia.
- “Electrical resistivity and conductivity (https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity)” on Wikipedia.
- “Soil resistivity (https://en.wikipedia.org/wiki/Soil_resistivity)” on Wikipedia.