

Relative permittivity

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The **relative permittivity** of a material is its dielectric permittivity expressed as a ratio relative to the permittivity of vacuum.

Permittivity is a material property that expresses the force between two point charges in the material. Relative permittivity is the factor by which the electric field between the charges is decreased relative to vacuum.

Likewise, relative permittivity is the ratio of the capacitance of a capacitor using that material as a dielectric, compared to a similar capacitor that has vacuum as its dielectric. Relative permittivity is also commonly known as *dielectric constant*, a term deprecated in physics and engineering.

Relative permittivities of some materials at room temperature under 1 kHz

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Definition

Relative permittivity is typically denoted as $\epsilon_r(\omega)$ (sometimes κ or \mathbf{K}) and is defined as

$$\epsilon_r(\omega) = \frac{\epsilon(\omega)}{\epsilon_0},$$

where $\epsilon(\omega)$ is the complex frequency-dependent absolute permittivity of the material, and ϵ_0 is the vacuum permittivity.

Relative permittivity is a dimensionless number that is in general complex-valued; its real and imaginary parts are denoted as:^[1]

$$\epsilon_r(\omega) = \epsilon'_r(\omega) + i\epsilon''_r(\omega).$$

The relative permittivity of a medium is related to its electric susceptibility, χ_e , as $\epsilon_r(\omega) = 1 + \chi_e$.

In anisotropic media (such as non cubic crystals) the relative permittivity is a second rank tensor.

The relative permittivity of a material for a frequency of zero is known as its **static relative permittivity**.

Terminology

The historical term for the relative permittivity is *dielectric constant*. It is still commonly used, but has been deprecated by standards organizations,^{[12][13]} because of its ambiguity, as some older authors used it for the absolute permittivity ϵ .^{[13][14][15]} The permittivity may be quoted either as a static property or as a frequency-dependent variant. It has also been used to refer to only the real component ϵ'_r of the complex-valued relative permittivity.

Physics

In physics, permittivity is a complex quantity. The imaginary part corresponds to a phase shift of the polarization **P** relative to **E** and leads to the attenuation of electromagnetic waves passing through the medium. By definition, the linear relative permittivity of vacuum is equal to 1,^[15] that is $\epsilon = \epsilon_0$, although there are theoretical nonlinear quantum effects in vacuum that exist at high field strengths.^[16]

Measurement

The relative static permittivity, ϵ_r , can be measured for static electric fields as follows: first the capacitance of a test capacitor, C_0 , is measured with vacuum between its plates.

Then, using the same capacitor and distance between its plates, the capacitance C_x with a dielectric between the plates is measured. The relative dielectric constant can be then calculated as

$$\epsilon_r = \frac{C_x}{C_0}.$$

For time-variant electromagnetic fields, this quantity becomes frequency-dependent. An indirect technique to calculate ϵ_r is conversion of radio frequency S-parameter measurement results. A description of frequently used S-parameter conversions for determination of the frequency-dependent ϵ_r of dielectrics can be found in this bibliographic source.^[17] Alternatively, resonance based effects may be employed at fixed frequencies.^[18]

Applications

Energy

The dielectric constant is an essential piece of information when designing capacitors, and in other circumstances where a material might be expected to introduce capacitance into a circuit. If a material with a high dielectric constant is placed in an electric field, the magnitude of that field will be measurably reduced within the volume of the dielectric. This fact is

Material	ϵ_r
Vacuum	1 (by definition)
Air	1.000 589 86 ± 0.000 000 50 (at STP, for 0.9 MHz), ^[11]
PTFE/Teflon	2.1
Polyethylene/XLPE	2.25
Polyimide	3.4
Polypropylene	2.2–2.36
Polystyrene	2.4–2.7
Carbon disulfide	2.6
Mylar	3.1 ^[2]
Paper	3.85
Electroactive polymers	2–12
Mica	3–6 ^[2]
Silicon dioxide	3.9 ^[3]
Sapphire	8.9–11.1 (anisotropic) ^[4]
Concrete	4.5
Pyrex (Glass)	4.7 (3.7–10)
Neoprene	6.7 ^[2]
Rubber	7
Diamond	5.5–10
Salt	3–15
Graphite	10–15
Silicon	11.68
Silicon nitride	7–8 (polycrystalline, 1MHz) ^[5] ^[6]
Ammonia	26, 22, 20, 17 (−80, −40, 0, 20 °C)
Methanol	30
Ethylene glycol	37
Furfural	42.0
Glycerol	41.2, 47, 42.5 (0, 20, 25 °C)
Water	88, 80.1, 55.3, 34.5 (0, 20, 100, 200 °C) for visible light: 1.77
Hydrofluoric acid	83.6 (0 °C)
Formamide	84.0 (20 °C)
Sulfuric acid	84–100 (20–25 °C)
Hydrogen peroxide	128 aq–60 (−30–25 °C)
Hydrocyanic acid	158.0–2.3 (0–21 °C)
Titanium dioxide	86–173
Strontium titanate	310
Barium strontium titanate	500

commonly used to increase the capacitance of a particular capacitor design. The layers beneath etched conductors in printed circuit boards (PCBs) also act as dielectrics.

Communication

Dielectrics are used in RF transmission lines. In a coaxial cable, polyethylene can be used between the center conductor and outside shield. It can also be placed inside waveguides to form filters. Optical fibers are examples of *dielectric waveguides*. They consist of dielectric materials that are purposely doped with impurities so as to control the precise value of ϵ_r within the cross-section. This controls the refractive index of the material and therefore also the optical modes of transmission. However, in these cases it is technically the relative permittivity that matters, as they are not operated in the electrostatic limit.

Environment

The relative permittivity of air changes with temperature, humidity, and barometric pressure.^[19] Sensors can be constructed to detect changes in capacitance caused by changes in the relative permittivity. Most of this change is due to effects of temperature and humidity as the barometric pressure is fairly stable. Using the capacitance change, along with the measured temperature, the relative humidity can be obtained using engineering formulas.

Chemistry

The relative static permittivity of a solvent is a relative measure of its chemical polarity. For example, water is very polar, and has a dielectric constant of 80.10 at 20 °C while *n*-hexane is non-polar, and has a dielectric constant of 1.89 at 20 °C.^[20] This information is important when designing separation, sample preparation and chromatography techniques in analytical chemistry.

The correlation should, however, be treated with caution. For instance, dichloromethane has a value of ϵ_r of 9.08 (20 °C) and is rather poorly soluble in water (13 g/L or 9.8 mL/L at 20 °C); at the same time, tetrahydrofuran has its $\epsilon_r = 7.52$ at 22 °C, but it is completely miscible with water. In the case tetrahydrofuran, the oxygen atom can act as a hydrogen bond acceptor; where as dichloromethane cannot form hydrogen bonds with water.

This is even more apparent when considering the ϵ_r of acetic acid (6.2528)^[21] and that of iodoethane (7.6177).^[21] The large numerical value of ϵ_r is not surprising in the second case, as the iodine atom is easily polarizable; nevertheless, this does not imply that it is polar, too (electronic polarizability prevails over the orientational one in this case).

Lossy medium

Again, similar as for absolute permittivity, relative permittivity for lossy materials can be formulated as:

$$\epsilon_r = \epsilon'_r + \frac{i\sigma}{\omega\epsilon_0},$$

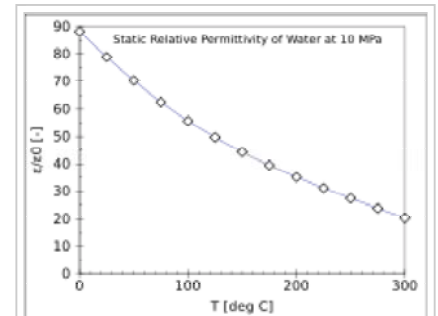
in terms of a "dielectric conductivity" σ (units S/m, siemens per meter), which "sums over all the dissipative effects of the material; it may represent an actual [electrical] conductivity caused by migrating charge carriers and it may also refer to an energy loss associated with the dispersion of ϵ' [the real-valued permittivity]" (^[11] p. 8). Expanding the angular frequency $\omega = 2\pi c/\lambda$ and the electric constant $\epsilon_0 = 1/(\mu_0 c^2)$, it reduces to:

$$\epsilon_r = \epsilon'_r + i\sigma\lambda\kappa,$$

where λ is the wavelength, c is the speed of light in vacuum and $\kappa = \mu_0 c/2\pi \approx 60.0 \text{ S}^{-1}$ is a newly introduced constant (units reciprocal of siemens, such that $\sigma\lambda\kappa = \epsilon_r$ remains unitless).

Metals

Barium titanate ^[7]	1200–10,000 (20–120 °C)
Lead zirconate titanate	500–6000
Conjugated polymers	1.8–6 up to 100,000 ^[8]
Calcium copper titanate	>250,000 ^{[9][10]}



Temperature dependence of the relative static permittivity of water

Permittivity is typically associated with dielectric materials, however metals are described as having an effective permittivity, with real relative permittivity equal to one.^[22] In the low-frequency region, which extends from radio frequencies to the far infrared and terahertz region, the plasma frequency of the electron gas is much greater than the electromagnetic propagation frequency, so the complex index n of a metal is practically a purely imaginary number, expressed in terms of effective relative permittivity it has a low imaginary value (loss) and a negative real-value (high conductivity).^[23]

See also

- Curie temperature
- Dielectric spectroscopy
- Dielectric strength
- Electret
- Ferroelectricity
- Green–Kubo relations
- High-k dielectric
- Kramers–Kronig relation
- Linear response function
- Low-k dielectric
- Loss tangent
- Permittivity
- Refractive index

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