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Fraunhofer Institute for Electron
Beam and Plasma Technology FEP

# Coatings

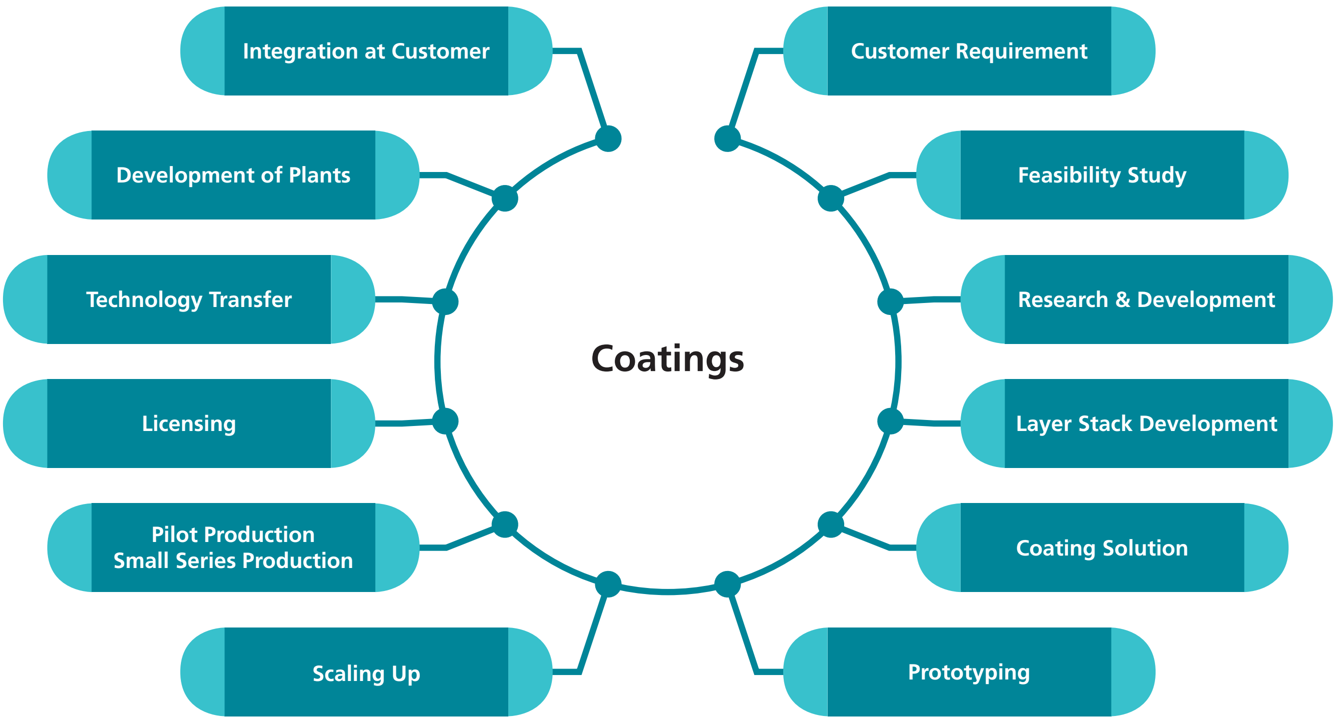
**Research and Development:**
Applications – Materials – Substrates –
Technologies – Systems

# Foreword

Coatings of the highest precision are required for numerous applications in optics, electronics, sensor technology, energy and medical technology, mechanical engineering and automotive technology. Fraunhofer FEP develops processes and technologies to apply, for example, electrical, optical, acoustic or magnetically effective coatings and layer systems precisely and homogeneously to large surfaces using vacuum processes. In addition to the high environmental compatibility, the advantage of our processes is the almost inexhaustible range of depositable layer materials, which exceeds that of conventional surface finishing processes by far.

**For our customers, we develop efficient technologies for the manufacture of innovative products** whose functions are the combination of different layer properties is essential. Our services range from feasibility studies, layer stack development, small series coating and pilot production to the transfer of the technology into production based on high-performance components developed at Fraunhofer FEP. In addition, we are constantly expanding the range of substrate materials and coating technologies that we can use, thus advancing into new applications.

On the following pages you will find an excerpt of developed layers and coatings, presented from the perspective of the various subsequent fields of application that Fraunhofer FEP has realized in more than 25 years of research activity. These explanations are intended to give you an idea of the possibilities we can offer for you. Of course, all combinations and layer developments are adaptable with regard to materials, processes and customer- as well as application-specific conditions and parameters.



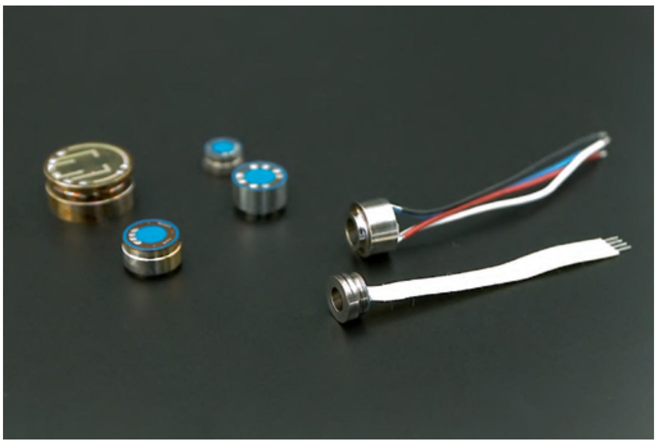
# Optics and decoration

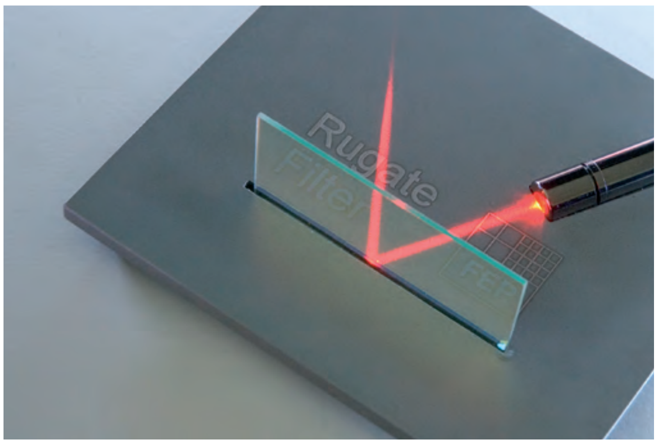
| Applications | Materials | Substrates | Technologies |
|---|---|---|---|
| Antireflex (AR)/Antireflex-Antistatic (ARAS) | Dielectrics: $Al_2O_3$, $Cr_2O_5$, MgO, $Nb_2O_5$, $SiO_2$, $Si_3N_4$, $SnO_2$, $Ta_2O_5$, $TiO_2$, ZnO, $ZrO_2$<br><br>Transparent conductive oxides (TCO): ITO, IZO, ZnO-based TCO, $TiO_2$-based TCO<br><br>Metals: Ag, Al, Cr, Cu, Mo, Sn, Ta, Ti, Zr, TiN | Glass, plastics, metal strips, metal sheets | Unipolar or bipolar magnetron sputtering, high-rate electron beam evaporation, plasma-activated electron beam evaporation, anodic arc evaporation |
| Electromagnetic shielding of electronic devices | | | |
| Energy efficient construction (low-E, solar control) | | | |
| Mirror coatings (highly reflective mirrors, baroque mirror coatings, blue mirrors) | | | |
| Decorative layers | | | |
| Optical filters for laser optics, spectroscopy applications | $SiO_2$, $Si_3N_4$, $Ta_2O_5$, $TiO_2$, $Al_2O_3$, $HfO_2$, $Nb_2O_5$ | Glass, plastics | Reactive pulse magnetron sputtering, high-rate PECVD |
| Anti-reflective coatings on eyeglass lenses | | | |
| Anti-counterfeiting labels, Decorative foils | $SiO_2$, $TiO_2$, Ag, Al | Polymer films, thin metal strips, flexible glass, membranes, textiles, paper, radiation-curable lacquers | Pulse magnetron sputtering, high-rate PECVD, high-rate electron beam evaporation, plasma and ion surface treatment, slot die coating, electron beam lacquer hardening |

»We develop your custom-fit, application-specific coating solution!«

# Electronics / sensors

| Applications | Materials | Substrates | Technologies |
|---|---|---|---|
| High-barrier and functional webs for flexible and organic electronics<br>Solar cells | ZnSnO, $TiO_2$, $Al_2O_3$, organics, radiation-curing lacquers, ormocers | Polymer films, thin metal foils, flexible glass (thickness: 50 µm … 100/200 µm | Pulse magnetron sputtering, high-rate PECVD, high-rate evaporation, plasma and ion surface treatment, slot die coating, electron beam lacquer hardening, atomic layer deposition (ALD) |
| Piezoelectric applications:<br>▪ Microsystems (MEMS), BAW, SAW<br>▪ Electroacoustic devices<br>▪ Ultrasonic microscopy<br>▪ Piezoactuators and sensors<br>▪ Microenergy harvesting systems | Crystalline AlN and AlScN layers with strong c-axis orientation | Silicon, steel, $LiNbO_3$, $LiTaO_3$, quartz | Reactive pulse magnetron sputtering, magnetron PECVD |
| Electrical insulation applications:<br>▪ Sensors (including device-integrated)<br>▪ Microelectronics<br>▪ Photovoltaics | $Al_2O_3$, $SiO_2$, $Si_3N_4$, $Al_XO_YN_Z$ | Silicon, steel, copper, aluminum, glass, ceramics | Reactive pulse magnetron sputtering, magnetron PECVD |
| Heat dissipation components:<br>▪ Laser diodes<br>▪ Cooling for electronics<br>▪ Thermoelectrics, peltier cooler<br>▪ Electronics development | AlN, $Al_XO_YN_Z$ | Copper, aluminum | Reactive pulse magnetron sputtering, magnetron PECVD |
| Passivation, protective and barrier layers:<br>▪ Sensors<br>▪ Electronic components | $Al_2O_3$, $SiO_2$, $Si_3N_4$ | Silicon, steel, plastics, glass | Reactive pulse magnetron sputtering, magnetron PECVD |
| Electronic and MEMS components | $SiO_2$, TaN, $HfO_2$ | Silicon, ceramics, titanium, $LiNbO_3$, $LiTaO_3$, covar | Reactive pulse magnetron sputtering, magnetron PECVD |
| Gas and humidity sensors | $TiO_2$, Fe, Ag, CuSn | Silicon, ceramics, glass | Reactive pulse magnetron sputtering, magnetron PECVD |
| Multilayer for electrical insulation layers with parylene | Parylene | Glass, polymer films, metal foil, silicon, thin glass, printed circuit boards | CVD at room temperature |





# Corrosion / Scratch protection

| Applications | Materials | Substrates | Technologies |
|---|---|---|---|
| Corrosion protection | Ti, Al, Cr, Cu, Sn, ZnMg, Zn<br>Thickness: 10 µm | Steel, stainless steel, precoated steel, copper, aluminum and their alloys | Vacuum based, e. g. physical vapor deposition (PVD) |
| | Parylene | Glass, polymer film, metal foil, silicon | CVD at room temperature |
| Wear protection, friction reduction, scratch protection, corrosion protection | a-C, ta-C<br>(hydrogen-free amorphous carbon layers) | Steel, stainless steel, carbide, tools, sheet steel | Plasma assisted electron beam evaporation |
| Transparent scratch protection | $SiO_x$, $Al_2O_3$<br>Thickness: 1 … 10 µm<br>radiation curing lacquers | Decorative films, decorative papers, high-pressure laminate (HPL) boards | Plasma assisted electron beam evaporation, electron beam varnish hardening |

# Energy conversion, transportation and storage as well as battery technology

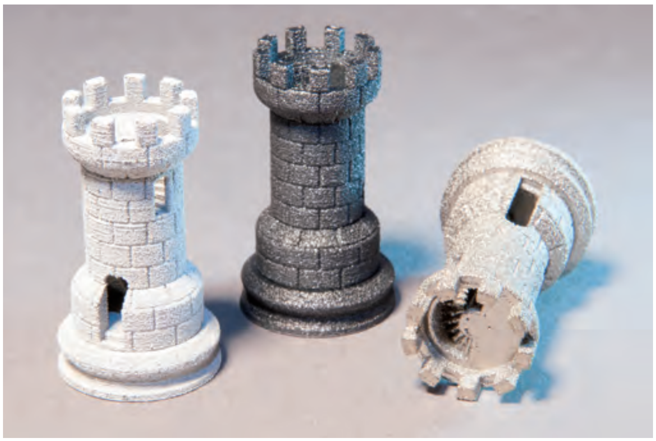
| Applications | Materials | Substrates | Technologies |
|---|---|---|---|
| Current arresters for batteries and solar cells | Cu, Al | Polymer films, silicon wafer | Magnetron sputtering, electron beam evaporation, thermal evaporation |
| Thin-film photovoltaics | CdTe, CdS, Mo, CIGS, TCO | Glass, metal foil | Close spaced sublimation (CSS), plasma-enhanced close spaced sublimation (PECSS), magnetron sputtering, thermal evaporation, anodic arc evaporation |
| Crystalline photovoltaics | TCO, AlN, perovskite (for tandem cells), silicon thin film absorber | Silicon wafer, glass, steel | Magnetron sputtering, anodic arc evaporation, thermal evaporation, electron beam evaporation, electron beam crystallization |
| Anode materials for Li-based batteries | Silicon | Metal foil | Magnetron sputtering, high-rate electron beam evaporation |
| Solid electrolytes | LiPON | Metal | Thermal evaporation, electron beam evaporation |

# Permeation barrier layers

| Applications | Materials | Substrates | Technologies |
|---|---|---|---|
| Non-optical functional layers:<br>▪ Magnetic memories<br>▪ Scratch protection coatings on plastics<br>▪ Surface metallization<br>▪ Hard coatings | Dielectrics: $Al_2O_3$, $Cr_2O_5$, MgO, $Nb_2O_5$, $SiO_2$, $Si_3N_4$, $SnO_2$, $Ta_2O_5$, $TiO_2$, ZnO, $ZrO_2$<br><br>Transparent conductive oxides (TCO): ITO, IZO, ZnO-based TCO, $TiO_2$-based TCO<br><br>Metals: Ag, Al, Cr, Cu, Mo, Sn, Ta, Ti, Zr | Glass, plastics | Unipolar or bipolar magnetron sputtering, anodic arc evaporation |
| Coating of flexible materials:<br>▪ Barrier films for packaging<br>▪ High-barrier for encapsulation of electronic components (e. g. solar cells, wearables, OLEDs, ...) | $Al_2O_3$, $SiO_2$, ZnSnO, SiN, Al, radiation-curing lacquers, ormocere | Polymer films | Pulse magnetron sputtering, high-rate PECVD (arc-PECVD), high-rate evaporation, electron beam lacquer hardening, slot die coating |
| ▪ Ultra-high barrier coatings in combination with ALD or sputter coatings<br>▪ Barrier films and substrates<br>▪ Direct encapsulation (3D) | Parylene | Glass, polymer films, metal foil, silicon, thin glass, printed circuit boards | CVD at room temperature |
| Corrosion protection | Radiation-curing lacquers | Polymers, wood, metal sheet, papers, foils, glass, ceramics, metal | Electron beam lacquer hardening |

# Parts, components, bulk materials

| Applications, Functions | | Materials | Substrates | Technologies |
|---|---|---|---|---|
| Electrical function | Electrical conductivity, electromagnetic shielding | Metals, alloys, transparent conductive oxides | Plug contacts, chemical plant components, plastic housing | Electron beam evaporation, pulse magnetron sputtering, anodic arc evaporation |
| | Electrical isolation | Metal- and semiconductor oxides | Additively manufactured contact structures | Electron beam evaporation, pulse magnetron sputtering |
| Thermal function | Thermal conductivity | Metals | Heat storage granules | Thermal evaporation |
| | Thermal insulation | Stabilized $ZrO_2$ | Turbine blades | Electron beam evaporation |
| Chemical barrier function | Corrosion protection | Aluminium-based, Cr, CrN | Rivet connectors, structural components in aviation | Thermal evaporation, Pulse magnetron sputtering |
| Mechanical protection function | Wear protection | Hard coatings | Tools, transmission small parts | Pulse magnetron sputtering |
| | Friction reduction | Metal alloys (AlSn base) | Plain bearings | Electron beam evaporation, pulse magnetron sputtering, high-rate PECVD |
| | | Carbon based materials | Automotive and mechanical engineering components | |
| | Scratch protection | Metal nitrides | Commodities | Pulse magnetron sputtering |
| | | $Al_2O_3$, $Si_3N_4$ | Glass components | |
| Decorative functions | Metallic looks | Metals | Plastic components, sanitary pipes | Pulse magnetron sputtering |
| | Body colors | Metal nitrides | Fittings, spectacle frames | Pulse magnetron sputtering |
| | Interference colors | Metal oxides | Medical instruments | Pulse magnetron sputtering |
| Other functions | Specific optical function | Solar absorber layer systems | Solar collector tubes | Pulse magnetron sputtering |
| | Photoactivability, photocatalytic function | Titanium oxide | Dental implants | Pulse magnetron sputtering |



# Biomedical applications

| Applications | Materials | Substrates | Technologies |
| --- | --- | --- | --- |
| Biocompatibility for packaging and encapsulation | Parylene | Glass, thin glass, polymer film, metal foil, silicon | CVD at room temperature |
| Biocompatibility | ITO, ZnO:Al, AZO, $TiO_2$, Ag, Cu | Plastics, metals, thermolabile materials, organic materials and fabrics, ceramics, textiles, hydrogels, electronic components, polymer films, glass | Electron beam treatment, plasma treatment, vacuum-based processes for thin film deposition, roll-to-roll coating of flexible materials |
| Biofunctionality | | | |
| Antimicrobial coatings | Ag, Cu, Ag & Cu, $TiO_2$, doped $TiO_2$ | | |
| Electron beam based grafting | | | |

# Other functional coatings

| Applications | Materials | Substrates | Technologies |
| --- | --- | --- | --- |
| Hard coatings | TiN, TiC, WC, $Al_2O_3$, a-C(:H)(:Ti/W) | Metal sheets and strips | Pulse magnetron sputtering, plasma-assisted electron beam evaporation |
| Electrically conductive | Al, Cu, Sn, Mo | Metal sheets and strips | Pulse magnetron sputtering, plasma-assisted electron beam evaporation |
| Solderable and weldable | Cu, Sn, Si | Metal sheets and strips | Pulse magnetron sputtering, plasma-assisted electron beam evaporation |
| Photocatalytic | $TiO_2$, $TiO_XN_Y$ | Metal, glass, ceramics, plastics | Reactive pulse magnetron sputtering, plasma-assisted electron beam evaporation |
| Photo-induced superhydrophilic coating | $TiO_2$, $TiO_XN_Y$ | Silicon, ceramics, glass, metal, lithium niobate, lithium tantalate | Reactive pulse magnetron sputtering, plasma-assisted electron beam evaporation |
| Functional coatings for electroacoustic components | $SiO_2$, TaN, F:$SiO_2$, AlN, AlScN | | Reactive pulse magnetron sputtering, magnetron PECVD |
| Substrate smoothing, Laser stop layers | Parylene | Silicon | CVD at room temperature |

# Pre-treatment for coating

In order to be able to coat substrates effectively, it is usually necessary and useful to pretreat the surfaces. Fraunhofer FEP has many years of expertise in various processes for pre-treatment or surface functionalization, which create the basis for high-quality coating and layer adhesion.

## Cleaning technologies

A coordinated cleaning technology is essential here so that the coating systems can be applied in an adhesive manner. Cleaning is therefore an important step in the value chain, which forms the basis for minimizing rejects, reducing costs and manufacturing high-quality products. A wide variety of impurities, in some cases down to atomic scales, as well as different requirements for the surfaces demand a range of different cleaning processes in order to achieve optimum results.

At Fraunhofer FEP, this range includes, among other things, wet chemical fine or ultra-fine cleaning for metallic components or precision parts made of glass and plastic, plasma cleaning for components made of metal and plastic in a vacuum, local functional surface cleaning with electron beam in vacuum, and sterilization, disinfection and inactivation with accelerated electrons.

## Surface functionalization

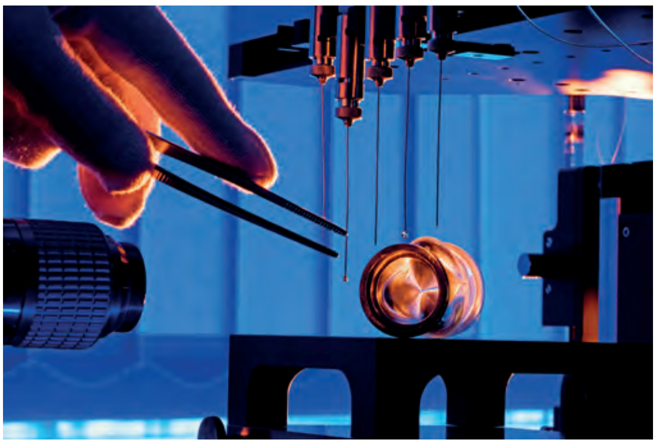
Furthermore, Fraunhofer FEP is researching and working on surface functionalization. Here, accelerated, low-energy electrons are used to specifically treat the relevant surfaces and generate, for example, antibacterial effects or self-cleaning surfaces. Electron beam treatment leads, for example, to an adjustment of the wettability of the surface (surface hydrophilicity). In this way, the interaction of the surface with the environment can be influenced in a targeted manner.

## Electron beam hardening

A special type of surface treatment is the hardening of suitable ferrous materials with the electron beam. In this process, a focused, high-frequency electron beam deflected over the workpiece surface leads to rapid, local heating of the material. The penetration depth can also be precisely controlled. The high heat conduction into the surrounding material then forces a high cooling rate without additional coolant (self-quenching), which leads to hardening of this surface layer in suitable materials. This allows local functional surfaces with excellent wear properties to be produced.

## Surface smoothing

In addition, the electron beam can be used to smooth rough surfaces of many metallic components and thus prepare them for coating. The process is thus particularly suitable for the post-processing of additively manufactured parts. The active principle is that local energy input causes a momentary surface melting. The resulting melt immediately solidifies again, with the surface tension leading to a leveling of the height differences. With a suitable choice of parameters, smoothing takes place homogeneously over a wide area and, as far as possible, without material removal.

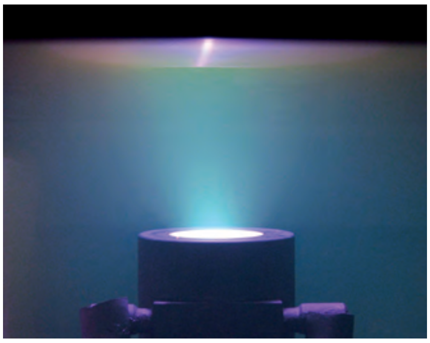


# Technologies / Processes

### Electron beam technology

Thanks to our many years of expertise, we are able to utilize accelerated electrons in the energy range of 10 – 300 keV to apply thermal, chemical, and biological effects in a wide range of technological applications. Our strength is developing and delivering electron-beam technologies up through full industrial readiness. One unique selling proposition is the combination of technological and technical process developments and the development of special electron beam sources from a single source.

### Plasma surface technology

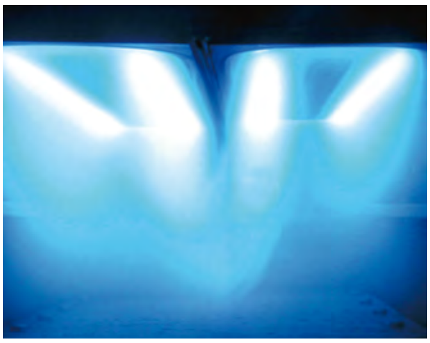


Plasma-assisted coating processes allow the production of customized coatings for many areas of application. Our strength lies in qualifying these plasma-assisted coating processes for industrial production and the coating of large surfaces.

The core competence comprises the PVD processes of plasma-activated high-rate evaporation and pulse magnetron sputtering as well as PECVD processes for plasma-activated chemical vapor deposition with various high-performance plasma sources. A key unique selling point is the combination of extremely dense plasmas with extremely high deposition rates for the economical deposition of high-quality coatings.

The combination of cost-effectiveness with precision in terms of process control and coating properties opens up new applications. For these coating processes, we also develop the cleaning processes and plasma pre-treatments required to ensure layer adhesion.

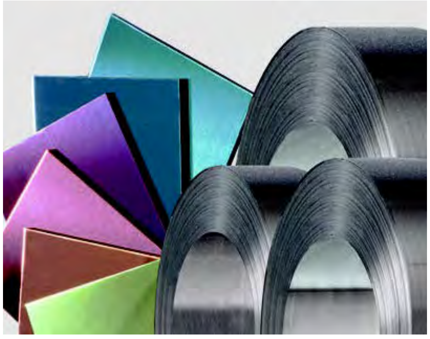
### Sputter technology



Sputter technology at Fraunhofer FEP is a highly developed method for coating materials. By applying thin layers through cathode sputtering, surface properties such as hardness, corrosion resistance, and optical characteristics can be enhanced. This technique is utilized across various industries to improve the performance and durability of products. Fraunhofer FEP employs advanced sputtering methods to develop innovative solutions for complex coating requirements.

# Substrates

### Metallic sheets and strips



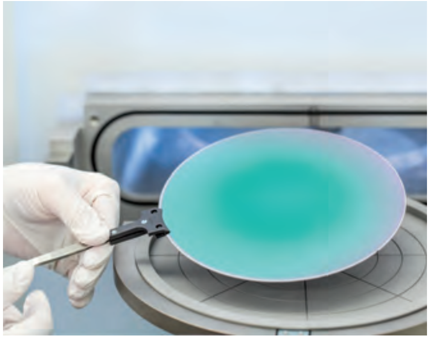
### Bulk material and 3D components

### Flexible films

### Ultra-thin glass

### Tools

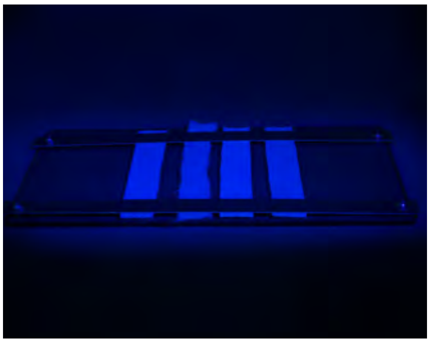
### Wafer



### **Cultural heritage** (decoating)

### **Seeds** (treatment)

### Tissues and textiles



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