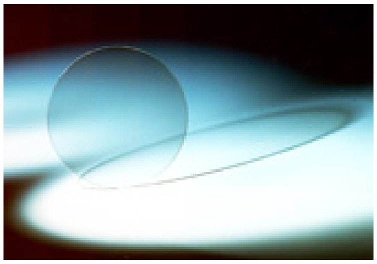
CVD Diamond

CVD Diamond

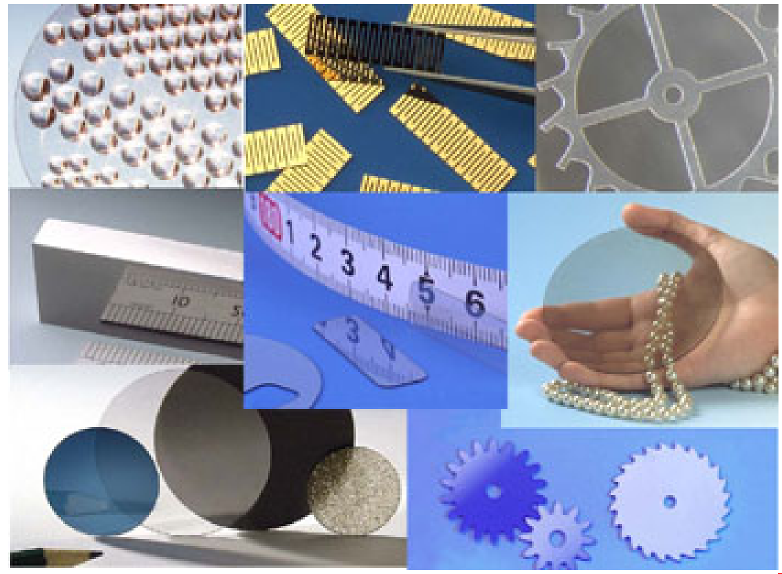


Due to its combination of unique physical properties diamond is an outstanding material. Besides its unrivaled hardness diamond exhibits ultrabroadband transparancy ranging from deep UV to the microwave regime, and a thermal conductivity at room temperature which is higher than that of any other material. The excellent mechanical, thermal, optical and insulating properties of diamond became accessible through the advent of low pressure Chemical Vapour Deposition (CVD) techniques which allow diamond in the form of extended films and free-standing wafers to be fabricated.

Fraunhofer IAF has grown large-area (2 to 6 inches in diameter) CVD diamond wafers with thickness beyond 2 mm applying its patented microwave plasma reactor technology. Presently, various ellipsoid plasma reactors with microwave power levels of 6, 8, 12 and 60 kW are used to prepare diamond wafers. Subsequent double-sided finishing is applied to achieve perfectly smooth and flat surfaces. Phase purity, surface profile, optical absorption, and heat conductivity are routinely characterized.

The application of diamond wafers e.g. as laser windows require extremely flat surfaces and low absorption coefficients; the preparation of diamond heat-spreaders involves several manufacturing steps such as grinding and polishing, laser cutting and metallization; incorporations of additional features such as temperature sensors and resistive heaters into the diamond surface give rise to „smart" diamond heat spreaders for precise device temperature control - meeting such requirement is a strength of Fraunhofer IAF.

Products



Fraunhofer has been working on a variety of CVD diamond products which take advantage of the amazing properties of this material.

Our R&D Service

We will consult you on CVD diamond utilization, should you want to do business with CVD diamond. We provide technology licensing and continuous support. You may also be served by characterized CVD diamond samples. We process CVD diamond wafers further to application-specific specimens. Larger diameters and thicknesses of CVD diamond wafers are the objectives of our further developments.

Your Advantage

You may use complete CVD diamond wafers or want to develop your application-specific specimens with us - we guarantee rapid prototyping. We are capable of transforming sample specimen manufacturing to small volume production. Your exploitation of our long-standing experience on CVD diamond saves you time and costs.

Target Applications

- Laser windows for high-power CO_2 lasers
- Microwave transmitting windows for high-power gyrotrons and klystrons
- Dielectric submounts for microwave and millimeter wave ICs
- Heat-spreaders for high-power microelectronic circuits and diode lasers
- Smart heat-spreaders
- Highly refractive microoptics

If you have questions, suggestions, or other needs, please don't hesitate to get in touch with us.

Contact

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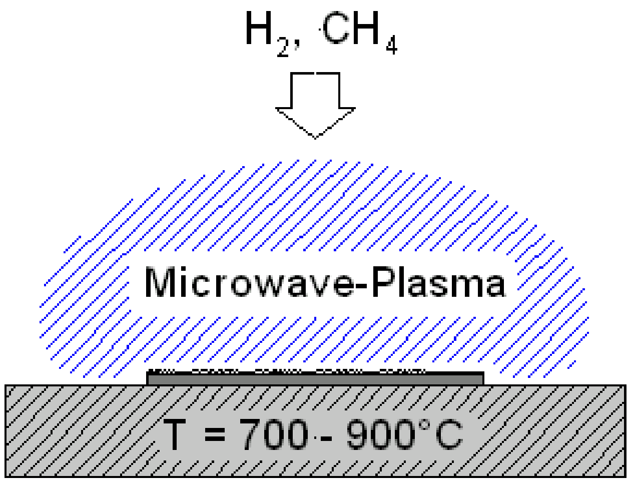
CVD Diamond: General Information

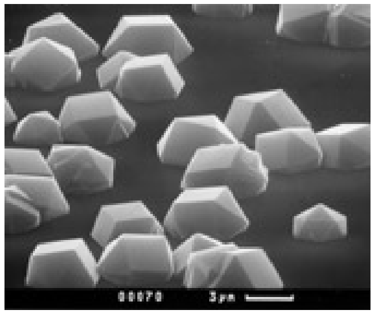
Chemical Vapor Deposition

Diamond has always been an outstanding and desirable material. With the invention of synthetic growth techniques at high pressures and temperatures in the fifties, it became technical material, especially for mechanical applications. However, it was the advent of low pressure deposition techniques that made accessible the excellent mechanical, thermal, optical and electronic properties. With these chemical vapour deposition (CVD) techniques diamond became available in the form of extended thin films and free-standing plates or windows. Doping during deposition could be realized, making diamond a p-type semiconductor. With CVD-diamond a wealth of new applications opened up.

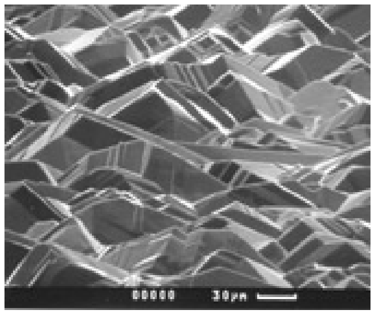


Deposition from the gas phase

The fundamental problem of diamond synthesis is the allotropic nature of carbon. Under ordinary conditions graphite, not diamond, is the thermodynamically stable crystalline phase of carbon. Hence, the main requirement of diamond CVD is to deposit carbon and simultaneously suppress the formation of graphitic sp^2-bonds. This can be realized by establishing high concentrations of non-diamond carbon etchants such as atomic hydrogen. Usually, those conditions are achieved by admixing large amounts of hydrogen to the process gas and by activating the gas either thermally or by a plasma.



Initial diamond nuclei formed on the substrate surface



Surface morphology of a polycrystalline diamond film

Hence, a common feature of all diamond CVD techniques is a gas-phase nonequilibrium, i.e. a high supersaturation of atomic hydrogen and of various hydrocarbon radicals. Typical deposition conditions are: 1 % methane in hydrogen as source gas, 700-1000°C deposition temperature and gas pressures in the range 30-300 Torr.

The various diamond CVD techniques differ mainly in the way of gas phase activation and dissociation. The most common techniques include a) thermally assisted CVD, usually realized by gas activation with a hot filament, b) microwave plasma assisted CVD, c) deposition in a combustion flame sustained e.g. by acetylene and oxygen, and d) arc jet CVD. Each of these techniques has its pros and cons. The distinguishing features are the deposition rate, the deposition area and the quality of the deposited diamond. The maximum growth rate reported so far amounts to almost 1 mm/h. However, those high growth rates are usually limited to very small deposition areas (« 1 cm^2). In general there is an inverse relationship between film quality and growth rate. Optically transparent films with high thermal conductivities are usually deposited at rates not exceeding 10 µm/h, regardless of the deposition technique.The excellent optical properties of diamond have been known for a long time. However, optical applications require extended discs or thin coatings not provided by natural diamond crystals. With the development of CVD techniques the situation has changed completely.

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CVD Diamond: Microwave Plasma Deposition

Reactor Development

Microwave Plasma Deposition

Proprietary deposition technology: Ellipsoidal microwave plasma reactors

For the deposition of CVD diamond wafers several microwave plasma reactors powered with 6 to 12 kW microwave power have been set up. Upscaled versions operating at 915 MHz microwave frequency are used for the production of large area (up to 6") diamond wafers. The design of these microwave plasma reactors is based on numerical simulations. The reactors are optimized with respect to the homogeneous coating of large area substrates with reasonable growth rates.

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CVD Diamond: Plasma Reactors

Increasing applications of chemical vapour deposited (CVD) diamond have raised the need for efficient and robust microwave plasma reactors which are optimized for the large area deposition of diamond films and wafers. On the basis of extended numerical simulations Fraunhofer IAF has developed a novel microwave plasma CVD technology. An ellipsoidal cavity is used to focus the microwave energy into an intense and extended plasma. These ellipsoidal plasma reactors exhibit a combination of beneficial properties including

- Large area deposition: homogeneous deposition of CVD diamond on 3" (2.45 GHz) and 6" (915 MHz) substrates possible.
- Stability: Long-term operation possible, no plasma instabilities.
- Versatility: The reactor can be run under various conditions (pressure, power etc.).
- Growth of high-purity diamond: Properties of CVD diamond disks are identical to those of perfect single

diamond crystals.

In cooperation with AIXTRON AG this patented reactor technology is now commercialized. The two figures show ellipsoidal plasma reactors which are fully computer controlled and equipped with all the safety units necessary for the operation in an industrial environment. The reactors are operated at 2.45 GHz, 6 kW (upper figure) and 915 MHz, 30-60 kW (lower figure), respectively.

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CVD Diamond: Properties

General properties
Demonstrated properties
Optical properties
Thermal properties
Mechanical properties
Dielectric properties

General Properties

Diamond has a unique combination of optical, thermal, mechanical and electronic properties that can be useful for a number of technical applications:

Property	Value
Hardness*	10,000 kg/mm^2
Strength, tensile	>1.2 GPa
Sound velocity*	17,500 m/s
Density	3.52 g/cm^3
Atom density*	1.77×10^{23} 1/cm^3
Young's modulus*	1140 GPa
Poisson's ratio	0.069
Thermal expansion coefficient	1.1 ppm/K
Thermal conductivity*	20.0 W/cmK
Debye temperature*	2,220 K
Refractive index	2.41
Optical transparency	UV to far IR
Loss tangent at 140 GHz	$< 10^{-5}$
Dielectric constant	5.7
Dielectric strength	10,000,000 V/cm
Electron mobility	2,200 cm^2/Vs
Hole mobility	1,600 cm^2/Vs
Bandgap	5.45 eV
Resistivity	10^{13} - 10^{16} Ωcm

*highest value of all solid materials

Demonstrated Properties

At the Fraunhofer Institut IAF we have specialized in the preparation of high-quality CVD diamond disks. The properties of these disks approach those of perfect natural diamond crystals. In particular, we have demonstrated:

Demonstrated properties

Thermal properties	Thermal conductivity k = 21.5 W/cmK at 20°C, k = 54.0 W/cmK at -150°C
	Thermal expansion 1.0 ppm/K at 20°C 1.6 ppm/K at 100°C 2.3 ppm/K at 200°C 3.5 ppm/K at 400°C
Mechanical properties	Fracture strength 800 MPa at 200 µm thickness 400 MPa at 800 µm thickness
	Young's modulus 1000 GPa
Optical properties	Optical absorption < 0.04 cm^{-1} (10.6 µm)
	Optical scattering < 0.8 % (633 nm, BDTF 2°-80°)
Dielectric properties	Loss tangent $\tan \delta = 1\text{-}2 \times 10^{-5}$ at 140 GHz

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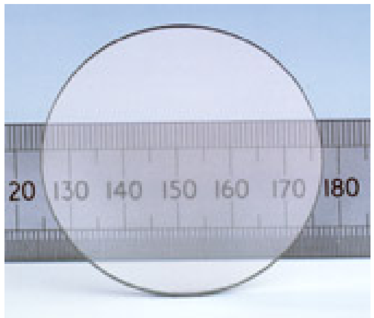
CVD Diamond: Optical Properties

Optical transmission
Applications



The excellent optical properties of diamond have been known for a long time. However, optical applications require extended discs or thin coatings not provided by natural diamond crystals. With the development of CVD techniques the situation has changed completely.

Broadband transparency

Diamond is transparent from the UV (230 nm) to the far infrared. Only minor absorption bands resulting from two phonon absorption exist between 2.5 and 6 µm. Hence diamond is an ideal material for multispectral optical applications.

Wide band gap

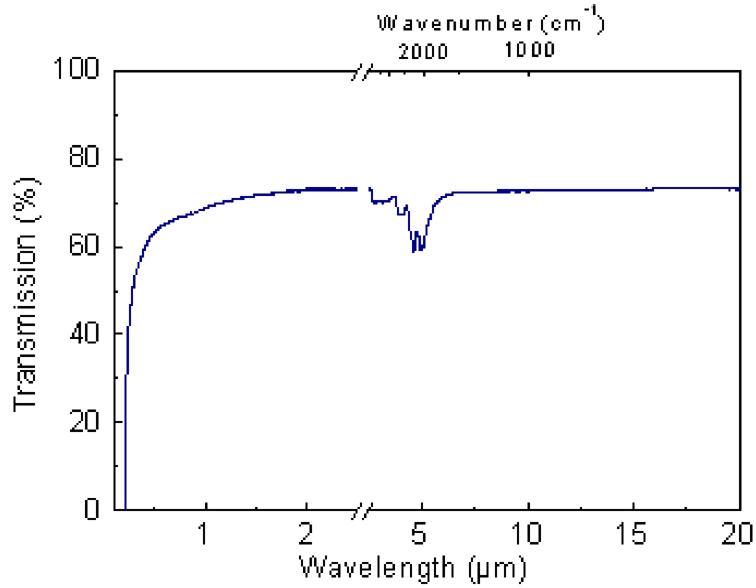
No thermal generation of charge carriers at elevated temperatures, hence no "thermal run away" as in the case of Germanium under laser irradiation. Furthermore, diamond does not become nonlinear at high radiation intensities.

High thermal conductivity

Absorbed energy is quickly dissipated to the edges of a diamond window where it can be removed by appropriate heat sinks and cooling techniques.

Mechanical and chemical stability

Diamond is extremely hard, wear resistant and chemically inert.
It is an ideal material for hostile, highly erosive atmospheres.



Optical transmission spectrum of CVD diamond

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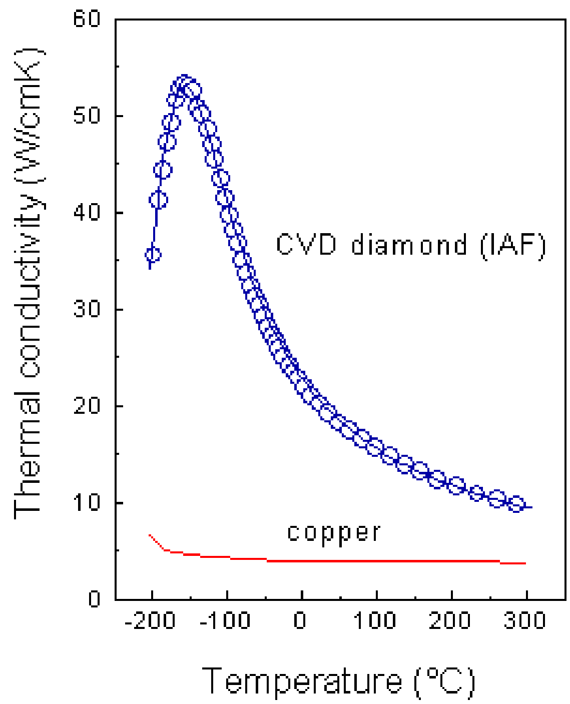
CVD Diamond: Thermal Properties

Applications

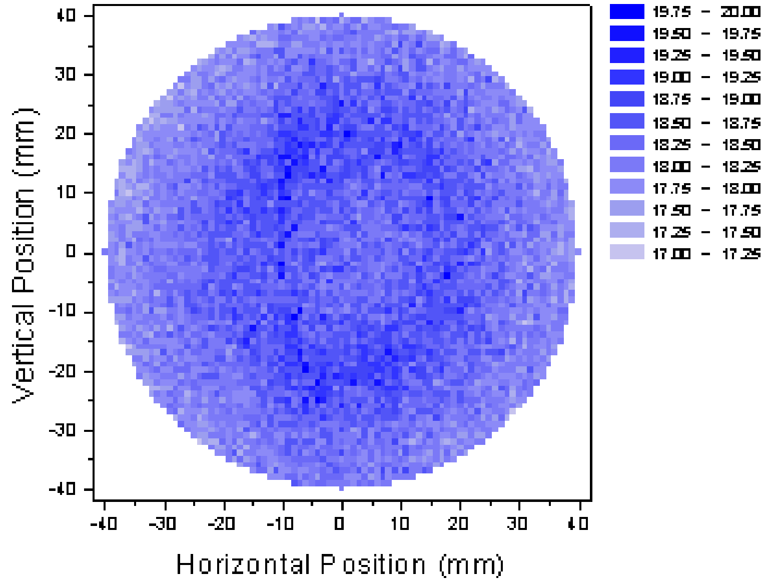
Thermal Conductivity

One of many remarkable properties of diamond is its uncompeted thermal conductivity. In contrast to metals, where conduction electrons are responsible for the high thermal conductivity, heat is conducted in electrical insulators by lattice vibrations. With a sound velocity of 17500 m/s, diamond is the material with the highest Debye temperature (2220 K), exceeding that of most other insulating materials by an order of magnitude and leading to the highest thermal conductivity of any material at room temperature (20-25W/cmK), exceeding that of copper by a factor of five.



Thermal conductivity of CVD diamond vs. temperature. For comparison, the thermal conductivity of copper is shown in red.

Large area CVD diamond films have been proposed for many thermal management applications, though the first thermal conductivity measurements in the late 80's were not very promising. In recent years, however, the quality of CVD diamond improved dramatically, and large area CVD diamond plates with thermal conductivities around 20 W/cmK became available. Today, CVD diamond is used for various thermal management applications such as submounts for integrated circuits and heat spreaders for high power laser diodes.



Mapping of the thermal conductivity

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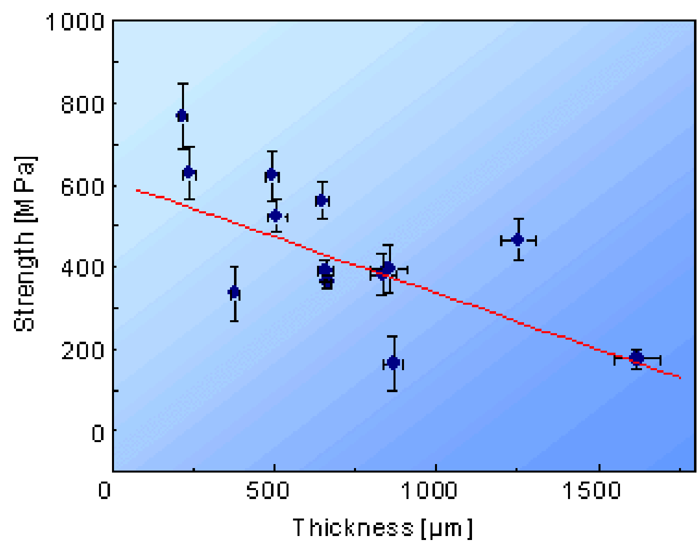
CVD Diamond: Mechanical Properties

Applications

Diamond is known for its extreme hardness. It exhibits an exceptional wear resistance and a low coefficient of friction. These properties make CVD diamond an ideal choice for highly demanding applications such as cutting tools for non-ferrous materials, surgical knives and wear resistant coatings.



Mechanical strength vs. thickness for various CVD diamond samples of different quality

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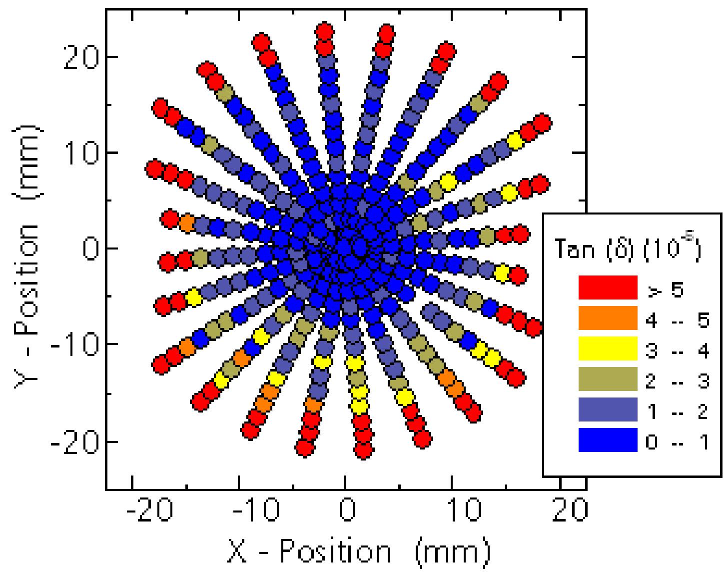
CVD Diamond: Dielectric Properties

Applications

CVD diamond exhibits remarkable dielectric properties including a low dielectric constant of 5.7, a loss tangent below 0.00005 at 145GHz and a high dielectric strength of 1 000 000 V/cm. In combination with the extremely high thermal conductivity, low thermal expansion coefficient and high mechanical strength CVD diamond is an ideal dielectric window material. In particular for high-power microwave tubes (Gyrotron) with power levels exceedings 1 MW edge cooled diamond windows have found tremendous interest.



Mapping of the dielectric losses (FZK, Karlsruhe)

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