

= Material properties of diamond =

Diamond is the allotrope of carbon in which the carbon atoms are arranged in the specific type of cubic lattice called diamond cubic . Diamond is an optically isotropic crystal that is transparent to opaque . Owing to its strong covalent bonding , diamond is the hardest naturally occurring material known . Yet , due to important structural weaknesses , diamond 's toughness is only fair to good . The precise tensile strength of diamond is unknown , however strength up to 60 GPa has been observed , and it could be as high as 90 ? 225 GPa depending on the crystal orientation . The anisotropy of diamond hardness is carefully considered during diamond cutting . Diamond has a high refractive index ( 2 @. @ 417 ) and moderate dispersion ( 0 @. @ 044 ) properties which give cut diamonds their brilliance . Scientists classify diamonds into four main types according to the nature of crystallographic defects present . Trace impurities substitutionally replacing carbon atoms in a diamond 's crystal lattice , and in some cases structural defects , are responsible for the wide range of colors seen in diamond . Most diamonds are electrical insulators but extremely efficient thermal conductors . Unlike many other minerals , the specific gravity of diamond crystals ( 3 @. @ 52 ) has rather small variation from diamond to diamond .

= = Hardness and crystal structure = =

Known to the ancient Greeks as ?????? ? adámas ( " proper " , " unalterable " , " unbreakable " ) and sometimes called adamant , diamond is the hardest known naturally occurring material , scoring 10 on the Mohs scale of mineral hardness . Diamond is extremely strong owing to the structure of its carbon atoms , where each carbon atom has four neighbors joined to it with covalent bonds . The material boron nitride , when in a form structurally identical to diamond ( zincblende structure ) , is nearly as hard as diamond ; a currently hypothetical material , beta carbon nitride , may also be as hard or harder in one form . It has been shown that some diamond aggregates having nanometer grain size are harder and tougher than conventional large diamond crystals , thus they perform better as abrasive material . Owing to the use of those new ultra @-@ hard materials for diamond testing , more accurate values are now known for diamond hardness . A surface perpendicular to the [ 111 ] crystallographic direction ( that is the longest diagonal of a cube ) of a pure ( i.e. , type IIa ) diamond has a hardness value of 167 GPa when scratched with a nanodiamond tip , while the nanodiamond sample itself has a value of 310 GPa when tested with another nanodiamond tip . Because the test only works properly with a tip made of harder material than the sample being tested , the true value for nanodiamond is likely somewhat lower than 310 GPa .

The precise tensile strength of diamond is unknown , however strength up to 60 GPa has been observed , and it could be as high as 90 ? 225 GPa depending on the perfection of diamond lattice and on its orientation : Tensile strength is the highest for the [ 100 ] crystal direction ( normal to the cubic face ) , smaller for the [ 110 ] and the smallest for the [ 111 ] axis ( along the longest cube diagonal ) . Diamond also has one of the smallest compressibilities of any material .

Cubic diamonds have a perfect and easy octahedral cleavage , which means that they only have four planes ? weak directions following the faces of the octahedron where there are fewer bonds ? along which diamond can easily split upon blunt impact to leave a smooth surface . Similarly , diamond 's hardness is markedly directional : the hardest direction is the diagonal on the cube face , 100 times harder than the softest direction , which is the dodecahedral plane . The octahedral plane is intermediate between the two extremes . The diamond cutting process relies heavily on this directional hardness , as without it a diamond would be nearly impossible to fashion . Cleavage also plays a helpful role , especially in large stones where the cutter wishes to remove flawed material or to produce more than one stone from the same piece of rough ( e.g. Cullinan Diamond ) .

Diamonds crystallize in the diamond cubic crystal system ( space group Fd3m ) and consist of tetrahedrally , covalently bonded carbon atoms . A second form called lonsdaleite , with hexagonal symmetry , has also been found , but it is extremely rare and forms only in meteorites or in laboratory synthesis . The local environment of each atom is identical in the two structures . From theoretical considerations , lonsdaleite is expected to be harder than diamond , but the size and

quality of the available stones are insufficient to test this hypothesis . In terms of crystal habit , diamonds occur most often as euhedral ( well @-@ formed ) or rounded octahedra and twinned , flattened octahedra with a triangular outline . Other forms include dodecahedra and ( rarely ) cubes . There is evidence that nitrogen impurities play an important role in the formation of well @-@ shaped euhedral crystals . The largest diamonds found , such as the Cullinan Diamond , were shapeless . These diamonds are pure ( i.e. type II ) and therefore contain little if any nitrogen .

The faces of diamond octahedrons are highly lustrous owing to their hardness ; triangular shaped growth defects ( trigons ) or etch pits are often present on the faces . A diamond 's fracture may be step @-@ like , conchoidal ( shell @-@ like , similar to glass ) or irregular . Diamonds which are nearly round , due to the formation of multiple steps on octahedral faces , are commonly coated in a gum @-@ like skin ( nyf ) . The combination of stepped faces , growth defects , and nyf produces a " scaly " or corrugated appearance . Many diamonds are so distorted that few crystal faces are discernible . Some diamonds found in Brazil and the Democratic Republic of the Congo are polycrystalline and occur as opaque , darkly colored , spherical , radial masses of tiny crystals ; these are known as ballas and are important to industry as they lack the cleavage planes of single @-@ crystal diamond . Carbonado is a similar opaque microcrystalline form which occurs in shapeless masses . Like ballas diamond , carbonado lacks cleavage planes and its specific gravity varies widely from 2 @.@ 9 to 3 @.@ 5 . Bort diamonds , found in Brazil , Venezuela , and Guyana , are the most common type of industrial @-@ grade diamond . They are also polycrystalline and often poorly crystallized ; they are translucent and cleave easily .

Because of its great hardness and strong molecular bonding , a cut diamond 's facets and facet edges appear the flattest and sharpest . A curious side effect of diamond 's surface perfection is hydrophobia combined with lipophilia . The former property means a drop of water placed on a diamond will form a coherent droplet , whereas in most other minerals the water would spread out to cover the surface . Similarly , diamond is unusually lipophilic , meaning grease and oil readily collect on a diamond 's surface . Whereas on other minerals oil would form coherent drops , on a diamond the oil would spread . This property is exploited in the use of so @-@ called " grease pens , " which apply a line of grease to the surface of a suspect diamond simulant . Diamond surfaces are hydrophobic when the surface carbon atoms terminate with a hydrogen atom and hydrophilic when the surface atoms terminate with an oxygen atom or hydroxyl radical . Treatment with gases or plasmas containing the appropriate gas , at temperatures of 450 ° C or higher , can change the surface property completely . Naturally occurring diamonds have a surface with less than a half monolayer coverage of oxygen , the balance being hydrogen and the behavior is moderately hydrophobic . This allows for separation from other minerals at the mine using the so @-@ called " grease @-@ belt " .

= = Toughness = =

Unlike hardness , which denotes only resistance to scratching , diamond 's toughness or tenacity is only fair to good . Toughness relates to the ability to resist breakage from falls or impacts . Because of diamond 's perfect and easy cleavage , it is vulnerable to breakage . A diamond will shatter if hit with an ordinary hammer . The toughness of natural diamond has been measured as 2 @.@ 0 MPa m<sup>1/2</sup> , which is good compared to other gemstones , but poor compared to most engineering materials . As with any material , the macroscopic geometry of a diamond contributes to its resistance to breakage . Diamond has a cleavage plane and is therefore more fragile in some orientations than others . Diamond cutters use this attribute to cleave some stones , prior to faceting .

Ballas and carbonado diamond are exceptional , as they are polycrystalline and therefore much tougher than single @-@ crystal diamond ; they are used for deep @-@ drilling bits and other demanding industrial applications . Particular faceting shapes of diamonds are more prone to breakage and thus may be uninsurable by reputable insurance companies . The brilliant cut of gemstones is designed specifically to reduce the likelihood of breakage or splintering .

Solid foreign crystals are commonly present in diamond . They are mostly minerals , such as olivine

, garnets , ruby , and many others . These and other inclusions , such as internal fractures or " feathers " , can compromise the structural integrity of a diamond . Cut diamonds that have been enhanced to improve their clarity via glass infilling of fractures or cavities are especially fragile , as the glass will not stand up to ultrasonic cleaning or the rigors of the jeweler 's torch . Fracture @-@ filled diamonds may shatter if treated improperly .

= = = Pressure resistance = = =

Used in so @-@ called diamond anvil experiments to create high @-@ pressure environments , diamonds are able to withstand crushing pressures in excess of 600 gigapascals ( 6 million atmospheres ) .

= = Optical properties = =

= = = Color and its causes = = =

Diamonds occur in various colors : black , brown , yellow , gray , white , blue , orange , purple to pink and red . Colored diamonds contain crystallographic defects , including substitutional impurities and structural defects , that cause the coloration . Theoretically , pure diamonds would be transparent and colorless . Diamonds are scientifically classed into two main types and several subtypes , according to the nature of defects present and how they affect light absorption :

Type I diamond has nitrogen ( N ) atoms as the main impurity , at a concentration of up to 1 % . If the N atoms are in pairs or larger aggregates , they do not affect the diamond 's color ; these are Type Ia . About 98 % of gem diamonds are type Ia : these diamonds belong to the Cape series , named after the diamond @-@ rich region formerly known as Cape Province in South Africa , whose deposits are largely Type Ia . If the nitrogen atoms are dispersed throughout the crystal in isolated sites ( not paired or grouped ) , they give the stone an intense yellow or occasionally brown tint ( type Ib ) ; the rare canary diamonds belong to this type , which represents only ~ 0 @.@ 1 % of known natural diamonds . Synthetic diamond containing nitrogen is usually of type Ib . Type Ia and Ib diamonds absorb in both the infrared and ultraviolet region of the electromagnetic spectrum , from 320 nm . They also have a characteristic fluorescence and visible absorption spectrum ( see Optical properties ) .

Type II diamonds have very few if any nitrogen impurities . Pure ( type IIa ) diamond can be colored pink , red , or brown owing to structural anomalies arising through plastic deformation during crystal growth ; these diamonds are rare ( 1 @.@ 8 % of gem diamonds ) , but constitute a large percentage of Australian diamonds . Type IIb diamonds , which account for ~ 0 @.@ 1 % of gem diamonds , are usually a steely blue or gray due to boron atoms scattered within the crystal matrix . These diamonds are also semiconductors , unlike other diamond types ( see Electrical properties ) . Most blue @-@ gray diamonds coming from the Argyle mine of Australia are not of type IIb , but of Ia type . Those diamonds contain large concentrations of defects and impurities ( especially hydrogen and nitrogen ) and the origin of their color is yet uncertain . Type II diamonds weakly absorb in a different region of the infrared ( the absorption is due to the diamond lattice rather than impurities ) , and transmit in the ultraviolet below 225 nm , unlike type I diamonds . They also have differing fluorescence characteristics , but no discernible visible absorption spectrum .

Certain diamond enhancement techniques are commonly used to artificially produce an array of colors , including blue , green , yellow , red , and black . Color enhancement techniques usually involve irradiation , including proton bombardment via cyclotrons ; neutron bombardment in the piles of nuclear reactors ; and electron bombardment by Van de Graaff generators . These high @-@ energy particles physically alter the diamond 's crystal lattice , knocking carbon atoms out of place and producing color centers . The depth of color penetration depends on the technique and its duration , and in some cases the diamond may be left radioactive to some degree .

Some irradiated diamonds are completely natural ; one famous example is the Dresden Green

Diamond . In these natural stones the color is imparted by " radiation burns " ( natural irradiation by alpha particles originating from uranium ore ) in the form of small patches , usually only micrometers deep . Additionally , Type IIa diamonds can have their structural deformations " repaired " via a high @-@ pressure high @-@ temperature ( HPHT ) process , removing much or all of the diamond 's color .

= = = Luster = = =

The luster of a diamond is described as ' adamantine ' , which simply means diamond @-@ like . Reflections on a properly cut diamond 's facets are undistorted , due to their flatness . The refractive index of diamond ( as measured via sodium light , 589 @.@ 3 nm ) is 2 @.@ 417 . Because it is cubic in structure , diamond is also isotropic . Its high dispersion of 0 @.@ 044 ( variation of refractive index across the visible spectrum ) manifests in the perceptible fire of cut diamonds . This fire ? flashes of prismatic colors seen in transparent stones ? is perhaps diamond 's most important optical property from a jewelry perspective . The prominence or amount of fire seen in a stone is heavily influenced by the choice of diamond cut and its associated proportions ( particularly crown height ) , although the body color of fancy ( i.e. , unusual ) diamonds may hide their fire to some degree .

More than 20 other minerals have higher dispersion ( that is difference in refractive index for blue and red light ) than diamond , such as titanite 0 @.@ 051 , andradite 0 @.@ 057 , cassiterite 0 @.@ 071 , strontium titanate 0 @.@ 109 , sphalerite 0 @.@ 156 , synthetic rutile 0 @.@ 330 , cinnabar 0 @.@ 4 , etc . ( see dispersion ) . However , the combination of dispersion with extreme hardness , wear and chemical resistivity , as well as clever marketing , determines the exceptional value of diamond as a gemstone .

= = = Fluorescence = = =

Diamonds exhibit fluorescence , that is , they emit light of various colors and intensities under long @-@ wave ultraviolet light ( 365 nm ) : Cape series stones ( type Ia ) usually fluoresce blue , and these stones may also phosphoresce yellow , a unique property among gemstones . Other possible long @-@ wave fluorescence colors are green ( usually in brown stones ) , yellow , mauve , or red ( in type IIb diamonds ) . In natural diamonds , there is typically little if any response to short @-@ wave ultraviolet , but the reverse is true of synthetic diamonds . Some natural type IIb diamonds phosphoresce blue after exposure to short @-@ wave ultraviolet . In natural diamonds , fluorescence under X @-@ rays is generally bluish @-@ white , yellowish or greenish . Some diamonds , particularly Canadian diamonds , show no fluorescence .

The origin of the luminescence colors is often unclear and not unique . Blue emission from type IIa and IIb diamonds is reliably identified with dislocations by directly correlating the emission with dislocations in an electron microscope . However , blue emission in type Ia diamond could be either due to dislocations or the N3 defects ( three nitrogen atoms bordering a vacancy ) . Green emission in natural diamond is usually due to the H3 center ( two substitutional nitrogen atoms separated by a vacancy ) , whereas in synthetic diamond it usually originates from nickel used as a catalyst ( see figure ) . Orange or red emission could be due to various reasons , one being the nitrogen @-@ vacancy center which is present in sufficient quantities in all types of diamond , even type IIb .

= = = Optical absorption = = =

Cape series ( Ia ) diamonds have a visible absorption spectrum ( as seen through a direct @-@ vision spectroscope ) consisting of a fine line in the violet at 415 @.@ 5 nm ; however , this line is often invisible until the diamond has been cooled to very low temperatures . Associated with this are weaker lines at 478 nm , 465 nm , 452 nm , 435 nm , and 423 nm . All those lines are labeled as N3 and N2 optical centers and associated with a defect consisting of three nitrogen atoms bordering a vacancy . Other stones show additional bands : brown , green , or yellow diamonds show a band in

the green at 504 nm ( H3 center , see above ) , sometimes accompanied by two additional weak bands at 537 nm and 495 nm ( H4 center , a large complex presumably involving 4 substitutional nitrogen atoms and 2 lattice vacancies ) . Type IIb diamonds may absorb in the far red due to the substitutional boron , but otherwise show no observable visible absorption spectrum .

Gemological laboratories make use of spectrophotometer machines that can distinguish natural , artificial , and color @-@ enhanced diamonds . The spectrophotometers analyze the infrared , visible , and ultraviolet absorption and luminescence spectra of diamonds cooled with liquid nitrogen to detect tell @-@ tale absorption lines that are not normally discernible .

= = Electrical properties = =

Except for most natural blue diamonds , which are semiconductors due to substitutional boron impurities replacing carbon atoms , diamond is a good electrical insulator , having a resistivity of  $10^9 \text{ } \Omega \cdot \text{m}$  to  $10^{18} \text{ } \Omega \cdot \text{m}$  (  $10^{11}$  to  $10^{18} \text{ } \Omega \cdot \text{m}$  ) . Natural blue or blue @-@ gray diamonds , common for the Argyle diamond mine in Australia , are rich in hydrogen ; these diamonds are not semiconductors and it is unclear whether hydrogen is actually responsible for their blue @-@ gray color . Natural blue diamonds containing boron and synthetic diamonds doped with boron are p @-@ type semiconductors . N @-@ type diamond films are reproducibly synthesized by phosphorus doping during chemical vapor deposition . Diode p @-@ n junctions and UV light emitting diodes ( LEDs , at 235 nm ) have been produced by sequential deposition of p @-@ type ( boron @-@ doped ) and n @-@ type ( phosphorus @-@ doped ) layers .

Diamond transistors have been produced ( for research purposes ) . FETs with SiN dielectric layers , and SC @-@ FETs have been made .

In April 2004 , the journal Nature reported that below the superconducting transition temperature 4 K , boron @-@ doped diamond synthesized at high temperature and high pressure is a bulk superconductor . Superconductivity was later observed in heavily boron @-@ doped films grown by various chemical vapor deposition techniques , and the highest reported transition temperature ( by 2009 ) is 11 @. @ 4 K. ( See also Covalent superconductor # Diamond )

Uncommon magnetic properties ( spin glass state ) were observed in diamond nanocrystals intercalated with potassium . Unlike paramagnetic host material , magnetic susceptibility measurements of intercalated nanodiamond revealed distinct ferromagnetic behavior at 5 K. This is essentially different from results of potassium intercalation in graphite or C60 fullerene , and shows that sp<sup>3</sup> bonding promotes magnetic ordering in carbon . The measurements presented first experimental evidence of intercalation @-@ induced spin @-@ glass state in a nanocrystalline diamond system .

= = Thermal conductivity = =

Unlike most electrical insulators , diamond is a good conductor of heat because of the strong covalent bonding and low phonon scattering . Thermal conductivity of natural diamond was measured to be about  $22 \text{ W / ( cm } \cdot \text{ K )}$  , which is five times more than copper . Monocrystalline synthetic diamond enriched in the isotope <sup>12</sup>C ( 99 @. @ 9 % ) has the highest thermal conductivity of any known solid at room temperature :  $33 @. @ 2 \text{ W / ( cm } \cdot \text{ K )}$  . Because diamond has such high thermal conductance it is already used in semiconductor manufacture to prevent silicon and other semiconducting materials from overheating . At lower temperatures conductivity becomes even better , and reaches  $410 \text{ W / ( cm } \cdot \text{ K )}$  at 104 K ( <sup>12</sup>C @-@ enriched diamond ) .

Diamond 's high thermal conductivity is used by jewelers and gemologists who may employ an electronic thermal probe to distinguish diamonds from their imitations . These probes consist of a pair of battery @-@ powered thermistors mounted in a fine copper tip . One thermistor functions as a heating device while the other measures the temperature of the copper tip : if the stone being tested is a diamond , it will conduct the tip 's thermal energy rapidly enough to produce a measurable temperature drop . This test takes about 2 ? 3 seconds . However , older probes will be fooled by moissanite , a crystalline mineral form of silicon carbide introduced in 1998 as an

alternative to diamonds , which has a similar thermal conductivity .

= = Thermal stability = =

Being a form of carbon , diamond oxidizes in air if heated over 700 ° C. In absence of oxygen , e.g. in a flow of high @-@ purity argon gas , diamond can be heated up to about 1700 ° C. Its surface blackens , but can be recovered by re @-@ polishing . At high pressure ( ~ 20 GPa ) diamond can be heated up to 2500 ° C , and a report published in 2009 suggests that diamond can withstand temperatures of 3000 ° C and above .

Diamonds are carbon crystals that form deep within the Earth under high temperatures and extreme pressures . At surface air pressure ( one atmosphere ) , diamonds are not as stable as graphite , and so the decay of diamond is thermodynamically favorable (  $\Delta H = 2 \text{ kJ / mol}$  ) . So , contrary to De Beers ' ad campaign extending from 1948 to at least 2013 under the slogan " A diamond is forever " , diamonds are definitely not forever . However , owing to a very large kinetic energy barrier , diamonds are metastable ; they will not decay into graphite under normal conditions .