

Diamond Material

This invention relates to changes to the absorption characteristics of some types of nitrogen-containing diamond material that may occur when that diamond material is exposed to certain conditions. In particular the invention relates to a method involving controlled irradiation of that diamond material to minimise the changes. Preferred methods according to the invention relate to controlled irradiation of diamond material made by chemical vapour deposition (so-called CVD synthetic diamond material). The invention also relates to diamond material *per se*. Preferred embodiments of diamond material according to the invention relate to CVD synthetic diamond material which has been subjected to controlled irradiation.

A particular type of rare fancy-coloured, naturally occurring diamond, known as chameleon diamond, is known, which shows changes to its absorption characteristics under certain conditions. Being rare and deemed valuable, there are not known to be any reports of non-reversible treatments on these diamonds.

The term "fancy-coloured diamond" is a well-established gem trade classification of stronger and more unusual colours in diamond material.

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Pink type IIa natural diamonds also form another important class of diamonds that exhibit colour changes. These have been shown to change colour from pink to brown upon ultraviolet (UV) illumination as described by de Weerd and van Royen (Diamond and Related Materials, 10 (2001), 474-479). The pink colour is a result of a broad optical absorption feature at 550 nm that is bleached by ultraviolet radiation and also diminishes on cooling.

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In the manufacture of synthetic diamond material, in particular CVD synthetic diamond material, it is known to dope the diamond material by the addition of low concentrations of nitrogen to the gases fed into the synthesis chamber during the CVD process. It is known in the art that this can be advantageous, the nitrogen increasing the growth rate of the CVD synthetic diamond material. It is also known that the presence of the low concentrations of nitrogen in the CVD growth environment can affect the nature and concentration of the defects that are incorporated as the material grows.

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As mentioned above, this invention relates to controlled irradiation of diamond material to minimise changes to the absorption characteristics of some types of nitrogen-containing diamond material that may occur when that diamond material is exposed to certain conditions. Irradiation of diamond material is known in the prior art. For example, EP 0615954 and EP 0316856 describe irradiation of synthetic diamond material with an electron beam or a neutron beam to form lattice defects in the crystal. Thereafter the diamond crystal is annealed in a prescribed temperature range, so that nitrogen atoms are bonded with the lattice defects to form colour centres, such as that comprising a substitutional nitrogen atom adjacent to a vacancy, referred to as an "[N-V] colour centre" or just "N-V", which can give the diamond material a desirable colour, such as purple or red/pink, i.e. they introduce a desired fancy colour into the diamond material. Similarly "Optical Absorption and Luminescence" by John Walker in "Reports on Progress in Physics", Volume 42, 1979, describes the steps of forming lattice defects in crystals by electron beam irradiation, and if necessary annealing to cause the lattice defects to combine with nitrogen atoms contained in the crystals. In the prior art the whole purpose of the irradiation and annealing steps is to produce so-called colour centres, that is to introduce colour into the diamond material. The irradiated and annealed diamond material of EP 0615954A and EP 0316856A contains so-called N-V defects as identified by significant absorptions at about 570 nm.

Similarly "CVD Grown Pink Diamonds" by Wuyi Wang, of GIA Laboratories, published 30 April 2009 on www.gia.edu/research-resources describes CVD synthetic diamond material where some significant amount of the nitrogen present is in the form of N-V centres which strongly absorb yellow and orange light, thus creating a pink to red colour. These diamond materials, like those described in the two EP publications (EP 0615954 and EP 0316856) contain N-V centres as evidenced by *inter alia* strong absorptions at about 570 nm.

We have observed that some nitrogen doped synthetic diamond material, particularly some nitrogen doped synthetic diamond material when made by chemical vapour deposition (CVD synthetic diamond material), also show changes to their absorption characteristics, which can be observed as a colour change, under certain conditions. Thus, like the chameleon diamonds, we have noticed that the colour of such synthetic diamond material may vary across a colour range, the colour being unstable across this colour range, and the observed colour at any particular time depending on the recent history of the diamond material. For example exposure to radiation, particularly to

radiation with an energy greater than 2.0 eV, for example exposure to ultraviolet radiation, tends to change the diamond material to a lower grade colour, which is generally considered less desirable, whereas thermal treatment at elevated temperatures tends to change the diamond material to a higher grade colour, which is generally considered more desirable. Low and high grade colours are defined later in the specification. Since for most applications the usual state for diamond material is one in which it is exposed to radiation in the form of light, the usual colour of the diamond material tends towards the lower, less desirable colour grades of their unstable colour range. In this specification we shall refer to this usual colour for the diamond material, i.e. the colour of the diamond material when it is exposed to radiation, or has recently, been exposed to radiation, particularly to radiation with an energy greater than 2.0 eV, as its "equilibrium colour", and the usual state of diamond material, i.e. the state where it is exposed to radiation, or has recently been exposed to radiation, as its "equilibrium state" or "equilibrium condition".

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As mentioned above, it is known that the presence of the low concentrations of nitrogen in a CVD growth environment can affect the nature and concentration of the defects that are incorporated in a CVD synthetic diamond material as the diamond material grows.

Electron paramagnetic resonance (EPR) and optical absorption spectroscopy have been used to study the nature of defects introduced into the diamond material as a direct consequence of the CVD growth process in which low concentrations of nitrogen are introduced. The presence of the nitrogen in the grown CVD synthetic diamond material can be evidenced by looking at absorption spectra for the grown diamond material, and while the exact nature of all the defects in this diamond material are not fully understood, analysis of these spectra gives some indication of the relative proportions of different types of defect present in the grown CVD synthetic diamond material as a result of the presence of low concentrations of nitrogen during the growth process. A typical spectrum for grown CVD synthetic diamond material grown with nitrogen added to the synthesis environment shows a peak at about 270 nm, which is generated by the presence of neutral single substitutional nitrogen (SSN) atoms in the diamond lattice. Additionally peaks have been observed at about 350 nm and approximately 510 nm corresponding to other defects characteristic and unique to CVD synthetic diamond material, and furthermore a so-called "ramp", that is a rising background of the form $c \times \lambda^{-3}$ has been observed, where c is a constant and λ is the wavelength. The combination of these features (SSN, 350 nm peak, 510 nm peak and ramp) affect the

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colour in the visible part of the electromagnetic spectrum (which is generally considered to cover the wavelength range 380 nm to 750 nm), and are believed to be responsible for the brown colour usually seen in nitrogen doped CVD synthetic diamond material.

- 5 In practice it has been found that the precise width and position in the spectrum of these characteristic absorption bands can vary. The position of peak maxima is most easily ascertained by using the second differential of the spectrum. It has been found that absorption spectra can generally be deconstructed into a number of approximate components, and it is useful to carry out this deconstruction, since when the well understood components are subtracted from any recorded spectrum, then the contribution of other, less well understood, components can more easily be seen. For example, it is known to subtract the spectral component of standard synthetic diamond material from any observed spectrum. In the present case, for diamond material referred to in the present invention, we have used the spectral decomposition set out in the numbered paragraphs below and shown in Figure 1. For ease of comparison the following limits are measured from 0 cm^{-1} on the individual spectral component, with the spectrum being made to be 0 at 800 nm.
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- 20 1) Single substitutional nitrogen component with an absorption coefficient at 270 nm that is generally within the range 0.05 cm^{-1} and 20 cm^{-1} and an absorption coefficient at 425 nm that generally lies between 0.04 cm^{-1} and 1 cm^{-1} .
- 25 2) An absorption band centred at 3.54 eV (350 nm) ± 0.2 eV with a full width at half maximum (FWHM) of approximately 1 eV and a maximum contribution to the absorption spectrum generally between 0.05 cm^{-1} and 8 cm^{-1} at its centre.
- 30 3) An absorption band centred at 2.43 eV (510 nm) ± 0.4 eV with a FWHM of approximately 1 eV and a maximum contribution to the absorption spectrum generally between 0.02 cm^{-1} and 4 cm^{-1} at its centre.
- 35 4) A small residual wavelength dependent component of the measured absorption coefficient (in cm^{-1}) that is found to have a wavelength dependence of the following approximate form: $c \times (\text{wavelength}, \lambda, \text{ in } \mu\text{m})^{-3}$ where $c < 0.2$ such that the contribution of this component at 510 nm is generally less than 1.5 cm^{-1} .

Figure 1 shows the absorption spectrum of a typical CVD synthetic diamond layer (curve B) which has been removed from its growth substrate, and the components into which it can be deconvoluted. The first step in the spectral decomposition is the subtraction of the spectrum of a type Ib high pressure high temperature (HPHT) synthetic diamond material (curve A), scaled so that the residual shows no 270 nm feature. The residual spectrum is then be deconvoluted into a $c \times \lambda^{-3}$ component (curve C) and two overlapping bands, one centred at 350 nm and the other centred at 510 nm of the kind described above in numbered paragraphs (2) and (3) above. The two overlapping bands are shown as curve D in Figure 1.

It is known that the form of UV/visible optical absorption spectra of CVD synthetic diamond material grown using a range of different processes can be specified by sums of the components described above, with different weighting factors for the components in different cases. For the purposes of specifying the shape of the spectrum the contributions of the different components are given in the following ways.

270 nm: The peak 270 nm absorption coefficient of the type Ib component is measured from a sloping baseline connecting the type Ib spectrum either side of the 270 nm feature that extends over the approximate range from 235 nm to 325 nm.

350 nm band: The peak absorption coefficient contribution of this band.

510 nm band: The peak absorption coefficient contribution of this band.

Ramp: The contribution of the $c \times \lambda^{-3}$ component to the absorption coefficient at 510 nm.

In the present specification, for all quoted absorption coefficients, the absorption coefficients have been measured by normalising the spectra so that they start at 0 cm^{-1} at 800 nm.

The method according to the present invention is particularly applicable to synthetic diamond material, more particularly to CVD synthetic diamond material.

As noted above, diamond materials that exhibit a pronounced amount of colour are known as "fancy" coloured diamonds in the field. Other diamond materials that do not show such pronounced colour may be graded using the Gemological Institute of America

(GIA) scale. That scale grades diamond materials alphabetically from D to Z. The GIA scale is well known. D represents the highest grade and most colourless diamond material on the GIA scale, and Z represents the lowest grade on the GIA scale, a diamond material of grade Z appearing light yellow to the naked eye. Higher grade diamond materials (those on the GIA scale nearer to grade D) are generally considered more desirable than lower grade diamond materials (those nearer to grade Z), both in the gem trade and for industrial applications. When a diamond material's colour is more intense than the Z grading it enters the realm of "fancy" diamond of which chameleon diamonds are a sub set.

There are three visual attributes to colour, these being hue, lightness and saturation. These terms are well understood by the person skilled in the art. Briefly: hue is the attribute of colour that allows it to be classified as red, green, blue, yellow, black or white, or and intermediated thereof; lightness is the attribute of colour that is defined by the degree of similarity with a neutral achromatic scale starting with white and progressing through grey to black; saturation is the attribute of colour that is defined by the degree of difference from an achromatic colour of the same lightness. Saturation is also a descriptive term corresponding to the strength of the colour. A system for quantifying colour, known as the "CIE L*a*b*" colour space" or more simply "CIELAB", exists which defines the saturation by a parameter known as C*. Where the colour of a diamond material falls within the GIA scale, the correlation between C* values and GIA grades respectively is 0=D, 0.5=E, 1.0=F, 1.5=G, 2.0=H etc for a round brilliant cut (RBC) diamond and where the saturation (C*) is determined from the absorbance spectrum measured along the axis of the stone through the complete depth of the material. In practice, all measurements on the GIA scale in this document are for an equivalent 0.5 ct round brilliant cut gemstone. C* values are also applicable to fancy coloured diamonds.

Our invention is applicable to all colours of diamond materials, including diamond materials whose colour falls only within the GIA scale of D to Z, and fancy diamonds whose colour may be outside the GIA scale of D to Z.

The perceived colour of an object depends on the transmittance/absorbance spectrum of the object, the spectral power distribution of the illumination source and the response curves of the observer's eyes. The CIELAB chromaticity coordinates quoted in this patent application have been derived in the way described below. Using a standard D65 illumination spectrum and standard (red, green and blue) response curves of the eye (G.

Wyszecki and W. S. Stiles, John Wiley, New York-London-Sydney, 1967), CIE $L^*a^*b^*$ chromaticity coordinates of a parallel-sided plate of diamond material have been derived from its transmittance spectrum using the relationships below, between 350 nm and 800 nm with a data interval of 1 nm:

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S_λ = transmittance at wavelength λ

L_λ = spectral power distribution of the illumination

x_λ = red response function of the eye

y_λ = green response function of the eye

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z_λ = blue response function of the eye

$$X = \sum_\lambda [S_\lambda x_\lambda L_\lambda] / Y_0$$

$$Y = \sum_\lambda [S_\lambda y_\lambda L_\lambda] / Y_0$$

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$$Z = \sum_\lambda [S_\lambda z_\lambda L_\lambda] / Y_0$$

$$\text{Where } Y_0 = \sum_\lambda y_\lambda L_\lambda$$

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$$L^* = 116(Y/Y_0)^{1/3} - 16 = \text{Lightness} \quad (\text{for } Y/Y_0 > 0.008856)$$

$$a^* = 500[(X/X_0)^{1/3} - (Y/Y_0)^{1/3}] \quad (\text{for } X/X_0 > 0.008856, Y/Y_0 > 0.008856)$$

$$b^* = 200[(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}] \quad (\text{for } Z/Z_0 > 0.008856)$$

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$$C^* = (a^{*2} + b^{*2})^{1/2} = \text{saturation}$$

$$h_{ab} = \arctan(b^*/a^*) = \text{hue angle}$$

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Modified versions of these equations must be used outside the limits of Y/Y_0 , X/X_0 and Z/Z_0 . The modified versions are given in a technical report prepared by the Commission Internationale de L'Eclairage (Colorimetry (1986)).

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It is possible to predict how the a^*b^* coordinates of diamond material with a given absorption coefficient spectrum will change as the optical path length is varied. In order to do this, the reflection loss must first be subtracted from the measured absorbance spectrum. The absorbance is then scaled to allow for a different path length and then

the reflection loss is added back on. The absorbance spectrum can then be converted to a transmittance spectrum which is used to derive the CIELAB coordinates for the new thickness. In this way the dependence of the hue, saturation and lightness on optical path length can be modelled to give an understanding of how the colour of diamond material with given absorption properties per unit thickness will depend on the optical path length.

The C* (saturation) numbers can be divided into saturation ranges of 10 C* units and assigned descriptive terms as below.

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0-10	weak
10-20	weak-moderate
20-30	moderate
30-40	moderate-strong
40-50	strong
50-60	strong-very strong
60-70	very strong
70-80+	very very strong

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20 As mentioned above, we have observed that the colour of some CVD synthetic diamond material may vary across a colour range, the colour being unstable across this colour range, and the observed colour at any particular time depending on the recent history of the diamond material.

25 We have surprisingly found that irradiation (performed in a controlled manner) can be used, not to introduce colour as has been used in the aforementioned prior art, but to reduce the colour range over which the diamond material can exist. This means that the controlled irradiation tends to stabilise the colour of the diamond material regardless of its environmental conditions or its recent thermal/illumination history. In preferred
 30 embodiments we have also found that not only can the colour be stabilised, but also the equilibrium colour (as hereinbefore defined) can be improved, by which we mean that the equilibrium colour of the diamond material that has been subjected to the controlled irradiation treatment is a higher colour grade (nearer to D on the GIA scale and/or has a lower C* value), i.e. it has what is generally considered to be a more desirable colour (or
 35 lack of colour) than the equilibrium colour of the same diamond material prior to the controlled irradiation.

Our observations have shown that, for a nitrogen containing CVD synthetic diamond material round brilliant with a colour grade on the GIA scale, and in particular for a nitrogen containing CVD synthetic diamond round brilliant with a starting colour grade in the range F to Z (corresponding to 1 to 11 on the C* scale especially for a nitrogen containing CVD synthetic diamond material with a starting colour grade in the range I to K on the GIA scale (corresponding to 2.5 to 3.99 on the C* scale), exposure to radiation, and in particular to UV radiation results in a colour change of the diamond material to lower colour grades (i.e. away from D grade on the GIA colour scale), while thermal treatment, for example at a temperature of 525°C for one hour, causes the diamond material to change colour in the opposite direction to the higher, generally more desirable, (i.e. towards D grade on the GIA colour scale) colour grades. For example for a CVD synthetic diamond round brilliant of starting colour grade K (C* 3.5-3.99) it is observed that exposure to UV radiation for 20 minutes results in a colour change to a lower colour grade L (C* 4-4.49), while subsequent heating to 525°C for 1 hour results in a colour change to higher grade I (C* 2.5-2.99), i.e. a total colour grade difference of L to I (i.e. 3 colour grade difference on the GIA scale, corresponding to a C* change of 1.5). Overall we have observed that for any given CVD synthetic diamond sample the overall colour grade change when exposed to radiation and then thermally treated may vary by up to 1, up to 2, up to 3, up to 4, up to 5, even up to 6 colour grades as measured on the GIA scale (corresponding to a C* change of up to 0.5, 1, 1.5, 2, 2.5 or even up to 3).

Similarly for fancy diamond ($C^* > 11$), a change of at least 0.5, or for some embodiments a change of at least 1 or 1.5 or 2, up to 4, 5 or even 6 in the value of C* may result from exposure to radiation and then thermal treatment.

This variation in colour, and the associated variation in the absorption characteristics of the electromagnetic spectrum of the synthetic diamond material, on exposure to radiation (e.g. light) and heating is undesirable for some applications. As will be elucidated further, while the observed colour of the synthetic diamond material is associated with specific defects (with specific electronic configuration) within the diamond material which give rise to absorption, colour instability can be associated with charge transfer between these same defects in the crystal lattice, these charge transfer effects modifying the absorption spectrum. In practice it has been found that exposure of the diamond material to any radiation with energy greater than 2.0 eV leads to an increase in the absorption in the visible part of the spectrum, causing the diamond material colour to

change to a lower (generally considered less desirable) colour grade (nearer to Z on the GIA scale if applicable, and/or higher C^* value). While this increase can be removed by a simple low temperature (e.g. $\sim 500^\circ\text{C}$) thermal treatment, for most usual applications the diamond material will ordinarily be exposed to radiation with energy greater than 2.0 eV (for example sun light, fluorescent room lights etc). This means that for these usual applications the diamond material is always pushed towards a state where it contains those specific defects and associated specific electronic configurations that increase the absorption of the diamond material in the visible part of the spectrum, leading to lower, generally considered less desirable colour grades (nearer to Z if the GIA scale is applicable, and/or to higher C^* values). As mentioned above we refer to this "usual" state of a diamond material, when the diamond material is, or has recently been exposed to radiation, particularly to radiation with energy greater than 2.0 eV, as the "equilibrium state" or "equilibrium condition" and the colour of the diamond material in this state as the "equilibrium colour".

When a diamond material exhibits colour instability this may be undesirable for a number of applications. Similarly the fact that the "equilibrium condition" corresponds to the highest absorption across the colour range over which the diamond material is unstable is also undesirable for a number of applications.

Also where a diamond material exhibits colour instability, this, as explained previously, can also impact the materials carrier properties (for example carrier mobility) and thus the material can show variable carrier mobility depending on the history of the diamond material. For some applications carrier mobility instability and, for example, the related instability in other electronic properties of the diamond material may be undesirable.

As examples of applications where the colour instability and/or the carrier property instability, and/or the tendency for the equilibrium condition of the diamond material to correspond to the highest absorption across the colour range over which the diamond material is unstable is undesirable, there may be mentioned the following:

(i) For diamond material used in certain optical applications such as Raman lasers or as a passive optical element in a high power laser operating the range from 225 nm to 1600 nm it is desirable that the absorption is minimized and stable.

(ii) In electronic devices made of diamond material, a key performance indicator is related to the carrier mobility. The mobility is reduced in materials which contain a high concentration of ionized (charged) impurities through carrier scattering. Any process which can lead to the number and type of these ionized impurities changing is undesirable as it can lead to an unstable electronic device.

(iii) While there are some exceptions in the field of fancy natural diamonds, it is undesirable for a diamond used in ornamental purposes to show colour instability, not least related to difficulties associated with grading such a diamond.

The colour change observed in the CVD synthetic diamond material on exposure to radiation and/or thermal treatment is thought to be due to a change in the charge state of one or more of the defects in the diamond material. This change in charge state is thought to arise from an electron or other charge transfer effect taking place within the diamond lattice. Thus the colour instability that we observe is thought to result from these electron or other charge transfers.

Without limiting the invention in any way, a possible explanation for the charge transfer effects which give the colour changes on exposure to radiation and heating is as follows.

Neutral single substitutional nitrogen atoms (N_s^0) act as electron donors. Thermal or optical excitation of an electron from N_s^0 sites occurs as a result of either heating or radiation exposure respectively, the excited electrons being captured in some other kind of defect in the diamond structure, which defect sites we shall call "X". This charge transfer effect can be written as follows:



We believe that exposure of the diamond material to radiation, particularly to radiation with energy greater than 2.0 eV, and more specifically UV radiation, causes the equation to move to the left, resulting in changes to the absorption spectrum of the diamond material that result in a lower colour grade (for example nearer to Z on the GIA scale and corresponding to a higher C^* value); while thermal treatment of the diamond material causes the equation to move to the right, resulting in changes to the absorption spectrum of the diamond material that result in a higher colour grade (for example nearer to D on the GIA scale and corresponding to a lower C^* value). It is thought that the colour that is observed in diamond material is associated with the presence of defect X in the diamond

lattice, the charged defect X^- being associated with a colourless state, or at least more colourless state.

Specifically we use X here to cover the unknown defect(s) in nitrogen doped CVD synthetic diamond material which take place in the charge transfer process. These defect(s) are thought to be responsible for the visible absorption features characterized by one or some combination of the 350 nm, 510 nm and the Ramp components.

A first aspect of the present invention provides a method comprising:

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a) providing a nitrogen-containing diamond material which shows a measurable difference in at least one of its absorption characteristics in first and second states, the first state being after exposure to radiation having an energy of at least 5.5 eV, and the second state being after thermal treatment at 798 K (525°C),

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b) treating the said nitrogen containing diamond material by controlled irradiation of the said nitrogen-containing diamond material so as to introduce sufficient defects in the diamond material so as to produce one or both of:

- (i) an absorption coefficient measured at 77 K of at least 0.01 cm^{-1} and at most 1 cm^{-1} at a wavelength of 741 nm; and
- (ii) an absorption coefficient measured at 77 K of at least 0.01 cm^{-1} and at most 0.5 cm^{-1} at a wavelength of 394 nm;

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whereby the measurable difference in the said absorption characteristics of the irradiation treated diamond material in the said first and second states, having been exposed to the same radiation and thermal treatment as the provided diamond, is reduced relative to the measurable difference in the said absorption characteristics of the provided diamond material in the said first and second states.

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When we say the diamond material shows a *measurable* difference in its absorption characteristics we include any differences that can be recorded. This includes for example numerical absorption coefficients of the diamond material at various wavelengths, and visible changes, e.g. colour changes that may be observed by the naked eye, or with the aid of magnification equipment.

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The step of actually growing the CVD diamond material may or may not form part of the method of embodiments of the invention. Providing a CVD diamond material may mean growing the CVD diamond material, or may simply mean, for example, selecting a pre-grown CVD diamond material.

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By "controlled irradiation" we mean applying an amount of irradiation so as to introduce the said sufficient defects in the diamond material so as to produce one or both of:

- (i) an absorption coefficient measured at 77 K of at least 0.01 cm^{-1} and at most 1 cm^{-1} at a wavelength of 741 nm; and
- 10 (ii) an absorption coefficient measured at 77 K of at least 0.01 cm^{-1} and at most 0.5 cm^{-1} at a wavelength of 394 nm.

We have observed that for the diamond materials of interest to the present specification exposure to radiation changes at least one of the absorption characteristics of the diamond material, the change increasing as the period of exposure is increased, and then levelling off after a certain period of exposure. The time at which this "levelling off" occurs depends on the intensity of the radiation and its energy. Preferably, in order to make worthwhile comparisons of diamond materials treated by methods according to the invention, the period of exposure to the said radiation is until substantially no further measurable change in the said absorption characteristics are found to occur. For example, for a diamond material whose colour is one on the GIA scale, the period of exposure is preferably until the diamond material shows no further change in colour grade on the GIA scale, for example such that sequential measurements show no further change in colour on the GIA scale. As another measure, the period of exposure is preferably until the diamond material shows substantially no further change in its C^* value, e.g. such that sequential measurements on the diamond material show a C^* change of less than 0.5, preferably less than 0.4, more preferably less than 0.3, and even less than 0.2 or 0.1. Sequential measurements may be taken, for example, every hour, or every 20 minutes, or every two minutes, or every minute or every 30 seconds.

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In use, the diamond material may be exposed to radiation with an energy less than 5.5 eV, e.g. less than 4.5 eV or less than 3.5 eV or even less than 2.5 eV, and for some diamond materials this lower wavelength exposure will also cause changes to its absorption characteristics, which it is desirable to stabilise. Such diamond material would also show changes to its absorption characteristics when exposed to radiation having an energy greater than 5.5 eV. The value of 5.5 eV is defined in this specification

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to encompass the broadest scope of diamond material that show changes to its absorption characteristics when exposed to radiation.

Those skilled in the art will realize that charged particles other than photons of electromagnetic radiation can also introduce electron hole pairs with energy >5.5 eV into the diamond lattice and hence affect the absorption characteristics. As examples there may be mentioned beta and alpha particles. The rest of this discussion focuses on the use of photons but this excitation source should not be seen to limit the invention, and reference in the invention to radiation of energy of at least 5.5 eV includes in its broadest scope charged particles of electromagnetic radiation other than photons with an energy greater than 5.5 eV.

Similarly we have observed that for the diamond material of interest to the present specification thermal treatment changes at least some of the absorption characteristics, the change increasing as the period of thermal treatment is increased, and then levelling off after a certain period of thermal treatment. The time at which this "levelling off" occurs depends *inter alia* on the temperature of the thermal treatment, and the nature of the diamond material. Preferably the period of thermal treatment is until substantially no further measurable changes to the said absorption characteristics are found to occur. For example, for a synthetic diamond 0.5 ct round brilliant with measured $C^*=3$, the period of thermal treatment is preferably until the diamond shows no further change in colour grade on the GIA scale, for example such that sequential measurements show no further change in colour on the GIA scale. As another measure, the period of thermal treatment is preferably until the diamond material shows substantially no further change in its C^* value, e.g. such that sequential measurements on the diamond material show a C^* change of less than 0.5, preferably less than 0.4, more preferably less than 0.3, and even less than 0.2 or 0.1. As before, sequential measurements may be taken, for example, every hour, or every 30 minutes, or every 10 minutes, or every two minutes, or every minute or every 30 seconds.

In use, the diamond material may be exposed to elevated temperatures for various lengths of time, and these elevated temperatures may be less than 525°C, but nonetheless result in absorption characteristic changes to the diamond material. For example exposure to elevated temperatures of at least 150°C, at least 200°C, at least 250°C, at least 400°C, or at least 450°C for periods of 30 minutes, 1 hour, 5 hours, 10 hours or 24 hours, or even a week may result, for some diamond material in changes to

its absorption characteristics, which it is desirable to stabilise. Such diamond material would also show changes to its absorption characteristics when thermally treated at 525°C. The recitation of thermal treatment at 525°C is defined in this specification to encompass the broadest scope of synthetic diamond material that show changes to its absorption characteristics when exposed to elevated temperatures.

Thus if diamond material is shown to exhibit a change in at least one absorption characteristic when exposed to radiation of energy of at least 5.5 eV and a thermal treatment at 525°C, then it is diamond material which would benefit from controlled irradiation according to the method of the invention, even if in use it would never be exposed to such high temperatures or to light or other electromagnetic radiation of such high energy.

It is not fully understood why the irradiation step reduces the differences in the absorption characteristic of the diamond material in its first and second states (e.g. stabilises the colour), but it is thought that it may be because the controlled irradiation introduces specific defects into the diamond's crystal lattice which act as alternative donors/acceptors for electrons/holes (alternative to the X defects) subsequently excited by UV radiation or thermally treated, thereby substantially preventing, or at least reducing or minimising charge transfer to the optical sites that were active in the diamond material prior to its treatment by controlled irradiation.

According to the invention the provided nitrogen-containing diamond material shows a measurable difference in at least one of its absorption characteristics in first and second states. Preferably it is the majority volume of the diamond material which shows this measurable difference, by which we means at least 55% and preferably at least 80% and most preferably at least 95% of the whole volume of the diamond material.

Defects can be introduced by any means that lead to the production of interstitials and vacancies within the diamond lattice. Those skilled in the art will be aware of a number of different routes to achieve this. The most common route is to use one or some combination of electrons, neutrons or gamma photons. Therefore in a preferred method according to the invention the controlled irradiation is provided by one or more of electrons, neutrons and gamma photons.

When energy is imparted to the diamond lattice there are four possible outcomes. Firstly the lattice may be undamaged and the energy transferred dissipated in the form of a phonon. Secondly, a carbon atom may be temporarily displaced from its lattice position but without sufficient energy to remain free from its original position, recombination
 5 occurring. Thirdly, the carbon atom may be displaced to a new interstitial site thus creating a vacancy. This vacancy-interstitial pair is known as a Frenkel defect. Fourthly, a carbon atom may receive enough energy to be moved out of its lattice position and knock other carbon atoms out of their lattice positions, producing a cascade of damage resulting in numerous interstitials and vacancies. Neutral vacancies are referred to in the
 10 field as V^0 and negatively charged vacancies as V^- .

Factors which affect the type, concentration and depth of damage include (a) the irradiation/implantation dose which has a primary impact on the density of defects produced, (b) the damaging particle's energy which affects the depth of damage and
 15 whether there is point damage or extended cascade damage, (c) the type of sample, for example the damage production rate in type Ib diamond material is ~7x times higher than for type IIa diamond material, (d) the temperature at which irradiation is carried out, this impacting both the type of defects formed (e.g. if the sample temperature exceeds 500 K) and the concentration of defects. The irradiation process itself can lead to in-situ
 20 annealing processes if the sample temperature is not carefully controlled. This is particularly an issue when using large beam currents/fluxes.

During the irradiation the sample temperature is preferably maintained at temperature below 400°C. For some preferred embodiments it is preferably maintained at a
 25 temperature less than 300°C, or less than 250°C, less than 200°C, less than 150°C, less than 100°C, less than 80°C, less than 50°C, less than 30°C. For some preferred embodiments it is preferably maintained at a temperature no lower than -200°C (i.e. minus 200°C, preferably no lower than -150°C (i.e. minus 150°C).

30 For diamond material, the absorption characteristic at 741 nm and/or at 394 nm are characteristic of defects introduced by irradiation, and are discussed in more detail later in the specification. In general, when a diamond material is irradiated the higher the irradiation dose the higher the absorption coefficients at 741 nm and/or 394 nm.

35 We have found that the required controlled amount of irradiation is one that introduces sufficient interstitial defects in the diamond material as to produce an absorption

coefficient measured at 77 K of at least 0.01 cm^{-1} and at the most 1 cm^{-1} at the wavelength of 741 nm (this is known in the field as the GR1 characteristic wavelength), and/or an absorption of at least 0.01 cm^{-1} and at the most 0.5 cm^{-1} at a wavelength of 394 nm (this is known in the field as the ND1 characteristic wavelength).

5

The maximum values of these coefficients recited in this specification, define the point when in themselves they add measurable absorption to distort the colour of the diamond object, and the minimum value is that when enough additional defects have been created on irradiation to compete with the charge transfer process in Equation 1 and yield diamond material whose measurable difference in its absorption characteristics in its first and second states is reduced.

An absorption coefficient of at least 0.01 cm^{-1} and at the most 1 cm^{-1} at the wavelength of 741 nm (the so-called GR1 characteristic wavelength), corresponds to a concentrations of V^0 of at least 4 parts per billion (ppb) and at the most 0.15 parts per million (ppm). An absorption of at least 0.01 cm^{-1} and at the most 0.5 cm^{-1} at a wavelength of 394 nm (the so-called ND1 characteristic wavelength), corresponds to a concentration V^- of at least 1 ppb and not more than 0.2 ppm. Concentrations of vacancies in ppm are calculated in a known standard manner by integrating the area of peaks from the absorption spectrum of the diamond material, and using published coefficients for comparison to calculate concentration. The coefficients that are used for the calculations of concentrations of vacancies in the present specification are those set out by G. Davies in Physica B, 273-274 (1999), 15-23, as detailed in Table A below.

25 Table A

Defect	Calibration
V^-	$A_{\text{ND1}} = (4.8 \pm 0.2) \times 10^{-16} [V^-]$
V^0	$A_{\text{GR1}} = (1.2 \pm 0.3) \times 10^{-16} [V^0]$
NV	$A_{\text{NV}} = (1.4 \pm 0.35) \times 10^{-16} [N-V]$

In Table A, "A" is the integrated absorption (meV cm^{-1}) in the zero phonon line of the transition, measured at 77 K, with the absorption coefficient in cm^{-1} and the photon energy in meV. The concentration of the defect is in cm^{-3} .

30

A preferred irradiation dose of electrons corresponds to an electron fluence of at least 1×10^{15} electrons/ cm^2 , and/or preferably of at most 2×10^{17} electrons/ cm^2 , more

preferably to an electron fluence of at least 5×10^{15} and/or preferably of at most 4×10^{16} electrons/cm² (where "electrons/cm²" is sometimes abbreviated to "e⁻/cm²"). One skilled in the art will realize that the required minimum and maximum dose will depend on the starting characteristics of the diamond material. By simple way of illustration a diamond sample containing a higher concentration of N and X may need a greater dose than a sample containing a lower concentration. Typically a 4.5 MeV electron beam can be used to provide the irradiation. It may provide a current in the range 0.5 mA to 400 mA e.g. 20 mA. It may be applied for a period of 10 seconds to 100 hours, e.g. about 2 minutes. As an example a 4.5 MeV electron beam with a current of 20 mA applied for 2 minutes provides a dose of 3.2×10^{16} electrons/cm². It is preferred that the electrons are sufficiently energetic to impart a substantially uniform distribution of damage through the thickness of the diamond material. All doses/energies quoted in this specification are based on this presumption, but in principal the invention can be enacted using lesser energies, particularly a distribution of lesser energies.

We have found that the time for irradiation to achieve the desire electron fluence is preferably in the range 10 seconds to 10 hours, more generally in the range 10 seconds to 2 or 3 hours.

The irradiation treatment may be carried out at any suitable pressure, and is conveniently carried out at or near atmospheric pressure.

As mentioned above the measurable difference in at least some of the absorption characteristics of the treated (irradiated) diamond material in the said first and second states is reduced relative to that of the provided diamond material in the said first and second states by the method of the invention. What is typically desired is that the variation in the absorption characteristics leading to *variation in colour* in the first and second states is reduced by the controlled irradiation treatment. Other features of the absorption spectrum, e.g. the absorption coefficient at 741 nm or 394 nm would be expected to rise due to the irradiation.

In preferred embodiments according to the invention (i) the absorption spectrum of the provided diamond material in one or both of its first and second states has (a) an absorption coefficient of at least 0.1 cm^{-1} at 270 nm, and one or both of (b) an absorption coefficient of at least 0.05 cm^{-1} at 350 nm and (c) an absorption coefficient of at least 0.02 cm^{-1} at 510 nm; (ii) the measurable difference in the absorption characteristics of

the provided diamond material in its first and second states is a difference in the absorption coefficient at one or both of 350 nm and 510 nm is at least 0.15 cm^{-1} ; and (iii) the controlled irradiation treatment step reduces the said difference between the absorption coefficients in the first and second states at one or both of 350 nm and 510 nm by at least 0.05 cm^{-1} , preferably by at least 0.1 cm^{-1} , preferably at least 0.15 cm^{-1} . Thus in these embodiments precise measurement of the absorption coefficients can be used as the measure to determine the colour stabilisation achieved by the controlled irradiation.

10 In other embodiments according to the invention, the measurable difference in the absorption characteristics of the provided diamond material in its first and second states is a difference in the colour grade saturation value C^* of the provided diamond material in its first and second states of at least 0.5, and in some cases may be up to 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7 or 8.

15 C^* is dependent on the size and geometry of the diamond material since it depends on the path length through the diamond material. Where C^* values are given in the present specification they are based on a size and geometry for a diamond material that is a 0.5 carat (ct) round brilliant cut (RBC) stone. Where the diamond material used is actually a
20 different size and geometry from a 0.5 ct RBC stone, then the measured C^* value is adjusted. Therefore throughout this specification quoted C^* value are those for an equivalent 0.5 ct RBC stone.

The difference in colour saturation value C^* is preferably reduced by 0.25, more
25 preferably by 0.5, even by 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, or even 8 by the controlled irradiation step. Preferably the treated diamond material has an absolute C^* range between its first and second states of at most 0.5, or at most 1, 1.5, 2, or 3.

Thus in these embodiments measurement of C^* is used as the measure to determine the
30 absorption characteristic stabilisation, e.g. the colour stabilisation achieved by the controlled irradiation.

In other embodiments according to the invention, the measurable difference in the absorption characteristics of the provided diamond material in its first and second states
35 is a difference of at least two colour grades or even 3, 4, 5, 6, 7, or 8 colour grades, as measured on the GIA scale for diamond material.

As with C*, GIA scale measurements depend on path length, and as used in this specification all quoted GIA grades are for diamond material made into an equivalent 0.5 ct round brilliant cut stone.

5

The stated difference in GIA colour grade is preferably reduced by the controlled irradiation step by at least one grade, and in some cases by preferably at least two grades, three grades, four grades five grades, six grades, seven grades, or even eight grades, as measured on the GIA scale. Preferably the difference is colour grades
10 between the diamond material in the first and second states is reduced so that the diamond material has the same colour grade in its first and second states, or has a colour grade difference in its first and second states that differs by no more than one grade, two grades, or three grades.

15 Thus in these embodiments optical analysis of the colour and grading on the GIA scale is used as the measure to determine the colour stabilisation achieved by the controlled irradiation.

Preferably the colour grade on the GIA scale of the irradiated diamond material in its
20 equilibrium condition (as hereinbefore defined) is the same colour grade or higher (i.e. nearer to D) than the colour grade of the provided diamond material in its equilibrium condition, higher grades generally being considered preferable for most applications. Thus, in these cases the controlled irradiation can be seen not only to stabilise the colour against changes due to exposure to radiation and temperature, but also to improve the
25 absolute colour of the diamond material. This is a significant difference to the prior art, with irradiation resulting in a higher colour grade (lower C*) in the equilibrium condition, in addition to the colour stabilisation effect. In contrast in the prior art irradiation (which is not in the limited controlled manner of the present invention) results in more colour (higher C*). More preferably the colour grade of the irradiated diamond material in its
30 equilibrium condition is at least one, preferably at least two, or even at least 3 or 4 grades higher than that of the provided diamond material in its equilibrium condition.

This preferred colour improvement achieved by irradiation may also be defined in terms of the change in C* value of the diamond material. The preferred colour improvement
35 achieved by irradiation in terms of the C* value of the irradiated diamond material in its equilibrium condition (adjusted to be that of an equivalent 0.5 ct RBC stone) is the same

as, or preferably at least 0.5, 1, 1.5 or even 2 lower than the C^* value of the provided diamond material in its equilibrium condition.

- In preferred methods according to our invention the irradiated diamond material has an absorption coefficient at 570 nm that is less than 0.04 cm^{-1} . Preferably the irradiated diamond material has an absorption coefficient at 570 nm that is less than 0.02 cm^{-1} , more preferably less than 0.01 cm^{-1} , especially preferably less than 0.05 cm^{-1} . In general measurable levels of noise in spectra are of the order of 0.05 cm^{-1} , so it is difficult to measure peak absorption coefficients that are less than 0.05 cm^{-1} . The low absorption coefficient at 570 nm is evidence that the irradiated diamond material has no, or limited numbers of NV defects, as distinguished from the prior art referred to hereinbefore which irradiates and anneals diamond material to introduce colour and which has significant numbers of NV defects.
- Methods according to the invention find particular application where the nitrogen concentration in the diamond material is such that there is a measurable difference in the absorption spectra of the provided diamond material after UV exposure and thermal treatment, that is in situations where there is typically a colour change to stabilise. In practice this is found for diamond samples which contain SSN concentrations >0.01 ppm, preferably >0.03 ppm, preferably >0.05 ppm, preferably >0.08 ppm, preferably >0.10 ppm, preferably >0.15 ppm, preferably >0.20 ppm, preferably >0.30 ppm, preferably >0.40 ppm, preferably >0.50 ppm, preferably >0.8 ppm, preferably >1 ppm, preferably >1.5 ppm, preferably >2.0 ppm, preferably >3.0 ppm, preferably >4.0 ppm, preferably >5.0 ppm, preferably >8.0 ppm, preferably >10 ppm, or preferably >20 ppm.
- Methods according to the invention are preferably applied to diamond material not dominated by high SSN. The methods are preferably applied to diamonds with SSN concentrations <150 ppm, preferably <100 ppm, preferably <75 ppm, preferably <50 ppm.
- A second aspect of the present invention provides diamond material which has an absorption spectrum with one or both of the following characteristics:

Designation	Peak	Absorption coefficient (at peak)
V^0	741 nm	$0.01 \text{ cm}^{-1} - 1 \text{ cm}^{-1}$ (at 77 K)
V^-	394 nm	$0.01 \text{ cm}^{-1} - 0.5 \text{ cm}^{-1}$ (at 77 K)

These characteristics are an indication that controlled irradiation of the diamond material, as hereinbefore described with reference to the method according to the first aspect of the invention, has taken place.

- 5 The diamond material preferably has both of the characteristics designated V^0 and V^- set out above.

Preferably the diamond material is a synthetic diamond material.

- 10 Preferably the synthetic diamond material is CVD diamond material and has an absorption spectrum with the following additional characteristics

(i)

Designation	Starts	Ends	Peak	Absorption coefficient (at peak)
270 nm	220 nm	325 nm	270 nm	$0.05 \text{ cm}^{-1} - 20 \text{ cm}^{-1}$

- 15 and

(ii) one or more of

Designation	Starts	Ends	Peak	Absorption coefficient (at peak)
350 nm band	270 nm	450 nm	350 nm $\pm 10 \text{ nm}$	$0.05 \text{ cm}^{-1} - 10 \text{ cm}^{-1}$
510 nm band	420 nm	640 nm	510 nm $\pm 50 \text{ nm}$	$0.02 \text{ cm}^{-1} - 10 \text{ cm}^{-1}$
Designation	Form of Curve			Absorption Coefficient
Ramp	Rising background of form Absorption coefficient (cm^{-1}) = $C \times \lambda^{-3}$ (C =constant, λ in μm)			Contribution at 510 nm is: $< 1.5 \text{ cm}^{-1}$

Preferably the CVD synthetic diamond material has any two, or more preferably all three, of the characteristics set out in (ii) above.

20

Preferred values of the absorption characteristics are shown in the table below.

Designation	Starts	Ends	Peak	Absorption coefficient (at peak)
270 nm	220 nm	325 nm	270 nm	0.05 cm ⁻¹ – 20 cm ⁻¹ , preferably 0.1 cm ⁻¹ – 8 cm ⁻¹ , more preferably 0.2 cm ⁻¹ – 5 cm ⁻¹
350 nm band	270 nm	450 nm	350 nm ±10 nm	0.05 cm ⁻¹ – 10 cm ⁻¹ , preferably 0.10 cm ⁻¹ – 5 cm ⁻¹ , more preferably 0.20 cm ⁻¹ – 3 cm ⁻¹
510 nm band	420 nm	640 nm	510 nm ±50 nm	0.02 cm ⁻¹ – 10 cm ⁻¹ , preferably 0.03 cm ⁻¹ – 4 cm ⁻¹ , more preferably 0.1 cm ⁻¹ – 2 cm ⁻¹
V ⁰			741 nm	0.01 cm ⁻¹ – 1 cm ⁻¹ preferably 0.05 cm ⁻¹ – 0.5 cm ⁻¹ more preferably 0.1 cm ⁻¹ – 0.3 cm ⁻¹ (all at 77 K)
V ⁻			394 nm	0.01 cm ⁻¹ – 0.5 cm ⁻¹ preferably 0.015 cm ⁻¹ – 0.4 cm ⁻¹ more preferably 0.02 cm ⁻¹ – 0.2 cm ⁻¹ (all at 77 K)
Designation	Form of Curve			Absorption Coefficient
Ramp	Rising background of form Absorption coefficient (cm ⁻¹) = C x λ ⁻³ (C=constant, λ in μm)			Contribution at 510 nm is: < 1.5 cm ⁻¹ , preferably < 1.0 cm ⁻¹ , more preferably < 0.5 cm ⁻¹

Preferred diamond materials according to the invention may have one or more of the preferred absorption coefficient characteristics, in any combination.

5

Where a range of preferred absorption coefficients are given, these are to be interpreted to represent separate preferred upper and lower limits. For example for the 270 nm designation band, the preferred absorption coefficient range from 0.15 cm⁻¹ to 8 cm⁻¹ represents a preferred minimum coefficient of 0.15 cm⁻¹ and a preferred maximum coefficient of 8 cm⁻¹.

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The provided diamond material in the method according to the first aspect of the invention, and the diamond material of the second aspect of the invention are preferably

single crystals. In certain embodiments according to the first and second aspects of the invention, where the diamond material is a single crystal, the single crystal is in the form of a gemstone. As an alternative the diamond material may be polycrystalline. Polycrystalline diamond materials lead to light scatter in the visible part of the spectrum.

- 5 The invention is therefore likely to find most application for polycrystalline diamond material when the stabilization that is required is related to properties other than optical absorption, for instance dielectric loss and carrier mobility.

Embodiments and examples of the invention will now be described, by way of example,
10 with reference to the following figures, wherein:

Figure 1, which has been referred to above, shows a spectral decomposition of the UV/visible absorption spectrum of an orangish brown CVD synthetic diamond layer;

- 15 Figure 2a shows a room temperature absorption spectrum for a CVD synthetic diamond material according to Example 1, as-grown (curve A), after UV exposure (curve B), and after thermal treatment at 525°C (curve C), but prior to the controlled irradiation treatment of the method of the present invention;

- 20 Figure 2b shows a "difference" absorption spectrum for the CVD synthetic diamond material according to Example 1 after exposure to ultraviolet radiation and thermal treatment at 525°C after an electron irradiation dose according to a method of the present invention (curve B) and in the as-grown provided state (curve A).

- 25 Figure 3 shows an absorption spectrum, measured at 77 K, of the grown CVD synthetic diamond material of Example 1 after controlled irradiation treatment;

- Figure 4 shows a room temperature absorption spectrum for a CVD synthetic diamond sample according to Example 3, as grown (curve A), after UV exposure (curve B) and
30 after thermal treatment (curve C), but prior to the controlled irradiation treatment of the method of the present invention;

- Figure 5 shows the room temperature absorption difference spectra for CVD synthetic diamond material according to examples 2 and 3, deduced by subtracting the absorption
35 coefficient values as a function of wavelength measure after thermal treatment from those measured after UV exposure.

Figures 6a and 6b are optical micrographs showing example 2 after thermal treatment and UV radiation exposure respectively;

- 5 Figures 6c and 6d are optical micrographs showing example 3 after thermal treatment and UV exposure respectively; and

Figure 7 shows the absorption spectra measured at 77 K for examples 10-15 which have been irradiated with different doses.

10

Example 1

A CVD diamond material sample was grown on an HPHT substrate in the manner described in WO2003/052177 as set out below.

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HPHT diamond substrates suitable for synthesising single crystal CVD synthetic diamond material of the invention were laser sawn, lapped into substrates, polished to minimise subsurface defects such that the density of defects is below $5 \times 10^3 / \text{mm}^2$, and generally is below $10^2 / \text{mm}^2$. Polished HPHT plates 3.6 mm x 3.6 mm laterally by 500 μm thick, with all faces substantially {100} and having a surface roughness R_q (also known as the root mean square roughness) of less than 1 nm on the surfaces where homoepitaxial diamond growth will subsequently take place, were mounted on a molybdenum disk, and introduced into a CVD synthetic diamond growing reactor. By substantially {100} faces we means faces that are exactly {100} faces and also faces that deviate from this by up to 10° .

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Growth stages

- 1) The CVD synthetic diamond reactor was pre-fitted with point of use purifiers, reducing unintentional contaminant species in the incoming gas stream to below 80 ppb.
- 2) An *in situ* oxygen plasma etch was performed using 50/40/3000 sccm (standard cubic centimetre per second) of $\text{O}_2/\text{Ar}/\text{H}_2$ and a substrate temperature of 760°C .
- 3) This moved without interruption into a hydrogen etch with the removal of the O_2 from the gas flow.
- 4) This moved into the growth process, at a suitable pressure, by the addition of the carbon source (in this case CH_4) and dopant gases. In this instance was CH_4

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flowing at 165 sccm and 0.7 ppm N₂ was present in the process gas mix. The temperature at this stage was 875°C.

- 5) On completion of the growth period, the substrate was removed from the reactor and the CVD synthetic diamond layer removed from the substrate by laser sawing and mechanical polishing techniques.

This grown CVD synthetic diamond material is the "provided diamond material" defined by the claims of the present specification.

- 10 The room temperature absorption spectrum of the grown sample was then measured using a Perkin Elmer Lambda 19 spectrophotometer. The recorded spectrum is shown as trace A on Figure 2a. The sample was subsequently exposed to 20 minutes UV radiation from a deuterium lamp source set at 230 mA and 76 V and the room temperature absorption spectrum was then re-measured. The deuterium lamp source was an EEO plc lamp source, catalogue number 37-4702, serial number 246/031. The re-measured room temperature absorption spectrum is trace B on Figure 2a. The sample was then removed from the spectrometer and heated in an Elite Thermal System tube furnace at 798 K for 1 hour in the dark under vacuum, and the room temperature optical absorption spectrum was retaken. This is shown as trace C on Figure 2a.

It will be seen from Figure 2a that the spectrum showed typical CVD characteristic features at 350 nm and 510 nm as well as a broad band at 270 nm, the latter being associated with single substitutional nitrogen. The absorption coefficients at each of these wavelengths, as measured from the spectra, are shown in Table 1 below:

Table 1

	270 nm	350 nm	510 nm
As grown = "provided diamond material"	1.16 cm ⁻¹	0.78 cm ⁻¹	0.30 cm ⁻¹
Post 20 minutes UV exposure	1.46 cm ⁻¹	0.87 cm ⁻¹	0.34 cm ⁻¹
Post 1 hour thermal treatment	0.92 cm ⁻¹	0.62 cm ⁻¹	0.18 cm ⁻¹

From measurements taken from the 270 nm peak the sample was found to have nominally 0.1 ppm neutral single substitution nitrogen.

CIELAB C* values for the as grown (or "provided") CVD synthetic diamond material, the UV exposed diamond material, and the thermally treated diamond material were derived from traces A B and C respectively of the absorption spectra of Figure 2. The method for obtaining these is well known, and is described for example in US patent application 2004/0194690. The derived C* values are shown in Table 2, alongside the equivalent GIA scale colour grade letter.

Table 2

	As grown	Post UV exposure	Post thermal treatment	Change
C*	3.72	4.37	2.97	1.4
GIA equivalent colour grade (0.5 ct RBC stone)	K	L	I	4 grade range

From Figure 2a and the data shown in Table 2, it can be seen that the grown CVD synthetic diamond material's absorption spectrum is not stable to exposure to these different conditions (UV exposure then thermally treated). The change in C* is 1.4, and in terms of the GIA colour grading system this change in C* (Table 2) is equivalent to a range of 4 colour grades. The GIA grading of the CVD synthetic diamond material is K post growth, L following the UV exposure and I following the thermal treatment (a colour range of I, J, K, L i.e. 4 colour grades).

In a known manner an absorption spectrum was then recorded at 77 K (not shown) to determine the upper limits of the concentration of vacancy (V^0 and V^-) and nitrogen vacancy defects ($[N-V]^0$ and $[N-V]^-$) in the diamond material. These concentrations were determined in a known manner by integrating the areas of the peaks from the absorption spectrum at the wavelengths known to be characteristic of these defects. The UV-Visible spectra were taken at a scan speed of 60 nm/min, at 0.2 nm data intervals and the baseline subtracted before the peaks areas were integrated. These upper limits are shown in Table 3. As is known, it is usual to carry out this analysis of defect concentrations associated with vacancy and nitrogen-vacancy defects at low temperatures, e.g. 77 K, since at higher temperatures the peak in the absorption spectrum that is associated with them defect is smoothed and therefore less visible.

Table 3

Absorption Peak	Defect Model	Defect concentration cm^{-3} [ppm]
741 nm	V^0	$<6 \times 10^{14}$ [<0.004]
394 nm	V^-	$<2 \times 10^{14}$ [<0.001]
637 nm	$[N-V]^-$	$<5 \times 10^{14}$ [<0.003]
575 nm	$[N-V]^0$	$<5 \times 10^{14}$ [<0.003]

The sample was then exposed to daylight for six hours. Daylight exposes the diamond material to radiation with an energy greater than 2.0 eV. The absorption spectrum was re-measured and was characterized by a C^* value of 3.50 with an equivalent GIA colour grade of K. Further exposure to daylight was shown not to significantly alter the properties of the diamond. After a second UV treatment similar to the first the absorption spectrum returned to that shown in Figure 2a (curve B). The spectrum was re-measured after a period of 24 hours and did not change from that shown in Figure 2a (curve B). Following a second thermal treatment at 798 K the spectrum was re-measured and found to be identical to that in Figure 2a (curve C). This cycling between the extreme colour grades following thermal treatment/UV radiation procedure was repeated three further times. Each time the absorption properties were characterized by the same characteristics as the first time. This indicates that even after repeated cycling of UV exposure and thermally treating the sample's absorption properties in each state are consistent but that they are not stable.

The sample, uncoated, un-mounted and clean, was then subjected to a controlled irradiation treatment according to the method of the invention. To do this the sample was treated using 4.5 MeV electrons at a beam current of 20 mA for 2 minutes, corresponding to an approximate dose of 3.2×10^{16} electrons/ cm^2 .

Following this treatment the UV/Visible spectra of the sample in the irradiated form, after subsequent exposure to UV radiation and after subsequent heating were plotted (not shown) and CIELAB C^* values were derived from the absorption spectra. The derived C^* values are shown in Table 4.1:

Table 4.1

	Post electron irradiation	Post electron irradiation and UV exposure	Post electron irradiation and thermal treatment	Change
C*	3.99	3.96	3.32	0.67
GIA equivalent colour grade (0.5 ct RBC stone)	K	K	J	2 Grade range

Comparing the data in Table 2 and Table 4, it is clear that the impact of the electron irradiation has led to a significant reduction in the variation in the sample's absorption properties compared with the pre-treated sample.

Table 4.2 below shows the reduction in change of absorption between the two states following the addition of a short irradiation. In some parts of the spectrum the absorption can increase, but the difference is reduced and the colour in terms of C* and GIA is improved because of the flattening of the spectrum. In table 4.2 the measured absorption coefficients post the electron irradiation are shown. When these are compared with those in Table 1 it can be seen that the difference between absorption coefficients measured after UV exposure and heat treatment reduces after irradiation as follows:, at 350 nm from 0.25 cm⁻¹ to 0.13 cm⁻¹, at 510 nm from 0.16 cm⁻¹ to 0.01 cm⁻¹.

Table 4.2

	270 nm	350 nm	510 nm
Post 2 minutes electron irradiation	1.74	1.19	0.39
Post 20 minutes UV exposure	1.70	1.13	0.36
Post 1 hour thermal treatment	0.95	1.26	0.37

Thus it can be seen from the comparison of the results in Table 4.2 and Table 1 that the difference in absorption coefficient after exposure to ultraviolet radiation and then subject to thermal treatment is reduced by the step of applying a controlled irradiation to the

diamond material. This reduction is similarly illustrated in Figure 2b which is an absorption difference spectrum which plots the difference in the absorption coefficient at any given wavelength calculated by subtracting the absorption coefficient after thermal treatment from the absorption coefficient after exposure to UV radiation. In Figure 2b curve B shows the absorption difference spectrum for the diamond material after the controlled irradiation treatment, and curve A shows the absorption difference spectrum of the as-grown provided diamond material.

In a known manner, as described earlier, a UV/visible spectrum was then taken at 77 K of the irradiated sample to investigate defect concentrations within the sample. The spectrum is shown in Figure 3 and shows that in addition to improving the sample's absorption stability, a number of features are present which are characteristic of the electron irradiation treatment. Specifically these include the vacancy related absorptions at 394 nm (ND1) and 741 nm (GR1) corresponding to the negative and neutral charge states respectively of the single vacancy in diamond material. From these absorptions the concentration of characteristic irradiation damage defects was derived and these are shown in Table 5. These derivation techniques are known in the art and described for example in G. Davies, *Physica B*, 273-274 (1999), 15-23.

Table 5

Absorption Peak	Defect Model	Peak Height (cm ⁻¹)	Defect concentration cm ⁻³ [ppm]
741 nm	V ⁰	0.21	5.13 x 10 ¹⁵ [0.029]
394 nm	V ⁻	0.05	2.02 x 10 ¹⁵ [0.012]
637 nm	[N-V] ⁻	0	<5x10 ¹⁴ [<0.003]
575 nm	[N-V] ⁰	0	<5x10 ¹⁴ [<0.003]

Further photoluminescence recorded at 77 K using 458 nm excitation showed features at 533 and 467 nm which are thought to be unique and characteristic of CVD synthetic diamond material. In addition, to more usual irradiation damage features (for example TR12 at 471.2 nm) features at 512.6 nm, 526.4 nm and 486.2 nm with Raman normalized intensities of 0.095, 0.001 and 0.01 respectively were also present post the electron irradiation but not prior.

Examples 2 and 3

Example 2 and 3 were grown using the method of Example 1 with the exception the concentrations of nitrogen (measured as N₂ equivalent) in the gas phase were increased to 7 ppm and 11 ppm respectively. These samples were processed into polished single crystal CVD plates with dimensions 3.4 mm x 3.5 mm x 2.2 mm (Example 2) and 3.7 mm x 3.6 mm x 1.1 mm (Example 3).

Room-temperature UV/visible optical absorption data between 200 nm and 800 nm for Example 3 in its initial grown provided state (A, solid line), following heating up to 798 K (B, dashed line) and following exposure to ultraviolet radiation for a duration of 40 minutes (C, dotted line) is shown in Figure 4.

Using the optical absorption spectra for the grown ("provided") diamond but un-irradiated sample of Example 3, following ultraviolet illumination and following heating, the concentration of N_s⁰ centres were derived using the 270 nm absorption peak and the absorption coefficients of the 350 nm and 510 nm absorption bands were noted. These are shown in Table 6:

Table 6

	Before treatment	Following UV irradiation	Following heating
N _s ⁰ [270 nm band] (ppm)	0.50	0.30	0.65
350 nm band (cm ⁻¹)	0.4	0.2	0.5
510 nm band (cm ⁻¹)	0.3	0.1	0.3

UV/Visible/NIR (near-infrared) absorption difference spectra were then derived for Example 2 and Example 3. These are shown in figure 5, deduced by subtracting the absorption coefficient values as a function of wavelength measured after ultraviolet illumination (40 minutes duration) with those values measured after heating (to 798 K). More positive values indicate a feature has increased in strength after illumination, and more negative values indicate that it has increased after heating. From these the changes in absorption coefficient at 270 nm, 350 nm and 510 nm after the UV exposure/thermal treatment are evident. In Figure 5, the "sample 1" curve corresponds to Example 2, and the "sample 2" curve corresponds to Example 3.

Optical micrographs were taken of Example 2 and are shown in Figures 6a and 6b. Figure 6a shows the example after heating to 798 K, Figure 6b shows the example following 40 minutes of ultraviolet irradiation, Figure 6c shows Example 3 after heating to 823 K and Figure 6d shows example 3 following 40 minutes of ultraviolet irradiation. All micrographs were taken at room temperature using a transmission microscope. From the micrographs it can be seen that UV exposure tends to intensify the colour of the samples, whereas thermal treatment tends to de-intensify the colour of the samples. In this specification the micrographs are shown in greyscale. In fact the true colours are clear (Figure 6a), light pink (Figure 6b), light brown (Figure 6c) and dark brown (Figure 6d).

C* (scaled to give values for thickness equal to the depth of a 0.5 ct round brilliant cut stone) values were calculated from the absorption spectrum shown in Figure 5 for Example 3 and are shown in Table 7 below.

Table 7

	As grown	Post UV exposure	Post heating	Change
C*	4.85	5.43	1.64	3.79

As with Example 1, this example shows a clear change in C* when exposed to UV and then thermally treated. Similarly to Example 1, it was found that the absorption spectrum could be repeatedly driven between the two extremes on UV exposure/thermal treatment indefinitely clearly indicating colour instability.

Extrapolating from our experimental testing on Example 1, it is believed that the diamond materials of Examples 2 and 3 when electron irradiated to a total dose of $4 \times 10^{16} \text{ cm}^{-2}$ using similar conditions to that for Example 1 would result in a reduction in the change in C* of the diamond materials when measured in their first and second states of at least 20%. That is we would predict that the C* value change in its first and second state would reduce by about 0.5 after the irradiation.

Examples 4-7

Four more CVD synthetic diamond samples with the same nitrogen content as Example 1, and grown and prepared into plates in identical fashion to Example 1 were subjected

to UV radiation/thermal treatment in the same manner as for Example 1, in order to ascertain the repeatability of the method of the invention. In all four examples, the colour grade was again shown to change by 3-4 colour grades when measured after exposure to UV radiation and then after the thermal treatment. These CVD synthetic diamond samples were subsequently electron irradiated in the same manner as the sample of Example 1. The results after electron irradiation are summarized in Table 8. The C* values and colour grades are derived from the measured absorption spectra according to the method described above.

Table 8

Example	After 20 minutes UV exposure - C* (GIA colour grade)	After 1 hour thermal treatment at 525°C - C* (GIA colour grade)	Colour Grade range
Ex 4	3.83 (K)	3.06 (J)	2 grades
Ex 5	3.02 (J)	3.00 (J)	1 grade (i.e. no change)
Ex 6	2.92 (I)	2.55 (I)	1 grade (i.e. no change)
Ex 7	1.96 (G)	1.96 (G)	1 grade (i.e. no change)

From table 8 it can be seen that irradiation causes the colour variation between the two extremes (after UV exposure and thermal treatment) to reduce to less than a grade (on the GIA scale), corresponding to a change in C* of less than 0.8. The examples therefore show stabilisation of colour after irradiation similar to that illustrated for Example 1. C* values and colour grades are derived from the absorption spectra using the methods described hereinbefore.

Example 8 (comparative)

A CVD sample prepared with low nitrogen concentration was prepared by a manner similar to that described for Example 1, but with nitrogen concentration in the gas phase that was nominally 92 ppb giving rise to a concentration of 0.01 ppm in the solid. The modelled C* and GIA grades for a 0.5 ct round brilliant produced from the sample after UV exposure and thermal treatment are shown in Table 9 below.

Table 9

Example	Starting colour C* (GIA grade)	Colour after 20 minutes UV C* (GIA grade)	Colour after 1 hour at 525°C C*(GIA grade)	Colour grade range
8	0.59 (E)	0.57 (E)	0.72 (E)	1 grade (i.e. no change)

The results for the comparative Example 8 show that when the N_s^0 and X concentrations are low enough the colour change affect is not seen on exposure to UV irradiation/thermal treatment. This is a comparative example since there is not measurable difference in the absorption characteristics in the first and second states (after UV exposure and after thermal treatment). While there are slight differences in the C* values these are too small to be significant. There is no change in the GIA colour grades in the first and second states.

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This sample was not irradiated since it is a comparative example and there was no colour change to stabilise.

Examples 9-15

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CVD grown synthetic diamond samples of the same composition and grown in the same manner as the sample of Example 1 were irradiated for different doses as shown in Table 10. Figure 7 shows the absorption spectra for each example, with curves A , B, C, D, E corresponding to Examples 10, 11,12, 13, 14, 15 respectively.

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Table 10

Example Number	Dose 4.5 MeV, 20 mA (e^-/cm^2)	V^0 concentration (ppm)	V^- concentration (ppm)	Comment
9	1.3×10^{15}	0.0027	0.0005	No visible colour
10	8.2×10^{15}	0.0072	0.003	No visible colour
11	3.7×10^{16}	0.029	0.012	No visible colour
12	6.5×10^{16}	0.050	0.014	No visible colour
13	1.3×10^{17}	0.10	0.022	No visible colour
14	2.6×10^{17}	0.17	0.033	Pale blue – dose too high
15	1.95×10^{18}	0.85	0.20	Vivid blue – green

From table 10 and Figure 7 it can be seen that while a dose as small as 1.3×10^{15} electrons/ cm^2 is enough to stabilize the colour, if the dose is too high (e.g. when it was 2.6×10^{17} electrons/ cm^2) the concentration of irradiation damage defects is sufficient to introduce its own added absorption features. These absorption features are evident as a blue colour (see table 10) , and as the ND1 and GR1 peaks on the absorption spectra (Figure 7) which are undesirable in near-colourless faceted stones for jewellery or in material tailored for a high power laser application requiring low absorption coefficient.

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For easy comparison, the characteristics of examples that have different compositions or have been irradiated different amount (1, 3, 8 (comparative), and 9-15) are set out in Table 11 below.

Table 11

Example	State	Characteristics	Colour apparent to eye	Absorption coefficient of broad 270 nm peak indicative of N_s^0 , cm^{-1}	Proportion N_s^0 calculated from 270 nm peak, ppm	Absorption coefficient at 350 nm	Absorption coefficient at 510 nm	C^*	GIA grade	V^0 cm^{-3}	V^- cm^{-3}	NV^0 cm^{-3}	NV^- cm^{-3}
1	provided diamond material	N 0.7 ppm in process gas	colourless	1.16	0.1	0.78	0.30	3.72	K	<5 x 10^{14}	<5 x 10^{14}	<5 x 10^{14}	<5 x 10^{14}
1	provided and post UV			1.46		0.87	0.34	4.37	L				
1	provided and post thermal treatment 798K for 1 hour			0.92		0.62	0.18	2.97	I				
1	Difference in absorption characteristic of provided diamond material after UV and thermal treatment			1.46-0.92 = 0.54		0.87-0.62 = 0.25	0.34-0.18 = 0.16	4.37-2.97 = 1.4	I to L = 4 grades				
1	Post irradiation		colourless	1.74		1.19	0.39	3.99	K	5.13 x 10^{15}	2.02 x 10^{15}	<5 x 10^{14}	<5 x 10^{14}
1	Post irradiation and UV			1.70		1.13	0.36	3.96	K				
1	Post irradiation and thermal treatment			0.95		1.26	0.37	3.32	J				
1	Difference in absorption characteristic of irradiated diamond material after UV /thermal treatment			1.70-0.95 = 0.75		1.26-1.13 = 0.13	0.37-0.36 = 0.01	0.67	J to K = 2 grades				

Example	State	Characteristics	Colour apparent to eye	Absorption coefficient of broad 270 nm peak indicative of N_s^0 , cm^{-1}	Proportion N_s^0 calculated from 270 nm peak, ppm	Absorption coefficient at 350 nm in cm^{-1}	Absorption coefficient at 510 nm in cm^{-1}	C^*	GIA grade	V cm^{-3}	V^- cm^{-3}	NV^0 cm^{-3}	NV^- cm^{-3}
3	Provided diamond material	7 ppm N_2 equivalent in process gas	Dark brown	Not measured	0.5	0.4	0.3	4.85	Not measured				
3	provided and post UV				0.3	0.2	0.1	5.43					
3	provided and post thermal treatment 798 K for 1 hour				0.65	0.5	0.3	1.64					
3	Difference in absorption characteristic of provided diamond material after UV and after thermal treatment					0.5-0.2 = 0.3	0.3-0.1 = 0.2	3.79					
3	Post irradiation		Light brown		Not measured			Not measured					
3	Post irradiation and UV												
3	Post irradiation and thermal treatment												
3	Difference in absorption characteristic of irradiated diamond material after UV and thermal treatment (predicted value)							0.75					

Example	State	Characteristics	Colour apparent to eye	Absorption coefficient of broad 270 nm peak <i>indicative of N_s^0</i> cm^{-1}	Proportion N_s^0 calculated from 270 nm peak ppm	Absorption coefficient at 350 nm	Absorption coefficient at 510 nm	C*	GIA grade	V^0 ppm	V^- ppm	NV^0 cm^{-3}	NV^- cm^{-3}
8*	Provided	92 ppb N_2 equivalent in process gas	colourless	Not measured	0.01	Not measured		0.59	E	Not measured			
8*	Provided post UV							0.57	E				
8*	Provided post thermal treatment							0.72	E				
8*	Difference in absorption characteristic after UV/thermal treatment							0.72-0.57 = 0.05	No change				
8*	Irradiated sample		Not tested – no colour change to stabilise										
9	As example 1, but irradiated 4.5 MeV, 20 mA for dose specified in characteristics column (e^-/cm^2)	1.3×10^{15}	colourless	Not measured						0.0027	0.0005	Not measured	
10		8.2×10^{15}								0.0072	0.003		
11		3.7×10^{16}								0.029	0.12		
12		6.5×10^{16}								0.050	0.14		
13		1.3×10^{17}								0.1	0.022		
14		2.6×10^{17}	Pale blue	0.17	0.033								
15		1.95×10^{18}	Vivid blue/green	0.85	0.2								

* Example 8 is a comparative example

Claims

1. Diamond material which has an absorption spectrum with one or both of the following characteristics:

Designation	Peak	Absorption coefficient (at peak after baseline subtraction)
V^0	741 nm	$0.01 \text{ cm}^{-1} - 1 \text{ cm}^{-1}$ (at 77 K)
V^-	394 nm	$0.01 \text{ cm}^{-1} - 0.5 \text{ cm}^{-1}$ (at 77 K)

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2. Diamond material according to claim 1, which is a synthetic diamond.
3. Diamond material according to claim 2, which is CVD diamond material and which has an absorption spectrum with the following additional characteristics:

(i)

Designation	Starts	Ends	Peak	Absorption coefficient (at peak after baseline subtraction)
270 nm	220 nm	325 nm	270 nm	$0.05 \text{ cm}^{-1} - 20 \text{ cm}^{-1}$

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and

(ii) one or more of

Designation	Starts	Ends	Peak	Absorption coefficient (at peak after baseline subtraction)
350 nm band	270 nm	450 nm	350 nm ±10 nm	$0.05 \text{ cm}^{-1} - 10 \text{ cm}^{-1}$
510 nm band	420 nm	640 nm	510 nm ±50 nm	$0.02 \text{ cm}^{-1} - 10 \text{ cm}^{-1}$
Designation	Form of Curve			Absorption Coefficient
Ramp	Rising background of form Absorption coefficient (cm^{-1}) = $C \times \lambda^{-3}$ (C =constant, λ in μm)			Contribution at 510 nm is: $< 1.5 \text{ cm}^{-1}$

4. Diamond material according to any of claims 1 to 3, which has an absorption coefficient at 570 nm that is less than 0.04 cm^{-1} after baseline subtraction.
5. Diamond material according to any of claims 1 to 4, which has a photoluminescence spectrum in its equilibrium state showing one or more of the following features:

Wavelength (nm)	Raman normalized intensity
512.6	0.095
526.4	0.001
486.2	0.01

6. Diamond material according to any of claims 1 to 5, which is a single crystal.
7. Diamond material according to claim 6, wherein the single crystal is in the form of a gemstone.