

## METHOD OF PRODUCING WHITE COLOUR MONO-CRYSTALLINE DIAMONDS

### **Field of the invention**

The invention relates to a method of producing white colour mono-crystalline diamonds having gem grade quality in a chamber capable of operating microwave plasma chemical vapour deposition.

### **Background**

A process of growing polycrystalline grains of diamond was disclosed in US Patent No. 3,030,187. Since then, various Chemical Vapour Deposition (CVD) techniques have been devised to produce poly-crystalline diamonds and mono-crystalline diamonds.

Poly-crystalline diamond, in spite of having similar properties as mono-crystalline diamond, is not a recommended material for new industrial applications due to the presence of grain boundaries and defects contained therein. In addition, the thermal conductivity of a poly-crystalline diamond is inferior to that of a mono-crystalline diamond. Furthermore, the grain boundaries in poly-crystalline diamonds also inhibit exhibition of superior properties unique to natural diamonds because the grain boundaries act as scattering centres for phonons and thereby deteriorate the thermal conductivity and other properties as well. The presence of large angle as well as small angle in grain boundaries in poly-crystalline diamonds are a major drawback in industrial applications.

Accordingly, there is a clear preference for using mono-crystalline diamonds in industrial applications. However, it is difficult to grow mono-crystalline diamonds with the same texture, clarity, purity and finish as those of a natural diamond. Although mono-crystalline diamond has superior properties compared to poly-crystalline diamond, microscopic and macroscopic graphitic and non-graphitic inclusions, feathers (long line defects) are very common in CVD-grown mono-crystalline diamond. As a result, the potential of CVD- grown mono-crystalline diamond to be used as a gem quality product is diminished.

Detailed characterization of defects in CVD grown mono-crystalline diamond can be performed by Raman spectroscopy and X-ray diffraction (XRD) which reveals the defects comprising of graphitic regions having a size in the range of submicrons to several microns contained therein.

One of the problems when producing CVD grown mono-crystalline diamond is the low growth rates. Although the growth rates of 70-100 microns per hour is possible with addition

of large concentration of nitrogen gas to gases supplied during the CVD process, defects are prevalent and defect density generally increases with the growth rate.

US publication number 07277890 discloses a method for synthesizing diamond for use as semi-conductor, electronic or optical components or for use in cutting tools. Specifically, US publication no. 07277890 disclose a method of growing diamond in the presence of gas containing nitrogen having a ratio of nitrogen to hydrogen of 3 ppm to 1000 ppm or gas containing oxygen in a ratio of oxygen to carbon of 3% to 100% in order to increase growth rates.

A scientific paper authored by Yan et. al. (PNAS, 1 October 2002, Vol. 99, no. 20, 12523-12525) discloses a method of producing mono-crystalline diamond having a growth rate of 50 to 150 microns per hour by microwave plasma chemical vapour deposition (MPCVD). In particular, the method discloses a CVD process been carried out at 150 torr and involves adding nitrogen gas to gases supplied during CVD process and having a ratio of nitrogen to methane of 1% to 5%  $N_2/CH_4$ . Yan et. al. submits that nitrogen in the stated ratio can enhance growth rates due to creation of more available growth sites as a result of changes of {111} crystal planes to {100} crystal planes.

The importance of nitrogen content in gases supplied during CVD process is disclosed in US Patent No. 5,015,494 (Yamazaki) which teaches a method of growing diamond with customized properties for dedicated industrial applications. US Patent No. 5,015,494 discloses forming diamond by electron cyclotron resonance CVD. Nitrogen is added to prevent lattice defects from growing by virtue of external or internal stress. Nitrogen is added such that a ratio of nitrogen-compound gas to carbon-compound gas of 0.1% to 5% is obtained. The resultant diamond has a nitrogen concentration of 0.01 to 1 wt%. US Patent No. 5,015,494 discloses a requirement to add boron gas to the gases supplied during CVD process to form boron nitride which would be deposited on a substrate so as to improve adhesion to the substrate of the resultant diamond.

According to Yan et. al. and US Patent No. 5,015,494, nitrogen is used to enhance growth rates of CVD grown mono-crystalline diamond and also to prevent lattice defects in electron cyclotron resonance CVD grown mono-crystalline diamond.

Nitrogen containing gas in combination with the diborane containing gas perform a critical role when growing mono-crystalline diamond during a CVD process. A disadvantage of using nitrogen in quantities disclosed in Yan et. al. and US Patent No. 5,015,494 is that the

resultant diamonds exhibit nitrogen-based defects such as micro cracks, micro inclusions etc. Such diamonds exhibit brown colour and are not suitable for gem applications.

The Applicant of the present invention submits that very small amounts of nitrogen containing gas in combination with the diborane containing gas, and optionally with oxygen, in gases supplied during CVD process will result in substantially defect-free mono-crystalline diamonds of white colour and having a quality which are useful for gems applications. It is submitted that the amount of nitrogen containing gas and diborane containing gas disclosed in the present invention is considerably less than the amount of nitrogen to carbon disclosed in US Patent No. 5,015,494.

Nitrogen containing gas and diborane containing gas play important role in diamond growth. In particular, nitrogen containing gas is known to mesh into the diamond structure naturally. Without an appropriate amount of nitrogen containing gas, a number of defect configurations may be resulted and thereby affect the properties of the diamond significantly. For instance, the presence of nitrogen in singly substituted configuration imparts diamond its yellowish brown colour. The donor type defect centre corresponding to singly substituted nitrogen lies at about 1.72 eV in the band gap of diamond and is positively charged partially as shown in FIGURE 1. When white light is incident on the diamond, all the wavelengths below the yellow colour (that is, blue, violet and ultra violet) are absorbed and as a result the diamond appears red or brown in colour.

In contrast, the presence of boron in diamond structure gives rise to a negatively charged acceptor states at 0.38 eV above the valance band as shown in FIGURE 1. The blue colour of the diamond originates as the holes from valance band can fill these centers which are neutralized by the electrons from the conduction band. When white light is incident on the diamond doped with Boron, all the wavelengths below blue colour are absorbed and thereby giving blue light out from the diamond.

It is an objective of the present invention to provide a method of producing white colour diamond having gem grade quality which is substantially free of defects by adding very small quantities of these dopants in the form of nitrogen and diborane. Nitrogen and diborane containing gases in combination with the methane and hydrogen gases is supplied during microwave plasma chemical vapour deposition (MPCVD) process adapted for growing diamonds to enhance the colour to white and the clarity of the diamond mono-crystals which happens due to the compensation of the Boron and Nitrogen centres. It is submitted that heating the diamonds up to a high temperature of 2300°C enhances the colour to white and

also improve the clarity of the diamond.

It is submitted that gases supplied during a CVD process comprises of relatively small amounts of nitrogen containing gas in combination with the diborane containing gas in the gas mixture of which it results in diamond being formed with optical centres related to C-N and C-B-N bonds that lead to the deterioration of the colour and purity of the monocrystals of diamond. Large concentrations of nitrogen containing gas in the gas mixture also lead to the micro inclusions and growth cracks in the crystals. Owing to the difference in bond length between nitrogen-carbon and carbon-carbon, and boron-carbon, the defects operate as phonon scattering centres, and thereby diminishing the electrical, optical and mechanical properties of the resultant mono-crystalline diamond.

It is submitted that the form of the inclusions is dependent on the concentration of nitrogen containing gas in the gas mixture.

It is submitted that although a relatively small amount of nitrogen containing gas is required, there must be at least some nitrogen containing gas in combination with the diborane containing gas to be present in the gases supplied during the CVD process so as to increase the growth rate of the diamonds. In addition, by using very small quantities of Nitrogen containing gas in combination with diborane containing gas, the colour and the clarity of the diamond crystals can be improved significantly. It is submitted that the presence of boron in the diamond structure containing nitrogen atoms will turn the diamond from yellow brown colour to white colour and having gem grade quality.

It is submitted that using relatively small quantities of nitrogen containing gas in combination with diborane containing gas in gases mixture used during the CVD process, can cause the diamond to be formed by step-growth mechanism, in which a layer of diamond having an edge, defined by a step, grows at the edge as a front. Such step-growth mechanism differs from the existing layer-growth mechanism occurring during CVD process.

It is submitted that the mono crystalline diamonds grown by step-growth mechanism with the pre-determined quantities of nitrogen containing gas in combination with diborane containing gas are free of microscopic and macroscopic graphitic inclusions (most notably nitrogen-based inclusions) and defects that are associated with growth of diamond by the existing layer-growth mechanism. Therefore, there must be at least some nitrogen containing gas included in the gas mixtures used during the CVD process so as to avoid the formation of graphitic inclusions in the grown mono crystalline diamond.

The diamond grown from the diamond seed up to a thickness of 2 mm is not oriented exactly in {100} crystalline orientation but it can lose such orientation and thus resulting in other crystalline orientations.

It is submitted that if the crystalline orientation of the diamonds grown up to a thickness of more than 2 mm, other crystalline orientations can also be present in small quantity.

### **Summary of the invention**

According to an aspect of the present invention, there is provided a method of producing white colour mono-crystalline diamonds having gem grade quality, the method comprising:

- (a) providing a substrate having a diamond seed with a pre-determined size and with a pre-determined optical orientation disposed thereon,
- (b) disposing the substrate having the diamond seed in a chamber capable of operating chemical vapour deposition (CVD),
- (c) supplying the chamber with hydrogen gas,
- (d) adjusting conditions within the chamber suitable for operating chemical vapour deposition,
- (e) commencing the chemical vapour deposition process in the chamber,
- (f) supplying the chamber with carbon containing hydrocarbon gas,
- (g) supplying the chamber with nitrogen-containing gas and diborane-containing gas, both of which are adapted to expedite the growth rate of diamond on the substrate,
- (h) supplying electrical field to the chamber to form plasma in the vicinity of the substrate and thereby resulting in step-growth of diamond on the substrate,
- (i) ending the chemical vapour deposition process in the chamber,
- (j) cutting and removing the unwanted carbon from the grown diamond,
- (k) cleaning and cutting diamond annealed under predetermined temperature for a suitable period of time,
- (l) subjecting the diamond to final cutting, polishing and colour assortment.

### **Brief description of the drawings**

A preferred embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

**FIGURE 1** is the Energy-band diagram of the diamond grown during a CVD process and it shows the position of Nitrogen donor levels, and Boron acceptor levels in the band gap.

These donors and acceptors levels may be partly charged.

**FIGURE 2** is a flow chart of the process showing Nitrogen (0.015 vol %) and Diborane (0.005 vol %) been used in optimal quantities in the gas mixture in accordance with an embodiment of the present invention.

**FIGURE 3** is the flow chart of the process when only Nitrogen flow is used in the gas mixture.

**FIGURE 4** is the flow chart of the process where Nitrogen and Diborane are not used and diamond is grown with only using Methane and Hydrogen in the gas mixture.

**Figure 5** is an FTIR spectrum of diamond deposited in a CVD process utilising Nitrogen in the CVD gases in the range of 0.02 to 0.1 % in combination with Diborane in the range 0.01 to 0.05 %. The IR peaks relating to C-B-N centres can be seen showing the incorporation of N and B in the samples.

**Figure 6** is a photoluminescence spectrum of diamond deposited in a CVD process in accordance with an embodiment of the present invention and utilising Nitrogen in the gases supplied during the CVD process in the range of 0.0001 to 0.02 vol % in combination with the Diborane flow in the mixture of 0.00005 to 0.005 %. The photoluminescence spectrum shows that the diamonds deposited using Nitrogen in combination with Diborane with the specified volume % have a strong peak at 605 nm and a broad band of low intensity at 700 nm. The peak at 605 nm is an indication of the good quality of the samples.

In contrast the photoluminescence spectrum of the diamonds grown utilizing only Nitrogen flow in the range of 0.0001 % – 0.02 % without Diborane show no peak at 605 nm and a high intensity broad band at 700 nm (**FIGURE 7**) indicating the presence of the impurities in the diamonds.

**FIGURE 8** is a Raman spectrum of the samples grown in the process. A strong intense line at  $1332\text{ cm}^{-1}$  shows the excellent quality of the diamonds grown in the process.

**FIGURES 9** is the optical microscope images at high magnifications of the diamonds grown in a CVD process including 0.015 % Nitrogen and 0.005 % Diborane in accordance with the embodiment of the present invention and showing step-growth of diamond.

**Figure 10** shows optical microscope images at high magnifications of the diamonds grown in a CVD process including 0.02 % Nitrogen without Diborane and showing step-growth of diamond. However the steps are not clean and straight but uneven with defects.

### **Detailed description**

The present invention provides a method of producing white colour mono-crystalline diamond which includes a CVD process that utilises microwave plasma.

Diamond is grown from a diamond seed disposed on a substrate. The diamond seed may vary in size between 3mm x 3mm and 5mm x 5mm and having a thickness ranging from 1mm to 3mm.

Figure 2 shows the flow chart whereby the optimal supply of nitrogen containing gas and diborane containing gas during a CVD process in accordance with an embodiment of the present invention. It is submitted that this can enable the diamonds to grow at a rate of about 18-20 microns per hour.

The process starts in 202.

At the next step 204, the crystallographic orientation of the diamond seed is pre-determined and diamond seeds having an orientation other than {100} are rejected. Diamond seeds having an orientation of {100} are polished to optical finish (orientation within <0.1 degree) with roughness of the order of the wavelength of visible light in preparation for the CVD process thereafter. The diamond seed is then disposed on a substrate.

The substrate with the diamond seeds is then disposed inside the chamber capable of operating CVD process. At step 206, the CVD process starts. Hydrogen gas is first supplied into the chamber. Before the CVD process starts, conditions within the chamber are adjusted to suit the CVD operation. In particular, the temperature inside the chamber is increased from ambient temperature to a temperature in the range of 750°C to 1200°C and the pressure inside the chamber is reduced to a pressure in the range of 120 mbar to 160 mbar. The chamber is then supplied with gases suitable for growing diamond in accordance to a preferred embodiment of the present invention. In step 208, carbon containing hydrocarbon gas, such as Methane (CH<sub>4</sub>), is supplied into the chamber.

At step 210, nitrogen containing gas is supplied into the chamber and at the same time, at step 212, diborane containing gas is supplied into the chamber. Nitrogen (N<sub>2</sub>) containing

gas in combination with the diborane containing gas ( $B_2H_4$ ) are supplied in a quantity of 0.0001% to 0.1% by volume of the gases for growing diamond from the diamond seed.

It is submitted that the nitrogen-containing gas may be in the form of nitrogen in hydrogen gas, nitrogen in oxygen gas, nitrogen in helium gas, nitrogen in nitrous oxide gas or nitrogen with diborane gas.

Other gases including helium ( $He$ ) and oxygen ( $O_2$ ) are also supplied into the chamber. These gases are passed through the chamber at a gas flow rate of 30 l/hr.

An electrical field is applied in the surrounding region of the diamonds seeds so that plasma is generated from the gases inside the chamber. The electrical field is generated by a magnetron operating at a power of 6000 Watt and a frequency of 2.45 GHz. The generated electrical field causes the hydrogen gas to ionise and thereby forming plasma in the vicinity of the diamond seeds, which results in diamond growing from the diamond seeds. It is submitted that the growth pattern of the diamond is a step-wise pattern in which the diamond is able to grow without defects and free of impurity as shown in Figure 9.

At step 214, the CVD process ended.

At step 216, unwanted or parasitic carbon is cut and removed from the grown diamond.

At step 218, the diamond which have been cleaned and cut, is annealed under a predetermined temperature for a suitable period of time. In particular, the diamond which have been cleaned and cut, is annealed at  $2300^{\circ}C$  for 20 minutes to form the complexes of boron and nitrogen to enhance the colour and clarity of the diamonds significantly.

At step 220, the diamond undergo final cutting, polishing and colour assortment.

At step 222, the diamond exhibit the final colour G and H, according to diamond grading.

The process ends at step 224.

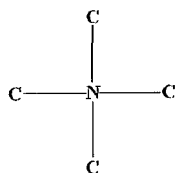
Figure 3 shows the similar flow chart except that the supply of Nitrogen containing gas 310 is being altered to comprise of 0.005% to 0.02% by volume without diborane. It is submitted that the resultant diamond crystals exhibit light brown and dark brown colour, which is not desirable.

Figure 4 shows the similar flowchart except that no Nitrogen containing gas and Diborane containing gas combination are supplied. It is submitted that diamond crystals exhibit white colour but with the presence of substantial degree of the defects, which is not desirable.

Fourier transform infrared spectroscopy (FTIR) can be used to determine the concentration and bonding of nitrogen and boron in samples of diamonds. The FTIR spectra of samples of diamonds grown are shown in Figure 5.

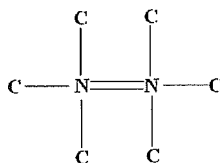
As shown in Figure 5, the FTIR spectra of the samples of diamond, which is grown with Nitrogen in the gas mixture in the range of 0.02% to 0.1 % in combination with Diborane in the range 0.01% to 0.05 %, exhibit clear and strong signatures of the boron-nitrogen centres in the samples along with some typical nitrogen centres. Specifically, intense bands related to boron-nitrogen centres are evident at  $1370\text{ cm}^{-1}$ . The bands at  $1210\text{ cm}^{-1}$  and  $1280\text{ cm}^{-1}$  might belong to nitrogen centres along with the C-C bands at  $1978\text{ cm}^{-1}$ ,  $2026\text{ cm}^{-1}$  and  $2160\text{ cm}^{-1}$ . The nitrogen centres in the diamond samples may exist in many configurations detailed below.

- Single atom substitution:



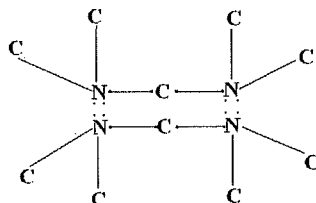
The characteristics peaks in FTIR spectra exist at  $1130\text{ cm}^{-1}$  and  $1350\text{ cm}^{-1}$  and EPR gives a "g" value of 2.0024 for this centre. This centre appears as a weak signature in the samples around  $1100\text{ cm}^{-1}$  in the samples grown with nitrogen in the range of 0.005% to 0.02%.

- "A" aggregate:



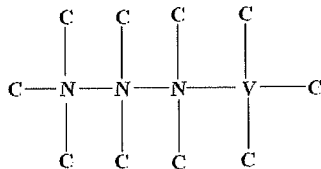
$480\text{-}490\text{ cm}^{-1}$  and  $1282\text{ cm}^{-1}$  are the characteristic peaks of A-aggregate in FTIR. These peaks are evident in the method as shown in Figure 2 for samples produced with concentrations of nitrogen much greater than for the invention. The Aaggregates are also present in natural diamond samples in large concentration which was used as a substrates in an embodiment of the present invention.

- "B" aggregate:



B-aggregate in diamond is believed to consist of 4 or 8 nitrogen atoms in pair with carbon atoms. These peaks are evident in natural diamonds mostly and may not be present in samples of the embodiment of the present invention.

- N3 Centre:



N3 centre is not FTIR active and, accordingly, does not appear in Figures 1 and 2. However, N3 centres show a sharp band at 415 nm in photoluminescence (PL) and UV spectroscopy. This centre consists of three nitrogen atom surrounding a vacancy (V).

- Platelets:

Platelets consist of one or two extra atomic layers inserted in the diamond lattice. The nature of the platelets is analysed in detail in diamond lattice. However, the fact that the corresponding IR band is observed only in diamonds containing an appreciable amount of nitrogen suggests that platelet contain nitrogen, and probably consist either partly or entirely of nitrogen. The position of the platelet peak varied from 1354-1384  $\text{cm}^{-1}$  from sample to sample. This variation of position is attributed to the susceptibility of the platelets to strain induced into the crystal by the A and B-aggregates defects. The presence of the platelet absorption indicates A-aggregates start to diffuse to form B-aggregates. The platelet peak position is inversely correlated to platelet size.

It is submitted that in the samples grown with the flow rates of nitrogen in the range 0.005 % to 0.02 %, nitrogen is present in the form of single substitution and small concentration of A-aggregates.

Photoluminescence spectroscopy is performed on samples produced with a nitrogen gas flow of 0.0001 to 0.02 vol % in combination with the diborane flow in the mixture of 0.00005 to 0.005 %. The results are shown in FIGURE 6 showing intense peaks at 605 nm (2.05 eV) and a low intensity broad band around 700 nm. The broad band is assigned to the impurities that degrade the quality of gem grade diamond. In contrast the photoluminescence spectra of the diamonds prepared using only Nitrogen flow in the range of 0.0001 % – 0.02 % without Diborane show no peak at 605 nm and a high intensity broad band at 700 nm as shown in Figure 7.

No boron centre is visible in photoluminescence spectra as it is possible that boron compensates nitrogen increasing the optical clarity and purity of the diamond single crystals. Optical microscopy images of the samples grown at Nitrogen concentrations in combination with Diborane in the range according to an embodiment of the present invention is shown FIGURES 9 and 10. These images are taken in the range of magnification 500-5000 and the step-wise growth of diamond is evident from the surface of diamond shown in the images.

A high density of the growth steps on the surface of a sample grown diamond with nitrogen flow in an embodiment of the present invention as shown in Figure 9. These growth steps are present due to the screw dislocation in the crystal growth process of a number of materials and are a clear signature that the diamond in accordance with an embodiment of the present invention grows with the help of dislocations and with a step growth mechanism.

In contrast, it is submitted that diamond grown in the gas using optimal quantity of nitrogen containing gas in combination with Diborane containing gas during the CVD process, in accordance with an aspect of the present invention, depicts regular equidistant steps and is substantially free of graphitic inclusions.

It is submitted that a concentration of Nitrogen higher than 0.015 vol % in the gas phase can results in microscopic and macroscopic graphitic inclusions as shown in Figure 10. Such inclusions and defects form on the steps and adversely affect the properties of the formed diamond.

The step-growth mechanism in the nitrogen concentration regime specified in an embodiment of the invention appears to be advantageous because it is less susceptible to incorporating defects and inclusions in the formed diamond, with the result that formed diamond is substantially free of defects and inclusions. Such formed diamond has gem quality and has superior electrical, optical and mechanical properties compared to other forms of diamond grown by other method. In addition, the properties of the formed diamonds also approach the properties of natural diamond.

Many modifications may be made to the preferred embodiment of the present invention as described above without departing from the spirit and scope of the present invention.

**CLAIMS:**

1. A method of producing white colour mono-crystalline diamonds having gem grade quality, the method comprising:
  - (a) providing a substrate having a diamond seed with a pre-determined size and with a pre-determined optical orientation disposed thereon,
  - (b) disposing the substrate having the diamond seed in a chamber capable of operating chemical vapour deposition (CVD),
  - (c) supplying the chamber with hydrogen gas,
  - (d) adjusting conditions within the chamber suitable for operating chemical vapour deposition,
  - (e) commencing the chemical vapour deposition process in the chamber,
  - (f) supplying the chamber with carbon containing hydrocarbon gas,
  - (g) supplying the chamber with nitrogen-containing gas and diborane-containing gas, both of which are adapted to expedite the growth rate of diamond on the substrate,
  - (h) supplying electrical field to the chamber to form plasma in the vicinity of the substrate and thereby resulting in step-growth of diamond on the substrate,
  - (i) ending the chemical vapour deposition process in the chamber,
  - (j) cutting and removing the unwanted carbon from the grown diamond,
  - (k) cleaning and cutting diamond annealed under predetermined temperature for a suitable period of time,
  - (l) subjecting the diamond to final cutting, polishing and colour assortment.
  
2. The method of producing white colour mono-crystalline diamond according to claim 1, the nitrogen-containing gas in combination with the diborane-containing gas are supplied in a quantity of 0.0001% to 0.1% by volume of the gases for growing diamond from the diamond seed.
  
3. The method of producing white colour mono-crystalline diamond according to claims 1 or 2, wherein the nitrogen-containing gas may be in the form of nitrogen in hydrogen gas, nitrogen in oxygen gas, nitrogen in helium gas, nitrogen in nitrous oxide gas or nitrogen with diborane gas.
  
4. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the conditions includes increasing the temperature to a range of 750°C to 1200°C and reducing the pressure to the range of 120 mbar to 160 mbar.

5. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the carbon containing hydrocarbon gas comprise of methane.
6. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the chemical vapour deposition occurs in the presence of microwave plasma and with hydrogen gas.
7. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the plasma in the form of microwave plasma is generated by a magnetron operating at a power of 6000 Watt and a frequency of 2.45GHz.
8. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the gases are passed through the chamber at a gas flow rate of approximately 30 l/hr.
9. The method of producing white colour mono-crystalline diamond according to claim 8, wherein the gases includes oxygen gas and helium gas.
10. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the diamond seed is oriented in the {100} crystalline orientation.
11. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, wherein the diamond seed has a size between 3mm X 3 mm and 5mm X 5mm and having a thickness ranging from 1mm to 3mm.
12. The method of producing white colour mono-crystalline diamond according to any one of the preceding claims, further comprising of polishing the substrate to optical quality finishing after the substrate is disposed in the chamber.
13. The method of producing white colour mono-crystal diamond according to claim 1, wherein the temperature is increased to 2300°C for 20 minutes to form complexes of boron and nitrogen so as to enhance the color and clarity of the diamond.

14. A white colour mono crystalline diamond having gem grade quality produced by the method according to any one of the previous claims.