

ELECTRONIC DEVICE GRADE SINGLE CRYSTAL DIAMONDS AND METHOD OF PRODUCING THE SAME

Field of the Invention

The invention relates to electronic device grade single crystal diamonds and a method of producing electronic device grade diamonds grown by microwave plasma chemical vapour deposition (MPCVD) process.

Background

The demand for electronics device grade single crystal diamonds has been increasing steadily through the years due to its wide-range of scientific and industrial applications, beside gems. The remarkable intrinsic properties of electronic grade single crystal diamonds is one of the reasons why it is a preferred material for industrial and scientific applications, as well as gems.

Diamond deposition by CVD process on various solid substrates have been extensively described in various patent documents and also extensively investigated by researchers and published in scientific journals and other technical literatures. The process of diamond growth by CVD process involves the deposition of carbon atoms that originate from the dissociation of a carbon-containing gas precursor (i.e. C_xH_y ($x= 1$ to 4)) on a solid substrate under the reaction of a mixture of several gases (H_2 , Ar, O_2 , N_2 , CO_x , CF_x etc.). Polycrystalline or single crystal CVD diamonds can be produced and their crystalline quality strongly depends not only on the process chemistry of the gases used, but also on the nature and condition of the solid substrate as well.

Several patent documents and scientific literatures disclose various methods of producing large poly-crystalline diamond films for radiation wave detection. The disadvantages of these large poly-crystalline diamond films is that the films are not only limited in thickness but also limited in charge collection distance due to the presence of grain boundaries that drastically affect their electronic properties.

European patent publication No. EP19830380A2 discloses the method of producing diamonds suitable for electronic applications by CVD process. However, the electronics properties of these diamonds are believed to be affected by the presence of minute impurities ($>1\text{ppm}$) and lattice defects which will reduce their charge collection efficiency/distance. Production of full collection distance at lower bias field ($<0.2\text{V}/\mu\text{m}$) detectors based on single crystal diamond with extremely high reproducibility through sufficient control of the growth process and tight selection of solid substrate by CVD process has not been disclosed.

US Patent No. 7,887,628 discloses a layer of single crystal CVD diamond having a thickness of greater than 2mm , wherein the layer has a level of any single impurity of not greater than 1 ppm and a total impurity content of not greater than 5 ppm whereby the impurity excludes hydrogen in isotopic forms and in electron paramagnetic resonance (EPR), a single substitutional nitrogen centre $[\text{N-C}]^0$ at a concentration $<100\text{ ppb}$.

US Patent Application Publication 2013/0202518 discloses a single crystal CVD diamond having a level of any single impurity of not greater than 5 ppm and a total impurity content of not greater than 10 ppm wherein impurity excludes hydrogen in isotopic forms, and in electron paramagnetic resonance (EPR), a single substitutional nitrogen centre $[\text{N-C}]^0 < 40\text{ ppb}$.

It is an object of the present invention to provide a method of utilising microwave plasma chemical vapour deposition (MPCVD) process to produce electronic device grade single crystal diamonds having a size up to $10\times10\times2\text{ mm}^3$ and also with a charge collection efficiency (CCE) of 100% when the bias field is at least $0.2\text{ V}/\mu\text{m}$.

The reason of growing thick electronic device grade single crystal diamond is to prevent the formation of crystal defects such as thread dislocations, crystal plane twinning, “petal-shape” defects and step-growth related dislocations. Generally, these crystal defects grow and propagate during growth and eventually results in highly stressed MPCVD diamonds. These stresses are known to degrade the charge carrier mobilities and lifetimes of diamond based detectors. The method described herein includes the step of pre-growth conditioning on the diamond substrate so as to suppress the crystal defects from growing and preparing the substrates that are substantially free of crystal defects and impurities.

Other objects and advantages of the present invention will become apparent from the following description, taken in connection with the accompanying drawings, wherein, by way of illustration and example, an embodiment of the present invention is disclosed.

Summary of invention

In accordance to a first aspect of the present invention, there is provided a method utilising microwave plasma chemical vapour deposition (MPCVD) process of producing electronic device grade single crystal diamond comprising of: (a) selecting a diamond seed or substrate having a pre-determined orientation, (b) cleaning and / or etching of non-diamond phases and other induced surface damages from the diamond seed or substrate, whereby this step can be performed one or more times, (c) growing a layer of diamond surface on the cleaned / etched diamond seed or substrate, whereby this step can be performed one or more times, and further comprises pre-growth process for production of electronics device grade single crystal diamond by microwave plasma chemical vapour deposition (CVD) on the growth surface of the diamond seed takes place at a temperature from about 700°C to about 1200°C in a MPCVD chamber, wherein the atmosphere comprises of a mixture of about 1% to about 15% CH₄ per unit of H₂ only or with some additional mixture from about 1% to about 50% O₂ per unit of CH₄, and (d) growing electronics device grade single crystal diamond on top of the layer of the diamond surface.

In accordance to a second aspect of the present invention, there is provided An electronic device grade single crystal diamond comprising: a charge of collection efficiency (CCE) of 100% when the bias field is at least 0.2V/μm, a low level of nitrogen defined by an absence of a signal for single substitutional nitrogen centres [N-C]⁰, indicating a concentration of said single substitutional nitrogen centres of <100ppb using FTIR and <100ppb using UV-VIS absorption spectroscopy at 270nm, and typically <30ppb using electron paramagnetic resonance (EPR), an absence of C-H stretch absorption and hydrogen related vibrations in the infrared (IR) spectral range of 2500 cm⁻¹ to 3400 cm⁻¹ when infrared transmittance is greater than 70% in a FTIR spectrum, and a concentration of silicon related vacancies of <50 ppb defined by an absence of traces of silicon related vacancy peaks (SiV) at 738nm, nitrogen related vacancy peaks (NV-) at 637nm using photoluminescence spectroscopy.

Brief description of drawings

This then generally describes the invention but to assist with understanding reference will now be made to the accompanying drawings which show preferred embodiments of the invention.

Figure 1 shows a plot of the charge collection efficiency (CCE) (CCE = 100%) measured at the top (red) and bottom (blue) layer of the CVD diamond biased at $0.8\text{V}/\mu\text{m}$ bias field according to a preferred embodiment of the invention. Energy spectrum was obtained when electronic device grade single crystal diamond detector is exposed to a radiation source in the form of Americium (^{241}Am) alpha source.

Figure 2 shows a plot of the CCE as a function of electric field (bias voltage/sample thickness) according to a preferred embodiment of the invention. Full charge collection efficiency of 100% is obtained at bias field of at least $0.2\text{V}/\mu\text{m}$.

Figure 3 shows a plot of the drift velocity against electric field at room temperature (295K) according to a preferred embodiment of the invention. The fit result shows low-field mobility and saturation velocity for both holes and electrons.

Figure 4 shows a plot showing collected charge (C) against the inverse of drift velocity at room temperature (295K) according to a preferred embodiment of the invention. The fit result shows the carrier lifetimes for both holes and electrons.

Figure 5 shows charge signal distribution measured from electronic device grade single diamond detector when it is exposed to a radiation source in the form of Strontium (^{90}Sr) radiation source according to a preferred embodiment of the invention. The landau fit result shows that FWHM/MP is approximately 0.3.

Figure 6 shows the photoluminescence spectrum obtained from 514.5 nm laser excitation measured at room temperature (295K) according to a preferred embodiment of the invention. There is no visible peak from nitrogen and silicon related vacancies.

Figure 7 shows the map of the rocking curve width throughout the entire sample at different crystallographic planes according to a preferred embodiment of the invention. The histogram

shows a narrow distribution of the rocking width and at least 90% volume of electronic device grade single crystal diamond lies below 40 micro radians (μRad).

Figure 8 shows the cross-polarized image taken from the electronic-device grade single crystal diamond produced by the method at 40x magnification according to a preferred embodiment of the invention. There are no visible traces of large dislocations. However, there are petal-shape defects and inclusions occurring as brighter contrast in the cross-polarized image.

Figure 9 shows a plot of the typical FTIR spectrum of the electronic-device grade single crystal diamond according to a preferred embodiment of the invention.

Figure 10 shows a plot of the UV-VIS spectrum measured from the electronic-device grade single crystal diamond according to a preferred embodiment of the invention. As shown, there is no traces of detectable nitrogen related peaks at 270nm in the UV region and silicon related peaks at 738nm.

Figure 11 shows the photoluminescence spectra of diamonds having similar level of intensities for energy resolution dependence study according to a preferred embodiment of the invention.. The insert shows energy spectrum when electronic device grade single crystal diamond detector is exposed to a radiation source in the form of Americium (^{241}Am) radiation source taken at $0.8\text{V}/\mu\text{m}$ bias field. The spectrum is fitted using the landau equation.

Figure 12 shows the map of the rocking curve width of various samples of diamond based detectors and the corresponding histograms of RC width for quantification of average RC peak and RC width distribution according to a preferred embodiment of the invention.

Detailed Description

This application claims the benefit of, and priority to, Singapore Provisional Application No. 10201500278Y, filed 14 January 2015, the contents of which are incorporated by reference herein in its entirety.

The Figures are diagrammatic and not drawn to scale. In the Figures, elements which correspond to elements already described have the same reference numerals.

According to an aspect of the present invention, there is provided a method utilising microwave plasma chemical vapour deposition (MPCVD) process to produce electronic device grade single crystal diamonds.

The first step comprises of selecting a diamond seed or substrate having a pre-determined orientation. In a preferred embodiment of the present invention, the orientation of the diamond seeds or substrate is {001}. In a preferred embodiment of the present invention, the selection of the substrate having a pre-determined orientation is performed by looking at the high magnification optical images of 100X to check for surface defects, polishing induced defects, etch pits and inclusions. In another embodiment of the present invention, the high magnification optical images of 40X may be used. In a preferred embodiment of the present invention, a cross-polarized imaging may be performed on the High Pressure, High Temperature (HPHT) grown, natural, or MPCVD grown diamond to check for the presence of any lattice imperfection as a result due to strain. Crystal-axis check of the substrate is also performed to ensure that off-axis angle relative to the {100} orientation axis does not exceed 3 degrees. If necessary, etching the top surface of the substrate to reveal and/or remove the surface damage is performed to reduce the overall defect density.

The second step comprises of cleaning and / or etching of non-diamond phases and other induced surface damages from the diamond seed or substrate. Non-diamond phases are removed from the substrate by cleaning it in a boiling acid bath having temperature greater than 300°C and subsequently underwent different plasma etching for 30 to 180 minutes. Plasma etching of acid cleaned substrates by microwave plasma chemical vapour deposition (MPCVD) involves etching temperature from about 700°C to about 1200°C in a MPCVD chamber having an atmosphere with a pressure of about 100 to 300 torr, wherein the atmosphere therein comprises of about 0.1% to about 10% oxygen per unit of hydrogen. The plasma etching method for substrate preparations take place in a MPCVD chamber considerably free of nitrogen. The MPCVD chamber also comprises of gas precursors which are well purified such that the total impurities is less than 500 ppb in a preferred embodiment of the present invention. In other embodiments, the impurities may be less than 1ppm.

The third step comprises of growing a layer of diamond surface on the cleaned / etched diamond seed or substrate. The pre-growth process for production of electronic device grade single crystal diamond by microwave plasma chemical vapour deposition (MPCVD) on the growth surface of the diamond seeds takes place at a temperature from about 700°C to

about 1200°C in a MPCVD chamber , wherein the atmosphere therein comprises of a mixture of about 1% to about 15% CH₄ per unit of H₂ only and additionally with some additional mixture of about 1% to about 50% O₂ per unit of CH₄.

The fourth step comprises of growing electronic device grade single crystal diamond on top of the layer of diamond surface. The method of growing electronic device grade single crystal diamond includes controlling temperature of a growth surface of about 700°C to about 1200°C in a MPCVD chamber, wherein the pressure therein comprises of about 100 to about 300 torr and the atmosphere therein comprises of a mixture of about 0.1% to about 15% CH₄ per unit of H₂.

It is submitted that the growth rate of electronic device grade single crystal diamond is about 1 µm/hour to 15 µm/hour.

In other embodiments of the present invention, the second and third steps may be repeated more than one time so as to achieve a desired and optimum result.

During the whole process of pre-growth and growth of electronic device grade single-crystal diamond, the incorporation of impurities is well controlled by making sure that the MPCVD chamber where the diamond growth takes place is considerably free of nitrogen. In addition, gas precursors are also well purified such that the total impurities is less than 500ppb in a preferred embodiment of the present invention. In other embodiments, the impurities may be less than 1ppm.

It is submitted that the method produces an electronic device grade single-crystal diamond with the characteristics as described hereinafter.

In accordance with an aspect of the present invention, the electronic device grade single-crystal diamond comprises of a charge collection efficiency (CCE) of 100% when the bias field of at least 0.2V/µm as shown in Figure 2. Charge collection efficiency (CCE) is the ratio of the total charge detected to the total charge generated by radiation source in the form of Alpha Americium source. The measured charge collection distance of electronic device grade single crystal diamond produced by MPCVD process is limited by the sample thickness. Collection distance of 1000 µm can be obtained at 200V electrical bias when using a radiation source in the form of beta radiation source (Strontium ⁹⁰Sr).

In accordance with an aspect of the present invention, the electronic device grade single crystal diamond exhibits a low level of nitrogen. The low level of nitrogen is determined in photoluminescence spectrum in Figure 6 and in the typical FTIR spectrum in Figure 9. In a preferred embodiment of the present invention, there is an absence of a signal for single substitutional nitrogen centres $[N-C]^0$ which indicates a concentration of said single substitutional nitrogen centres of $<100\text{ppb}$ using FTIR and $<100\text{ppb}$ using UV-VIS absorption spectroscopy at 270nm, and typically $<30\text{ppb}$ using electron paramagnetic resonance (EPR).

As shown in a typical FTIR spectrum in Figure 9, when infrared transmittance is greater than 70% which approaches theoretical demand for diamond, there is an absence of C-H stretch absorption and hydrogen related vibrations in the infrared (IR) spectral range of 2500 cm^{-1} to 3400 cm^{-1} . In a preferred embodiment of the present invention, the substitution nitrogen has values of $[NVH]^0 = 3123\text{ cm}^{-1}$, $Ns^+ = 1332\text{ cm}^{-1}$ and $Ns^0 = 1344\text{ cm}^{-1}$ and the hydrogen related vibrations has a value of 2500 cm^{-1} to 3400 cm^{-1} .

In other embodiments, the level of nitrogen may be quantified by other suitable experimental techniques.

In accordance with an aspect of the present invention, the electronic device grade single crystal diamond also exhibits concentration of silicon related vacancies of $<50\text{ ppb}$. The concentration of silicon related vacancies of $<50\text{ ppb}$ using photoluminescence spectroscopy as shown in a plot of the UV-VIS spectrum measured from the diamond is shown in Figure 10. In a preferred embodiment of the present invention, there is an absence of traces of silicon related vacancy peaks (SiV) at 738nm, nitrogen related vacancy peaks (NV-) at 637nm.

In a preferred embodiment of the present invention, the resistance of the electronic device grade single crystal diamond produced by MPCVD process at room temperature is greater than $1 \times 10^{15}\ \Omega$ as obtained from I-V measurement. The C-V measurements show that the capacitance of less than 2pF can be easily obtained. The capacitance approaches close to the theoretical limit.

In accordance with an aspect of the present invention, the electronic device grade single crystal diamond has low field electron mobility $\mu_{0,e}$ greater than $1800\text{ cm}^2/\text{Vs}$ and low field

hole mobility $\mu_{0,h}$ greater than 2600 cm²/Vs for both electrons and holes at room temperature respectively. The saturation velocity(v_{sat}) for electrons and holes are $v_{sat,e} > 1.0 \times 10^7$ cm/s and $v_{sat,h} > 1.4 \times 10^7$ cm/s respectively. The carrier mobility and drift velocity of the diamond are obtained by transient current technique (TCT) as shown in Figure 3. The carrier lifetime (τ) for electrons, $\tau_e > 20.0$ ns whereas the carrier lifetime for holes, $\tau_h > 25.0$ ns can be obtained as shown in the plot in Figure 4.

In a preferred embodiment of the present invention, the charge signal distribution of the electronic device grade single crystal diamond has the shape of a Landau distribution curve where the most probable peak of the charge signal distribution depends on the density of defects and impurities in the electronic device grade single crystal diamond. The ratio of full-width-at-half-maximum (FWHM) to the most probable peak (MP) from charge (positive Landau) signal distribution (FWHM/MP) is smaller than 0.3. The charge signal distribution measured from the electronic device grade single crystal diamond detector is obtained when it is exposed to a radiation source in the form of Strontium (⁹⁰Sr) radiation source is shown in Figure 5.

Figure 11 shows the fluorescence spectra of three (3) samples of diamond based detectors having nearly the same level of fluorescence intensity (impurities) in a preferred embodiment of the present invention. The inset shows the ²⁴¹Am energy spectra obtained from these 3 samples at 0.8V/ μ m bias field. The data was fitted with negative landau distribution with amplitude A , $f(x) = A \exp\left(\frac{-1}{2} \left\{ \frac{-x+x_0}{B} + e^{-\left(\frac{-x+x_0}{B}\right)} \right\}\right)$, in order to obtain the most probably peak (x_0) for CCE calculation. The width of the energy spectrum provides the energy resolution response of the diamond based detector which can be obtained from parameter B . The fitting results are depicted at the inset labelled as FWHM/Width. As shown, although the level of fluorescence intensities (impurities) of the 3 samples are the same, but the level of CCE of the three diamond based detectors are different.

Figure 12 shows the map of x-ray rocking curve (RC) width of the three samples accompanied by their respective histograms. Sample 17 which has broader distribution of RC width and higher average RC width shows a drop in the CCE even though it has the lowest fluorescence intensity (impurities) among the three samples. The FWHM/MP widens as the RC width distribution is broadened. Energy resolution of less than 0.7% can be obtained for RC width distribution of less than 4.0 μ Radian.

The ratio of full-width-at-half-maximum (FWHM) to the most probable peak (MP) from charge (negative Landau) signal distribution is $FWHM/MP < 3.0\%$ when the electronic device grade single crystal diamond detector is exposed to a radiation source in the form of Americium (^{241}Am) radiation source is shown in Figure 12.

This result implies that the energy resolution of the diamond based detector is mostly affected by the value of RC width distribution. The smaller the RC width distribution, the higher the CCE, as shown In Figure 12.

Thus, the electronic device grade single diamond has a lattice defect when the energy resolution of the diamond based detectors is low, which correspond to a small rocking curve (RC) width distribution range less than 45 micro radian which result in a high CCE. As shown in Figure 12, sample S15 has a CCE of 100% when the RC width distribution is 3.43, which is lower than that of those of other samples.

Thus, the RC width distribution is a method used to further assess the electronic properties (i.e. CCE) of the electronic device grade single crystal diamond. However, such a method is restricted to only for diamond with already very low impurities. Hence, RC width as well as the ultra-low fluorescence play a very important role in making a good detector base on diamond.

In a preferred embodiment of the present invention, the ratio of the 2nd order Raman peak (~596nm) to the photoluminescence line of negatively charged nitrogen vacancy ($\text{NV}^- = 637\text{nm}$) and silicon vacancy ($\text{SiV} = 738\text{nm}$) is greater than 2.5 as shown in the photoluminescence spectrum in Figure 6. The photoluminescence spectrum is obtained from 514.5nm Argon excitation source at room (295K) temperature. Low temperature (77K) photoluminescence at 488nm laser excitations does not show any visible defects or fluorescence intensity (impurities) in the range of 490-900nm. All peaks are normalised with respect to Raman first order line at 552 nm. Thus, low fluorescence intensity (impurities) is determined when low temperature (77K) photoluminescence at 488nm laser excitations does not show any visible defects in the range of 490nm to 900nm, whereby the photoluminescence spectrum is obtained from 514.5nm Argon excitation source at room (295K) temperature.

In accordance with an aspect of the present invention, the electronic device grade single

diamond having a thickness up to 2500 μm is produced. In a preferred embodiment of the present invention, a diamond seed layer having a thickness of less than 2500 μm may be attached to a substrate.

Beside impurities which affects the electronic device grade single crystal diamond's electronic properties, it is found that lattice defects and dislocations reduce the carrier lifetimes by trapping radiation generated charges at the defect sites. The electronic device grade single crystal diamond of the present invention has a very narrow average rocking curve width that does not exceed 40 micro radians in at least 90% volume of the electronic device grade single diamond as shown in the map of the rocking curve in Figure 7 in the preferred embodiment of the present invention. The corresponding distribution of the rocking curve width is displayed as histogram. Generally, a smaller rocking curve width (darker regions) indicates good lattice structure and a larger rocking curve width (brighter region) indicates lattice imperfection. This is true for different crystallographic planes (220), (331), (400).

Cross-polarized image showing nearly an absence of brighter areas indicates that the electronic device grade single crystal diamond has substantially low stress and low lattice imperfection as shown in Figure 8. As shown, no inclusions and petal like structures are observed. Other characteristics include low fluorescent intensity (impurities).

It is submitted that the inclusion in the electronic device grade single crystal diamond affects the electronic characteristics in a detrimental manner. It is preferably that the aerial density of inclusions must be $<10^3/\text{m}^2$ so as not to affect the electronic characteristics of the electronic device grade single crystal diamond.

It is apparent to a person skilled in the art that many modifications, alternatives and variations 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. Accordingly, it is intended to embrace all such modifications, alternatives and variations that fall within the scope of the included claims.

CLAIMS:

1. An electronic device grade single crystal diamond comprising:
 - a charge of collection efficiency (CCE) of 100% when the bias field is at least $0.2\text{V}/\mu\text{m}$,
 - a low level of nitrogen defined by an absence of a signal for single substitutional nitrogen centres $[\text{N-C}]^0$, indicating a concentration of said single substitutional nitrogen centres of $<100\text{ppb}$ using FTIR and $<100\text{ppb}$ using UV-VIS absorption spectroscopy at 270nm , and typically $<30\text{ppb}$ using electron paramagnetic resonance (EPR), an absence of C-H stretch absorption and hydrogen related vibrations in the infrared (IR) spectral range of 2500 cm^{-1} to 3400 cm^{-1} when infrared transmittance is greater than 70% in a FTIR spectrum, and
 - a concentration of silicon related vacancies of $<50\text{ ppb}$ defined by an absence of traces of silicon related vacancy peaks (SiV) at 738nm , nitrogen related vacancy peaks (NV-) at 637nm using photoluminescence spectroscopy. .
2. The electronic device grade single crystal diamond according to claim 1, wherein the substitution nitrogen has values of $[\text{NVH}]^0 = 3123\text{ cm}^{-1}$, $\text{Ns}^+ = 1332\text{ cm}^{-1}$ and $\text{Ns}^0 = 1344\text{ cm}^{-1}$ and the hydrogen related vibrations has a value of 2500 cm^{-1} to 3400 cm^{-1} .
3. The electronic device grade single crystal diamond according to claim 1 or 2, wherein the diamond comprises of having a resistance greater than $1 \times 10^{15}\Omega$ as obtained from I-V measurement, and the diamond has low field electron mobility $\mu_{0,e}$ greater than $1800\text{ cm}^2/\text{Vs}$ and low field hole mobility $\mu_{0,h}$ greater than $2600\text{ cm}^2/\text{Vs}$ for electrons and holes at room temperature.
4. The electronic device grade single crystal diamond according to any one of the preceding claims, wherein the saturation velocity (v_{sat}) for electrons and holes are $v_{\text{sat},e} > 1.0 \times 10^7\text{ cm/s}$ and $v_{\text{sat},h} > 1.4 \times 10^7\text{ cm/s}$ respectively, and the carrier lifetime (τ) for electrons, $\tau_e > 20.0\text{ ns}$ whereas for holes, the carrier lifetime $\tau_h > 25.0\text{ ns}$.
5. The electronic device grade single crystal diamond according to any one of claims 10 to 13, further has a charge signal distribution with the shape of a Landau distribution curve where the most probable peak of the charge signal distribution depends on the density of defects and impurities in the electronic device grade single crystal

diamond, and the ratio of full-width-at-half-maximum (FWHM) to the most probable peak (MP) from charge (Landau) distribution (FWHM/MP) is smaller than 0.3.

6. The electronic device grade single crystal diamond according to any one of the preceding claims, further has a low lattice defect defined by the low energy resolution of the diamond based detectors, which correspond to a small rocking curve (RC) width range less than 45 micro radian which result in a high CCE.
7. The electronic device grade single crystal diamond according to claim 6, wherein the rocking curve (RC) width distribution is less than 4.0 μ Radian, which is used to obtain an energy resolution of less than 0.7%, wherein the low percentage of the energy resolution correspond to the low value of the ratio of full-width-at-half-maximum (FWHM) to the most probable peak (MP) from charge (negative Landau) signal distribution, FWHM/MP, in which $\text{FWHM/MP} < 3.0\%$ when the electronic device grade single crystal diamond detector is exposed to a radiation source in the form of Americium (^{241}Am) radiation source.
8. The electronic device grade single crystal diamond according to any one of the preceding claims, further comprise of low fluorescence intensity (impurities) defined by low temperature (77K) photoluminescence at 488nm laser excitations which does not show any visible defects in the range of 490nm to 900nm, whereby the photoluminescence spectrum is obtained from 514.5nm Argon excitation source at room (295K) temperature.
9. The electronic device grade single crystal diamond according to any one of the preceding claims, wherein the diamond seed layer having a thickness up to 2500 μm is attached to a substrate, and the diamond has very narrow average rocking curve width that does not exceed 40 micro radians in at least 90% volume of the diamond.
10. The electronic device grade single crystal diamond according to any one of the preceding claims, further has an aerial density of inclusion $< 10^3/\text{m}^2$.
11. A method utilising microwave plasma chemical vapour deposition (MPCVD) process of producing electronic device grade single crystal diamond according to claims 1 to 10, comprising of:

- (a) selecting a diamond seed or substrate having a pre-determined orientation,
 - (b) cleaning and / or etching of non-diamond phases and other induced surface damages from the diamond seed or substrate, whereby this step can be performed one or more times,
 - (c) growing a layer of diamond surface on the cleaned / etched diamond seed or substrate, whereby this step can be performed one or more times, and further comprises pre-growth process for production of electronics device grade single crystal diamond by microwave plasma chemical vapour deposition (CVD) on the growth surface of the diamond seed takes place at a temperature from about 700°C to about 1200°C in a MPCVD chamber, wherein the atmosphere comprises of a mixture of about 1% to about 15% CH₄ per unit of H₂ only or with some additional mixture from about 1% to about 50% O₂ per unit of CH₄, and
 - (d) growing electronics device grade single crystal diamond on top of the layer of the diamond surface.
12. The method according to claim 11, wherein the diamond seed or substrate have an orientation of {100}.
 13. The method accordingly to claim 11 or 12, wherein step (a) comprises of looking at the high magnification optical images of 100X to check for surface defects, polishing induced defects, etch pits and inclusions.
 14. The method according to any one of claims 11 to 13, wherein step (a) further comprises of subsequently performing cross-polarised imaging on the diamond seed to check for the presence of any lattice imperfection as a result of strain, and performing crystal-axis check of the substrate to ensure that off-axis angle relative to the {100} orientation axis does not exceed 3 degrees, and if necessary, etching the top surface to reveal and / or remove the surface damage to reduce the overall defect density.
 15. The method according to any one of claims 11 to 14, wherein step (b) further comprises of removing non-diamond phases from the substrate by cleaning it in a boiling acid bath having temperature greater than 300°C and subsequently underwent different plasma etching for 30 to 180 minutes, and subsequently performing plasma etching of acid cleaned diamond substrates by microwave plasma chemical vapour

deposition (CVD) involves etching temperature from about 700°C to about 1200°C in a MPCVD chamber having an atmosphere with a pressure of about 100 to 300 torr, wherein the atmosphere therein comprises of about 0.1% to about 10% oxygen per unit of hydrogen.

16. The method according to claim 15, wherein the plasma etching method for diamond preparations take place in a MPCVD chamber considerably free of nitrogen, and the MPCVD chamber comprises of gas precursors which are well purified such that the total impurities is less than 500ppb.
17. The method according to any one of claims 11 to 16, wherein step (d) further comprises of controlling temperature of a growth surface of about 700°C to about 1200°C in a MPCVD chamber , wherein the pressure comprises of about 100 to about 300 torr and the atmosphere comprises of a mixture of about 0.1% to about 15% CH₄ per unit of H₂, wherein the growth rate of electronics device grade single crystal diamond is about 1 µm/hour to 15 µm/hour.
18. The method according to any one of claims 11 to 17, wherein the incorporation of impurities are well controlled by making sure the MPCVD chamber where the diamond growth take place are considerably free of nitrogen, and also by making sure gas precursors are well purified such that the total impurities is less than 500ppb.

ELECTRONIC DEVICE GRADE SINGLE CRYSTAL DIAMONDS AND METHOD OF PRODUCING THE SAME

ABSTRACT

A method utilising microwave plasma chemical vapour deposition (MPCVD) process of producing electronic device grade single crystal diamond comprising of: (a) selecting a diamond seed or substrate having a pre-determined orientation, (b) cleaning and / or etching of non-diamond phases and other induced surface damages from the diamond seed or substrate, whereby this step can be performed one or more times, (c) growing a layer of extremely low crystal defect density diamond surface on the cleaned / etched diamond seed or substrate, whereby this step can be performed one or more times, and (d) growing electronics device grade single crystal diamond on top of the layer of the low crystal defect density diamond surface.

Figure 1

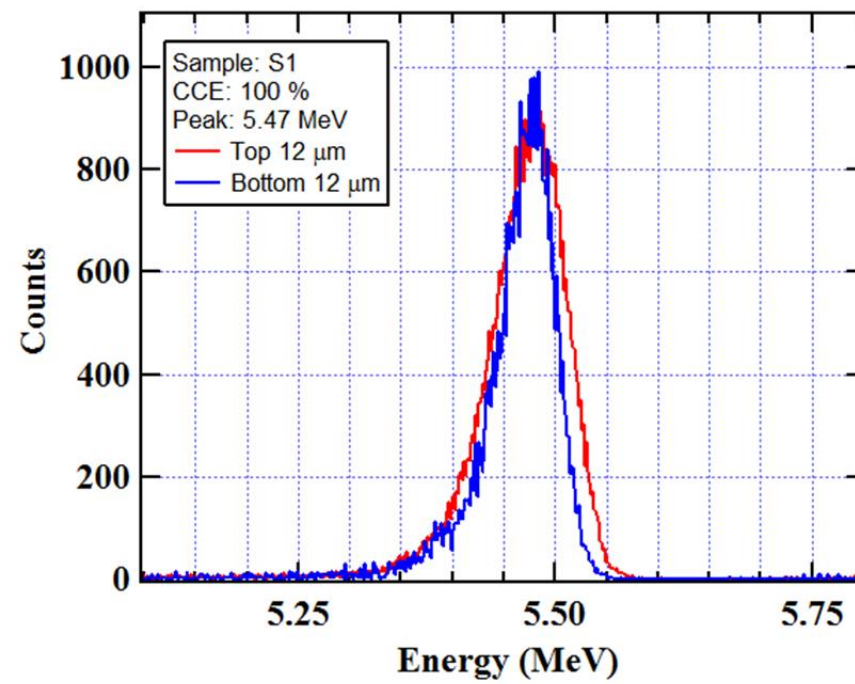


Figure 1

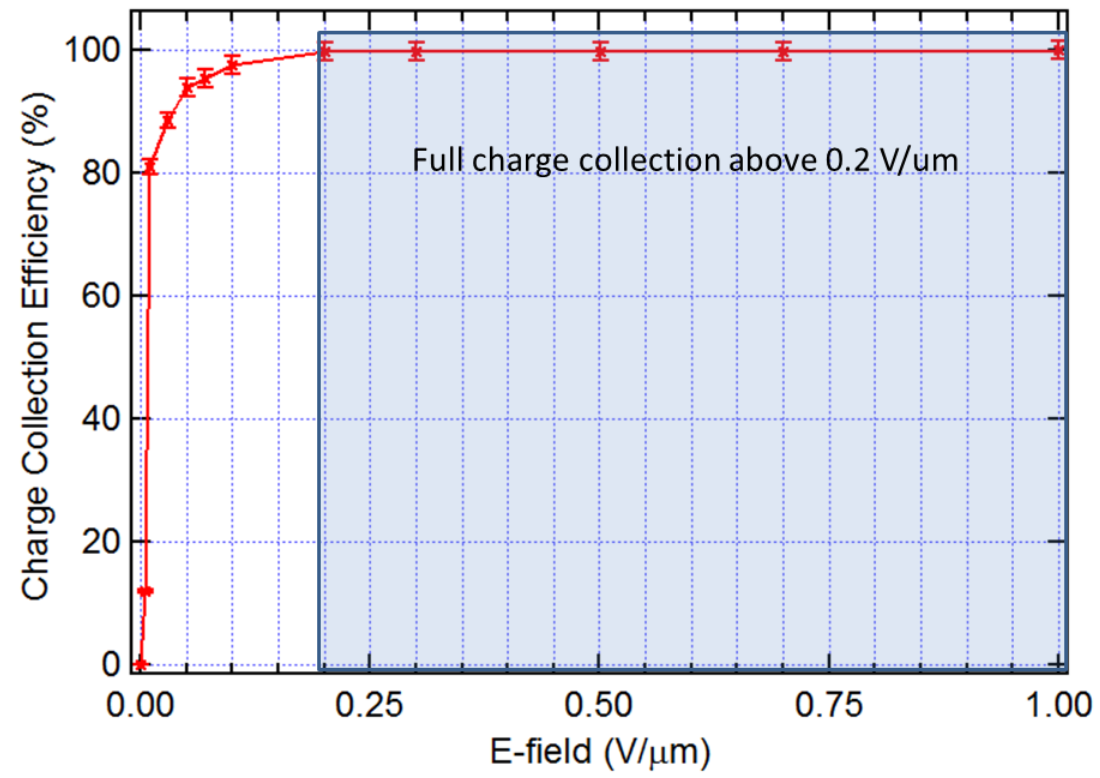


Figure 2

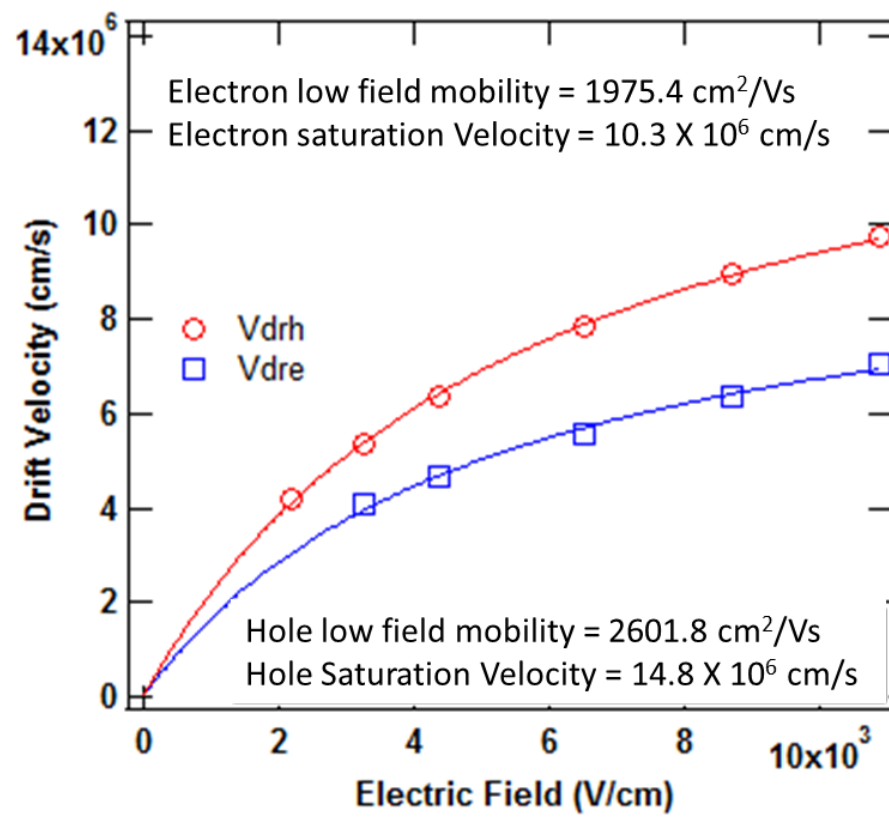


Figure 3

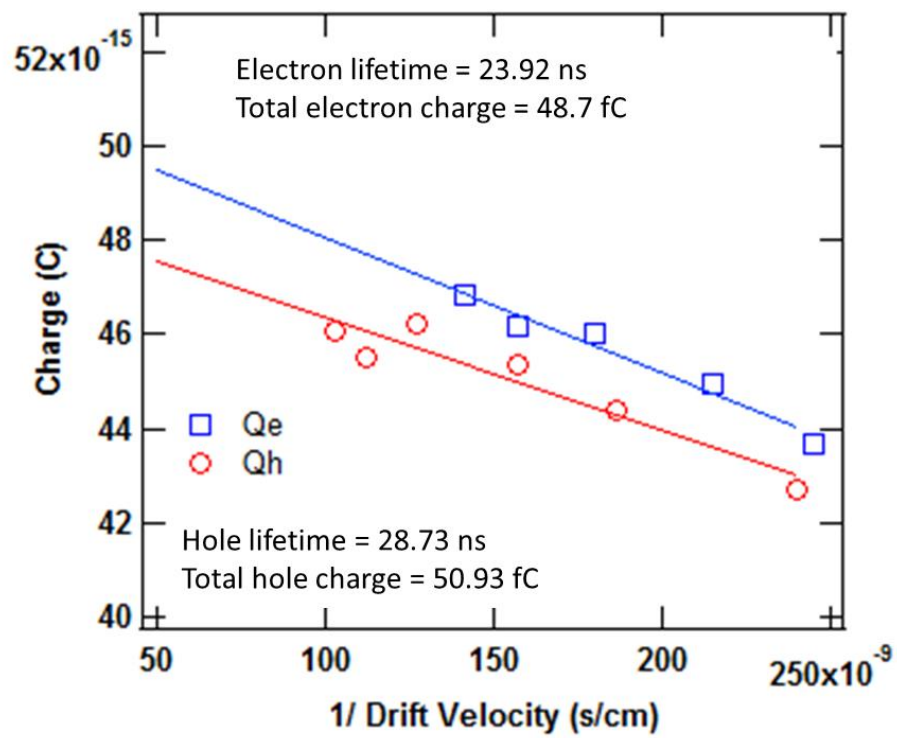


Figure 4

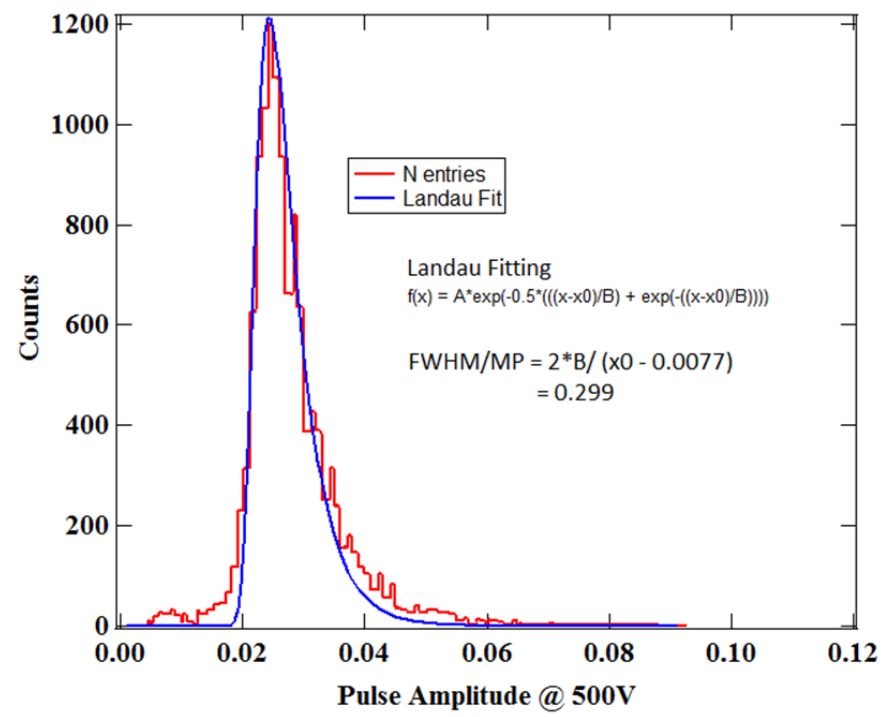


Figure 5

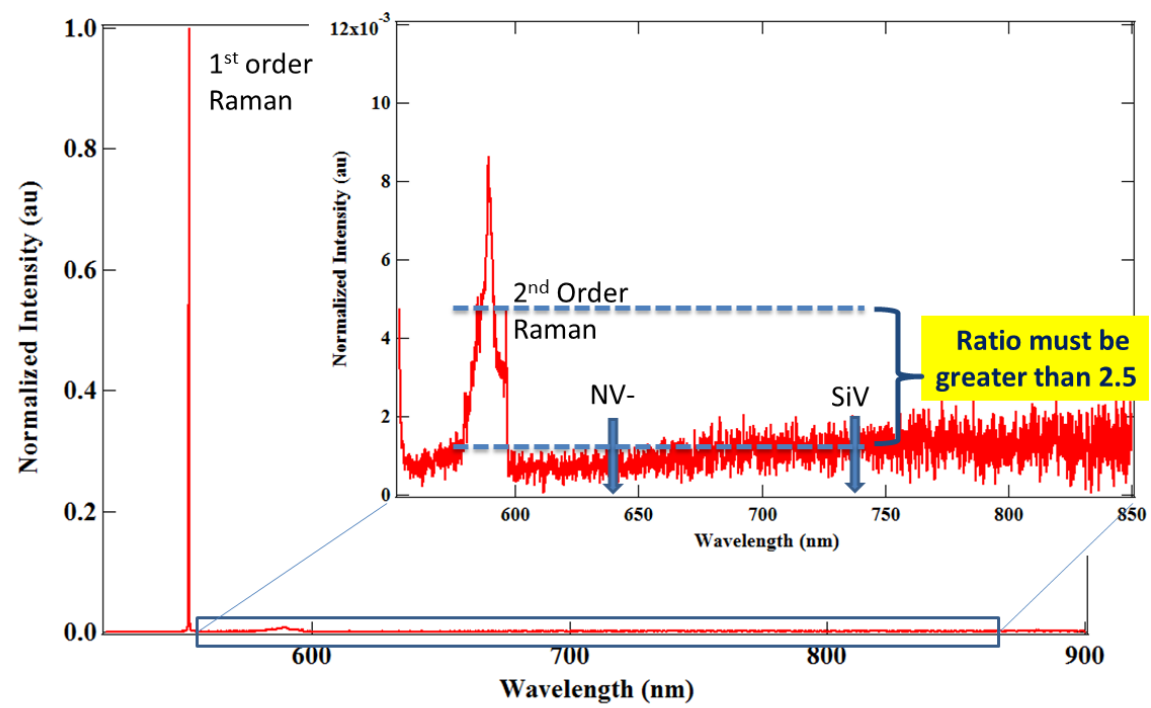


Figure 6

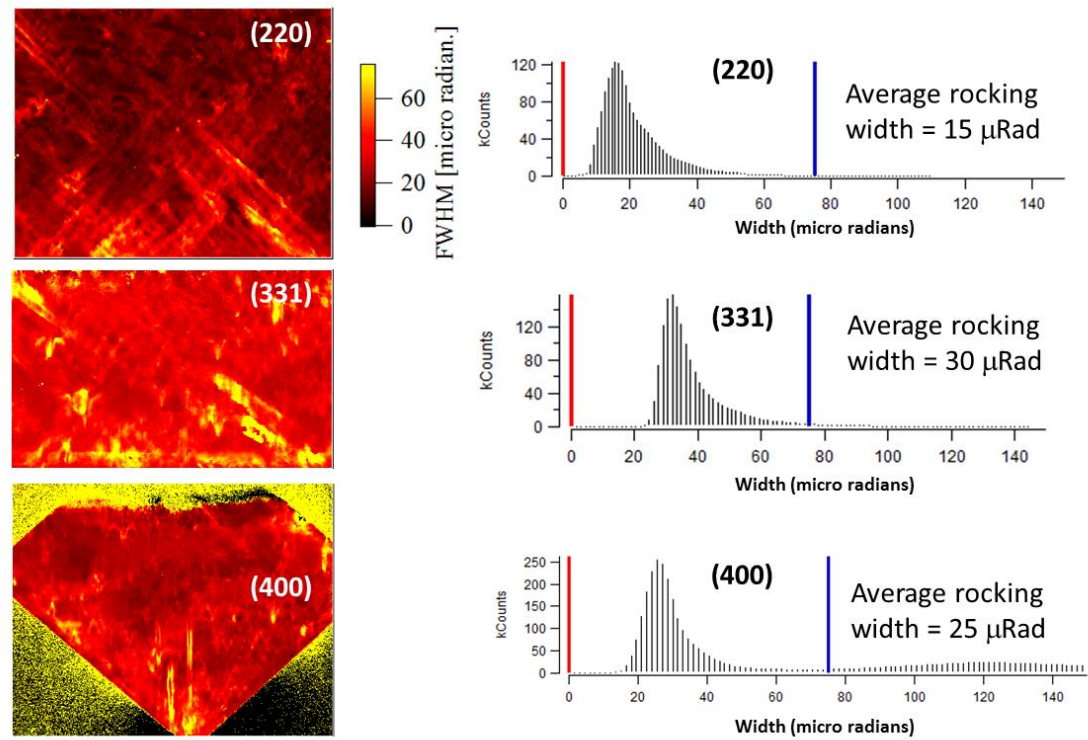
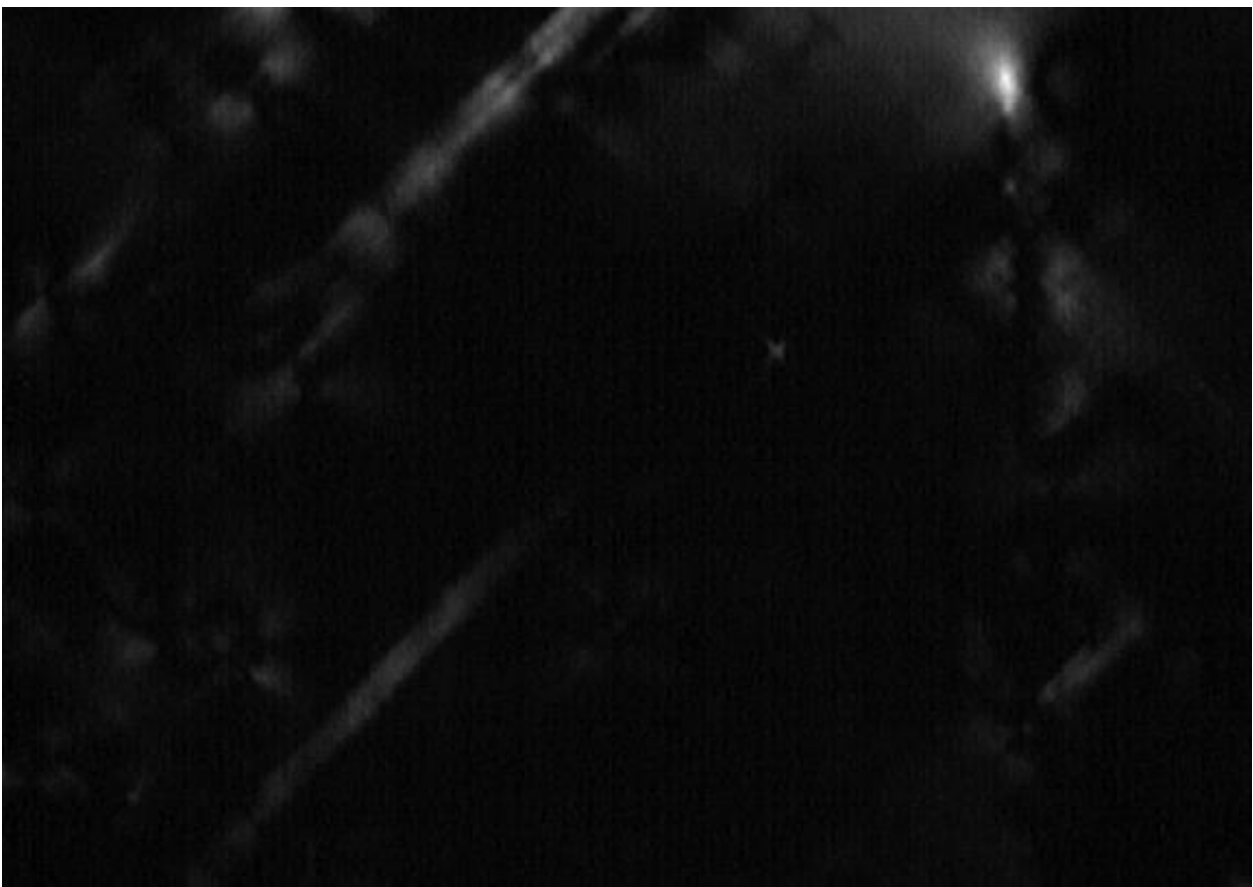


Figure 7



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Figure 8

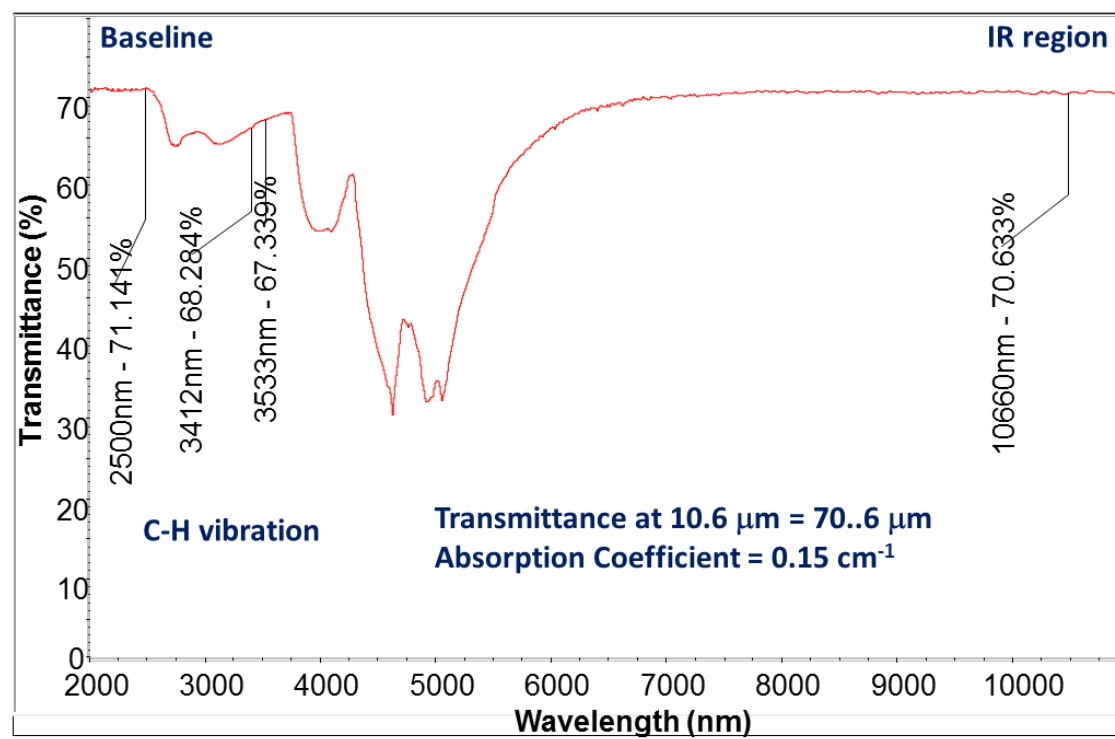


Figure 9

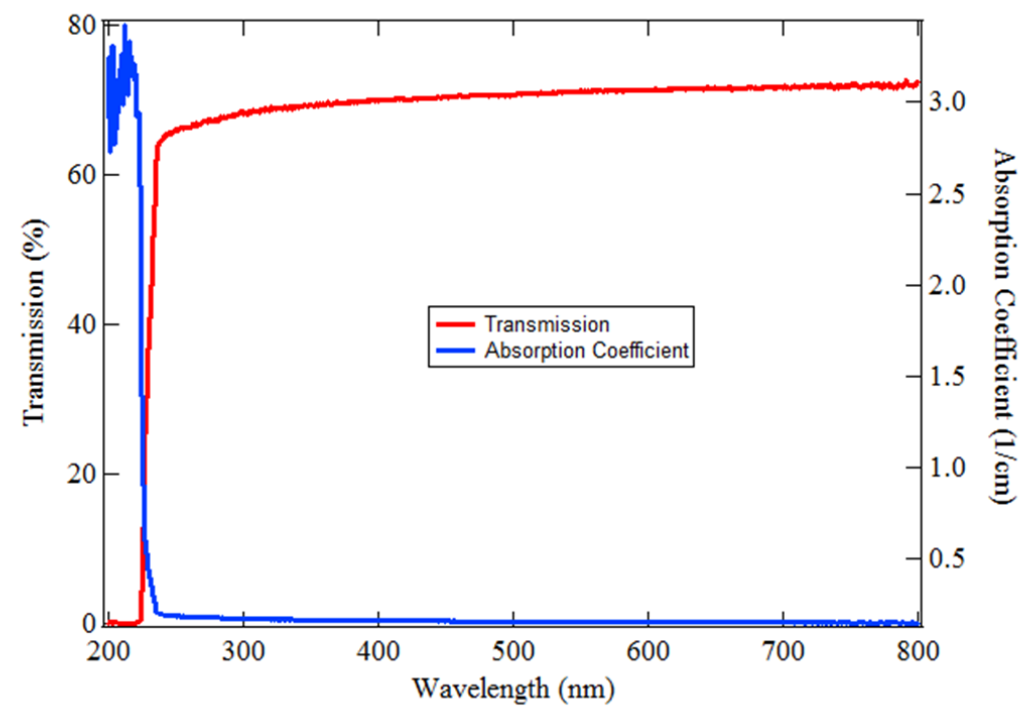


Figure 10

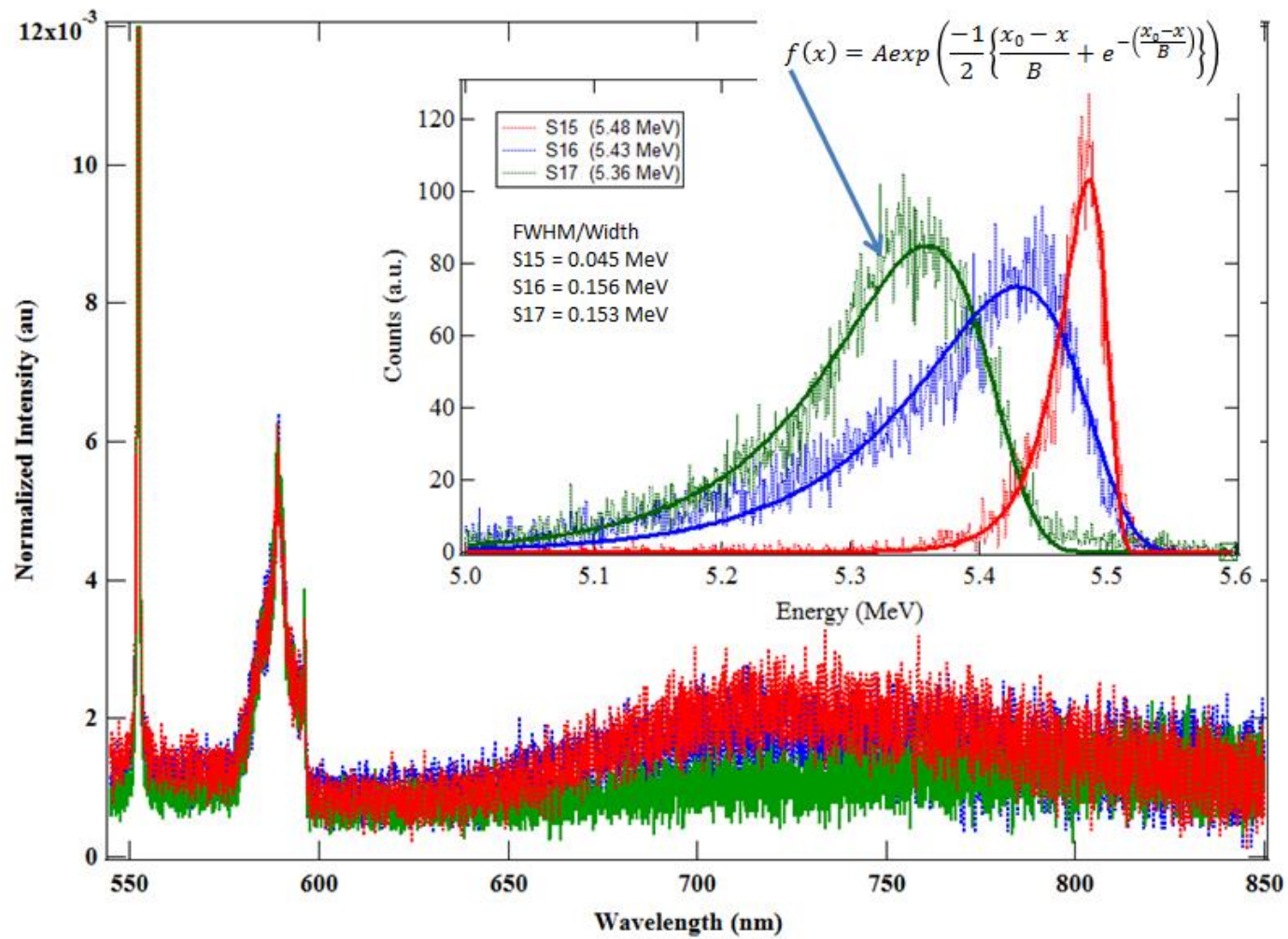


Figure 11

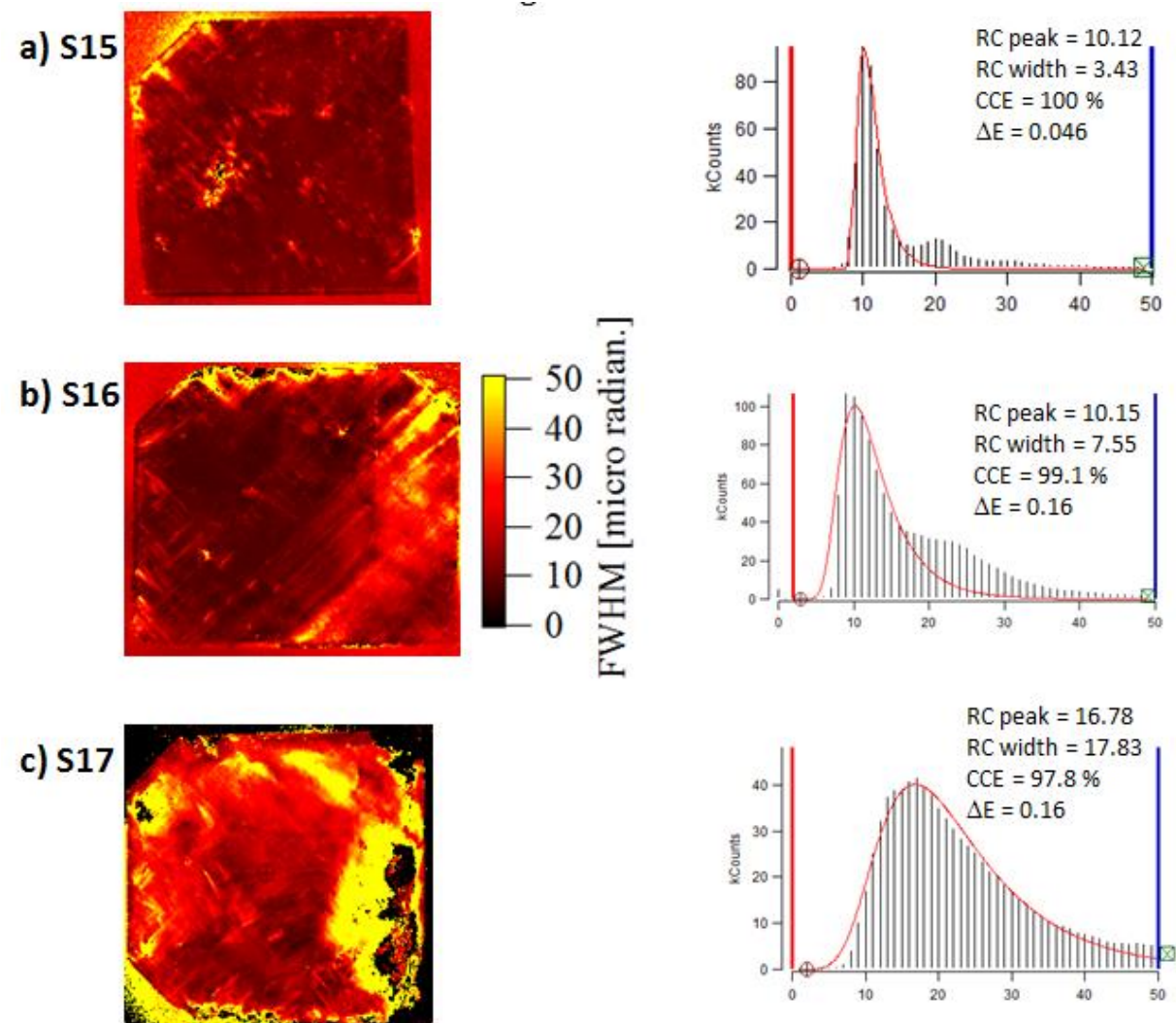


Figure 12