# Micron Semiconductor Limited

# DIAMOND DETECTORS

MICRON SEMICONDUCTOR LIMITED

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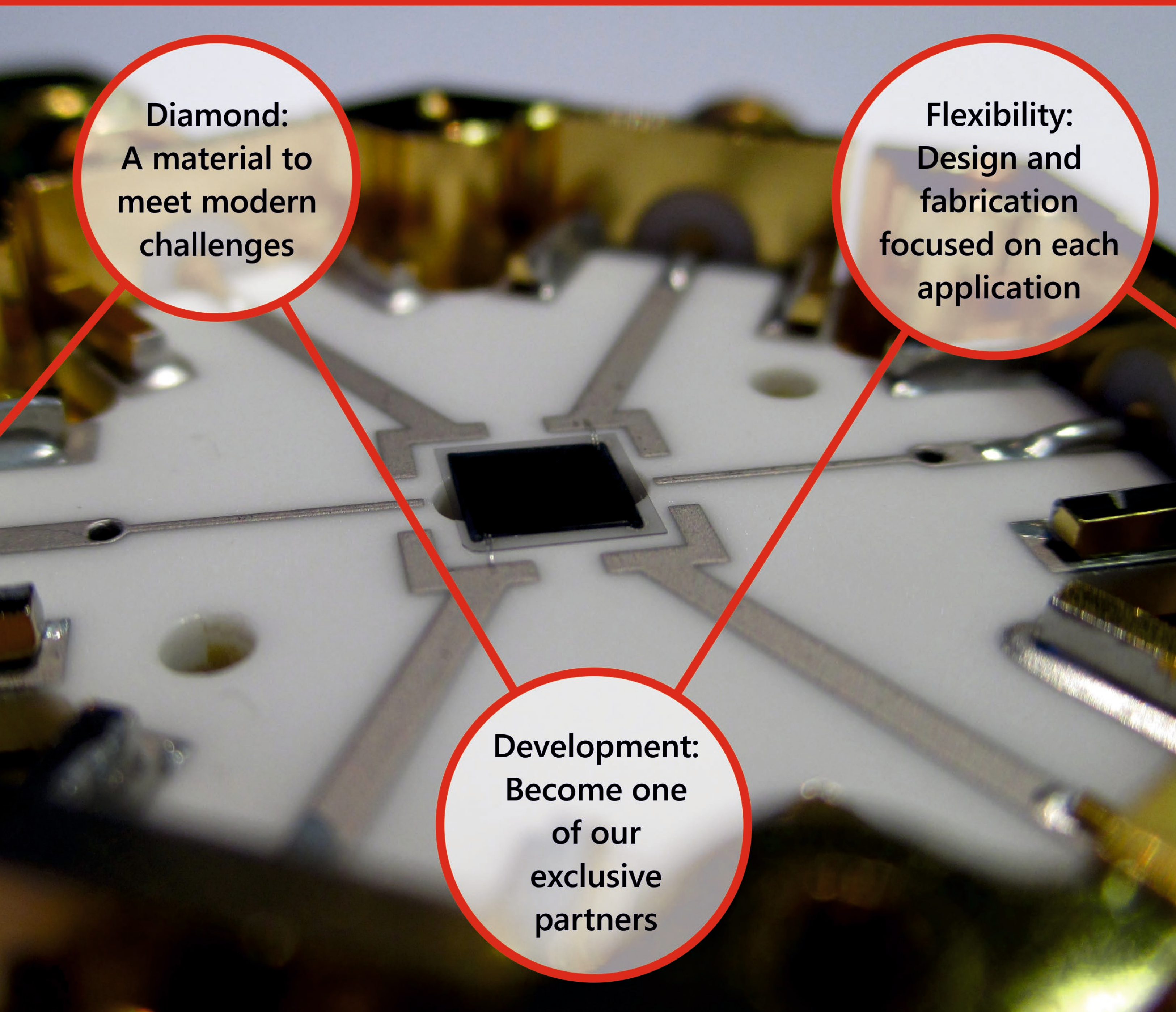

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# Micron Semiconductor Ltd

**Micron Semiconductor Ltd (MSL)** is a semiconductor radiation sensor design and manufacturing company established in **1983** and based in Lancing in the south of England.

In **2019** we opened our EU-based subsidiary in Paris, **Micron Semiconductor Europe S.A.R.L.**

We also benefit from a worldwide network of trusted agents.

***Figure1****: World map of Micron Semiconductor Ltd locations.*

*Global headquarters shown in red.*

We cater for a wide range of applications, from space exploration to medical imaging, civil and defence nuclear and academic research. Our focus is on tailor-made radiation sensors that are to be operated in challenging environments, such as the high-radiation CERN particle collider or in satellites, where available space and power are both limited.

Specifications of the sensing material are essential to the quality of the product but packaging and connectivity solutions are equally important to enable the handling, operation and protection of the detectors. We specialize in designing all these components and provide ready-to-use devices.

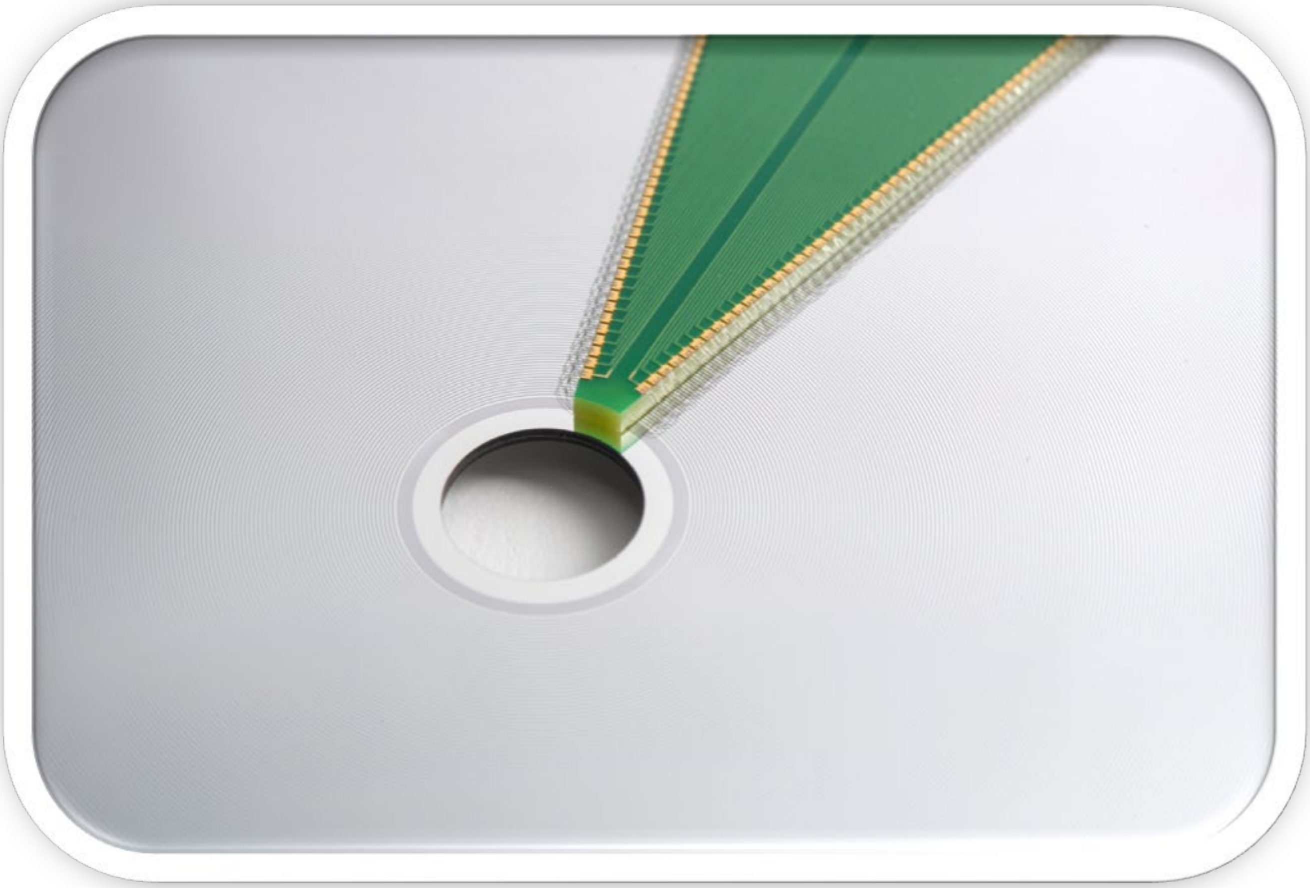

***Figure 2**: S4 Silicon detector produced by Micron Semiconductor Ltd.*

Our high level of specialization and flexibility ensures our success both as collaborator and supplier. We aim to work with our customers to ensure that their projects are approved and accomplished.

The historic core of MSL activity is silicon products. However, for a range of various challenging environments, diamond is now an excellent, fully-operational alternative.

Our diamond sensor branch opened in 2013 and has developed exponentially since then. In this booklet we are pleased to introduce our range of products and services related to diamond devices.

***Figure 3**: MSL-DD-01 Diamond detector produced by Micron Semiconductor Ltd.*

# CVD Diamonds

Diamond is one of the best-known and most sought-after gemstones. It is prized for its pure clarity and transparency, the way it appears to play and disperse light, as well as for its extreme physical hardness. It has been used ornamentally and in jewellery for many thousands of years and its popularity has never faltered.

Today, diamonds are also used in many industrial applications: the most widely known as cutting tools and abrasives. Radiation sensors are amongst the latest additions.

There are many ways to explore the characteristics of a material as versatile as diamond. The important point to keep in mind is that appearance and optical properties are often not relevant when judging the radiation sensor potential. This section aims to give the necessary background to understand the differences between various types of diamonds.

***Did you know?***
*Diamond is the hardest natural material. Hardness is defined by the Mohs scale, which measures the resistance to scratches and abrasion. However, a hard material is also brittle, which means that diamond can break, especially if they are very thin or have sharp corners!*

***Figure 4****: Natural diamonds are cut to exploit their optical properties.*

*CVD Diamonds used for making diamond detectors are usually of a higher purity.*

*(Mario Sarto, CC BY-SA 3.0)*

**From the volcanoes to the clean room**

Most natural diamonds were formed several billion years ago, deep in the Earth's mantle. At a depth of approximately 200 km, the high pressure and temperature made the carbon atoms arrange themselves into this particular crystalline pattern we call diamond.

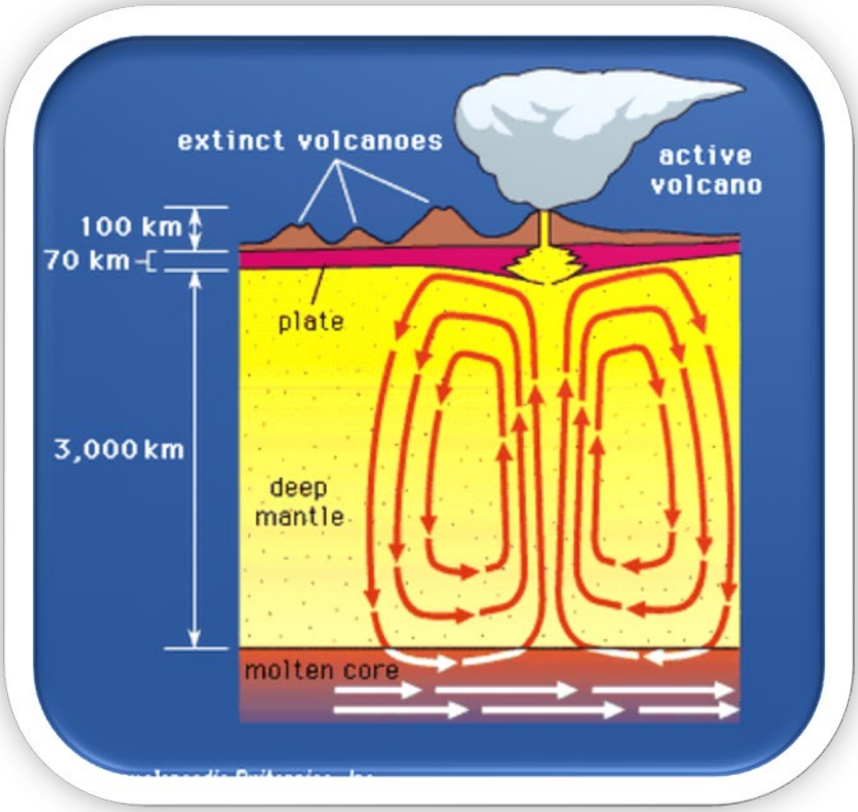


***Figure 5***: *Geological cycle – Diamonds are formed somewhere close to the top of the yellow layer, known as the mantle. (Encyclopaedia Britannica)*

Natural diamonds were the first to be studied for their potential as radiation sensors. However, their encouraging results could not hide the reality of an unpredictable variability in their performance. In short, all natural diamonds do not possess the qualities required for detecting radiation. Defects can be hidden in a diamond beyond a careful optical inspection. In order to detect ions, electrons, x-rays etc, the structure must be as pure as possible at the atomic scale.

From the 1950s onwards, the first generation of man-made diamonds replicated the natural, geological conditions in which diamonds are made. These High Pressure, High Temperature diamonds (HPHT) are produced in huge anvils, but they often fail to reach the high degree of purity required for radiation sensors.

A new technology for diamond growth was developed in the 1980s, the Chemical Vapour Deposition (CVD). The CVD process is used to grow several different materials and diamond is only one of them. This process uses a “seed” and gas, or gasses, of the appropriate composition and grows a diamond one atomic layer at a time. Research is still going on to understand the exact atomic processes at play in CVD growth, but CVD diamonds finally present the levels of purity and quality required to detect different types of radiation.

**Did you know?**

*80% of all mined diamonds (approx. 27 t) are unsuitable for use as gemstones and are used industrially instead.*

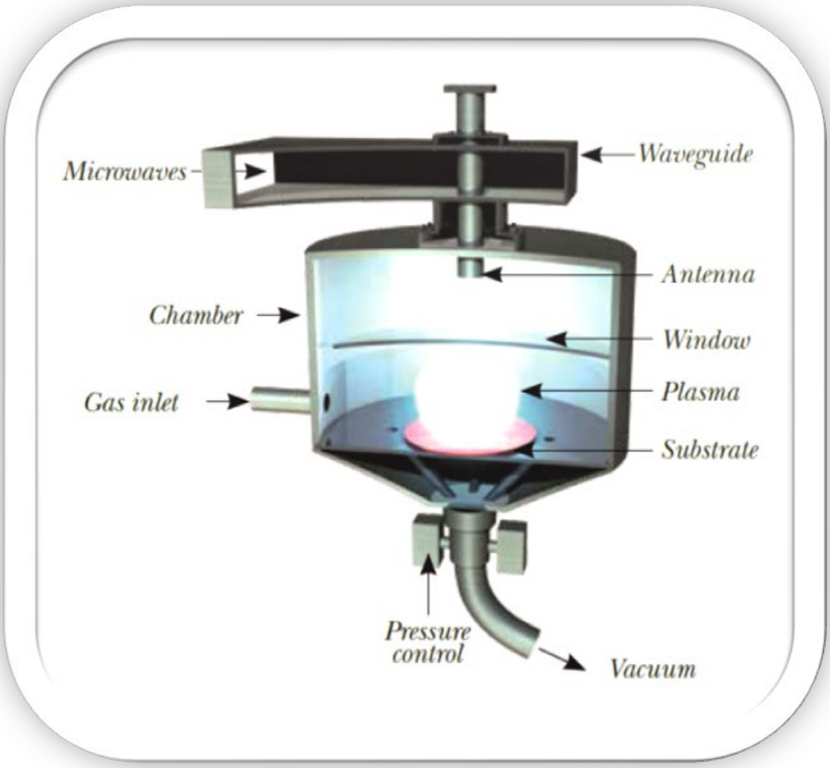


***Figure 6**: Principle of a chemical vapour deposition (CVD) reactor (courtesy of Element6).*

**Diamond Structure and Properties**

Natural, HPHT and CVD diamonds are all diamonds. What defines a diamond is its structure (the way its atoms are arranged in a regular pattern called a crystal) and not the way it was made.

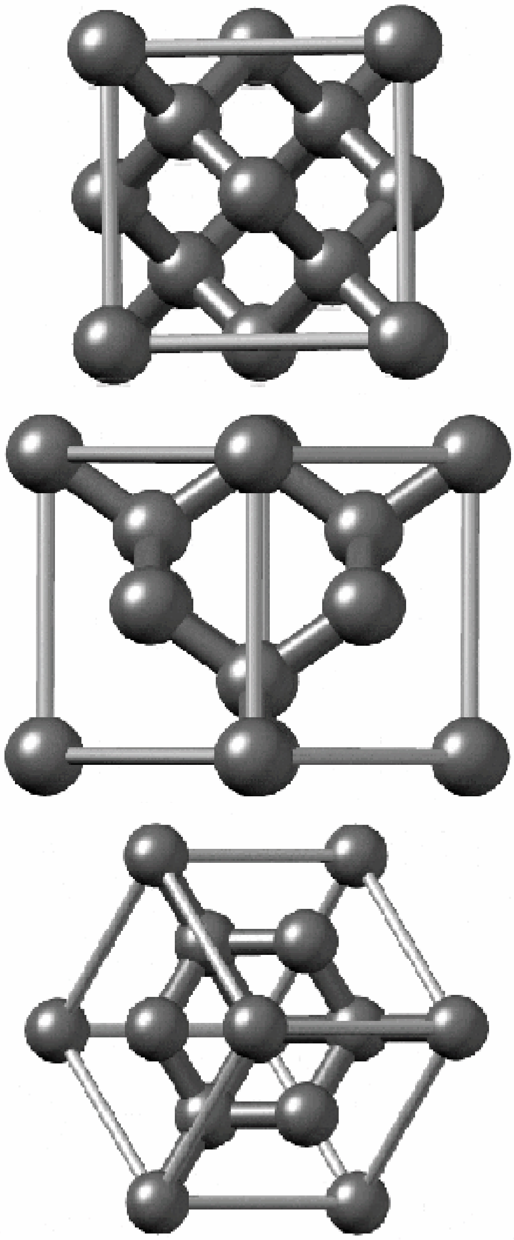

***Figure 7**: A crystal is a repetitive atomic structure. The repetition offers a certain degree of symmetry and is exploited in crystallography to understand the properties of a material. These 3 illustrations show the 3 different symmetries of diamonds (Top to bottom, view along the directions {100}, {110} and {111}).*

*(Marina Vladivostok public domain)*

An ideal diamond is a crystal made of exclusively carbon atoms arranged in a specific way called a diamond lattice. In fact, it is not the most stable state of crystallized carbon: only graphite can make that claim.

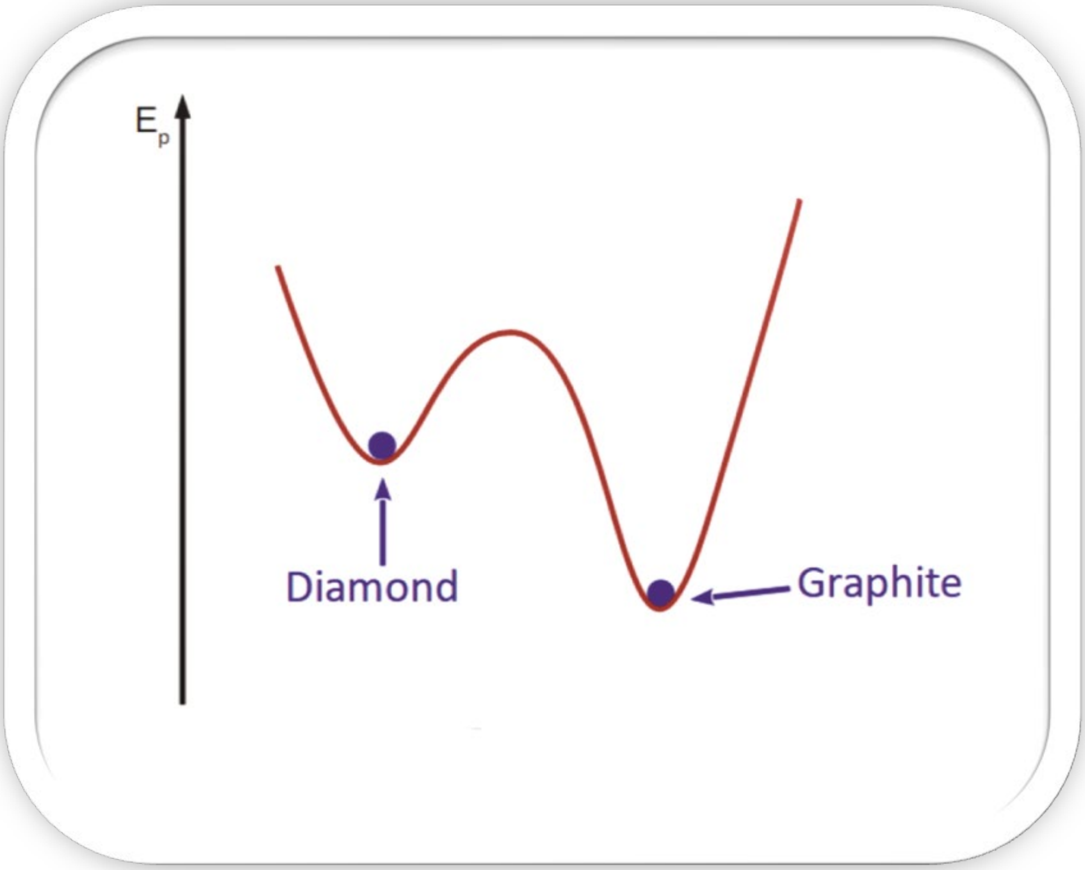


***Figure 8****: Energy wells for graphite and diamond.*

***Did you know?***

*Graphite and diamonds are called allotropes: they are different 3D structures made with the same building blocks, carbon atoms. There are several hundreds allotropes of carbon, including the famous graphene.*

Carbon is a very small atom, which makes it possible to arrange in a compact structure. This tight, dense and rigid lattice structure is what gives diamond most of its exceptional properties.

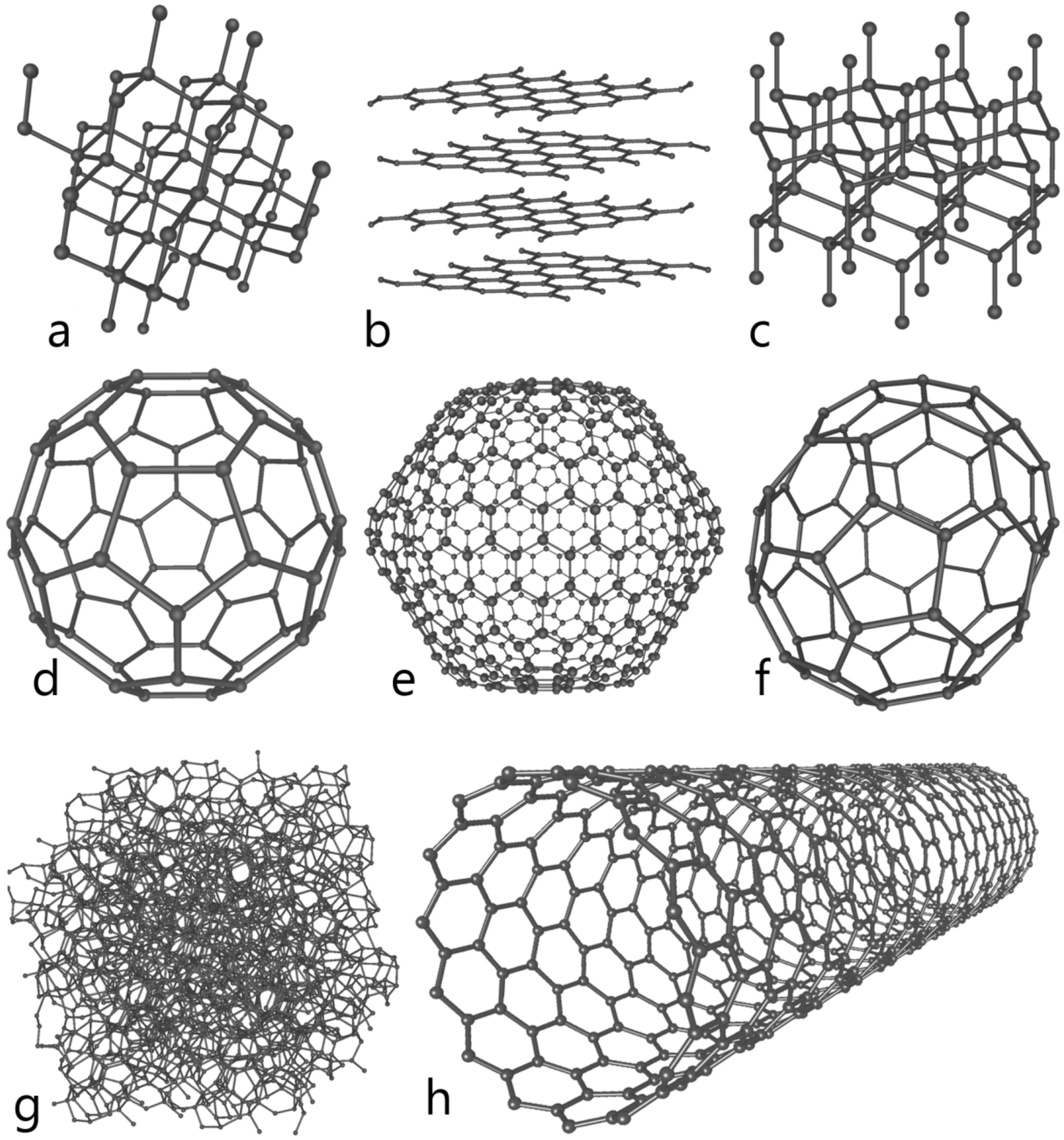


***Figure 9***: *These illustrations depict eight of the allotropes (different molecular configurations) that pure carbon can take: a) Diamond b) Graphite c) Lonsdaleite d) C60 (Buckminsterfullerene) e) C540 (Fullerene) f) C70 (Fullerene) g) Amorphous carbon h) single-walled carbon nanotube.*
*(Michael Stroeck CC BY-SA 3.0)*

***Did you know?***

*"The modern industrial world consumes approximately 800 t of synthetic diamond, around 150 times the amount of the natural diamond mined as gemstones." (Courtesy of Element6)*

It is already worth mentioning that, while a theoretical diamond lattice is made of only carbon atoms, a real one will contain some imperfections and impurities. The typical impurities are nitrogen atoms, and to a certain extent boron atoms, because their size is very close to that of carbon (since they are carbon's neighbours in the periodic table).

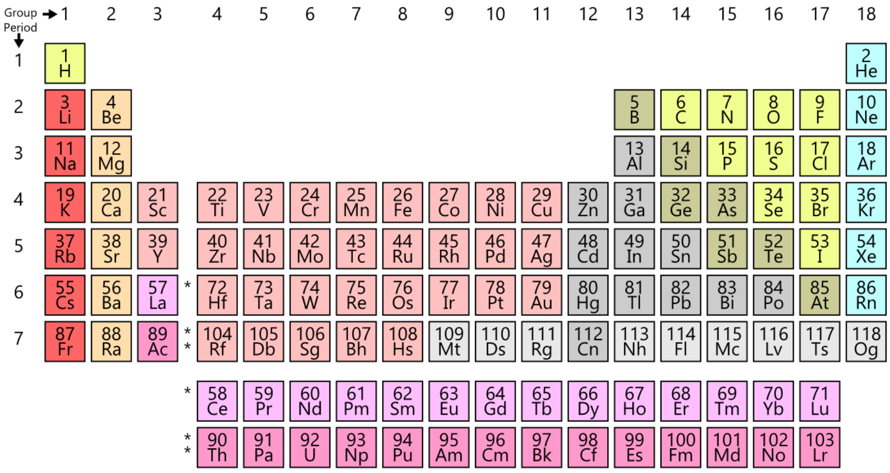


***Figure 10**: Periodic table (public domain).*

The wide range of applications of diamond can take advantage from these impurities: boron doping creates a conductive zone in the diamond, whereas carefully engineered nitrogen impurities called nitrogen vacancies are exploited in quantum information research.

However, for radiation detection applications, the highest purity is often required as structural defects, boron and nitrogen all act as impurities that interfere with the signal generated in the diamond.

## Classification of Diamonds

The wide range in diamond quality and specifications led to establishing a classification shown below.

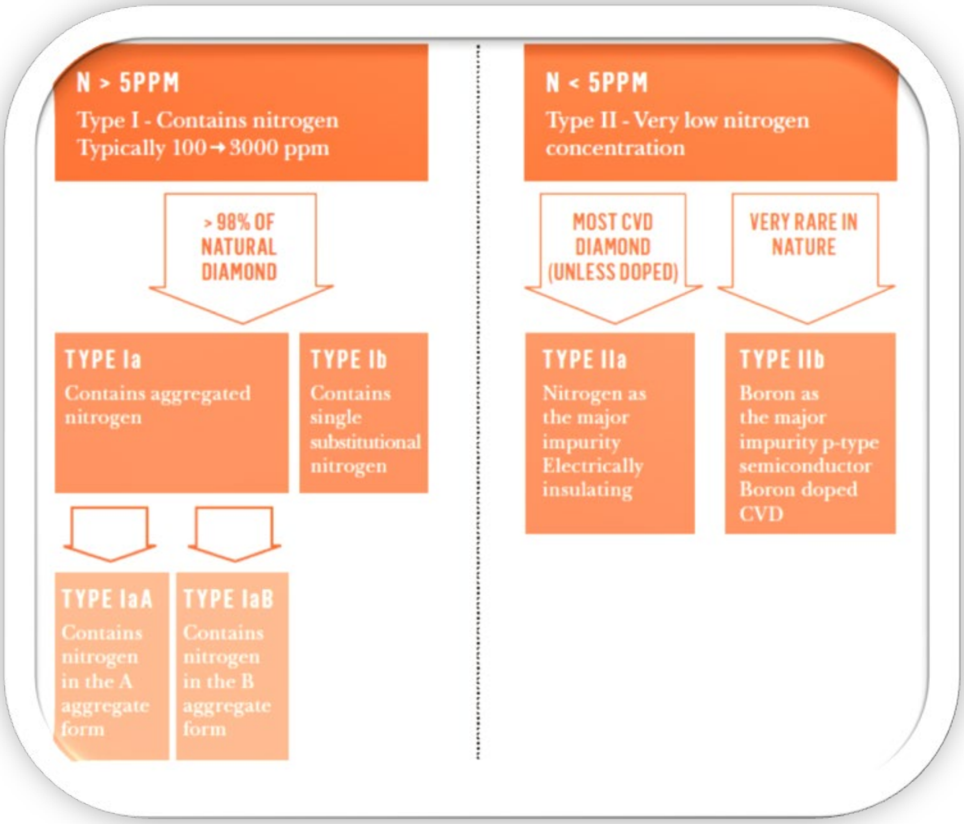


***Figure 11****: Diamond classification (courtesy of Element6).*

This historical table was established to distinguish the natural diamonds based on their optical properties. In fact, it also holds when non-optical properties are looked at, such as the fluorescence signatures and the IR and UV absorptions.

However, this table alone is no longer sufficient: diamond growth, especially with CVD technology, has become increasingly complex and now allows the tailoring  the material’s characteristics for optical, thermal, mechanical, electrochemical or electronic applications. An idea of this complexity is represented by adding a dimension to the previous table, according to the size of the crystallites.

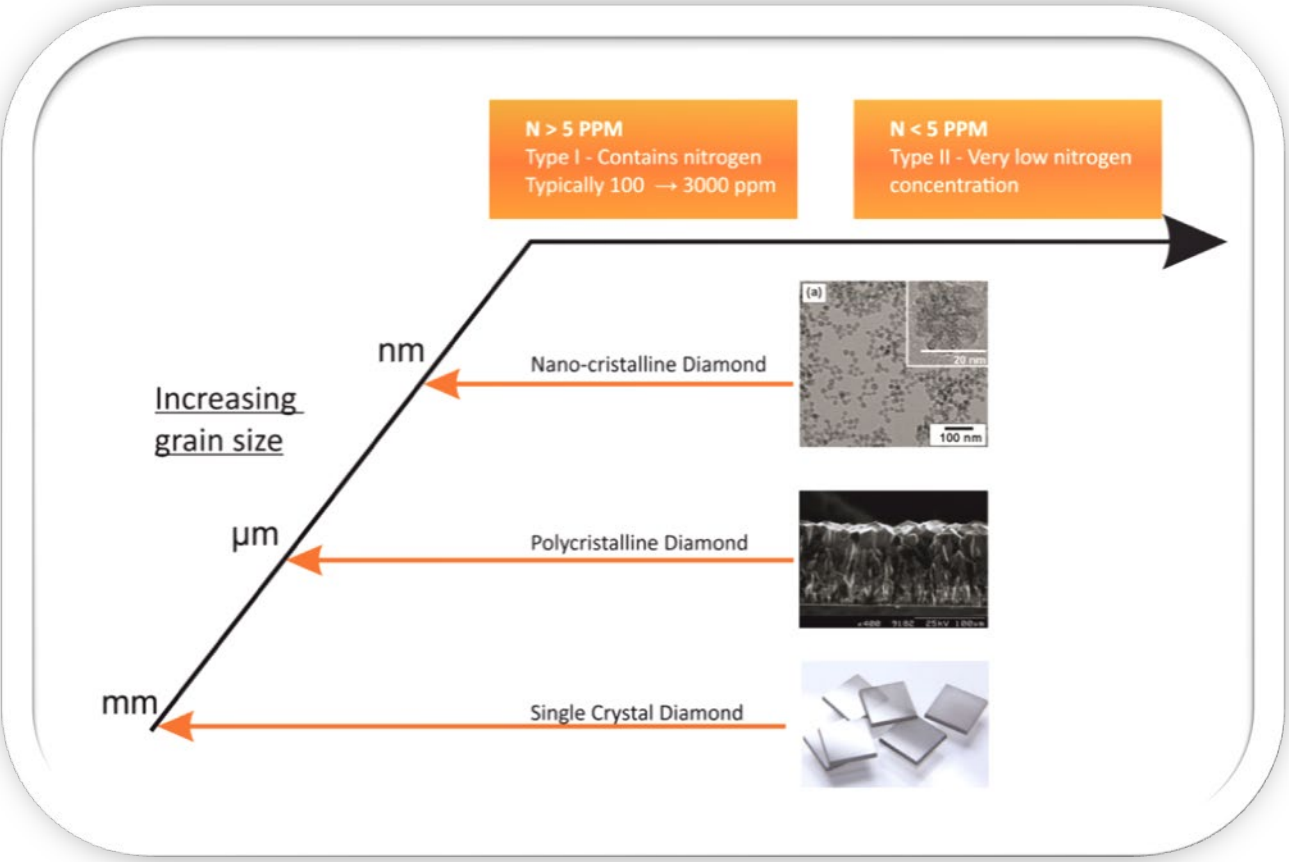


***Figure 12**: CVD diamond is a complex material that can be engineered to suit a wide range of applications. At Micron Semiconductor Limited, we work mainly with single crystal and polycrystalline CVD diamonds.*

Unlike silicon, where the entire wafer is always a single crystalline structure, CVD diamond plates can be made of smaller monocrystalline grains grown together. The size of these grains, or crystallites, can also be used to classify the diamonds: nanocrystals have grains of size < 50 nm, microcrystalline diamonds (more commonly called polycrystalline diamonds) have grain size between 50 and 500 nm, and monocrystalline diamonds (more commonly called single crystal diamonds) have a uniform structure similar to silicon.

For the purpose of radiation detection, we will focus on the most appropriate type of diamond, the type IIa, polycrystalline and monocrystalline, with low impurity concentration and low defect density.

***Figure 13****: Left – At the macro scale and under natural light single crystal and polycrystalline diamonds are indistinguishable (courtesy of Element6).*

*Right –Polycrystalline diamonds are made of individual grains, the boundaries of which act as deep defects.*

Polycrystalline diamonds (PC) and single crystal diamonds (SC) look the same by eye, but the crystallites can easily be seen with a polarising microscope.

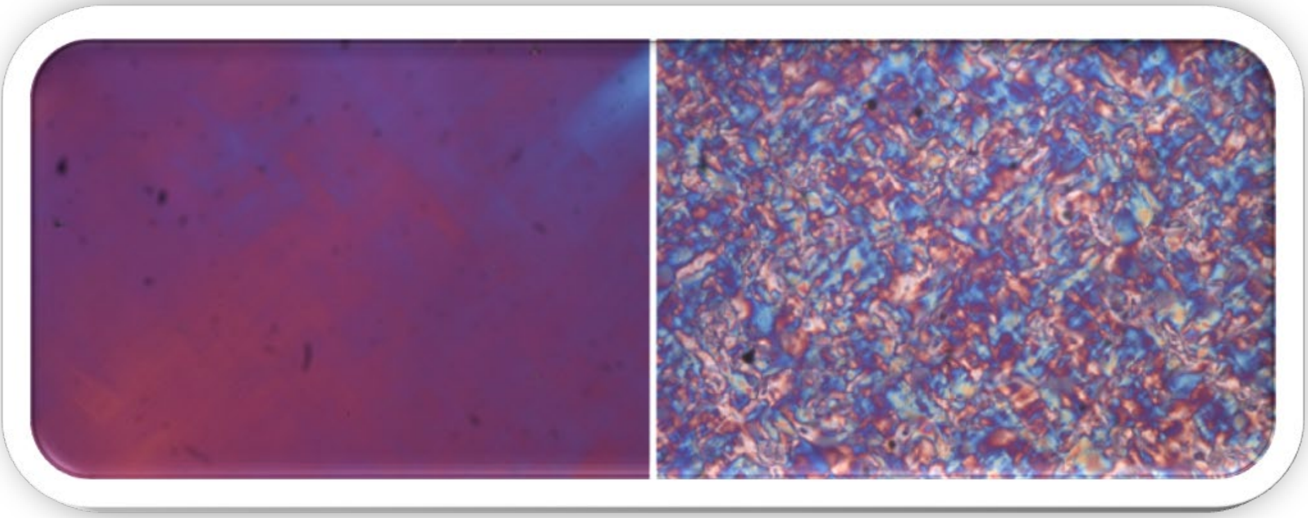

***Figure 14****: Under polarised light, the difference between single crystal (left) and polycrystalline (right) diamonds are clear.*

PC and SC diamonds also differ in their available sizes: while PC can be grown in wafers up to an approximate diameter of 120 mm, SC are, for the moment, grown to a finished size of 4.5 x 4.5 mm. The requirements of homogeneity and purity for type IIa SC still constrain the growth size. However, MSL has developed solutions to tile several such SC and thus increase the total sensitive area (see our **Design Service** and **Examples of our designs**).

It could seem that the larger surface areas available for PC diamonds make this type more attractive for applications requiring a large detector. However, the microstructures created by the grains often prevent such uses. Overall, the appropriate type of diamond is defined by the application itself.

# Diamond Sensor Applications

The detection of radiation is a generic expression that covers a wide range of purposes. This section aims to give an idea of which type of diamond should be used for which type of application.

**Diamond as a Radiation Sensing Material**

Diamond is a wide band-gap semiconductor that displays a large number of properties that are key to the detection and the measurement of radiation in challenging environments:

- Its large band-gap and high thermal conductivity make for a low-noise device that can be operated at room temperature, or even at high temperature, without the need for cooling.

- Its large displacement energy (43 eV) makes it radiation hard.

- The band-gap value of 5.47 eV translates into a wavelength of 225 nm: pure diamond is insensitive to visible light. We say that diamond is naturally solar-blind, hence it doesn't need to be operated in darkness.

- Made of almost only carbon atoms, its atomic number is very close to the average composition of the human body. This property, added to its chemical inertness, makes diamond an excellent candidate for safe and precise radiological and medical diagnostic application.

- Its high carrier velocity and resistivity, coupled with a low capacitance, allow for a very fast signal collection.

The table below lists the most relevant properties of diamond. Such tables often compare diamond to silicon, a widely used and studied material. While such comparisons are useful to understand the potential of diamond among other materials, one must keep in mind that their range of applications are very different. The larger available surface areas and smaller band-gap make silicon a more interesting option for large, sensitive detectors (but that require cooling), whereas the diamonds are naturally better suited for more challenging operating conditions such as highly radiative or high temperature environments.

| property | Diamond | Silicon |
|---|---|---|
| band gap *[eV]* | 5.47 | 1.12 |
| breakdown field *[V.cm$^{-1}$]* | 1 - 2 x $10^{7}$ (*) | 3 x $10^{5}$ |
| intrinsic resistivity *[Ω.cm]* | ~ $10^{12}$ | 2.3 x $10^{5}$ |
| electron mobility *[cm$^{2}$.V$^{-1}$.s$^{-1}$]* | > 2 000 (*) | 1 350 |
| hole mobility *[cm$^{2}$.V$^{-1}$.s$^{-1}$]* | > 2 000 (*) | 480 |
| saturation velocity *[cm$^{2}$.s$^{-1}$]* | 2 x $10^{7}$ | 0.8 - 1 x $10^{7}$ |
| density *[g.cm$^{-3}$]* | 3.51 | 2.33 |
| average atomic number | 6 | 14 |
| dielectric constant | 5.68 | 12 |
| displacement energy *[eV]* | 45 | 13 - 20 |
| thermal conductivity *[W.m$^{-1}$.K$^{-1}$]* | > 2 000 | 150 |
| energy to create e-h *[eV]* | ~ 12 | 3.63 |

(*) for single crystal diamond

***Figure 15:*** *Electronic properties of diamond and silicon.*

**Radiation**

In its most general definition, radiation is the way energy is transported through space. This energy can take the form of particles or waves (electromagnetic, acoustic or gravitational). Diamond is sensitive to a large range of particles as well as electromagnetic waves, i.e. photons.

Radiation occurs in the natural world (such as natural radioactivity or in space) as well as in man-made situations (for example, in nuclear plants, scientific research facilities or in medical equipment).

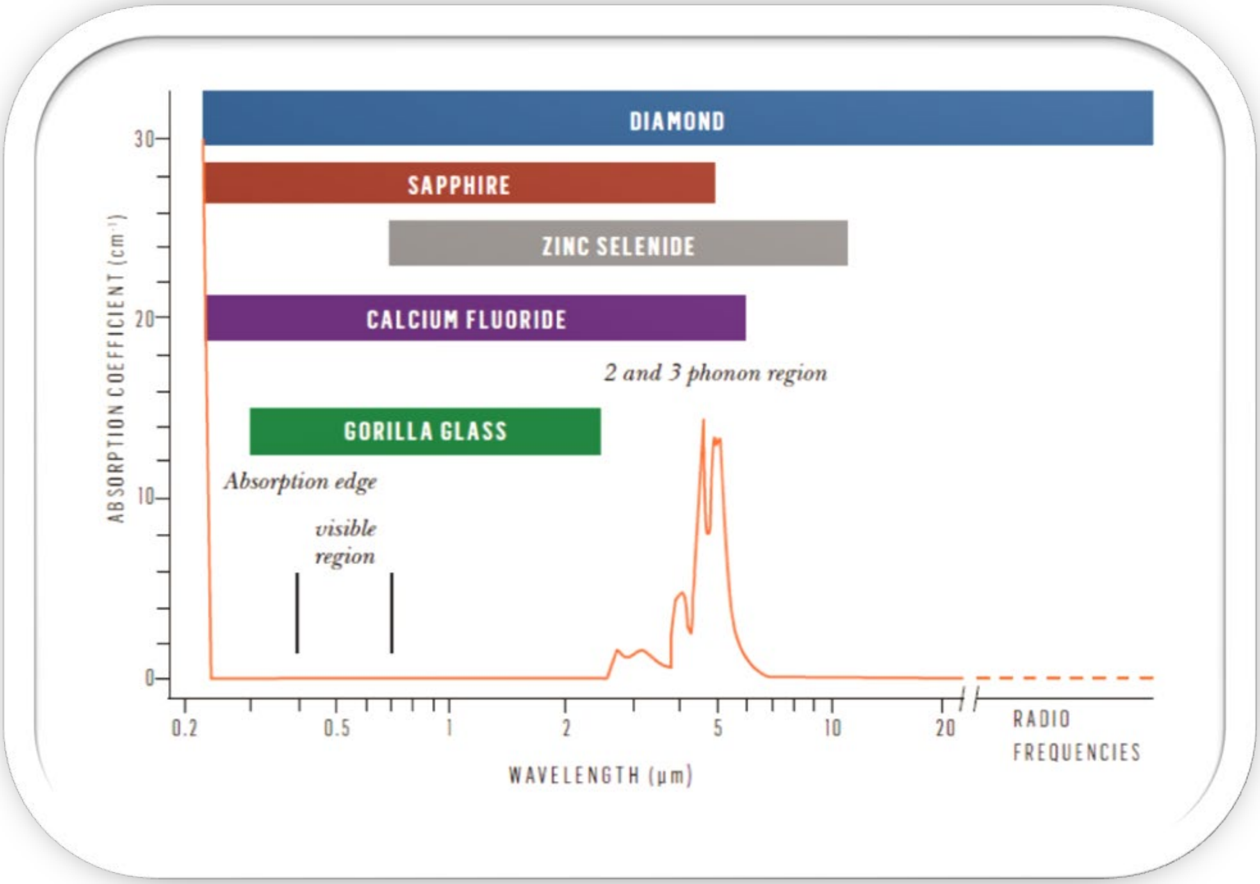


***Figure 16:*** *Absorption spectrum of several materials, including diamond. Diamond is naturally transparent to visible light but will absorb UV photons below 225nm. This feature is of particular interest to many space applications (Courtesy of Element6).*

Diamond is a good material for the detection of most charged particles (ions, protons, electrons, muons) as well as a few notable neutral particles (neutrons and UV photons).

## Measurements

Depending on the context, radiation can present several interesting characteristics that one may wish to measure, such as:

- The energy
- The time of impact or duration
- The number of hits
- The current generated
- The position…

All these properties can be measured by a diamond sensor, provided it is designed appropriately. As a general rule, the measurement of an energy requires a high purity, homogeneous material. For these types of applications the appropriate material is single crystal diamond.

For other applications, the material of choice will depend on the nature of the radiation to measure and its intensity (whether it takes the form of a stream of well separated single particles or a beam), as well, of course, as the purpose of the measurement and the possible background radiation present in the immediate environment. These will also heavily influence the design of the sensor itself.

***Figure 17:*** *Plasma fusion aims to recreate and control the fusion reactions taking place in the sun. These could become the next source of energy for humanity. CVD diamond detectors could help thanks to their radiation and temperature resistance. (D111-D vacuum vessel, R S Wilcox CC BY-SA-1.0)*

Diamond can be utilized in a wide number of fields, amongst others:

- High energy physics: beam monitoring and positioning in synchrotrons or colliders; heavy ions experiments...

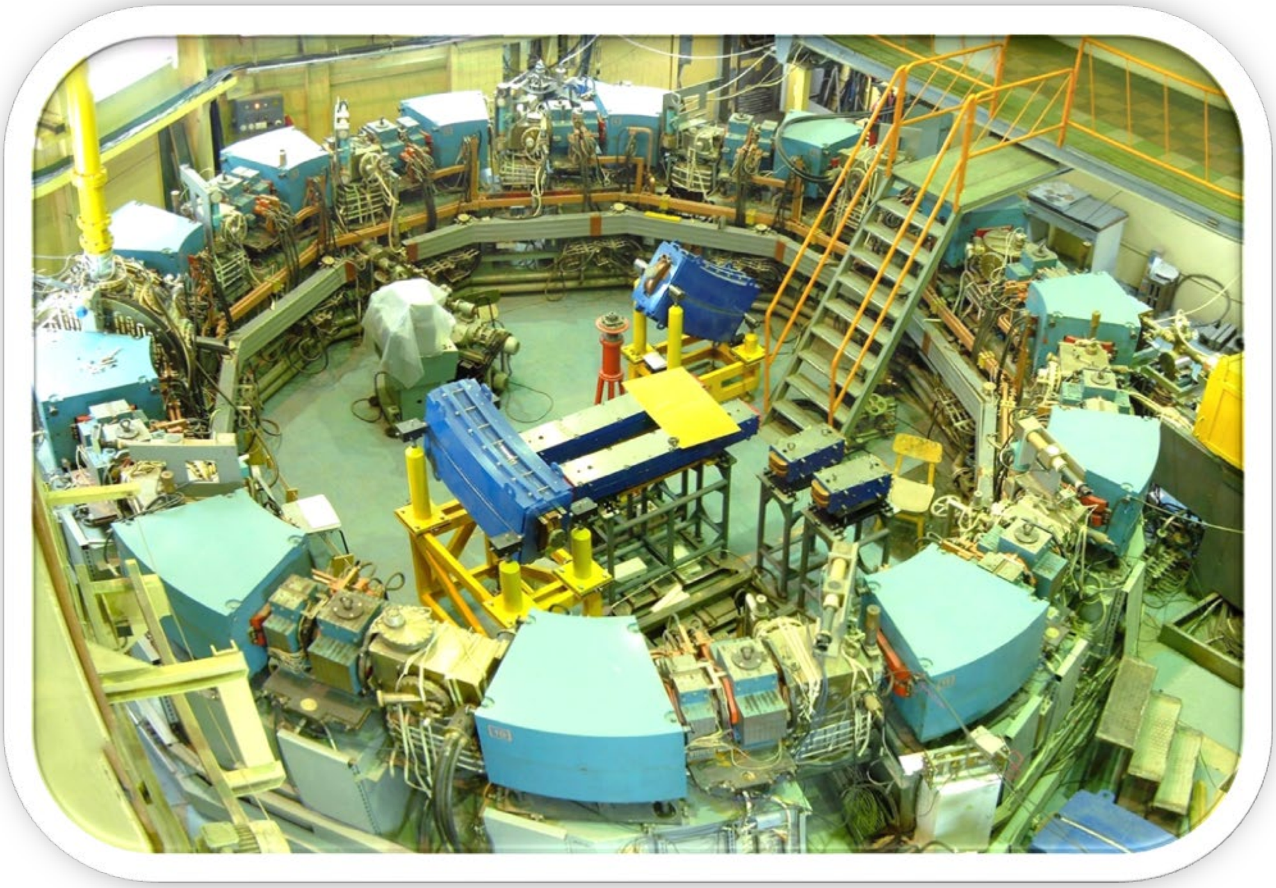

***Figure 18:*** *BEP — booster of electrons and positrons at VEPP-2000 collider complex (BINP, Novosibirsk). Energy ranges from 100 to 900 MeV (Eto Shorcy, CC BY-SA 3.0).*

- Dosimetry: radiation therapy, equipment calibration, active exposure monitoring…
- Nuclear applications: neutron detection for security or exploration purposes, fusion energy…

***Figure 19:*** *Micron Semiconductor Limited manufactures sensors capable of functioning under a high level of mechanical stress (vibrations and shock), which allows the operation of diamond detectors in challenging environments such as gas exploration and drilling. (Nestor Galina CC BY 2.0)*

- Space exploration: solar physics, exploration of the solar system...

***Figure 20:*** *The small size of CVD diamonds coupled with their radiation hardness can be a significant advantage where space is limited, such as in a satellite or exploration probe. (GOES-8 NOAA Photo library, public domain)*

# Our Fully Personalized Design Service

Micron Semiconductor Ltd offers the greatest level of flexibility in detector design and a fully-personalized design service. This section lays out our methodology.

### What's in a Detector?

A radiation sensor, or detector, is made of the following three components, equally crucial:

- The sensitive material, here high purity diamond. It is patterned with a metal electrode in order to extract the signal created within its bulk.
- A package, such as a printed circuit board onto which the diamond is connected, and if necessary, a protective casing.
- Connectors, for example cables, SMA or BNC connectors, pins...

Several standard solutions exist for these three elements, but different applications often carry different constraints, for example available space and/or power or operating conditions. Our design service aims to find the best combination for a given application.

***Flexibility**:*
*We can also supply non-assembled diamond sensors or mount them on customer-supplied printed boards. Feel free to discuss these various options with us.*

1. We start with a free, in-depth discussion about the application. This is an essential step to ensure optimal integration of the diamond sensor with the existing instrumentation in the user's set-up. For example, space and access can be limited around the sensor (as in a satellite), or it might be necessary to use specific connectors to plug the device in the acquisition chain.

   The more information we can gather at this stage, the better. We can advise on the most suitable design and on the potential performance of the sensor. We will also look into the feasibility and the suitability of the solutions.

2. When sufficient information has been gathered, we present a technical and financial proposal. We often include options with various advantages and compromises to facilitate the decision-making process.

3. Once a formal agreement is reached, we develop the design and, if necessary, iterate according to the customer's feedback. This suite of proposals will offer and explain the design of the diamond sensor itself (type, dimensions, thickness, electrode nature and pattern…) as well as that of its packaging and connector(s). The manufacture starts once one of the designs is formally approved by the customer.

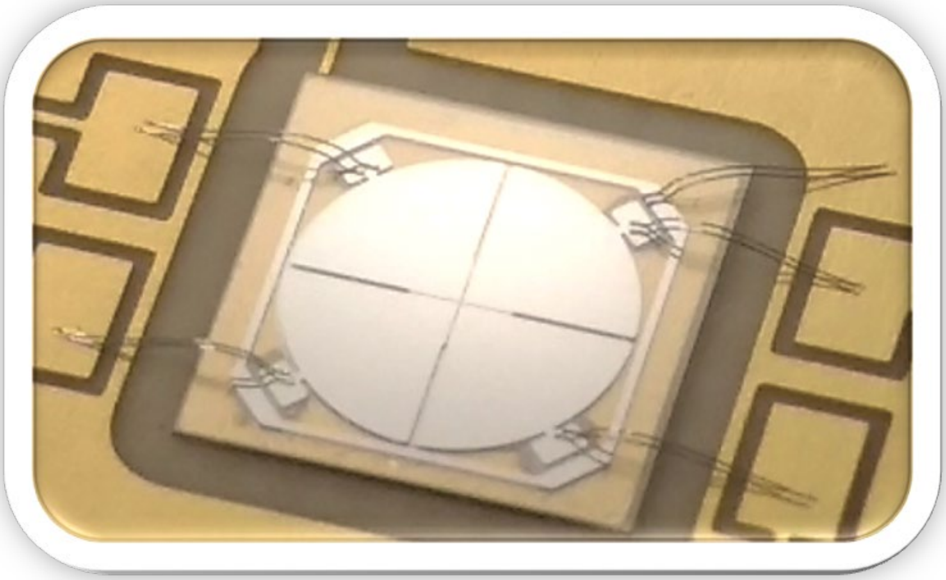

***Figure 21**: Example of a quadrant beam monitor designed and manufactured at Micron Semiconductor Ltd, and assembled by Micron Semiconductor Ltd on a customer-supplied PCB.*

## Scientific Collaborations: Help Us to Help You

Innovation comes equally from ourselves and our many academic customers. Since its creation in 1983, Micron Semiconductor Ltd has nurtured a wide, multidisciplinary R&D ecosystem with worldwide partners.

Today, more than ever, strong relationships are essential to the continuous development of a product as specialized as a diamond sensor. The growing complexity of their operating environments and performance requirements often necessitates a one-of-a-kind solution. For these applications, a new design may not be sufficient. Iterations on the design or specific tests may be required, that neither the end-user nor Micron Semiconductor could conduct on their own. In that context, partnerships have proven to be an effective time- and cost-saving option for both parties.

Contact us for a free consultation about your project to see if it could qualify for a partnership.

# Examples of Solutions

This section introduces a selection of our board and case designs. We are always designing and manufacturing new solutions, capable of housing one or several CVD sensors of various dimensions.

## Packaging

The diamond sensors can be assembled on standard or custom-made packages. The majority of printed boards are made from ceramic (96% alumina) for operation in ultra-high vacuum environments. They are made with gold-free contacts and can be supplied as transmission packages with a custom-diameter through-hole. The cases are usually aluminium, bare or gold-coated. In addition, various FR4 or ceramic board shapes and sizes are available, as well as the entire range of Micron Semiconductor Ltd packages.

***Does your application require a different solution to what you see here?*** *We can design and manufacture it. Please refer to the* ***Design Service*** *section for more details, and get in touch for a free consultation.*

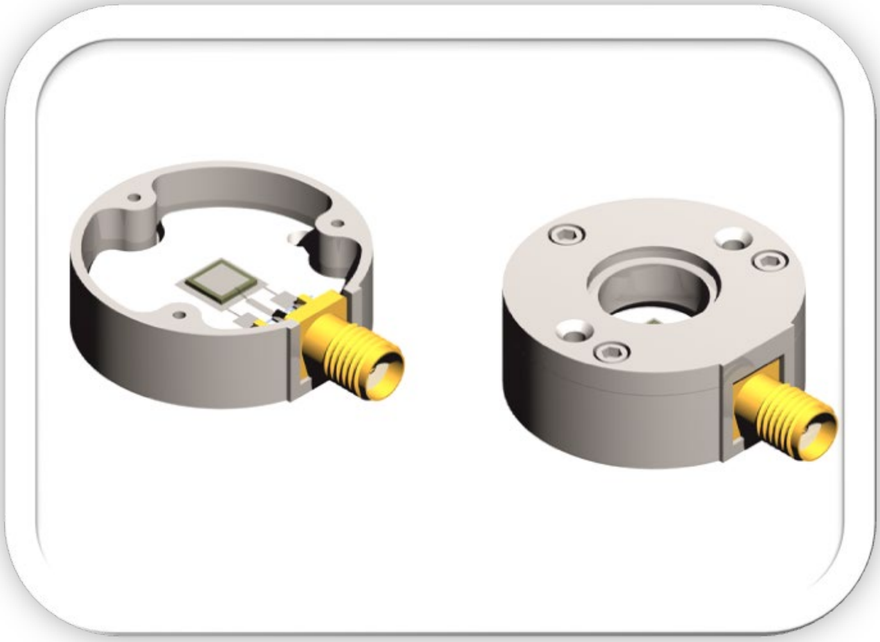

***Figure 22:*** *Our most versatile design, MSL-DD-01, is a transmission ceramic board in a light aluminium casing with a coaxial SMA connector. This is usually the favoured option for exploring the potential of diamond detectors for various spectroscopy or timing applications.*

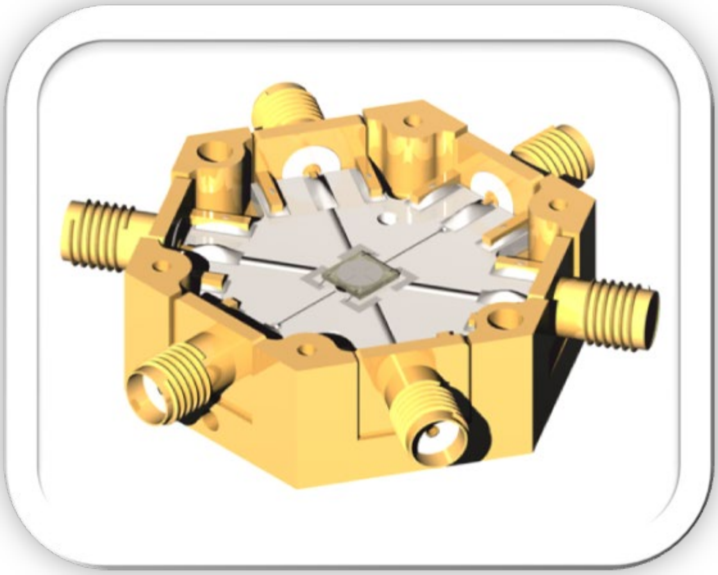

***Figure 23:*** *MSL-DD-04 is a quadrant diamond detector designed and made by Micron Semiconductor Ltd. The versatility of the board and casing designs allows for the accommodation of CVD diamonds of different sizes and thicknesses.*

### Connectors

The compact SMA connector tends to be the favoured solution for use in limited spaces. Other connectors, such as TNC, BNC coaxial, triaxial connectors or pins, are available on request.

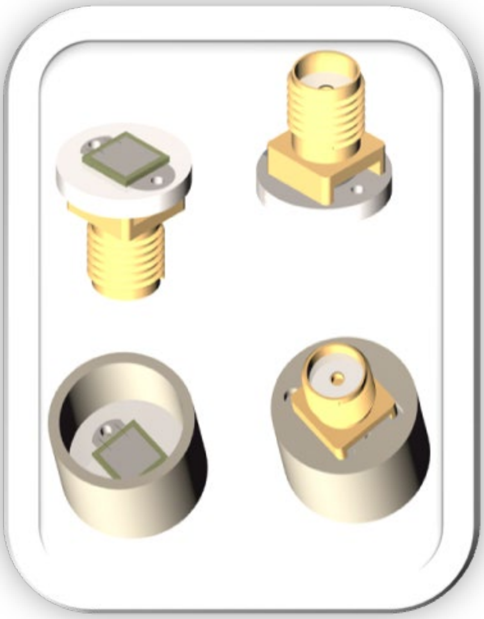

***Figure 24:*** *The design MSL-DD-07 is one of our most compact solutions with an SMA connector. The casing can be fully closed to protect the detector.*

**Chip only**

For users wishing to assemble devices themselves, we can supply the metallized diamond sensors only.

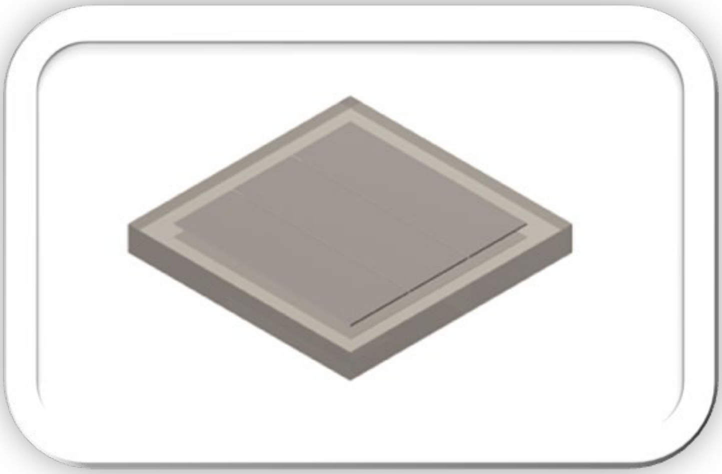

***Figure 24:*** *CVD diamonds of the required dimensions, thickness and quality can be cleaned and metallized at Micron Semiconductor Ltd and then sent to customers to use unassembled or to assemble themselves.*

## Mosaic Designs

The current limitations on the diamond dimensions should not be a limitation on the project. For those that require a large sensitive surface area, we can design and provide a “mosaic”, in which several diamond sensors are tiled on a single board. One or several output channels are available, depending on the application.

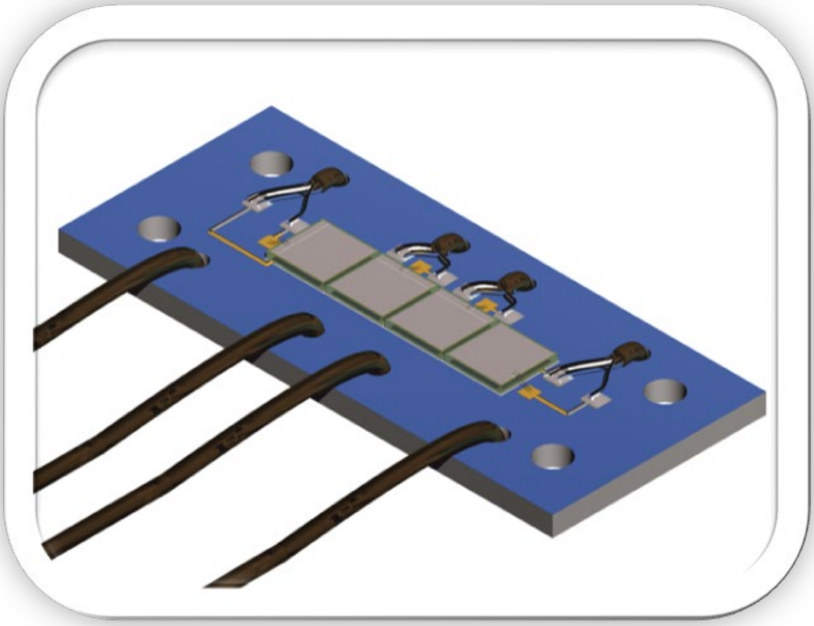

***Figure 25:*** *The MSL-DD-09 design can hold up to four 4.5 x 4.5 mm CVD diamonds connected in parallel. This space-qualified board features a strain-relief cable mounting.*

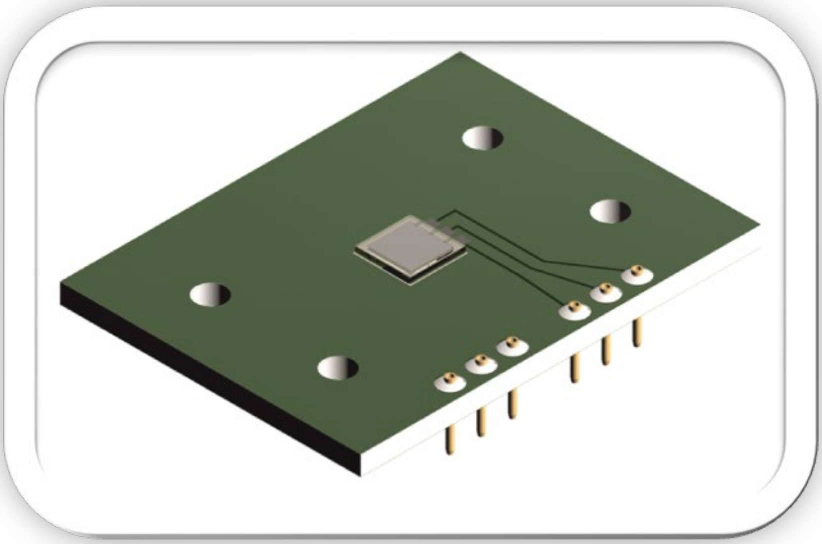

***Figure 26:*** *MSL-DD-10 Strip design allowing a beam positioning in X and Y due to orthogonal strips on each face of the single crystal diamond*

**Assembly**

We can also assemble our devices on customer-supplied printed boards.

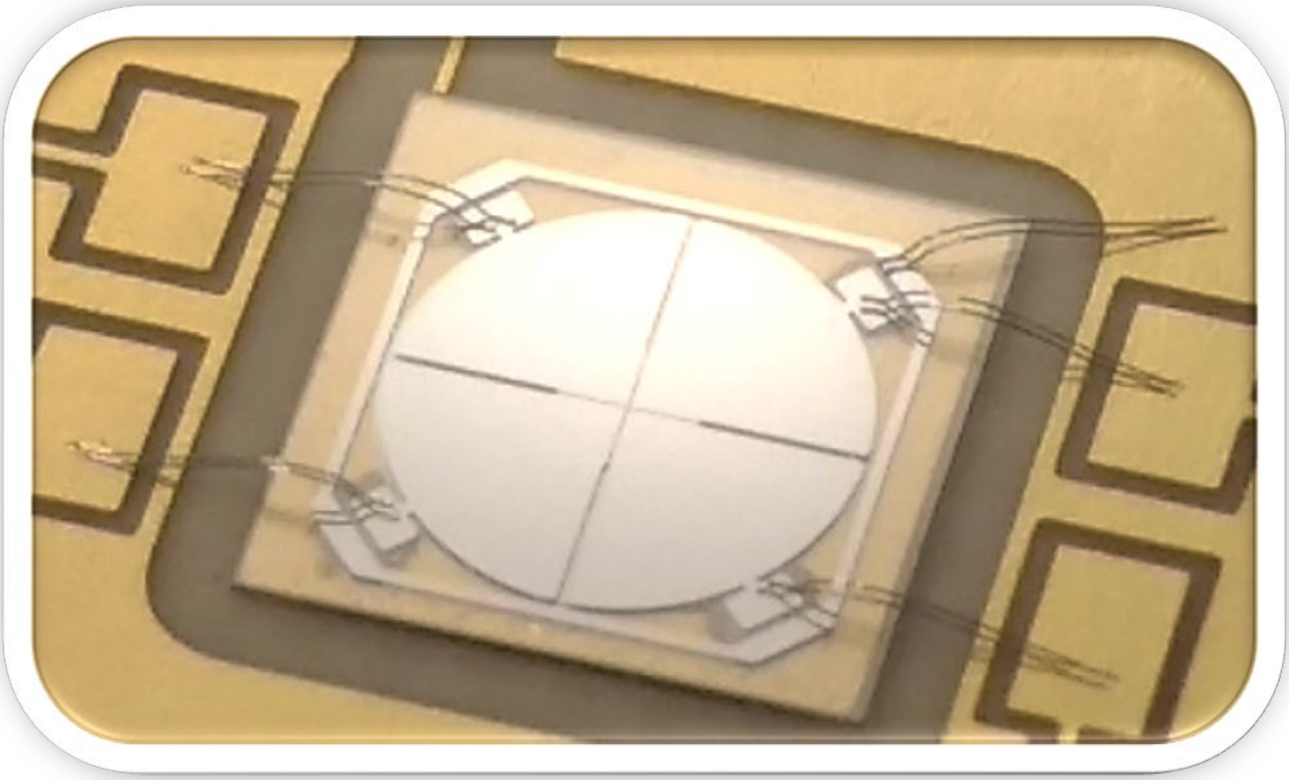

***Figure 27****: Example of a quadrant beam monitor designed and manufactured at Micron Semiconductor Ltd, and assembled by Micron Semiconductor Ltd on a customer-supplied PCB. This design can also be assembled on the MSL-DD-04 board*

# Appendix – Contact Form

## Micron Semiconductor Ltd

### Quotation Request Form

***This form aims to be a basis for discussing your project with Micron Semiconductor Ltd. Please fill in to the best of your knowledge and send it to us at diamond@micronsemiconductor.co.uk.***

| YOUR DETAILS | | | |
|---|---|---|---|
| **Customer name** | | **Project or Tender ID** | |
| Customer e-mail | | Tender Deadline | |

| YOUR APPLICATION | |
|---|---|
| **Request** | CVD dimensions: |
| ☐ CVD diamond only, bare (not metallized) | CVD thickness: |
| ☐ Metallized CVD diamond, not assembled | Number of items: |
| ☐ Metallized and assembled CVD diamond device | Delivery schedule: |

| **Measurement** | | |
|---|---|---|
| ☐ Energy<br>☐ Time<br>☐ Counting<br>☐ Current | ☐ Protons or ions<br>☐ Electrons / beta<br>☐ Neutrons<br>☐ X-rays<br>☐ UV | **Energy Range** |

| **Constraints** | ***Please specify for applicable constraints*** |
|---|---|
| ☐ Limited available space: | |
| ☐ Limited available power: | |
| ☐ Space project (satellite or other): | |
| ☐ Operation in high temperature: | |
| ☐ Operation in high radiation environment: | |
| ☐ Other: | |

**Please detail any additional information or question relevant to this project:**

# Micron Semiconductor Limited

MICRON SEMICONDUCTOR LIMITED

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