Jörg Wrachtrup

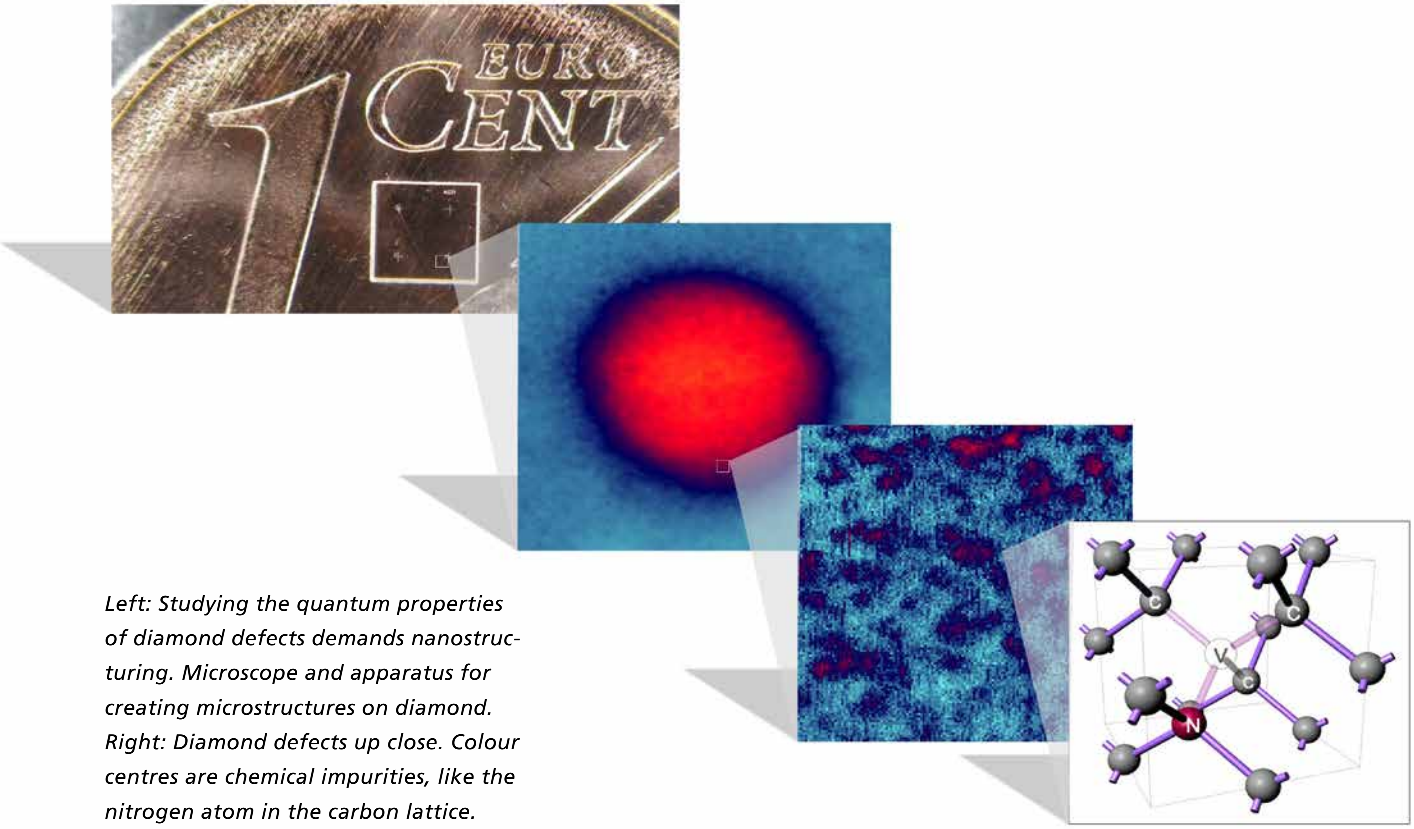
Goodbye Carats, Hello Quanta

The properties that make diamonds so spectacular as precious gems also give them incredible applications in quantum technology. A Research Unit is investigating the basic characteristics of diamond in quantum physics and opening up new avenues in semiconductor technology, quantum information processing and medicine.

When most people look at a diamond, they admire the numerous optical reflections on the facets of the polished stone. Recently, however, quantum physicists, material scientists and chemists have become curious about the quantum nature of this material and in particular the defects within diamonds. The Research Unit "Diamond Materials for Quantum Applications", made up of teams in Stuttgart, Freiburg, Ulm, Mainz, Leipzig, Munich, Berlin, Saarbrücken and Würzburg, is exploring the extraordinary properties of diamond and seeking to exploit them in quantum science.

Pure diamond is made of carbon. The low mass of carbon atoms and their strong chemical bond in a

Illustration: Lehrstuhl Wrachtrup



Left: Studying the quantum properties of diamond defects demands nanostructuring. Microscope and apparatus for creating microstructures on diamond. Right: Diamond defects up close. Colour centres are chemical impurities, like the nitrogen atom in the carbon lattice.

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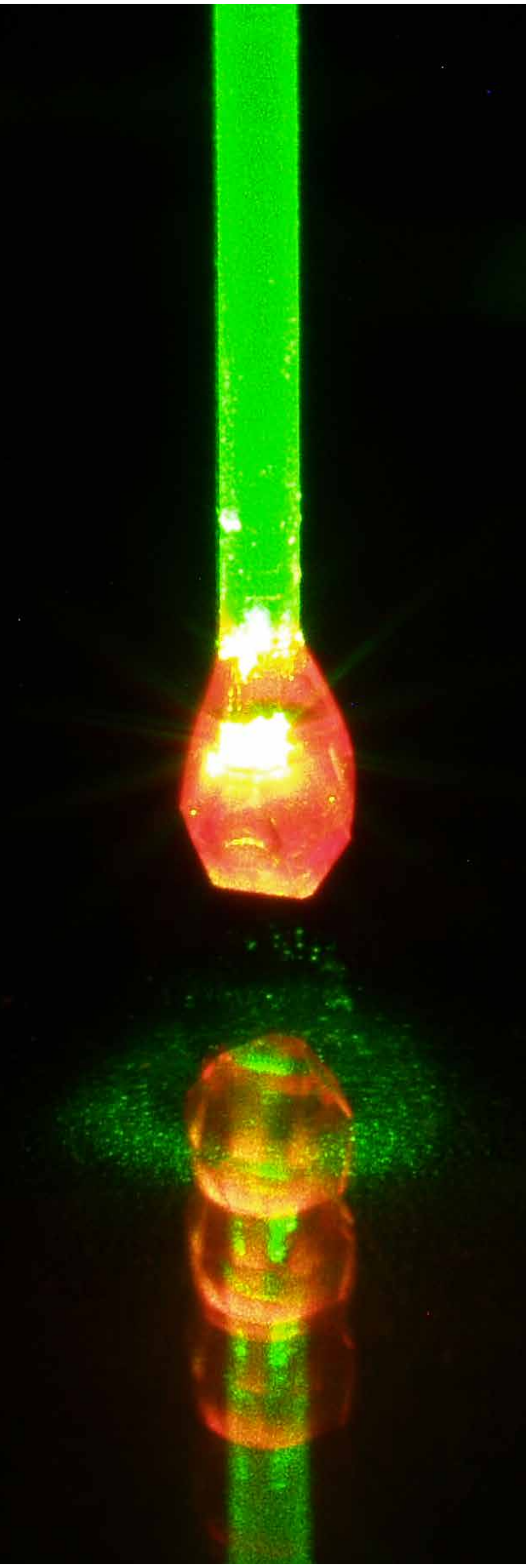
crystal lattice make diamond crystals one of the hardest materials known and also make the material optically transparent. Another remarkable property, a high index of refraction, causes light to be reflected from the surface. The result is the familiar sparkle that gives the gemstone its brilliant fire in the hands of a skilled cutter. A pure diamond appears absolutely colourless; a relatively small amount of impurities lends it colour and usually makes it especially valuable. The colour of the diamond depends on the chemical characteristics of the atom that has become incorporated in the lattice. Around 50 different types of atom can be introduced into a diamond lattice, giving a whole palette of coloured diamonds.

For the work of the Research Unit it is especially important to be able to manufacture artificial diamonds of high purity using different processes. In one method that has proved especially effective for technical and scientific purposes, the diamond is precipitated from the gas phase – to be precise a mixture of hydrogen and methane. This technique can be used to manufacture diamonds of almost any shape and size. For quantum physics research, this means it is possible to make diamonds of any given purity and introduce the desired impurity atoms. This is an essential requirement for the many uses of diamonds in quantum physics. The research team in Freiburg is working to produce exceptionally pure diamonds, which are then made available to the other teams in the unit.

One of the main challenges of working with diamonds in quantum technology is the controlled placement of the impurity atoms. This process, known as "doping", demands an accuracy to within 10 nanometres. Researchers in Mainz and Leipzig have achieved considerable expertise in this area. Using various methods, they are now able to place individual defect atoms in the crystal lattice of the diamonds delivered from Freiburg with an accuracy of just a few nanometres.

The team in Mainz first catches the impurity atoms in an ion trap in order to implant them in the diamond. In Leipzig, scientists are



using metal films with tiny holes to position impurity atoms precisely in the diamond. Both technologies are of great interest in semiconductor technology. Doping, the insertion of the impurity atoms, also plays a decisive role in the function of electronic components such as transistors. As components get ever smaller, their functionality increasingly depends on the precise placement of the foreign atoms.

The defects introduced to a diamond must be carefully embedded in control structures to allow the results of the quantum manipulation to be evaluated. In Berlin, Munich and Saarbrücken, researchers are therefore developing special structures that alter the optical properties of diamond in order to effectively manipulate the defects.

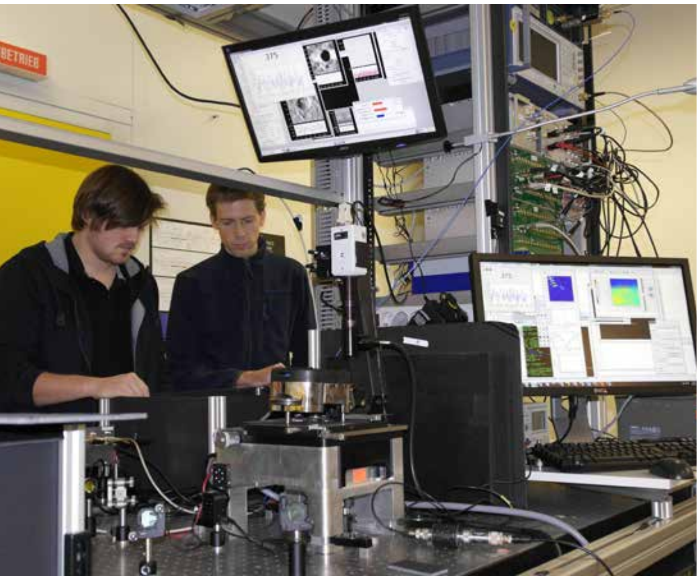
In a classic semiconductor chip, individual electronic elements are manipulated in a complex integrated circuit using control electrodes, and the intention is to do the same with individual defects in diamond. In diamond technology this is still difficult owing to the extremely small dimensions required in the control structures. Diamond is also an exotic material in semiconductor technology, with a range of physical principles still awaiting investigation in terms of nanostructure engineering. With this goal in mind, the group in Munich is seeking to create transistor structures and semiconductor nanostructures on diamond surfaces, and then supply these to the teams in Ulm, Stuttgart, Berlin and Saarbrücken to pursue their own avenues of research.

The colour centres in a diamond crystal make the diamond glow red under green laser light.

The main reason that diamond is so attractive in quantum research is that it can be studied by means of relatively simple experiments. Most quantum experiments require precautions such as low temperatures or ultra-high vacuums. Because of its hardness and chemical composition, the diamond lattice protects the defects inside it very effectively against environmental influences, allowing the atomic impurities to be observed reliably for long periods of time without major experimental precautions. If the diamond only contains a few colour centres, a fluorescence microscope is sufficient to view the individual impurity atoms in the diamond lattice.

Another factor that is important to research and technology applications is the fact that specific quantum states can be achieved on the defects. Researchers can control the material by manipulating the magnetic moment of the electrons in the defects. Magnetic moment, or to be more precise the spin of the electron or nuclei, is either parallel or antiparallel to an external magnetic field. If the direction of the field changes, the spin follows suit.

This mechanism has a possible application in quantum information processing. Researchers are attempting to exploit quantum mechanical effects in order to process information extremely effectively. The Research Unit is using the electrons and nuclei of defect centres as quantum bits, the value of which is determined by the orientation of the spin: a parallel orientation to the magnetic field



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Above: Doctoral researchers Thomas Häberle and Thomas Öckinghaus working with a diamond magnetometer. Right: Laser spectroscopy is an essential tool in any laboratory where researchers work with diamond defects.

represents 1 and an antiparallel orientation represents 0. To exploit the full potential of quantum information processing, quantum bits must exist in a state that can be both 1 and 0. This coherent superposition is one of the effects used in quantum information processing, for example to develop highly effective search algorithms. This effect is labile, and can be converted very quickly into the other state, whether parallel or antiparallel to the magnetic field, by lattice vibrations. But the exceptional hardness of diamond means that there are few lattice vibrations that could influence these superposition states. The research teams in Ulm and Stuttgart are exploiting this special quality of diamonds to try and utilise the defects for quantum information processing.

One field of diamond quantum technology that is attracting a lot of attention is sensor applications. The team in Stuttgart discovered some time ago that diamond defects are extremely sensitive sensors for magnetic fields on the nanoscale. Interestingly, these sensors achieve their sensitivity under normal environmental conditions, giving them possible applications in the life sciences. Other members of the Research Unit have since demonstrated that diamond defects are also sensitive sensors for temperature and electrical fields.

To use the defects for these purposes, they are packaged in very small diamond crystallites measuring just a few nanometres across. The members of the research team in Würzburg are world-leading experts in the production and chemical modification of nanodiamonds. These nanodiamonds are made by grinding up large diamonds doped with colour centres in Freiburg. Particles of suitable size are selected from the ground material and then chemically modified. Nanodiamonds are now much in demand worldwide because they have so many uses – for example as sensors for cellular or medical examinations. By carrying out basic research in both physics and materials science, the Research Unit is delivering results that are of direct interest both in quantum physics and in a range of practical applications.

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