Laboratoire des Sciences des Procédés et des Matériaux – UPR 3407.
Institut des Sciences de l'Ingénierie et des Systèmes (INSIS)

PhD subject:	**Study of hydrogen impurities and stress in CVD diamond films containing NV colour centres for quantum technologies**
Laboratory:	**Laboratoire des Sciences des Procédés et des Matériaux (LSPM – UPR 3407)**
Teams:	**Diamant et Matériaux Carbonés (DMC)**
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Nitrogen-Vacancy (NV) centres in diamond are one of the most promising solid state systems for applications in quantum technologies because of the possibility of manipulating and optically reading their electronic spin state, even at room temperature. They could thus enable the creation of ultra-sensitive, high-performance and innovative sensors (gyroscopes, spectrum analysers, magnetic imaging, etc.) which would find direct applications in the field of quantum communications, cryptography, or would enable the development of innovative components for microwave chains and inertial sensors. Recently, a continuous emission MASER (microwave laser) operating at room temperature has been demonstrated using a diamond crystal in which a very high density NV centre has been created. Finally, applications such as NMR could also benefit from the properties of this specific defect.

But for such applications, it is necessary to have diamond films of very high crystalline quality in which the density, environment, orientation and spatial location of the introduced coloured centres are perfectly controlled. Thanks to Plasma-Assisted Chemical Vapour Deposition (PA-CVD), a reproducible material of unequalled purity (< 1ppb nitrogen) is now available in which even the ^{12}C isotopic concentration can be controlled, making it possible to achieve record coherence time values close to 2.5 ms[1].Most of the NV-based quantum devices developed rely on the progresses achieved in the material synthesis , which can be described as a "**key enabling technology**". The Diamond and Carbon Materials team of the LSPM laboratory (UPR 3407 of the CNRS) is particularly well identified in the international scientific community for the development of innovative manufacturing diamond processes allowing the synthesis of a material that largely fulfils these requirements[2],[3],[4]. Obtaining high

[1] E.D. Herbschleb et al. Ultra-long coherence times amongst room-temperature solid-state spins, Nature Communications, 10 (2019) 3766.
[2] J. Achard et al. Chemical vapour deposition diamond single crystals with nitrogen-vacancy centres: a review of material synthesis and technology for quantum sensing applications, Journal of Physics D: Applied Physics, 53 (2020) 313001.
[3] Horsley, A., et al., Microwave Device Characterization Using a Widefield Diamond Microscope. Physical Review Applied, 2018. 10(4): p. 044039.
[4] Tallaire, A., et al., Highly photostable NV centre ensembles in CVD diamond produced by using N2O as the doping gas. Applied Physics Letters, 2017. 111(14): p. 143101.

NV densities (> 100 ppb) is still difficult due to their low creation efficiency, but the recent development of post-treatment irradiation with either electrons or light ions such as helium, combined with optimised thermal annealing, has made it possible to considerably improve the yield and consequently their density[5]. However, the CVD growth process requires the use of a gas phase mainly composed of molecular hydrogen which can lead to the formation of numerous parasitic defects (NVH, VH...) that deteriorate the coherence properties. Moreover, the quantum quality of homoepitaxial films is also strongly dependent on residual stress that affects spin coherence times and reproducibility. Thus, the optimisation of growth conditions allowing to limit the formation of stress and defects is an extremely important issue, especially if we wish to address applications requiring dense ensembles of NV centres.

Thus, the main objectives of this thesis will be **to study the formation of point defects related to the presence of hydrogen in diamond films and to optimise the growth process of nitrogen-doped diamond in order to limit the occurrence of stress**. Specific studies will be carried out to: (i) evaluate the influence of the presence of hydrogen in diamond films and the interaction that this element can have with the NV centres. For this objective, we will use an ion implanter available at LSPM which will allow the controlled introduction (dose and depth) of hydrogen into the films previously doped with nitrogen. (ii) Determine the parameters which limit the appearance of stress during epitaxy. In particular, we will study the role of the input parameters of the reactor (gas phase composition, substrate temperature, microwave power etc.) and the influence of substrates used. The films will be characterised on the one hand at the LSPM by photoluminescence and cathodoluminescence, and on the other hand at IRCP - Chimie Paristech –Paris Sciences et Lettres (PSL) by ODMR and birefringence stress imaging.

This thesis will also be supported by funding obtained in the framework of the European Quantera project entitled MAESTRO (Mastering Technologies For Scalable Spin-Based Solid-State Quantum Processors). The objective of the project is to develop technological building blocks for the development of solid-state qubit architectures based on NV centres operating at room temperature. The PhD candidate will thus be able to rely on a strong network of European collaborations and will be able to visit different laboratories for specific measurement campaigns.

Profile and skills :

Master 2 or Engineering schools with majors in Material Sciences and/or Physics. Skills: Material synthesis, Material characterizations, Optics, quantum physics.

[5] M. Ngambou et al. Improving NV centre density during diamond growth by CVD process using N2O gas, Diamond and Related Materials, 123 (2022) 108884.