Todo list

Extra long title which spans serveral lines and therefore has to be split manually and the vertical spacing has to be adjusted

My Name

My university

(Diploma/doctoral...) Thesis

Supervisor:

Prof. Dr. Supervisor

Supervisor's Department, University of ...

March 2013

Abstract

A novel method... It is based on...

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Acknowledgements

First of all, I want to thank my supervisor...

I am very grateful for the guiding help of...

I am grateful to...

Chapter 1

Coupling Nanodiamonds to Photonic Structures

In the last chapter, we saw that the spectroscopic properties of SiV centers vary strongly among individual nanodiamonds. Nanodiamonds are further implemented in photonic structures for the application in metrology as well as in quantum cryptography or quantum computing. Therefore, it is important to have a good knowledge of the spectroscopic properties of the individual SiV center. A preselection of nanodiamonds including an SiV center with desired properties is performed. The selected nanodiamond is then transferred to target structures. In the scope of this thesis, nanodiamonds including SiV centers were coupled to two different kinds of structures:

think of other word

- Vertical-Cavity Surface Emitting Lasers: The aim is to create a hybrid-integrated single photon source, where an electric current is employed to create single photons. The diamond containing an SiV center is placed directly on the beam output. Hence the SiV center is directly pumped by the laser beam. This system is interesting for metrological applications, as it is the major building block for a portable device ready to calibrate single photon detectors.
- Plasmonic Nanoantennas: The aim is to enhance photoluminescence intensity. As described in previous chapters, not only ZPL position and linewidth, but also the photoluminescence intensity varies strongly among individual SiV centers. However, in metrology a photon flux rate high enough to be measured by a low optical flux detector is needed [**?**]. This increase in intensity is achieved by coupling the SiV centers in nanodiamonds to plasmonic antennas.

1.1 Additional Experimental Methods

To couple nanodiamonds to photonic structures, we pursued several different methods:

1. Directly spin-coat the structures with a nanodiamond solution and consecutively look for a structure containing a nanodiamonds with an SiV center exhibiting the desired spectroscopic properties. This method was tried with the antenna structures, as there are many antenna structures on one substrate (see Figure 1.10a), therefore there is a

chance that a suited nanodiamond is incidentally ends up at the right spot. However, it is not suitable for the VCSELs, first because of the morphology of the VCSELs and secondly, because there is a very limited number of VCSELs on one substrate.

2. Use an iridium substrate covered with nanodiamonds containing SiV centers, look for a suited nanodiamond and transfer it with a pick-and-place technique using a nanomanipulator. The nanomanipulator is essentially a thin tip in a scanning electron microscopy. The iridium substrate is prepeocessed with markers, to record the position of the preselected nanodiamond. The huge advantage is that the very best suited nanodiamond can be preselected. However, disadvantages of this process include the electron radiation during the pick-and-place process, which might affect SiV center fluorescence light and the further restriction that the nanodiamonds must be big enough to be picked up with the nanomanipulator.

3. Similar to method 2, however the transfer is performed with an atomic force microscope. While this method has the advantage that the nanodiamonds are not irradiated with electrons, the disavantage is that it is not possible to observe the picking process in real time. The area of the preselected nanodiamond has to be scanned after every pick-up try, which is very time consuming and therefore was not further pursued after some trials.

In the following paragraphs, the pick-and-place technique of method 2 is described in more detail. It is the coupling method most extensivly deployed in the scope of this thesis and requires a range of experimental setups. The pick-and-place process was carried out with major help from C. Pauly, group of xxx Mücklich, Saarland University. The nanomanipulator setup was provided by the same group.

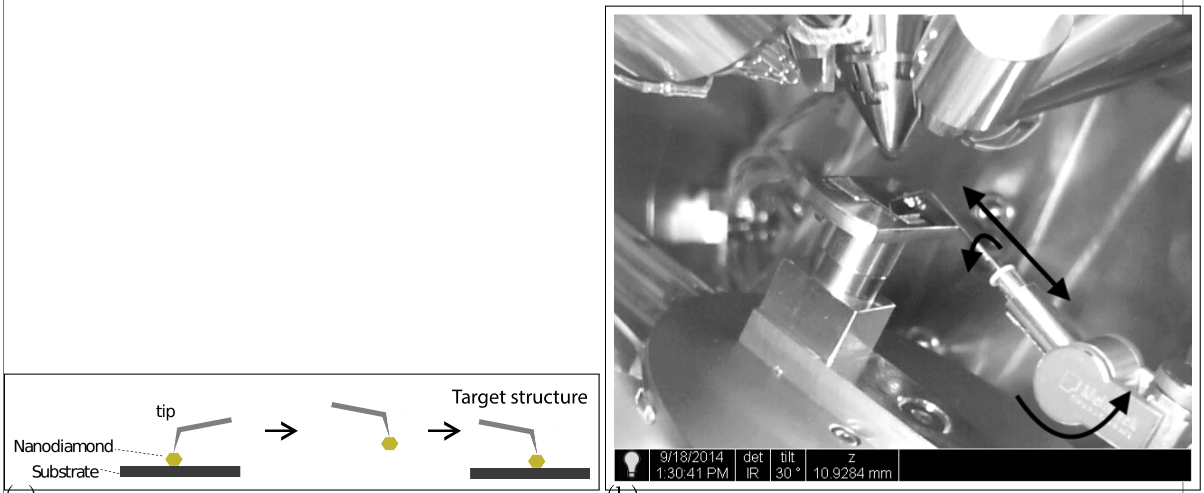
Nanomanipulator

In general, nanomanipulator is a tip mounted inside an SEM. The one used for our experiments was built by the company Kleindiek (model MM3A-EM) and has a changeable tungsten tip (see Figure 1.1b). It is mouted inside a Thermo Scientific™ Helios NanoLab™ DualBeam™ microscope, which combines a focussed ion beam and an electron microscope. The bent nanomanipulator tip has 3 degrees of freedom: up/down and left/right both in an arc up to 240° and 12 mm in/out (see arrows in Figure 1.1b). Before nanomanipulation the tip was "sharpened" with the focussed ion beam by etching away tungsten with gallium ions. This sharpening was performed to meet the size criteria necessary to pick up the nanodiamonds. In Figure 1.3a the sharpened tip is shown. The small tip sticking out of the bigger cone is the sharp tip used for pick-and-place.

Determination of The Position of Nanodiamonds

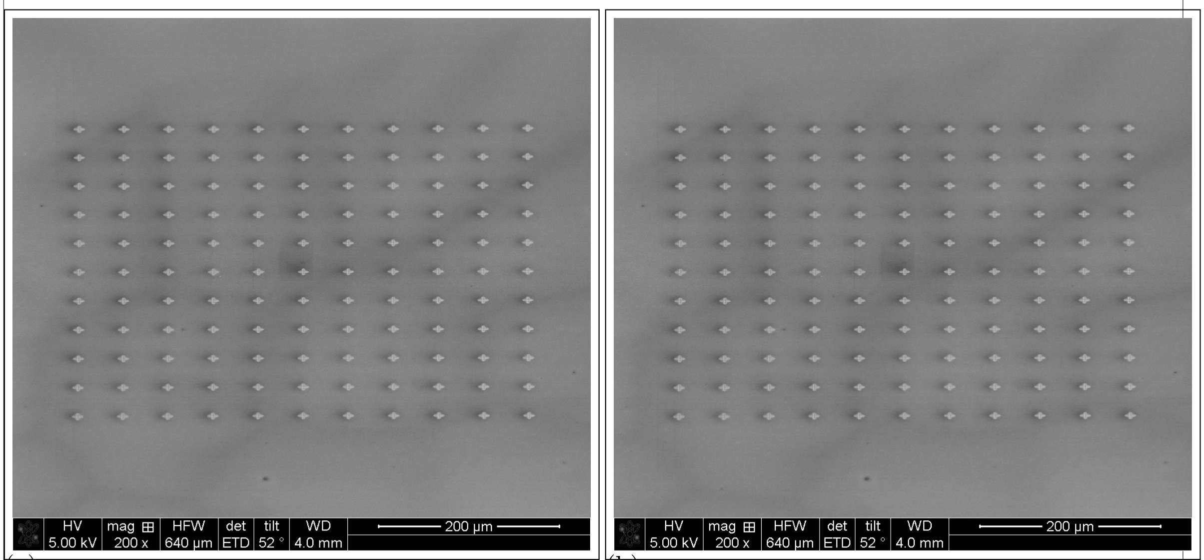
An nanodiamond pre-characterized in the confocal setup exhibiting the preferred optical properties (e.g. narrow linewidth, high count rate) has to be found again in the SEM setup where the nanomanipulator is installed. Therefore, we milled cross markers into the iridium coating of the silicon substrate using the focussed ion beam prior to spin-coating the substrate with nanodiamond solution.The crosses' size is $10{\times}10\,\mu m^2$ are exhibit a nominal depth of 40 nm.

fib parameter



(a) (b)

Figure 1.1: (a) Sketch of the pick-and-place process exploiting a nanomanipulator. (b) Image of the nanomanipulator mounted in the FIB. The arrows indicate the degrees of freedom of motion of the nanomanipulator. The custom made workbench is situated in the middle of the picture. On top of it, there is a $1\,\mathrm{cm}^2$ substrate with coated nanodiamonds, the nanomanipulator tip pointing to the middle of it. Behind it, there is the target vertical-cavity surface emitting laser. Perpendicular to the workbench, the objective of the electron microscope can be seen. The pointier cone perpendicular to the image top image edge is the objective of the focussed ion beam.



(a) (b)

Figure 1.2: (a) Overview of a field of cross markers. The field spans $0.5{\times}0.5\,\mathrm{mm}$ (b) White light scan of an area with a cross marker in all four corners.

Four crosses are the cornerpoints of a $50\times50\,\mu m^2$ sqaure. The 10×10 crosses spaned one field of crosses; we usually put 3 fields of crosses on one substrate.
To record the position of a nanodiamond with respect to a cross marker, we used two different methods:

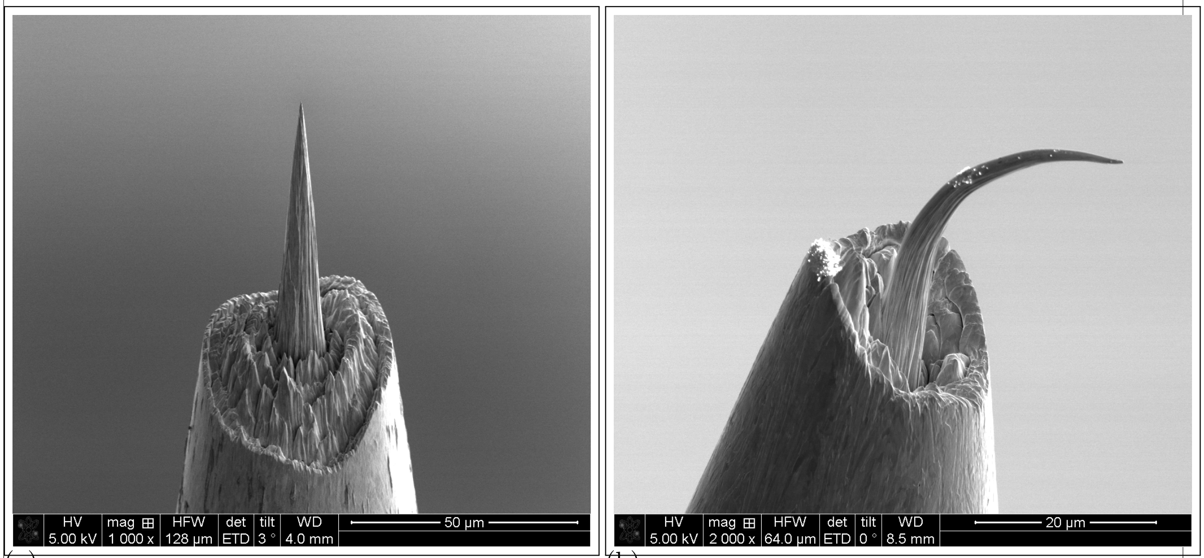
- Scanning the sample in the confocal setup while a white light source illuminates the sample from the side in an acute angle. The edges of the cross markers are visible in the fluorescence scan. After turning the white light lamp off, the same area is scanned once more to record the fluorescence from the SiV centers. An overlay of the two images identifies the position of flourescent SiV centers with respect to the cross markers. The disadvantage of this method is, that it takes a lot of time, as every scan has to be performed twice. Also, as only fluorescence light scans are performed, no information of the nanodiamonds is accesessible, such as the size of the individual nanodiamonds or the distribution of the nanodiamonds. put in a pic of white-lightscan
- The substrate was first scanned in a commercial laser scanning microscope . The laser scanning microscope is a confocal microscope where the focus of a laser is used to obtain the height of a structure. It is possible to scan a whole field of cross markers in several minutes. The obtained image is a greyscale image, where the greyscale corresponds to the height deviation of a structure. Therefore, both the crosses and the nanodiamonds appear in darker shades of grey. So in contrast to the provious method, information on the nanodiamonds is accesessible. After scanning the substrate with the laser scanning microscope, it is put into the confocal setup. While observing the surface with the CCD camera, a specific cross marker is chosen as the starting point of a fluorescence light scan. Comparing the laser scanning microscope image and a fluorescence light scan, fluorescent dots of the fluorescence light scan are attributed to nanodiamonds in the laser scanning microscope scan (see Figures 1.9a and 1.9b). specs verify info

Technical Issues of the Pick-And-Place Process

- FIB Spezifikationen 1kV, 0.17nA - Hochaufloesungsmodus geringer arbeitsabstand von 5mm, higher magn. field - 70nm nanodiamonds zu klein - Anfahren mit Fokus

1.2 Coupling Nanodiamonds to Vertical-Cavity Surface Emitting Lasers

For metrology, the photon flux rate has to be high enough to be measured by a low optical flux detector [**?**].



(a) (b)

Figure 1.3

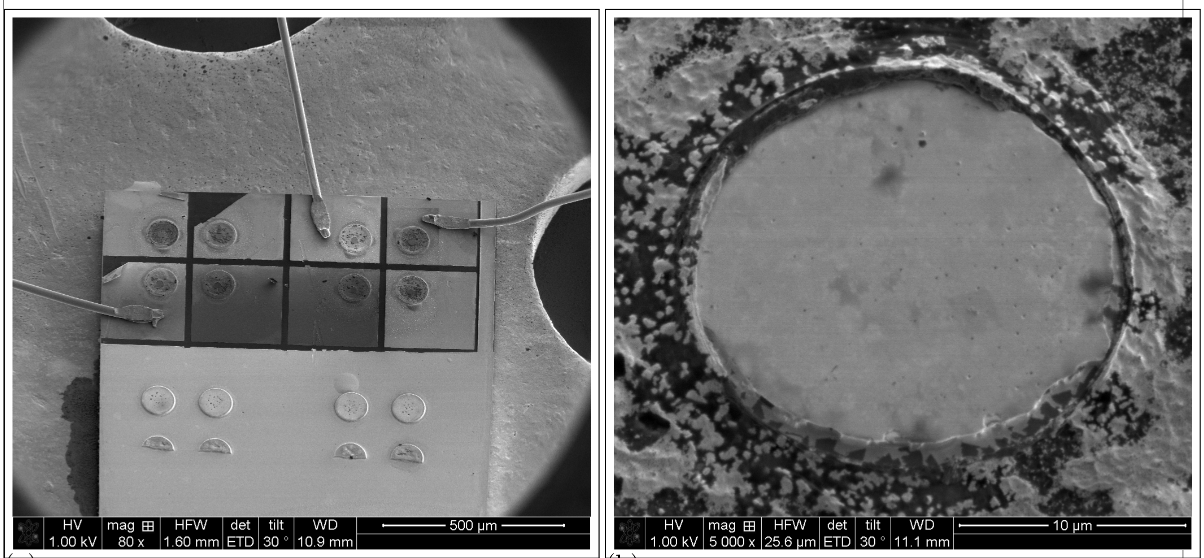


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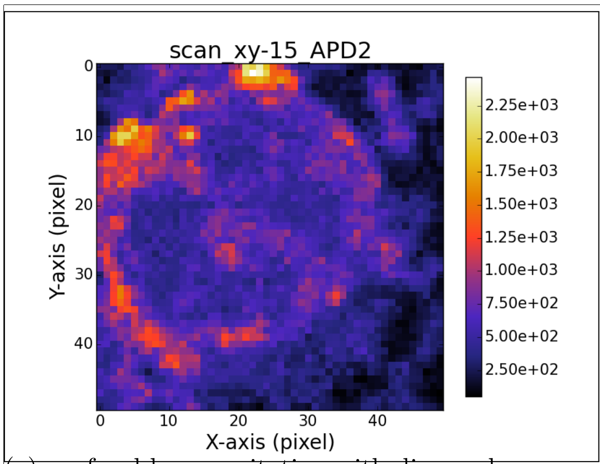
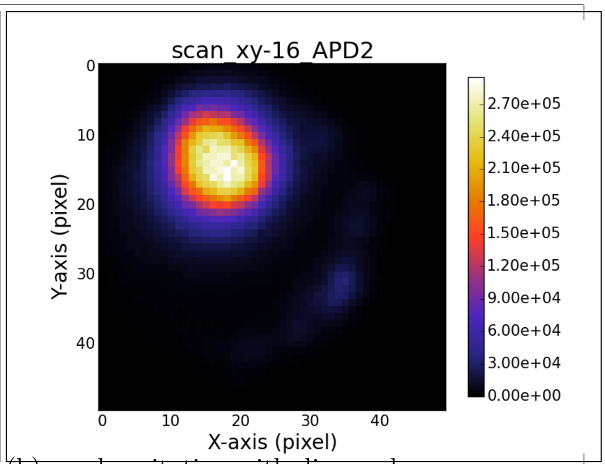
Figure 1.4: <caption>

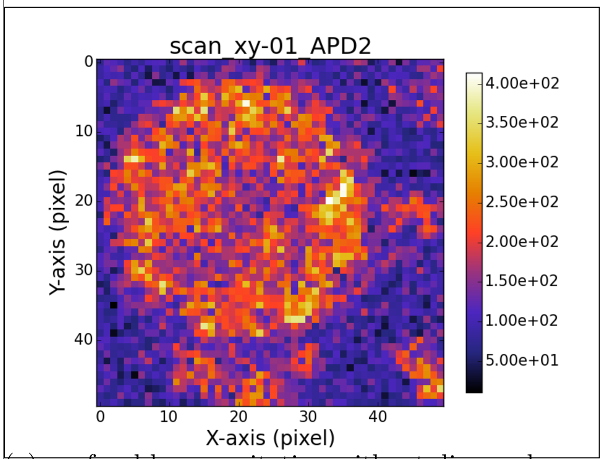


(a) confocal laser excitation with diamond

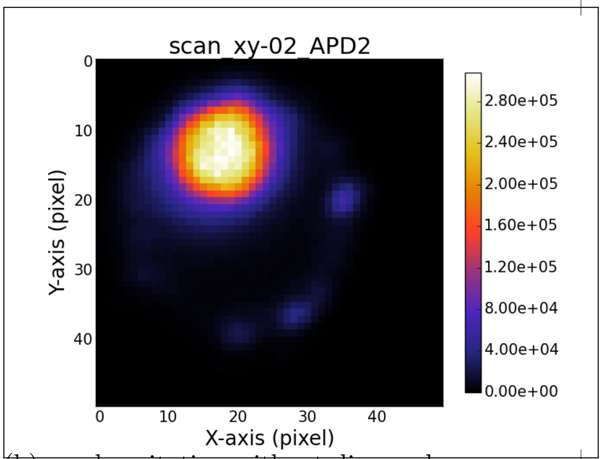


(b) vcsel excitation with diamond

Figure 1.5

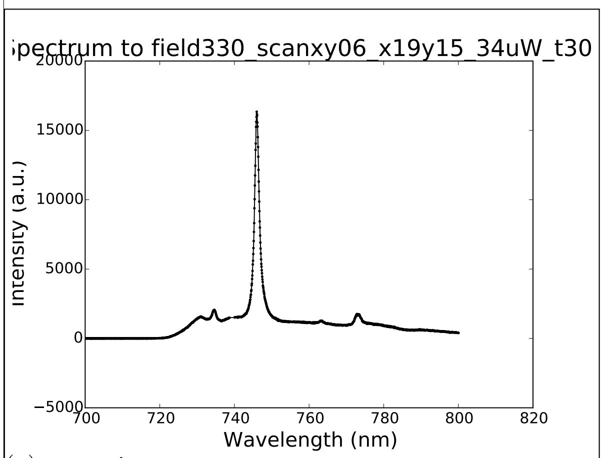


(a) confocal laser excitation without diamond

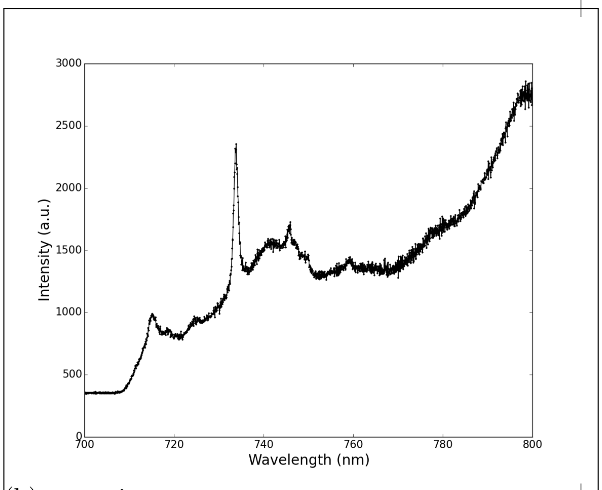


(b) vcsel excitation without diamond

Figure 1.6: <caption>

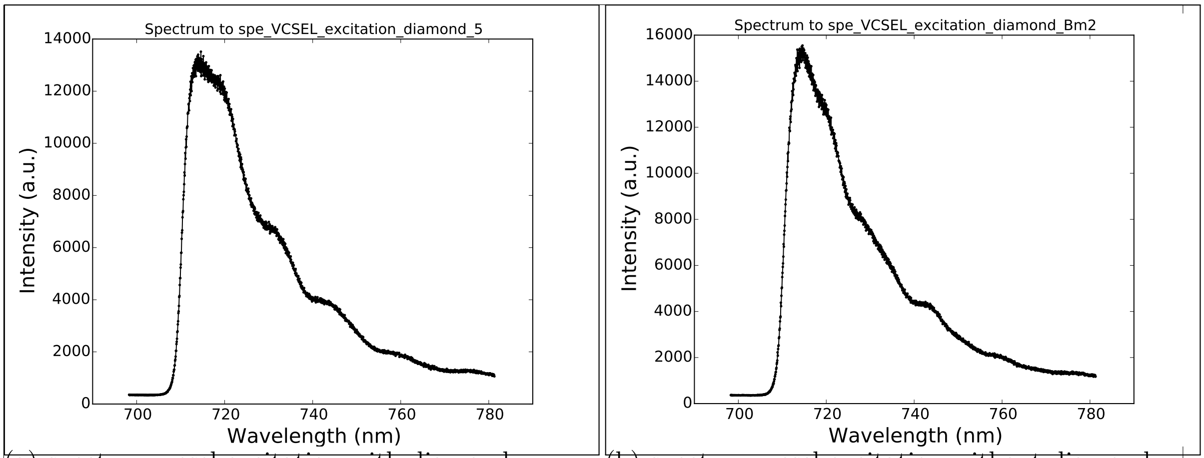


(a) <caption>



(b) <caption>

Figure 1.7: <caption>



(a) spectrum vcsel excitation with diamond

(b) spectrum vcsel excitation without diamond

Figure 1.8: <caption>

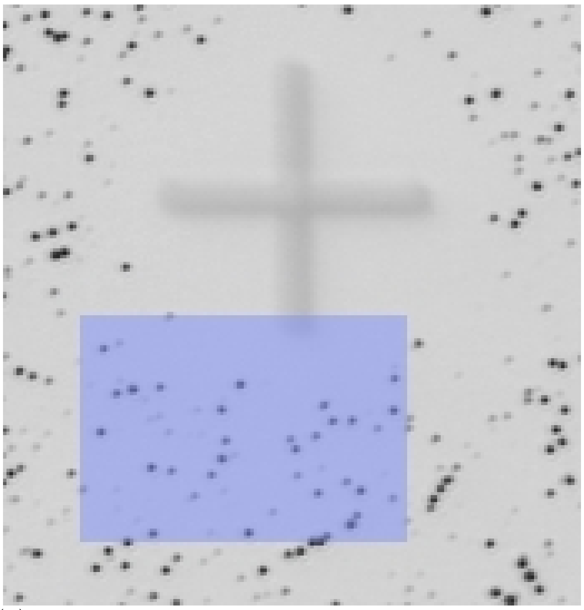
1.2.1 Pick-And-Place Process to Vertical-Cavity Surface Emitting Laser

1.2.2 Spectroscopic Measurements of Nanodiamond in Vertical-Cavity Surface Emitting Laser

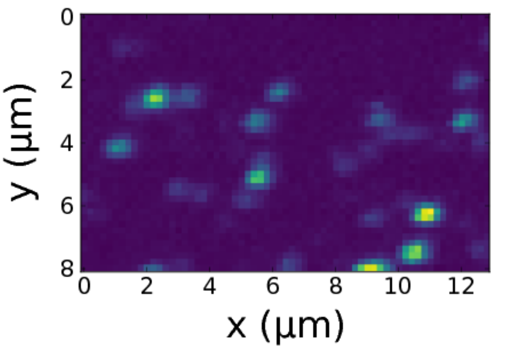
1.3 Coupling Nanodiamonds to Double Bowtie Antenna Structures

1.3.1 Nanodiamond With Multiple SiV centers Coupled to Antenna

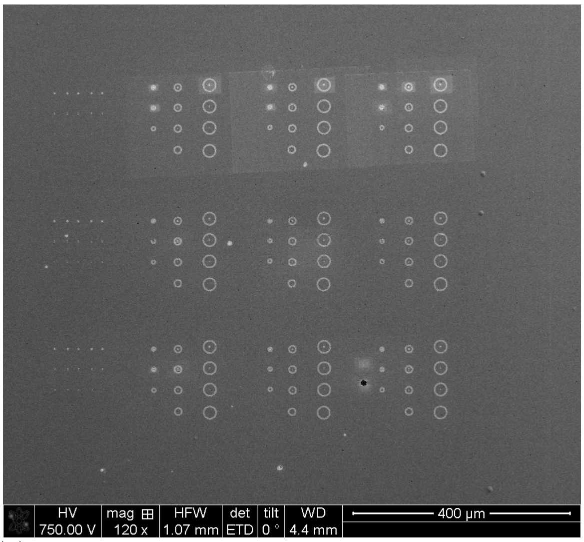
1.3.2 Nanodiamond With Single SiV center Coupled to Antenna



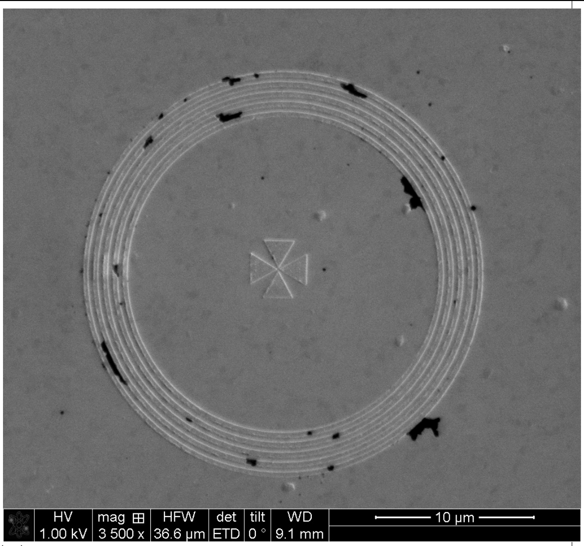
(a) Picture recorded with a commercial high resolution laser scanning microscope. The area shaded in blue represents the photoluminescence scan in image b)



(b) Photoluminescence scan of a 8 µmx13 µm

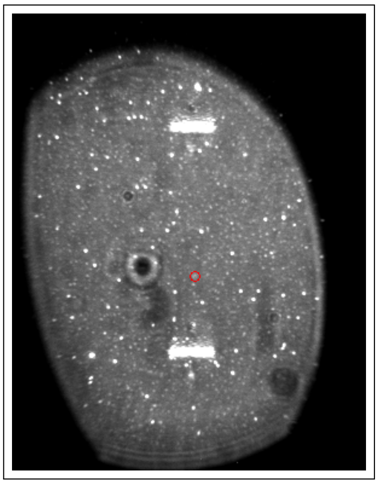


(a) <caption>



(b) <caption>

Figure 1.10: <caption>



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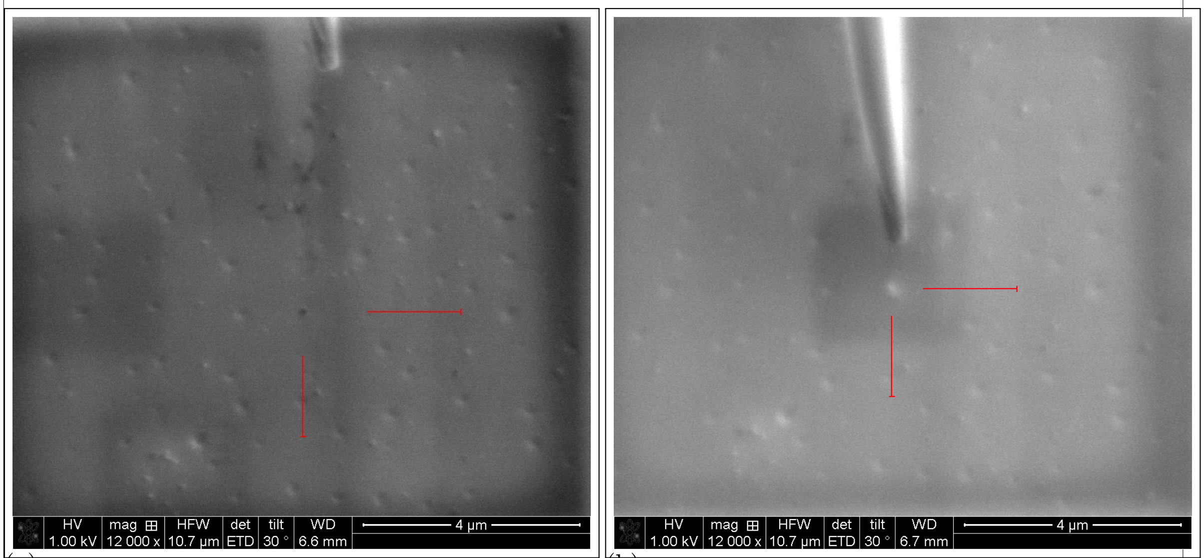
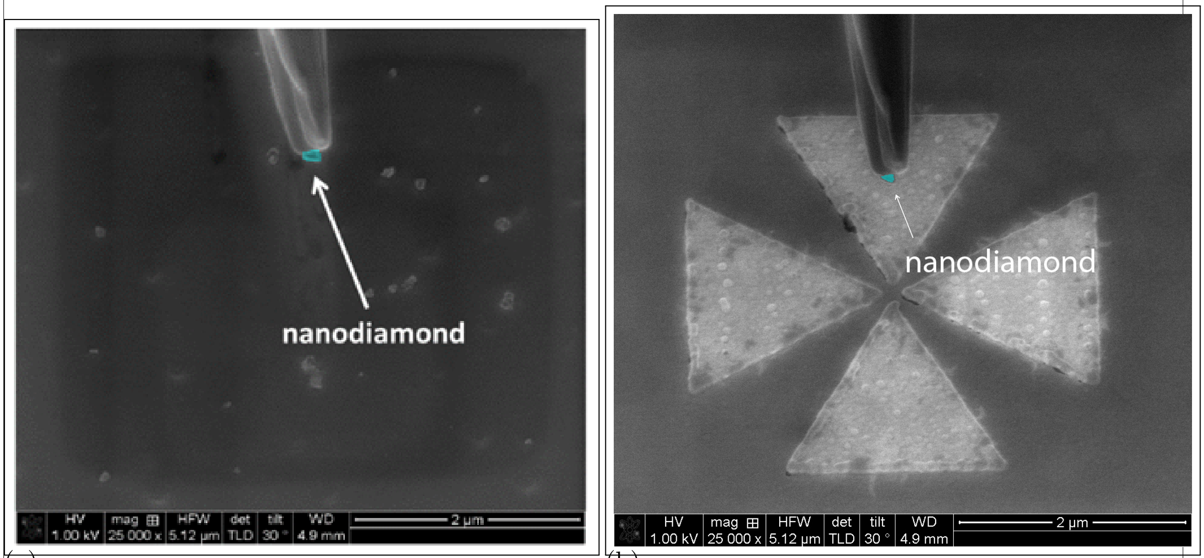


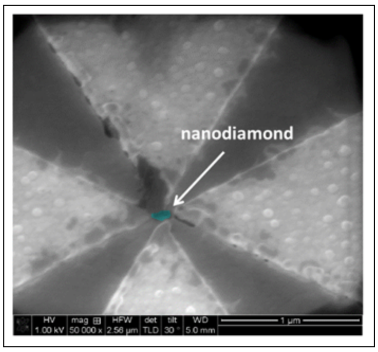
(a) (b)

Figure 1.12: caption



(a) (b)

Figure 1.13



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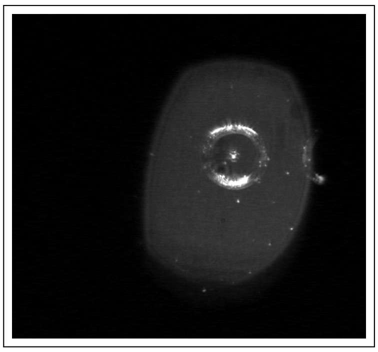

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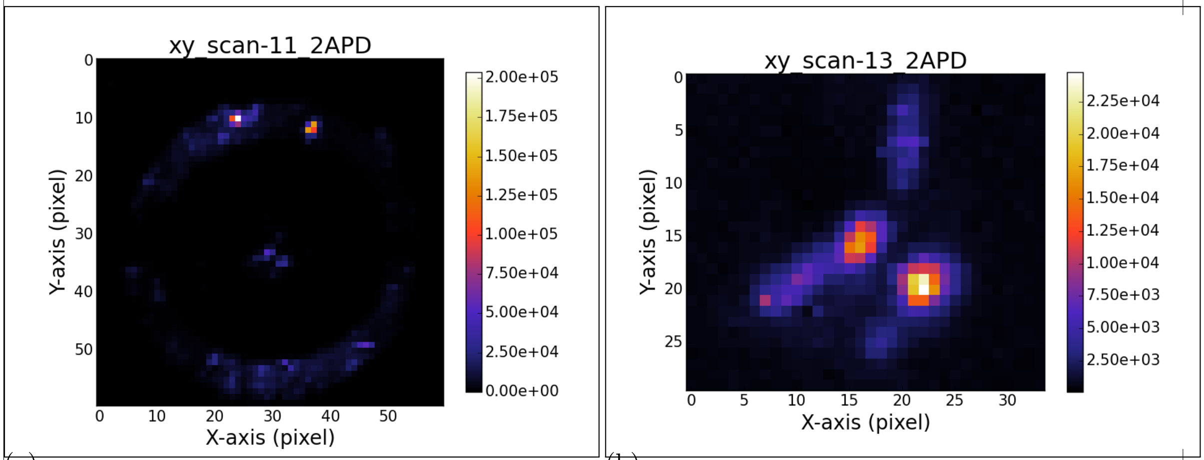
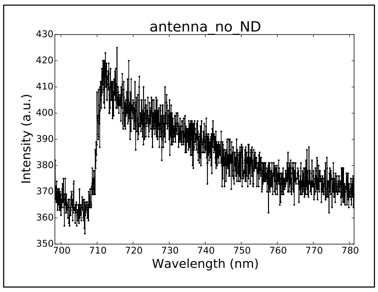


(a) (b)

Figure 1.16: <caption>



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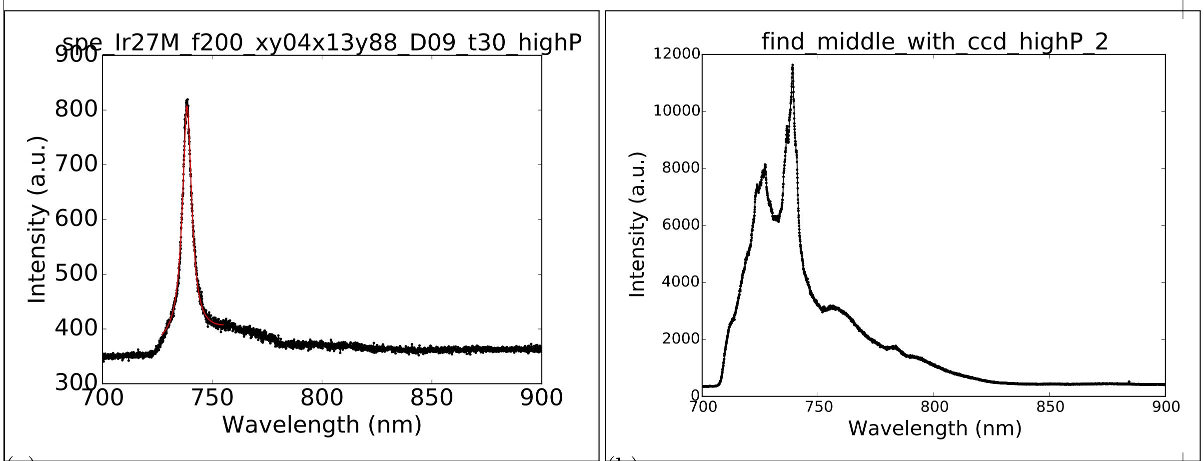
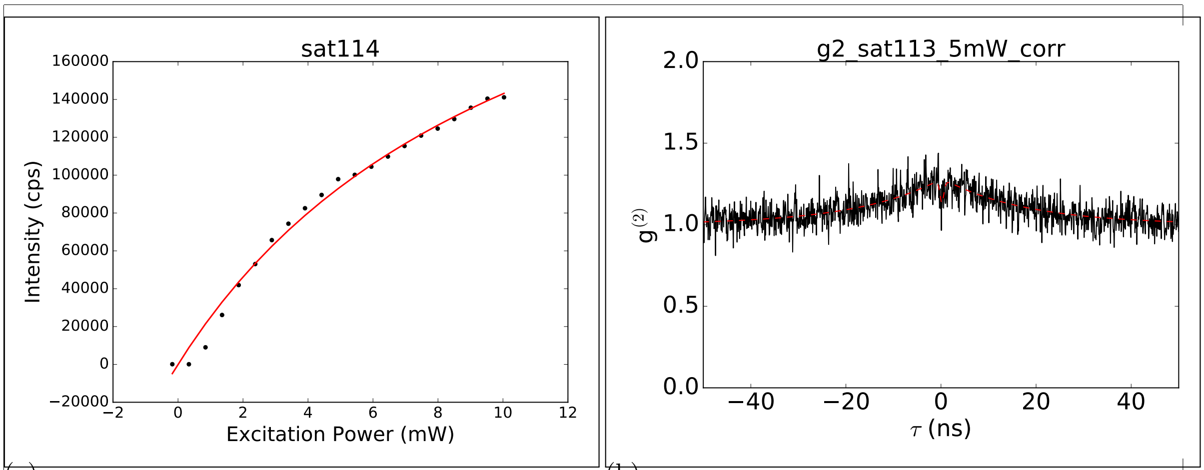


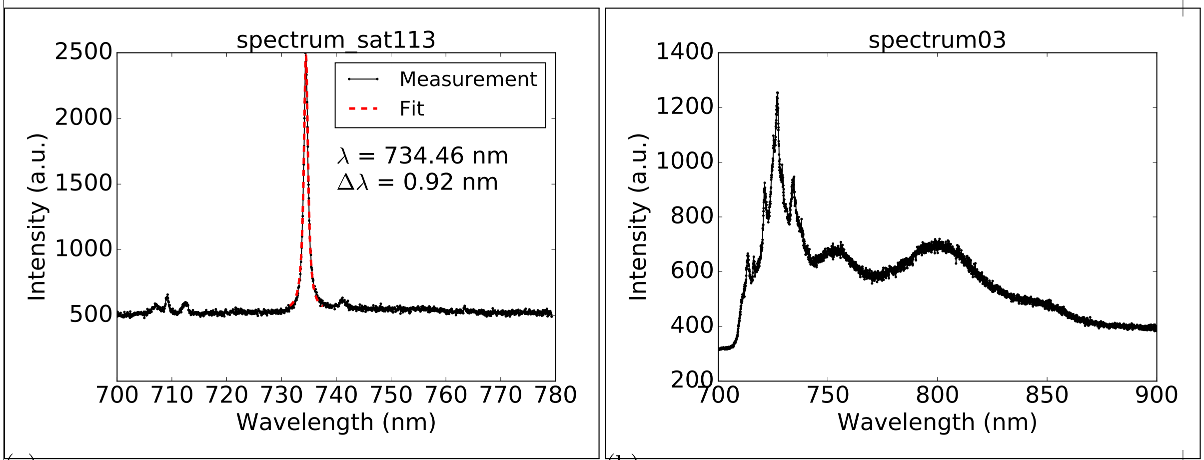
(a) (b)

Figure 1.18: <caption>



(a) (b)

Figure 1.19: <caption>



(a) (b)

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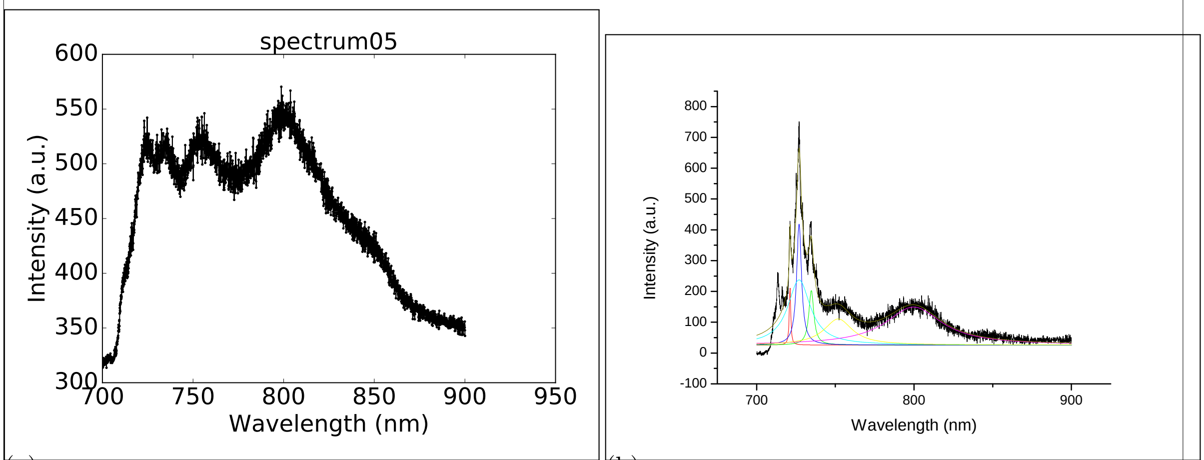

(a) (b)

Figure 1.21: <caption>

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