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**Title:** Manipulating carbon nanotubes towards the application as novel field emission sources  
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This thesis is about the research I performed on novel field emission sources. A field emission source, or electron field emitter, is used to obtain an electron beam by means of applying a high voltage difference between the emitter (cathode) and an extractor (anode) in vacuum. Some time ago, we all used to gaze at electron beam “images” produced by CRT (Cathode Ray Tube) televisions or computer monitors. However, such an electron beam can also be used for microscopy (electron microscope) or lithography (electron beam lithography, used in the chip industry to produce electronics, etc.), where it can be focused into a much smaller spot than possible with photons (light). Hence it is possible to obtain a higher resolution – study smaller objects or write smaller structures – than with optical microscopy or lithography. The quality of the electron beam determines, amongst others, resolution and throughput time of these processes. To have a better electron beam it is possible to improve either the electron optics, or the electron source, and we have chosen to do the latter. Having a better electron source can reduce the time needed to obtain an electron microscope image and enable studying processes at a higher resolution. In electron beam lithography instruments, a better source could provide a higher throughput.

We chose to fabricate electron sources by means of mounting individual nanometer-sized structures, such as nanotubes and nanowires, onto sharp conductive needles. In this context, nano means the diameter of such a nanotube or nanowire is of the order
of a nanometer up to tens of nanometers. Its length, however, is not constrained and therefore such a structure can have a large aspect ratio. These nanostructures have interesting electrical and/or mechanical properties, which make them attractive candidates for novel field emission sources. By using a nanomanipulator inside an electron microscope, we could select and mount an individual nanostructure onto a sharp needle. In a field emission setup, the needle with the nanostructure (cathode or emitter) is placed in front of an extractor (anode) and a voltage difference is applied between. The resulting electric field has its maximum value at the end of the protruding nanostructure; hence the electrons leave the emitter through the end of the nanostructure. The resulting electron beam can be studied in several ways. The total current of the electron beam can be measured and observed as a function of time, but it is also possible to map the electron density of the beam’s cross section, also called a field emission pattern. The field emission pattern, obtained with a Field Emission Microscope (FEM), provides information on the shape and electronic structure of the emitting nanostructure. In this situation, where we have a sample with only a single emitting structure, it is possible to also study the structure’s morphology before and/or after field emission experiments inside a high resolution Transmission Electron Microscope (TEM) and relate it to the electron emission characteristics. The theory behind the field emission process and the FEM is described in Chapter 2.

A carbon nanotube can be thought of as a sheet of carbon atoms inside a hexagonal lattice – also known as graphene – rolled up into a cylinder. The two ends of this cylinder can be either open or closed, where the closed end state is the energetically favorable and more stable configuration. As in a field emission experiment electrons are most likely to come from one of the nanotube’s end states, it is imperative to know, or even better, to control the end state in our experiments. We found that the emission pattern from a naturally closed carbon nanotube showed a symmetry that can be related to the symmetric positions of the carbon atoms that make up the hemi-spherically shaped cap. Such a cap can be envisioned as one half of a soccer ball, consisting of five- and six-membered rings, also known as pentagons and hexagons. The carbon atoms are located at the corners of the pentagons and hexagons that make up the closed cap. Experiments on carbon nanotubes with such
a closed cap are described in Chapter 6.

In the selecting and mounting process of a nanostructure, the performance of the electron microscope, in which the mounting is done, determines what is feasible. For example: Is it possible to identify single nanostructures at all? Does the electron imaging harm the nanostructure? A new high resolution scanning electron microscope in our group in Leiden asked for its own nanomanipulator. As this microscope put more constraints on the materials being used, it was not possible to copy the setup we had been using at the Philips Research Labs. Based on these constraints and on experiences operating nanomanipulators, such as the one at Trinity College in Dublin, we came up with a completely new design. Although it took longer than planned, the result was an instrument much more versatile than we had envisioned, as you can read in Chapter 3. Collaborations with other groups, such as the Quantum Transport group at Delft University of Technology and the Quantum Optics group at Leiden University, led to successful experiments on samples fabricated using our nanomanipulator setup. The techniques used when mounting nanostructures onto sharp needle-shaped tips, are described in Chapter 4.

We discovered that we could use the high current electron beam of the new electron microscope to cut through our nanotubes and hence control their length. As this affected the end configuration of the nanotubes, we needed to find a way to “repair” them. We succeeded in re-obtaining closed caps during field emission experiments on carbon nanotubes that were previously cut by using this method, see Chapter 5.

Besides carbon nanotubes, we also studied the field emission properties of indium arsenide (InAs) nanowires. Nanowires are solid cylinders of a certain material, with specific electrical and/or mechanical properties. In the case of semiconductor InAs nanowires, we expected to obtain an electron beam with a very low energy spread. In Chapter 7 we describe how we mounted and controlled the length of such nanowires on sharp tips and performed field emission experiments.

Not to be found in this thesis, however, are the experiments performed on sources I made for FEI Beamtech, Hillsboro, USA. Measurements at their laboratory yielded
promising results, but it is a long road towards an application. Although, in my opinion, they had a great success in managing to operate a closed capped MWNT at their facility – that had been produced in our laboratory – it was not good enough to match the requirements set by Beamtech.