Optical near-field electron microscopy: merging light and electron imaging

Stam, W.G.

Summary

Microscopy is the science of imaging matter at length scales smaller than what the naked eye can distinguish. The most well-known example is the optical microscope, which can effectively resolve structures down to approximately half the wavelength of light. Below this limit, conventional optical microscopes are restricted by the diffraction limit. For visible light, this means that objects as small as about 200 nm can still be imaged well.

For even smaller structures, an electron microscope can be used. Due to the much shorter *de Broglie* wavelength of electrons, electron microscopes encounter the diffraction limit at much smaller scales. A high-quality electron microscope can achieve a resolution of 0.05 nm, allowing individual atoms to be distinguished. However, imaging with high-energy electrons is not suitable for all samples. Biological materials, such as proteins, are particularly vulnerable to damage from the electron beam, significantly limiting imaging times. Additionally, imaging objects in liquids with an electron beam remains a challenge.

In this thesis, we introduce a novel technique called Optical Near-field Electron Microscopy (ONEM), which aims to combine the advantages of both optical and electron microscopy: the high resolution of electron microscopy and the low sample damage of optical microscopy. This approach is described in detail in Chapters 1 and 2 and works as follows: In ONEM, the sample is illuminated from the backside with visible light. The light passes through the sample, is modified by it, and then reaches a thin photocathode. In this thin layer, the light is converted into electrons. Areas receiving less light, because the light is blocked by an object, such as a virus, generate fewer electrons. The emitted electrons are then accelerated and imaged using the electron optics of a low-energy electron microscope (LEEM). The key idea is that ONEM bypasses the optical diffraction limit by capturing the optical near field in close proximity to the sample using the photocathode. The resulting "snapshot" of the optical near field is thus taken with electrons, which themselves have a much smaller diffraction limit than light.

A crucial component of ONEM is the photocathode, which is responsible for converting light into electrons. The photocathode must be efficient to ensure a sufficient signal while also being thin and smooth to preserve the optical near field and avoid distortions in the image. In Chapter 3, we develop a new growth procedure for the

well-known Cs_3Sb photocathode and demonstrate that this growth method yields the required properties for ONEM.

In the following chapters, we present the first successful ONEM experiments. In Chapter 4, we image samples by illuminating them from the backside with UV light. This represents an initial step, but since UV light does not require a photocathode for electron emission, the technique remains closely related to photoemission electron microscopy (PEEM) rather than full ONEM.

In Chapters 5 and 6, we employ visible light for ONEM. In Chapter 5, we experimentally investigate the achievable resolution of our technique. Using a sample structured with small regions of silica and chromium, fabricated by electron beam lithography, we demonstrate that ONEM can achieve a resolution of 31 nm. Given that the wavelength of the employed light was more than ten times larger, this represents a significant improvement compared to conventional optical microscopy.

In Chapter 6, we apply ONEM to a mouse brain sample prepared for electron microscopy in connectomics research. The goal of this field is to map all neural connections within an entire (mouse) brain, forming a so-called connectome. The major challenge is the rapid imaging of ultrathin sections. Consequently, there is extensive research into improving imaging techniques or developing alternative approaches. In this chapter, we compare ONEM to PEEM as an imaging technique for connectomics.

The thesis concludes with an outlook on other potential applications of ONEM. For example, ONEM could be used to study objects in liquid environments, such as proteins in their native conditions. Another promising application is electrochemistry: while electron beam imaging of liquid cells can interfere with chemical processes and thus distort experiments, ONEM enables non-invasive observations. Finally, ONEM provides a novel way to study optical near fields themselves, including plasmons and other intriguing optical structures.