Matter lens for electrons imaging

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Introduction

Transmission electron microscopy is one of the most powerful techniques to investigate the microstructure of materials down to atomic scale. In conventional TEM, magnetic lens with large sizes (centimeters) are used for focusing electrons into Angstrom probe. The whole microscope containing multiple lens could be up to 4 meters high, which is bulky, complicate and extremely expensive (Fig. 1). In addition, the axially symmetric magnetic field generated by a magnetic lens has an intrinsic spherical aberration, which limits the spatial resolution of the microscope. In this work, we proposed a new matter lens for direct electrons imaging. The lens is only a few micrometers in size and it could focus the electrons efficiently without intrinsic spherical aberrations.

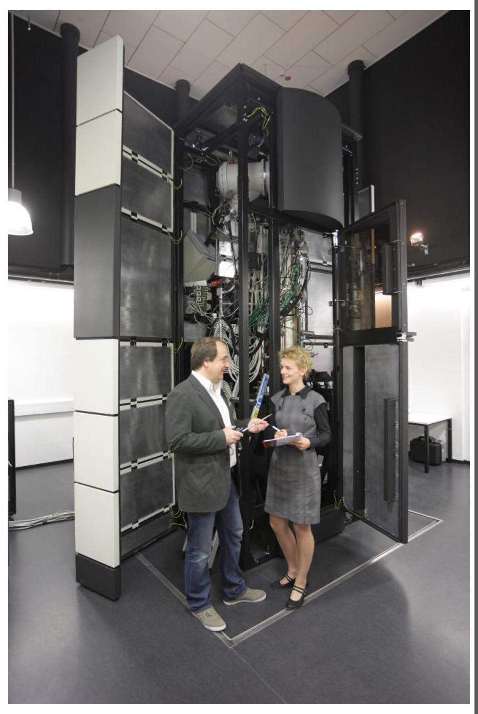


Figure .1 Modern transmission electron microscope.

Convex lens: quadradic phase shift

When parallel beam passes through a convex lens, it will be concentrated to a point. According to physical optics, the lens provides a quadratic phase shift to the incident beam behind the lens.

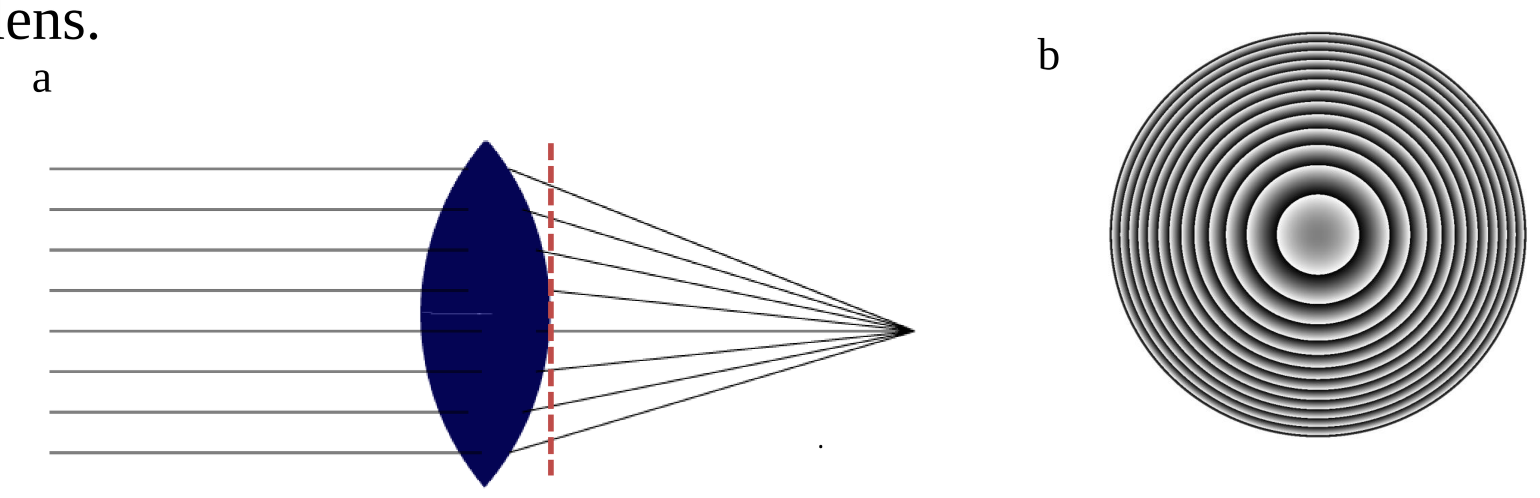
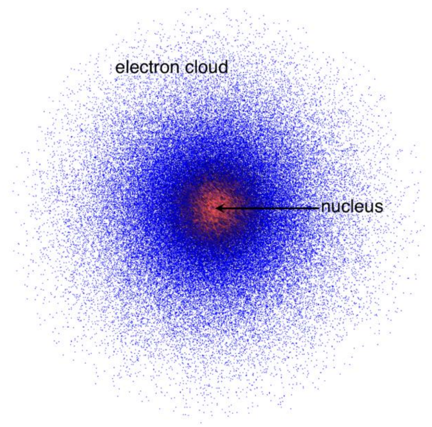


Figure 2a: Incident wave converges into a point. b: The phase shift of the incident wave behind a lens.

In our design, the phase of incident electron beam will be modulated by the electrostatic potential and magnetic field of matter.

$$\phi(r) = C_E \int_{-\infty}^{\infty} V_0(r,z)\,dz - \frac{e}{\hbar}\int_{-\infty}^{\infty}\int_{r}^{\infty} B_n(\rho,z)\,dr\,dz \quad (1)$$

Electrons lens with a single atom



In theory, the electrostatic potential of a single atom (generated by the positive charged nucleus and negative charged electrons) could focus the incident electrons Into an angstrom probe, even there is a strong spherical aberration. The projected potential of a single atom and the introduced phase shift are calculated in figure 3 . However, it is difficult to apply a single atom for electron imaging.

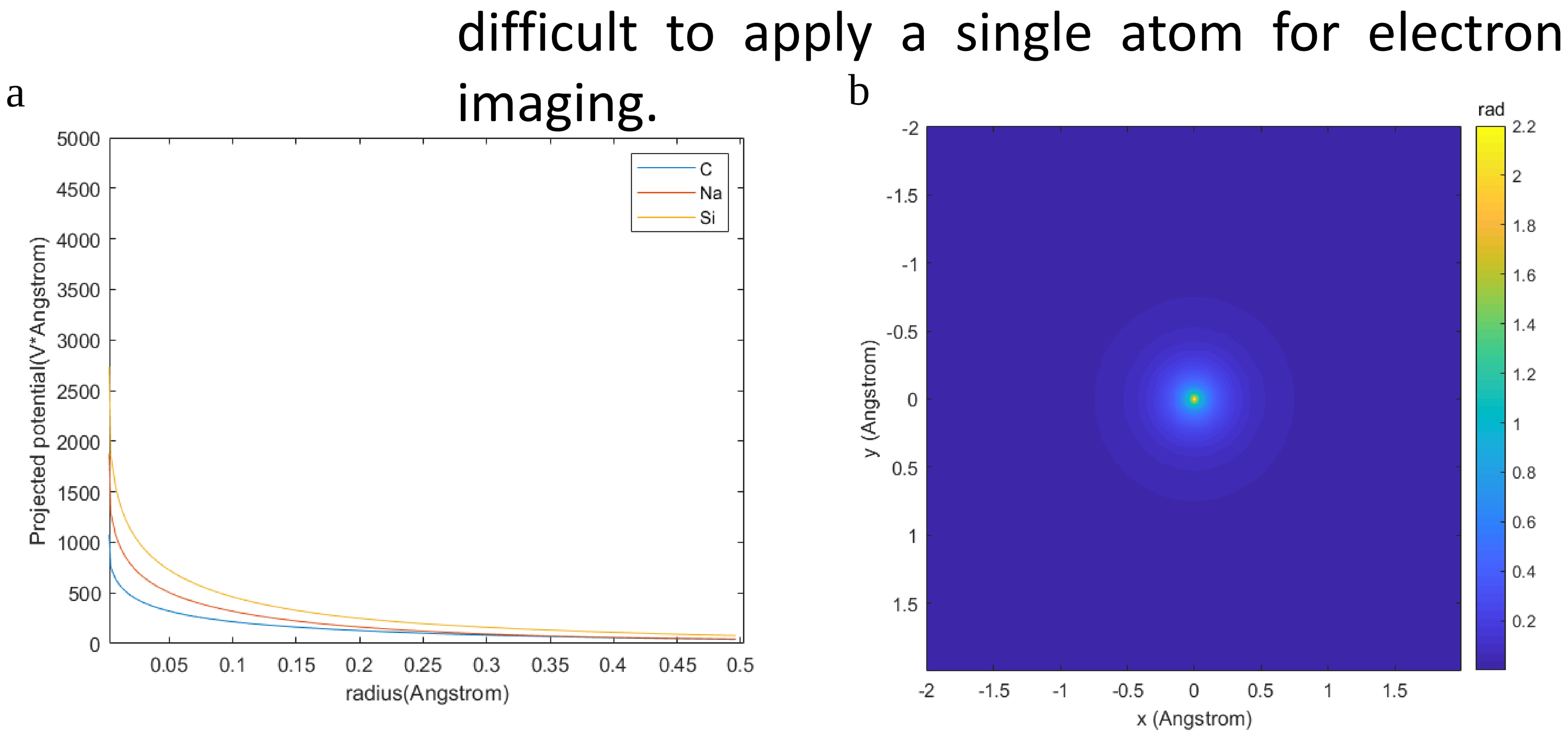


Fig. 3a: single atom projected potential with different elements. b: The introduced phase shift for 100 keV incident electrons by a single Fe atom.

Electrons imaging with a crystal lens

Instead of using a single atom, we proposed a method to focus high energy electrons using a small crystal lens. The mean inner coulomb potential (MIP) of atoms in crystal could also change the phase shift of incident electron beam. By carefully designing the shape of a micro crystal, the electrons could be efficiently focused without intrinsic spherical aberration. Figure 4 shows a nanocrystal with parabolic shape (MIP: 8V, bottom radius: 100 nm, height: 100 nm). The simulated electron probes with different propagation distance are shown in figure 4b-c. The focal distance is 0.72 mm.

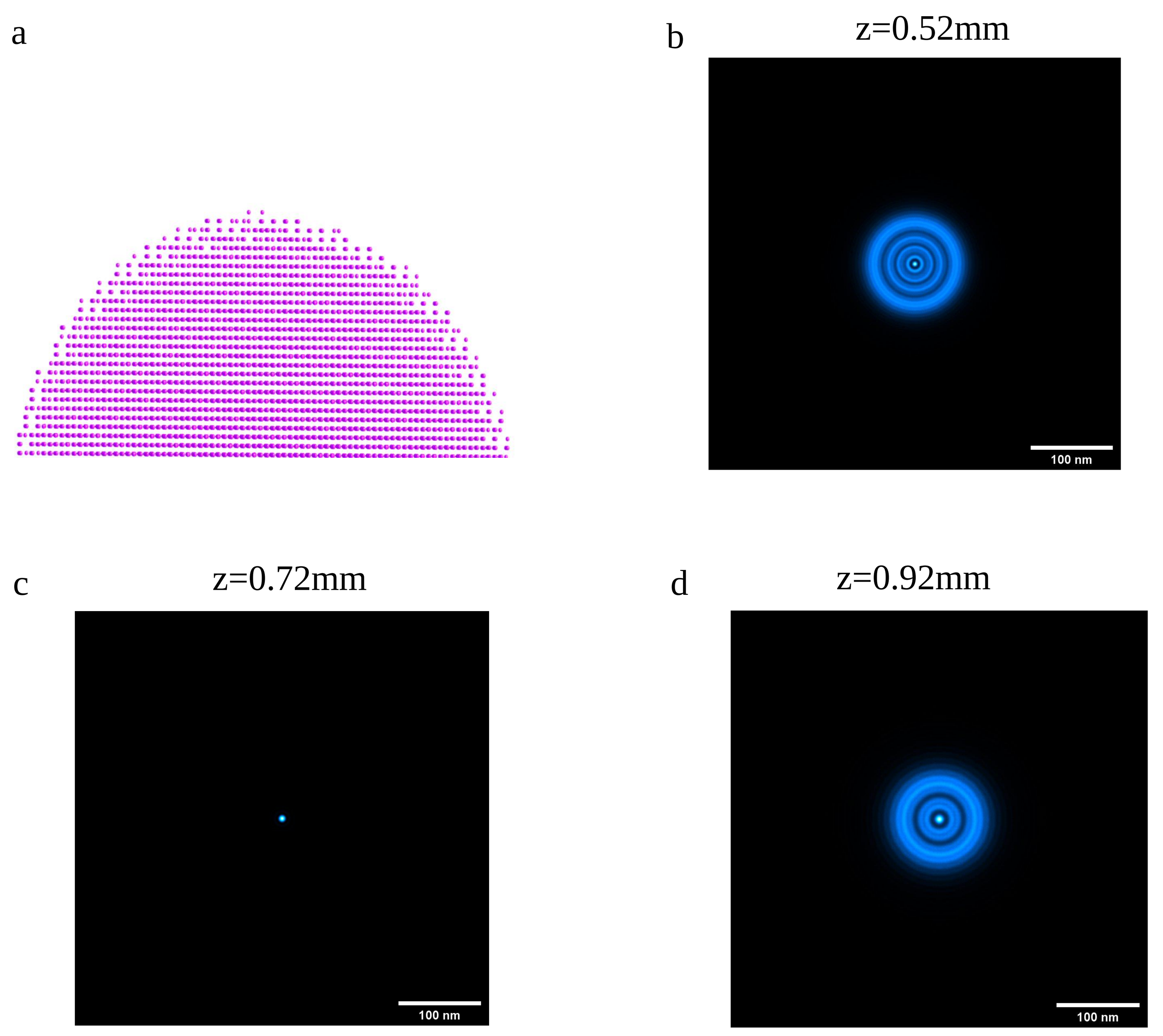


Figure 4a: A parabolic crystal and it can introduce the phase shift of k^2 to the electron wave, according to the $\phi(r) = C_E Vt$. C_E is the interaction constant depending on the accelerate voltage. V and t is the mean inner potential and thickness of the crystal, respectively. Figure 4b-d show the simulated beam at different propagation distance from the lens, the size of the sampling space is 500x500nm.

Electron lens with magnetic vortex

To modify the phase shift using crystal MIP, the thickness needs to be changed largely. According to equation 1, it is also possible to modify the incident beam phase shift using magnetic field in magnetic materials. We designed a magnetic matter lens for electrons using magnetic vortex structure in soft magnetic materials.

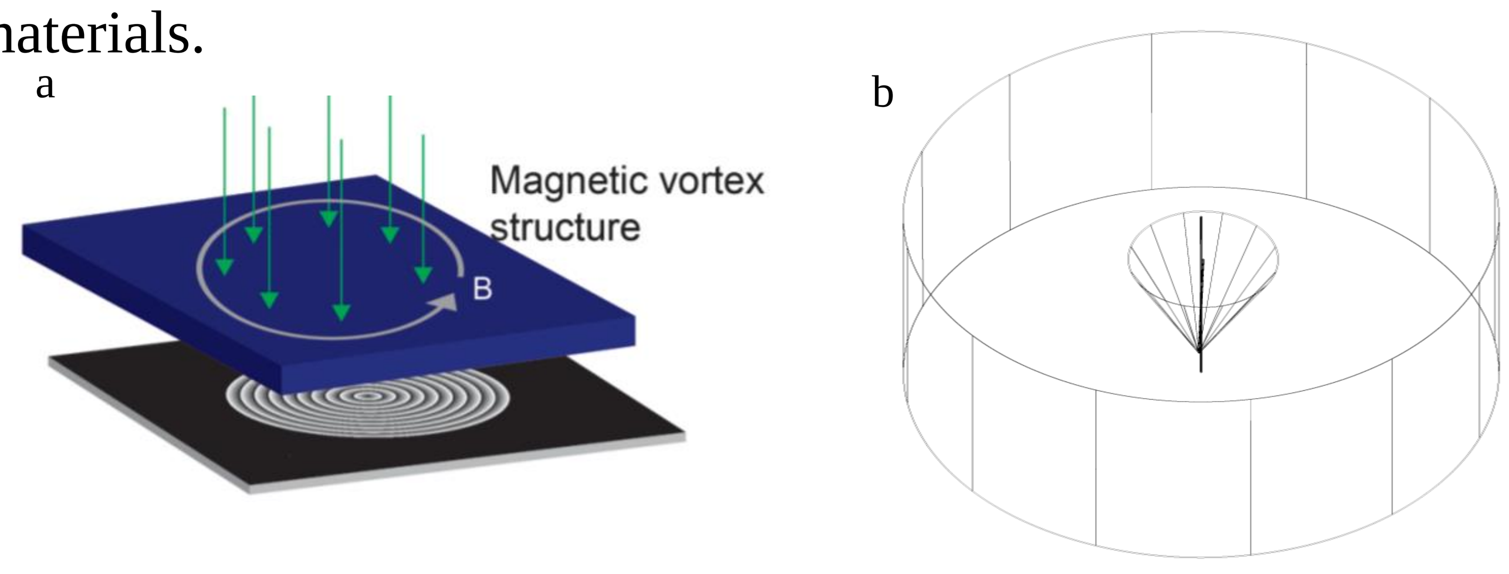


Figure 5 | a, The magnetic field strength is uniform in the magnetic vortex. According to $\phi_{\mathrm{mag}}(r) = \phi_{\mathrm{mag}}(0) + \frac{e}{\hbar}B_n S$, it can induce a linear phase ramp, S is the area of the integral area. b, We dig a cone in the magnetic vortex, then S is proportional to the square of the radius. It can also cause the phase shift of k^2 .

Conclusion

We design two kinds of material lenses in theory. we demonstrate that the focal length is better than the magnetic lens in the TEM. However, further study are needed in order to get the actual sample of material lenses.

Acknowledge

This is a graduation work for a undergraduate, thanks for the help of Xian Li.