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Design and implementation of a micron-sized electron column fabricated by focused ion beam milling

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ABSTRACT

We have designed, fabricated and tested a micron-sized electron column with an overall length of about 700 microns comprising two electron lenses; a micro-lens with a minimal bore of 1 micron followed by a second lens with a bore of up to 50 microns in diameter to shape a coherent low-energy electron wave front. The design criteria follow the notion of scaling down source size, lens-dimensions and kinetic electron energy for minimizing spherical aberrations to ensure a parallel coherent electron wave front. All lens apertures have been milled employing a focused ion beam and could thus be precisely aligned within a tolerance of about 300 nm from the optical axis. Experimentally, the final column shapes a quasi-planar wave front with a minimal full divergence angle of 4 mrad and electron energies as low as 100 eV.

1. Introduction

In past decades, electron microscopy has made significant progress, in particular by the realization and implementation of aberration correcting elements [1–2]. This has led to commercial transmission electron microscopes that routinely deliver atomic resolution in material science research. A current trend is to reduce beam energies from 100 keV, a typical value 10 years ago, down to energies in the several 10 keV regime [3–4]. The goal is to minimize knock-out damage and thus tolerate a reasonably high electron dose to achieve good signal to noise ratios and to even envision acquiring spectroscopic data on a single atom level.

Even lower energies in the 100 eV range are employed to operate microscopes with high surface sensitivity which has led to the impressive technology of LEEM pioneered by Telieps and Bauer some 30 years ago [5]. Recent versions of these surface sensitive tools are also equipped with aberration correctors to push the lateral resolution limit to or even below the nanometer range [6–7]. Related devices, also using a cathode lens close to the sample to decelerate the electron beam, are lately used in the SEM and STEM modes [8–9].

Comparably few efforts have been made in the development of electron microscopes operating in the 100 eV regime by which the electron energy is kept low throughout the entire electron column [10–13] instead of decelerating the beam just where the low energy is needed, close to the sample. Such efforts require scaled down electron lenses and enable technologies like coherent diffraction with low-energy electrons which has recently entered the 2 Angstrom resolution regime in imaging freestanding graphene [14].

Scaling down lens dimensions while maintaining atomic source size [15] and low emission voltages right at the field emission tip level leads to reduced lens aberrations. This concept is illustrated in Fig.1. For reaching a scaling factor of 1000 or more, lenses need to be machined with sub-micron precision.

If the geometrical dimensions of a given electrostatic electron lens are scaled down by a constant factor k while the ratio of the electrode potentials to the beam energy remains unchanged, the run of the electron trajectories is scaled down by the same factor k. The geometrical aberrations given as deviations of the ray trajectories from the optical axis in the Gaussian image plane thus scale with k as well.

2. Concept

In coherent diffraction imaging (CDI), micro-fabricated electron lenses have proven to be a suitable tool to shape a spherical wave front emitted from a field emission tip into a nearly parallel one [16–17]. A micron-sized two electrode electron lens (micro-lens) has already been successfully employed in CDI experiments [14]. To get more control over the beam properties, we took the effort to incorporate a second electron optical element placed behind such

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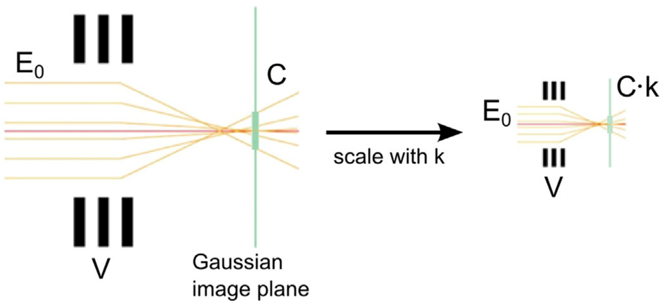

Fig. 1. Downsizing approach for low aberrations in electrostatic electron lenses. When scaling down the size of a lens by a factor *k*, the geometrical aberrations are reduced by that same factor, provided that the ratio of the electron energy E_0 to the electrode potential *V* is preserved. *C* denotes the transversal spherical aberration of the lens.

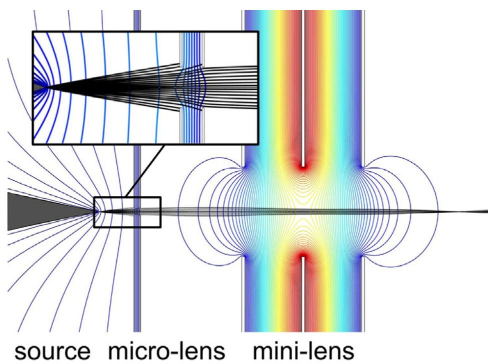

Fig. 2. Schematic of the working principle of the micro-column, not drawn to scale. Potential differences applied between the two micro-lens electrodes and between the middle and outer mini-lens electrodes create an electrostatic field distribution which has a focusing effect on the divergent electron beam emitted by the field emission source. The inset shows an enlarged view of the micro-lens apertures.

a micro-lens. Sticking to the downsizing approach, an electrostatic three electrode lens (mini-lens) with small dimensions was chosen as the second element to keep the aberrations low.

The setup of this five electrode electron optical column (micro-column) is illustrated in Fig. 2. It consists of a micro-lens with aperture diameters in the range of 1 to 5 μm, followed by a mini-lens with a maximum aperture diameter of 50 μm. The micro-lens acts as both, beam limiting aperture and extractor for field electron emission. If a potential difference between the two electrodes is applied, an electrostatic field distribution around the apertures is formed, which has a focusing effect on a penetrating electron beam.

Pre-shaped like this, the electron beam subsequently enters the mini-lens. The outer electrodes of the latter are usually kept at ground potential and either a negative (retarding mode) or a positive voltage (accelerating mode) is applied to the middle electrode. In either mode, the electrons experience a net acceleration towards the optical axis and provided that the voltage relative to the electron energy is high enough, the electron beam converges.

In order to control the beam energy throughout the column, the electron emitter as well as the micro-lens can be biased with respect to the mini-lens. This is of particular relevance for diffraction experiments in view of tuning the wavelength of the electrons.

3. Micro-column fabrication procedure

The building blocks for the micro-column fabrication are commercially available 100 nm thick silicon nitride membranes covering a 250x250 μm^2 window in a 100 μm thick silicon substrate. According to the number of electrodes, the micro-lens and the mini-lens are pre-assembled to stacks of two and three building blocks respectively, using vacuum compatible epoxy. The fabrication procedure is summarized in Fig. 3.

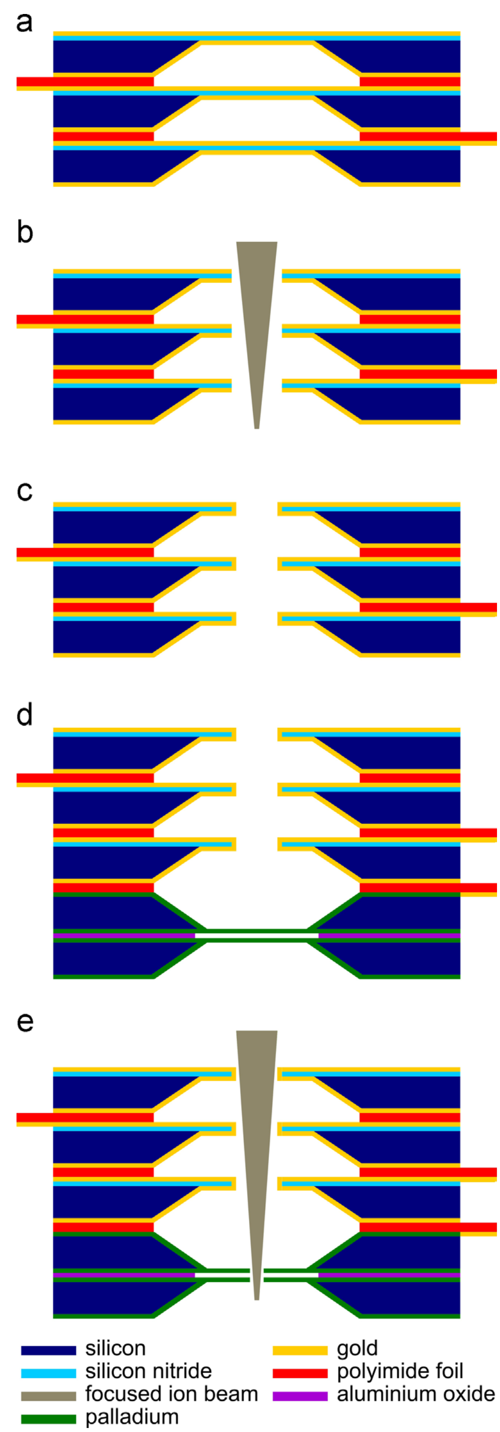

Fig. 3. Illustration of the micro-column fabrication procedure. (a) Three silicon chips are stacked for the mini-lens fabrication. (b) The apertures of the mini-lens are milled using a focused gallium ion beam. (c) The apertures are sputter coated with gold to cover the silicon nitride revealed during milling. (d) The micro-lens stack is bonded to the mini-lens. (e) Finally the micro-lens apertures are milled via the mini-lens apertures.