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Concept and design of a beam blanker with integrated photoconductive switch for ultrafast electron microscopy

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ABSTRACT

We present a new method to create ultrashort electron pulses by integrating a photoconductive switch with an electrostatic deflector. This paper discusses the feasibility of such a system by analytical and numerical calculations. We argue that ultrafast electron pulses can be achieved for micrometer scale dimensions of the blanker, which are feasible with MEMS-based fabrication technology. According to basic models, the design presented in this paper is capable of generating 100 fs electron pulses with spatial resolutions of less than 10 nm. Our concept for an ultrafast beam blanker (UFB) may provide an attractive alternative to perform ultrafast electron microscopy, as it does not require modification of the microscope nor realignment between DC and pulsed mode of operation. Moreover, only low laser pulse energies are required. Due to its small dimensions the UFB can be inserted in the beam line of a commercial microscope via standard entry ports for blankers or variable apertures. The use of a photoconductive switch ensures minimal jitter between laser and electron pulses.

1. Introduction

Ultrafast electron microscopy (UEM) is an emerging field where the aim is to achieve sub-picosecond temporal resolution with spatial resolution in the nanometer scale. This capability enables imaging in space and time of phenomena such as spin dynamics [1], excited state dynamics [2], optical near fields [3–6], quantum optical effects [7] and motion of atoms [8]. Almost all applications of UEM rely on pump-probe experiments, where a laser pulse serves as the pump modifying the characteristics of the sample and the electron pulse probes the relaxation of the sample towards equilibrium. Thus, accurate, preferably jitter-free, locking of the ultrashort electron pulses to a laser clocking pulse is of paramount importance. Also, the repetition rate of the electron pulses should be equal to the repetition rate of the laser.

Typically, pulsed electron beams are created by modifying the source unit of an electron microscope (EM) to allow laser-triggered emission. For example, a flat photocathode illuminated with a femtosecond laser can be employed to create femtosecond electron pulses [9]. However, flat photocathodes have a low brightness. For this reason tip based photo-field emitters are used [10–12], which can have brightness values comparable to regularly used Schottky emitters [13] as measured by Feist et al. [14] and also by Dominik et al. because coherence is related to the reduced brightness [15].

A known alternative to a laser triggered source is the use of a beam blanker. Beam blankers allow both pulsed electron beam operation for time-resolved measurements and DC operation mode for normal imaging, where a user can relatively quickly switch between both modes of operation. For a laser triggered Schottky source, switching between DC and pulsed modes of operation can take up to 1 h [14]. Beam blankers based using microwave cavities to create ultrashort electron pulses were envisioned and realized by Oldfield [16] and Ura and co-workers. In this way, electron pulses of 200 fs were created [17]. At that time, the electron pulses were used to measure switching speeds in electronic circuits and transistors by means of voltage contrast [18,19]. Lassise et al. and van Rens et al. calculated that a TEM_{110} cavity positioned conjugate to the electron beam focal point is able to create ultrashort electron pulses while maintaining the brightness of the continuous electron beam, recently such a TEM_{110} cavity is incorporated in a commercial TEM [20–22]. Advances in technology now allow synchronization between an RF microwave cavity and a laser clock pulse to values of 100 fs and shorter, where additionally care has to be taken to match the GHz microwave frequency to typical MHz laser repetition rates [23,24]. Beam blanking triggered by a laser clocking pulse would directly and in a straightforward way synchronize electron and laser pulses.

Here, we present such an approach to create ultrafast electron pulses with a laser-triggered beam blanker. In our concept fem-

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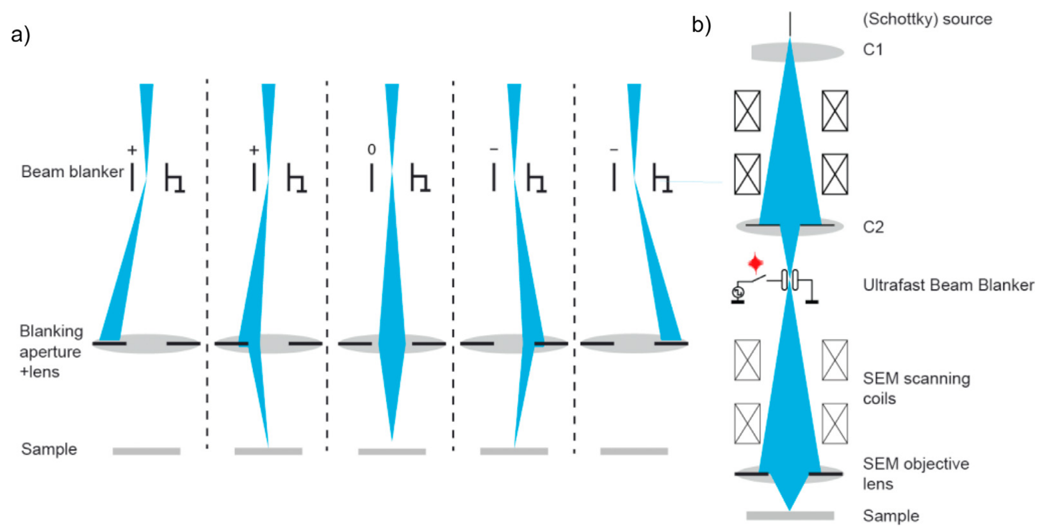

Fig. 1. (a) Schematic drawing indicating conjugate beam blanking using an electrostatic deflector to sweep the electron beam over a blanking aperture. The deflector is in a conjugate plane with respect to the image/sample plane to ensure that the electron probe is always at the same location at the sample irrespective of the electric field strength in the deflector, neglecting abberations of the objective lens. (b) System overview of a commercial SEM, which can have a high brightness Schottky electron source. C1 and C2 denote condenser lenses to focus the electron beam between the blanker plates. The UFB is positioned at the standard entry port for blankers or variable apertures.

tosecond electron pulses are achieved through a combination of an electrostatic beam blanker and a photoconductive switch illuminated with femtosecond laser pulses [25]. The use of a photoconductive switch enables miniaturization of the ultrafast beam blanker (UFB) such that it can be directly inserted in an existing, commercial EM. Also the UFB is jitter-free locked to the laser pulse, essential for achieving electron pulses deep in the femtosecond time range. We will first present the concept of our UFB and discuss the basic requirements for realization. We will then turn more in-depth to the requirements on the photoconductive switch and physical properties of available materials, which leads to a set of parameters for the actual design. Based on these we derive the spatial and temporal resolution that could be achieved with such a design. This shows that electron pulses in the 100 femtosecond time range with sub-10 nm spatial resolutions may be feasible.

2. UFB concept and requirements

Electrostatic beam blankers are commonly used in EM's to ensure that the sample is exposed to the electron beam only when demanded, for example for electron-beam lithography. In such a blanker the electron beam is deflected and then blocked by an aperture. The preferred position for the blanker is in a plane conjugate to the image plane located at the sample, as indicated in Fig. 1 [26,24]. This ensures that the position of the electron spot is at a steady position at the sample while the blanker deflects the electron beam. We want to use this same concept to generate femtosecond electron pulses, sweeping the electron beam over an aperture in (sub-) picosecond time scales.

A first requirement for our beam blanker is that the electron beam sweeps back and forth over the aperture at (sub-)picosecond timescales. Obviously, this needs inversion of the voltage over the deflector. As we want to synchronize the electron pulses to the output of a femtosecond laser (see details later), another important requirement is that the electron pulses are generated at a rate equal to the repetition rate of the laser. In order to sweep the electron beam ultrafast over the aperture in both positive and negative direction, we propose the innovative scheme shown in Fig. 2.

By electrically connecting the photoconductive switch and beam deflector in series, the voltage at the feed plate can be inverted each time the switch has been illuminated with the laser pulse. For this to be possible the photoconductive switch has to return to its insulating state after laser illumination on a timescale fast compared to the interval between the laser pulses. In that case the voltage at the feed plate can be inverted while the voltage at the deflector plate remains constant. This then ensures that the electron beam is swept over the blanker aperture in opposite directions for consecutive laser pulses. Hence, below the blanking aperture we will generate electron pulses at a repetition rate equal to the femtosecond laser system.

To increase the average current in the pulsed electron beam, it is advantageous to work at highest possible laser repetition rates, in practice about 100 MHz. This requirement limits the pulse energy available for operating the photoconductive switch to the nanojoule range, as this is the typical operation energy for high repetition rate femtosecond lasers.

For pump-probe measurements with a laser and electron pulse the temporal resolution is not only set by the electron pulse length but also by the amount of jitter between the laser pulse and electron pulse. The latter requirement of minimal jitter is relatively easily satisfied because we use a photoconductive switch illuminated with a laser pulse to change the deflection voltage at the beam blanker. In other words there is a direct link between the laser pulse and the change in voltage. A minimal amount of timing jitter is still present, we will discuss this at the end of the paper.

In general, for photoconductive switches, a short recombination time is important to generate short voltage pulses. However, in our case this is not important, because we directly connect the photoconductive switch to the beam blanker (see Fig. 2) and only use the rising part to charge the deflector plate and sweep the beam. When the laser illuminates the photoconductive switch, electrons are excited to the conduction band, and, under influence of the bias electric field, diffuse to the blanker plate and (de)charge it.

Finally, to create ultrashort electron pulses with the concept discussed here, it is essential that photoconductive switch and deflector have a short response time. For this reason we discuss the physical processes occurring in the photoconductive switch and resulting implications for the design in the next paragraphs. We start with a short literature discussion that shows that photoconductive switches are known to have ultrashort response times. We then discuss the requirements on the semiconductor material to be used