Broadband transmission grating spectrometer for measuring the emission spectrum of EUV sources

Extreme ultraviolet (EUV) light sources and their optimization for emission within a narrow wavelength band are essential in applications such as photolithography. Most light sources however also emit radiation outside this wavelength band and have a spectrum extending up to deep ultraviolet (DUV) wavelengths. This out-of-band radiation can be hazardous in the rest of the lithography process, hence monitoring of it is necessary. In this article we present a broadband spectrometer based on a transmission grating for spectral monitoring of EUV sources from EUV to DUV wavelengths. The transmission geometry enables a compact design and a straightforward alignment. Measurements that were carried out with the spectrometer at two different EUV sources provide detailed spectral information that is immediately available for analysis and optimization of the source conditions.

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Extreme ultraviolet (EUV) light sources are currently of much interest for a number of scientific and high-tech applications such as free-electron laser research, astronomy, elemental fluorescence analysis and photolithography. The latter, which will be under focus in this article, is a process to fabricate integrated circuit chips to be used virtually in all electronic devices. The EUV light sources for lithography are designed to emit at a wavelength of 13.5 nm but they inevitably emit also at some longer wavelengths. For achieving a high throughput of integrated circuit chips in the lithography process, it is important to maximize the emission in a narrow wavelength band (called in-band and defined as 2 % bandwidth around the central 13.5 nm) and conversely to minimize parasitic emission at other wavelengths. This need for critical optimization implies a demand for spectral diagnostic of the source with high precision. In the past, a team from the EUV community developed a measurement scheme comprising a monochromator, in the form of a EUV reflecting multilayer mirror, and a detector, based on a filtered photodiode. This compact scheme enabled the measurement of in-band EUV source emission and allowed a worldwide benchmarking of EUV sources under development in those days [1]. This device and the benchmarking action, nicknamed Flying Circus (FC), due to its mobile nature, was very successful as it allowed a true performance comparison of the EUV light sources around the world. Moreover, it managed to unify the many different measurement methods used by the source manufacturers and as a consequence set a measurement standard that is maintained up to present. Currently, source manufacturers are developing in-band detectors that are very similar to the FC measurement scheme.

In contrast to the success of the in-band measurements, no information could be collected on the parasitic out-of-band light that may cause undesired exposure of the light sensitive photoresist in the lithography process. Assessment of the undesired out-of-band light requires a

Box 1: Transmission grating spectrometer

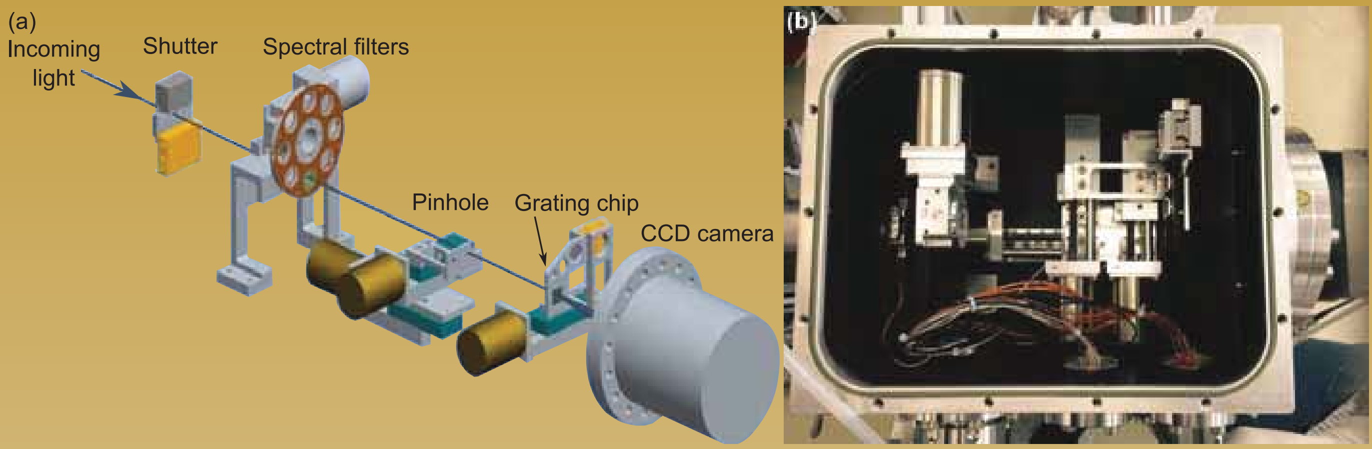

Figure 1 **(a) Schematic drawing of the components of the spectrometer. (b) Top-view picture showing the spectrometer vacuum chamber and the components in it.**

The inner structure of our spectrometer, as shown in figure 1(a), comprises a shutter at the entrance of the spectrometer, a filter wheel for selecting specific wavelength bands from the source spectrum, a pinhole or a slit, a transmission grating chip for dispersing the light and a detector that is a back-illuminated CCD camera for detection of the spectrum. The light from the EUV source is directed to the grating which diffracts each wavelength at a different angle towards the CCD camera: light with a long wavelength is diffracted at larger angles. Consequently the spectral content of the incoming beam can be calculated back from the image recorded by the CCD camera. All the components of the spectrometer are contained in a vacuum chamber, figure 1(b), that is equipped with a turbomolecular pump (Pfeiffer HiCube 80 Eco) and a pressure gauge (Granville-Phillips 390 Micro-Ion ATM). The chamber can be pumped down to 10^{-6} mbar and used in a differential pumping configuration with ultra-high-vacuum source chambers. The inner walls of the vacuum chamber are blackened by anodization for stray light suppression. The components in the vacuum chamber are mounted on vacuum-compatible motorized translation stages that can be controlled with a computer using a graphical user interface. The control system allows automated and in situ alignment with ease. A typical measurement setup where the spectrometer is mounted to a EUV light source is shown in figure 2.

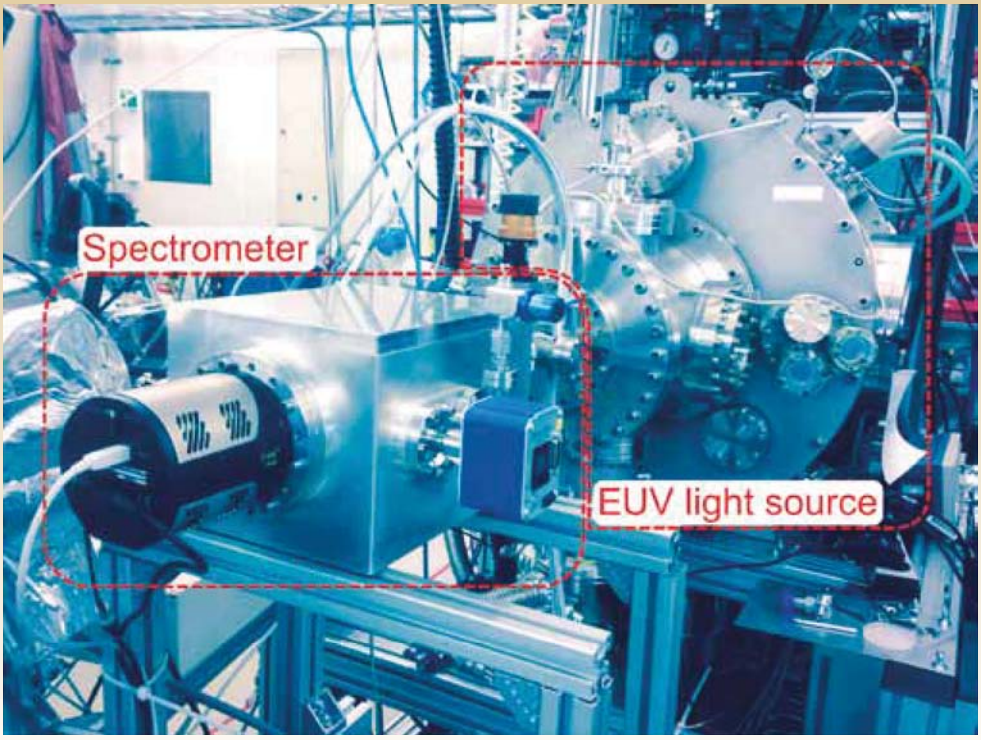

Figure 2 **A typical measurement setup with the spectrometer.**

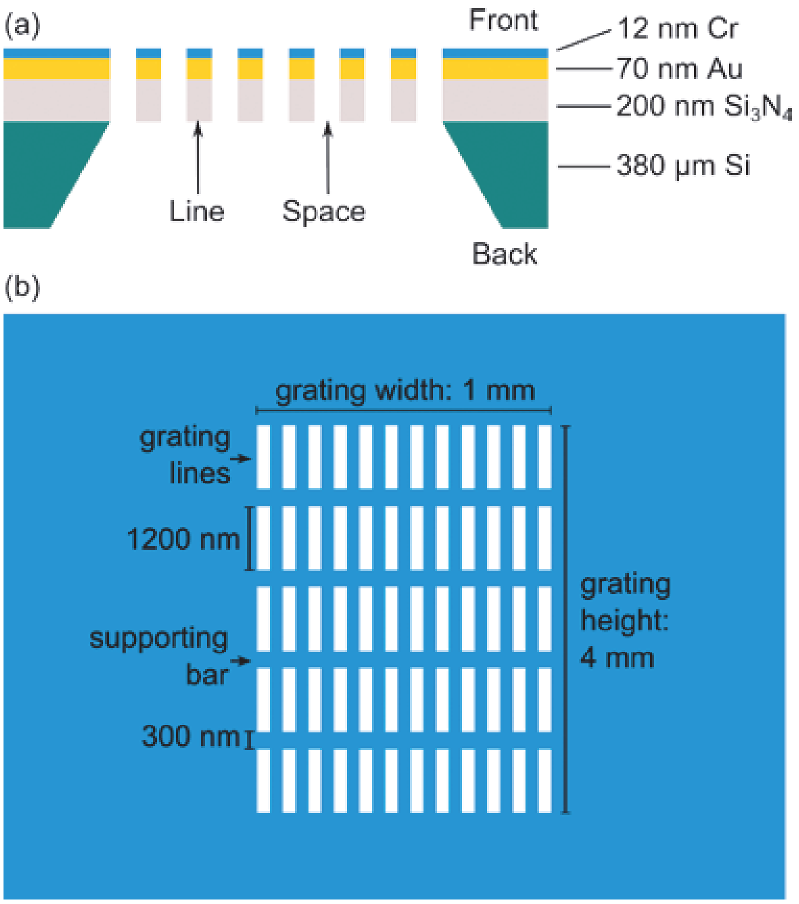

Figure 3 **(a) Cross-section and (b) front view from part of a single grating.**

broadband measurement method since the out-of-band spectrum spans a very broad wavelength range, from EUV to deep ultraviolet (DUV) wavelengths. Spectrometers are highly relevant for this purpose as they allow to disperse incoming light into its spectrum and measure the power level for each wavelength. However, currently available spectrometers have several disadvantages: typically they work in reflection mode using a grazing incidence geometry that leads to bulky designs and difficulties in alignment.

Transmission grating spectrometer

In this article, we present a compact and easy-to-align spectrometer based on a transmission grating (see box 1) and show the measured in-band and out-of-band spectra of two different EUV light sources. The spectral range and the spectral resolution is mainly determined by the line density of the grating. The grating chip contains an array of gratings with different line densities. Gratings with a specific line density can be selected *in situ* via the graphical user interface, allowing easy adjustment of the spectral range and the spectral resolution. With these features, the spectrometer allows direct measurement of both the in-band and out-of-band spectrum, the pulse-to-pulse intensity stability, the source size and source-facing condenser lifetime/cleanliness. When the light source is measured from its different ports, it is also possible to determine the angular distribution of the source output.

Structure of the high resolution transmission grating

As the transmission grating is one of the most essential components in the spectrometer, we first explain the structure of such a grating and then its fabrication process. The cross-section and front view of the grating is shown schematically in figure 3. As shown in figure 3(a), the free-standing grating comprises a 12 nm thick Cr layer, a 70 nm thick Au layer and a 200 nm thick Si_3N_4 layer that are carried by a frame of a 380 µm thick Si substrate. These specific materials and thicknesses are chosen to yield a flat transmission efficiency curve down to a wavelength of 10 nm. The overall dimensions of a single grating, shown in figure 3(b), are 1 mm × 4 mm, and it is divided into smaller areas that are 1200 nm high and separated by 300 nm high support bars. The support bars are necessary in order to increase the mechanical stability of individual grating lines that can be extremely fine in order to be able to resolve fine spectral features at short wavelengths. For instance, to achieve a spectral resolution of at least a few tenths of a nanometer at 13.5 nm wavelength, the grating period needs to be as small as 100 nm. For a 50 % bar-width-to-period ratio, the bar needs to have a very fine width of only 50 nm. This small dimension of the bar implies a very strict fabrication accuracy that is challenging even with state-of-the-art nanofabrication methods. Currently used methods for nanofabrication of high density transmission gratings include electron beam lithography (EBL) [2] and interference lithography [3, 4]. However, EBL is limited in terms of speed, and interference lithography is limited in terms of resolution.

Fabrication of the transmission gratings

For the fabrication of the gratings, we utilized UV based nanoimprint lithography (UV-NIL) that is especially suitable for our purpose since it has a comparable resolution to EBL and significantly higher speed. A summary of the fabrication process for the transmission gratings is shown in box 2 and figure 4, whereas the details can be found in [5].

A scanning electron microscopy (SEM) image of one of the 10,000 lpmm gratings is shown in figure 5. The SEM im-

Box 2: Fabrication of the transmission grating

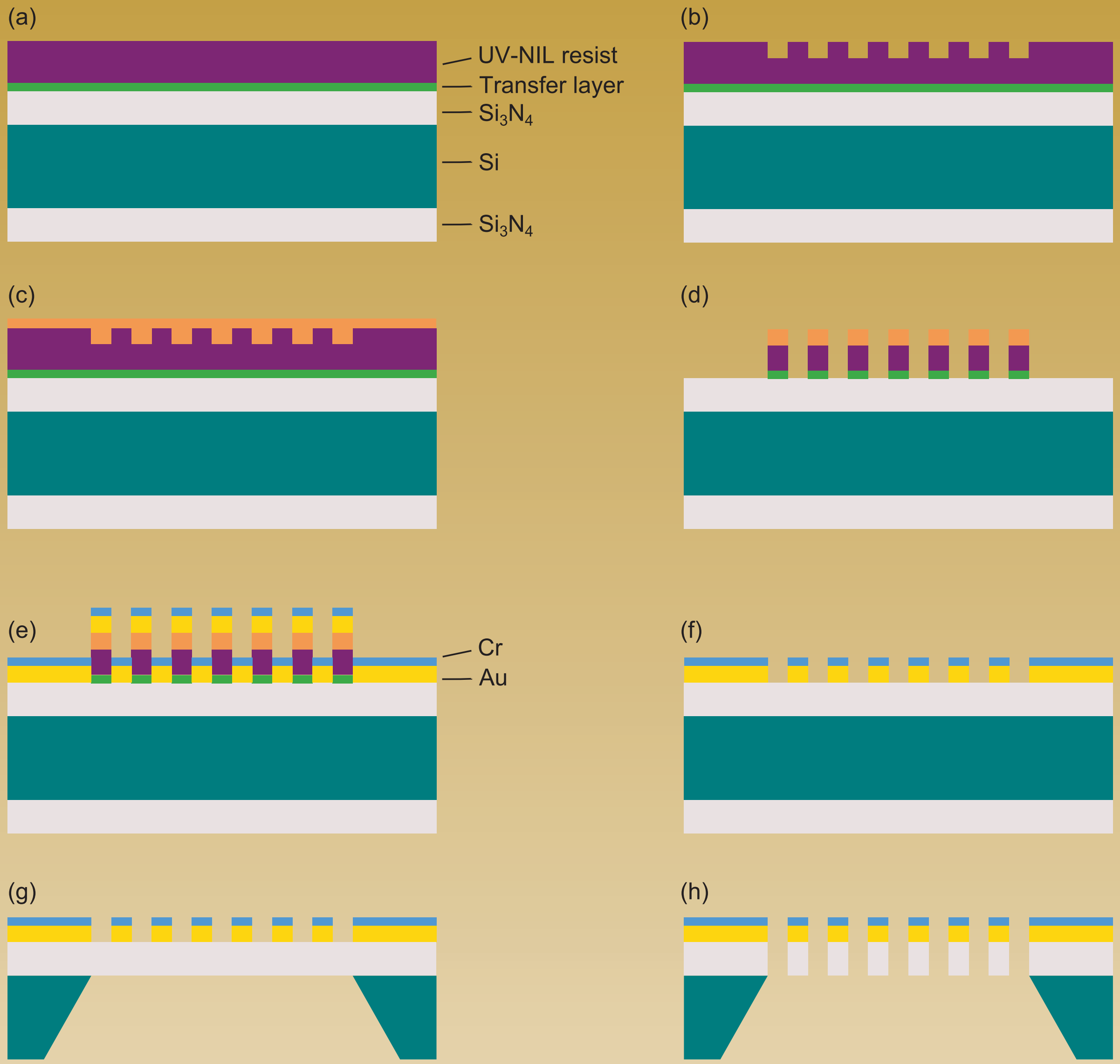

Figure 4 Eight steps, a-h, in the fabrication of the transmission grating.

In the first step of fabrication, a Si wafer is coated from both sides with 200 nm thick Si_3N_4 layers, followed by deposition of a 100 nm thick transfer layer and a UV-NIL resist layer to the front of the substrate [figure 4(a)]. In the second step, high-resolution grating patterns are defined by pressing the imprint template to the UV-NIL resist and curing with UV exposure. The imprint template has a 16 mm × 16 mm area that is containing 21 individual gratings arranged in a 3 by 7 matrix. Line densities of the gratings in the matrix are 500 lines per mm (lpmm), 780 lpmm, 1000 lpmm, 1500 lpmm, 1850 lpmm, 2000 lpmm, 2500 lpmm and starting from 3000 lpmm up to 10,000 lpmm (multiple from it) with 1000 lpmm increments [figure 4(b)]. A planarization layer is deposited [figure 4(c)], and the planarization layer, imprint resist and transfer layer over the patterned hills are removed by reactive ion etching (RIE) for the pattern transfer [figure 4(d)]. The Au absorber layer (70 nm) and the Cr etch-stop layer (12 nm) are deposited using metal evaporation [figure 4(e)]. In the following, a lift-off step is used to define the Au absorber layer and the Cr etch-mask [figure 4(f)]. The openings for the individual gratings (1 mm × 4 mm size) at the back are formed by photolithography and etching [figure 4(g)]. In the final step, the top Si_3N_4 layer is removed by RIE from the front using the Cr layer as the etch-mask [figure 4(h)].

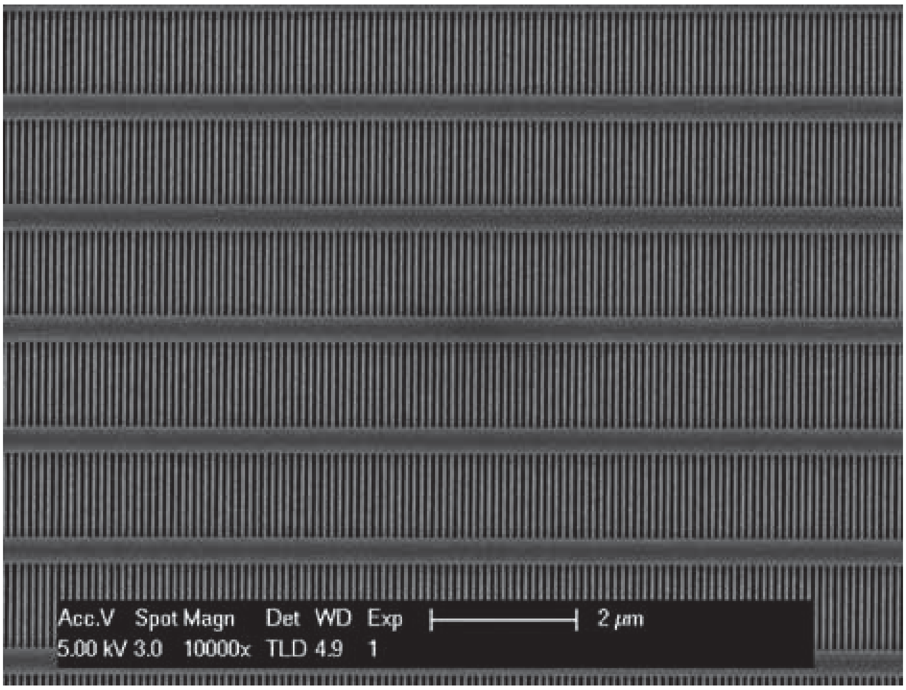

Figure 5 **Scanning electron microscopy image of the fabricated 10,000 lpmm gratings.**

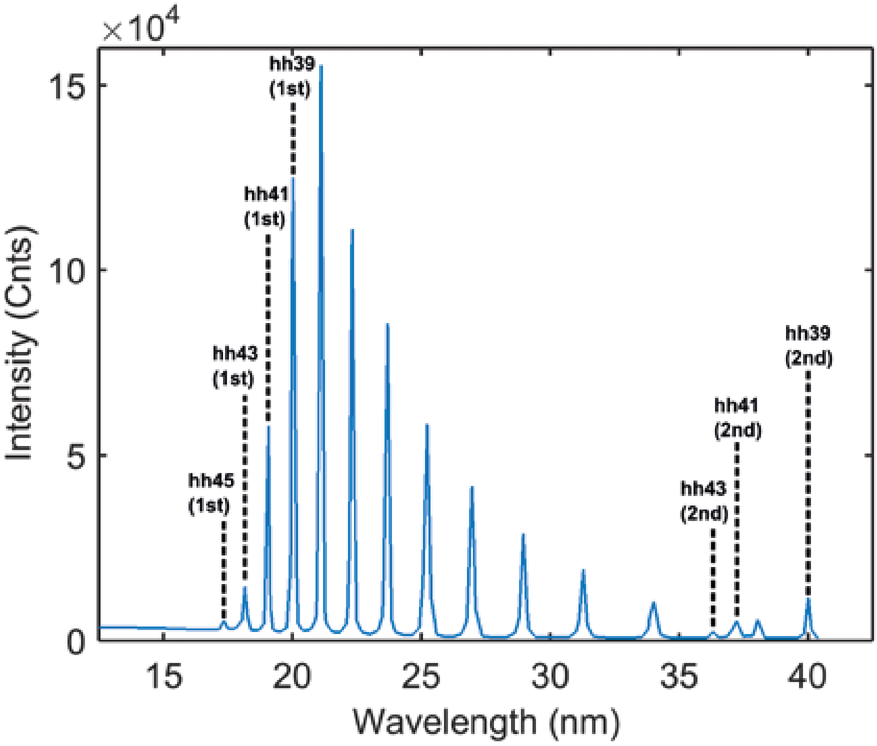

Figure 6 **Spectral measurement of a high harmonic generation light source in the extreme ultraviolet wavelength range. Spectral peaks up to the 45th harmonic and their second diffraction orders are labeled [5].**

age shows that the fine vertical grating lines are periodic and also the line edge roughness is rather low. Both of these observations demonstrate the success of the UV-NIL method in fabricating high resolution gratings and are important for enhancing the performance of the spectrometer.

Spectral measurements and discussion

Spectral measurements were performed at two different sources. The first source is a high harmonic generation (HHG) source in which the radiation is generated in the highly non-linear interaction of a focused high intensity beam from an infrared (IR), ultrashort pulse laser and a gas medium, typically a noble gas. The radiation produced in the HHG process is broadband including EUV wavelengths and comprises narrow spectral peaks occurring at the odd integer fractions of the focused laser wavelength, i.e. odd harmonics of the focused laser frequency. In this measurement EUV radiation was produced by focusing a Ti:Saphire IR laser with 780 nm central wavelength to a Ne gaseous medium. With this setup [5], it is expected theoretically to observe up to the 45th harmonic order which corresponds to 17.5 nm wavelength. In the spectral measurement, two 200 µm Al filters were used to block the IR beam that is co-propagating with the HHG radiation. An important point in this measurement is that the peaks in the HHG spectrum are very narrow and can be used to demonstrate the high spectral resolution of the spectrometer. The measured spectrum in figure 6 reveals the distinct spectral peaks of the HHG radiation and demonstrates that the spectrometer can resolve each peak successfully. It is possible to identify the highest harmonic (45th harmonic) at 17.5 nm wavelength as expected theoretically. Also the second diffraction orders of the harmonics are visible in the spectrum. The spectral resolution determined from the full-width-at-half-maximum of the strongest harmonic order, i.e. 37th harmonic, at 21.1 nm is found to be 0.13 nm. This fine resolution capability of the spectrometer can be extremely useful in identifying very narrow spectral features such as atomic line transitions at EUV wavelengths.

The second source that was measured is a laser produced plasma (LPP) source

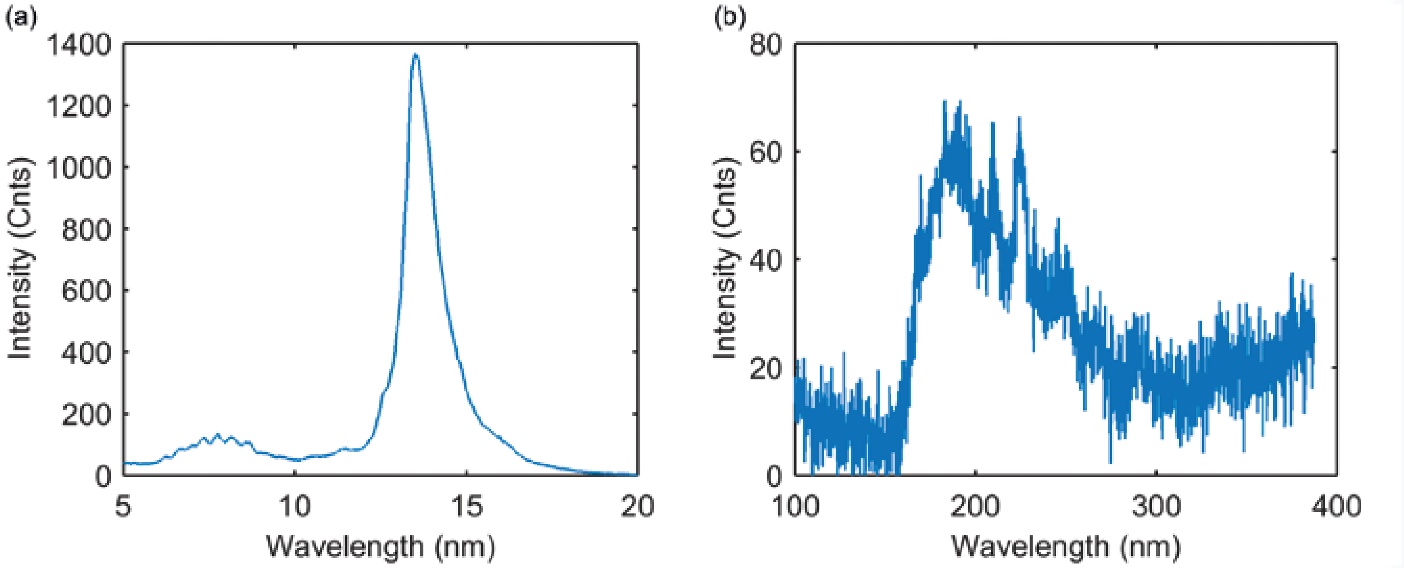

Figure 7 **Spectral measurement of a laser produced plasma source in the (a) extreme ultraviolet and (b) deep ultraviolet wavelengths.**

in which a pulsed, high power IR laser is focused onto molten droplets of tin to produce a highly ionized plasma. The resulting plasma emits strongly around 13.5 nm wavelength, and also at shorter and longer wavelengths, though weakly. In figure 7, two different spectra measured from the LPP source are shown. The EUV spectrum in figure 7(a) shows a strong peak at 13.5 nm as expected, but also reveals intensity peaks in the 5 nm to 8 nm wavelength band, apparently due to higher ionization stages in the tin plasma. This is a valuable information for further development of the EUV source as there is still room for enhancing the intensity at the 13.5 nm wavelength through optimization of the plasma conditions. For the same LPP source the DUV spectrum is also measured by changing *in situ* to a coarser grating. The level of intensity in this wavelength range is much lower compared to the 13.5 nm wavelength, so a quartz filter is used to suppress the 13.5 nm peak and a long exposure (10 s) is used to bring the DUV intensity above the noise level. The quartz filter efficiently suppresses the 13.5 nm peak and allows observation of the emission spectrum above 150 nm. The DUV spectrum presented in figure 7(b) has a distinguishable increase in the intensity for wavelengths longer than 150 nm as an indication of the transmission behaviour of the quartz filter and shows many spectral features of the source spectrum.

In conclusion, we have presented a micro-mechanical vacuum based broadband spectrometer using proprietary high resolution transmission gratings for monitoring the spectral emission of EUV sources. With the spectrometer it is possible to resolve very fine spectral features as narrow as 0.13 nm, enabling detailed spectral analysis. The spectrometer enables to record both EUV and DUV spectra of EUV light sources with *in situ* exchange of gratings. The spectrometer provides broadband spectral information to make an in-depth analysis of the plasma conditions and optimize the light source for enhanced EUV emission.

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