Coherent EUV Light Source by High Harmonic Generation for EUV Metrology

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Abstract: Coherent extreme ultraviolet (EUV) light was generated by high harmonic generation in Ne gas from a mode-locked Ti:Sapphire laser with a pulse width of 35 fs at 796 nm. The EUV light was analyzed by an EUV spectrometer to have a peak wavelength of 13.5 nm corresponding to the 59th harmonics of the fundamental beam. The energy of the EUV light was measured by an EUV photodiode to be 428 pJ. This coherent EUV light source is expected to be used for EUV metrology to inspect EUV masks.

Key-Words: coherent, EUV, high harmonic generation, mode-locked, Ti:Sapphire laser, spectrometer

1 Introduction

As higher resolution is required for semiconductor processes for higher density integration, the light source for lithography has also evolved from Hg g-line(435nm) for 1.2 µm, Hg i-line(365nm) for 0.8 µm, KrF laser (248nm) for 0.13 µm, and ArF laser (193nm) for 90 nm[1]. Moreover, as the light source technology has confronted the limit, additional techniques were developed to obtain higher resolution than 90 nm such as the immersion lithography and the double patterning lithography [2]. However, to obtain higher resolution it is inevitable to make a quantum leap which can change the paradigm in the lithography technology introducing various new technologies called the NGL (Next Generation Lithography) including the EPL (Electron Projection Lithography, ML2 (Mask-Less Lithography), PEL (Proximity Electron-beam Lithography), PXL (Proximity X-ray Lithography), EBDW (Electron-beam Direct Writing), and the EUVL (Extreme Ultraviolet Lithography) [3].

EUVL (13.5 nm) is considered as the most promising technology capable of mass production and various studies have been carried out all over the world and recently major semiconductor companies have introduced EUVL equipments and are in the pilot production stage. The main difference of EUV from conventional lithography is that it must adopt the reflective optics instead of the transmission optics since there is no material to be used as an EUV lens. Moreover, EUVL uses reflective-type masks which must be inspected at the actinic wavelength (same wavelength as that of the lithography light source).

Various mask inspection tools have been developed such as dark-field inspection tool using Schwarzschild optics, EUV microscope using Fresnel zone plate, EUV microscope using EUV zooming tube [4]. However, the optics in these inspection tools are very difficult to manufacture and align, and thus increasing the magnification is very limited. Another EUV inspection tool called the coherent scattering microscope (CSM) based on x-ray diffraction microscopy has no objective optics but requires coherent EUV light, which can be generated only by spatial filtering of radiation from a synchrotron or by high harmonic generation (HHG) from a high power femtosecond laser [5, 6].

In this paper, we generated coherent EUV light by HHG from a high power femtosecond laser and characterized it by EUV CCD camera, EUV energy meter, and EUV spectrometer.

2 Experimental Setup

Figure 1 shows the experimental setup for the EUV light source and characterization. A fundamental laser beam at 796 nm (35 fs, 5mJ, 1 kHz, Spectra-Physics) was incident into a Ne gas cell to generate high harmonic laser beam at EUV. The fundamental laser beam was spatially expanded two times to reduce the intensity and eliminate spectral broadening by self phase modulation at the vacuum chamber window which induces pulse broadening.
The laser beam was focused by a concave mirror with a long focal length around 150 cm to have a long depth of focus providing a long interaction length with the Ne atoms to maximize the HHG conversion efficiency. The gas cell was placed on a vacuum X-Y-Z stage to make fine adjustments without opening the vacuum chamber. Using a rotary pump and a turbo pump, we pumped out the air in the chamber down to 10^{-4} torr before introducing the Ne gas. The HHG EUV beam has the same direction, polarization, and phase as the fundamental laser beam and consists of only odd harmonics due to the isotropy of the gas atoms [6]. To eliminate the fundamental laser beam, we used two Zr filters with an extinction ratio of 10^{-6} at the EUV wavelength. We used an EUV CCD camera (PI-MTE, Princeton Instruments, 2048 x 2048 pixels, 27.6 x 27.6 mm) to detect the spatial profile of the EUV beam and to measure its spectrum in the EUV spectrometer. The diffraction grating (CN30-002, Shimadzu) in the EUV spectrometer was a flat field EUV grating with a line density of 1200 l/mm and a size of 50 x 30 x 10 mm. The grating was an aberration-corrected laminar-type replica diffraction grating with unequally spaced curved-grooves for flat-field polychromators suitable for detection at the flat CCD surface. The grating has less high-order light due to laminar type grooves configuration, low stray light by holographic manufacturing technology, high diffraction efficiency by Au coating, and high resolution from aspherical-wave exposure method. The grating was designed for wavelengths 5-20 nm to distribute between 83.0-77.1° at the incident angle of 87° as shown in Fig. 2.

3 Results and Discussions

Figure 3 shows the spatial profile of the HHG EUV beam detected by the EUV CCD camera for various pulse widths of the fundamental laser beam with the same pulse energy.
Figure 4 shows the EUV spectrum of the HHG EUV beam measured with the EUV spectrometer described above. We can find that high harmonics of the order of 45th (17.7 nm) to 63rd (12.6 nm) are observed with the peak wavelength at 59th (13.5 nm). The dotted line shows the theoretical values of the wavelength and consists well with our experimental values shown by the solid line.

Table 1. Theoretical values of the Harmonic order

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Wavelength (nm)</th>
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<tbody>
<tr>
<td>45</td>
<td>17.7</td>
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<tr>
<td>47</td>
<td>16.9</td>
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<tr>
<td>49</td>
<td>16.2</td>
</tr>
<tr>
<td>51</td>
<td>15.6</td>
</tr>
<tr>
<td>53</td>
<td>15.0</td>
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<tr>
<td>55</td>
<td>14.5</td>
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<tr>
<td>57</td>
<td>13.9</td>
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<tr>
<td>59</td>
<td>13.5</td>
</tr>
<tr>
<td>61</td>
<td>13.0</td>
</tr>
<tr>
<td>63</td>
<td>12.6</td>
</tr>
</tbody>
</table>

Table 1 shows the theoretical values of the wavelengths of the HHG EUV beam according to the harmonic orders shown on Fig. 4 as the dotted lines as described above.

The total pulse energy of the EUV beam was measured by an EUV photodiode to be 428 pJ corresponding to an average power of 428 nW, while the pulse energy of the 59th harmonics only was measured to be 60 pJ corresponding to an average power of 60 nW, which shows a HHG conversion efficiency of 0.8x10^-8.

4 Conclusion

We generated coherent EUV light by high harmonic generation in Ne gas from a mode-locked Ti:Sapphire laser with a pulse width of 35 fs and a pulse energy of 5 mJ operating at 1 kHz at 796 nm. The EUV spectrum of the HHG beam was analyzed by an EUV spectrometer to distribute between 12.6 nm (63rd) and 17.7 nm (45th) with the peak wavelength at 13.5 nm (59th), which coincided well with the theoretical values of the HHG wavelengths. The total pulse energy of the EUV beam was measured to be 428 pJ (428 nW), while the pulse energy of the 59th harmonics was measured to be 60 pJ (60 nW), which shows a HHG conversion efficiency of 0.8x10^-8.

We expect this coherent EUV light source to be used for EUV metrology in coherent inspection tools such as the CSM to inspect EUV masks.

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References:


