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EUV Generation by plasmonic field enhancement using nanostructures

Seunghwoi Han^a, Hyunwoong Kim^a, Young-Jin Kim^b and Seung-Woo Kim^{a,*}

^aDepartment of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, 305-701, South Korea

^bNanyang Technological University (NTU), 50 Nanyang Avenue, Singapore

ABSTRACT

Plasmonic field enhancement using metal nanostructures is investigated to boost the peak intensity of the incident femtosecond laser by a factor of greater than 20 dB while retaining the original ultrashort pulse dynamics. This method enables extreme ultraviolet (EUV) light generation directly from moderate femtosecond pulses of $\sim 1 \times 10^{11}$ W/cm² intensities without auxiliary power amplification, demonstrating a possibility of achieving robust and reproducible EUV sources of the nano-scale for diverse EUV applications for microscopy, lithography and spectroscopy.

Keywords: EUV light source, plasmonic field enhancement, femtosecond pulse lasers.

1. INTRODUCTION

EUV light in the wavelength range of 10 – 120 nm is produced from gaseous atoms or bulk crystalline solids with injection of a strong laser field of greater than 10^{13} W/cm² intensities. Such intense laser fields are attained preferably by chirped pulse amplification (CPA) of femtosecond light pulses. Recently plasmonic field enhancement using nanostructures draws attention because it is capable of uplifting the peak intensity of femtosecond pulses by a factor of greater than 20 dB without auxiliary power amplification. Accordingly, the nanostructure-based field enhancement allows moderate pulses emanated from a standard oscillator to be employed directly for generation of laser-induced EUV light. This method requires no reduction of the pulse repetition rate of more than tens of MHz, while the enhanced field retains the ultrashort pulse dynamics of the original laser pulses without dephasing. Further, the resulting EUV source size is narrowly localized on sub-wavelength length scales, providing unique possibilities to perform nano-scale spectroscopy, imaging, lithography, and atto-second physics. In the last few years the realization of plasmonic field enhancement for EUV generation was investigated mainly using metallic bow-tie and funnel-waveguide nanostructures which are found robust and reproducible when thermal damage is avoided by restricting peak intensities to be ~ 50 TW/cm² [1,2]

In this presentation the potential of nanostructure-based field enhancement is explored as a new method of EUV generation using a standard oscillator emitting moderate pulses of $\sim 1 \times 10^{11}$ W/cm² intensities without auxiliary power amplification. To this end, three subjects are addressed in sequence. Firstly, the femtosecond laser technology is deliberated for efficient generation of laser-induced EUV light sources. Secondly, the plasmonic field enhancement process is described with bow-tie nanostructures designed and fabricated for optimum EUV light conversion. Finally, experimental results are discussed with emphasis on the possibility to achieve nano-scale EUV light sources for applications such as imaging, lithography and materials fabrication.

2. NANOSTRUCTURES

Laser-induced EUV generation requires intense laser fields with intensities of $\sim 1 \times 10^{13}$ W/cm² or stronger for ionization of neutral gaseous atoms. Therefore, nanostructures to be used for EUV generation from a standard oscillator should be capable of enhancing the incident laser intensity field at least by a factor of 20 dB. Such nanostructures are made of metals such as Ag and Au, of which the field enhancement mechanism is explained by resonance oscillation of free electrons in the form of localized surface plasmons (LSPs) or surface plasmon polaritons (SPPs). Being coupled to the incident laser, LSPs are generated stationary within the metal surface, while SPPs are formed to propagate along the dielectric-metal interface. Figure 1 shows a bow-tie specimen prepared to work on LSPs. The specimen comprises 500

bow-tie nanostructures arranged in a 2-D array with periods of 500 nm and 600 nm in the lateral x- and y-direction, respectively. The bow-tie nanostructure is designed through trial and error using finite difference time domain (FDTD) simulation so as to maximize the hot-spot volume of above 20 dB intensity enhancement. The result is a particular shape characterized by the dimensions; thickness $t = 135$ nm, length $l = 175$ nm, vertex angle $\theta = 55^\circ$, gap distance $d = 15$ nm. The bow-tie structure is fabricated using the focused-ion-beam (FIB) process on a sapphire substrate covered with a thin Au layer of 135 nm. The fabricated specimen is coated with a SiO_2 thin film of 5 nm thickness to strengthen the thermal durability against melting so that the incident laser intensity can be increased above 0.5 TW/cm^2 without thermal damage. FDTD calculation predicts that a single bow-tie sustains a hot-spot volume of $150,000 \text{ nm}^3$.

Another type of nanostructure referred to as the funnel-waveguide used for our experiments is described in detail in ref [3]. This 3-D nanostructure works on SPPs, of which the spatiotemporal characteristics of the enhanced field are well verified using FDTD calculations together with two-photon photoluminescence experiments. Both of the observations agreed well with the fact that the intensity enhancement of ~ 300 is induced in the hot spot of the funnel-waveguide, which is strong enough for EUV generation with enhanced field intensities above 10 TW/cm^2 .

Figure 1. Bow-tie nanostructures; SEM images of top view (top left) and tilted view (top right). Field enhancement by FDTD calculation (bottom left) and major dimensional parameters (bottom right)

3. EXPERIMENTS

EUV light is strongly absorbed by gas molecules in air, thus a good level vacuum less than 10^{-3} torr is needed for its generation and subsequent uses. Fig. 2 depicts the vacuum chamber system designed for our experiments, which is comprised of three main sub-chambers; the source chamber, intermediate chamber and detector chamber. The source chamber is the place where the nanostructure is illuminated by the incident femtosecond laser and at the same time noble gases are injected on the nanostructure through a nozzle of $50 \mu\text{m}$ with backing pressure up to 15 bars. The intermediate chamber inserted in the middle of the whole chamber system accommodates a toroidal mirror which collects the EUV radiation from the nanostructure with an extended acceptance angle. Then collected photons are refocused by the same toroidal mirror on to the entrance slit aperture of the diffraction grating. Finally, the detector chamber is equipped with a MCP (micro-channel plate) attached to a CCD (charge coupled detector) camera to monitor the power spectrum of the EUV radiation spread by the diffraction grating along the Rowland circle. The three sub-chambers are differentially pumped using multiple turbo-type vacuum pumps, so the relatively high pressure of the source chamber which is inevitably raised to 10^{-3} torr due to the injection of noble gases on the nanostructure is not transferred to the detector

chamber which requires 10^{-6} torr vacuum for proper operation of the MCP screen. Detailed technical specifications of each sub-chamber are summarized in Table 1.

Figure 2. Overall hardware configuration for EUV generation and spectrum measurement.

Table 1. Major specifications for the chamber system for EUV generation and spectrometry.

1. Three-stage differential pumping for high pressure gas supply & low noise EUV detection: <ul style="list-style-type: none"> - Source chamber: 10^{-3} torr for up to 10 bar gas pressure - Intermediate chamber: two slits installed sequentially with three separate turbo-pumps - Detector chamber: 10^{-6} torr for effective MCP operation
2. Grazing (84 degree) diffraction grating for high EUV efficiency: <ul style="list-style-type: none"> - Wavelength range: 20 – 300 nm (0.1 nm resolution) - Diffraction efficiency at 40 nm wavelength: > 0.2 - An auxiliary grating for detection of soft X-ray wavelengths (< 20 nm)
3. Multiple sensors installed in the detector chamber: <ul style="list-style-type: none"> - MCP with a CCD camera - X-ray CCD camera - PMT (photo-multiplier tube)

4. DISCUSSIONS AND SUMMARY

EUV spectra were monitored from He, Ne, Ar, Kr and Xe gases while the backing pressure set to inject the gases on to the nanostructures was varied so as to maximize the EUV radiation yield. Fig. 3 shows an exemplary EUV spectrum obtained from the bow-tie specimen with injection of Ar gas. The absolute wavelength position of the used spectrometer system was calibrated with reference to well-identified plasma lines of He, Ne and Ar gases. Our experiments revealed that the bow-tie nanostructure is robust enough to attain reproducible EUV generation with field enhancement reaching more than 20 dB in the hot spot volume to providing intensities above 10 TW/cm^2 to induce tunneling ionization. Measured EUV spectra appear to be strongly related to fluorescent ALE (atomic line emission) of neutral and ionized atoms, unlike typical EUV spectra obtained from gaseous atoms by high harmonic generation (HHG). Nonetheless, EUV peaks are observed for short wavelengths (<50 nm), indicating that the enhanced field in the bow-tie nanostructure well exceeds the ionization threshold of neutral Ar atoms. The ALE dominance may be attributable to the small size of the hot volume which restricts the interaction length between the gas atoms with the enhanced field which has to be extended to achieve a sufficient amount of coherent build-up of the HHG signals [4-6]. Furthermore, the high repetition rate of the incident laser pulses near 100 MHz tends to provoke plasma formation resulting in severe incoherent fluorescent ALE emission [7]. Similar observations for the coexistence of HHG signals with ALE emission were reported with Xe gas [8-10].

In the process of laser-induced EUV generation from gaseous atoms, it is not in contradiction to observe both coherent HHG signal and incoherent fluorescent emission together at the same time since they both are produced at laser intensities above the ionization threshold. Moreover, ALE-dominant EUV emission may maintain a high level of

coherence, due to enhanced atomic resonance by means of high-repetition stimulation by strong laser pulses. Further work is being underway for more precise evaluation of the coherence of EUV radiation from nanostructures by diffraction microscopy using different laser sources. In addition, theoretical work is being conducted to establish a more comprehensive model of EUV generation which enables one to estimate the coherence of both the HHG and ALE emission processes. Another way of reducing ALE emission is to replace gaseous atoms with solid targets of crystals or dielectric materials which are capable of emitting coherent HHG radiation by means of Bloch oscillations within bounded lattice structures.

In conclusion, even though plasmonic EUV generation may not be competitive with well-established conventional methods in terms of the signal coherence and yield, it may offer unique advantages owing to its capabilities of enduring high repetition pulse rates from tens of MHz to few GHz regime and also confining EUV generation to the field enhanced hot volume of small source sizes. This optimistic view leads to more experimental and theoretical investigations, which will turn into reality the possibilities of achieving robust and reproducible EUV sources of the nano-scale for diverse EUV applications for microscopy, lithography and spectroscopy.

Figure 3. Optical spectrum of EUV radiation generated from Ar gas using bow-ties.

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