M7: EUV Lab Course Instructions

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1. EUV/XUV Radiation and Its Applications

Extreme ultraviolet radiation (EUV or XUV) is the electromagnetic radiation in the spectral range between vacuum ultraviolet and soft x-rays. Therefore, as shown in Figure 1, its photon energy extends from 30 eV to 250 eV (spectral range between 5 nm to 40 nm) [1]. The radiation in this specific spectral region is absorbed by most of materials within nanometers or micrometers. This historically limited the development of EUV applications. However, with the short wavelength, EUV light has the potential to reveal and modify small structures as in microscopy and lithography with resolution down to several nanometers. The strong interaction with matter also gives high elemental contrast. Taking into account the recent progress in the development of sources and optics a multiplicity of EUV applications in the semiconductor industry, thin film technology, life and material sciences is envisioned at present.

![Figure 1. Spectrum of electromagnetic radiation.](image)

Manufacturing microelectronic semiconductor devices is the driving force for the development of EUV lithography. Presently it uses deep UV (DUV) radiation. The most popular radiation source is the ArF excimer laser [2] radiating at a wavelength of 193 nm. In order to reduce the size of the elements further, advanced lithography technologies based on EUV and X-ray radiation, electron and ion beams are being investigated by semiconductor manufacturers. EUV lithography is being considered as one of the most promising methods. Due to the existence of powerful light sources and efficient optics at 13.5 nm this wavelength was suggested for EUV lithography. It utilizes radiation around 13.5 nm with a bandwidth of 2%.

1.1. EUV Optics

Due to the strong absorption of EUV radiation in all materials, all system components (source, optics, detectors, samples, etc.) along its propagation have to be placed in vacuum. In addition to that due to the same reason, only non-refractive optics can be used. For imaging applications all the optical elements make use of diffractive optics as zone plates or multilayer mirrors which reflect light by interlayer interference although any one of these mirrors will absorb around 30% of the incident light. Mo/Si multilayers are widely used for wavelengths above 12.4 nm (Si 2p absorption edge) and are suitable
for 13.5 nm used in EUV lithography. The typical structure of the binary multilayer mirror is shown in Figure 2. By choosing the layer thickness depending on the wavelength $\lambda$ and the angle of incidence $\varphi$, there is a constructive interference of the waves partly reflected at many interfaces. The maximum first order reflectance is achieved for the thickness of a bilayer pair $d$ corresponding to the refraction corrected Bragg's law dependence [3]:

$$\lambda = 2d \sin \varphi \times \left(1 - \frac{4\delta d^2}{\lambda^2}\right) \quad (1),$$

where $\varphi$ is measured from the surface and $\delta$ is the bilayer weighted real part of the refractive index ($n = 1 - \delta + i\beta$). The adaptability to curved surfaces enables its use as reflective optics.

Reflection and refraction

When light passes through a medium (Figure 3), some part of it will always be absorbed. This can be conveniently taken into account by defining a complex index of refraction

$$\tilde{n} = n + ik.$$

Here, the real part of the refractive index $n$ indicates the phase velocity while the imaginary part $k$ indicates the amount of absorption losses when the light wave propagates through the material. For x-ray and extreme ultraviolet radiation the complex refractive index deviates only slightly from unity and usually has a real part smaller than 1. Therefore, it is normally written as

$$n = 1 - \delta + i\beta.$$

According to Snell’s law, the total reflection will happen when the incidence angle is large enough. For EUV radiation, the high reflectivity of the optics is desired. Therefore the grazing angle ($\theta = 90^\circ - \varphi$) is more commonly used in EUV optics. The dependence of the reflectivity on the grazing angle on different surface materials is shown in Figure 4.
Figure 3. Scheme of the wave propagation from vacuum to a different medium. The wave vector inside the medium is \( k' = \frac{\omega}{c} (1 - \delta) \).

Figure 4. Dependence of the reflectivity of EUV light at 13.5nm wavelength on the grazing incidence angle (measured from the surface) for different materials.

1.2. Contamination of EUV Optics

One of the most dramatic limiting factors, preventing presently for implementing the EUV technology in semiconductor manufacturing processes, is the limited lifetime of the EUV optics due to its relatively quick contamination and subsequent damage caused by debris from the light source or caused by EUV radiation itself.

Oxidization of the silicon layer and carbonization on the mirror surface are the two main contaminations mechanisms induced by EUV irradiation. The photons and secondary electrons generated at the mirror surface cause dissociation of water and/or hydrocarbon molecules usually present at the mirror surface. During oxidation, oxygen...
radicals react with Si layers to form SiO$_2$. In addition to that, carbon layers can be formed on the mirror surface due to the dissociated hydrocarbons, as shown in Figure 5. The carbon contaminants strongly absorb the EUV radiation and create dark spots causing significant reflectivity loss of the mirrors.

![Figure 5. a. Mechanism of a carbon layer formation on the mirror surface; b. Mirror damage caused by EUV-induced surface chemistry processes.](image)

These two processes are influenced by the partial pressure of water and hydrocarbons in the vicinity of the mirror, by EUV intensity, and also by the hydrocarbons composition at the mirror surface. Although carbonization is a much faster process than oxidation, the carbon layer can be removed relatively easily. The oxidation of the mirrors is irreversible and should be avoided. Besides the (EUV) radiation, the light source emits also some amount of debris and particles such as fast ions, atoms, metal clusters, droplets, etc. This debris, besides damaging the optics, can also shorten significantly the lifetime of the vacuum system.

In order to maintain high system performance, regular calibration on the optical components and detectors is required. On the other hand, it is very important to develop cleaning strategies and slow down the carbon layer formation.

1.3. EUV Light Sources

The development of a suitable light source is one of the biggest challenges in EUV lithography. At present powerful sources of EUV photons may be based on either relativistic electrons (synchrotron radiation and free electron laser) [4], plasmas [5] (produced by laser irradiation or by gas discharges), x-ray lasers, laser-generated high harmonics and x-ray tubes adapted for the EUV spectral region [6]. The plasma based thermal radiators are considered to be suitable candidates for EUV lithography because they are powerful, compact and cost efficient.


**Synchrotron light source**

Synchrotron radiation is generated by accelerating relativistic electrons or positrons through a sequence of permanent magnets [7]. There are three types of magnetic structures commonly used to produce synchrotron radiation: bending magnets, undulators, and wigglers, as show in Figure 6. The bending magnet radiation has a broad radiation spectrum with a small emission angle (typically $1/\gamma$), where $\gamma$ is the Lorentz contraction factor. The undulator spectrum can be very narrow and its radiation is extremely bright and partially coherent. The undulator radiation cone is much smaller than $1/\gamma$.

![Figure 6. a. Synchrotron radiation from a bending magnet; b. Synchrotron radiation from an undulator.](image)

**Free electron laser**

The research of applying free electron laser (FEL) in EUV lithography is recently carried out [8] though the idea was proposed about a decade ago [9]. FEL’s emit undulator radiation and are sources for EUV radiation as well. The lasing process is initiated by the spontaneous undulator radiation. It has the widest frequency range of any laser type, and can be widely tuned [10] ranging from microwaves to EUV radiation and X-rays.

**High harmonic generation**

High harmonics are a tunable table-top source of EUV/Soft X-rays synchronized with the driving laser and produced with the same repetition rate. It was observed in interaction of intense CO$_2$ laser pulses with plasma generated from solid targets. Nowadays, high harmonics in gases is far more widespread in application. The working principle is shown on Figure 7 [11]. At first the Coulomb potential of a gas atom is lowered by the laser field allowing for an electron to tunnel out of the barrier to the vacuum level. Once free, the electron is accelerated away from the atom and back again by the electric field of the laser and recombines with the ionized atom emitting radiation. High harmonic generation strongly depends on the driving laser field and as a result the harmonics have similar temporal and spatial coherence properties [12]. The pulse duration of high
harmonics is shorter than that of the driving laser and can be as short as a few tens of attoseconds ($1 \text{ as} = 10^{-18} \text{s}$).

Figure 7. Three step model of laser high harmonic generation.
2. Plasma and Plasma-based EUV Light Sources

The present experiment utilizes hot and dense plasmas as an EUV radiation source. Plasma is one of the four fundamental states of matter (the others being solid, liquid, and gas). Heating a gas may ionize its molecules or atoms (reducing or increasing the number of electrons in them), thus turning it into plasma, which contains charged particles: positive ions and negative electrons or ions. Ionization can be induced by other means, such as strong electromagnetic field applied with a laser or by the application of an electric field on a gas, where the underlying process is the Townsend avalanche.

Plasmas are highly efficient light sources, e.g. stars, lightings, arc discharges, etc. The total emitted radiation power $P_{\text{rad}}$ is contributed mostly by the Bremsstrahlung radiation, $P_{\text{br}}$, recombination radiation, $P_{\text{rec}}$, and spectral line emission, $P_{\text{line}}$, and can be expressed as:

$$P_{\text{rad}} = P_{\text{line}} + P_{\text{rec}} + P_{\text{br}}.$$ 

The contributions are:

- **Bremsstrahlung**: Radiation is emitted by the free electrons that are decelerated in the Coulomb field of ions. It is a free-to-free electronic transition. Bremsstrahlung has a continuous spectrum.
- **Recombination radiation**: Free electrons recombining with ions emit the binding energy as light. This radiation has due to free-to-bound electronic transitions a continuous spectrum.
- **Spectral line radiation**: Electrons bound to ions or atoms can get excited in the plasma to higher energy bound states. The energy for this process is provided by collisions between plasma constituents or by light absorption. This energy is released in a form of radiation when the excited electrons relax back to the equilibrium state or other lower lying states. Since the atomic level structure has a discrete character, the radiation spectrum consists of narrow spectral lines in contrast to broadband recombination and Bremsstrahlung spectra.

The contribution of each process to the overall radiation spectra depends on the density, temperature, composition, and lifetime of the plasma.

According to Kirchhoff’s law of thermal radiation, the maximal power a body of arbitrary material can radiate is limited by the radiation power of a black body at the same temperature. In this case, the spectral radiance is given by Planck formula:

$$L_{\lambda} = \frac{2c^2h}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{k_B\lambda T}\right) - 1} \quad (2),$$

$L_{\lambda}$: Spectral radiance, $k_B$: Boltzmann constant, $\lambda$: Wavelength, $c$: Light velocity, $h$: Plank constant, $T$: Absolute temperature.

Applying Wien’s displacement law to the EUV radiation that relates the black body temperature to wavelength corresponding to the radiance maximum, one finds that the temperature required for observing the peak of the radiance at $\lambda = 13.5$ nm is 18.5 eV:
\[ \lambda \cdot T = \text{const.} = 2.898 \cdot 10^{-3} \, \text{m K} = 250 \, \text{nm eV}. \]

The plasma temperature defines not only the maximal achievable radiance but also the ionic charge distribution and, therefore, the emission spectrum. As an example, let us consider Xenon gas as the source fuel. Figure 8 shows a change in ionic charge distribution at different temperatures. The emission in the EUV spectral range is contributed mostly by line emission of XeXI \((\text{Xe}^{10+}, \text{when 10 electrons are stripped from Xe-atom})\). In order to generate high abundance of these ions in the plasma, the temperature must achieve several tens of electron-volts.

In hot and dense plasmas, the sharp emission lines are Doppler and Stark broadened, due to the motion of emitting ions and collisions between ions and electrons. In addition, particularly in the case of heavy elements (with correspondingly complex electronic structure), the spectrum is broadened by the amount of possible transitions. For example, there are about 500 energy levels with about 80,000 transitions between the 5 most common electron configurations and the ground state of XeXI [13].

Another important parameter under consideration is the plasma density. For low densities, the radiance of the plasma increases linearly with the density until the collision rate between electrons and ions becomes comparable to the relaxation rate of ionic excited states. Above this limit, the radiance becomes independent of the density since the excited state populations reach thermodynamic equilibrium. Thus, the radiance approaches the blackbody limit [13].

![Figure 8. Ionization balance for xenon as a function of electron temperature for \( n_e = 10^{19} \, \text{cm}^{-3} \).](image-url)
2.1. Plasma EUV Light Sources

Discharge-produced plasma (DPP) and laser-produced plasma (LPP) are the leading technologies for generating high-power EUV radiation at 13.5 nm. In both technologies, hot plasma of ≈ 20 – 50 eV of the chosen fuel material is generated, which produces EUV radiation (see Table 1). In DPP, magnetic pinching of low-temperature plasma generates the high-temperature plasma. In LPP, the target material is heated by a laser pulse to generate high-temperature plasma. Xenon and Tin are the most popular fuel materials for EUV sources in the environment of EUV lithography.

**Laser Produced Plasma (LPP)**

In LPPs the Inverse Bremsstrahlung mechanism is utilized to transfer energy from the incident laser radiation to the plasma. An intense pulsed laser beam, which is focused onto a fuel substrate, evaporates and ionizes the fuel. The resulting hot plasma radiates and expands rapidly during the laser pulse. Then, after the pulse ends, the plasma continuing its expansion cools down and recombines within several microseconds. Important advantage of LPPs is their small emission spot size leading to high brilliance of LPP sources. Among disadvantages is a fast degradation of the target material and therefore special arrangements of the target regeneration are necessary.

**Discharge Produced Plasma (DPP)**

DPPs work with discharges of gases. A high voltage (typically 1 – 10 kV) between two, close electrodes lead to an electrical breakdown of the (low pressure) gas in between. The electrical avalanche effect of the flowing electrons leads to an ionization of the gas atoms and plasma is created. In DPPs hot plasmas are readily produced by the pinch effect. This term describes the self-constriction accompanied by heating of discharges by the magnetic field of the current. Pinching starts when the magnetic field pressure exceeds the plasma particle pressure, and it stops when the two are equal; this condition describes a magnetically confined plasma column. DPPs mostly differ in electrode design, which controls the dimension, stability and location of the plasma. Advantages of DPP compared to LPPs are lower debris production, higher possible ionization states and lower overall cost. Even though the electrode is not consumed like the target in LPP, its degradation is a weak spot of the DPP concept.
### Table 1. Comparison of parameters of laser and discharge produced plasmas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LPP</th>
<th>DPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration</td>
<td>ns</td>
<td>0.1 – 50</td>
</tr>
<tr>
<td>Energy</td>
<td>J/pulse</td>
<td>0.1 – 1.5</td>
</tr>
<tr>
<td>Size of emission zone</td>
<td>µm</td>
<td>50 – 300</td>
</tr>
<tr>
<td>Max. repetition rate</td>
<td>kHz</td>
<td>50</td>
</tr>
</tbody>
</table>

2.2. Hollow-Cathode-Triggered Gas Discharge

The present lab experiment uses a hollow-cathode-triggered (HCT) pinch plasma source to create EUV radiation. Schematic of the setup is shown in Figure 9. This DPP-type source consists of a charging circuit, a capacitor array, and an electrode chamber filled with the fuel gas. Below four phases of the source operation are described in detail: gas breakdown initiation (dark current) phase; hollow cathode discharge phase; plasma pinching phase; and plasma recombination phase.

![Figure 9. Electrode design of the hollow-cathode-triggered EUV light source [14].](image-url)
Dark current phase

During initial stages of the discharge when a voltage drop is initiated between two electrodes in gaseous atmosphere, the Townsend current starts flowing between the electrodes due to natural abundance of free charges in the gas. This current leads to avalanche ionization of the gas. In the described device, the electrode geometry and gas pressure are chosen such that this avalanche ionization occurs only at the edges of the electrode bore hole.\(^1\) The Paschen curve in Figure 10 illustrates this effect. This curve relates the gas breakdown voltage to the inter-electrode distance, \(d\), the pressure of the fuel gas, \(p\), and the material constant of the working gas. The gas pressure in the inter-electrode region is selected such that the source is operated in the left-hand part of the Paschen-curve (the breakdown voltage drops with the increase of the \(p \cdot d\) product). The breakdown starts at the edges of the bore hole where the effective inter-electrode distance is larger than everywhere else leading to larger \(p \cdot d\) product and, therefore, to lower breakdown threshold. This is essential for generating plasma in the bore region, from which the plasma radiation can be effectively collected during the pinching phase.

\(^1\)As the charged particles follow the electrical field, which is bend at the edge of the electrodes, their effective travel distance increases. The electrodes are close (~mm) and the pressure is low (1 – 100 Pa) and therefore only at the edges of the bore the traveling distance of the electrons is long enough to produce an ignition.

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**Figure 10. The Paschen curve shows the minimal voltage needed to create an electrical breakdown between two electrodes as a function of the pressure \(p\) and electrode distance \(d\) for different gases [15].**
Hollow cathode phase

In order to enhance and stabilize the initial discharge, a special geometry of the cathode electrode is employed – the so-called “hollow cathode”. Behind the bore drilled through the cathode, an additional enclosed compartment filled with the same gas is attached (see Figure 11). Due to a negative charge of the compartment walls, they attract ions from the inter-electrode gap. These ions striking the walls produce secondary electrons that accelerate back to the bore region. Before reaching the bore, the secondary electrons may bounce between the hollow cathode walls ionizing the fuel gas on the way. This effect enhances substantially the breakdown process.²

Pinch plasma phase

After the gas breakdown is initiated (that takes several tenths of nanoseconds), a highly conductive plasma column bridges the electrodes in the bore space. The charge accumulated in the capacitor bank begins flowing through the plasma generating a pulse of high current (typically ~10 kA). A strong magnetic field of the current interacting with the charged particles of the plasma through the Lorentz force, compresses the plasma column (inwards) towards the axis of the bore. Due to rapidly changing current (and the magnetic field) and high conductivity of the plasma, the diffusion of the plasma particles across the magnetic field is suppressed (skin-effect). The latter leads to dramatic reduction of the volume occupied by the plasma during the compression and, therefore, to the increase of the plasma density and temperature necessary to get EUV radiation. In particular, in the present setup, the current pulse of 200 ns duration

²This effect is so strong that it enables to control the ignition time with the size of the compartment and/or an additional triggering electrode in the compartment.
peaking at 8 kA generates magnetic field of up to 4T that compresses 2.5 mm diameter plasma column to 0.5 mm diameter column. This plasma compression process is called pinching or pinch effect and is illustrated in Figure 12. The compression stops when the magnetic pressure is balanced by dynamic pressure of plasma particles. The resulting temperature, density, and column radius can be approximated using the Bennett relation [16]:

$$\frac{\mu_0 I_0^2}{8 \pi^2 r_p^2} = (n_i + n_e)kT_e \quad (4).$$

Assuming tenfold ionization $n_e = 10 n_i$, a starting pressure of $p = 10$ Pa and a starting radius of $a = 2.5$ mm, this gives an estimate of $T_e = 35$ eV for the electron temperature taking $r_p = 0.5$ mm, $n_e = 10^{18}$ cm$^{-3}$, and the peak current of $I = 8$ kA. The plasma under these conditions is an effective emitter of the EUV radiation.

Figure 12. Pinching of the plasma by its self-induced magnetic field.
Recharge and recombination phase

Upon completion of the capacitor bank discharge, the current stops flowing through the plasma, and the magnetic field pressure drops to zero. Because the dynamic pressure of the plasma is not balanced anymore by the magnetic field pressure, the plasma begins expanding freely (at the speed of about 4000 m/s) into the inter-electrode space hitting eventually the walls and recombining. This process may take up to several hundreds of microseconds depending on fuel gas and geometry of the electrodes (in particular of the hollow cathode compartment where the charged particles need longer to diffuse to the walls). This time limits, together with the recharging time of the capacitors, the repetition rate of the DPP-source, since the requirements for optimal source performance dictate that every discharge pulse must begin at the same initial state of the fuel gas in the inter-electrode space.

A more engineering limit to the repetition rate is the cooling of the electrode system. Increasing the repetition time needs sophisticated cooling concepts. Without any additional cooling the repetition rate is limited to a few tens of Hz.

Conversion efficiency

The electrical energy stored in the capacitor bank of the source is coupled into the plasma during the discharge and pinching phases. This energy is converted into the particle motion energy and also into energy of radiation. Due to the complex radiation mechanisms described above, the spectrum of plasma radiation spans from far infrared to X-ray spectral regions. A figure of merit for optimization of the source is the conversion efficiency factor, \( \eta_{CE} \):

\[
P_{\Delta \lambda} = f \cdot E_{\Delta \lambda} = f \cdot \eta_{CE} \cdot E_{C} \quad (5).
\]

\( P_{\Delta \lambda} \) and \( E_{\Delta \lambda} \): In-band radiation power and energy,

\( f \): Repetition rate, \( E_{C} \): Electrical energy,

which is a ratio between average radiation power emitted into the spectral region of interest, \( P_{\Delta \lambda} \), and the average electrical power spent to maintain the repeated discharge. Typical values of the conversion efficiency factor are around \( \eta_{CE} \sim 0.2 \% \) into the bandwidth of \( \pm 0.135 \text{ nm} \) around \( \lambda = 13.5 \text{ nm} \) for sources operating in low-kHz repetition rate range. For generation of, e.g. 100 W of the average radiation power, one needs around 50 kW average electrical power. Figure 6 illustrates the energy distribution in the pinch plasma. The conversion efficiency can be optimized by changing electrodes geometry, discharge parameters, and the fuel gas.
Figure 14. Pie chart for the power distribution of a DPP EUV light source operating with Xe gas [17].
3. EUV Metrology and Lab Course Procedure

3.1. EUV Metrology

**Photodiode**

For measurements of the energy per pulse within a certain region of EUV spectrum reflected by the Bragg mirrors (for this lab course between about 17 nm and 25 nm wavelength) we use a calibrated Si photodiode sensitive to EUV radiation (AXUV 100G from Opto Diode Corp.). When these photodiodes are exposed to photons of energy greater than 1.12 eV (wavelength less than 1100 nm) electron-hole pairs (carriers) are created. These photo-generated carriers are separated by the electric field of the p-n junction and a current proportional to the number of created electron-hole pairs flows through an external electric circuit. The current pulse is measured indirectly as a voltage pulse on the oscilloscope setting the input resistance to 50 Ω. For EUV photons, it takes only 3.7 eV to generate one electron-hole pair. Therefore, many electron-hole pairs are created by one photon. This results in device quantum yield (electrons seen by an external circuit per incident photon) much greater than unity. The photodiodes are also characterized by a spectral responsivity curve (shown in Figure 8). The spectral responsivity is used to convert the measured voltage pulse to total energy per pulse of EUV radiation incident onto the photodiode.

![Figure 15. Responsivity of the AXUV 100G photodiode used in the energy monitor.](image-url)
CCD detector

A detector, which allows measurements of spatial distribution of light intensity, is a CCD-camera (Charge Coupled Device). A single pixel of CCD consists of p-doped Si substrate covered with layers of SiO$_2$ and polycrystalline Si that form the gate electrode. The positively biased gate creates a potential well where electrons are confined. Electron-hole pairs are created by incident photons by means of the internal photoelectric effect. The positively charged holes are drifting away while the electrons are trapped in the potential well of the gate. The number of photo-generated electrons is proportional to the intensity of the incident radiation. A shift register enables the readout of each single pixel. Thus the detector gains spatial resolution. Due to the high absorption in the EUV spectral range, the conventional CCD detector has to be modified. Otherwise the incident EUV radiation will be mostly absorbed in the polycrystalline Si and SiO$_2$. Figure 16 illustrates two concepts allowing for increasing the sensitivity of the CCD detector in the EUV spectral region. One possibility is to deposit a layer of scintillating material (e.g. Tb-doped Gd$_2$O$_2$S) on top of the gate in order to convert the EUV radiation into visible light, which penetrates into the Si and generates electron-hole pairs. Alternatively, the backside of the Si substrate is etched all the way down to the photosensitive region, and the EUV radiation is directed to the CCD from the backside. This type of CCD detector (e.g. Andor iKon M, 1024 pixel x 1024 pixel, 13 µm pixel size) is used in the present lab course.

![Figure 16. The layer structure of a charge-coupled device (CCD). In the visible spectral range, the light penetrates through the layers of polycrystalline Si and SiO$_2$ to the photosensitive region of p-doped Si and generates electron-hole pairs (left). Due to the high absorption in the EUV spectral range, the CCD has to be modified in order to efficiently detect EUV radiation. Either a scintillator layer is deposited on top of the gate (middle) or the EUV radiation illuminates from the backside of the etched Si substrate (right).](image-url)
In-band energy monitor

To determine the average in-band EUV power of the pulsed light source, i.e. the power emitted within a defined spectral region, it is required to determine the in-band energy per pulse. In our lab course, we will determine the energy per pulse at 20.5 nm wavelength (FWHM of 1.3 nm, see Fig. 17). This wavelength corresponds to the 3p absorption edge of cobalt. Selecting spectral lines at the cobalt 3p absorption edge enables element-selective signals and even ferromagnetic contrast if the light is circularly or linearly polarized. The setup used in the lab course is dedicated to circularly polarize the initially unpolarized light and to obtain ferromagnetic contrast by the x-ray circular magnetic dichroism (XMCD) effect at the 3p absorption edges of iron (23.5 nm), cobalt (20.5 nm) and nickel (18.7 nm).

The energy monitor consists of two multilayer mirrors ([Si(9.09 nm)/B₄C(6.06 nm)]₅₀ₓ on Si) which are designed to simultaneously maximize the reflectivity at 20.5 nm and to linearly polarize the light at the Brewster angle (s component is reflected, p component is absorbed). Both requirements lead to the choice of the incidence angle of 48.2° with respect to the mirror surface (grazing incidence). The signal is detected by a photodiode (AXUV 100G from Opto Diode Corp.) and monitored on the oscilloscope. The emission of the gas discharge plasma light source ranges from infrared to the soft x-ray spectral region and includes EUV radiation. In order to suppress wavelengths above 80 nm and between 5 nm and 17 nm we use Al filters (200 nm freestanding Al foils).

In the next step, we will derive the important expression which connects the energy per pulse and solid angle for a wavelength region between λ₀ − Δλ/2 and λ₀ + Δλ/2 around λ₀, the voltage pulse from the photodiode and the parameters of the energy monitor. We start with the general expression

\[ \int_0^\infty d\lambda S(\lambda) T_{gas}(\lambda) R_1(\lambda) R_2(\lambda) T_{filter}(\lambda) D_{diode}(\lambda) = \frac{1}{\Delta \Omega R_{scope}} \int_0^{t_p} dt U_{diode}(t) \tag{6} \]

where on the left side \( S(\lambda) \) denotes the spectral energy per pulse and solid angle (in J/(sr·m)), \( T_{gas}(\lambda) \) denotes the transmission of the gas between the source and the photodiode, \( R_1(\lambda) \) and \( R_2(\lambda) \) are the reflectivities of the multilayer mirrors, \( T_{filter}(\lambda) \) is the filter transmission and \( D_{diode}(\lambda) \) denotes the photodiode responsivity (in A/W, for AXUV 100G photodiode see Fig. 14). On the left side, \( \Delta \Omega \) is the solid angle, \( R_{scope} \) denotes the resistance of the oscilloscope (usually 50 Ω), \( U_{diode}(t) \) is the voltage pulse from the photodiode and \( t_p \) the pulse duration.

First we approximate \( T_{gas}(\lambda) = T_{gas} = \text{const.} \), i.e. the gas transmission is wavelength independent. Then we define the sensitivity of the energy monitor

\[ D_{sens}(\lambda) = R_1(\lambda) R_2(\lambda) T_{filter}(\lambda) D_{diode}(\lambda) \tag{7} \]
and also normalize $S(\lambda)$ to be

\[ S(\lambda) = S_0 \cdot \tau(\lambda) , \]

where \( \int_0^{\infty} d\lambda \tau(\lambda) = 1 \). For the energy per pulse and solid angle \( E_{\Delta \lambda} \) between \( \lambda_0 - \Delta \lambda/2 \) and \( \lambda_0 + \Delta \lambda/2 \) around \( \lambda_0 \) we can write

\[ E_{\Delta \lambda} = S_0 \int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} d\lambda \tau(\lambda) = \frac{S_0 \int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} d\lambda \tau(\lambda) \cdot \frac{1}{\Delta \Omega R_{\text{scope}} T_{\text{gas}}} \int_0^{t_p} dt U_{\text{diode}}(t)}{S_0 \int_0^{\infty} d\lambda \tau(\lambda) D_{\text{tool}}(\lambda)} . \]

Finally, we can define the energy monitor calibration factor

\[ \chi = \frac{\int_0^{\infty} d\lambda \tau(\lambda) D_{\text{tool}}(\lambda)}{\int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} d\lambda \tau(\lambda)} \]

and write

\[ E_{\Delta \lambda} = \frac{1}{\chi} \cdot \frac{1}{\Delta \Omega R_{\text{scope}} T_{\text{gas}}} \int_0^{t_p} dt U_{\text{diode}}(t) \quad (8). \]

In practice, the a priori knowledge of \( \tau(\lambda) \) and therefore of the spectral distribution is necessary to determine \( E_{\Delta \lambda} \). For the \( O_2 \) and \( N_2 \) spectrum \( \tau(\lambda) \) can be written as a sum of weighted Dirac delta functions with weighting factors \( a_i \)

\[ \tau(\lambda) = \sum_i a_i \cdot \delta(\lambda - \lambda_i) \]

due to the very narrow bandwidth of spectral lines \( \left( \frac{\Delta \lambda}{\lambda} = 10^{-3} - 10^{-4} \right) \). Consequently \( \chi \) can be written as

\[ \chi = \frac{\int_0^{\infty} d\lambda \sum_i a_i \delta(\lambda - \lambda_i) D_{\text{tool}}(\lambda)}{\int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} d\lambda \sum_j a_j \delta(\lambda - \lambda_j)} = \frac{\sum_i a_i D_{\text{tool}}(\lambda_i)}{\sum_j a_j} . \]

It has to be noted that the weighting factors \( a_i \) with index \( i \) have to be taken for the whole spectrum while the weighting factors \( a_j \) with index \( j \) have to be taken only between \( \lambda_0 - \Delta \lambda/2 \) and \( \lambda_0 + \Delta \lambda/2 \).

In our case, we are interested in \( E_{\Delta \lambda} \) for \( \lambda_0 = 20.5 \) nm and \( \Delta \lambda = 1.3 \) nm. Parameters to determine \( E_{\Delta \lambda} \) from lab course measurements are summarized in Tab. 2.
Table 2. Parameters required to determine the energy per pulse and solid angle at $\lambda_0 = 20.5$ nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference/Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$, $R_2$ of the multilayer mirror [Si(9.09 nm)/B$<em>4$C(6.06 nm)]$</em>{50}$ on SiO$_2$</td>
<td></td>
</tr>
<tr>
<td>angle of grazing incidence 48.2°</td>
<td>CXRO webpage$^3$</td>
</tr>
<tr>
<td>be careful: the light is unpolarized before mirror 1 and s-polarized</td>
<td></td>
</tr>
<tr>
<td>before mirror 2</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{filter}}$ of the Al foil (200 nm)</td>
<td>CXRO webpage$^4$</td>
</tr>
<tr>
<td>$D_{\text{diode}}$</td>
<td>Fig. 14</td>
</tr>
<tr>
<td>$T_{\text{gas}}=1$</td>
<td></td>
</tr>
<tr>
<td>$R_{\text{scope}}$=50 $\Omega$ or 1 M$\Omega$</td>
<td></td>
</tr>
<tr>
<td>$\Delta\Omega$</td>
<td>area (10 x10 mm$^2$)</td>
</tr>
</tbody>
</table>
|                                                                            | into account, measure the source-aperture distance |}

$^3$ http://henke.lbl.gov/optical_constants/multi2.html

$^4$ http://henke.lbl.gov/optical_constants/filter2.html
EUV spectrometer

The EUV spectrometer used in the present lab course consists of a slit (50 µm width), a spherical grating (radius of curvature $R = 1000$ mm) and a CCD detector (see Figure 16 and Table 3). A circle with a radius $R/2$ which arc intersects the central point of a spherical surface with radius $R$ is called Rowland circle. If an object is placed somewhere on the Rowland circle it will be imaged with magnification $M=1$ on another place on the Rowland circle. This imaging property of a spherical surface is employed in the EUV spectrometer to enhance the spectral resolution. For that purpose, the slit is placed on the Rowland circle and is (spectrally resolved) imaged by the grating onto the CCD detector located at the corresponding position on the Rowland circle. If $r$ denotes the distance between the slit and the grating, $r'$ denotes the grating-CCD detector distance, $α$ is the angle of incidence of the beam, and $β$ the angle of reflection (diffraction) measured with respect to the grating normal, the condition for the slit to be imaged onto the CCD detector reads:

$$ r = R \cdot \cos(α) $$
$$ r' = R \cdot \cos(β). $$

For $R = 1000$ mm and $α = 80°$, $r = 174$ mm. On the other hand, $β$ depends on the diffracted wavelength and therefore $r'$ is also wavelength dependent. In general, the grating equation reads:

$$ m \cdot λ = d \cdot (\sin(α) + \sin(β)) \quad (9), $$

where $λ$ denotes the wavelength, $m=±1,±2,...$ the diffraction order, and $d$ the grating constant. The angles $α$ and $β$ are measured from the grating normal, and positive angles are defined for counterclockwise rotation and negative angles - for clockwise rotation. In order to avoid any sign confusion, we rewrite the grating equation accordingly:

$$ m \cdot λ = d \cdot (|α| - |β|). $$

![Figure 17. EUV spectrometer used in the lab course. The EUV radiation shines through a thin slit located on the Rowland circle of the spherical grating. The diffracted light is focused at another point of the Rowland circle where the CCD detector is placed.](image)
The CCD detector is positioned at distance \( z \) from the grating, and \( x \) denotes the position on the chip (\( x = 0 \) for specularly reflected beam). With the condition:

\[
\tan(|\alpha| - |\beta|) = \frac{x}{z}
\]

the equation for wavelength calibration reads:

\[
\lambda(x) = \frac{d}{m} \cdot \left\{ \sin(|\alpha|) - \sin \left( |\alpha| - \tan \left( \frac{x}{z} \right) \right) \right\} \quad (10).
\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>grating constant ( d )</td>
<td>1/1200 mm (1200 lines/mm)</td>
</tr>
<tr>
<td>angle of incidence ( \alpha )</td>
<td>80°</td>
</tr>
<tr>
<td>radius ( R )</td>
<td>1000 mm</td>
</tr>
<tr>
<td>ruled area ( A )</td>
<td>260 mm x 260 mm</td>
</tr>
<tr>
<td>blaze angle ( \gamma )</td>
<td>2.4°</td>
</tr>
<tr>
<td>distance grating-CCD detector ( z )</td>
<td>250 mm</td>
</tr>
<tr>
<td>CCD pixel size ( p )</td>
<td>13 µm</td>
</tr>
<tr>
<td>number of pixel ( N )</td>
<td>1024</td>
</tr>
</tbody>
</table>

**Table 3. Parameters of the EUV spectrometer.**

Following parameters determine the spectral resolution of the spectrometer \( \Delta \lambda \):

- grating dispersion \( \frac{d\lambda}{dx} \)
- slit size
- position of the CCD detector with respect to the Rowland circle
- number of illuminated grooves of the grating
- angular resolution
- imperfections of the grating

The grating dispersion is the first derivative of \( \lambda \) with respect to \( x \) (Eq. 10). For 20.5 nm wavelength, \( \frac{d\lambda}{dx} = 0.92 \) nm/mm. The best spectral resolution is achieved for the wavelength \( \lambda_0 \), which is located at the pixel intersecting with the Rowland circle. Let’s denote \( \Delta x \) the distance on the CCD detector between \( \lambda_0 \) and the wavelength of consideration \( \lambda \). The resolution \( \Delta \lambda \) is proportional to \( \Delta x \). Furthermore the wavelength resolution depends on the angular resolution. Here it is important to remember that the EUV plasma light source emits radiation into \( 2\pi \) solid angle (divergent light source) and that the source has finite size. If we denote \( W_S \) the source size perpendicular to the optical axis and \( D_S \) the source-slit distance, for the divergence angle \( \varphi_D \) we find:

\[
\tan \varphi_D = \frac{W_S}{D_S}
\]
Typically, for \( W_s = 1 \text{ mm} \) (for \( O_2 \) pinch) and \( D_s = 1500 \text{ mm} \), \( \varphi_D \) amounts to \( 6.7 \times 10^{-4} \text{ rad} \). Taking all the different contributions into account, the spectral resolution is:
\[
\Delta \lambda = \frac{d \lambda}{dx} \cdot c_g \Delta x \cdot \tan \varphi_D \quad (11),
\]
where \( c_g \) denotes a grating specific factor (\( c_g = 3.9 \) for our 1200 lines/mm grating). For the parameters given above, \( \Delta \lambda \approx 10^{-2} \text{ nm} \) for \( \lambda = 20.5 \text{ nm} \).

### 3.2. Lab Course Procedure

The lab course is divided into three tasks:

1. Characterization of the EUV discharge plasma light source operating with two different gases (\( O_2, N_2 \)) including measurements of the energy per pulse at 20.5 nm wavelength (cobalt 3p absorption edge).

2. Measurements of the source spectra using the EUV spectrometer when the source is operating with different gases (\( O_2, N_2 \)).

3. Measurements of the spectral reflectivity curve of Bragg mirrors near 20.5 nm wavelength.

In details:

1. The EUV light source will be operated with two different gases (\( O_2, N_2 \)). The discharge energy and repetition rate are varied by changing the cathode voltage and gas flow (see Tab. 4). The temporal profile of the cathode voltage will be monitored using the oscilloscope. From these measurements, the discharge energy and repetition rate will be extracted. The electrical discharge energy:
\[
E_D = \frac{1}{2} CU^2 \quad (12)
\]
depends on the total capacitance \( C \) (8 x 0.250 \( \mu \text{F} \)=2 \( \mu \text{F} \)) and the discharge voltage \( U \).

The goal of the following measurements is to determine the energy per pulse and solid angle around 20.5 nm wavelength (cobalt 3p absorption edge). The emitted light is spectrally filtered using two Bragg mirrors ([\( \text{Si}(9.09 \text{ nm})/B_{4}C(6.06 \text{ nm}) \])\(_{50x} \) on SiO\(_{2} \)) (spectral reflectivity see Fig. 17) in combination with a thin-foil Al filter. The signal is measured using the calibrated Si photodiode (AXUV 100G) and recorded on the oscilloscope. The task is to determine the radiation energy per solid angle and per pulse following the above written procedure (see the part ‘In-band energy monitor’). The solid angle
\[
\Omega = \frac{A_{Aperture}}{r^2} \quad (13)
\]
depends on the distance \( r \) between the source and the aperture and the aperture area \( A_{Aperture} \).
Table 4. The working gas, cathode voltage and repetition rate will be varied and the energy per pulse around 20.5 nm will be determined.

Calculate the ratio between the energy per pulse and the electrical discharge energy. This value is called conversion efficiency (Eq. 5).

2. and 3.

In the second and third part, the EUV spectra of two different gases (O₂ and N₂) will be measured before and after the 20.5 nm Bragg mirror using the EUV spectrometer (see above). In the spectrometer, the light passes through a narrow entrance slit (50 µm) and is reflected and diffracted by a curved grating (R=1000 mm) under 80° normal incidence. The curved grating images the entrance slit (spectrally resolved in different diffraction orders) on the Rowland circle which intersects with the CCD detector. The spectral lines are then recorded by the CCD detector. The wavelength calibration (conversion of the pixel numbers to wavelengths) will be performed by identifying recorded spectral lines using the NIST Atomic Spectra Database ([http://physics.nist.gov/PhysRefData/ASD/lines_form.html](http://physics.nist.gov/PhysRefData/ASD/lines_form.html)). In order to determine the relative spectral reflectivity of the Bragg mirror, the spectra recorded before and after the mirror will be normalized and related to each other.
Figure 1B: Calculated spectral reflectance of a multilayer filters for 20.5 nm wavelength corresponding to the 2D absorption edge. The reflectance is calculated for s- and p-polarized light.
4. References


