Chapter 35

Electrode and Condenser Materials for Plasma Pinch Sources


Contents

35.1 Introduction 916
35.2 Electrode Thermal Response 917
  35.2.1 Thermal response 919
  35.2.2 Erosion mechanisms 922
  35.2.3 Conclusions on electrode thermal response 924
35.3 Materials Selection for Plasma Pinch Sources 925
  35.3.1 Selection of electrode candidate materials 926
  35.3.2 Selection of high-temperature insulator ceramics for EUV sources 929
  35.3.3 Conclusions on materials selection for plasma pinch sources 930
    35.3.3.1 Electrode materials 930
    35.3.3.2 Insulator materials 931
35.4 Testing of Materials in Plasma-Gun Facilities 932
  35.4.1 Plasma-gun-device setup 933
  35.4.2 Diagnostics of plasma stream 935
  35.4.3 Irradiation of target materials by hot Xe plasma 935
  35.4.4 Target design 936
  35.4.5 Surface and material loss diagnostics 936
  35.4.6 Irradiation by Xe and H plasmas 938
  35.4.7 Copper surface damage 938
  35.4.8 Tungsten surface damage 942
  35.4.9 Conclusions on testing materials in plasma-gun facilities 944
35.5 Modeling and Testing Condenser-Optic Response 946
  35.5.1 Erosion and redeposition at condenser-optic material surfaces 948
  35.5.2 Condenser-optics materials testing 949
  35.5.3 Oblique-incidence erosion of Ru bombarded by Xe⁺ 951
35.6 Conclusions 953

References 953
35.1 Introduction

This chapter presents a summary of plasma-surface interactions in electrode and condenser-optic materials in plasma pinch sources for EUV light generation, with special emphasis on DPPs. In DPP EUV devices, electrodes at the source are exposed to short (10–20-ns) high-intensity plasmas, leading to a variety of erosion mechanisms. Erosion of the electrodes is dictated by the dynamics of the plasma pinch for configurations such as the dense plasma focus (DPF), Z pinch, and capillary. The transient discharge deposits 1–2 J/cm² per pulse on electrode surfaces. Large heat flux is deposited at corners and edges, leading to enhanced erosion. Understanding of how particular materials respond to these conditions is part of the rigorous design of DPP electrode systems. Erosion mechanisms can include physical sputtering, current-induced macroscopic erosion, melt formation, and droplet and particulate ejection. Erosion at the surface is also governed by the dynamics of how a plasma can generate a vapor cloud, leading to a self-shielding effect, which results in ultimate protection of the surface bombarded. Determining which will dominate—either microscopic erosion mechanisms such as physical sputtering, or macroscopic mechanisms such as melt formation and droplet ejection—remains an open question in DPP electrode design. This is because such mechanisms are inherently dependent on the pinch dynamics and operation of the source.

In addition to plasma-surface interactions in electrodes, for condenser optics, especially collector optics, erosion is due to fast ions and neutrals born in the plasma pinch, leading mainly to physical sputtering and other bombardment-induced mechanisms. If the surface is composed of more than one species, which is mostly the case, then radiation-induced and thermally activated effects govern the behavior of the surface and govern lifetime levels of the exposed material. Exposure includes debris from electrodes, high-energy ions and neutrals, highly charged ions (HCl's), background impurities, photon radiation [13.5-nm and out-of-band (OOB)], and redeposited eroded mirror material. Figure 35.1 presents an overview of DPP plasma-surface interaction modeling that can be complemented by materials testing. It shows the transient plasma region (region 1) to the left and the quiescent expanding plasma region (region 3) to the right where the collector optics is located. Region 2 comprises a number of debris mitigation schemes that can also be modeled and experimentally tested. A number of modeling simulators can couple regions 1–3 in a self-consistent manner. This can be useful in designing mirrors that are compatible with the debris mitigation schemes selected as well as the EUV fuel used at the source. This is especially important if alternative EUV radiator fuels are selected, such as Sn or Li. Designs at the source with alternative radiator fuels can be studied and their effect on mirrors assessed.

The goal of this chapter is to provide an overview of current modeling and testing utilized to evaluate and test candidate materials for electrode and condenser-optics applications in EUV plasma-pinch DPP sources. A summary of electrode thermal response is followed by a section on materials selection for DPP electrodes and insulators. Then a section on materials testing in a high-intensity plasma pinch
device is presented, describing the testing of copper and tungsten materials. That section is followed by a section on materials selected as electrodes and tested in a DPF EUV device. The chapter ends with summaries on condenser-optics modeling and testing.

### 35.2 Electrode Thermal Response

The rapid heating of the electrodes due to radiation and ion energy deposition may lead to melting and subsequently to surface evaporation. The HEIGHTS-EUV modeling package includes comprehensive models to describe the behavior of conductive flow in the magnetic field due to current displacement triggered by the discharge. In modeling functioning DPP devices, such as the Z pinch and DPF, the organization of the correct energy exchange is important for proper simulation. The energy exchange is determined by a set of energy transport processes, including magnetic diffusion, thermal conduction, and radiation energy loss. The result of the magnetohydrodynamics (MHD), radiation transport, and thermal conduction core HEIGHTS-EUV package is the hydrodynamic, radiative, and magnetic state of the source environment at each time step of the discharge, which gives a full description of the energy loads on the electrodes. Details of these calculations and results of numerical experiments can be found elsewhere.1,2

The major mechanisms of electrode heating include radiation absorption (the energy that reaches the electrode surface due to photon transport), plasma particle bombardment (the energy of moving plasma ions and electrons), and electric
current dissipation in the skin layer, which results in heating of the wires due to current flow. As a result, the electrodes are exposed to photon radiation and particle fluxes with a wide range of energies. Soft x-rays deposit their energy within a micron of the surface, very rapidly heating a thin layer on the electrodes. Electric current dissipation may additionally input heat on the skin layer near the surface. Harder energy spectra penetrate longer distances into the material, therefore heating a larger mass to a lower temperature. Additionally, due to the heating, the loads may cause various kinds of secondary damage due to other erosion mechanisms, such as change of phase (melting, evaporation, sublimation), debris-surface interactions due to physical/chemical sputtering or radiation-enhanced sublimation, ablation due to macroscopic metal droplets from splashing, hydrodynamic instabilities, and other erosion mechanisms, which will lead to severe erosion of the electrodes.

The primary interactions of photons with materials include the photoelectric effect, coherent and incoherent scattering, and pair production. Cross sections for each of these reactions have been tabulated in various forms and are available for numerical calculation. The wall thermal response to photon deposition can be determined if the photon spectrum is specified.\(^3\)

HEIGHTS-EUV is a computer simulation package designed to model the hydrodynamic and optical processes that occur in DPP devices. The developed model will eventually address three main subjects: plasma evolution and MHD processes, detailed photon radiation transport, and interaction between plasma/radiation and material. The total variation diminishing (TVD) scheme in the Lax-Friedrich formulation for the description of magnetic compression and diffusion in a cylindrical multidimensional geometry is the most suitable and is used in our model. Depending on the complexity of the problem and the availability of computer time, a combination of various atomic and plasma models is being developed and implemented in the package for calculating populations of atomic levels, ion concentrations, plasma properties, and opacity, such as a collisional radiation equilibrium (CRE) plasma model, a Hartree-Fock (HF) self-consistent-field atomic model, and a Hartree-Fock-Slater (HFS) method with splitting of atomic levels. Due to its importance and its influence on the whole dynamics of the discharge, radiation transport for both continuum and lines, with detailed spectral profiles, is calculated using two alternative approaches, viz., discrete-ordinate and Monte Carlo methods. The features of the package allow the study of the hydrodynamics and radiation of two-gas mixtures in DPF devices in the presence of impurities and erosion products that can affect radiation output. If not otherwise stated, all results below correspond to the modeling of a Xe-based EUV source.

The output of the HEIGHTS-EUV package includes the hydrodynamic state of the modeled device, its radiation both over a wide range of energies and in the specified EUV range, and magnetic field and current profiles at each time step of the simulation. These data are used later in evaluating the radiation flux, heat flux, and electron and ion fluxes, i.e., the mechanisms that contribute to the electrodes' thermal response.
Various mechanisms contribute to the electrode heating in DPP devices, as mentioned above. Some of them are schematically shown in Fig. 35.2. There is one more source of energy coming from the plasma to the electrode, which is heat conduction. Additionally, the DPP device works repetitively at some frequency (repetition rate), which defines the duration of cooling of the source between two discharges. An increase of the repetition rate linearly increases the energy load on the electrodes, which leads to a higher temperature on the electrode and more damage.

Consider a typical DPF device. Figure 35.3 presents results of numerical simulation of the radiation load on the anode at chosen time steps (top), and at chosen representative anode points (bottom). As one may expect, the highest energy load corresponds to the time of maximal radiation output of the source (which is near the moment of the pinch) at the point closest to the pinch. In one simulation, the internal wall of the electrode near the top is found to receive its highest load between 500 and 700 ns of the discharge. The top of the electrode is also found to be exposed to a high radiation load, but due to the longer distance and sharp angle, the load is slightly less. Other places are relatively safe from radiation damage.

### 35.2.1 Thermal response

HEIGHTS-EUV includes comprehensive models for calculating the electrode thermal hydraulic response by solving the thermal conduction equation, which takes account for the energy coming from the radiation flux, the electron flux, and the
current flowing through the skin layer of the electrode:

\[
\frac{\partial \varepsilon}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \chi \frac{\partial T}{\partial r} \right) - \frac{\partial}{\partial z} \left( \chi \frac{\partial T}{\partial z} \right) = \Omega, \tag{35.1}
\]

\[\Omega = \Omega_{\text{rad}} + \Omega_{\text{p}} + \Omega_{\text{cur}},\]

where \(\varepsilon\) is the internal energy density, \(\chi\) is the thermal conductivity coefficient, \(T\) is the temperature, and \(\Omega\) is the source of the heat, which includes \(\Omega_{\text{rad}}\) (radiation heating), \(\Omega_{\text{p}}\) (plasma particle heating), and \(\Omega_{\text{cur}}\) (heating from the electric current.
in the skin layer of the electrode). This simple model may be extended to include the effect of variable thermal properties and the coolant heat transfer coefficient, so as to reliably compare different electrode materials for a specific source geometry such as Cymer’s DPF or Philips Extreme’s hollow-cathode triggered (HCT) pinch plasma source.

An additional parameter of our simulation is the repetition rate, which determines the frequency of pinching and the time when the plasma source needs to be restored into its initial condition.

Figure 35.4 presents results of HEIGHTS-EUV calculations of the temperature of a tungsten anode for typical discharges with 1- and 5-kHz repetition rates. We assume that the ground surface of the electrode is constantly cooled to room temperature. At the 1-kHz rate the electrode is heated but not destroyed; at 5 kHz, however, its surface is evaporated and the anode is partly destroyed. Unfortunately, the problem of optimizing a particular EUV source is a very complex one with multiparameter tasks, which include not only increasing the output EUV by creating a brighter, more powerful EUV pinch by changing the initial design of the source and the temperature and/or pressure in the source chamber, but also improving the collection efficiency of the source by generating a smaller pinch, and increasing the lifetime of the source components, especially the electrodes.

Figure 35.5 displays a combination of various simulations, including the calculation of the scaling laws by changing initial parameters of the EUV source (shown on the abscissa scales), the EUV output of the device (shown by the contours labeled with the relative values of the collectible EUV output), and the highest temperature of the tungsten-made electrode at a given repetition rate (given by the gray scale in kelvins). Figure 35.5(a) corresponds to simulating a DPF device with fixed input energy into the discharge and fixed initial parameters of a Xe plasma. As shown, increasing the width of the anode would decrease the anode temperature, but as seen from the contours that present the corresponding collectible EUV, the optimal EUV output appears at intermediate values of the width. By carefully choosing the initial parameters of the discharge, it is possible to increase the output of the source and at the same time keep the temperature of the electrodes low enough. The circle and the triangle in Fig. 35.5(a) show the experimentally measured values reported by EUV source suppliers. A similar situation to the DPF appears in modeling a HCT pinch plasma source, shown in Fig. 35.5(b). In this case, the input energy load can be selected so that the output is optimized at lower energy input, where the electrode temperature is not high. Another limiting case is shown analytically for a tungsten electrode in Fig. 35.6. Here a 5-kHz repetition rate with a power density of 5 kW/cm² is shown. The figure shows the time dependence of the temperature on a tungsten surface. Note that during the pulse (∼20 ns, oscillations too close to see in the figure) the temperature can increase to levels above melting.
35.2.2 Erosion mechanisms

The erosion mechanisms of debris-surface interaction include physical sputtering, chemical sputtering, and radiation-enhanced sublimation (RES). High-Z materials, such as tungsten, show low sputtering yield at low ion energies and therefore
may be the preferred choice. The relatively high incident particle energies in the discharge condition will likely cause lower sputtering yields. However, if a working gas is employed without sufficient density to stop these energetic ions, it may result in higher sputtering erosion.

Chemical erosion of carbon-based materials (CBMs) strongly depends on the electrode surface temperature and reaches its maximum around 800 K. For graphite, besides erosion by chemical sputtering, RES yields were calculated for ion bombardment at target temperatures above 1200 K. Chemical sputtering and RES remain major erosion mechanisms, compared to the erosion by physical sputtering. Although the tungsten wall lacks both chemical sputtering and RES, its physical-sputtering erosion is still significant and can play a very important role in the total erosion yield.\textsuperscript{3}
The surface vaporization losses of various materials can be lowered by different protection methods. However, ablation due to macroscopic metal droplets from splashing and to hydrodynamic instabilities is a concern. The ejected macroscopic particles will form an aerosol cloud near the target surface. An alternative to gas protection is the use of thick liquid walls or jets, but fragmentation models have shown that the strong shock waves initiated in the thick liquid wall as a result of neutron-deposited energy will lead to severe damage to the wall. The produced fragments with very high velocity will seriously aggravate the chamber clearing required prior to next target injection, as well as shortening the wall lifetime.

### 3.5.2.3 Conclusions on electrode thermal response

Models have been developed and implemented in the comprehensive HEIGHTS-EUV package to study the dynamic behavior of DPP devices. The hydrodynamic response of the electrodes, photon radiation transport, plasma particle bombardment, and dissipation of the current heat are calculated in detail as a function of the deposited energy.

Several erosion-causing mechanisms are modeled and evaluated for assessing electrode lifetime, such as vaporization, chemical and physical sputtering, RES, melt-liquid splashing, and macroscopic erosion. Depending on the discharge energy yield and EUV-source gas pressure, most of these erosion mechanisms could be important factors in determining the best choice of material and the overall lifetime of the electrodes in DPP devices. No obvious choice of chamber protection mechanism is identified. More detailed analysis is needed to determine if a
DPP source of EUV energy will be economically feasible and meet both the Intel Lithography Roadmap goals for high-volume manufacturing (HVM) in the future. One challenge to DPP source devices, as discussed, is the lifetime of electrodes and other plasma-facing components. The next section will discuss the selection of materials for such application.

### 35.3 Materials Selection for Plasma Pinch Sources

Materials selection and lifetime issues for EUVL are of critical importance to the success of this technology for commercial applications. This section reviews current trends in production and use of plasma-facing electrodes, insulators, and wall materials for EUV sources. Ideal candidate materials should be able to withstand high thermal shock from the short-pulsed plasma, withstand high thermal loads without structural failure, reduce debris generation during discharge, and be machined accurately. We reviewed the literature on current and proposed fusion plasma-facing materials as well as current experience with plasma guns and other simulation devices. Both fusion and EUV source materials presented problems of surface erosion by particle sputtering and heat-induced evaporation/melting. These materials are either bare structural materials or surface coatings.

EUV materials can be divided into four categories: wall, electrode, optical, and insulator materials. For electric discharge sources, all four types are required, whereas LPP EUV sources do not require electrode and insulator materials. Several types of candidate alloy and other materials and methods of manufacture are recommended for each component of EUVL light sources.

The DPP (e.g., Cymer Inc., San Diego), the Z pinch (e.g., XTREME technologies GmbH), the LPP (e.g., Sandia National Laboratory, Livermore), the capillary discharge (e.g., EUVA, Sandia National Laboratory), and the HCT (e.g., Philips Extreme) are techniques being developed as light sources for EUVL. Materials selection and lifetime issues are of critical importance to the success of these techniques for commercial applications. The ideal candidate materials should be able to withstand high thermal shock from the short-pulsed plasma; be resistant to ion bombardment, including that by HCl; withstand high thermal loads without structural failure (requiring a high melting point, high thermal conductivity, thermal shock resistance, etc.); minimize debris generation during discharge; and be able to be machined accurately to the required geometry. The focus of this section is on thermal and related issues; plasma particle erosion issues are being studied in detail and will be reported on in the future.

Good sources of information about candidate plasma-facing materials for EUV source components are the national and international fusion programs. General issues for both fusion and EUV applications are thermomechanical, electrical, and vacuum properties. Both fusion and EUV source materials involve surface erosion by particle sputtering and heat-induced evaporation/melting. (Fusion additionally involves neutron damage, which is of course not present in EUV applications, thus
permitting more materials options.) In the context of the International Thermonuclear Experimental Reactor (ITER), the development of new plasma-facing materials has generated a unique base of experimental data on material response to powerful heat and plasma fluxes.

Numerous scientific studies for the high-tension spark-gap and heavy-current electrode technologies also provide essential data for review and analysis to select the best candidate plasma-facing components materials for EUV sources based on current laboratory devices.

The study of damage, structural changes, and property alterations of the materials exposed to intense ion and thermal pulses is very important for developing candidate plasma-facing materials for EUV sources and predicting the materials' behavior in different modes of source exploitation.\textsuperscript{8,9}

The problem of modeling the effect of powerful plasma pulses is particularly interesting. As with fusion, evaluations of candidate materials are greatly aided by simulation facilities for plasma-material interaction. Facilities operating with intensive plasma beams,\textsuperscript{10–14} electron accelerators,\textsuperscript{15–18} and laser beams\textsuperscript{19,20} generally present the possibility of implementing such a model experimentally.

### 35.3.1 Selection of electrode candidate materials

The choice of an electrode material (both anode and cathode) for powerful plasma sources must take into account diverse and sometimes conflicting requirements. For the usual metals, required physical properties are refractoriness and high hardness in combination with high thermal and electrical conductivity, high resistance to ionic and thermal erosion, absence of discharge-induced welding, and exceptional material transfer properties.

Except for the material structure, the electrophysical and high-temperature strength and vacuum properties are all influenced by the size of the material grains, the texture, and the presence of impurities. The reproducibility of properties of the manufactured electrode products is important to consider when choosing the material. This condition must be satisfied for materials with high erosion resistance and durability under various modes of working loads, in diverse gas environments, and at different operating temperatures.

The use of traditional metallurgical technologies may not allow achieving the diverse and complicated set of characteristics necessary for the material of an electrode in one homogeneous material. For this reason, most modern electrode materials are composites. The so-called pseudo-alloys are manufactured from components that do not dissolve each other either in solid or in liquid phases, such as W-Cu, Mo-Cu, Mo-Ag, Ag-C, Ag-Ni, and Ag-CdO. These materials have a heterogeneous structure consisting of a matrix with implanted dispersed phases joined to the matrix by a strong adhesive connection, but do not react to form solid solutions or chemical compounds.

The same effect may also be achieved by reinforcing spatial grids of fibers and crystals or materials with threadlike crystals implanted into the matrix. Both in the
matrix and in the dispersive phase, the materials may be either metallic or nonmetallic. The additive combination of the required properties in cathode materials is obtained from the corresponding phase constituents.

Extended operation of the electrodes in powerful plasma sources leads to irreversible changes of both working surfaces and bulk properties. The type of changes, as well as the area and the depth of affected material, is determined by the magnitude and type of energy deposited in the volume or at the working surface. In turn, the amount of energy deposited depends upon the value, density, and transit time of the electric current, as well as the specific and intermediate resistance of the electrode material. The heat generated can result in recrystallization and weakening of the material, and, depending upon design, its plastic deformation. When an electric arc is initiated, the temperature of the electrodes and vicinity may be increased by thousands of degrees. This can melt and vaporize the electrode material around the contact surface. In the course of electrode use, the factors mentioned above can lead to the appearance of craters, cracks, and debris as a result of thermal and fatigue stresses.

For the development and manufacture of materials in the energy-intensive region of the cathode and anode, electrodes are generally made of pseudo-alloy. One component of the alloy is a refractory, solid, heat-resistant, arc-suppressing material forming a spatial skeleton matrix. The second component is a fusible, electrically and thermally conductive filler uniformly permeating all pores and discontinuities. To ensure reliability, the pseudo-alloy material must maintain its integrity, requiring low porosity and high strength of the interphase adhesive bond. The recourse in manufacture is to add dopants to decrease the contact angle of wetting and to increase the capillary pressure and the strength of the adhesive bond. Fine dispersible inert fills limit sintering of the surface layers of the porous refractory framework and improve infiltration of ingrown melt and its uniform spread by porous channels in the bulk. For the refractory components, the following materials are usually used: metals such as W, Mo, Pd, Ni, Ta, and Cr; some nonmetals such as C and B; oxides such as CdO, WO₅, MoO₃, Ta₂O₅, and CuO; carbides such as WC and Mg₂C; and borides, silicides, and nitrides. The refractory components of the composite electrode materials are selected so that they have arc-suppressing properties.

The occurrence of small electric arcs in the course of operating the plasma source with these materials results in the formation of tiny amounts of molten metal in the regions of fusible microphases. Generally, the composite material keeps its integrity, and the probability of forming macro-melt areas at the surface is significantly reduced.

Copper, silver, and their alloys are usually used as fusible components. Refractory components are used not only as a pseudo-alloy framework but also as dopants in the fusible component, providing high-temperature strengthening by means of solidification or hardening of the dispersibles. Titanium and zirconium are dispersible strengthening dopants for copper. The intermetallic compounds Cu₃Zr and Cu₄Ti result from their reaction with the copper. Different oxides and refractory
materials used as dispersible strengthening dopants play an essential role in increasing electrode endurance and erosion resistance. These heat-absorbing materials provide arc suppression through thermal dissociation. The main heat-absorbing component in a pseudo-alloy is the fusible phase, ablating under melting and vaporization. It is partly held in a liquid state in pores and channels of the refractory framework by means of capillary pressure.

Other important electrode materials are pyrolytic graphite and carbon-fiber composites (CFCs). These materials do not melt and have high resistance to erosion from vaporization. In addition, CFCs can be manufactured with very high thermal conductivity. These materials are not recommended for fusion applications because they are susceptible to neutron damage, but that does not exist in the EUV environment. Chemical erosion and RES may be of some concern, however. Endothermic phase changes and phase transformations, as well as additives to the electrode material with low ionization potential, provide active heat removal from the contact points of the arc to the electrode surface. Adding impurities with low work functions allows us to control the formation and movement of cathode spots at the surface of the electrode.

The technologies of powder metallurgy allow us to develop and implement electrodes with a complex design that can consist of several parts (main part, inserts with greater ionic- and thermal-erosion resistance, arc-suppressing inserts, etc.) having different functions.21 A supplemental benefit of adding impurities is increased durability as a result of dispersive solidification. The same outcome may also be achieved by forming a pseudo-alloy that adds a strengthening component. However, the requirement that the material maintain a sufficiently high plasticity, allowing as high as 20%–90% compression, restricts the amount of such impurities. The fine structure of the material influences the durability and reliability of the electrode in many respects. Despite having higher-dispersion structure, the electrode materials exhibit lower plasticity, but they show essential advantages in erosion resistance in contrast with coarse-grained electrodes.

The advantages of tungsten electrodes become particularly apparent if a dispersible and fibrous structure is applied, ensuring the production of fibers normal to the working surface of an electrode. Such electrodes are not only more durable and erosion-resistant, but also firmer and easily manufactured.

From the facts mentioned above, one may conclude that to manufacture the electrodes of EUV sources, the candidate materials near the energy-intensive parts should likely be a frame-structured pseudo-alloy based on tungsten, molybdenum, or tungsten carbide with silver or copper. These pseudo-alloys were developed by various American and other companies.22–26

The refractory component in a pseudo-alloy can be up to 70–80 wt%. To improve the heat removal from the most energy-intensive surfaces of the electrode, the main component can be made of copper, while the working surfaces can be made from arc-resistant pseudo-alloy film of the required depth. Such a combined electrode is expected to survive longer than traditionally manufactured electrodes. At the same time, the new-design electrode should have higher resistance to the
erosion caused by both ion sputtering from the gas environment and the impact of the electric arc.

The electrode material should not, however, contain any adsorbed or dissolved gases. For this purpose, it is desired to employ iron-copper-, tungsten-copper-, or molybdenum-copper-based materials with volatile metallic dopants. These metals could also be fused to the areas of working surfaces that are in the most energy-intensive working parts. The saturation of liquid copper in a pre-sintered refractory skeleton is an attractive process for manufacturing this grade of electrode. Electrode inserts made of tungsten, molybdenum, or tungsten carbide pseudo-alloys, which provide the welding or brazing of the electrode to the main frame, can be supported by a copper or silver sublayer.

35.3.2 Selection of high-temperature insulator ceramics for EUV sources

The choice of an insulator material for plasma-facing components of EUV sources is determined by the physicochemical and electrophysical properties of the material, its vacuum-sorption properties, the operating temperature of the EUV source, and the operating parameters of the plasma-forming gas. Currently, most insulators are made of high-temperature ceramics based on the sufficiently studied oxides and carbides or on the less-studied nitrides.

The thermophysical and electrophysical properties of oxides are widely presented in the literature. In contrast, little is known about the electrophysical properties of nitrides, even at low voltages. The reason is that powdered boron nitride and aluminum nitride isolators are not manufactured by large commercial or industrial organizations. Therefore, their properties are substantially determined by the powder impurities and the technology of powder generation and sintering. Thus, precise measurements are especially needed for the high-voltage electrophysical characteristics of anisotropic polycrystalline materials—for example, pyrolytic boron nitride.

Among a number of candidate high-temperature dielectrics, the best insulator properties are believed to be those of corundum (α-Al₂O₃), zirconium dioxide (ZrO₂), beryllium oxide (BeO), and nitrides of aluminum (AlN) and boron (BN); Al₂O₃, BeO, BN, and AlN are manufactured in the form of powder, and the isolators are made by hot pressing.

The method of gas-phase sedimentation for manufacturing products out of boron nitride was developed in the last few years. The material obtained is called pyrolytic boron nitride (PBN). The advantage of such powder materials is the opportunity of pressing the insulators to the desired size and thickness. The peculiar feature of BN and PBN is the anisotropy of their properties in mutually perpendicular directions, explained by their graphitelike hexagonal crystal structure. Taking into account the complexity of desired physicochemical properties, especially the dependence of thermophysical and mechanical parameters of the materials on temperature, BN and PBN are considered to be the most appropriate dielectric materials capable of effectively working in the high-temperature and plasma-loading
conditions typical of EUV sources. Their high melting point, low evaporation rate, high mechanical resistance to thermal erosion at high temperature, and other properties allow us to successfully use these two materials as insulators for the energy-intensive parts of powerful plasma sources.

PBN possesses a high thermal conductivity in a direction parallel, and a low one in the direction perpendicular to the sedimentation surface. Also, because of its high-temperature conductivity, PBN has excellent thermal resistance, not being prone to cracks or segregation. The best oxide ceramic, BeO, performs worse than PBN. In contrast to the other ceramics, PBN is very stable under thermal shock tests. Under stretching, bending, and compression, the mechanical durability of PBN at low temperatures is lower than that of other ceramics, but at higher temperatures (>1000 K), it becomes comparable to or even considerably exceeds the others.

For BN and PBN, the approximate density is 2 g/cm$^3$ (the theoretical density is 2.28 g/cm$^3$). This density is optimal from the standpoint of both manufacture of the insulators and required material properties. Decreasing the density of PBN to 1.8–1.7 g/cm$^3$ would lead to decreasing its mechanical durability by a factor of approximately two; its chemical stability would also go down, and the probability of product segregation would be increased. PBN is easily processed by mechanical methods and possesses good enough vacuum properties. Soldering PBN by the contact-jet method with Ti-based solders forms vacuum-dense joints of titanium and copper.

The following conclusions were reached about candidates for insulator ceramics for EUV sources:

- The material properties of pyrolytic boron nitride allow us to unequivocally recommend it as capable of working in the conditions of high temperature, intense pulsed plasma loading, and arcing.
- Thick-wall insulators or insulators of complicated geometry may also be produced out of hot-pressed boron nitride, beryllium oxide, or aluminum nitride.
- To make a final choice of an insulator material capable of working in a multipulse mode, we need additional experimental measurements of their high-voltage electrophysical properties, as well as their lifetime in conditions similar to the working conditions of EUV sources.

### 35.3.3 Conclusions on materials selection for plasma pinch sources

#### 35.3.3.1 Electrode materials

Suitable choices are apparent for electrode materials for low-frequency, low-power devices. However, for higher-power and -frequency commercial EUV sources, it is very difficult to decide which material is the best for electrodes. This depends on the specific tasks of the device and on the given experimental conditions. The best design may well depend not only on the choice of material but also on the shape and size of the electrodes. Copper is the most common material in standard
plasma guns as well as in standard plasma focus devices. Here a “standard” device means one that works with a single shot (one shot in a few minutes) and with a moderate discharge current (systems with an electrical energies of 100 kJ to 1 MJ and electrode sizes of tens of centimeters up to 1 m).

In recently manufactured powerful plasma devices with a large current density and dense plasma at a high pressure, erosion of the electrodes was the main observed problem. Several electrode materials were tested that were produced in the former Soviet Union, such as Cu (oxygen-free high-conductivity copper), Cu-Al₂O₃ alloy (containing 1% of micron-size Al₂O₃ particles), Cu/Mo (thin layers of Cu and Mo, produced by implosion), W-Cu sintered alloy (produced using powder technology), Mo, Ti, Ta, and W.

In high-power devices, a Cu electrode suffers the most erosion and damage, while W suffers the least. However, the best plasma properties of the discharge were obtained with Cu electrodes. Recently, composite materials such as W-Cu alloys, though anticipated to have better performance as electrode materials, have been disappointing. Copper is eroded from the electrode surface, and the surface layer becomes porous and flakes away. This is a typical problem for most composite materials. Another possibility is to use electrodes made of sintered copper-tungsten composites at different locations on the electrode.

35.3.3.2 Insulator materials

Properties of insulators are particularly critical for plasma-focus devices. In plasma focuses, various ceramics based on Al₂O₃ are usually used. It is well known among experimentalists that ceramics are good insulators; however, such insulators must be treated with hundreds of preliminary discharges before the device works well. Sometimes a laser is used for treating the insulator surface before operation. As an alternative, BeO and BN can be used to reduce debris formation and improve operating conditions.

Insulator materials in DPF devices should also withstand damage and redeposition caused by the erosion products that are emitted from the electrodes and then travel to the insulator surface. This may not be a common problem for plasma guns and DPF devices if the insulator in these devices is placed in a special protective gap. For a final choice of electrode, wall, and insulator materials, a number of experiments are necessary to determine their resistance to high thermal shocks from shot-pulsed-plasma impingement and intensive ion bombardment, including that of HCIs.

The materials shown in Table 35.1 are proposed to initiate the overall comparative analysis. Note that the properties of materials, especially ion and thermal erosion, will depend importantly not only on their chemical composition, but also on the technology of their manufacture. For example, for a material such as boron nitride or tungsten-copper pseudo-alloy, it is recommended that samples be obtained from several manufacturers. This approach will permit unequivocal evaluation and choice of electrode and insulator materials for EUV-source plasma-facing components.
Table 35.1 The major candidate materials for EUV source plasma-facing components.

<table>
<thead>
<tr>
<th>Material</th>
<th>EUV-source plasma-facing component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-alloy, 75% W, 25% Cu</td>
<td>Electrodes or the inserts for energy-intensive parts</td>
</tr>
<tr>
<td>Pseudo-alloy, 80% Mo, 20% Cu</td>
<td>Electrodes or the inserts for energy-intensive parts</td>
</tr>
<tr>
<td>Pseudo-alloy 75% W, 20% Cu, 4% Ni, 1% La₂O₃</td>
<td>Electrodes or the inserts for energy-intensive parts</td>
</tr>
<tr>
<td>Single-crystal W with 2% Re</td>
<td>Inserts for energy-intensive parts</td>
</tr>
<tr>
<td>Copper</td>
<td>Electrode</td>
</tr>
<tr>
<td>Sintered tungsten</td>
<td>Electrode</td>
</tr>
<tr>
<td>Pyrolytic graphite and carbon-fiber composites (CFCs)</td>
<td>Electrode</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Wall of vacuum chamber</td>
</tr>
<tr>
<td>Corundum (α-Al₂O₃)</td>
<td>Insulator</td>
</tr>
<tr>
<td>Beryllium oxide (BeO)</td>
<td>Insulator</td>
</tr>
<tr>
<td>Pyrolytic boron nitride (PBN)</td>
<td>Insulator</td>
</tr>
<tr>
<td>Thin-film Ru, Pd, or W</td>
<td>Condenser optics (grazing-incidence mirror)*</td>
</tr>
</tbody>
</table>

* Mirror materials are discussed in a later section of this chapter.

This section has pointed to candidate materials for plasma-facing DPP electrodes and insulators. The next section will cover testing of candidate materials under dense-plasma-relevant conditions. This is done in simulated experiments in high-intensity plasma facilities briefly discussed in this section.

35.4 Testing of Materials in Plasma-Gun Facilities

Small plasma pinch devices operating with frequencies of 5–10 kHz, pulse energies on the order of 1–100 J, and gas mixtures of Xe and He are very promising as sources of EUVL radiation (λ = 13.5 nm). A serious problem in the design of such EUV sources concerns erosion of the pinch components under the action of electric currents, hot plasma particles, and photon radiation. Material erosion limits the lifetime of plasma-facing components, thereby reducing the practical feasibility of DPP EUV sources. Investigation of erosion mechanisms and their dependences on the operational parameters is quite important for successful development of commercial DPP EUV devices.

Experiments described in this section investigate material erosion caused by hot, dense Xe and H plasmas on copper and tungsten sample targets. The experiments were carried out at the plasma-gun facility MK-200, at TRINITI, Russia. A pulsed plasma gun is used as the source of Xe or H plasma. The gun accelerates low-temperature Xe plasma to a high velocity. Then the plasma stream collides with the structural material to be investigated. Due to collision of the supersonic plasma stream with the solid target, a shock front arises in the plasma stream, and a cloud of hot, dense Xe plasma is formed near the target surface. Thus the target surface is exposed to the interaction of energetic particles and photon radiation from the hot Xe plasma, as in DPP EUV devices.
A cloud of Xe plasma is formed at a temperature $T = 30–50$ eV, similar to those found in EUV plasma pinch devices. This magnitude of temperature is needed for the tenfold ionization of Xe to produce Xe$^{+10}$ ions emitting spectral lines at the wavelength $\lambda = 13.5$ nm. Theoretical analysis shows that the required temperature can be obtained in the shock wave if the plasma stream moves with a velocity of the order of $10^7$ cm/s. Therefore, the first task of the experiment was to produce Xe plasma streams with sufficiently high velocity. Besides a high velocity, the plasma stream must have a rather large energy and pulse duration. In this manner, material testing and lifetime assessment could be realized during a short time.

The experiments performed are a first step toward understanding the problem of material damage induced by hot Xe plasma. They were focused mainly on the development of appropriate experimental techniques relevant to conditions in high-heat-flux regions on electrodes in DPP EUV devices. Initial results indicate various mechanisms of material erosion (such as vaporization, sputtering, and melt splashing) and surface modification (bubble and blister growth and cavity formation) that can all exist in regions of high heat flux in DPP EUV device electrodes.$^{7,8}$

### 35.4.1 Plasma-gun-device setup

As stated earlier, the experiment was performed at the MK-200 facility, consisting of two plasma gun devices: MK-200UG and MK-200CUSP.$^{28}$ The basic scheme of MK-200UG is shown in Fig. 35.7. The facility consists of a pulsed plasma gun, a long drift tube, and a target chamber with attached diagnostic tools. The plasma gun is fed from a 1152-$\mu$F capacitor bank. As a rule, the gun operating voltage is 20–25 kV. This voltage range corresponds to 230–360 kJ of energy stored in the capacitor bank.

The plasma gun injects a H or Xe plasma stream into the drift tube, consisting of a 6.5-m cylindrical section and a conical section with a length of 3.0 m. The diameter of the cylindrical tube is 30 cm. In the conical section, the tube diameter reduces towards its exit from 30 cm to 15 cm.

The drift tube is filled with a longitudinal magnetic field. The magnetic field induces thermal isolation of the plasma stream from the tube wall. For this reason, the plasma stream is transported over large distances (10 m) with negligible energy loss. The magnetic field is used also to control the plasma stream’s properties. In
the conical section, where the magnetic field increases, the plasma stream is compressed radially, leading to an increase in plasma density. It should be noted that plasma-stream parameters in the target chamber depend strongly on the magnetic field profile in the drift tube. By changing the magnetic field profile the plasma stream’s properties (density, pulse duration, velocity, and others) might be varied widely. The cylindrical tube is filled with a uniform magnetic field of 0.7 T. In the conical section the magnetic field rises from 0.7 to 2.0 T. Samples to be studied are placed in the target chamber. The diameter of the chamber is 30 cm, and its length 50 cm. The magnetic field is 2.0 T in the target chamber.

Table 35.2 shows parameters of the plasma stream measured in the target chamber. The values are very close to those that are required for testing of materials in Xe plasma. However, the parameters listed in Table 35.2 were obtained for a H plasma stream and not for Xe.

The MK-200CUSB machine is schematically shown in Fig. 35.8. The plasma gun is fed from a 1152-μF capacitor bank. The gun injects the plasma stream into the cylindrical tube \((L = 50 \text{ cm}, D = 30 \text{ cm})\) with a longitudinal magnetic field of 1 T. Then the plasma stream comes into the conical section \((L = 50 \text{ cm})\), where the diameter of the tube reduces towards its exit from 30 to 14 cm while the magnetic field strength rises from 1 to 2.6 T. The low-energy tail of the stream cannot traverse the steep magnetic gradient, and it stops in the magnetic cone. The high-energy leading part of the stream passes through the increasing magnetic field, and it is radially compressed.

<table>
<thead>
<tr>
<th>Table 35.2 Parameters of H plasma stream at MK-200UG.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total energy</strong></td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
</tr>
<tr>
<td><strong>Pulse duration</strong></td>
</tr>
<tr>
<td><strong>Velocity</strong></td>
</tr>
<tr>
<td><strong>Plasma density</strong></td>
</tr>
<tr>
<td><strong>Plasma stream diameter</strong></td>
</tr>
</tbody>
</table>

![Figure 35.8 Basic scheme of the MK-200CUSB high-intensity plasma gun.](image-url)
Table 35.3 Parameters of H plasma stream at MK-200CUSP.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy</td>
<td>$Q = 20$–$30$ kJ</td>
</tr>
<tr>
<td>Energy density</td>
<td>$q = 1$–1.5 kJ/cm$^2$</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>$\tau = 7$–$15$ $\mu$s</td>
</tr>
<tr>
<td>Velocity</td>
<td>$V = (3$–$5) \times 10^7$ cm/s</td>
</tr>
<tr>
<td>Plasma density</td>
<td>$n &gt; 10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma-stream diameter</td>
<td>$D = 5$ cm</td>
</tr>
</tbody>
</table>

The scheme of MK-200CUSP is very similar to that of MK-200UG. The main difference is the shorter length ($l = 1.2$ m) of the drift tube in the MK-200CUSP. In the short drift tube the plasma-stream density is greater than in a long drift tube. Table 35.3 shows the plasma-stream parameters measured at the target position in MK-200CUSP.

35.4.2 Diagnostics of plasma stream

The first objective of the present experiment was to obtain a Xe plasma stream having a velocity of the order of $10^7$ cm/s and total energy 20–50 kJ. Diagnostic tools that are suitable for the measurements of plasma velocity and energy were applied.

The plasma stream energy was measured by using large and small calorimeters. Large calorimeters (trapping the whole plasma stream) were applied for the measurement of the total plasma stream energy, and small calorimeters (1.5–2 cm in diameter) for the measurement of radial distribution in the plasma stream energy. All the calorimeters have a cylindrical form; their lengths are 3–5 times larger than their diameters. The growth of the calorimeter temperature (which is proportional to the absorbed plasma energy) was measured by thermocouples.

The velocity of the plasma stream was measured by a time-of-flight method using magnetic probes, which are distributed along the whole length of the magnetic drift tube at various distances from the gun. The probes are placed in the vicinity of the tube wall; they do not contact the plasma, and thus they do not affect the plasma-stream properties. When the plasma stream moves in the drift tube, the magnetic field increases near the wall because of the diamagnetic effect (the plasma pushes away the magnetic field).

35.4.3 Irradiation of target materials by hot Xe plasma

Tungsten and copper are typically used as structural materials for DPP electrodes. These materials were exposed to Xe plasma streams in the MK-200CUSP. The targets were irradiated by Xe plasma with energy density 100–200 J/cm$^2$. Since a hot Xe plasma cloud is formed in front of the exposed target, the target surface is exposed to the interaction of Xe plasma particles and photon radiation.

Besides Xe plasma, the targets were also tested with hydrogen plasma streams having practically the same energy density as Xe plasma streams. The experiment
focused on investigation and comparison of surface damage caused by Xe and H plasmas. This type of experimental data is quite important for understanding whether the numerical models used in HEIGHTS-EUV, for example, which are being developed for simulation of material damage caused by H plasmas, can also be applied and benchmarked for modeling of material damage induced by Xe plasmas with applications to numerical modeling of DPP high-intensity-plasma–material interactions.

### 35.4.4 Target design

Four targets were tested: two identical tungsten targets and two identical copper targets. The targets were produced in the form of rectangular plates fully overlapping the plasma stream. The plates were manufactured absolutely flat, and their face surfaces were prepolished, which is required for profilometry measurement of the exposed surface after irradiation.

Each target was equipped with a diaphragm having a 3-cm hole [Fig. 35.9(a)]. The diaphragm was placed in front of the target face at a distance of 1–2 mm. A gap between the target surface and the diaphragm was produced by using an intermediate plate as shown in Fig. 35.9(b).

The target was equipped with a diaphragm for the following reasons. The diaphragm reduces the size of the plasma-irradiated area to a diameter of 3 cm. This allows the surface profile to be analyzed using a standard mechanical profilometer. The scanning length of the profilometer is limited to 5 cm. When the target is exposed to the whole plasma stream, the diameter of the eroded area is larger than 5 cm.

The melt, which is splashed from the plasma-irradiated region, falls outside the region protected by the diaphragm from plasma irradiation. Therefore the splashed metal melts again in subsequent plasma shots, and it retains its original properties. This clarifies whether the melt is splashed in the form of droplets and jets or moves as a whole.

### 35.4.5 Surface and material loss diagnostics

The profile of the exposed target surface was measured by using a mechanical profilometer. Because of deep surface cracks and open surface cavities, the diamond pin that is typically used in the mechanical profilometer could not be applied in the present experiment for analysis of the exposed surface profile. Instead, a small ball was used as the sensing element. The ball sensor is well suited for the measurement of the averaged surface profile, but it is not good for analysis of the surface cracks and small surface cavities. Surface damage and surface microstructure were studied by the use of an optical microscope and a scanning electron microscope (SEM). The mass of the eroded material was measured by weighing the targets before and after the plasma test. The targets were exposed to 15 plasma shots, and then the mass loss $\Delta M$ was measured. Afterward, the mass loss per shot, $\Delta m = \Delta M/15$, was evaluated. The thickness of the eroded material, $d$, was evaluated from the
Figure 35.9 (a) Target equipped with diaphragm. (b) Intermediate plate placed between target and diaphragm.
measured mass loss as $d = \Delta m/\rho S$, where $\rho$ is the specific gravity of the target material, and $S$ is the plasma-irradiated area determined by the diaphragm hole of 3-cm diameter.

### 35.4.6 Irradiation by Xe and H plasmas

Copper and tungsten targets were exposed to 15 shots of Xe and H plasma at practically identical heat loads: 150–250 J/cm². The material erosion evaluated from the measured mass loss was found to be about 0.1 μm per shot for both copper and tungsten, under Xe and H plasma exposure. In principle, H plasma should cause lower mass loss, by about 30%, but the mass loss measured was nearly the same as for Xe. Thus the performed mass loss measurements have shown that copper and tungsten erosion caused by material evaporation, sputtering, and droplet ejection is limited to 0.1 μm per shot of Xe and only slightly less for H.

### 35.4.7 Copper surface damage

Figure 35.10(a) shows a photograph of the copper target after being exposed to 15 shots of H plasma. This photograph was taken when the diaphragm had been removed but the intermediate plate, which was placed between the target surface and diaphragm, remained in place. Examining the exposed target surface, one can see that the copper melt is partly splashed from the area exposed to the H plasma stream to the outside area protected by the diaphragm from plasma action. Melt splashing occurs in the form of droplets and jets moving in the radial direction. The displacement of the melt is limited to 1–2 mm. It is important to note that a leading part of the splashed melt is detached from the target surface and there is a small gap between the splashed melt and the target surface. In other words, the splashed melt is not well bonded to the target surface. The central zone of the exposed target area looks rather rough. The rough surface is formed due to boiling of the melt and to excitation of surface waves in the liquid metal under plasma action.

Figure 35.10(b) shows the surface of a copper target after 15 exposures to Xe plasma. In contrast to the experiment with hydrogen plasma [Fig. 35.10(a)], melt splashing does not occur under exposure to Xe plasma. Only a few traces of splashed droplets are seen outside the exposed area [Fig. 35.10(b)]. The macrostructure of the exposed surface looks very similar to that obtained in H plasma experiments.

The copper targets exposed to H and Xe plasmas were analyzed using a mechanical profilometer. The target regions protected by the diaphragm from the plasma action remain at the original (zero) surface level, and they are used as a reference in the profilometry measurements. The measured surface profiles are shown in Fig. 35.11(a) (H plasma) and Fig. 35.11(b) (Xe plasma).

The surface profile induced by the H plasma stream consists of an erosion crater and meltlike mountains at its edge. The crater is located in the plasma-irradiated region; the mountains, in regions protected by the diaphragm from the plasma. The
measured surface profile indicates that the H plasma stream stimulates melt motion in the radial direction from the plasma-irradiated area to the periphery. The measured mountain heights are rather large, up to 150 \( \mu \text{m} \), but this value is erroneous and cannot be used for evaluation of the melt volume accumulated in the mountains. This is because the splashed melt is detached from the target surface, thus leading to an overestimation of the mountain's height measured by the profilometer.

The depth of the erosion crater is 10–15 \( \mu \text{m} \) (i.e., the erosion rate is about 1 \( \mu \text{m} \) per shot). This means that the erosion caused by copper melt movement along the target surface is 10 times larger than the erosion caused by copper evaporation, sputtering, and droplet emission (the erosion mechanisms leading to mass loss).

In the case of Xe plasma [Fig. 35.11(b)], melt motion may also take place in principle. From the data, shorter melt mountains are in fact formed around the exposed target area. However, the melt motion is not as intense as in the H plasma.

**Figure 35.10** Copper target after 15 exposures to (a) H plasma, and (b) Xe plasma.
Figure 35.11 Surface profile of copper target after 15 plasma exposures to (a) H plasma, and (b) Xe plasma.

case, and therefore, the melt displacement does not produce a significant erosion crater.

The above experimental results show that a H plasma stream causes melt movement along the target surface, while a Xe plasma does not produce any notable melt displacement. Evidently the melt motion occurs because of the pressure gradient that forms at the target surface due to the action of the plasma stream. One could assume that the Xe plasma stream has a lower impact pressure than the H stream and that is why the melt movement is practically absent in the former case. However, this assumption does not agree with available experimental data. Xe and H plasma streams have very similar energy densities $Q = 150$–$250 \text{J/cm}^2$ and plasma pulse durations $t = 5$–$10 \mu$s. The plasma stream energy density is equal to

$$Q = \rho V^3 t = (\rho V^2) V t = PV t,$$

(35.2)

where $\rho$ is the mass density of the plasma stream, $V$ is the velocity of the stream, and $P$ is the impact plasma pressure. In the present experiment, the velocity of the Xe plasma, $V_{Xe} = (1-2) \times 10^7 \text{ cm/s}$, is slightly less than the velocity of the H plasma. Therefore, the impact pressure for Xe plasma must be larger than for H plasma, and the Xe plasma should also induce melt motion.

The experimental results might be explained by the following argument. Xe plasma emits much more intense radiation than H plasma. Therefore, after collision
of the Xe plasma with the target surface, a significant part of the plasma energy is lost from the plasma cloud into photon radiation. As a result, the Xe plasma stream produces weaker thermal action on the target surface than the H plasma stream, in spite of the fact that the plasma streams have identical energy densities. So, in the case of a Xe plasma we may predict a self-shielding effect, which leads to reduced action on the target surface.

It was mentioned above that the macrostructures of the target surfaces exposed to Xe and H plasmas look very similar. However, the details of the microstructures (e.g., surface morphology) are very different. Figure 35.12(a) shows SEM images of the copper surface exposed to H plasma. The surface is covered by open cavities, which form due to copper melt boiling. A typical size of the cavities is 10–30 μm.

![SEM image of copper surface after 15 exposures to (a) H plasma stream, and (b) Xe plasma stream.](image)

**Figure 35.12** SEM image of copper surface after 15 exposures to (a) H plasma stream, and (b) Xe plasma stream.
In the Xe plasma case [Fig. 35.12(b)], melt boiling does not occur. In contrast to H plasma, Xe plasma produces a regular wavy structure on the target surface. The nature of the observed differences is not clear.

### 35.4.8 Tungsten surface damage

Two identical tungsten targets were also exposed to 15 shots of H and Xe plasma streams. Figures 35.13(a) and (b) show tungsten targets after their irradiation by H and Xe plasma, respectively.

At the right side of the target surface shown in Fig. 35.13(a) (at a distance of 5–6 mm from the boundary the exposed target area), one can see the splashed droplets and jets. These droplets and jets were splashed from the diaphragm but not from the exposed tungsten area. Splashing of tungsten melt is practically absent. The central part of the target area is damaged by surface cracking. The cracks are parallel, and a typical distance between them is about 1 mm.

The action of Xe plasma also produces surface cracks. However, the cracking is not as intense as in the case of H plasma, and therefore the target surface exposed to Xe plasma looks smoother. Splashing of tungsten melt was not observed.

Figure 35.14(a) shows a measured profile of the tungsten surface exposed to the H plasma stream. The amplitude of the surface roughness is 20–30 μm. The observed surface roughness is caused by surface cracks. Surface cracks are formed not only in the target area directly exposed to the plasma stream, but also in the adjacent areas protected by the diaphragm from plasma action. No erosion crater or meltlike mountains are evident. Even if the melted tungsten moves under the action of H plasma (as in the experiment with the copper target), there is no accurate way to measure the erosion crater and the melt mountains against the background of large surface roughness caused by tungsten cracking.

Figure 35.14(b) shows the surface profile of the tungsten target irradiated by Xe plasma. The surface roughness is considerably less than in the case of H plasma.

![Figure 35.13](image)

**Figure 35.13** Tungsten target after 15 exposures to (a) H plasma, and (b) Xe plasma.
being no more than 10 μm. The exposed target region is shown to swell up with respect to the unexposed region. No such effect has ever been observed in experiments with hydrogen plasma.

Figure 35.15(a) shows SEM images of the tungsten surface after its irradiation by Xe plasma. One can see that the surface is covered entirely with bubbles (or blisters). Their size is 20–30 μm, and they are separated by small distances. As mentioned earlier, a small ball was used in the present experiment as the sensing element of the mechanical profilometer. The ball is not able to follow exactly the profile of a single bubble. Rather, it goes along the tops of the bubbles. For this reason, the measured profile shows swelling of the whole target surface. In reality, general surface swelling seems to be absent.

As shown in Fig. 35.15(a), the bubbles produce a regular wavy structure on the tungsten target surface. This fact indicates that the bubbles may be related to the surface waves that arise in the liquid metal under action of the plasma stream. At the melt cooling and solidification stage, the surface waves may fall into separate parts because of melt surface tension, and this process may produce small melt mountains, which resemble surface bubbles.

The microstructure of the tungsten surface induced by action of H plasma is shown in Fig. 35.15(b). The surface structure is very different from that obtained
in the case of Xe plasma. H plasma causes severe surface cracking. The cracks divide the surface into separate plates. There is no any evidence of melt motion or melt bubbles. The exposed tungsten surface consists of small flakes. The last fact shows that H plasma may cause the well-known brittle destruction of the tungsten surface in the form of flakes.

35.4.9 Conclusions on testing materials in plasma-gun facilities

Tungsten and copper targets have been tested with hot Xe plasma \( T = 30-50 \text{ eV} \) formed near the target surface due to collision of a supersonic Xe plasma stream with the solid target. The same materials have been tested also with a H plasma...
stream having similar energy density to the Xe one. Plasma-induced erosion and surface damage were studied.

The experimental results can be summarized briefly as follows:

- Copper and tungsten erosion caused by material evaporation, sputtering, and droplet injection (the erosion mechanisms leading to target mass loss) is about 0.1 μm per shot of Xe or H plasma.
- Hot Xe or H plasma produces a melt layer at the exposed target surface.
- Under the action of a plasma stream, copper melt is splashed from the exposed target area. Erosion of copper due to melt movement is about 1 μm per shot of H plasma. Xe plasma causes much less splashing of copper melt.
- Splashing of tungsten melt is practically absent.
- The microstructures of target surfaces exposed to Xe and H plasmas are quite different.

For copper, a H plasma causes melt boiling, producing open cavities at the exposed target surface. A copper target irradiated with a Xe plasma is entirely covered with surface waves. For tungsten, a H plasma causes severe cracking of the surface. A Xe plasma causes considerably milder cracking. A H plasma produces small flakes at the tungsten surface, causing brittle destruction of the tungsten. A Xe plasma produces a wavy structure on the tungsten surface, consisting of bubbles. These results show that surface damage induced by Xe plasma differs from that induced by H plasma.

One important observation is the variety of erosion mechanisms under high-intensity plasma exposure for materials such as copper and tungsten. The erosion is not only due to normal physical sputtering. It also depends on the effectiveness of the vapor shielding, which, in the case of Xe bombardment and the conditions in these experiments, is quite effective. Thus normal sputtering is not the only erosion mechanism, though the overall mass losses from Xe and from H are measured to be of the same order of magnitude.

Concerning implications of these results for DPP EUV devices, the following points are concluded. Xe damage at the surface is quite distinct from that due to other gases such as H. The details of surface damage are relevant, since the experiments presented here produce the same net energy deposition as that found in DPP devices. A Xe self-shielding effect should be expected during operation of DPP devices, and thus melt motion can be expected in certain regions on DPP electrode surfaces. The net energy deposited into the materials tested in the MK-200 plasma guns is between 1.5 and 2.5 J/cm², resembling conditions in DPP electrode regions exposed to high heat flux. More importantly, the experiments conducted with the MK-200 system studied the interaction of the He plasma over a long time (≈10–20 μs) compared to the characteristic time (≈20–50 ns) of the plasma pinch in a DPP device, in which melting occurs, providing for accelerated testing equivalent to 1000 shots in a DPP device.
The next section will extend the simulated experiments discussed above to experiments testing candidate materials in an actual DPP device. The DPF device was chosen for the tests, and a summary of the results is given in the next section.

### 35.5 Modeling and Testing Condenser-Optic Response

Critical to the performance of future EUV source systems is how operation of the source affects the region near and around the condenser 1 (C1) optic, that is, the collector optics. Degradation of the condenser optics is presently one key challenge for existing and future EUV source systems that will need to perform at frequencies greater than 5 kHz to reach powers near and above 100 W at intermediate focus (IF), meeting HVM demands. Operation under these conditions will lead to heavy electrode erosion and surface contamination, and even with debris mitigation schemes, condenser optics will face nontrivial degradation problems. Degradation of collector optics includes EUV-induced processes (e.g., oxidation, carbonization), and erosion and deposition of debris from various components in EUVL devices. Materials solutions will not likely lead to a factor 10–100 improvement in EUVL source performance. However, understanding of the C1 optic’s response to the operation of the source and debris mitigation schemes can lead to a window of opportunity for integrated solutions with respect to C1 optics that will ultimately result in significant improvements in EUVL source performance.

In order to address these issues one must complement debris mitigation efforts with a thorough, directed, fundamental, and pragmatic study of the behavior of condenser-optic material surfaces under high-power EUV source conditions. This can only be done by careful diagnosis of the condenser-optic region (COR) in existing EUV source devices. Fundamental understanding of the effects EUV radiation and additional particle interactions have on plasma-facing condenser mirrors can lead to the design of advanced collector-optic materials that possess unique surface properties extending the condenser optic (CO) lifetime and enhancing EUV source performance. In DPP devices, generation of EUV light is collected by grazing-incidence mirrors (GIMs), as stated earlier. Synergy in environmental conditions can have significant effects on GIM performance. For example, how singly charged fast ions and neutrals created at the source induce surface damage of candidate optical materials interacts with OOB radiation heating of the GIM surface. Such synergistic effects can be studied and candidate materials tested with experimental facilities such as IMPACT at the Argonne National Laboratory (ANL). Other facilities conducting condenser-optics erosion studies include the University of Illinois at Urbana-Champaign and the ETS source at Sandia National Laboratory at Livermore. Figure 35.16 shows a schematic of characteristic debris GIMs are exposed to.

One of the outstanding issues with DPP source devices for EUVL is the lifetime of the C1 optics. The lifetime is currently defined as the loss of EUV reflectivity of about 10% after operation with about $10^{11}$ shots. The fabrication characteristics and component properties of Mo/Si multilayer mirrors (MLMs) are determining
Figure 35.16 Schematic of various debris that interacts with a GIM surface in a DPP device. A typical GIM consists of a single thin-film layer with high EUV reflective properties.

factors for the reflective intensities of the C1 mirrors in LPP systems. The design of MLMs includes the choice of the optimum layer period as well as control of compressive versus tensile stresses. Optimization of these parameters as well as maintaining low surface roughness and using interface engineering results in increased C1 optic lifetime and greater mean reflective intensities for lithography. Additional issues include interlayer mixing.

In DPP EUV-source devices, GIMs are applied. These can consist of thin films of high-EUV-reflectivity materials (e.g., Ru, Mo, Pd). Understanding erosion mechanisms as well as additional thermodynamic and radiation-induced mechanisms is critical in the design of GIM materials for HVM operation. In addition, diagnosis of the environmental conditions that mirror surfaces are exposed to is critical to the advancement of GIM design. However, any materials improvement will have to be coupled with debris mitigation schemes near the source, due to the high heat load that electrodes at the source will be exposed to under HVM operation. In addition, understanding and diagnosis of the COR will be important for determining which erosion mechanisms will dominate at the surface. For example, OOB radiation can lead to local heating of the GIM surface. Therefore, the effect of fast ions and neutrals at the GIM surface must be taken into account under these conditions. This chapter summarizes key particle-surface interactions important for the design of GIM surfaces for HVM DPP EUV devices.

Near-surface composition modifications in multicomponent systems (MCSs) from ion bombardment have been observed from many alloy systems, both in the solid and in the liquid state. A number of nonthermal and thermally activated mechanisms can exist when a MCS is irradiated. All of these mechanisms work synergistically, leading to changes in the near-surface region—a region important
in determining the lifetime of condenser-optic materials under EUV-source system conditions.

Conceptually, the phenomenon of bombardment-induced compositional changes is simplest when only nonthermal processes exist, such as preferential sputtering (PS) and collisional mixing (CM). PS occurs in most MCSs due to differences in binding energy and kinetic energy transfer to component atoms near the surface. CM of elements in MCSs is induced by displacement cascades generated in the MCS by bombarding particles/clusters and is described by a diffusion model.

Irradiation can accelerate thermodynamic mechanisms such as Gibbsian adsorption (GA), or segregation, leading to substantial changes near the surface with spatial scales of the order of the sputter depth (a few monolayers). GA results from thermally activated segregation of alloying elements to surfaces and interfaces, reducing the free energy of the alloy system. Typically, GA will compete with PS, and thus, in the absence of other mechanisms, the surface reaches a steady-state concentration approaching that of the bulk. However, when other mechanisms are active, synergistic effects can once again alter the near-surface layer, and complex compositions can result.\textsuperscript{38,39}

These additional mechanisms include radiation-enhanced diffusion (RED) due to the thermal motion of nonequilibrium point defects produced by bombarding particles near the surface; and radiation-induced segregation (RIS), a result of point-defect fluxes, which at sufficiently high temperatures couples defects with a particular alloying element, leading to compositional redistribution in irradiated alloys in both the bulk and near-surface regions. Additional mechanisms include ion-induced mixing and preferential recoil implantation. All of these mechanisms must be taken into account in the design of proposed advanced materials, in addition to considering other bombardment-induced conditions (clusters, HCIs, neutrals, redeposited particles, debris, etc.).\textsuperscript{39}

\textbf{35.5.1 Erosion and redeposition at condenser-optic material surfaces}

Optic material surfaces will be eroded via sputtering by slow and fast ions from the expanding postdischarge EUV source plasma. For a He-Xe discharge, for example, sputtering will occur due to physical sputtering by He and Xe ions.

The source design should seek to minimize erosion by choice of geometry and optic materials, and possibly by optimizing the plasma constituents (e.g., He/Xe ratios). The net sputter erosion rate of any surface depends critically on the balance between gross erosion and redeposition. Gross physical-sputter fluxes depend on the incident particle fluxes and energy, the latter primarily determined by sheath acceleration. Redeposition occurs due to ionization of sputtered atoms by the plasma electrons and subsequent transport of those ions back to the surface via collisions with the incoming plasma. Net erosion rates approaching zero are possible under some plasma and material conditions.
Sputtering erosion and redeposition have been extensively studied in fusion-power research. The ANL REDEP code\textsuperscript{10} package is the world’s leading code for predictive simulations of plasma-surface interactions including erosion and redeposition, and will be used for EUV source studies. This code package contains hundreds of models for the relevant erosion and redeposition processes and has been extensively validated with experimental data. As stated earlier, the conditions near collector optics are believed to be characterized by a relatively warm plasma ($T_e \approx 20$–$30$ eV) and low to moderate electron density ($\sim$100–1000 times less than the source density). Such plasma conditions at the optical surfaces are actually similar to fusion edge conditions with regard to ion and electron temperatures and density ranges. Because of ANL’s extensive experience in this area, we have access to and can readily implement any additional process models relevant to EUV optical-surface sputtering and transport. One additional task is the characterization of an admixture plasma (viz., He and Xe) expanding toward the GIM surfaces. The expertise at ANL and contacts with other experts in the field facilitate our ability to effectively and efficiently implement plasma edge models.

### 35.5.2 Condenser-optics materials testing

Experimental facilities such as IMPACT at ANL, shown schematically in Fig. 35.17, can test candidate mirror materials under intense charged-particle irradiation. IMPACT consists of a well-collimated ion source with an energy range between 50 and 5000 eV, fluxes of $10^{11}$–$10^{17}$ ions/cm$^2$ s, and incident angles from normal incidence to about 60–70 deg with respect to normal. Base pressures are attainable down to $10^{-10}$ Torr with gas inlets for controlled impurity desorption/adsorption experiments. In addition, an \textit{in situ} heating design can vary the sam-

![Figure 35.17](image-url)
ple temperature from ambient conditions to about 1000°C. IMPACT currently has a quartz-crystal-microbalance–dual-crystal-unit (QCM-DCU) diagnostic system for *in situ* real-time total-erosion measurements and has additional *in situ* metrology, including low-energy ion scattering spectroscopy (LEISS), Auger analysis, and x-ray photoelectron spectroscopy (XPS), for multicomponent erosion measurements. The sample is fixed on a rotatable manipulator, whose rotation axis lies in the plane of the sample surface. This allows for angle-of-incidence measurements on the irradiated surface. In addition, the sample holder includes an *in situ* ultrahigh vacuum (UHV) heater system with a thermocouple located underneath the sample for temperature-variation tests. The heater is equipped with a set-point controller with the capability of also setting the heating rate (K/s). This is important because various microstructures and surface morphologies depend on the local surface condition. The sample sits in a stainless steel cup, allowing for exchange of samples in vacuo with a manipulator and transfer lock system. When the sample is removed from the ion beam, the beam is collected by a Faraday cup for beam profile analysis. The Faraday cup consists of four small pinholes about 0.125 mm in diameter and 2 mm apart.

**In situ** diagnosis is important for several reasons. A surface under ion irradiation is actively changing during the exposure dose. For example, RIS will drive certain target components to the surface, while RED will drive them away from the surface. Adsorbates will be active on a given surface according to the surface kinetics and thermodynamics, and their role in mechanisms such as sputtering and reflection can be assessed only by actively interrogating the surface irradiated.

Accelerated testing of candidate GIMs or MLMs can be done with ion sources affording a large range of ion-bombardment fluxes and long-term electron-gun exposures. IMPACT also is equipped with an *in situ* UHV heater providing for thermal annealing tests while the sample’s surface is diagnosed and for simulating OOB radiation heating effects. This chapter presents initial experiments in IMPACT on total single-component erosion by use of the QCM-DCU diagnostic system.

Figures 35.18(a) and (b) show results of total-sputtering measurements for Ar⁺ and Xe⁺ bombardment at normal incidence for energies ranging from 200 to 5000 eV. The results are compared with well-known experimental data, thus serving as good calibration references for the setup in IMPACT. The QCM-DCU technique works by depositing a quantity of eroded material on a gold-covered quartz crystal oscillator. The oscillator vibrates at a fundamental frequency of about 6 MHz. As mass is deposited on the surface of the oscillator, its frequency decreases. The measurement of total physical sputtering is very sensitive; therefore, a dual-crystal unit is applied. The unit works by one oscillator monitoring the eroded material and the other the background frequency. The frequency difference is then utilized in the calculation of the sputtering yield. Attention is paid to several important factors: the sticking coefficient of known species to the collector surface of known surface composition, the collecting solid angle, and the respattering of collected material by fast reflected ions or neutrals. Surface compositions are taken from previous surface analysis results.
Figure 35.18 Sputtering yield of copper bombarded by singly charged (a) Ar, and (b) Xe, at normal incidence in the IMPACT experiment at ANL.

35.5.3 Oblique-incidence erosion of Ru bombarded by Xe$^+$

The physical sputtering yield of Xe$^+$ bombardment of ruthenium at 45 deg was measured in IMPACT. The incident particle energy ranged from 500 to 1000 eV, and the results are shown in Fig. 35.19(a). The sputtering yield rises from about...
Figure 35.19 Sputtering yield of Ru bombarded by (a) Xe plasma stream, and (b) H plasma stream.

0.1 Ru atom/ion at 500 eV to about 0.4 Ru atom/ion at 1500 eV. Xe\(^{+}\) bombardment shows no indication of nonlinear erosion. This is because the binary collision approximation (BCA) based code ITMC is used to model the system for a number of incident particle energies. The model implemented in the ITMC code is con-
sistent with the linear sputtering model. There is very good agreement between
the model and experimental data, and thus we do not expect the Ru yield to rise
nonlinearly with temperature. For a GIM, the measurements of oblique incidence
of fast ions (e.g., Xe$^+$) are of interest due to the solid angle collecting EUV light,
which provides for very oblique angles in incidence for fast, singly charged ions,
as shown in Fig. 35.19(b). In these measurements a Ru oxide layer was assumed
to deposit on the collecting crystal of the QCM-DCU diagnostic. This assumption
needs further investigation using postexposure surface analysis.

35.6 Conclusions

Plasma-facing EUV-source device materials will need to be carefully designed to
stand up to the harsh environment they will be exposed to. Electrode materials must
be designed to provide erosion resistance and good thermal conductivity. High-
density plasmas in DPP devices will lead to serious erosion challenges as HVM
conditions are attained. However, with proper electrode design and robust debris
mitigation schemes, some opportunity exists for operation in HVM. Condenser-
mirror optics face the same challenge. The mirror surface will have to be designed
to contend with incident debris, highly energetic singly charged and multicharged
particles, and fast neutrals. More importantly, the synergy of such fluxes com-
bined with background impurities and OOB radiation will ultimately decide the
fate of plasma-facing mirrors. This is mainly dictated by the specification of the
condenser-optic lifetime for the collector optics. This specification requires that
only a 10% loss in EUV reflectivity occurs over 30,000 operating hours.

Proper design coupled with debris mitigation schemes will enable emerging
lithography technologies to operate under HVM conditions. This goal can be at-
tained in timely fashion by designing well-diagnosed, controlled off-line experi-
ments, such as the IMPACT experiment, to understand synergistic erosion mecha-
nisms that can lead to advanced mirror designs.

References

1. A. Hassanein, V. Sizyuk, V. Tolkach, V. Morozov, T. Sizyuk, and B. Rice,
"Simulation and optimization of DPP hydrodynamics and radiation transport
2. A. Hassanein, V. Sizyuk, V. Tolkach, V. Morozov, and B. Rice, "HEIGHTS
initial simulation of discharge produced plasma hydrodynamics and radiation
transport for extreme ultraviolet lithography," J. Microlithogr. Microfab. Mi-
3. A. Hassanein and V. Morozov, "Development of comprehensive and integrated
model for IFE cavity dynamics," Argonne National Laboratory, Report ANL-
ET/02-04 (2002).


For a biography of author V. Bakshi, see Chapter 1. Biographies for the other authors of this chapter were not available.