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Highly Efficient High-Power Continuous Extreme Ultraviolet Source for Irradiating Samples with a Large Total Area

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Abstract—An original arc-discharge source of cw extreme ultraviolet (10–75 nm) radiation is described, which provides an output power level of ~10 kW at an efficiency of ~10% (at least, in the 30–70 nm range). The source is simple to manufacture, possesses a working life of ~1000 h, and is capable of irradiating samples with a total exposed area of 0.1–1 m^2.

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In recent years, short-wavelength radiation sources have been extensively studied in many countries. Progress in the modern micro- and nanoelectronic device technology (in particular, projection lithography) and the processing of materials by beam erosion, radiation-induced modification (including the creation of a regular nanodimensional structure), and some other methods poses the task of developing short-wavelength radiation sources capable of operating under commercial production conditions.

The traditional sources of vacuum (VUV) and extreme (EUV) ultraviolet (or soft X-ray) radiation, including the synchrotron and gas-discharge sources with differential-pumped chambers for the extraction of radiation [1, 2]) did not find wide application because of their large dimensions, low efficiency, high cost, and small area of the output radiation beam.

In recent years, new VUV and EUV sources have appeared, including free electron lasers [3], high-flux high harmonic femtosecond pulsed lasers [4], plasma lasers (pumped with high-power discharge or laser pulses) operating on the lines of multiply charged ions [5], and sources of spontaneous emission from multiply charged ions in short discharge plasma pulses [6]. However, these sources possess the same disadvantages as indicated above and find no commercial applications. For example, even the low-inductance capillary discharge in Xe with the best characteristics provides an average spontaneous radiation power of ~10 mW at an efficiency on a level of ~10^{-4} and an average capillary lifetime of ~ 30 min [6].

The present Letter describes a new arc-discharge source [7] of high-power continuous EUV radiation based on high-current low-pressure plasma, which was previously used as an active medium for high-power argon ion lasers [8, 9]. This plasma was created by longitudinal dc arc discharge in sectioned tubes with a length of L ~ 0.4–4 m and a diameter of D ~ 1–40 mm at a current density of ~40–4000 A/cm^2. Figure 1 presents a schematic diagram of one section and shows the arrangement of samples in the discharge. The sample *2* is irradiated via a side (relative to the discharge axis O_1O_2) window with an area comparable with the discharge cross section. The source employs the most powerful radiation of ion resonance lines, which is not absorbed in a low-pressure gas filling the discharge

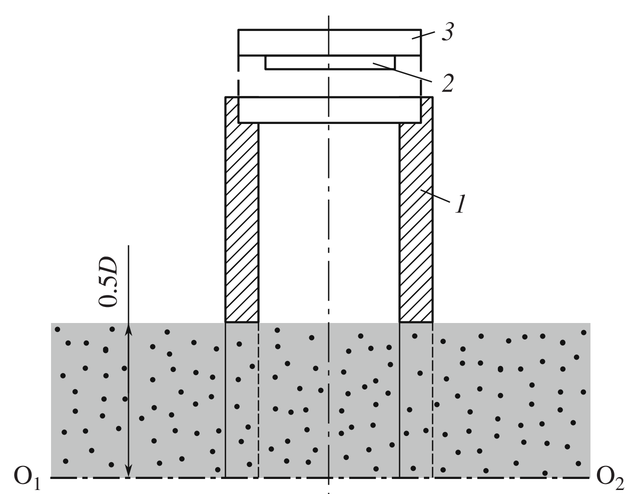

Fig. 1. Schematic diagram of the proposed EUV radiation source: (O_1O_2) longitudinal axis of discharge (plasma column is indicated by the shaded area); (*1*) discharge tube section; (*2*) irradiated sample; (*3*) sample holder.

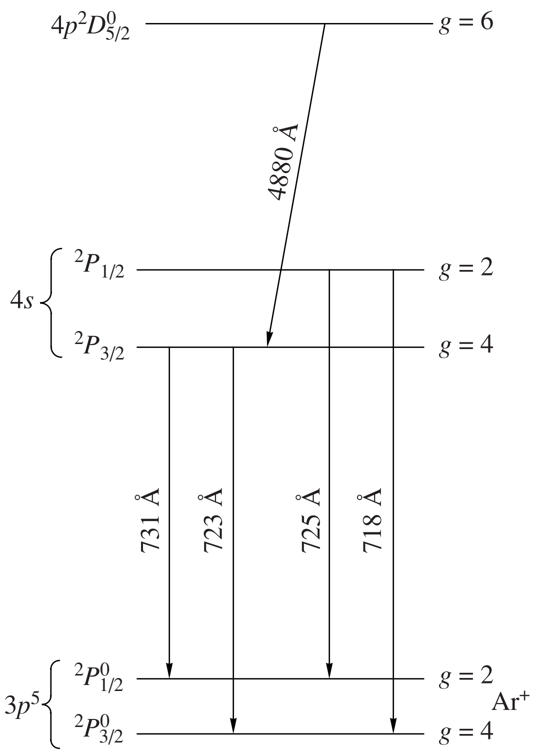

Fig. 2. Diagram of transitions from lower working levels.

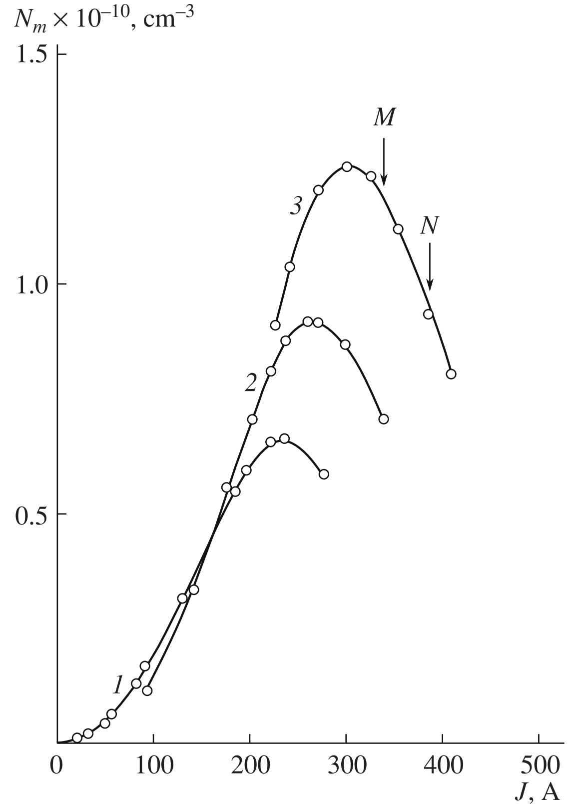

Fig. 3. Plots of the total (integrated over the discharge cross section) population N_m of the upper level for a 4880 Å line versus discharge current J for p = 0.3 (*1*), 0.65 (*2*), and 1 Torr (*3*).

tube. In model experiments with a tube diameter of D = 40 mm, the total area of the irradiated sample surface reached 65% of the entire side surface area (πDL) of the discharge column.

Since the plasma of argon lasers has been studied in sufficient detail, let us assess the energy characteristics of resonance VUV radiation of a source operating on Ar+ ion emission lines (Fig. 2). Direct absolute measurements of the intensity of resonance radiation meet certain technical difficulties, since the emission is reabsorbed and its measurement requires special vacuum equipment. However, the population of a lower (resonance) level for laser transitions (e.g., with a wavelength of λ = 4880 Å) can be readily evaluated using the known (measured) population of the upper level and the coefficient of absorption (amplification) at the center of a Doppler-broadened working line:

$$\kappa_0 = -G_0 = \sqrt{\frac{\ln 2}{\pi}}\frac{\lambda^2 A_{mn}}{\Delta\nu_D}\frac{g_m}{4\pi}\left(\frac{N_n}{g_n}-\frac{N_m}{g_m}\right), \qquad (1)$$

where κ_0 and G_0 are expressed in [cm^{-1}]; $\Delta\nu_D$ is the line width [s^{-1}]; A_{mn} is the probability of the radiative transition from the upper (*m*th) to lower (*n*th) level [s^{-1}]; N_m and N_n are the populations of the working levels [cm^{-3}]; and g_m and g_n are the corresponding statistical weights.

Figure 3 shows experimental plots of the population N_m of the upper laser level versus discharge current J at various initial (filling) pressures p in a discharge tube with D = 11 mm [8, 10].[1] Substituting the measured G_0 values into formula (1), one can see that the population of the lower level also exhibits saturation, but decays more sharply with increasing current J. Accordingly, a maximum in the power of lasing on the working transition is somewhat shifted toward greater currents (as indicated by arrow M on curve *3*; arrow N indicates the onset of discharge instability). The population N_n at the maximum lasing power is about half of N_m, while the populations N_n and N_m at currents up to 200 A are close. Thus, for the lasing conditions under consideration, the N_n and N_m values coincide to within a factor of two.

[1] Upon the initiation of discharge, a pressure close to the initial (filling) value is established only in the near-electrode regions (bulbs), while the working pressure near walls of the discharge channel is lower by a factor of 3–5. This circumstance allows the side-emitted VUV radiation loss for photoionization to be ignored even for Ar possessing large ionization cross sections (~3.5×10^{-17} cm^2), since a distance from the discharge column to the substrate is ~2 cm. At this distance, the resonance emission of atomic Ar lines (85–100 nm) exhibits complete resonance absorption.

Let us estimate the output radiation intensity (power per cubic centimeter) for a 723 Å line using the well-known relation

$$I^{723\ \text{Å}} = F(\kappa_0 R) A_{mn} N_m h\nu, \quad (2)$$

where N_m is the population of the upper level (for the transition at 723 Å) and A_{mn} is the probability of a spontaneous decay to the ground state, $F(\kappa_0 R)$ is the radiation yield factor ($R = D/2$), and $h\nu$ is the radiation quantum energy. The $F(\kappa_0 R)$ value can be estimated from the measured electron concentration ($n_e = 1.5 \times 10^{14}$ cm^{-3}), which is close to the population of the ground state of the ion. For the conditions under consideration, this estimation (see [8, p. 106]) yields $F(\kappa_0 R) \sim 0.4$. Substituting this and the other known numerical values ($A_{mn} = 2.5 \times 10^9$ s^{-1}, $N_m = 1 \times 10^{10}$ cm^{-3}) into formula (2), we obtain $I^{723\ \text{Å}} \sim 24$ W/cm^3. Taking into account that VUV emission from Ar^+ ions involves at least five strong lines in the 550–750 Å range (see, e.g., [1, Fig. 1.37]), we obtain a total intensity of about $I^{\Sigma} \sim 120$ W/cm^3.

Under the lasing conditions, the power deposited per discharge unit length is independent of D and amounts to $W_{\text{input}} \sim 840$ W/cm [8, 9], which allows the efficiency of VUV emission to be readily evaluated at ~14%. Although the population of the excited levels of Ar^+ ions decreases as $1/D$ with increasing D, the value of $F(\kappa_0 R)$ remains unchanged. Therefore, since the discharge cross section grows in proportion to D^2, the efficiency of VUV emission must increase linearly with the D value.

In addition to the usual cylindrical discharge, a promising design for the purposes under consideration is offered by discharge of the slit type (a rectangular cross section with significantly different side lengths) [11], in which the F value is determined by the smaller side.

The plasma of high-current continuous discharge in inert gases other than Ar is still insufficiently studied. Nevertheless, it is clear that the most powerful and short-wavelength emission due to resonance lines with wavelengths in the wavelength intervals of 230–304, 330–460, and 550–750 Å for the He^+, Ne^+, and Ar^+ ions, respectively, exhibits similar behavior. Apparently, good prospects can also be related to the use of resonance emission from high-current plasma in the intervals of 165–199, 100–135, and 85–100 Å for Li^+, Li^{2+}, and Be^{2+} ions, respectively. The corresponding atoms can be introduced into discharge with inert gases by means of electrophoresis or ion sputtering.

In conclusion, it should be noted that the proposed arc-discharge source [7] can be also useful in some other applications. For example, being filled with a mixture of hydrogen (at $p \sim 10$–100 Torr) and a small additive of a carbon-containing gas, this source can be used for depositing diamondlike carbon films [2, 12] on large-area substrates.

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