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Scientific session of the Physical Sciences Division of the Russian Academy of Sciences (31 January 2007)

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held in the Conference Hall of the P N Lebedev Physical Institute, RAS on 31 January 2007. The following reports were presented at the session:

(1) **Koshelev K N** (Institute of Spectroscopy, RAS, Troitsk, Moscow region), **Banine V E** (ASML, Veldhoven, the Netherlands), **Salashchenko N N** (Institute for the Physics of Microstructures, RAS, Nizhny Novgorod). "Research and development in short-wave radiation sources for new-generation lithography";

(2) **Balykin V I** (Institute of Spectroscopy, RAS, Troitsk, Moscow region). "Parallel fabrication of nanostructures via atom projection";

(3) **Lozovik Yu E, Popov A M** (Institute of Spectroscopy, RAS, Troitsk, Moscow region). "Properties and nanotechnological applications of nanotubes".

An abridge version of the reports is given below.

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Research and development in short-wave radiation sources for new-generation lithography

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In the impressive list of scientific, technical, and technological problems that lie ahead in the realization of short-wavelength lithography, the radiation source is far from last in terms of complexity of the problems encountered. A wavelength of 13.5 nm for new-generation lithography — extreme ultraviolet (EUV) lithography — had been accepted long before it became more or less clear how the source might be arranged to afford commercially expedient production — high volume manufacturing (HVM). The choice was made partly proceeding from the nature of fabrication and properties of multilayer mirrors and partly in the belief that the function of emitters would most likely be fulfilled by the Ly$_\alpha$ line of hydrogenlike Li^{+2} ions (13.5 nm) or the emission peak arising from radiative transitions in the Xe^{+9} ion.

The plasma radiating in the far vacuum ultraviolet (VUV) range has been long and much studied. However, the technical requirements imposed on an HVM source are so extraordinary that the seemingly simple task of heating the plasma to a temperature of several dozen electron-volts transforms into a whole set of challenging physical, engineering, and technical problems. We will consider these requirements in greater detail. In lithography, it is the practice to characterize the source by the radiation power at the so-called 'intermediate focus' (IF) at the output of the primary radiation collection system (Fig. 1).

One consequence of using the sophisticated optics of a lithographic apparatus with a large number (up to 11) of reflecting multilayer mirror surfaces is that only a narrow radiation band with a width of 2% centered at 13.5 nm may be employed to print microcircuits. The minimal required radiation power at the IF reaches 180 W. When the efficiency of the primary radiation collection (the solid angle of collection and the reflectivities) and the inevitable losses in the devices which shield the optics from 'contamination' are accounted for, one is led to the following estimate of the output source power: the average 'useful' power of radiation into a solid angle of 2π and a narrow 2% bandwidth should be no less than 2000 W. It is conventional to characterize the source by the electric energy-to-'useful' radiation conversion efficiency (CE). The effective size of the emitting volume should not exceed 1 mm^3; the source operating frequency is about 10 kHz, and the stability of the radiation dose is $3\sigma \leqslant 0.3\,\%$ (in 50 shots).

Lithium as the working material was rejected at a rather early stage of research, primarily due to extraordinary technological problems and the hazard of contamination of the entire lithography system by a chemically highly deleterious element. Experiments with the more convenient, chemically neutral xenon showed that the CE amounts to only 0.5 – 0.7% for a pulsed discharge plasma. This signifies that the average electric power released in the small source volume should be as high as 300 – 400 kW.

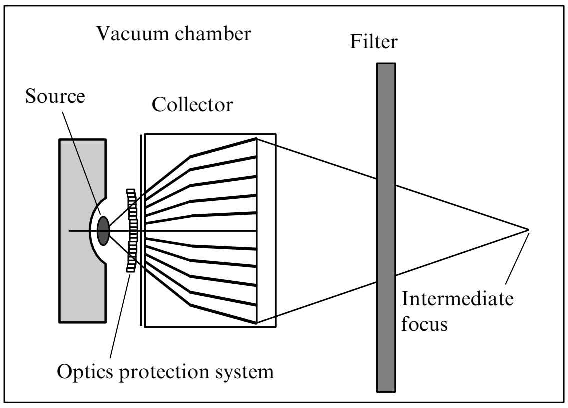

Figure 1. Defining the parameters of an EUV lithography source.

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The estimates given above apply to a discharge plasma-based source. Another possible candidate is a laser-produced plasma (LPP). The LPP as an EUV source offers several advantages over discharge plasmas. These include a somewhat higher CE, higher radiation collection efficiency, and what may be a simpler system of optics protection from the destructive effect of corpuscular radiation. However, the most significant and perhaps decisive argument for the source selection is the high cost of laser systems with an average output power of many dozens of kilowatts. Clearly, this argument is temporal in nature, since the commercial price of any hi-tech product tends to steadily decline. However, present-day plans of the main manufacturers of lithography apparatus place an emphasis on the use of discharge plasma-based EUV sources. Below, we will describe several results in the development of discharge sources and in so doing rely primarily on the collaboration of the Institute of Spectroscopy, Russian Academy of Sciences, with the leading manufacturer of lithography apparatus, ASML (the Netherlands), under the integrated project MoreMoore of the 6th Framework Program of the European Community.

The low efficiency of xenon stems, in particular, from the fact that only several lines of an Xe^{+9} ion radiate in the narrow spectral range employed. As a result, the useful radiation in nonstationary and nonuniform plasmas of pulsed discharges and laser jets occurs for a substantially shorter time than the total duration of the high-temperature phase, and by no means does the total volume of the temperature-nonuniform plasma emit useful photons. A possible solution to this seemingly insurmountable problem was prompted by atomic physics — using the radiation of multiply charged tin ions.

From the viewpoint of basic atomic spectroscopy there are several arguments in favor of acceptance of tin as the working material for the radiation source at a wavelength of 13.5 nm. The resonance transitions in $\mathrm{Sn}^{+8}-\mathrm{Sn}^{+13}$ ions are $4\mathrm{d}^k-(4\mathrm{d}^{k-1}4\mathrm{f}+4\mathrm{p}^5 4\mathrm{d}^{k+1})$ transitions. The strong 4d – 4f exchange interaction in the $4\mathrm{d}^{k-1}4\mathrm{f}$ configuration and 4p – 4d exchange interaction in the $4\mathrm{p}^5 4\mathrm{d}^{k+1}$ configuration have the effect that the energy levels of these configurations split into two bands, with the probabilities of transitions from the upper band being much higher than those from the lower band. The strong interaction between the $4\mathrm{d}^{k-1}4\mathrm{f}$ and $4\mathrm{p}^5 4\mathrm{d}^{k+1}$ configurations makes this band narrowing still stronger. As a result, the emission concentrates in a narrow spectral interval despite the presence of several hundred levels within a broad energy interval. Furthermore, owing to a weak dependence of the excitation energy in $n=4-n'=4$ transitions on the ion multiplicity, intense transitions in several neighboring ions fall into this interval. A comprehensive study of the tin plasma spectrum excited in a vacuum spark was pioneered by research on the EUV lithography source [2].

Even the first experiments with a discharge in tin vapor revealed a substantial rise in CE — from 0.5 – 0.7% to 2% or even 3%. The requirements for the power released in the discharge were considerably relaxed, but the requisite power was still equal to about 100 kW — a quantity too great for a single source of small size. Prior to formulating the approaches that permit operation in the mode of extreme thermal load, we address ourselves to the physics of the discharge employed. For a plasma source we selected a classical vacuum spark, i.e., a discharge between two electrodes, with the working material being fed to the interelectrode gap by way of cathode material (tin) ablation using laser radiation pulses. Research into axially symmetric discharges, and, in particular, vacuum sparks, showed that soft X-ray and VUV radiation is excited in plasmas with currents exceeding 10 kA at the moment the sausage type instability develops in the discharge column. It is known that these constrictions, or 'micropinches', are produced due to plasma outflow under conditions of great radiation losses, due to the line emission of multiply charged tin ions in this case (see, for instance, Ref. [3]). The plasma outflow from a pinch is accompanied by plasma compression, heating, and passage to progressively higher ionization stages. The pinch radius is defined by the balance between Joule heating and energy loss, primarily radiation loss in optically dense plasma.

The process continues until either the radiation loss ceases to compensate for the Joule heat release or anomalous resistance develops in the plasma due to the small number of current carriers. At this stage, a rapid plasma expansion and a micropinch decay occur. The instability development may be illustrated with the aid of a diagram (Fig. 2) which shows the pinch radius as a function of the total number of ions in the discharge cross section (the linear ion density N_{i}). The direction of development trajectory — the lowering of the linear density — is indicated by an arrow. At each instant of time, slowly contracting pinches satisfy (or almost satisfy) the thermal – magnetic pressure equilibrium condition, viz. the Bennett relation

$$N_{\mathrm{i}}(Z+1)\,T \sim I^2\,,$$

so that each point of the trajectory in Fig. 2 can be related to the plasma temperature rising along the trajectory. For fast, dynamic pinches, departures from the Bennett relation may be significant.

For currents $I \approx 10-30$ kA, the temperature $T \approx 20-40$ eV is reached when a plasma column is compressed to lateral dimensions of about 200 μm. The constrictions (micropinches) observed in the discharge column of the vacuum spark are exemplified in Fig. 3.

Several EUV-emitting micropinches are observed to occur (quite often sequentially in time). This phenomenon of radiative domain 'zippering' along the discharge axis determines the time-integrated axial source dimension.

This brings up a curious question: How can one hope for dose stability of the EUV radiation excited in the discharge in

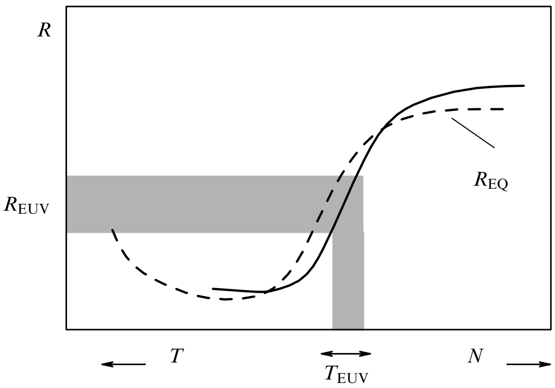

Figure 2. Equilibrium radius of the Bennett pinch (dashed line). The temperature T_{EUV} required for the excitation of EUV photons corresponds to constriction to a radius R_{EUV}.

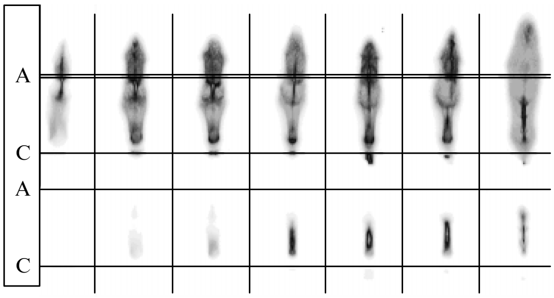

Figure 3. Images of the plasma column recorded in the intrinsic short-wave plasma radiation using a time-gated microchannel plate (MCP) detector adjustable from 3 to 50 ns. Images in the upper part of the picture correspond to radiation in the entire MCP sensitivity range (< 100 nm); the images in the lower part were produced via a Zr/Si filter. The distance between the anode A and the cathode C is 3 mm.

the course of instability development — in this case, the sausage type instability well known in plasma physics? The more so as we are dealing with a vacuum spark — a discharge with rather unstable initial parameters, first and foremost with the poorly reproducible initial distribution of the working material in the interelectrode gap. It turned out, however, that there is such a domain of parameters (the initial radius and the total amount of vaporized material) for which the instability development trajectory depends only slightly on them [4]. This circumstance is illustrated in Fig. 4a. This fact is amply borne out by experiments with an EUV source: Fig. 4b depicts superimposed (and well coincident) oscilloscope traces of the current and the EUV radiation from 256 laser-triggered vacuum spark discharges with a peak current of about 10 kA.

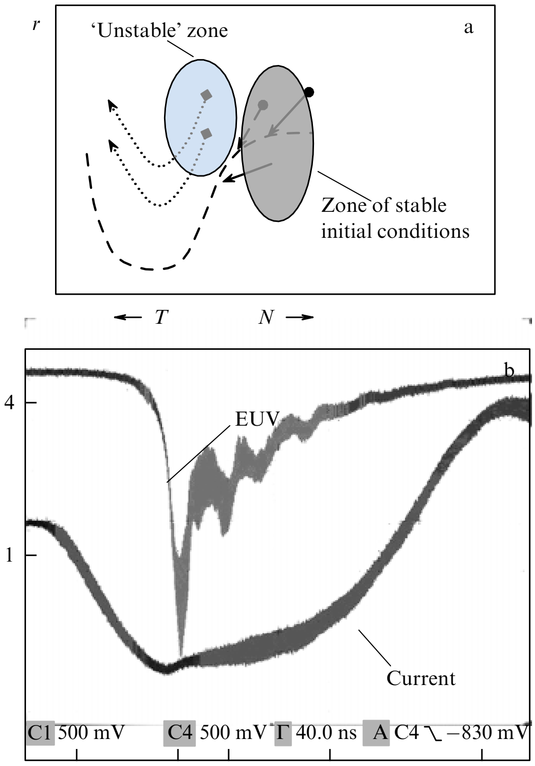

Figure 4. (a) Stable (dashed curve) and unstable (dotted curves) micropinch development trajectories in the coordinates of the pinch radius r and the linear particle density N. (b) Superimposed oscilloscope traces of the current and the EUV radiation from 256 laser-triggered vacuum spark discharges with a peak current of about 10 kA.

The changeover to a tin plasma as an EUV radiator with a CE as high as 2 – 3% permits relaxing the requirements for the electric power liberated in the discharge down to 100 kW. For a discharge with a size of several millimeters this still remains an inconceivably high value. A possible solution involves the so-called source 'multiplication', i.e., production of a multitude of radiation sources, so as to distribute the electric and thermal load among them. However, the requirement that the radiator be fixed in space and the high repetition rate (up to 10 kHz) are practically incompatible with a 'revolver' system with a mechanical reiteration of a large number of vacuum sparks having axially symmetric systems of electrodes and insulators. This is precisely the reason why the multiplication of a xenon source appeared to be practically infeasible.

The use of tin in combination with a laser initiation opens up new possibilities. Feeding the material to the interelectrode gap by vaporizing the electrode surface under pulsed laser irradiation ensures the initial axial symmetry irrespective of the electrode shapes: the initial plasma expands as a cone with its axis perpendicular to the electrode surface. One version of the system with revolving electrodes, the lower of which is covered with liquid tin (for ease of surface recovering), is schematically depicted in Fig. 5.

When the electrodes rotate, tin is vaporized from a new segment of the cathode ring with each new laser shot, the focal position remaining invariable. This therefore gives rise to a sequence of elementary vacuum sparks in the same point in space, which nevertheless pertain to different segments of the plane electrodes — the cathode and the anode. It is only desirable that the previous position of the laser focal spot should shift relative to the next one by a distance of 1 – 2 mm (the size of the surface zone temporarily 'spoiled' by the discharge) during the time interval between the pulses. For a repetition rate of 10^4 Hz this corresponds to the lowest admissible linear rotation velocity on the order of 10 m s^{-1}. Experiments and calculations show that these systems are capable of withstanding electrical power as high as 50 kW, and maybe 100 kW.

The idea of 'continuous multiplication' was further developed in the jet version of the EUV source. It has been suggested that two liquid jets of a metal or an alloy with a moderate melting temperature flowing out of metal nozzles at a high velocity should be used as the electrodes. Pumps maintain a liquid metal pressure in the system at several dozen atmospheres to make the jets move at a speed of several

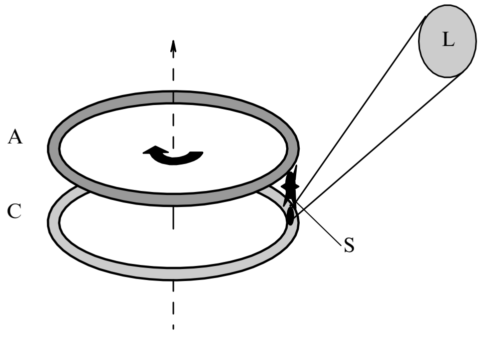

Figure 5. Schematic of the 'wheel' multiplication.

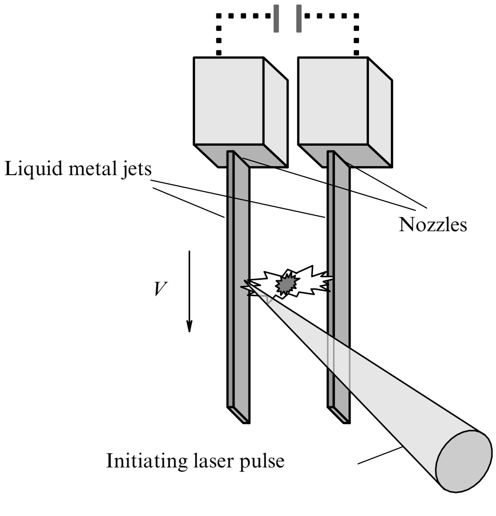

Figure 6. Schematic representation of the 'jet' EUV radiation source.

dozen meters per second, thereby ensuring nozzle cooling and the heat removal.

The voltage is applied across the jets, and the discharge between them occurs when laser radiation is focused onto one of them (Fig. 6). Not only do the jets remove the heat released in the discharge, but they also efficiently cool the metal elements closest to the discharge — the nozzles. The jets end up in the heat exchanger and return to the system after cooling with the aid of pumps. The power resource of this technical solution amounts to 200 kW.

In the foregoing, we discussed several approaches to the solutions of two problems — increasing the radiation power (the thermal load), and improving the radiation dose stability. Lying outside of the scope of our report were such important aspects of lithographic apparatus development as the lifetimes of the electrodes and optical elements, primarily, the radiation collector. The latter problem is directly related to the physics of the radiation source, because it arises from the so-called debris — corpuscular streams (atoms, ions, droplets of electrode material) emanating from the discharge region.

The demonstration EUV lithography apparatus (the so-called alpha tool) has already been made and is familiar to the industry. However, its main parameters are lower by a factor of ten or more than the parameters complying with the HVM requirements. The industry has allowed researchers the relatively little leeway of two years to overcome this gap.

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Parallel fabrication of nanostructures via atom projection

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1. Introduction

There are two radically different approaches to the development of nanotechnology. These approaches are commonly referred to as the 'top down' and 'bottom up' technologies. The top down approach involves reducing the dimensions of physical bodies to objects with nanometric parameters. For instance, semiconductor microelectronic devices are fabricated by the optical lithography technique whereby the intermediate product is processed by a laser beam and the minimal dimension of the elements of the created microelectronic circuit is defined by the laser radiation wavelength. We note that the diffraction limit of the resolution of conventional optical lithography is about 65 nm. There are several other approaches to top down technology, each of them possessing both advantages and disadvantages: charged-particle beam lithography encounters problems associated with batch production of structures and the significant part played by Coulomb repulsion; self-organizing fabrication still calls for a better understanding of the physical processes.

Bottom up technology consists in the nanoobject under fabrication being 'assembled' of individual atoms, molecules, biological cells, etc. The feasibility and promise of this approach was first pointed out by Richard Feynman in his report to the annual meeting of the American Physical Society in 1959 [1]. The practical realization of bottom up technology became possible with the development of the probe microscopy technique which enabled not only observations of nanoobjects with atomic resolution but also manipulations of single atoms and molecules. This was first accomplished by researchers at an IBM laboratory, who managed to inlay their company's name (IBM) with 35 xenon atoms on the surface of a nickel single crystal [2]. This technique opens up many possibilities for manipulations at the level of individual atoms and molecules. However, methods reliant on the employment of scanning probes are generally characterized by low productivity and high cost.

Fabricating nanostructures with a size of about 10 nm presents a complex technological problem which is important from both the practical and theoretical viewpoints, because these structures bridge the gap between the classical and quantum-mechanical worlds.

2. Atom optics and atom nanooptics

Atom optics is an alternative approach to nanotechnology based on the bottom up principle. Atom optics is the optics of material particles (along with electron, ion, and neutron optics) and it concerns with the problems of formation of the ensembles and beams of neutral atoms, control over them, and their application. The term *atom optics* is similar to the terms *light optics* or photon optics. Basically, atom optics relies on three main techniques: the first depends on atom–matter interactions, the second on the interaction between atoms having a magnetic or electric dipole moment and a static electric or magnetic field, and the third on the resonance