Large-aperture excilamps for microelectronic applications

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ABSTRACT

A windowless excilamp, a xenon excilamp with the high specific power of radiation and an air-cooling KrCl excilamp for microelectronic applications are described. The excilamps have the total radiating surface up to 900 cm^2. The VUV specific average power of a windowless excilamp is 3 mW/cm^2 and 5 mW/cm^2 for argon ($\lambda \sim 126$ nm) and krypton ($\lambda \sim 146$ nm) accordingly at distance of 3 cm from the emitting surface. The xenon excilamp ($\lambda \sim 172$ nm) has 50 W of the average total VUV power and 120 mW/cm^2 of density and the large-aperture air-cooling KrCl ($\lambda \sim 222$ nm) excilamp has 30 mW/cm^2 of the radiation density and the radiation homogeneity 12 %.

Keywords: excilamp, narrow-band ultra-violet, vacuum ultra-violet, microelectronic applications

1. INTRODUCTION

First of all, excilamps are simple gas-discharge sources of spontaneous narrow-band ultra-violet (UV) and vacuum ultra-violet (VUV) radiation with high efficiency (in comparison with lasers) and with an opportunity to irradiate a large area of the surface at once (in one step). Radiation sources of such type provide the energy of photons from 3 to 9.87 eV, which is sufficient for the application of excilamps practically in all known photoprocesses in which UV and/or VUV radiation is necessary [1]. The popularity of excilamp applications in various areas of science and engineering is explained by just listed properties.

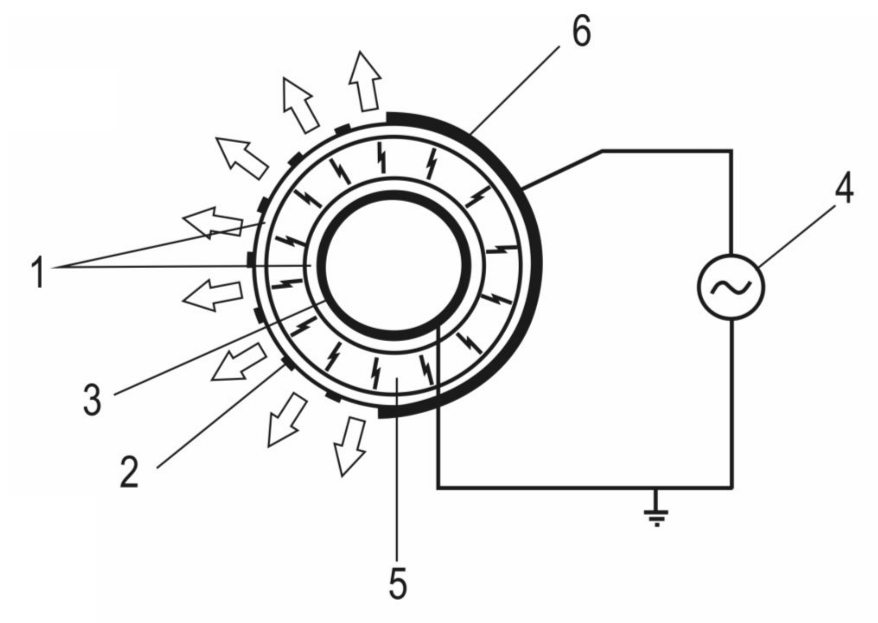

Fig. 1. Excilamp radiator. 1 – quartz tubes, 2 – grid electrode, 3 – reflective electrode, 4 – power supply, 5 – discharge gap, 6 – reflector.

Two or more parallel radiators are used in modular excilamps to increase the radiation surface. Modular excilamps are developed with the aim to receive the homogeneous and plane front of radiation with the large area of irradiation. Design of modular excilamps consists in join of two and more radiators with a power supply and a cooling system in one system.

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The idea of combination of coaxial radiators is not new and is widely used in the world, and even there are samples of modules which are produced commercially [2]. Constructions of excilamp radiators were represented two coaxial quartz tubes of different diameters soldered at ends. The reflector *6* was placed on a coaxial radiator in one half-plane to receive radiation, and the grid electrode *2* was used to extract radiation (Fig. 1.)
The purpose of this article is to present the modular excilamps developed in the Laboratory of Optical Radiation of the Institute of High Current Electronics, Siberian Branch of Russian Academy of Sciences.

2. MODULAR EXCILAMP ON INERT GAS DIMERS FOR WINDOWLESS APPLICATION

The process of surface cleaning in microelectronics is frequently performed using sources of VUV radiation, including excilamps with open windowless design [3]. In these systems, irradiated specimens occur in the same gas, with that the discharge gap of the lamp filled. Such sources are frequently employed for the excitation of argon and krypton, as the radiation with a wavelength shorter than 150 nm is absorbed by many usual optical materials, while windows made of LiF, CaF_2, and MgF_2 are rather expensive and typically have small dimensions. For the radiation of excilamps operating on argon dimers ($\lambda \sim 126$ nm), only LiF crystals possess sufficiently small absorption.
The aim of our developments was to determine conditions for realization of the high-efficiency emission from inert gas dimers and to create on this basis a large-aperture excilamp with the total radiating surface area of $23 \times 23 = 529$ cm^2.
The preliminary experiments were performed with three setups. The first setup had small dimensions and comprised a gas-discharge chamber (pumped by a turbomolecular pump to a residual pressure below 10^{-5} Torr) with a point cathode and a flat anode coated by a 3 mm thick layer of quartz. The discharge operated between the point and the quartz surface facing the cathode. The distance from the point tip to the quartz surface was ~10 mm. The radiation was extracted from the chamber through a LiF plate. The emission spectra were measured using a VM-502 vacuum monochromator (Acton Research Co.). The output radiation power in absolute units was determined using a C8026 calibrated photodetector (Hamamatsu Photonics) equipped with H8025-126 nm and H8025-172 nm photodetector heads. For the source operating on Kr, the radiation power was also measured using the H8025-126 nm head and calculated using readings with allowance for the spectral sensitivity of this head at $\lambda = 146$ nm.
The working gas was excited by a pulse voltage applied to the electrodes from a power supply, which generated voltage pulses of negative polarity with amplitude of up to 10 kV, duration of ~2 µs, and a repetition rate varied from 15 to 70 kHz. This lamp was tested with Ar, Kr, and Xe at pressures from 15 to 760 Torr.
The second setup comprised a chamber provided with an organic-glass window for discharge monitoring. The chamber accommodated four quartz tubes with an external diameter of 23 mm, which contained cylindrical anodes. The wires of the cathode were spaced 1 cm apart and oriented perpendicularly to the anodes. The distance from wires to the surface of quartz tubes could be varied from 0 to 10 mm.
The third setup represented a prototype of the proposed open windowless excilamp, which comprised ten quartz tubes with an external diameter of 23 mm, which contained cylindrical anodes and could be cooled by water flow (Fig. 2). The cathode had the form of 21 steel wires oriented perpendicularly to the quartz tubes. The voltage pulses of negative polarity were applied to the cathode. The emitting surface area was $23\times23 = 529$ cm^2. This excilamp was mounted in a chamber of greater size filled with argon at the pressure of 1 atm, at the controlled partial pressure of water vapor and oxygen. The radiation power was determined using an H8025-126 nm sensor mounted in the chamber.
A special feature of the corona discharge is a significant field enhancement near the point electrode. For this reason, even at a relatively small potential difference between electrodes, the electric field strength at the point tip is sufficiently high for the discharge initiation (probably due to the appearance of fast electrons at the cathode [4]). The discharge in all working gases (Ar, Kr, Xe) was characterized by broad emission bands. For Ar, the emission was observed in the interval of 115–135 nm with a maximum at ~126 nm; the corresponding data for Kr are 135–155 nm and 146 nm; for Xe, 155–185 nm and 172 nm. The spectral width (FWHM) for all emission bands increased with the decreasing gas pressure and remained unchanged during variation of the excitation power within broad limits (from tens to hundreds milliwatts).
The maximum output power and the efficiency of radiation for the first setup operating on xenon dimers were observed at the pressure of 380 Torr and amounted to $W \sim 320$ mW and $\eta \sim 45\%$ (full solid angle), respectively. In krypton, the maximum efficiency ($\eta \sim 25\%$) corresponded to the pressure of ~1 bar. The operation on argon dimers was characterized by a tenfold lower efficiency and was apparently related to the large content of impurities in this gas, which was indicated by a large number of emission lines in the 110–160 nm wavelength range.

The above results refer to the case of a single-point barrier corona discharge. However, practical applications require large-area radiation sources. In the second setup, we realized simultaneous operation of multiple corona discharges (up to 60) along the entire length of each of the four quartz tubes for all working gases. We also determined the optimum gap width between the wire cathode and the dielectric surface. The tests showed that all pulse corona discharges exhibit stable molecules (oxygen and water) in the gas phase. The radiation power density becomes proportional to the excitation power when the content of oxygen and water vapor in argon is below 10 ppm.
The results of our experiments showed the high efficiency of the open excimer lamp operating on inert gas dimmers for argon (λ ~ 126 nm), krypton (~146 nm), and xenon (~172 nm) under conditions of the pulse discharge between an insulator-coated anode and thin wire cathode. The most stable operation of the system was observed when the steel cathode wires were in contact with the surface of quartz tubes. The specific VUV power was 3 mW/cm^2 for dimers Ar_2* and 5 mW/cm^2 for dimers Kr_2* at distance of 3 cm from the radiation surface.

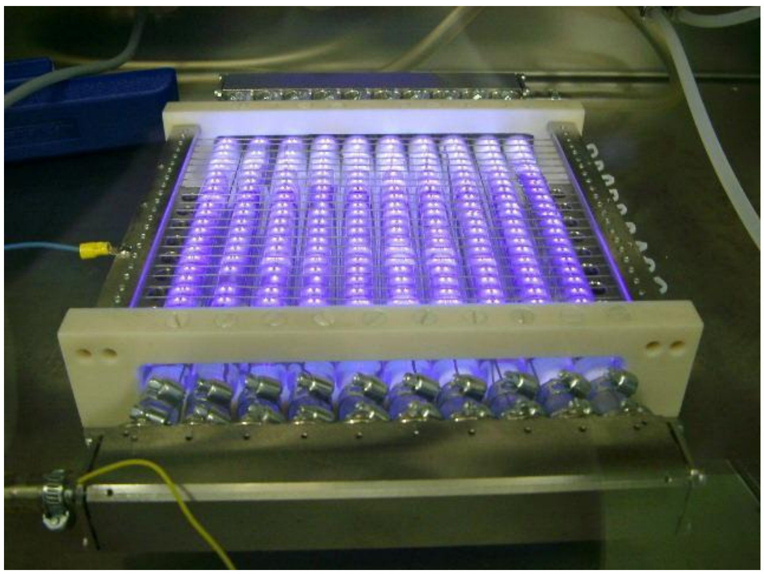

Fig. 2. Windowless modular excimer lamp.

3. MODULAR EXCILAMP ON XENON DIMERS WITH A HIGH SPECIFIC RADIATION POWER

Arnold et al. [5] reported on receiving an average output radiation power density of ~150 mW/cm^2, but their xenon excilamp had a rather complicated design. Indeed, as the high-voltage electrode was situated on the internal surface of an inner tube and water cooling of the external surface was impossible (because water strongly absorbs radiation of the excilamp), the inner tube was cooled by deionized water; the lamp was supplied with a power supply with an increased (up to 300 kHz) pulse repetition rate.
We succeeded in receiving the record high specific radiation power with the wavelength of 172 nm, owing to development of the modular excilamp on xenon dimers (Fig. 3.). The lamp comprises six identical quartz tube radiators of coaxial design, which are mounted on a supporting metal plate. The outer tubes are made of an F310 grade quartz and had an external diameter of 37 mm; the inner tubes are made of a GE-021 or KU-1 grade quartz and had an external diameter of 22–23 mm. Each radiator contains an inner electrode made of an aluminum-magnesium foil, which is placed inside the inner tube. The outer electrode has the form of a half-cylinder made of the same foil, is arranged along the outer tube of the radiator, and simultaneously serves a reflector. The remaining part of the tube surface is covered by a metal grid with a geometric transparency of above 90%.
The working gas (xenon) was excited by the pulse voltage applied to the electrodes from an oscillator, which generated bipolar voltage pulses with amplitude of up to 5.6 kV, duration of ~2 μs, and a repetition rate varied from 30 to 200 kHz. The power introduced into the gas-discharge plasma depended on the voltage pulse amplitude and repetition rate and

reached (at the maximum pulse repetition rate) 600 W for each of the six emitters. The lamp was designed so as to make possible the simultaneous operation of one, two, four, or six emitters.

The discharge is excited in the annular region between two coaxial tubes and consists of numerous diffuse microdischarges. The output radiation power of the excilamp in the absolute units was determined using a Hamamatsu photodetector C8026 equipped with an H8025 172 nm sensor. The excilamp was filled with high-purity xenon (99.9992% Xe according to the manufacturer's certificate).

In the experiments, we varied the xenon pressure and the excitation power and measured the output radiation power, the temperature of quartz tubes, and the current–voltage characteristics of discharge. The upper boundary of the working gas pressures studied was determined by the discharge-gap breakdown voltage (which increased with the gas pressure); the lower boundary was determined by a drop in the emission efficiency at low pressures. The optimum pressure of Xe at a maximum average radiation power was about 420 Torr.

The maximum average output radiation power during short-term operation without forced cooling exceeded 50 W, and the radiation power density in this regime reached 140 mW/cm^2. However, the operation under such conditions led to rapid heating of the emitter tubes and to a drop in the output radiation power. After switching off the lamp and cooling emitters down to room temperature, the regime of maximum radiation power was reproduced upon the repeated switching on. Thus, for the long-term operation of the excilamp, it is necessary to ensure effective heat removal from the gas discharge region.

For the given excilamp design, the most part of the heat can be removed by heat exchange first, with the supporting metal plate and second, with the inner electrode (provided its effective cooling). The remaining heat is dissipated from the part of the external tube surface covered by the grid by means of radiative transfer and by heat exchange with a medium situated between the lamp and the irradiated object.

In the course of experiments, the main attention was devoted to finding the regimes of cooling for the inner electrode and the supporting metal plate, which would ensure the optimum thermal regime of the lamp operation. The supporting plate was cooled by a flow of water in the internal jacket, while the inner electrode (to which a high voltage was applied) was cooled by air purged through the inner tube. The air was taken from and exhausted into the atmosphere, that simplified the lamp design as compared to that used, for example, in the system reported in [5]. The heat exchange between the tube and the air flow was improved using a heat exchanger with a developed surface, which had good thermal contact with the surfaces of the electrode and the quart tube.

The results of experiments with the lamp in which the inner electrode was cooled by air flow showed that a stationary thermal operation regime could be obtained even without forced water cooling of the supporting metal plate. The time variation of the emitter tube temperature and the average radiation power density at the emitter surface, which were measured in the excilamp cooled by air purged at a flow rate of ~300 l/min through the internal tube. A stationary regime is attained at about 10 min after the switching on the lamp, in which the average radiation power density amounts to ~120 mW/cm^2. In this regime, the average power radiated from all six emitters within a solid angle of 2π amounted to ~40 W from $20 \times 20 = 400$ cm^2 aria, and the maximum power radiated immediately upon the discharge ignition exceeded 50 W. Radiation was homogeneous with the specific radiation power of about 80mW/cm^2 at distance of 10 cm from the surface of radiators. Such module was fed from the six-channel power supply of the power of 2.1 kW.

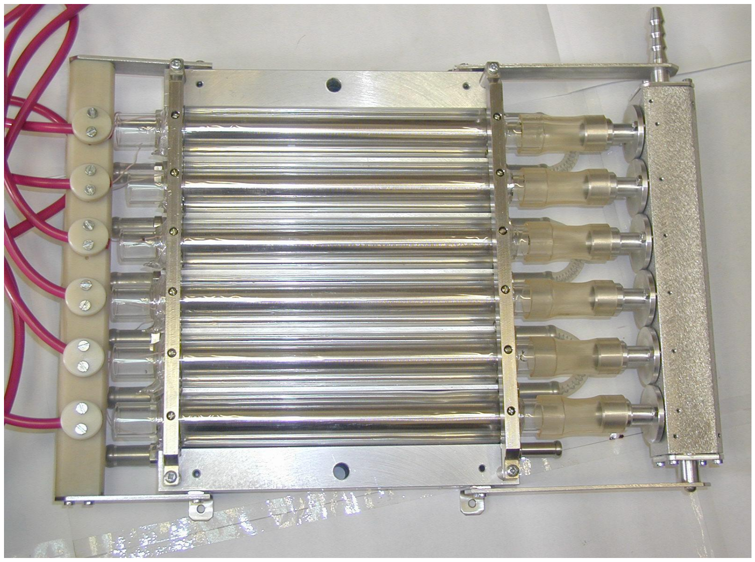

Fig. 3. Xe excilamp with a high specific radiation power.

4. MODULAR AIR-COOLED BARRIER-DISCHARGE EXCILAMP

The purpose of our development is to create an air-cooled single module based on excilamps with a flat exit window having an area of >900 cm^2. As working molecule, we selected KrCl* (λ ~ 222 nm).

The excilamp consists of seven cylindrical radiators equipped with reflectors, a seven power supplies and a fan air-cooling system. All the components are placed in a housing of 670x390x220 mm (Fig. 4). The radiators are made of two GE214 quartz pipes (wall thickness is 2 mm) of different diameters, which are placed coaxially and soldered at their ends. The length of the radiating surface is 300 mm, the diameter of the outer quartz pipe is 43 mm, and the diameter of the inner pipe is 23 mm. The outer electrode connected to the earth is made of a 150-μm diameter steel wire wound over the outer quartz pipe with a ~1 mm step. While optimizing the operating conditions of the excilamp, we also studied radiators without reflectors. An Al-Mg-foil high-voltage electrode, to which high-voltage pulses were applied, was inserted into the inner quartz pipe. A fan pumping the air through the excilamp inner pipe was used for cooling, and additional fans cooling the excilamp outer surface from the side of the reflector were also used. The radiators of the excilamps were excited by 4.2 kV pulses arriving with a 40-kHz repetition rate from pulse power supply.

As a result of optimizing the air-cooled excilamp operation, it was determined that the consumed power of seven radiators should not exceed 700 W for this design. In this case, the radiation power density of the KrCl-excilamp on its surface was 30 mW/cm^2, the average radiation power was ~28 W.

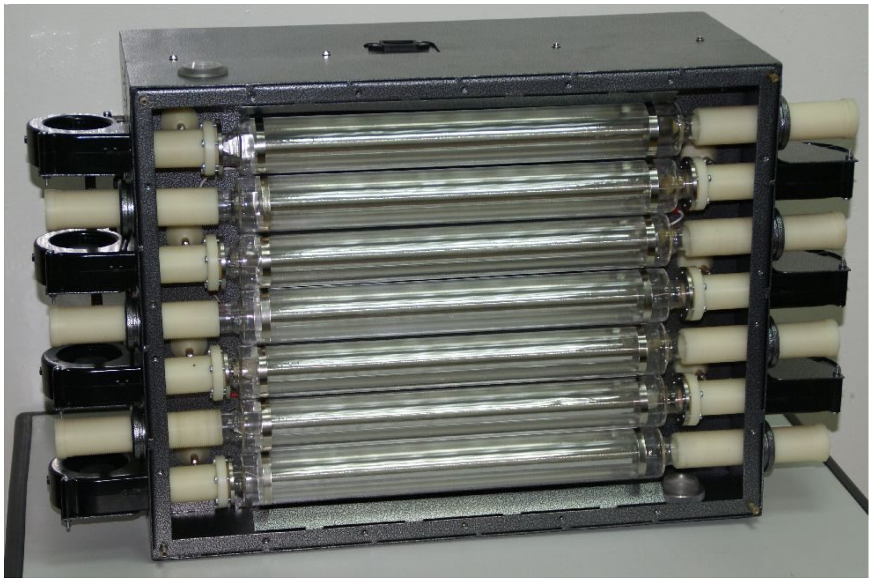

Fig. 4. Modular air-cooling KrCl excilamp.

Two parallel radiators are installed in the excilamp in order to increase transverse size of the radiation area. The size of the exit window of the excilamp is 30×31 cm. A flange with a quartz plate is fixed to the window. The flange forms a hermetic chamber, preventing the ozone from going out. The sealing flange allows one to irradiate surfaces in a special additional chamber and install thin samples on the surface of the exit window. In both cases, the volume with samples can be filled with various gases, and when the additional chamber is used, it is possible to use even corrosive gases.

As our investigations showed, the temperature of the radiator bulb must not exceed 120°C, which does not impose additional requirements on the heat resistances of the excilamp components. In this experiment, the temperature of the excilamp (110°C) depended on the excitation power and radiator air-cooling rate. At this temperature, the useful lifetime of the excilamp was 1000 h (time, in which the excilamp power dropped by 50%). Investigation of distribution of the radiation intensity on all radiating surface showed homogeneity up to 12 %.

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