Investigating the Effect of Cathode Electrode Doping on the Properties of Argon Flash Lamps

Farshad Khoshnood[a,c*] and Mohammad Sabaeian[b,c]

[a]Department of Physics, Technical and Vocational University (TVU), Tehran, Iran

[b]Department of Physics, Faculty of Science, Shahid Chamran University, Ahvaz, Iran

[c]Center for Research on Laser and Plasma, Shahid Chamran University, Ahvaz, Iran

[*]Corresponding author email: farshad.khoshnood@gmail.com

Regular paper: Received: May. 09, 2023, Revised: Jul. 21, 2023, Accepted: Jul. 22, 2023, Available Online: Jul. 24, 2023, DOI: 10.61186/ijop.17.1.3

ABSTRACT— The authors report on the impact of electrode doping on the optical and electrical properties of argon flash lamps. In this work, the lamps are made using borosilicate glass tubes with an outer diameter of 6 mm and a discharge distance of 35 mm. In the construction of the lamps, five types of tungsten electrodes doped with thorium at two different percentages, cerium, lanthanum as well as pure tungsten are used. Properties such as threshold voltage, light intensity, tube temperature, and flash time profile at various argon pressures are measured. The results indicated that, first, the threshold voltage is a linear function of gas pressure inside the tube. Second, the lamp with 1.7%-2.2% thorium doped tungsten cathode showed a lower threshold voltage, higher light intensity, and lower temperature rise at continuous wave operation. These characteristics of electrodes doped with thorium make them an appropriate option for use in the fabrication of argon flash lamps.

KEYWORDS: Flash lamp, Cathode electrode, Threshold voltage, Borosilicate glass

I. INTRODUCTION

One of the brightest pulsed light sources is the flash lamp using noble gases such as argon, krypton and xenon, emitting a wide range of wavelengths from ultraviolet to infrared, depending on the pressure of the gas inside [1]. The reason for using noble gases in the construction of flash lamps is their strong emission, easy stimulation, and very low reactivity compared to other gases.

Choosing the type of electrode to be used in the flash lamp requires knowledge and technical justification, and on the ground that the cathode starts the discharging current, a material should be used that has a low working function and a high melting point [2]. The cathode should also be formed in such a way that it can pass the maximum electric current and limit heat loss through thermal conductivity [2]-[3]. Other factors that are important for a suitable cathode electrode include good bonding to the glass and good performance at thermal stresses. Low energy consumption and not overheating can also be included in these properties. Since the performance of the lamp in some conditions can increase the temperature of the chamber even up to 2000 K, which in this case leads to rapid oxidation of the electrodes, the electrode material is a very significant issue in the construction of such lamps [4].

The commercial TIGs made from pure tungsten or oxides of radioactive elements such as thorium, barium, cesium, and lanthanides are suitable alternatives to be used as cathodes in flash lamps. Thorium with an atomic number of 90 is the second element in the group of actinides with an FCC lattice structure. It is silver in color and has a weak amount of radioactivity [5]. Applications of thorium include incandescent lamps, carbon arc lamps, tungsten welding rods, and heat-resistant laboratory pots, as well as catalysts [6]. Cerium, another element in the lanthanides row, is the most abundant rare earth element (about

0.0046% by weight of the Earth's crust) [7]. Cerium is used in pyrophoric alloys to make lighters. It is also used as a catalyst in sunscreens and gas sensors. Cerium has good optical properties and is used as a strong optical polish in the manufacture of glass [8]. With an atomic number of 57, lanthanum has a white and silver appearance in its elemental form and oxidizes rapidly. Lanthanum doped tungsten is a good alternative to be used in the manufacture of lamp electrodes, ion sources, and welding electrodes, having thermal and mechanical properties in the face of plasma [9].

Since the tungsten electrode has a high thermal conductivity, a high melting temperature (about 3410 °C) and a low working function in the range of 1.9 - 4.5eV (depending on the type and level of oxidation), the high electron emissivity and good bonding to glass (due to the proximity of the thermal expansion coefficient of tungsten alloys to borosilicate glass) is very suitable in lamp electrodes [10].

Few experimental types of research have been done on the effect of doping the cathode electrode in flash lamps but for instance, in the research of Liu et al., tungsten was doped with cerium and lanthanum oxides by powder metallurgy method, also the activation temperature of this sample was reported to be lower than the sample doped with cerium oxide [11]. Moreover, in both argon and xenon lamps, strong flickering caused by tungsten doping with lanthanum oxide annealed at 3000K which was the result of reducing the work function of the cathode electrode, has also been reported [12]. Flash lamps have a long life and a reasonable price, with important applications in medical fields such as dermal lasers, solid state lasers, sources for the production of UV wavelengths for disinfection of surfaces, sterile equipment and food, as well as in car headlights [2]. Flash lamps can be optimized for use in Nd: YAG and Nd: glass amplifiers based on the length and radius of the crystal. In order to remove excess hair, the intense pulse of this type of lamp is used in the wavelength range of 600 nm to 950 nm [2]. Intensely pulsed, continuous-wavelength (CW) lamps can be used in solid-state lasers as the pumping source. This type of lamp was used for the first time by Meiman in 1960 for pumping the solid-state laser crystal [4].

Depending on its application, the shape of the lamp chamber can be linear or spiral, and its emission spectrum overlaps as much as possible with the absorption spectrum of the laser crystal to increase efficiency. In general, the radiant efficiency of noble gas lamps is averagely about 45%, among which xenon has the highest radiant efficiency as a very rare and expensive gas. The radiant gain of argon is about 20%. In general, noble gases have strong emissions, relatively low thermal conductivity and easy stimulation compared to other gases [13]. High brightness, continuous emission spectrum, short pulse duration, operability in repeated pulse conditions, pulse repetition frequency and high electrical power are the advantages of this type of lamp [2].

In this work, all the steps of making the lamp and installing various electrodes have been done by ourselves in the CRLP lab. Also, the effect of diverse doping states of cathode electrodes impregnated with thorium, cerium and lanthanum atoms on the threshold voltage and temporal behavior under argon gas pressure were investigated where they have not been reported elsewhere. Moreover, since thorium is a common element for doping with tungsten, as a new investigation we compared the optical properties of two different percentages of its doping with tungsten. Light intensity and temperature tolerance for some samples at different pressures of argon gas were also measured and compared.

II. EXPERIMENTAL DETAILS

A. *Construction of lamp tubes*

To make the flash lamps, borosilicate glass tubes with a melting point of about 820°C and a coefficient of thermal expansion of $\alpha = 3.3 \times 10^{-6}$ /°C [14], with an outer diameter of 6 mm and an inner diameter of 4 mm were first cut at 60 mm length and washed in warm bleach and deionized water for one hour to remove all contaminants from inside and outside. Then, for each tube, a vertical base with a length of 50 mm is attached in a special process, and the final T-shapes were created through which vacuuming and aeration processes were made.

The characteristics of five lamp samples using different cathode electrodes with the same anode made of pure tungsten, with a work function of about 4.32 eV, are listed in Table 1.

The tip of the electrodes can vary, depending on the specific operation. The shape of the tip can be tapered or structured like a dome. The type of arc connection, plasma hot spot temperature, electrode voltage drop, and electric current at the electrode tip are determined by the shape of the electrode [3]. The cathode electrodes are used as emitters in the flash lamp. To have long pulses (about 1 millisecond) with a high current emission, cathodes are designed with sharp tips. Also, since the anode receives electrons and is subjected to electron bombardment, a wider surface area and higher mass would be optimum for this purpose [2].

Table 1. Number of samples and type of electrodes used.

Sample number	Type of cathode electrode	Doping Percentage	Type of anode electrode
L1	tungsten - thorium	1.7%-2.2%	pure tungsten
L2	tungsten - cerium	1.8%-2.2%	pure tungsten
L3	tungsten - thorium	0.35%-0.55%	pure tungsten
L4	tungsten - lanthanum	1.4%-1.6%	pure tungsten
L5	pure tungsten	0%	pure tungsten

Therefore, the anode electrodes in this study are rounded. The length of the electrodes both are 20 mm with 1.6 mm in diameter. The cathode electrodes used in this work contain radioactive elements such as thorium and cerium, which can emit electrons well due to good electronegativity (about 2.14 eV). Considering the discharge distance of 35 mm in all samples, the cathode and anode electrodes are welded to a glass tube using a butane-oxygen torch and then cooled gradually, so that no cracks or stresses were observed in these joints. A schematic of the flash lamp building is shown in Fig. 1.

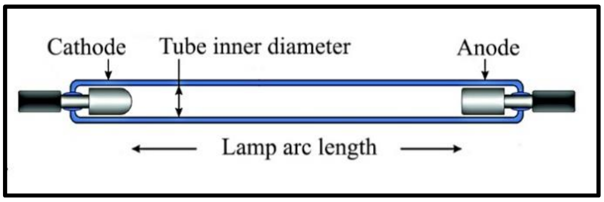

Fig. 1. Schematic of argon flash lamp along with its different parts.

B. *Turning on the lamp*

After making the lamp tubes and attaching electrode connections, they were used in the setup shown in Fig. 2, by attaching a T-base created in the distance between the electrodes in the lamp tube.

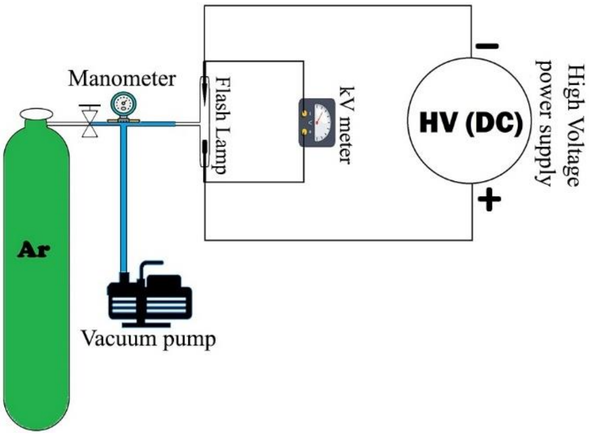

Fig. 2. A schematic of the system set up for measuring the flash lamp properties.

Using a vacuum pump made by Value company model VE115N with a flow rate of 43 m/h and a barometer, the pressure of argon gas entering the lamp chamber was controlled. To supply the required voltage of the flash lamp, a high voltage DC power supply was used which was able to supply voltage up to 40 kV. The lamp was fed through a laboratory argon gas capsule with a purity of 99.99%.

Figure 3 shows the photo of an argon lamp when it is turned on. By changing the gas pressure, the threshold voltages of the samples were measured. The light intensity was measured by placing a lux meter TES model 1336A in a dark box at a distance of 20 cm from the lamp. The temporal behavior of light intensity at different argon pressures was also recorded by a high-speed detector and a digital oscilloscope with a frequency of 200 MHz.

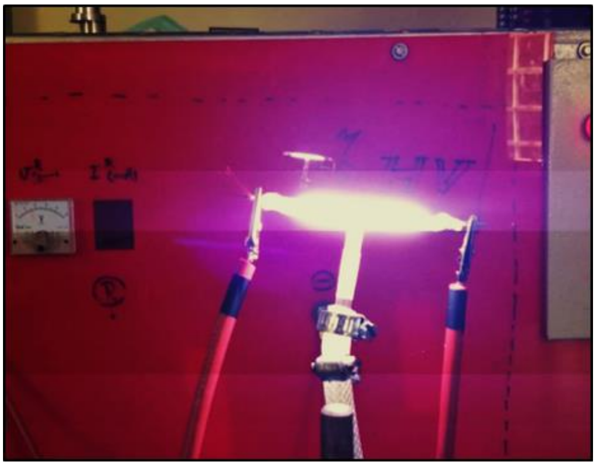

Fig. 3. The photo of a sample turned on at a pressure of 200 mbar argon gas.

To measure the temperature changes of the lamp, a laser thermometer made by BENETECH company model GM320 was used so that when the lamp was turned on at a certain threshold pressure and voltage, the tube temperature was red and recorded every three seconds. This measurement continued up to the point that the glass tube of the lamp started melting. The temporal temperature behavior was measured for three lamp samples at three different pressures for comparison.

A flash lamp has an impedance (K0), overcoming which by the threshold voltage causes the lamp to light up. The impedance of the flash lamp depends on the type and gas pressure, diameter and discharge distance of the lamp, which is given by Eq. 1 [1]:

$$K_0 = 1.28\frac{L}{d}\left(\frac{P}{N}\right)^{0.2} \quad (1)$$

where P is the gas pressure in torr and N is the gas constant, *i.e.*, 524.13 for argon. Also, L is the discharge length of the lamp and d is the inner diameter.

III. Results and Discussion

Figure 4 shows the threshold voltage variations of the flash lamps versus the gas pressure inside. In all samples, as the gas pressure increases, the threshold voltage also increases monotonically. Due to the instability of the currents passing through the lamp when the lamp was running, the graphs are obtained by fitting a linear curve through the data contained in the "error bar". For each point on the graph, three measurements were made, and in total, five different pressures were used to fit each curve. When the applied voltage reaches the gas ionization voltage (threshold voltage), the lamp turns on in an instant, in which case the source voltage drops rapidly due to the drop in gas resistance and the current flow in the lamp. In addition to the pressure, the threshold voltage of the gas is a function of the distance between the electrodes (discharge length), which is considered constant here and is equal to 35 mm. Due to the fact that a lower threshold voltage means less electricity consumption, less heat and consequently longer lamp life, our preferred lamp has a lower threshold voltage at different gas pressures.

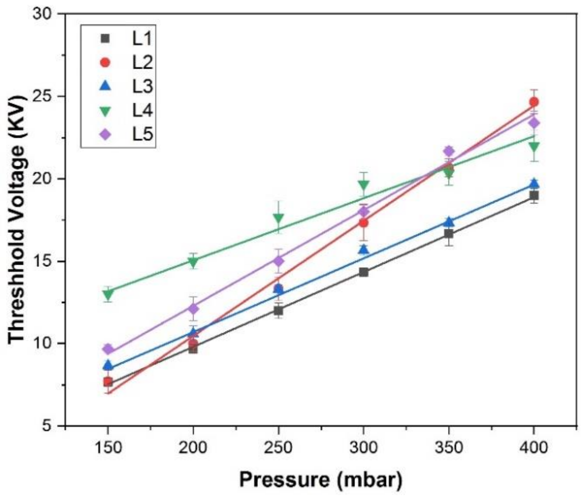

Fig. 4. Threshold voltage of lamps vs. the pressure of argon gas.

According to the diagrams of Fig. 4, one can see that L1 and L3 samples, whose cathode electrodes are doped with thorium, have an average lower threshold voltage compared to other samples. Between these two samples, L1 with a thorium doping of 1.7-2.2% has a lower threshold voltage and a more stable arc than L3 with a lower thorium doping percentage.

Low threshold voltage and low operating function (2.6 eV) lead to increasing in lamp lifetime, which has been previously reported [15]. Among samples, L2 has a tungsten cathode doped with cerium oxide. Cerium is a transition element and has good electron donating. However, according to the diagram, it is clear that at low pressures, it has a lower voltage threshold than L1 and L2 samples, but considering its general trend with its relatively steep slope, it is clear that it is not a good alternative at pressures above 150 mbar. Because at higher pressures, where the starting current is higher, the cerium tungsten electrode arc is more unstable, which causes the temperature of the electrode tip to rise, so cerium evaporates easily and the emission properties decrease. Therefore, cerium tungsten electrode cannot be a complete replacement for thorium tungsten electrode. The lamp whose cathode and anode are both made of tungsten, with a purity of 99.5%, illuminates at higher voltages than the other samples. This shows that the cathode electrode material is very effective in the threshold voltage of the lamp and tungsten doped rare metals are necessary to have an emission efficiency and favorable threshold voltage.

Figure 5 shows the temporal behavior of the light intensity of L1 to L5 respectively at a pressure of 200 mbar of argon gas, measured using a fast detector and a 200 MHz digital oscilloscope at a distance of 20 cm from the lamp in a closed chamber. This figure shows the lack of significant effect of the type of cathode electrode on the pulse shape of the flash lamp at the same discharge distance. Also according to this figure, due to the use of a direct current power supply, the temporal behavior of lamp-turn-on is quicker than the temporal behavior of its turn-off. This behavior is due to the cascading phenomenon of gas discharge. In this type of discharge, when the voltage drops across the two electrodes, the intensity of the discharge current increases until the voltage reaches a constant value.

At this point, the resulting plasma emits light uniformly, in fact, the density of electrons and energy is such that it can collide with the ionizer and emit light when they return to a steady state. In this discharge, different wavelengths are emitted depending on the type of gas [3]. By designing a suitable power supply that includes a simmer and a pre-ionization circuit, the temporal behavior of discharge onset can be greatly mitigated.

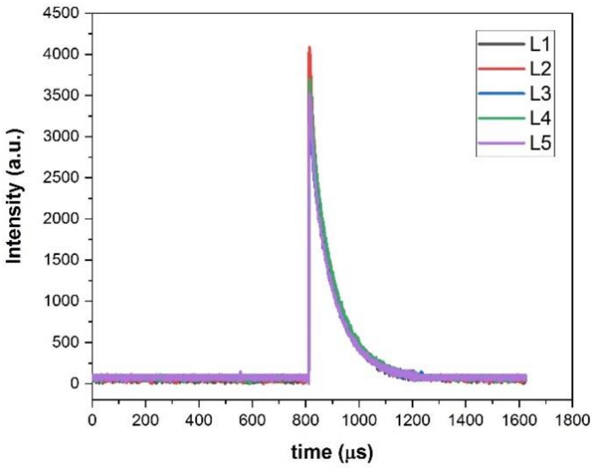

Fig. 5. Temporal behavior graph of the light intensity of all samples at a pressure of 200 mbar of argon gas.

To measure the light intensity, the lux meter detector was placed at a fixed distance from the samples and then at different gas pressures, the light intensity caused by the lighting of the lamp when the threshold voltage was reached was recorded through the computer.

Figure 6 shows the light intensity in terms of pressure of argon gas, from 150 to 600 mbar. Due to the non-consistency of the pulse duration of it in various measurements of light intensity at different pressure of argon gas and the deposition of material onto the inner wall of the lamp after running lamps, the horizontal error bars were prepared and shown in these graphs. According to these diagrams, which were obtained by fitting linear curves, it is clear that the light intensity in all samples increases linearly with increased gas pressure inside the lamp tube. Also, L1 and L2 samples, whose cathodes are made of tungsten doped with thorium and cerium, respectively, have higher light intensity than the other samples. The presence of appropriate electrical and radiation properties of thorium and cerium, including lower ionization energy compared to pure tungsten, increases the flow of electrons emitted toward the anode, as a result, the amount of electric current in these samples enhances and ultimately leads to an increase in light intensity [16]. In the case of L3 and L4 samples, it appears that at pressures below 250 mbar, they have higher brightness than the pure-tungsten type. However, at higher pressures, the latter having a pure tungsten cathode shows higher illumination compared to the two other samples.

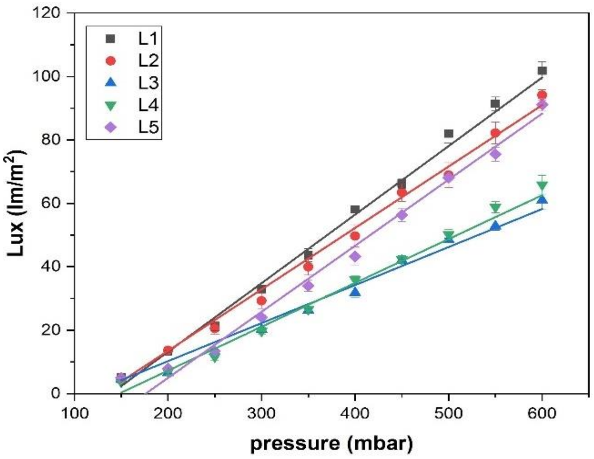

Fig. 6. Light intensity versus the pressure of the argon gas.

Figures 7a to 7c respectively show the variations of temperature versus the time for the L1 sample at 200 mbar, the L4 sample at 400 mbar, and the L5 sample at 600 mbar argon gas pressure. The existence of error bars in these graphs goes back to the repeated measurement of the temperature tolerance of the samples due to the lack of a cooling system for the lamps and also the presence of factors affecting the ambient temperature. The lamps were derived in CW operation. The L1 sample, working at lower pressure shows a lower temperature rise versus the time, so we had to expand the time interval to 60 s. The temperature reaches 161°C after 30 s and 351°C after 60 s. For the L4 and L5, the tube temperatures reach 202°C and 257°C after 30 s, respectively.

Although the tube temperature depends on the electrode type, our measurement shows this dependence is minor, and the main factor is the pressure. Higher pressure loads higher temperatures, that is, in higher pressure electron-ion and ion-ion collisions are larger. However, the L1 sample having thorium in its cathode generates higher intense light (See Fig. 6).

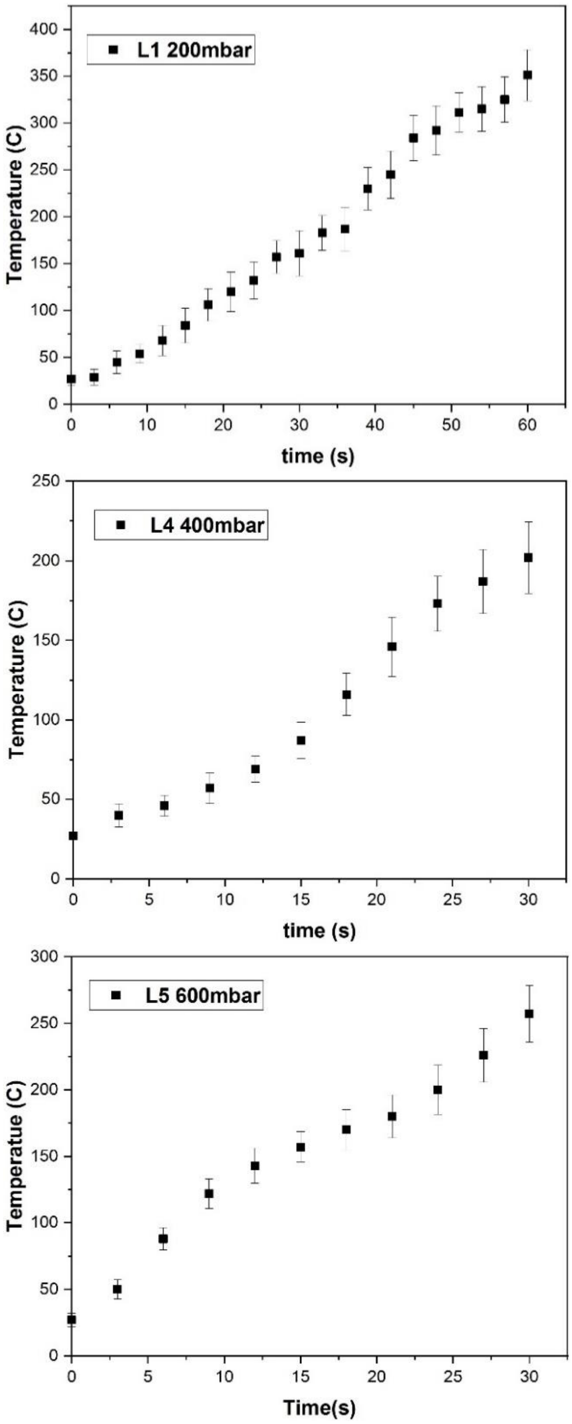

Fig. 7. Temperature of lamp tube as a function of time for three samples of (a) L1 at the pressure of 200 mbar, (b) L4 at the pressure of 400 mbar, and (c) L5 at a pressure of 600 mbar without a cooling system.

IV. CONCLUSION

In summary, in this work, the effect of doped cathode electrode on the characteristics of argon flash lamps was experimentally investigated. Tungsten cathodes doped with thorium, cerium and lanthanum as well as pure sample were used to make the lamps. In all samples, the distance between the cathode and anode was taken to be the same as 35 mm. Threshold voltage vs. tube pressure, time profile of flash, light intensity at continuous wave operation versus tube pressure, and tube temperature as a function of time were measured. For all samples, the threshold voltage showed a linear relationship with the gas pressure inside the tube. Also, all samples showed the same time profile for flash. However, overall the sample constructed with thorium (1.7%-2.2%) doped cathode showed a better performance in other characteristics. Compare to other samples it showed a lower threshold voltage at pressures above 150 mbar, higher light intensity and lower temperature rise due to the low work function of thorium which led to an increase in the amount of electron output from the cathode electrode. The thermal and mechanical resistance of the lamp at different pressures of argon gas was also examined. After continuous operation without a cooling system, the lamps melted without breaking or cracking.

ACKNOWLEDGMENT

F. Khoshnood would like to thank Technical and Vocational University (TVU) for providing him with sabbatical leave in the Center for Research on Laser and Plasma (CRLP). M. Sabaeian would like to thank Shahid Chamran University of Ahvaz for supporting this work under grant number SCU.SP1401.259.

REFERENCES

[1] W. Koechner, *Solid-State Laser Engineering*, New York: Springer, Ch. 6, 2006.

[2] L. Rebohle, S. Prucnal, and D. Reichel, *Flash Lamp Annealing*, New York: Springer, Ch. 2, 2019.

[3] P. Flesch and M. Neiger, “Time-dependent simulation of plasma and electrodes in high intensity discharge lamps with different electrode shapes,” J. Phys. D., Vol. 36, pp. 849-860, 2003.

[4] T.H. Maiman, “Stimulated optical radiation in ruby,” Nature., Vol. 187, pp. 493-494, 1960.

[5] J.D. Greiner and J.F. Smith, “Magnetic susceptibility of high purity Thorium,” Phys. Rev. B., Vol. 4, pp. 3275-3277, 1971.

[6] L. Kývala and D. Legut, “Lattice dynamics and thermal properties of thorium metal and thorium monocarbide,” Phys. Rev. B., Vol. 101, pp. 075117 (1-14), 2020.

[7] M. Melchionna, A. Trovarelli, and P. Fornasiero, *Cerium Oxide Synthesis Properties and Applications,* Amsterdam: Elsevier, Ch. 1, 2020.

[8] D. Bouzid, N. Belkhir, and A. Toufik, “Optical glass surfaces polishing by cerium oxide particles,” in IOP Conf. Materials Science and Engineering, Mahdia, pp. 012007 (1-6), 2012.

[9] S. Kanpara, S. Khirwadkar, S. Belsare, K. Bhope, R. Swamy, Y. Patil, P. Mokariya, N. Patel, T. Patel, and K. Galodiya, “Fabrication of Tungsten & Tungsten Alloy and its High Heat Load Testing for Fusion Applications,” Mater. Today, Vol. 3, pp. 3055-3063, 2016.

[10] A.W. Hull and E.E. Burger, “Glass-to-Metal Seals,” Appl. Phys., Vol. 12, pp. 384-405, 1934.

[11] J. Liu, H. Li, R. Wu, R. Shao, and B. Jiang, “Study of tungsten cathode doped with rare earth for pulsed xenon lamp,” Advanced Materials Research., Vol. 567, pp. 204-207, 2012.

[12] T. Hoebing, P. Hermanns, A. Bergner, C. Ruhrmann, H. Traxler, I. Wesemann, W. Knabl, J. Mentel, and P. Awakowicz, “Investigation of the flickering of La_2O_3 and ThO_2 doped tungsten cathodes,” Appl. Phys., Vol. 118, pp. 023306 (1-16), 2015.

[13] M. Sabaeian, Z. N. Tarkarani, and A. Ebrahimzadeh, “Design and construction of a homemade and cheaper argon arc lamp,” Opt. Rev., Vol. 25, pp. 493-499, 2018.

[14] R.M. Rulon, “Glass to Metal Seals,” in Springer Conf. Introduction to Glass Science, Boston, pp. 661–704, 1972.

[15] E.C. Horrigan, J. Haidar, and F. Righini, “Physical changes in tungsten and thoriated tungsten electrodes after subsecond heating,” Int. J. Thermophys., Vol. 17, pp. 1037-1044, 1996.

[16] L. Zhena, Y. Jiancanb, C. Jiec, and L. Yand, “Development and application of tungsten electrode materials,” Materials Science Forum., Vol. Vol. 817, pp. 348-354, 2015.

Farshad Khoshnood was born in Dezful in 1987. He received his B.Sc. degree in physics from Chamran University, Ahvaz, Iran in 2011. His MSc degree was in nanophysics from Maleke-Ashtar University of Technology, Isfahan, Iran, received in 2013.

He is currently envolved as an instructor of physics in Technical and Vocational University, Tehran, Iran. His research interests include nano materials, gas sensors, flash lamps, thin films and semiconductors.

Mohammad Sabaeian was born in 1979. He received the B.Sc. degree in physics from Shahid Chamran University, Ahvaz, Iran in 2001. He received his M.Sc. degree in atomic and molecular physics and Ph.D. degree in optics and laser physics from Shiraz University, Shiraz, Iran, in 2003 and 2008, respectively. His Ph.D. research areas were thermal effects in high-power solid-state and fiber lasers.

He is currently an associate professor of physics in optics and laser with the Department of Physics, Faculty of Science, Shahid Chamran University of Ahvaz. He founded the Center for Research on Laser and Plasma (CRLP) in 2016. His main research interests include the design and construction of solid-state lasers, especially short and ultrashort lasers, light-matter interaction in strong field regimes, spectroscopy, and laser applications in chemistry, biology, medicine, metrology, etc. He is also focusing on nanophotonics, especially metallic and graphene plasmonic.