IOP Publishing Physica Scripta

Phys. Scr. 95 (2020) 044002 (7pp) https://doi.org/10.1088/1402-4896/ab5e92

Investigation of the absorption process of the microwave radiation by metal wires with the same electrical conductivity

Marian Mogildea[1], George Mogildea[1], Cristian P Lungu[2], Cristina Popa[2] and Cornel Staicu[2,3]

[1] Institute of Space Science, RO-077125, Bucharest-Magurele, Romania
[2] National Institute for Laser, Plasma and Radiation Physics, Bucharest-Magurele, Romania
[3] Doctoral School of Physics, University of Bucharest, Romania

E-mail: george_mogildea@spacescience.ro

Received 26 July 2019, revised 29 November 2019
Accepted for publication 4 December 2019
Published 12 February 2020

Abstract

In this paper, we present a microwave-assisted absorption method for the metallic wires with same electrical conductivity (e.g. tungsten and molybdenum). Our experimental set-up uses a microwave plasma generator in order to generate the plasma from the metal wires and to obtain the metal powders. The microwave plasma generator (experimental model) contains a cylindrical cavity—TM_{011} propagation modes, a magnetron with 800 W microwaves power and 2.45 GHz frequency, a power supply and an electronic module. In the focal point of the cylindrical cavity we have a high energy of the electromagnetic radiation. The metallic wires from this are a was vaporized and ionized. The structure of the metal powders was investigated with scanning electron microscopy. The electron temperature regarding metallic plasma produced was estimated using the ratio of atomic emission lines acquired by a high definition of the optical multichannel spectrometer. We obtained a strong microwave absorption by tungsten (W) and molybdenum (Mo) wires which depend on the power of the microwave. The Mo and W wires can be vaporized with the microwave field, in air at atmospheric pressure and room temperature.

Keywords: microwave radiation, plasma generator, metal powders, ionization, thin film deposition

(Some figures may appear in colour only in the online journal)

1. Introduction

Microwaves are defined as a part of electromagnetic waves that have frequency range between 300 MHz and 300 GHz corresponding to wavelength from 1 mm to 1 m [1, 2]. Microwave application for heating has been applied to drying, cooking food and in the excitation of chemical reactions such as inorganic or organic synthesis. Microwave heating is a process of microwaves couple to materials, which can absorb the electromagnetic energy volumetrically and transform it into heat. Microwave heating of dielectric materials has been widely investigated and the interaction mechanism between microwave and materials is well documented.

Microwave applications for metal heating was not a well-studied area because the bulk metals are very good in radiation reflection and thus cannot be directly heated. Practical research [3] has shown that non-ionizing radiation can induce thermal effects in dielectric materials. Also, it is well known that bulk metals are very good radiation reflectors that cannot be heated with microwave radiation [4]. Microwaves are non-ionizing radiations with energy between 10^{-3} eV and 10^{-6} eV/photon. Microwave interaction with metals is restricted to its surface only; the metallic powders behave differently in the microwave field. Recently, it was been demonstrated that microwaves can be absorbed by metallic powders. Also, research studies from 2001 have revealed that metallic powders (tungsten carbide- cobalt) that are

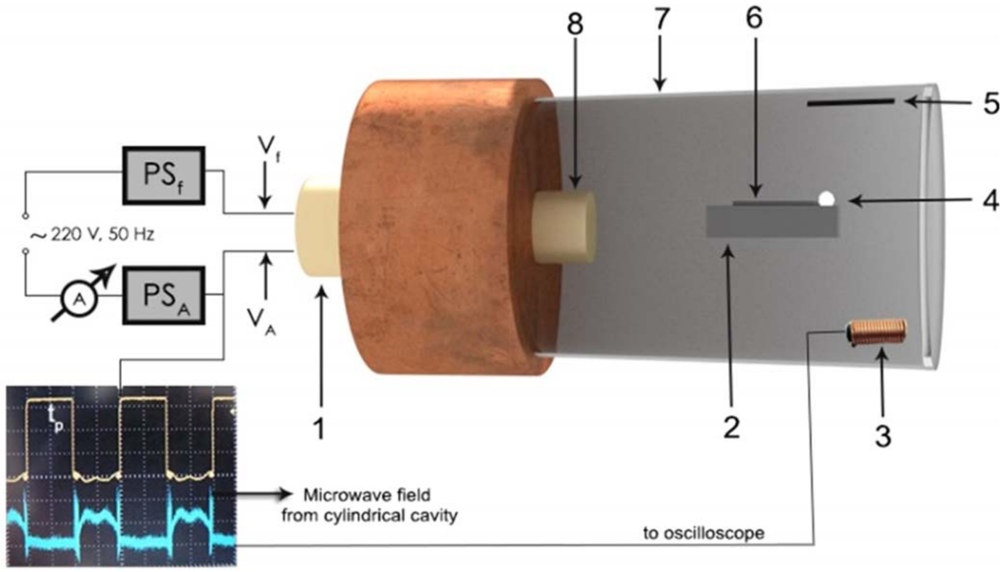


Figure 1. The microwave plasma generator- experimental set-up. 1—magnetron, 2—ceramic support, 3—microwave sensor, 4—high electromagnetic energy area, 5—Si-wafer support, 6—metal wire, 7—cylindrical cavity, 8—magnetron antenna.

introduced in a multimode cavity in a microwave field can absorb the microwave radiation [5]. The tungsten carbide-cobalt powder was exposed to a microwave field ($\nu = 2.45$ GHz) with the microwave power at 1.2 kW, and the time of exposure about 10 min. As a result, the tungsten carbide-cobalt powder reached higher temperatures in the transversal electric (TE) propagation mode, which means that the tungsten carbide-cobalt powder absorbed more microwaves in the TE mode.

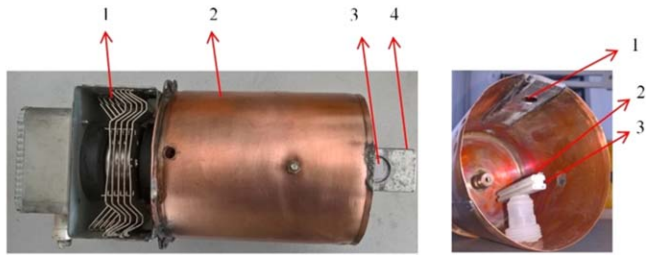
Other studies from in 2009 [6] showed that microwave absorption depends on the dimension of the metallic particle and the frequency of the electromagnetic radiation. In this experimental research Cu powders (particles between 6 and385 μm) were exposed to the microwave field in a multimode cavity for 10 min. The experiments results reveal that the Cu powder with particle dimension of 6 μm was the best microwave absorbent. After exposure, the Cu particles with the 6 μm diameter reached temperatures of $\sim$1000 °C. These studies reveal that microwave absorption of the metallic powders depends on the depth of penetration. Knowing that the depth of penetration for Cu is about 4 μm, calculated with formula (1) [6, 7] and that the highest temperature was reached by the Cu particles with diameters of 6 μm, we conclude that the metallic particles with dimensions close to the depth of penetration are the best microwave radiation absorbents

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}}, \tag{1}$$

where,

$\omega = 2\pi\nu$, $\nu = 2.45$ GHz, $\sigma_{\mathrm{Cu}} = 5.96 \times 10^{7}$ S m^{-1}, $\mu_{\mathrm{Cu}} = 1.25 \times 10^{-6}$ H m^{-1},
δ = skin depth, ω = angular frequency

Following these studies the microwave processing of metal/alloy powders have gained considerable potential in the field of material synthesis. Microwave heating is



(a) Lateral view (b) Front view

Figure 2. The microwave plasma generator: (a) 1—magnetron, 2—cylindrical cavity, 3—Si-wafer, 4—Si-wafer support; (b) 1—Si-wafer support, 2—metallic wire, 3—ceramic support

recognized for its prominent advantages such as: time and energy saving; rapid heating rates; considerably reduced processing cycle time and temperature; fine microstructures and improved mechanical properties; better product performance etc.

Other recent studies showed that the microwave absorption process can be present in the interaction of non-ionizing radiation with metallic objects that have dimensions much larger than the depth of penetration. In 2010 we reported the microwave absorption by metal wires [8]. We demonstrated that lead metal wires having diameters less than 0.5 mm can be vaporized and ionized by microwaves from the cylindrical cavity having the TM_{011} propagation mode. In the experiments a 2.45 GHz frequency, 800 W microwave power was used. Later, we investigated the possibility of controlling the quantity of metal (lead wires) which is vaporized and ionized in this manner [9]. In this experimental research cylindrical cavity was used the TM_{012} propagation mode and it was found that if the microwave pulse duration changes and the quantity of vaporized and ionized metal changes as well. In 2010 we investigated [10] the microwave heating behaviours of metal wires (lead) in vacuum conditions and found that at 10^{-5} milibar pressure, the vaporization and ionization

Table 1. Thermal and energetic parameters of the W and Mo.

The metal wire (0.5 mm diameter)	First ionization energy (eV)	Thermal conductivity (W mK^{-1})	Electrical conductivity (S m^{-1})
W	798	170	2×10^7
Mo	709	139	2×10^7

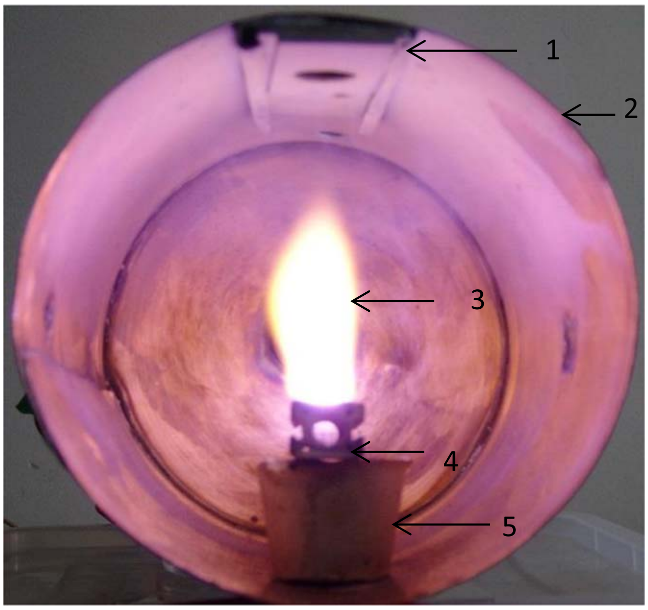


Figure 3. The metallic wire exposed in the microwave field: 1—wafer support, 2—cylindrical cavity, 3—metallic plasma, 4—ceramic support, 5—plastic support.

process of the metal wires does not occur and the metal wire is only heated up to melting temperature. In the air at normal atmosphere and at room temperature, the metallic wires can be heated up to plasma temperature while in vacuum conditions the metal wires do not exceed the melting temperature, was concluded that air molecules could contribute to the metal microwave absorption process. In order, to investigate if the gas molecules have any contribution to the microwave heating process of metallic wires we used a small Teflon piece. When the metallic wire together with Teflon piece in vacuum conditions was exposed in the microwave field, the metallic wire generated a strong electric field, then Teflon was heated and it was decomposed in gases [11]. This electric field ionized the Teflon gases and the heat generated by the Teflon ion gas could vaporized the metal wire. Then the metal vapors were ionized in the microwave electric field from the cavity.

In 2015 was used a rectangular cavity to create titanium plasma from titanium sample [12] and copper plasma from copper sample [13]. The plasma column was created when an electrode (titanium or copper) was brought into contact with a plate (titanium or copper) while irradiated by microwaves at 2.45 GHz generated by a 1 kW microwave power.

In 2015 [14] was investigated the microwave absorption of the metallic wires with a low melting point. These studies proved that microwave absorption depends on the electrical conductivity of each metal. Metal wires were exposed directly to the microwave field from the cylindrical cavity and electrodes were not used with the sample.

The present research paper investigates the absorption processes of the microwave radiation by W and Mo using the metal powders analysis and the measurement of the electron temperature from the obtained plasma.

We used a microwave plasma generator (experimental model) to generate plasma from metallic wires and after that we obtained the metallic powders.

Knowing that the microwave absorption by metallic wires depends on the electrical conductivity of each metal and the intensity of the electromagnetic field, in these studies we analyze two metals with the same electrical conductivity. The research was carried out in the air, at normal atmospheric pressure and at room temperature. As a result of the interaction of the W and Mo wires with the microwave field, plasma was generated in the focal point of the cylindrical cavity and the wires were vaporized locally on their entire surface. The metallic particle was been collected on a Si-wafer.

2. Experimental set-up

The vaporization and ionization of metal wires in a microwave field is an interesting area, both scientifically and technically. The aggregation state and the temperature of a metal exposed to microwave radiation are dependent on the power of the microwave field and on the state of the metal (powder or wires).

An important role of the microwave absorption process by metals is represented by the medium in which the experiment is realized. If the experiment is carried out in the air, under normal atmospheric conditions, the air molecules contribute to the absorption phenomena of non-ionizing radiation.

According with Poynting equation (2) [15], when the microwave power in the cylindrical cavity increases the electric field in the wire increases as well. The microwaves induce strong electric fields in metallic wires, causing the electric field to produce the gas ionization of the high electromagnetic energy area (figure 1). The ions of the plasma interact with the metallic wire and vaporize the metal

$$\vec{P} = \frac{1}{2}\mathrm{Re}\,(\vec{E} \times \vec{H}^{*}) = \frac{1}{2}\frac{|E|^2}{\eta}; \tag{2}$$

where,

P = Poyting vector, E = electric field,

H = magnetic field, η = impedance of medium.

The relationship between the microwave electric field and the current density (conduction and displacement current)

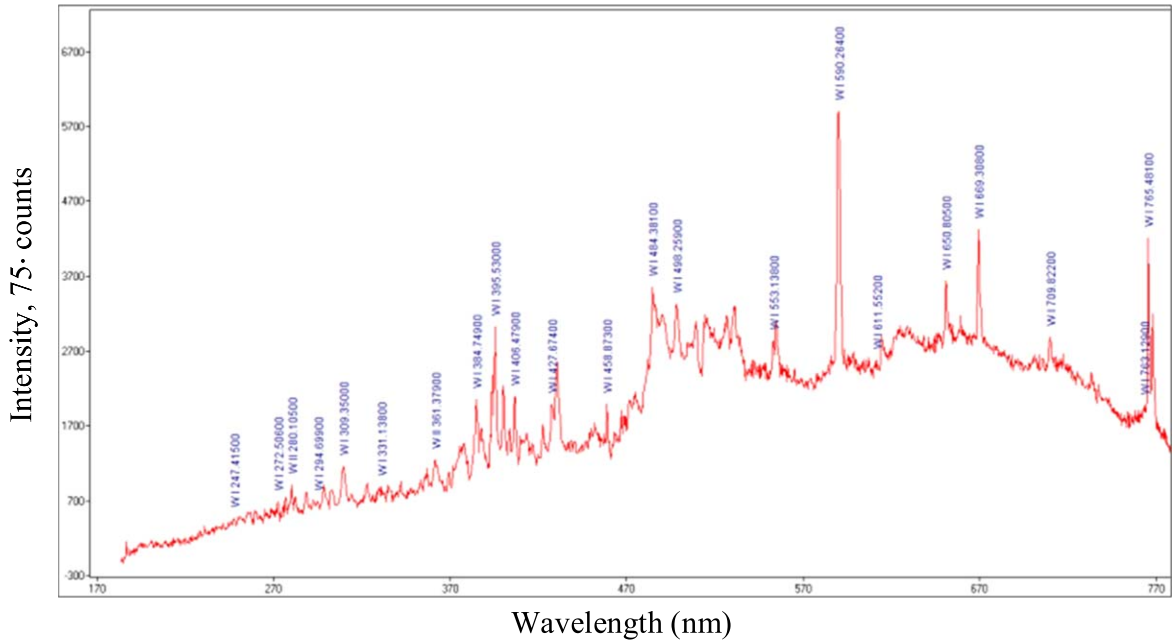


Figure 4. The thin film deposition of the W particles on Si-wafer.

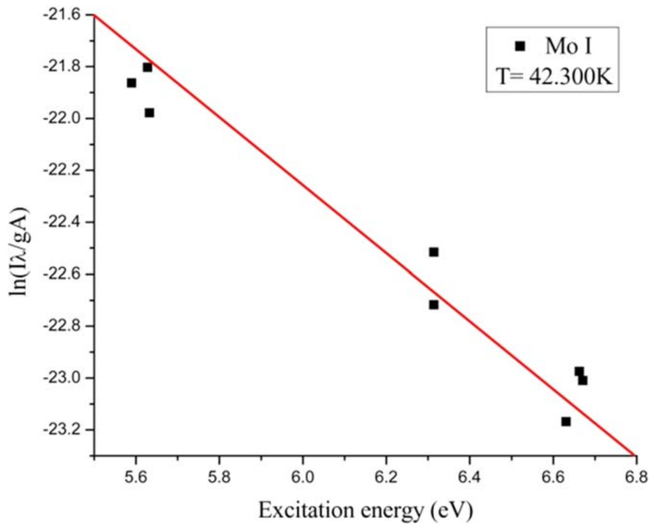


Figure 5. The thin film deposition of the Mo particles on Si-wafer.

from metallic wire is [15]:

$$J = (\sigma + j\omega\varepsilon)\vec{E}; \quad (3)$$

where:

J = current density in metallic wires,
σ = electrical conductivity of metallic wires,
ω = angular frequency, ε = electrical permittivity ,
E = electric field.

Because the metallic particles have dimensions much smaller than the skin depth of the microwave, the metallic particles are ionized in the microwave field.

To obtain an important absorption of the microwaves by metal wires with high dimensions much greater than the penetration depth of the electromagnetic radiation, we vaporized the W and Mo wires with microwave field. In our experiment we used a microwave plasma generator—experimental device (figures 1 and 2 and). We chose W and Mo because they have same electrical conductivity (table 1).

All metallic wires have a 0.5 mm diameter and a 50 mm length. The sample was placed on a ceramic support and introduced in to the cylindrical cavity (figures 1 and 2 and).

The microwave plasma generator consists of:

- a cylindrical cavity
- a microwave source (commercial magnetron) with $\nu = 2,45$ GHz and power of radio frequency of 800 W;
- a power supply. High voltage power supply for the magnetron anode and low voltage power supply for filament of the thermo-electronic source of the magnetron.
- an electronic module. The quantity of the vaporized metal is controlled by an electronic module of a high voltage power supply. This modifies the length of the electric impulses (duty factor) of the source that feeds the anode magnetron, thereby modifying the quantity of the vaporized metal.

Cylindrical cavity:

The TM cylindrical cavity dimensions were calculated with the following formula (4) [16, 17]

$$(f_r)^{\mathrm{TM}}_{mnl} = \left(\frac{1}{2\pi\sqrt{\mu\cdot\varepsilon}}\right)\cdot\sqrt{\left(\frac{p_{01}}{a}\right)^2 + \left(\frac{l\pi}{h}\right)^2}; \quad (4)$$

Where:

a—radius of the cylindrical cavity (m); h—height of the cylindrical cavity (m);

l—Longitudinal mode of the cavity;

μ—Permeability of the medium within cavity (H m^{-1});

ε—Permittivity of the medium within the cavity (F m^{-1});

p_{01}—First zero of the Bessel function (equal to approx. 2.405);

f_r—the resonant frequency of the cavity.

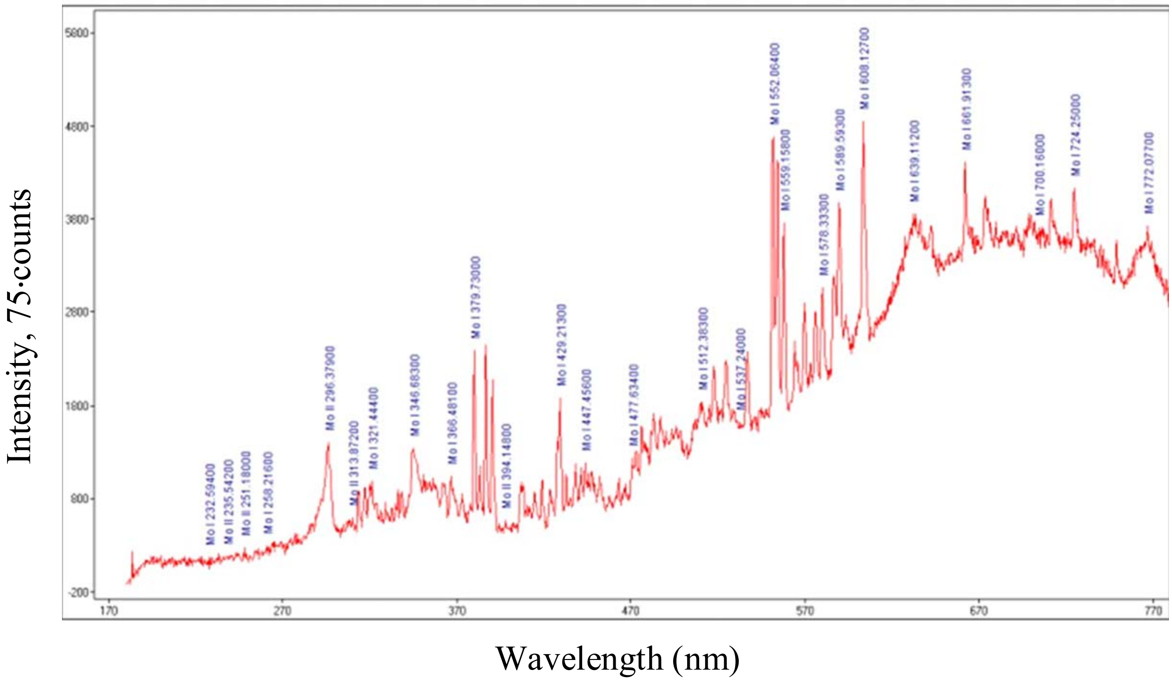


Figure 6. The emission spectrum of the plasma from Mo wire.

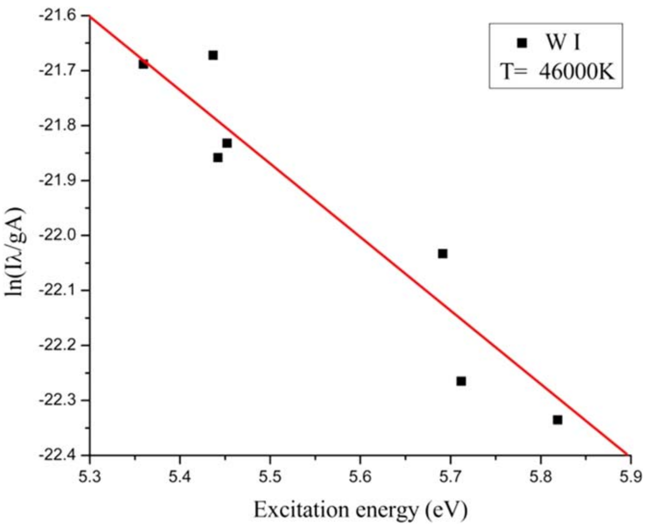


Figure 7. The emission spectrum of the plasma from W wire.

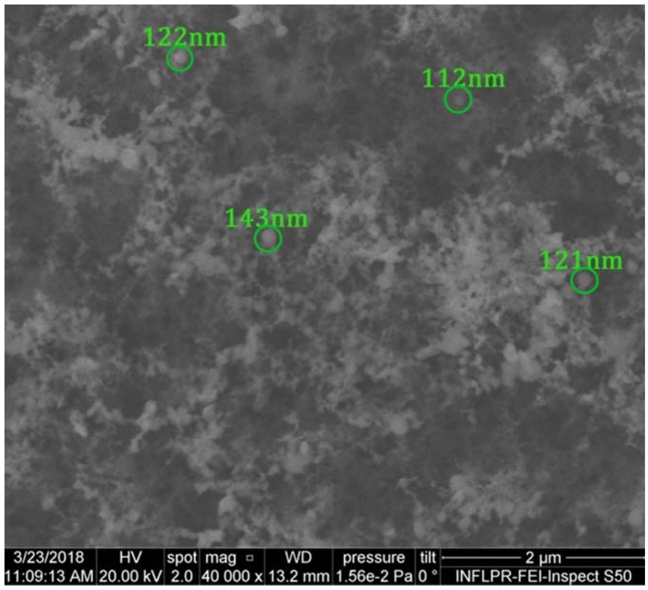


Figure 8. The Boltzmann plot and electron temperature of the plasma for the Mo wire.

The indices *mnl* of the TM propagation mode refers to the number of half wavelength variations in the radial, axial and longitudinal directions.

The optimal dimensions of the cylindrical cavity in our experimental data are the following:

- For the TM_{011} cylindrical cavity the diameter of the cavity is 11 cm and the length is 10.5 cm.

Generally, the microwave absorption by metals is characterized only by Ohm losses [6]. We investigated the microwave absorption by metallic wires through plasma parameters characterization and analysis of the metallic particles.

We have highlighted the microwave absorption of metallic wires by placing the W and Mo wires (50 mm length, 0.5 mm diameter) inside the cylindrical cavity. One end of the metallic wire was placed in the focal point of the cylindrical cavity. The high-density energy region (focal point) is located at a distance of 6, 1 cm from the magnetron antenna, which corresponds to half wavelength for 2.45 GHz microwave frequency.

Because in the TM_{011} propagating mode, the microwave electric field propagates along the axis of the cavity, the solid metal wire must be positioned along and as close as possible to that axis. All samples were exposed to the same microwave

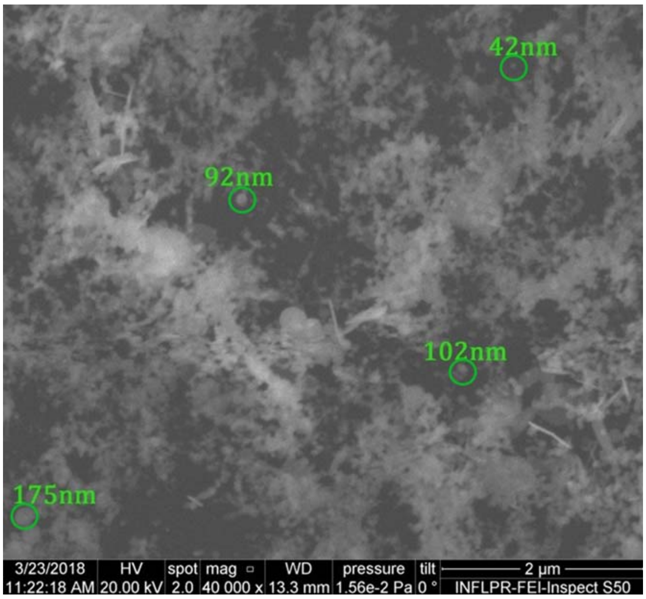


Figure 9. The Boltzmann plot and electron temperature of the plasma for the W wire.

power for 10 s and were vaporized and ionized during the interaction with the microwave field (figure 3). The energy to create plasma comes from the microwave field inside the cavity.

The plasma characterization has been determined by the optical emissions spectroscopy method [18, 19]. The optical emission spectra of the metallic plasma in the region of 200–850 nm has been recorded by an Ocean Optics USB 2000 + spectrometer. Plasma was created at 550 W microwave power in air, at normal pressure and ambient temperature.

To analyze the dimension of the metallic particles we deposited the metal particles on Si-wafer.

Before metal deposition, the Si-wafer was introduced to the wafer support and was placed above the focal point of the cylindrical cavity, so the metallic vapors within adhere to the Si-wafer (figure 3). After the interaction between the microwave and the metallic wire we obtained the metallic thin film (figures 4 and 5). The structures of the metal powders were investigated using scanning electron microscopy.

The quantity of metal vaporized (mg s^{-1}) was obtained by weighing each sample before and after to be introduced in the high density energy region of the cylindrical waveguide.

Our microwave plasma generator can be an efficient device for obtaining metallic vapors from metallic wires. After plasma generation we obtained a constant metallic vapors flux.

3. Results and discussion

In this experiment we used a 550 W microwaves power, the metallic wire was exposed 10 s in the microwave field. The optical emissions spectroscopy method was used for plasma characterization and electron temperature determination. Optical emission spectra of the plasma were obtained through interaction of the microwaves and the Mo and W wires (figures 6 and 7 and).

Spectrum Analyzer software [20] was used for the optical emission spectra of W and Mo plasma identification. The microwave field creates metal ions it was highlighted in evidence by the optical emission spectra (figures 6 and 7).

During the vaporization process of the metallic wires in cylindrical cavity, a cloud of metallic vapors was generated. The metal quantity vaporized was 21 mg s^{-1} for W and 28 mg s^{-1} for Mo.

Because the experimental set-up was conducted at atmospheric pressure, the free path of the charged particles from plasma was very short and the particles slow as the lose kinetic energy. The loss of energy by charged particles traveling through a medium is broken into two components based on the mechanism of energy transfer—either collision or radiative energy loss. Therefore we have just a small part of the metallic vapors deposited on the Si-wafer, most of the metallic vapor being deposited on the wall of the cylindrical cavity and falling into the cavity as a metallic powder (figure 3).

Electron temperature of W plasma and Mo plasma was determined using the Boltzmann plot method which assumes that local thermodynamic equilibrium is met within the plasma [21].

In Mo plasma the electron temperature was 42 300 K (figure 8) and in the W nplasma the electron temperature was 46 000 K (figure 9).

The thin films obtained from W and Mo wires had a different dimensions and structure.

The W particles has very close dimensions (figure 4)

The thin film of the Mo particles deposited on Si-wafers had metallic particles between 42 and 175 nm (figure 5).

4. Conclusions

The Mo and W wires can be vaporized and ionized with the microwave field, in air at atmospheric pressure and room temperature. In the same conditions, 21 mg s^{-1} of W and 28 mg s^{-1} of Mo were vaporized.

The thin films obtained from W and Mo wires has different dimensions and structure and the W particles has very close dimensions.

The metal wires having diameters larger than 0.5 mm become radiation reflectors when exposed to 800 W.

Using the microwave plasma generator to obtain the particle from metallic wires can be an efficient method because after plasma generation the metallic wire has a constant evaporation rate. Therefore, we have obtained constant metallic vapors flux.

Acknowledgments

This work was supported by the Romanian Space Agency -STAR Space Technology and Advanced Research Programme (project No. 161/2017 and project No. 173/2017).

ORCID iDs

George Mogildea https://orcid.org/0000-0003-3344-5885
Cristina Popa https://orcid.org/0000-0003-3881-6956

References

[1] Okeke C, Abioye A E and Yerima O 2014 Microwave Heating Applications in Food Processing *Iosr. Jeee.* **9** 29–34 (Accessed: 04 July 2019) https://researchgate.net/publication/264352691_Microwave_Application_for_food_Processing
[2] Mogildea M, Mogildea G and Popa C 2018 *Frontiers in Materials Science and Optoeletronics: Microwaves and Application Areas* (Riga, Latvia: Lambert Academic Publishing)
[3] Kanagasabay S 1982 *Non-Ioniz. Radiat.* **2** 134–68
[4] Sun J, Wang W and Yue Q 2016 Review on microwave-matter interaction fundamentals and efficient microwave-associated heating strategies *Materials* **9** 231
[5] Cheng J, Roy R and Agrawal D 2001 Experimental proof of major role of magnetic field losses in microwave heating of metal and metallic composites *J. Mater. Sci. Lett.* **20** 1561–3
[6] Mondal A, Agrawal D and Upadhyaya A 2009 Microwave heating of pure copper powder with varying particle size and porosity *J. Microwave Power Electromagn. Energy* **43** 5–10
[7] Marcuvitz N 1986 *Waveguide Handbooks* (Institution of Electrical Engineers Stevenage, UK: Peter Peregrinus LTD Publisher) 0863410588
[8] Mogildea G and Mogildea M 2010 Experimental investigation of the metals vaporization and ionization with microwave used as propellant for ionic propulsion *J. Optoelectron. Adv. Mater.—Rapid Commun.* **4** 352–6
[9] Mogildea M and Mogildea G 2010 Experimental research for the mass flow control of the metal vaporized and ionized with microwave used in electric propulsion *J. Optoelectron. Adv. Mater.—Rapid Commun.* **12** 1157–60
[10] Mogildea G and Mogildea M 2010 Experimental investigation of the microwave electrothermalthruster using metals as propellant *J. Optoelectron. Adv. Mater.—Rapid Commun.* **4** 1826–9
[11] Wall L A and Michaelsen J D 1956 Thermal Decomposition of Polytetrafluoroethylene In Various Gaseous Atmospheres *J. Res. Natl. Bur. Stand.* **56** https://nvlpubs.nist.gov/nistpubs/jres/56/jresv56n1p27_A1b.pdf
[12] Popescu S, Jerby E, Meir Y B, Barkay Z, Ashkenazi D, Mitchell J B, Garrec J L and Narayanan T 2015 Plasma column and nano-powder generation from solid titanium by localized microwaves in air *J. Appl. Phys.* **118** 023302
[13] Jerby E *et al* 2009 Nanoparticle plasma ejected directly from solid copper by localized microwaves *Appl. Phys. Lett.* **95** 191501
[14] Mogildea G, Mogildea M, Jivanescu I, Porosincu C, Lungu M, Chiritoi G and Mingireanu F 2015 Direct vaporization and ionization of the metals wires using microwave field *J. Optoelectron. Adv. Mater.—Rapid Commun.* **17** 367–71
[15] Chryssomallis M T and Christodoulou C G 2005 Antenna radiation patterns *Encyclopedia of RF and Microwave Engineering* ed K Chang 2 (New York: Wiley)
[16] Nordling D and Micci M M 1997 *Low-Power Microwave Arcjet Performance Testing* IEPC-97-089 Department of Aerospace Engineering and Propulsion Engineering Research Centre - Pennsylvania State University
[17] Robert E 1992 *Collin, Foundations of Microwave Engineering* (*The IEEE Press Series on Electromagnetic Wave Theory*) ed D G Dudley 2nd edn (New York: The Institute of Electrical and Electronics Engineers. Inc.)
[18] Isola L, Gomez B J A and Guerra V 2009 Determination of the electron temperature and density in the negative glow of a nitrogen pulsed discharge using optical emission spectroscopy *J. Phys. D: Appl. Phys.* **43** 015202
[19] Bazavan M, Teodorescu M and Dinescu G 2017 Confirmation of OH as good thermometric species for gas temperature determination in an atmospheric pressure argon plasma jet *Plasma Sources Sci. Technol.* **26** 075001
[20] Navrátil Z, Trunec D, Šmíd R and Lazar L 2006 A software for optical emission spectroscopy—problem formulation and application to plasma diagnostics *Czech. J. Phys.* **56** (Suppl. 2) B944–51
[21] Ohno N, Razzak M A, Ukai H, Takamura S and Uesugi Y 2006 Validity of electron temperature measurement by using boltzmann plot method in radio frequency inductive discharge in the atmospheric pressure range *Plasma Fusion Res.* **1** 028