Optical emission spectroscopy for studying the exploding copper wire plasma parameters in distilled water

Hammad R. Humud and Sawsan Hussein

Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

E-mail: dr.hammad6000@yahoo.com

Abstract

This work aims to study the exploding copper wire plasma parameters by optical emission spectroscopy. The emission spectra of the copper plasma have been recorded and analyzed The plasma electron temperature (T_e), was calculated by Boltzmann plot, and the electron density (n_e) calculated by using Stark broadening method for different copper wire diameter (0.18, 0.24 and 0.3 mm) and current of 75A in distilled water. The hydrogen (Hα line) 656.279 nm was used to calculate the electron density for different wire diameters by Stark broadening. It was found that the electron density ne decrease from 22.4×10^{16} cm^{-3} to 17×10^{16} cm^{-3} with increasing wire diameter from 0.18 mm to 0.3 mm while the electron temperatures increase from 0.741 to 0.897 eV for the same wire diameters. The optical emission spectrum (OES) emitted from the plasma have Hα line, small peak at 590 nm corresponding to sodium and others peaks belong to Cu I. The relationship between the plasma electron temperature, emission line intensity and number density with the formed copper nanoparticles size and concentration were studied. It was found that the nanoparticles concentration increase with emission line intensity while its size decrease. It can be conclude the existence of a controlled relationship between the plasma parameters and the formed nanoparticles concentration and size.

طيف الانبعاث الضوئي لدراسة معاملات بلازما سلك النحاس المتفجر في الماء المقطر

حمد رحيم حمود و سوسن حسين عبدالله

قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

يهدف هذا البحث الى دراسة معاملات بلازما سلك النحاس المتفجر كهربائيا بطيف الانبعاثات الضوئي. الطيف المنبعث من بلازما النحاس يسجل ويحلل، وتحسب درجة حرارة الالكترون باستعمال معادلة بولتزمان و كثافة الالكترونات من معادلة ستارك ولاقطار مختلفة من اسلاك النحاس (0.18، 0.24، 0.3) ملم وتيار 75 أمبير في الماء المقطر. واستعملت قمة الهيدروجين Hα عند 656.275 نانومتر لحساب كثافة الالكترون ولاقطار مختلفة من الاسلاك وجد ان كثافة الالكترون تقل من $10^{16} \times 22.4$ الى 17×10^{16} cm^{-3} مع زيادة قطر السلك من 0.18 الى 0.3 ملم بينما درجة حرارة الالكترون تزداد من 0.741 الى 0.897 الكترون فولت لنفس الاقطار. طيف الانبعاث الضوئي للبلازما يمتلك قمة تعود للهايدروجين واخرى صغيرة عند 590 نانومتر تعود للصوديوم وقمم اخرى لذرة النحاس. تم دراسة العلاقة بين درجة حرارة الالكترون وشدة خطوط الانبعاث والكثافة الالكترونات مع حجم وتركيز الجسيمات النانوية المتكونة من خلال الدراسة وجد ان تراكيز الجسيمات النانوية تزداد مع زيادة شدة خط النبعاث ويقل حجمها.

Introduction

Optical emission spectroscopy is one of plasma diagnostics method. It is used to obtain information about the nature of plasma, such as the chemical compositions and plasma species, density of the plasma and electron temperature [1]. Emission spectrum often consists of a number of characteristic atomic or ionic spectral lines [2].

The spectral line intensity (I_{ji}) can also be described as [1]:

$$I_{ji} = \frac{N}{U(T)} g_j A_{ji} h\upsilon_{ji} e^{-E_j/k_B T_e} \qquad (1)$$

where $U(T)$ is the partition function, N number of levels, g_j is the density of states, E_j is the upper level energy, A_{ji} transition probability between the transition states of upper level (j) and lower level (i) and T_e is the electron temperature. Thus the electron temperature of plasma can calculated using Boltzmann relation [3]:

$$Ln\left(\frac{I_{ji}\lambda_{ji}}{g_j A_{ji}}\right) = \left(-\frac{E_j}{KT_e}\right) + \left(\frac{N(T)}{U(T)}\right) \qquad (2)$$

where λ_{ji}, are the wavelength corresponding to the transmission between level j and level i.
While, the electron density can be calculated, utilizing stark broadening relation [4]

$$n_e(cm^{-3}) = \left[\frac{\Delta\lambda}{2\omega_s(\lambda,T_e)}\right] N_r \qquad (3)$$

where, $\Delta\lambda$ is the FWHM of the line, and ω_s is the electron impact parameter, that can be found in the standard tables, N_r is the reference electron density which equal to 10^{16} (cm^{-3}) for neural atoms and 10^{17} (cm^{-3}) for singly charged ions.

There are many parameters used to characterize the plasma such as Debye length (λ_D) which calculated as follows [5]:

$$\lambda_D = \left(\frac{k_B T_e}{4\pi e^2 n_e}\right)^{1/2} \qquad (4)$$

where T_e and n_e are the electron temperature and electron density. Plasma frequency ω_p which can be calculated as [5, 6]

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_o m_e}} \qquad (5)$$

The nanoparticles are produce by different techniques like chemical, physical, mechanical and biological methods etc. One of them is wire explosion technique, which has recently gained high attention [7]. Plasma formed by exploding wires using high electric energy pass throw it within short time in different ambient. Several parameters have a control in exploding wires technique such as voltage, current pulse, material type and their wire dimension, and the medium in which the explosion is performed, etc. [8].

Experimental part

The explosion of wire is characterized by the energy introduced into the wire, which is higher than the evaporation energy of the material. The energy input time is shorter than the time required for the current to spread into the wire. The basic circuit for exploding the copper wires used in produce nanoparticle is shown in Fig. 1. A copper wire with different diametr (0.18, 0.24 and 0.3 mm) and 20 mm long is used to produce nano copper particles in volume of 100 ml distilled water. The emitted spectrum produced by the exploding wire was carried by optical fiber to be analyzed using a spectrometer connected with a computer to record the spectra, which then used to study the effect of wire diameter on the properties of the produced plasma.
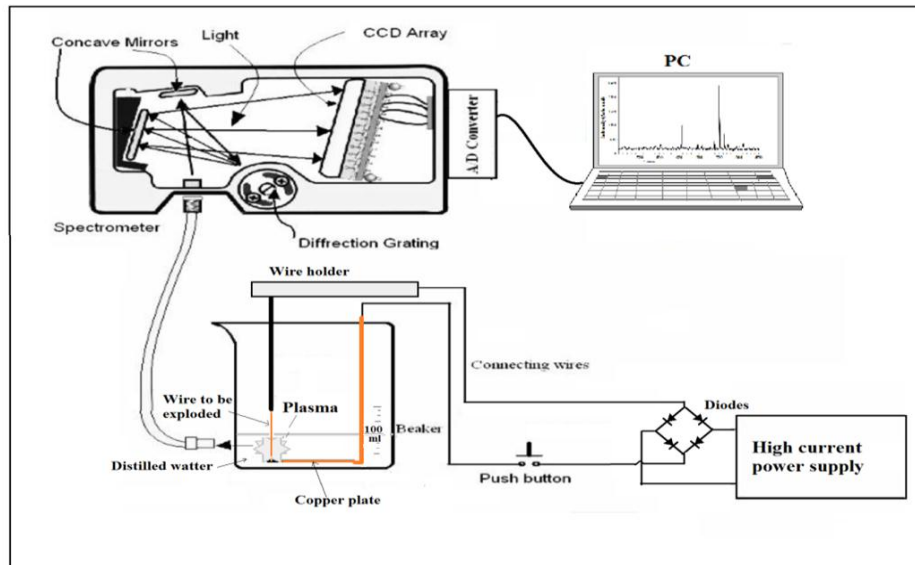
Fig. 1: Schematic diagram for the basic circuit used for exploding the copper wires and produce nanoparticles.

Results and discussion

Fig. 2 shows the optical emission spectrum (OES) emitted from the Plasma produced by exploding copper wire with different diameter (0.18, 0.24 and 0.3 mm) and current of 75 A. from the figure the peak located at 656 nm corresponding to H_α line for hydrogen atoms produced from water molecular dissociate. The small peak at 590 nm corresponding to sodium which comes from the impurity in the water. The others peaks belong to atomic copper peaks (Cu I) as the index to each of them, and some of ionic oxygen lines as shown in the inset figure. It can be noticed that the peaks intensities increase with decreasing of wire diameter, which corresponding to increase the current density passed into copper wire. This result is in agreement with reference [7].

The electron temperature (T_e) were calculated by Boltzmann plot using twelve of Cu I lines (at 406.16, 427.12, 450.93, 453.37, 458.66, 464.77, 510.15, 515.03, 520.52, 529.07, 578.31 and 569.97) nm for different wire diameter, as shown in Fig. 3. The T_e values were deduced from reveres of best fitting line for the relation between $Ln\left(\frac{I_{ji}\lambda_{ji}}{hc\, g_j A_{ji}}\right)$ versus upper energy level (E_j). The constants values for the copper emission lines taken from reference [9]. The equations of fitting lines and the R^2 were shown in the figure where R^2 is the statistical coefficient indicating the goodness of the linear fit.
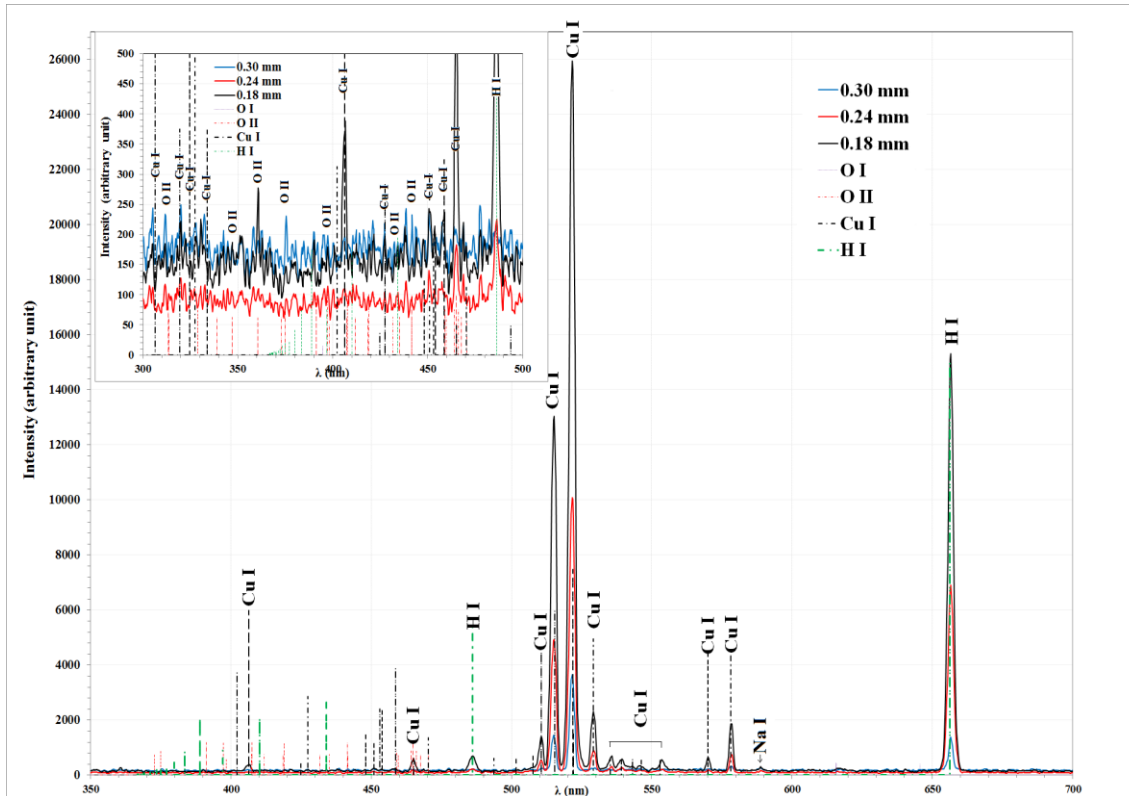
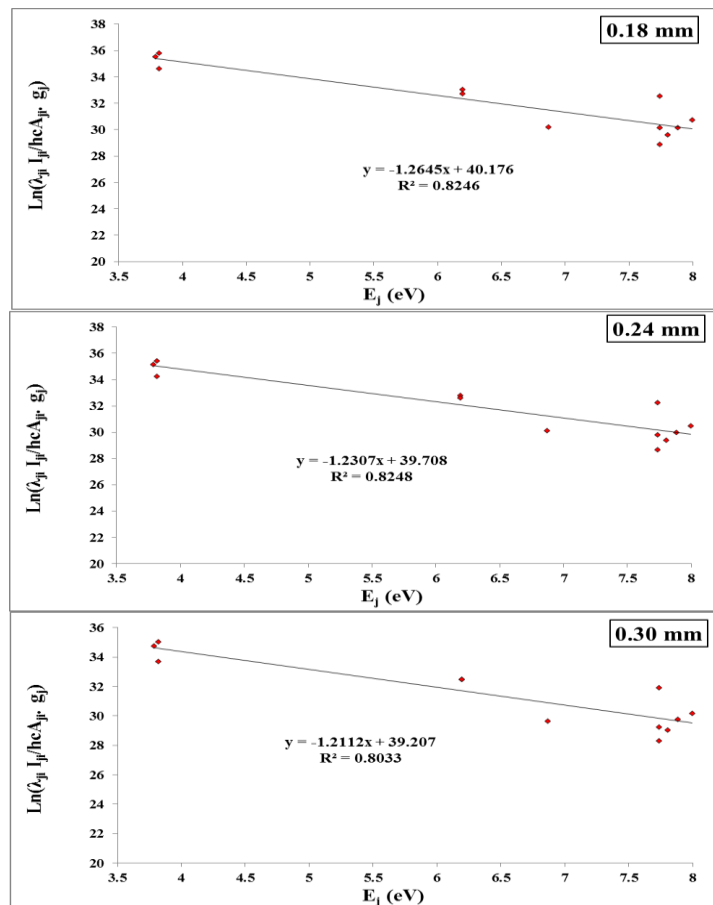*Fig. 2: Emission spectra for copper exploding wire.*

Fig. 3: Boltzmann plot from the Cu I lines produced by exploding wire with different diameters in distilled water and the current of 75 A.

Fig. 4 shows the 656.279 nm copper line peak profile. Where the full width at half maximum was found by Gaussian fitting. From the measured width which depending on Stark effect and the standard line width which equal to 0.901nm when $n_e=9\times10^{16}$ cm^{-3} [10] for this line, the electrons density were calculated by Eq. (3) for the different samples.
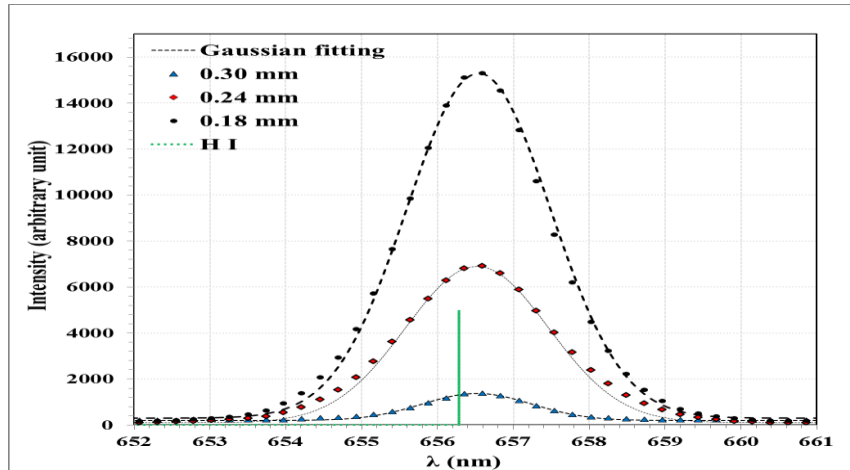

Fig. 4: Cu I 656.279 nm peaks broadening and there Gaussian fitting using different wire diameters.

Fig.5 shows the variation of electron temperature (T_e), calculated by Boltzmann plot, and electron density (n_e), using Stark broadening effect, with wire diameter. This figure shows that the n_e decrease from 22.4×10^{16} cm^{-3} to 17×10^{16} cm^{-3} with increasing wire diameter from 0.18 mm to 0.3 mm as a result of decreasing current density. This result is agree with reference [7]. The decrement in concentration cause decreasing in collision which caused to increase in electron temperature, where the electron temperature lose by different ways excitation and ionization collisions.
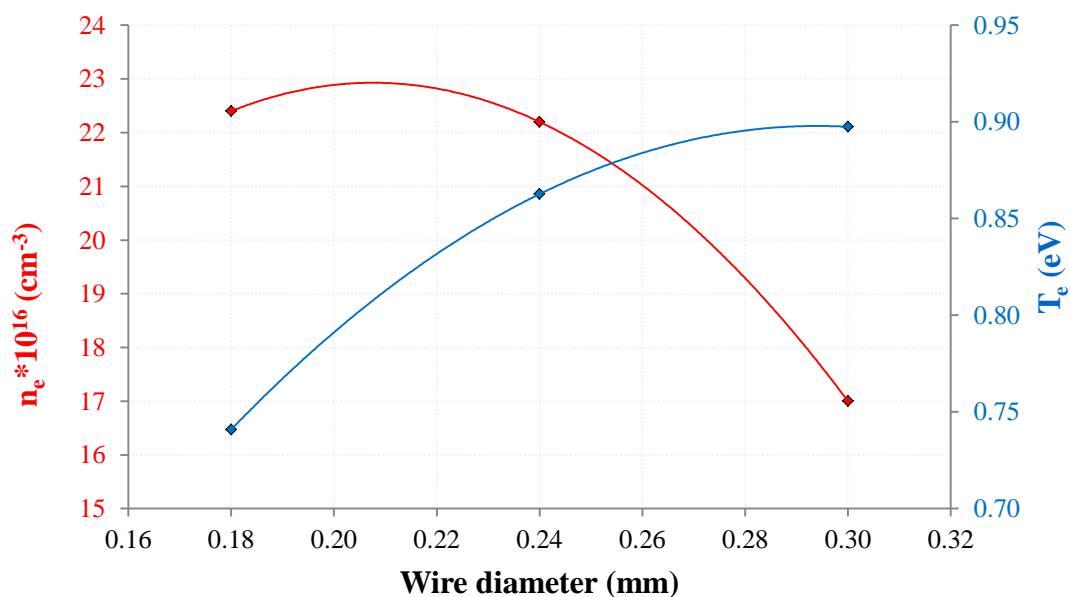

Fig. 5: Electron temperature T_e and electron density n_e for copper plasma produced by exploding wire for three different wire diameters.

Table 1 shows the calculated Debye length (λ_D) and plasma frequency (ω_p) for copper plasma produced by exploding wire for three different wire diameters at 75A dc current.

This table also shows a comparison between T_e, n_e and the copper nanoparticles concentration, where the copper nanoparticles concentration measured by atomic absorption spectrometer. It can be seen that the Cu nanoparticle concentrations decrease with increasing wire diameter and when compared with the intensity Fig. 2 of the copper emission lines, there is a clear correlation between the lines intensity and the copper nanoparticle concentration.it can be say that increasing wire diameter leads to decrease electron density cause to reduce the nanoparticles yield (The amount of material produced for a single pulse).

Table 1: Plasma parameters calculated from emission spectrum lines emitted from copper plasma produced by exploding wire with different wires diameters and produced nanoparticle per one pulse.

Wire diameter (mm)	T_e (eV)	FWHM (nm)	$n_{e*}10^{16}$ (cm^{-3})	ω_p *10^{12} (rad/s)	λ_D *10^{-6}(cm)	Yield (µg)
0.18	0.741	2.240	22.4	26.70	1.351	7.336
0.24	0.863	2.220	22.2	26.58	1.465	5.423
0.30	0.897	1.700	17.0	23.27	1.707	3.166

Conclusions

Study the optical emission spectroscopy from exploding copper wire in distilled water shows many points as follows:

- The electron density decrease from 22.4×10^{16} cm^{-3} to 17×10^{16} cm^{-3} with increasing wire diameter from 0.18 mm to 0.3 mm as a result of decreasing current density. While the electron temperature increase from 0.741 to 0.897 with it.

- There is a controlled relationship between the plasma parameters and the formed nanoparticles concentration and size. There is a high-intensity peak at 656 nm corresponding to H_α line which indicates the dissociation of water molecules by plasma effect this effect needs more attention.

References

[1] D. M. Devia, L. V Rodriguez-Restrepo, E. Restrepo-Parra, Eng. Sci., 11, 21 (2015) 239-267.
[2] M. Zhukov, Plasma Diagnostics, Ch. 5. UK: Cambridge International Science Publishing, 2005.
[3] S. S. Hamed, Egypt J. Solids, 28, 2 (2005) 349-357.
[4] N. M. Shaikh, S. Hafeez, B. Rashid, M. A. Baig, Eur. Phys. J. *D*, 44 (2007) 371-379.
[5] S. Eliezer, Plasma Phys. Control. Fusion, 45, 2 (2003) 181-181.
[6] M. G. Umran Inan, Principles of Plasma Physics for Engineers and Scientists, vol.1. New York: Cambridge University Press, 2011.
[7] P. Wankhede, P. K. Sharma, A. K. Jha, J. Eng. Res. Appl., 3, 6 (2013) 1664-1669.
[8] A. Alqudami and S. Annapoorni, J. Nanopart Res, 10 (2008) 1027-1036.
[9] J. E. Sansonetti and W. C. Martin, Am. Inst. Phys., 34 (2005) 1-6.
[10] A. Lesage, J. Phys. Chem., 31 (2002) 819-927.