Open Access
Volume 1 Issue 2
Research Article

Journal of Physics and Chemistry Research

PUBTEXTO

Spectroscopic Study of the Decomposition of a Chalcopyrite Molecule in an Overstressed Nanosecond Discharge on a Mixture of Nitrogen with $CuInSe_2$ Vapor Compound

Shuaibov AK*, Minya AY, Gomoki ZT, Hrytsak RV, Malinina AA and Malinin AN

Department of Quantum Electronics, Uzhhorod National University, Ukraine

Article Info

Article History:
Received: 05 September, 2019
Accepted: 16 September, 2019
Published: 19 September, 2019

***Corresponding author:** Shuaibov AK, Department of Quantum Electronics, Faculty of Physics, Uzhhorod National University, Narodna sq. 3, Uzhhorod, Ukraine; E-mail: alexsander.shuaibov@uzhnu.edu.ua

Abstract

The characteristics of an overstressed, high-current nanosecond discharge in a nitrogen atmosphere (p = 5.3-202 kPa) between chalcopyrite electrodes (CuInSe2) are presented. As a result of the ecton sputtering mechanism of massive semiconductor electrodes, chalcopyrite vapor enter the plasma and is partially destroyed as a result of interaction with the plasma electrons, and partially deposited on a solid substrate installed near the discharge gap. The main products of the destruction of the chalcopyrite molecule in the plasma are found in excited states of atoms and ions of copper and indium; spectral lines of copper and indium are proposed, promising for real-time monitoring of the deposition of thin films of chalcopyrite by the gas-discharge technique.

Thin films of chalcopyrite in an oxygen-free environment were obtained on glass and quartz substrates, which effectively absorb radiation incident on their surface in a wide spectral range of 200-800 nm, which opens up prospects for their use in devices, which work is associated with the photovoltaic effect.

Keywords: Chalcopyrite molecule; Overstressed nanosecond discharge; $CuInSe_2$ vapor compound; Nitrogen; Spectroscopic study; Deposition of thin films

Introduction

$CuIn(Sb)Se_2$ chalcopyrites are widely used in various photovoltaic devices, which is associated with a high absorption coefficient of radiation in a wide range of wavelengths (ultraviolet, visible and near infrared spectral ranges) [1,2]. But for the use of these materials in real devices it is important to obtain thin films of a corresponding stoichiometric composition of a large area with minimal technology costs [3]. Such small area films are obtained by sputtering a massive chalcopyrite target with pulsed lasers [4], but this is a very expensive technology due to the high cost of laser and vacuum technology. Therefore, other cheaper physical methods for the synthesis of thin chalcopyrite films can be promising, for example, when sputtering massive electrodes in a strong electric field of a high-current nanosecond discharge in air or other gases due to the formation of ectons [5] or sputtering electrodes with plasma ions. The results of the use of such an approach to the sputtering of transition metals in the form of a study of the characteristics of the discharge and the properties of the synthesized nanostructures of copper, zinc and iron oxides are given in [6-9] and summarized in the monograph [10]. The results of the study of the spatial, electrical, and optical characteristics of an overstressed nanosecond discharge in atmospheric air between chalcopyrite electrodes, as well as estimates of the density and temperature of electrons, showed that chalcopyrite films with an identical stoichiometric composition of the electrode material ($CuInSe_2$) could be obtained in this way [11-15].

Nanosecond and sub nanosecond discharges in which it is possible to obtain beams of "runaway electrons" and the accompanying X-ray radiation can be fairly uniform and suitable for deposition of thin films on different substrates. But their characteristics and plasma parameters are most studied when using only metal electrodes with a distance between them of 1-15cm [16-18]. Less studied are nanosecond discharges between electrodes from chalcopyrite-type semiconductor clusters under conditions of strong overstress of the discharge gap when the distance between the electrodes is d = 1-3 mm in electrode systems with moderate non-uniformity of the electric field strength when using an oxygen-free gaseous medium (He, Ne, Ar, N_2) in the pressure range 5-300 kPa. This paper presents the results of a spectroscopic study of the decomposition of a $CuInSe_2$ molecule in a strong electric field of a nanosecond discharge with injection of the chalcopyrite-based electrode vapor into nitrogen due to sputtering of the electrodes.

Methods, Techniques and Experimental Conditions

Chalcopyrite electrodes ($CuInSe_2$) were installed in a sealed Plexiglas discharge chamber (Figure 1). The distance between the electrodes was 1 mm. The discharge chamber was pumped out to a residual air pressure of 5-10 Pa and then filled with nitrogen to pressures in the range of 5.3-202 kPa. The diameter of the cylindrical semiconductor electrodes was 5 mm. The radius of rounding of the working end part of the electrodes was 3 mm. To ignite the discharge, bipolar high-voltage nanosecond pulses with amplitudes of positive and negative polarity in the range of 10-40 kV were applied to the electrodes. The pulse repetition rate of the

modulator was in the range of 40-1000 Hz. The main part of the experiments was carried out at a frequency f = 100 Hz. The voltage pulses at the discharge gap and the discharge current were measured using a wide-band capacitive divider, a Rogowski coil, and a 6-LOR-04 wide-band oscilloscope.

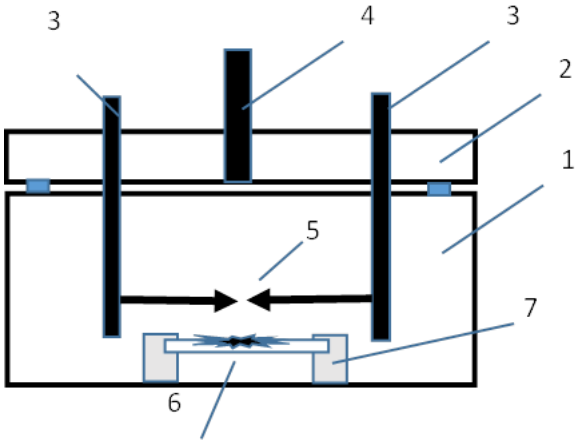

Figure 1: *Scheme of a discharge device for ignition of discharge and synthesis of thin films of chalcopyrite on the glass surface: 1 - gas-discharge chamber of plexiglass, 2 - upper flange, 3 - hermetic metal inputs, 4 - connection for connection to a vacuum gas mixing system, 5 - electrodes of chalcopyrite, 6 - glass substrate with a film on the basis of dispersed chalcopyrite electrodes, 7 - system of fastening of a plate.*

The time resolution of this registration system was 2-3 ns. To record the plasma emission spectra, an MDR-2 monochromator and an FEU-106 photomultiplier were used. The radiation of the discharge plasma was analyzed in the spectral range 200-650 nm. In more detail, the system for obtaining and studying the characteristics of the discharge is given in [10,15]. At the time of the existence of an overstressed nanosecond discharge in a pulsed-periodic regime (f = 40-200 Hz), for 2-3 hours on an insulating substrate mounted at a distance of 3 cm from the center of the discharge gap, the deposition of a gray-color film from the sputtering products of the electrodes material was recorded on the basis of the $CuInSe_2$ compound. The obtained samples of chalcopyrite based films were investigated for transmission in a wide range of radiation wavelengths using deuterium and heat lamps (200-850 nm). The study of the transmission spectra, deposited on quartz substrates, of chalcopyrite films was carried out using a spectral complex based on the MDR-23 monochromator at room temperature in accordance with the method described in [19].

In the electrode system "sphere-sphere" based on $CuInSe_2$ compound, at nitrogen pressures in the range of 5-200 kPa, the distance between the electrodes commensurate with the radius of curvature of the chalcopyrite electrodes, a high-current nanosecond discharge was sparked in the form of a sphere, which had a diffuse character, although it was initiated without using a separate preionization system. This is possible if the runaway electron beam, X-ray or ultraviolet radiation play the role of the pre-ionization system [17,18]. With a low nitrogen pressure (5.3 kPa), the generation threshold of runaway electrons in an overstressed nanosecond discharge plasma [20] is reached, and at atmospheric nitrogen pressures, preionization can occur from ultraviolet and X-ray radiation. The volume of the discharge is highly dependent on the repetition rate of the voltage pulses. The mode of operation of the plasma emitter in the form of a "point" lamp was achieved only at low repetition rates of the exciting pulses (f = 40-100 Hz). With increasing frequency from 40 to 1000 Hz, the volume of the emitting plasma increased from about 1 to 100 mm^3. A typical oscillogram of the voltage across the discharge gap and the electrical pulsed power of an overstressed nanosecond discharge at low and atmospheric pressure of nitrogen in the discharge chamber are shown in (Figures 2 and 3).

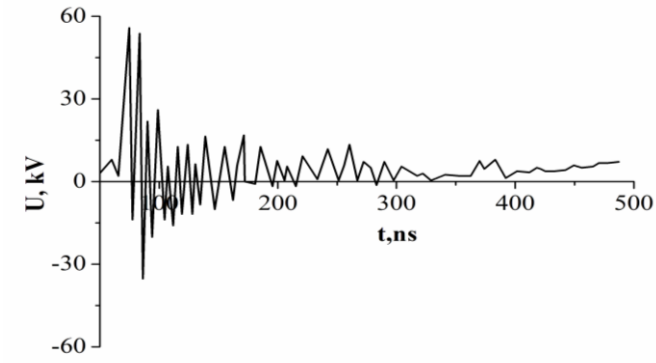

Figure 2: *Oscillogram of voltage between $CuInSe_2$ electrodes with nitrogen pressure 5.3 kPa (f = 100 Hz).*

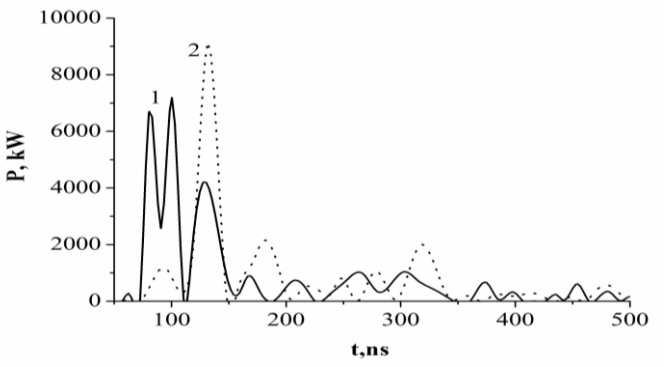

Figure 3: *The pulsed power of an overstressed nanosecond discharge at nitrogen pressures of 5.3 (1) and 202 (2) kPa (1).*

In the experiment, voltage oscillations were observed across the gap with a half-period of ~ 10 ns, which are caused by the mismatch of the output impedance of the high-voltage pulse

generator with the load. With a nitrogen pressure of 5.3 kPa, the maximum amplitude of voltage spikes reached 40-55 kV, and with increasing nitrogen pressure up to 101 kPa, the amplitude of voltage pulses of positive and negative polarity decreased to 40 kV. The current pulses had the form of current oscillations damping with time with the current spike amplitude of 130 -150 A. The main part of the electric power was introduced in the discharge in the first 100-200 ns. The maximum value of the pulsed electrical power introduced in the plasma reached ~ 7-9.3 MW. The maximum energy input was achieved at a nitrogen pressure of 202 kPa. In the time interval t = 200-400 ns, the discharge was maintained by pulsed power oscillations at a level of ~ 0.5-1.0 MW. The energy in the pulse that was introduced into the discharge was in the range of 350-375 mJ.

Such a behavior of the energy input, which is realized in the mode of mismatch of the output impedance of the generator of high voltage nanosecond voltage pulses with the resistance of the discharge plasma, contributes to the effective sputtering of the electrode material and its deposition on the glass substrate [21,22], as with low nitrogen pressure and high values of E/N (where: E is the electric field strength in the discharge gap, N is the density of the vapor-gas medium), when the ecton mechanism of electrodes' sputtering can be effectively implemented [5], and at atmospheric pressures of nitrogen, when it is possible to turn on the sputtering processes of the electrodes under the action of nitrogen ions [10,15].

Optical characteristics of plasma based on CuInSe2 compound

(Figures 4 and 5) present the plasma emission spectra of an overstressed nanosecond discharge between the electrodes from the $CuInSe_2$ compound at pressures of nitrogen of 5.3 and 101 kPa. (Tables 1) present the results of the interpretation of the most intense spectral lines of the bands in the plasma emission spectra shown in (Figures 4 and 5).

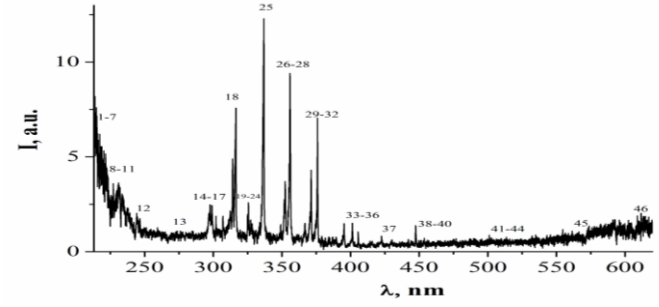

Figure 4: *The plasma emission spectrum of an overstressed nanosecond discharge at a nitrogen pressure of 5.3 kPa.*

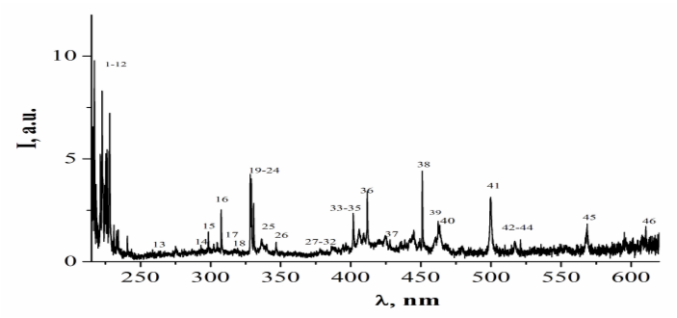

Figure 5: *The emission spectrum of an overstressed nanosecond discharge at p (N_2) = 101 kPa.*

With a low nitrogen pressure in the discharge chamber (p = 5.3 kPa), the emission spectrum of the discharge plasma in the wavelength range of 200-230 nm consisted of a group of closely spaced spectral lines of an atom and a single-charged copper ion, as well as low-intensity spectral lines of a single-charged indium ion (1-13; Table). The spectral lines of copper were approximately the same as for a plasma of an overstressed nanosecond discharge between copper electrodes at atmospheric pressure at an interelectrode distance of d = 2 mm [6,7]. When sputtering electrodes from a $CuInSe_2$ compound in atmospheric pressure air (d = 2 mm) in the same type of discharge, this group of spectral lines has not been previously studied [11,12,15].

The most intense group of spectral lines and bands was recorded in the spectral range of 290-410 nm (lines and bands 14-35; Table). Here the spectral lines of the copper atom (lines 16, 19-24, 26, 33) and the intense bands of the second positive system of the nitrogen molecule (bands 14, 18, 25, 27-32, 34, 35) were most characteristic. The presence of intense bands of the nitrogen molecule of the $C^3\Pi_u^+$-$B^3\Pi_g^+$ system and the spectral line of 427.99 nm Cu II indicates that, in addition to runaway electrons, the main body of the electron energy distribution function has electrons with energies of 9-18 eV, which are responsible for the emission of the nitrogen molecule in the spectral range 290- 410 nm.

The emission of atoms and singly charged indium ions in the visible region of the spectrum was represented by low-intensity spectral lines 410.17; 451.13 nm In I and 462.07; 609 nm In II. The characteristic spectral line of 500.52 nm N II, which is usually observed in the emission spectra of a nanosecond discharge in air [23-25], also appeared in the emission spectrum of overstressed nanosecond discharge plasma. In the yellow-red region of the spectrum, the radiation spectrum (Figure 4) shows the manifestation of a weak continuous spectrum in the form of a substrate for individual low-intensity spectral lines, which may be due to the emission of selenium molecules. With increasing nitrogen pressure from 5.3 to 101 kPa and, accordingly, reducing the value of the E/N parameter by about 20 times (from about 1.5 10^4 V/cm mm Hg), the emission spectrum of the plasma of an

overstressed nanosecond discharge changes dramatically (Figure 5). This may be due to a decrease in the efficiency of the ecton sputtering mechanism of chalcopyrite electrodes in a weaker electric field and the activation of the sputtering mechanism of the electrodes under the impact of positive nitrogen ions (N^+, N_2^+), which in excited states appear in the emission spectrum (Figure 5). In this case, the threshold for electron runaway is not reached in the discharge [20], the EEDF changes, and energy transfer processes from nitrogen molecules and nitrogen atoms in metastable states to chalcopyrite molecules or plasma destruction products in plasma become probable.

The main features of the plasma emission spectrum based on the nitrogen-$CuInSe_2$ vapor-gas mixture at p (N_2) = 101 kPa are associated with a significant increase in the intensity of the group of spectral lines Cu I, Cu II, In II in the wavelength range 200-250 nm, and also a decrease in their number. The intensity of the emission bands of the nitrogen molecule, at the same time, has sharply decreased. Instead of the bands of the nitrogen molecule in the spectral range of 290 - 460 nm, some intense spectral lines Cu I, In I, In II were recorded in the emission spectrum (lines 15-39; Table 1).

Table 1: *The results of the identification of the most intense spectral lines of the products of the destruction of chalcopyrite in an overstressed nanosecond discharge (p(N2) = 5,3; 101 kPa).*

№	λ,nm	I, a.u. (at (N_2) = 5.3 kPa)	I, a.u. (at p(N_2) = 101 kPa)	Object	E_i, eV	E_k, eV	Lower State	Upper State
1	216.50	4.42	9.8	Cu I	0.00	5.72	$4s\ ^2S$	$4p'\ ^2D^o$
2	218.172	5.13	3.76	Cu I	0.00	5.68	$4s\ ^2S$	$4p'\ ^2P^o$
3	220.97	4.12	2.25	Cu II	8.78	14.39	$4p\ ^3D^o$	$4d\ ^3D$
4	221.45	5.16	5.14	Cu I	1.39	6.98	$4s^2\ ^2D$	$4p''\ ^2P^o$
5	222.56	4.35	8.31	Cu I	0.00	5.57	$4s\ ^2S$	$4p'\ ^4D^o$
6	224.26	2.94	3.72	Cu II	3.26	8.78	$4s\ ^1D$	$4p\ ^3D^o$
7	224.70	2.10	5.26	Cu II	2.72	8.23	$4s\ ^3D$	$4p\ ^3P^o$
8	226.37	2.52	5.45	Cu II	8.92	14.39	$4p\ ^1F^o$	$4d\ ^3D$
9	227.62	2.64	5.37	Cu II	2.98	8.42	$4s\ ^3D$	$4p\ ^3P^o$
10	231.32	3.63	1.78	In II	12.10	17.46	$5s5d\ ^1D$	$5s9p\ ^1P^o$
11	233.45	2.87	1.50	In II	12.68	17.99	$5s5d\ ^3D$	$5s8f\ ^3F^o$
12	240.66	1.77	1.25	Cu I	1.64	6.79	$4s^2\ ^2D$	$6p\ ^2P^o$
13	274.97	0.90	0.65	In II	12.10	16.61	$5s5d\ ^1D$	$5s5f\ ^1F^o$
14	297.68	2.47	0.62	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (2;0)			
15	298.63	2.43	1.45	Cu II	14.20	18.35	$4d\ ^3S$	$5f\ ^1D^0$
16	307.379	3.98	2.53	Cu I	1.39	5.42	$4s^2\ ^2D$	$4p'\ ^2F^o$
17	314.27	4.9	0.52	In II	12.66	16.60	$5s5d\ ^3D$	$5s9f\ ^3F^0$
18	315.93	7.6	0.46	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (1;0)			
19	324.75	1.97	0.50	Cu I	0	3.82	$4s\ ^2S$	$4p\ ^2P^o$
20	327.39	1.68	0.50	Cu I	0	3.39	$4s\ ^2S$	$4p\ ^2P^o$
21	328.27	1.48	4.26	Cu I	5.15	8.93	$4p'\ ^4F^o$	$4d'\ ^2G$
22	329.05	1.13	4.04	Cu I	5.07	8.84	$4p'\ ^4F^o$	$4d'\ ^4F$
23	330.79	1.02	2.84	Cu I	5.07	8.82	$4p'\ ^4F^o$	$4d'\ ^4G$
24	333.78	1.55	0.66	Cu I	1.39	5.10	$4s^2\ ^2D$	$4p'\ ^4F^o$
25	337.13	12.3	0.85	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (0;0)			
26	348.37	1.29	0.41	Cu I	5.51	9.06	$4p'\ ^4D^0$	$4d'\ ^4G$
27	350.05	2.63	0.45	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (2;3)			
28	357.69	9.41	0.36	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (0;1)			
29	367.19	1.50	0.33	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (3;5)			
30	371.05	4.30	0.40	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (2;4)			
31	375.54	7.05	0.53	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (1;3)			
32	394.30	1.45	0.82	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (2;5)			
33	402.26	1.50	2.36	Cu I	3.79	6.87	$4p\ ^2P^0$	$5d\ ^2D$
34	405.94	1.04	1.6	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (0;3)			
35	409.48	0.45	1.4	N_2	Second positive system $C^3\Pi_u^+$-$B^3\Pi_g^+$ (4;8)			
36	410.17	0.36	3.42	In I	-	3.02	$5s^25p\ ^2P^o$	$5s^26s\ ^2S_{1/2}$

37	427.99	0.4	1.07	Cu II	15.07	17.96	$5p\ ^3D^o$	$7s\ ^3D$
38	451.13	0.6	4.41	In I	0.27	3.02	$5s^25p\ ^2P^o$	$5s^26s\ ^2S_{1\backslash 2}$
39	459.97	0.54	1.13	N_2^+	$^2\Sigma \rightarrow ^2\Sigma$ (2;4)			
40	462.07	0.4	1.97	In II	15.33	18.01	$5s4f\ ^3F^o$	$5s_{1/2F=4}\ 8g$
41	500.515	0.52	3.08	N II	25.50	27.97	$3s\ ^5P$	$3p\ ^5P^0$
42	510.55	0.45	0.82	Cu I	1.39	3.82	$4s^2\ ^2D$	$4p\ ^2P^o$
43	515.83	0.50	0.94	Cu I	5.69	8.09	$4p'\ ^2P^o$	$5s'\ ^2D$
44	521.82	0.58	1.07	Cu I	3.82	6.19	$4p\ ^2P^o$	$4d\ ^2D$
45	570.02	0.58	1.27	Cu I	1.64	3.82	$4s^2\ ^2D$	$4p\ ^2P^o$
46	609.59	1.52	1.33	In II	13.44	15.47	$5s6p\ ^3P^o$	$5s6d\ ^3D$

The radiation in the spectral range of 550-630 nm had the form of molecular bands, against the background of which individual low-intensity spectral lines of atoms or ions were also recorded. Probably, this part of the emission spectrum of the discharge is due to the emission of selenium molecules. Accurate identification of this part of the spectrum requires the use of a spectrophotometer with a higher spectral resolution. In order to diagnose the deposition of chalcopyrite films on solid substartes from glass or quartz in real time, it is possible to use intense spectral lines of copper and indium atoms in the spectral range 300-460 nm: 307.38 nm CuI, 329.05 nm Cu I, 410.17 nm In I and 451.13 nm In I (Table 1).

Transmission radiation spectra of chalcopyrite films

In the spectral range of 200-300 nm, the radiation absorption coefficient for films based on the $CuInSe_2$ compound decreases from $6x10^5$ to $4x10^5$ cm^{-1}, and in the range of 300-400 nm, the absorption coefficient was approximately constant and was equal to $4x10^5$ cm^{-1} [1-3]. With an increase in the wavelength from 400 to 1000 nm, it decreased to 10^4 cm^{-1}, and in the wavelength range of 1000-1200 nm, the absorption coefficient exponentially decreased to 10 cm^{-1}. As can be seen from these results, the absorption coefficients of chalcopyrite films are large and strongly depend on the wavelength of the incident radiation.

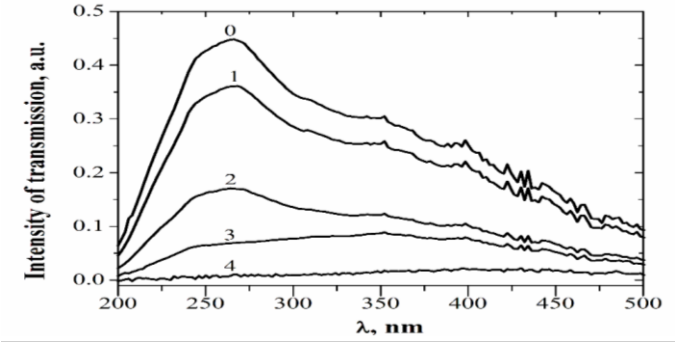

Figure 6: *Transmission spectra of chalcopyrite films deposited on quartz substrates depending on the pressure and type of the gaseous medium when probing films by radiation from a deuterium lamp: 0 - without sample; 1 - pure quartz glass; 2 - electrodes with $CuInSe_2$ with p (N_2) = 13.3 kPa; 3 - $CuInSe_2$ with p (N_2) = 101 kPa; 4 - electrodes with $CuInSe_2$ at air pressure 101 kPa.*

Consider the relative transmission spectra of thin chalcopyrite films synthesized using a nanosecond discharge under study in nitrogen and air. The characteristic transmission spectra of radiation of thin films based on the $CuInSe_2$ compound in the spectral region of 200-800 nm at different pressures of nitrogen and atmospheric air pressure are shown in (Figures 6 and 7).

The transmission of chalcopyrite films, as compared with the substrate transmission, decreased by approximately 2-2.5 times and for the film synthesized using a discharge in nitrogen was minimal at p (N_2) = 101 kPa. The transmission spectra of the chalcopyrite films at nitrogen pressures of 13.3 and 101 kPa were close. A decrease in the transmission of the film synthesized at p (N_2) = 101 kPa compared with the transmission of the film synthesized at p (N_2) = 5.5 kPa can be due to the lower thickness of the film synthesized at low nitrogen pressure. The minimum transmission of chalcopyrite films, which was about an order of magnitude smaller than the transmission of a clean substrate, was obtained for samples synthesized in air at atmospheric pressure. The presence of oxygen in such a plasma can lead to the implantation of it in the film, which can affect its photovoltaic characteristics. If, in this case, the coefficients of the conversion of radiation energy into electrical energy are sufficiently large, this opens up prospects for creating an open plasma-chemical reactor based on atmospheric air, in which deposition of chalcopyrite films of a large area is possible. An additional advantage of such a reactor will be the complete absence of vacuum technology and the use of the maximum available gas medium. The strong absorption of deuterium lamp radiation by chalcopyrite films in the wavelength range (200-500 nm) is due to the fact that when sputtering chalcopyrite films by the discharge method using electrodes based on the $CuInSe_2$ compound, they repeat the stoichometry of the electrodes. This is important for the use of the films obtained in photovoltaic devices. To accurately determine the composition of the synthesized chalcopyrite films, it is necessary to carry out their study by X-ray diffraction and electron spectroscopy.

When replacing a deuterium lamp with a heat one, the transmission spectra of the same chalcopyrite films were studied in the spectral range of 400-800 nm (Figure 7). In this case, the main features of the transmission spectra of chalcopyrite films at different nitrogen pressures and air pressures were correlated with the results

presented in (Figure 6).

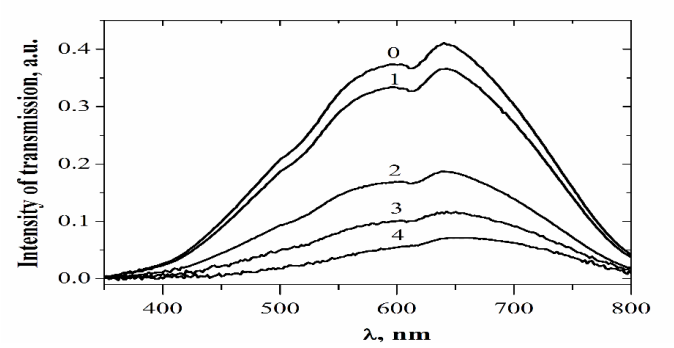

Figure 7: *Transmission spectra of chalcopyrite films deposited on quartz substrates depending on the pressure and type of the gaseous medium when probing films by radiation from a heat lamp: 0 - without reflection; 1 - pure quartz glass; 2 - electrodes from $CuInSe_2$ with a pressure of N_2 13.3 kPa; 3 - electrodes from $CuInSe_2$ with a pressure of N_2 101 kPa; 4 - electrodes from CuInSe2 with an air pressure 101 kPa.*

Comparison of the transmission spectra with regard to the probing radiation spectra and the transmission spectrum of the substrate with the dependence of the absorption coefficient on the wavelength are qualitatively correlated with each other, which indicates that the composition of the films is close to the composition of the electrodes and there are certain prospects for using the gas-discharge method of synthesizing thin films for chalcopyrite photovoltaic devices.

Conclusion

Thus, it was shown that at a pressure of nitrogen in the range of 5.3 - 202 kPa between the electrodes from the $CuInSe_2$ compound with a distance between them of 1 mm, a sufficiently uniform nanosecond discharge is ignited with a pulsed electrical power of 7-9.3 MW and the energy input to the plasma in one pulse 0.35-0.44 J. The study of the spectral characteristics of chalcopyrite plasma showed that the most intense are the spectral lines of the copper atom in the range 200-230 nm and the spectral lines of the indium atom and copper ions and indium ions in the longer wavelength region of the spectrum; at the same time, as the nitrogen pressure increased, the intensities of the copper atom lines in the spectral range 200-230 nm and the intensities of the ion lines in the spectral range 230-460 nm increased. The nature of the emission spectrum suggests the existence of selective mechanisms for the formation of excited atoms and ions of copper and indium in the plasma, associated with the transfer of energy from metastable atoms and argon molecules. Based on the measured relative intensities of the spectral lines of atoms and copper and indium ions, it is possible to make estimates of the temperature and density of electrons in the plasma under study. To diagnose the deposition of chalcopyrite films in real time, the following most intense and separately located in the spectral range 300-460 nm lines can be used: 307.38 nm CuI, 329.05 nm CuI, 410.17 nm In I, 451.13 nm In I. The study of the relative transmission spectra of probe radiation in the 200-800 nm wavelength range of chalcopyrite films synthesized by the pulsed gas-discharge method in nitrogen and air showed that the lowest transmission is characteristic for films synthesized at atmospheric pressure of nitrogen and air, which is important for their use in photovoltaic devices.

References

1. Vertsimakha YA, Lutsuk P, Lytvyn O, Gashin P. Features of fotovoltaic and optical properties of $CuInSe_2$ films prepared by flash evaportation. Ukr J Phys. 2007; 52: 399-405.
2. Novikov GF, Gapanovich MV. Third generation Cu-In-Ga-(S,-Se) based solar inverters. Phys Usp. 2017; 60: 161-178.
3. Milichko VA, Shalin AS, Mukhin IS, Kovrov AE, Krasilin AA, Vinogradov AV, et al. Solar photovoltaics: current state and trends. Phys Usp. 2016; 59: 727-772.
4. Chuchman MP, Laslov GE, Shuaibov AK. Radiation Dynamics of Low-Energy Laser Plasma of $CuSbSe_2$ Polycrstalline. High Temperature. 2014; 52: 497-500.
5. Mesyats GA. Ecton - Electron Avalanche from metal. Phys Usp. 1995; 165: 601-626.
6. Shuaibov AK, Minya AY, Malinina AA, Malinin AN, Danilo VV, Sichka M Yu, et al. Synthesis of Copper Oxides Nanostructures by an Overstressed Nanosecond Discharge in Atmospheric Pressure Air Between Copper Electrodes. Am J Mech Materials Eng. 2018; 2: 8-14.
7. Shuaibov AK, Minya AY, Gomoki ZT, Danilo VV, Pinzenik RB. Charachterristics of a High-Current Pulse Discharge in Air wich Ectonic Mechanism of Copper Vapor Injection into a Disharge Gapr. Surface Eng Applied Electrochem. 2019; 55: 65-69.
8. Shuaibov OK, Minya AY, Chuchman MP, Malinina AO, Malinin OM, Danilo VV, et al. Parameters of Nanosecond Overvoltage Discharge Plasma in a Narrow Air Gap between the Electrodes Containing Electrode Material Vapor. Ukr J Phys. 2018; 63: 790-801.
9. Minya AY, Shuaibov OK, Gomoki ZT, Danilo VV, Chavarga MM, Kukri LE. Optical characteristics of a nanosecond discharge on an air zinc vapor mixture. Scientific Herald of Uzhhorod University. Physics. 2016. 39: 93-99.
10. Shuaibov OK, Malinina AO, Malinin OM. New gas-discharge methods for obtaining selective ultraviolet and visible radiation and the synthesis of nanostructures of transition metal oxides. Monograph.Uzhhorod. Publishing house of UzhNU Hoverla: 2019; 188.
11. Shuaibov AK, Laslov GE, Minya AI, Gomoki ZT. Charachteristics and Parameters of Nanosecond Air Discharge Plasma between Chalcopyrite Electrodes. Technical Physics Letters. 2014; 40: 943-945.
12. Laslov, Shuaibov G, Szegeli A, Sandorm, Laszlo, Elemer. Spectroscopic Diagnostics of Sparc Discharge Plasma at Atmocpheric Pressure. J Chem Eng. 2014; 8: 302-305.
13. Laslov GE, Chuchman MP, Kozak YA, Yu Shuaibov OK. Optical characteristics of a spark discharge with composite and metal electrodes, Scientific Herald of Uzhhorod University. Physics. 2014; 35: 143-145.

14. Laslov GE, Chuchman MP, Shuaibov AK. Characteristics and parameters of nanosecond discharge with composite electrodes. Optics and Spectroscopy. 2015; 118: 199-201.
15. Shuaibov AK, Minya AY, Chuchman MP. Malinina AA, Malinin AN, Gomoki ZT, et al. Optical Charachteristics of overstressed nanosecond discharge in atmospheric pressure air between Chalcopyrite electrodes. Plasma Research Express. 2018; 1.
16. Baksht EH, Tarasenko VF, Shutko Yu V, Erofeev MV. A point source of UV radiation with a frequency of 1 kHz and a short pulse duration. Russian Phys J. 2011; 11: 91-94.
17. Avtaeva SV, Zhdanov OS, Pikulev AA, Sosnin EA, Tarasenko VF. New directions in research and applications of excilamps. Monograph. Tomsk. STT. 2013; 240.
18. Baksht E Kh, Tarasenko VF, Shut'ko Yu V. Erifeev MV. Point-like pulse-periodic UV radiation sourse wich a short duration. Quantum Electronics. 2012; 42: 153-156.
19. Holovey VM, Popovych KP, Prymak MV, Birov MM, Krasilinets VM. Sidey VI. X-ray induced optical absorption in $Li_2B_4O_7$ and $Li_2B_4O_7$: Cu single crystals and glasses. Physica B. 2014; 450: 34-38.
20. Kozhevnikov V Yu, Kozyrev AV, Dmitrieva NM. Theoretical 0 - D modeling of subnanosecond high-pressure gas discharge. IZVESTIYA VYSSHIKH UCHEBNYKH ZAVEDENII FIZIKA. Russian Physics Journal. 2014; 57: 130-133.
21. Lomaev MI, Beloplotov DV, Sorokin DA, Tarasenko VF. Spectral and amplitude - time characteristics of radiation of plasma of a repetitivevely pulsed discharge initiated by runaway electrons. Optics and Spectroscopy. 2016; 120: 171-175.
22. Beloplotov DV, Trigub MV, Tarasenko VF, Evtushenko GS, Lomaev MI. Laser monitor visualization of gas-dynamic processes under pulse-periodic discharge initiated by runaway electrons in atmospheric pressure air. Atmospheric and Oceanic Optics. 2016; 29: 371-375.
23. Pai David Z, Lacoste DA, Laux CO. Nanosecond repetitively pulsed discharges in air at atmospheric pressure - the spark regime. Plasma Sources Sci Technol. 2010; 19.
24. Van der Horst RM, Verreycken T, van Veldhuizen EM, Bruggerman PJ. Yime-resolved optical emission spectroscopy of nanosecond pulsed discharges in atmospheric-pressure N_2 and N_2/H_2O mixtures. J Phys D Appl Phys. 2012; 45.
25. Palomares JM, Kohut A, Galbacs G, Engeln R, Geretovszky Zs. A time - resolved imaging and electrical study on a high current atmospheric pressure spark discharge. Journal of Applied Physics. 2015; 118.