7th International Congress on Energy Fluxes and Radiation Effects (EFRE) - 19th International Conference on Radiation Physics and Chemistry of Condensed Matter - Tomsk - 2020

Deposition of Optically Transparent Copper Films on Dielectric Substrates Using the Plasma Focus Installation

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***Abstract*—Thin optically transparent homogeneous copper films on silicate glass substrates (size ~ 35×35 mm) were obtained at the Plasma focus facility (PF-4, LPI). The films were obtained by deposition from "metal plasma" formed during ablation of the copper anode of the PF installation. The films were deposited in the atmosphere of the plasma-forming gas argon at a pressure of ~ 1 Torr. The film uniformity was controlled by measuring the transmission spectrum in the middle and at the edge of the glass plate and was ~ 10%. Transmission spectra of films on glass substrates were measured in the range of 0.3-1.0 μ at temperature 300K. The transmission spectrum of Cu films is mainly determined by light scattering on small particles < 0.3 μ. Good adhesion of films is due to the formation of a transition layer on the surface of glass plates. Depending on the number of plasma pulses optical copper films were obtained as dielectric and also electrically conductive.**

Keywords—plasma focus, "metal" plasma, copper films, transmission spectrum, adhesion.

I. INTRODUCTION

Plasma focus (PF) installations were developed to produce pulsed high-temperature plasma for nuclear fusion [1, 2]. During the formation of a plasma pulse, the installation's anode is subjected to an intense electron and plasma beam [3–5]. During ablation, metal vapors are ejected from the anode, which contain multicharged ions and neutral atoms. This state of metal vapor is called "metal" plasma. At present, the method of intensive sputtering of inserts in the anode from various materials is used to obtain protective coatings on metal surfaces and magnetic nanofilms [6–8]. For the deposition of metal nanofilms, the method of spraying powders in plasma obtained in PF installations is also used [9]. At the same time, for optoelectronics, and also for the production of various elements of optics, it is of interest to obtain optically transparent metal films on dielectric substrates. Earlier in [10–12], optically transparent films of copper (Cu,) titanium (Ti) and carbon (C) were obtained on glass and sapphire substrates. However, the size of the deposition region of homogeneous optical films was small (not more than 1 cm) and, moreover, the films were inhomogeneous in thickness and in the plane of the substrate. The aim of this work was to obtain uniform optically transparent copper films on silicate glass substrates using ablation of the copper anode at the Plasma focus facility.

The work was supported by the Russian Science Foundation (grant No.16-12-10351). The authors express their gratitude to Ph.D. L. I. Kobeleva for measuring particle sizes in copper films and discussing the results.

II. EXPERIMENTAL SETUP

Optically transparent Cu films were sprayed on the Plasma focus facility (PF-4, LPI, Russia) with the Mather geometry of the electrodes [13]. The stored energy in capacitor banks with a capacity of 48 μF at a voltage of 12–14 kV was 3.5–4 kJ. The duration of the plasma pulse was ~ 100 ns. The plasma-forming gas was argon at a pressure of ~ 1–2 Torr in the working chamber.

The deposition of Cu films on glass substrates was performed similarly to [14], installing a protective Cu screen on the path of motion of a copper plasma jet. The screen size of ~ 35 mm × 35 mm protected the substrate from large Cu drops and ion beam effects. Fig. 1 shows the scheme of the experiment on deposition of optically transparent Cu films on glass substrates.

Glass substrates size 35×35 mm were made from photographic plates 1.5 mm thick. The substrates were washed with water and cleaned of fat with ethyl alcohol. The substrates were installed on the sample holder and the protective screen (Fig. 1). By changing the distance X from the screen to the anode and X_1 – the distance between the sample holder and the screen, Cu was uniformly deposited on the substrates. In our case, the optimal distances were X = 150 mm, X_1 = 15–20 mm.

Optical transmission spectra of Cu films on glass substrates in the range of λ = 0.35–1.0 μm were measured using a SF-46 spectrophotometer at temperature 300K. Particle sizes in the deposited Cu films were determined using a Leica DM ILM (Germany) microscope. The minimum particle size determined on the microscope was ~ 0.3 μm.

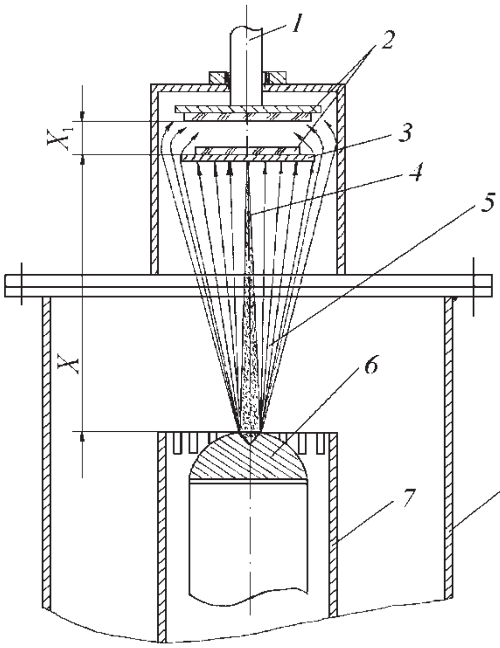


Fig. 1. Scheme of experiment on deposition of thin optically transparent Cu films on glass substrates: *1*-sample holder rod; *2*-glass substrates; *3* – metal screen (Cu); *4* – ion beam; *5* – plasma jet; *6* – copper anode; *7* – copper cathode; *8* – working chamber of the installation.

III. Experiment Results and Discussion

Direct deposition of copper films from "metal" plasma on glass substrates leads to mechanical destruction and uneven distribution of metal on the substrate. Due to different coefficients of linear expansion of the glass and copper film, it is separated from the substrate and destroyed (Fig. 2).

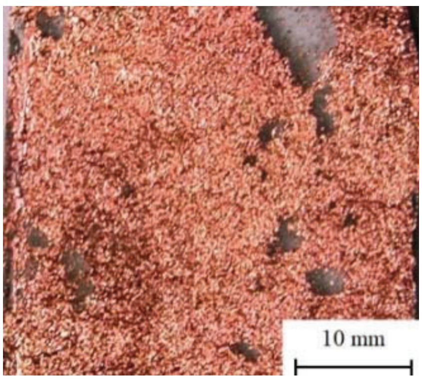
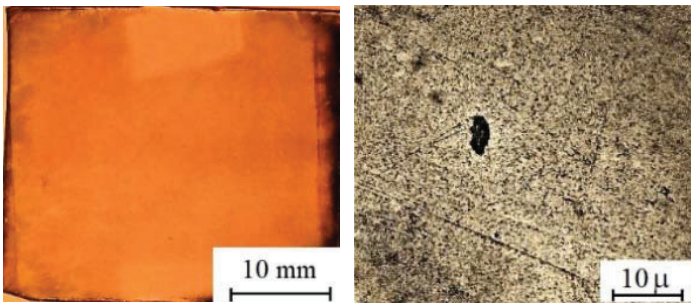


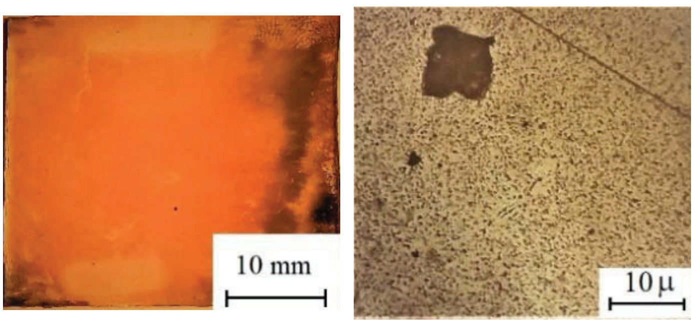
Fig. 2. A silicate glass plate with a Cu-deposited film under irradiation with 30 plasma pulses. The distance from the substrate to the installation anode is 170 mm. Feature 20-150 rel. units*).

Figs. 3–4. show glass substrates with deposited Cu films. As you can see, the deposited Cu films on glass substrates are obtained fairly uniform. However, Cu films are not continuous and represent a set of particles (Fig. 3b, 4b). In general, Cu particles are arranged on the substrate surface in a stochastic manner. However, in some places on the surface, you can see ring-shaped structures, the size of which can be large. The nature of these structures is currently unclear. No fractal structures are observed in the films. Fig. 5 shows histograms of the Cu particle size distribution in volume 1 (closer to the edge of the substrate) and in volume 2 (closer to the center of the substrate) for the sample (Fig. 3b). As you can see, the particle size ranges from units of microns to tenths of a fraction or less (Fig. 5). A similar distribution of particles in size is observed for the substrate Fig. 4b. When irradiating glass substrates with a small number of plasma pulses ~ 10–15, Cu films were dielectric. With an increase in the number of plasma pulses to ~ 20–30 or more, the films were electrically conductive. The adhesion of Cu films was determined by mechanical abrasion. The adhesion of Cu films to the glass surface was quite high, which is explained by the penetration of small Cu particles under the glass surface to a depth of tens of nanometers and the fusion of hot metal particles into the glass [11, 15]. It should be noted that after deposition of Cu films on the surface there is a fine dust containing components of silicate glass-Na, K, Mg, Si, etc. [15, 16].



(a) (b)

Fig. 3. Glass substrate with deposited Cu film (a) and film structure (b). The substrate was placed on the sample holder behind a metal screen (Fig. 1). The number of pulses of the plasma is n = 30. The amplitude of the feature is 10–110 rel. units.



(a) (b)

Fig. 4. Glass substrate with deposited Cu film (a) and film structure (b). The substrate was placed on a metal screen 3 (Fig. 1). The number of plasma pulses n = 24. The amplitude of the feature is 10–120 rel. units.

*) A feature is a short jump on the derivative of the current that occurs at the time of maximum compression of the plasma shell on the axis OZ of the installation. The amplitude of this feature characterizes the energy of the plasma pulse in relative units.

When measuring the transmission spectra of Cu films, this fine dust was removed with a wet cotton swab. In addition, elements such as Al, Fe, C [16] can fall on the films from the anode node. It is noted that when the substrates are stored in the air (for a month or more), the Cu films are oxidized, which leads to a decrease in the transmittance. Fig. 6 shows the transmission spectra of recently sprayed Cu films for the sample (Fig. 3a) at two points - in the center and at the edge of the spray area. The heterogeneity of the films is ~ 10%. The transmission spectra show a broad maximum in the wavelength range 450–750 nm, which is characteristic of Cu and its oxides CuO and CuO_2 [17, 18]. The presence of a wide maximum on the transmission spectra of films is associated with a significant effect of light scattering on small particles [19]. These considerations are consistent with particle size statistics (Fig. 5) and photos of Figs. 3b, 4b, where it is seen that the films consist of many small droplets.

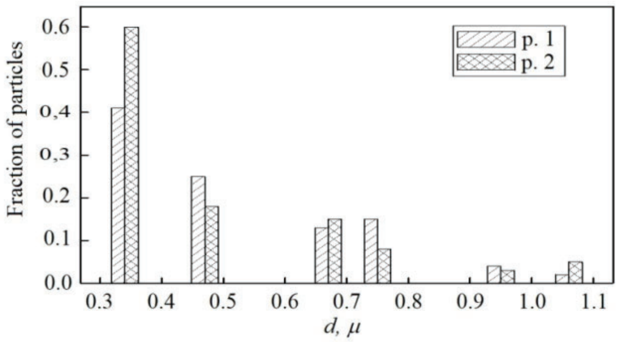


Fig. 5. Histograms of the size distribution of Cu particles (Fig. 3b): p.1 – at the edge of the substrate; p. 2 – closer to the center of the substrate.

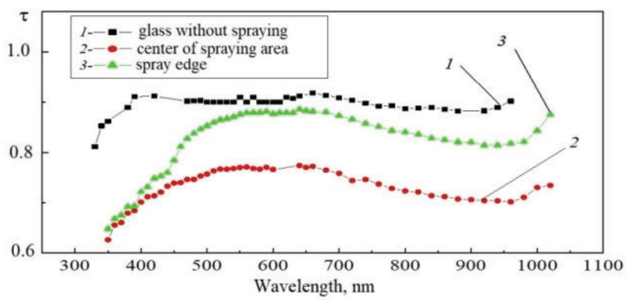


Fig. 6. Transmission spectrum of copper films on a glass substrate at two points: 1 – clear glass; 2 – closer to the center; 3 – closer to the edge of the deposition area (Fig. 3 a).

IV. CONCLUSION

Optically transparent thin homogeneous (~ 10%) copper films on silicate glasses with a size of ~ 3.5×3.5 cm^2 were obtained. Depending on the energy of the plasma jet and the number of plasma pulses, both dielectric and electrically conducting films can be deposited at the Plasma focus installation. Copper films have good adhesion to the glass substrate. During prolonged storage in air, the films oxidize, which requires the application of protective coatings.

ACKNOWLEDGMENT

The work was supported by the Russian Science Foundation (grant No.16-12-10351).

The authors express their gratitude to Ph.D. L.I. Kobeleva for measuring particle sizes in copper films and discussing the results.

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