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Technology of manufacturing thin-film aluminum nanostructures by dry aerosol printing

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Abstract. The article under discussion is about technology of creating film structures from aluminum nanoparticles synthesized in spark discharge that can be used for plasmon amplification of the electromagnetic field in the ultraviolet range. Nanostructures of various patterns were applied by dry aerosol printing on a substrate of polished quartz glass. The dependences of the line width on the printing parameters such as focus, speed of sample movement and gas flow were studied. The optimal printing parameters were defined to produce thin-films with different patterns: grids, arrays of lines and uniform distribution of nanoparticles over the surface (films).

Keywords: nanoparticles, aluminum, plasmonic nanostructures, dry aerosol printing

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Технология изготовления тонкопленочных алюминиевых наноструктур методом сухой аэрозольной печати

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Аннотация. Обсуждаемая статья посвящена технологии создания пленочных структур из наночастиц алюминия, синтезированных в искровом разряде, которые могут быть использованы для плазмонного усиления электромагнитного поля в ультрафиолетовом диапазоне. Наноструктуры различных рисунков наносились методом сухой аэрозольной печати на подложку из полированного кварцевого стекла. Были исследованы зависимости ширины линии от параметров печати, таких как фокусное расстояние,

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скорость перемещения подложки и расход газа. Были определены оптимальные параметры печати для получения пленок с различными рисунками: сетками, линиями и равномерным распределением наночастиц по поверхности.

Ключевые слова: наночастицы, алюминий, плазмонные наноструктуры, сухая аэрозольная печать

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Introduction

Recently, the efforts of researchers have focused on obtaining nanoparticles that are widely used in nanoelectronics, sensor technology, nonlinear optics and other fields [1]. The dry aerosol printing method has many advantages over other methods, such as electron lithography, vapor deposition [3], photochemical deposition [4]. The most valuable advantage is the ability to control the process of nanoparticles synthesis in real time due to a wide range of parameters of the spark discharge. It is also possible to use various nanomaterials for the synthesis in spark discharge generator, such as metals (Au, Ag, Cu, Al, Ge, etc.) and alloys, such as Ag-Cu and Cu-W [6]. Metal oxides can also be obtained due to the possibility of synthesis in an atmosphere of air [7]. The morphology of the plasmonic nanostructure has a great influence on the SERS signal amplification and luminescence due to the ability to influence the localization of the electromagnetic field. To demonstrate this influence, the authors carefully selected the pyramidal surface configuration and the thickness of the Au-Ag plasmonic layer [8]. Studies [9] reported on the enhancement of the luminescence of zinc oxide several times, depending on the configuration of the plasmonic aluminum layer. Aluminum nanoparticles are of particular interest in nonlinear optical spectroscopies [10]. The extinction peak of this nanoparticles is in the range of 200–500 nm, depending on the size and morphology of the nanoparticles [11]. Thus, the shift of peaks position on the extinction spectrum in the region to a longer wavelength with increasing diameter was demonstrated in this work [11]. It is known, that the packing density of metal nanoparticles, their size, shape and pattern on the surface can significantly affect the ability to amplify electromagnetic radiation due to surface plasmons [12]. In this article, we demonstrate the application of the dry aerosol printing method to create thin-film aluminum nanostructures. We also developed printing technology for the fabrication of various patterns of nanostructures for further study.

Materials and Methods

Printing of film nanostructures from Al nanoparticles was carried out at a spark discharge synthesis facility (Fig. 1) in the atmosphere of Ar gas (6.0) according to the principle described earlier [13]. First, the air was removed from the system, after that Ar gas was introduced. Ar gas passes through the anode and carries out with the flow the nanoparticles synthesized in the gas discharge chamber. Next, the synthesized nanoparticles are carried out through the nozzle. During the work, the following parameters varied: the focal length (S), the rate of the substrate relative to the nozzle (V), the flow of the carrier gas (Qa) and a distance between the lines (h). By varying the printing parameters it is possible to influence the line width and the surface concentration of particles. Polished quartz glasses of the KU-1 brand were used as substrates for printing.

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The constant installation parameters were as follows: the pressure in the nanoparticle generation chamber was 1.2 atm, the pressure of the cooling gas flow was 1.6 atm, a capacitor with a capacity of 107 nF was used, the pulse period was 2 ms, the focusing gas flow was 20 ml/min, the temperature was 25 °C. The width and height of the obtained nanostructures were determined from images taken using an optical 3D profilometer (S neox, Sensofar, Terrassa, Spain, Nikon EPI 10X lens, capture area 1689, 12×1413, 12 um). The surface morphology of the nanostructures of the samples was studied using scanning electron microscopy (JSM 7001F, JEOL) at an accelerating voltage of 3 kV. The optical density of aluminum nanostructures on quartz glass was studied using a JASCO V-770 spectrophotometer (Japan).

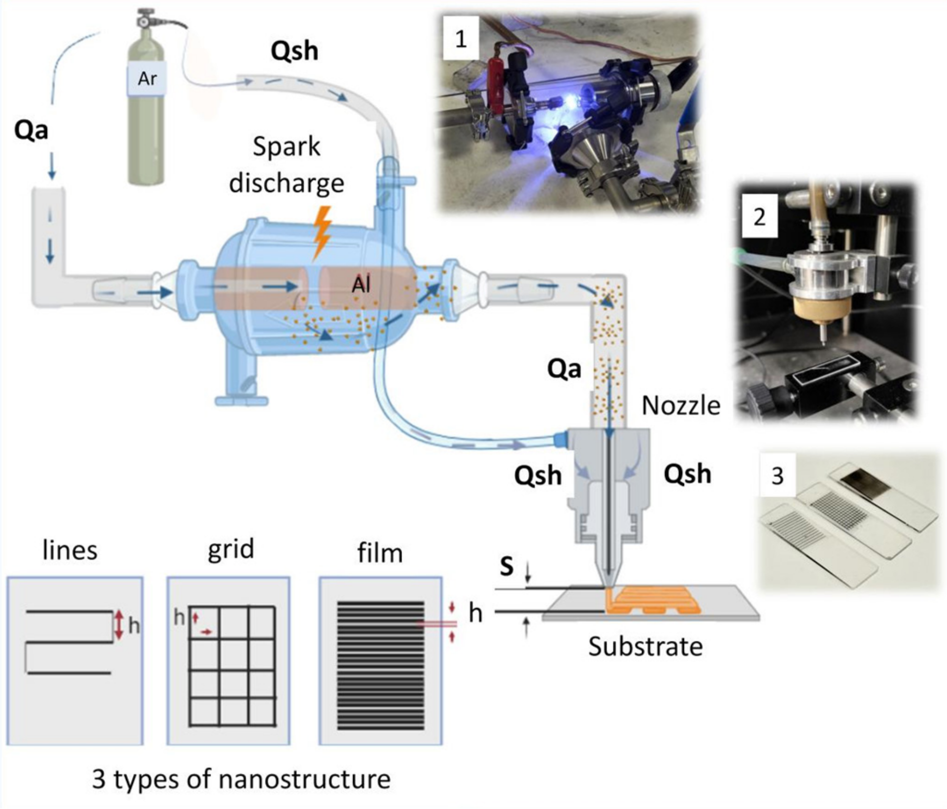

Fig 1. Spark discharge synthesis facility
Inset: real photos of the gas chamber (1), real photos of the nozzle (2), real photos of the substrates (3)

Results and Discussion

Studies have shown that an increase in the rate from 10 to 200 um/s leads to a decrease in the line width of the nanostructure from 470 ± 10 nm to 240 ± 50 nm (Fig. 2,*a*). By increasing the focal length from 1 to 2,5 mm, it is possible to reduce the line width by 19 ± 7 nm. With an increase in the gas flow from 50 to 600 ml/min at fixed parameters *S* and *V*, an increase in the line width from 170 ± 23 um to 500 ± 43 um is observed (Fig. 2,*b*). At the first stage, the dependences of the surface concentration of particles and the line width on the printing parameters were studied. Next, we selected the optimal printing parameters (Q_a, *V* and *S*) to create identical lines of aluminum nanoparticles: Q_a = 200 ml/min, *V* = 250 um/s, *S* = 1.5 mm. Aluminum nanostructures of various patterns (films, arrays of lines, grids) (Fig. 1) were applied on the surface of the quartz glass. During the experiments, 6 types of nanostructures were manufactured: grids (*h* = 1050 um, *h* = 2100 um), arrays of lines (*h* = 1050 um, *h* = 2100 um), films (*h* = 250 um, *h* = 350 um). Also, the roughness (R_a) was determined for the films, it was 0.16 ± 0.003 um.

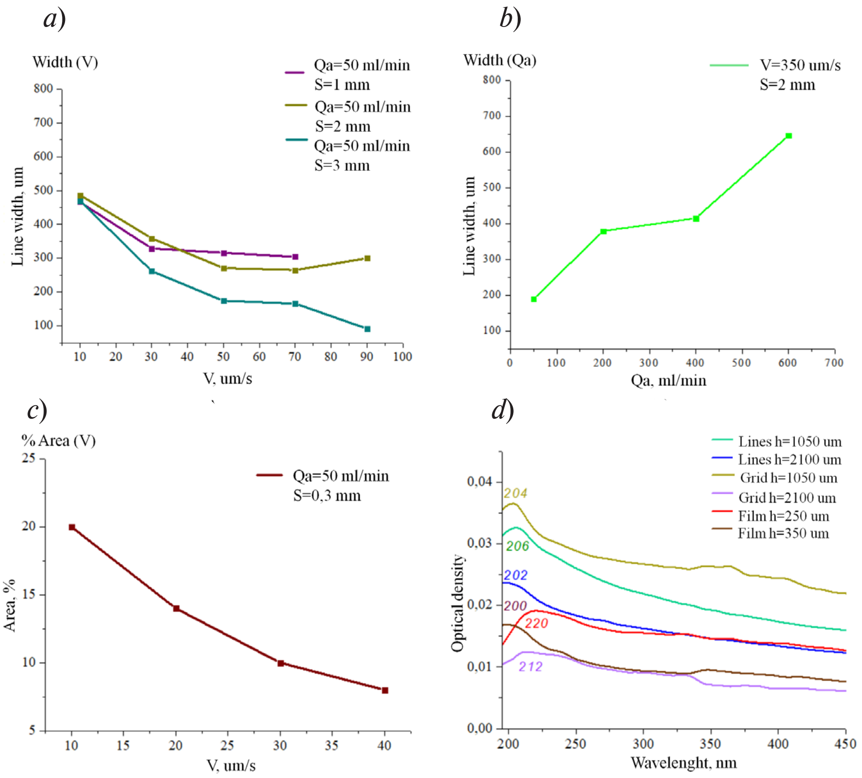

Fig. 2. Dependency graphs: line width from rate of the substrate movement (*a*), line width from the gas flow (*b*), area of nanoparticles from the rate of the substrate relative to the nozzle (*c*), absorption spectrum of nanostructures of various patterns (arrays of lines, grids, films) (*d*)

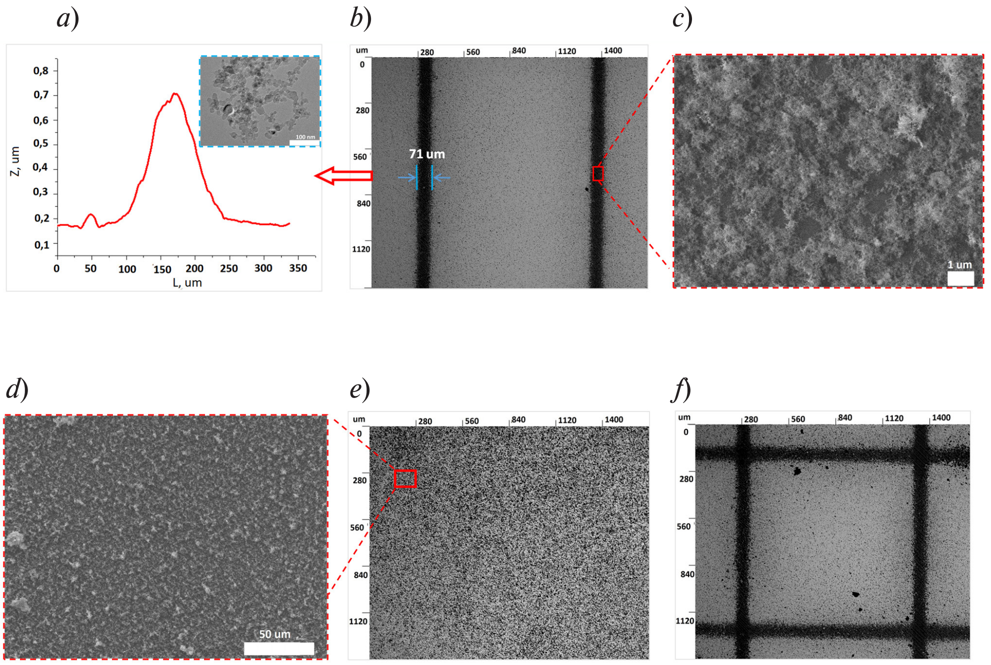

Fig. 3. Line profile from 3D profilometer (*a*); optical microscopy of various nanostructures: array of lines (*b*), film (*e*), grid (*f*) with printing parameters: Q_a = 200 ml/min, S = 1,5 mm, V = 250 um/s; SEM-image of the microstructure surface (*c*), (*d*); inset: TEM images of Al nanoparticles

We observed a peak in the optical density spectrum in middle ultraviolet range for each nanostructure. However, the morphology of the surface of the nanostructures and the pattern affect the location of the peak ambiguously. We observed a shift of peaks' maximums to a longer wavelength in films (h = 250 um) and grids (h = 2100 um) relative to other nanostructures (Fig. 2,*d*). The clearest peaks in the structures such as array of lines and grids (206 nm and 204 nm respectively) with h = 1050 um.

Conclusion

Thus, during the experiments, the technology of manufacturing thin-film nanostructures from aluminum nanoparticles was developed. Nanostructures of various patterns were obtained and the optical density of each nanostructure was investigated. It was found that regardless the pattern the obtained films had an extinction peak in the middle ultraviolet region in the wavelength range of 200–220 nm. At the same time, we have shown that the method of dry aerosol printing is a new clean way to create nanostructures of various configurations and morphologies.

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