ISSN 1063-7397, Russian Microelectronics, 2007, Vol. 36, No. 6, pp. 353–357. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © O.A. Ageev, B.G. Konoplev, V.V. Polyakov, A.M. Svetlichnyi, V.A. Smirnov, 2007, published in Mikroelektronika, 2007, Vol. 36, No. 6, pp. 403–408.

NANOLITHOGRAPHY

Photoassisted Scanning-Probe Nanolithography on Ti Films

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Received September 12, 2006

Abstract—An experimental investigation is reported on the influence of UV or IR incoherent irradiation on nanolithography by tip-induced local anodic oxidation as applied to titanium films. Both forms of irradiation are found to increase the uniformity of feature sizes and to improve the resolution of the lithographic technique. It is also shown that UV irradiation makes it possible to produce a conducting channel 11 nm wide.

PACS numbers: 81.16.Nd

DOI: 10.1134/S1063739707060017

INTRODUCTION

The emergence of quantum nanodevices [1] may be seen as a forerunner of a second quantum revolution in technology, but their fabrication still faces the challenge of ensuring lithographic reproducibility on the atomic scale.

Currently, nanolithography relies on extreme-ultraviolet (EUV) radiation, x rays, electron beams, or scanning probes [1–3] to produce nanodevices based on quantum-confined structures with a two-dimensional electron gas and on nanoscale metallic elements [1–4].

On the other hand, the above approaches suffer from some disadvantages. The resolution of x-ray and electron-beam techniques is degraded by scattering in the material being processed [5]. EUV lithography faces the problem of focusing at an operating wavelength of 13.4 nm. With a very limited choice of transparent materials in this spectral region, one has to employ costly catoptric devices that must satisfy stringent requirements [1, 2].

Scanning-probe nanolithography is free from those limitations. It offers a way to assemble devices by manipulation of individual nanoscale objects such as carbon nanotubes, fullerenes, or nanoclusters [2–5].

One promising method in this field is tip-induced local anodic oxidation [2–5]. However, it entails solving the problem of unstable transport of charge and mass across the tip–substrate gap due to local variations in the properties of the material, a factor that degrades the lithographic resolution and reproducibility [6, 7]. Ageev et al. [8] proposed introducing an activating agent, such as ultraviolet (UV) radiation, into the tip–substrate gap that would dominate the oxidation to reduce the influence of the above-mentioned variations.

In general, photoassisted oxidation is known to allow some control over the kinetics of oxidation and the properties of the oxide [9, 10]. Yet the underlying mechanism is not well understood despite its being discussed by quite a few authors.

This article reports on an experimental investigation into the influence of UV or infrared (IR) irradiation on nanolithography by tip-induced local anodic oxidation as applied to titanium films. Geometric parameters of test nanostructures are deduced from measurements and subjected to statistical data analysis.

EXPERIMENTAL CONDITIONS

Local anodic oxidation was carried out by dynamic-mode atomic-force microscopy (AFM) using a Solver P47 Pro scanning probe microscope (SPM) from NT-MDT (Russia), together with the software, attachments, and materials supplied with the instrument.

The process was carried out on a titanium film about 5 nm thick, which was formed on a silicon substrate by a pulsed-plasma method.

We used the Nova RC1 control program (version 1.0.26.097) and DSP-20 cantilevers with a conducting diamond coating, the voltage amplitude and scanning rate being 8 V and 2 μm/s, respectively. The relative air humidity was measured with an Oregon Scientific ETHG913R digital meter; it was $70 \pm 1\%$. The resulting oxidation reaction, involving the moisture adsorbed on the specimen surface, produced nanoscale structures of titanium oxide according to a preformed mask.

To investigate the effect of UV or IR stimulation on the local anodic oxidation, the oxidation region was irradiated with a 395-nm CREE light-emitting diode (LED), designed in the United States, or with a 900-nm AL-103A LED, respectively. In addition, reference nanostructures were fabricated without irradiation.

The test structure was chosen to be an array of a suitably large number of nanosized oxide dots to allow reliable statistical processing of experimental results. Indeed, arrays of scattering centers with controlled topology and parameters are widely used in nanoelectronics, e.g., as part of ballistic rectifiers [5, 11].

Geometric Parameters of Oxide Nanodots

Parameter	No stimulation	UV stimulation	IR stimulation
Cross-sectional area, $\times 10^3$ nm^2	9.5 ± 2	6.7 ± 1.5	6.1 ± 1.5
Maximum height, nm	2.7 ± 0.35	2.6 ± 0.3	2.2 ± 0.18

An example AFM image of the test structure is shown in Fig. 1.

The determination and statistical processing of parameters for the oxide nanostructures was carried out with the Image Analysis 2.0 software package. The results are presented in Table. The mean values and standard deviations of cross-sectional area and maximum height for the nanostructures were taken as characterizing the process resolution and reproducibility. The plane of section was taken to be parallel to the substrate plane, lying at a height of 0.5 nm.

Figures 2 and 3 show respective MathCAD histograms of the two geometric parameters.

The effect of UF or IR stimulation was also investigated for the formation of quasi-one-dimensional chan-

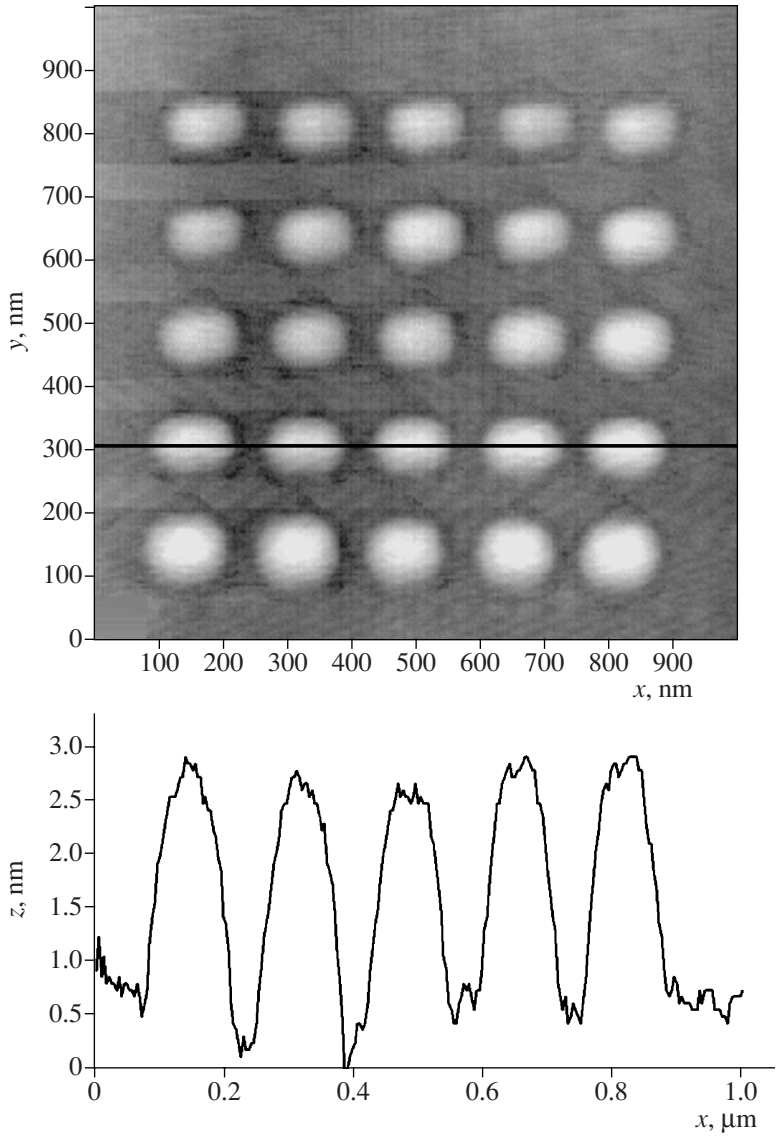

Fig. 1. Topology of the surface of a titanium film after local anodic oxidation and its surface height profile.

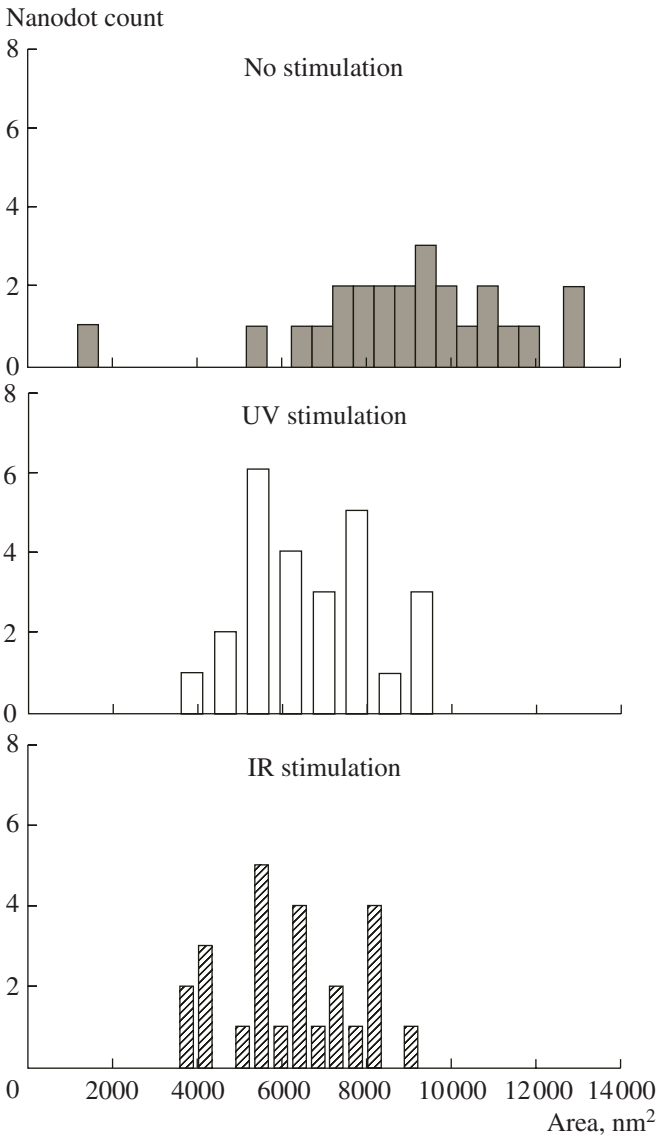

Fig. 2. Histogram of cross-sectional area for oxide nanodots.

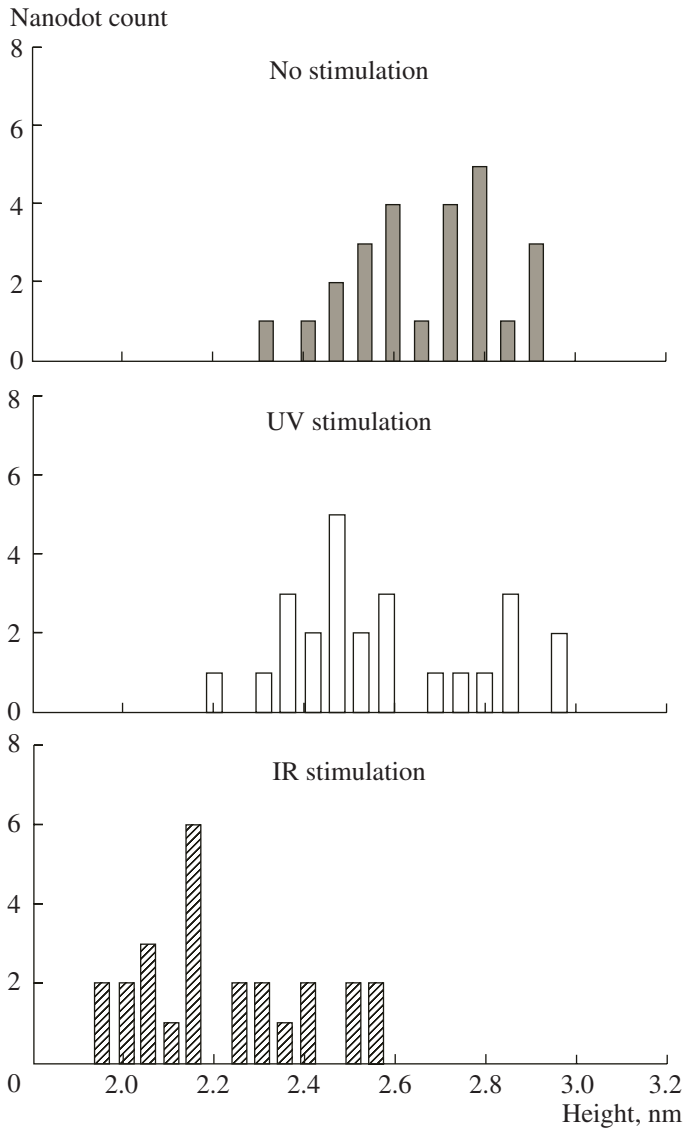

Fig. 3. Histogram of maximum height for oxide nanodots.

nels. Three line pairs were formed in a scanning cycle with or without stimulation (Fig. 4).

RESULTS AND DISCUSSION

The body of data presented (table; Figs. 2, 3) shows that both UV and IR stimulation reduce the mean values and standard deviations of the nanostructure cross-sectional area and maximum height.

Lower standard deviations point to higher uniformity of the geometric parameters. This result along with the decrease in mean value for the cross-sectional area imply an improvement in lateral resolution and reproducibility.

Metal nanoelectronic elements are made by formation of quasi-one-dimensional conduction channels in thin metal films. If such channels are about 10 nm wide, they are known to exhibit transverse quantization of electron energy and quantum conduction at room temperature [3–6].

To verify the above conclusions and to further investigate the effect of stimulation, we produced nanosized channels by the method concerned using a mask consisting of three identically spaced line pairs; the result is shown in Fig. 4. Under UV stimulation, a channel of titanium about 11 nm wide, which was uniform along the whole length, was formed between any two adjacent oxide lines (Fig. 5). With no stimulation or with IR irradiation, oxide lines grew together and no channels were formed (Fig. 6).

The variation in the two geometric parameters may be associated with the influence of the radiation on the formation of ions in the oxidation region. According to the model of low-temperature oxidation, the applied

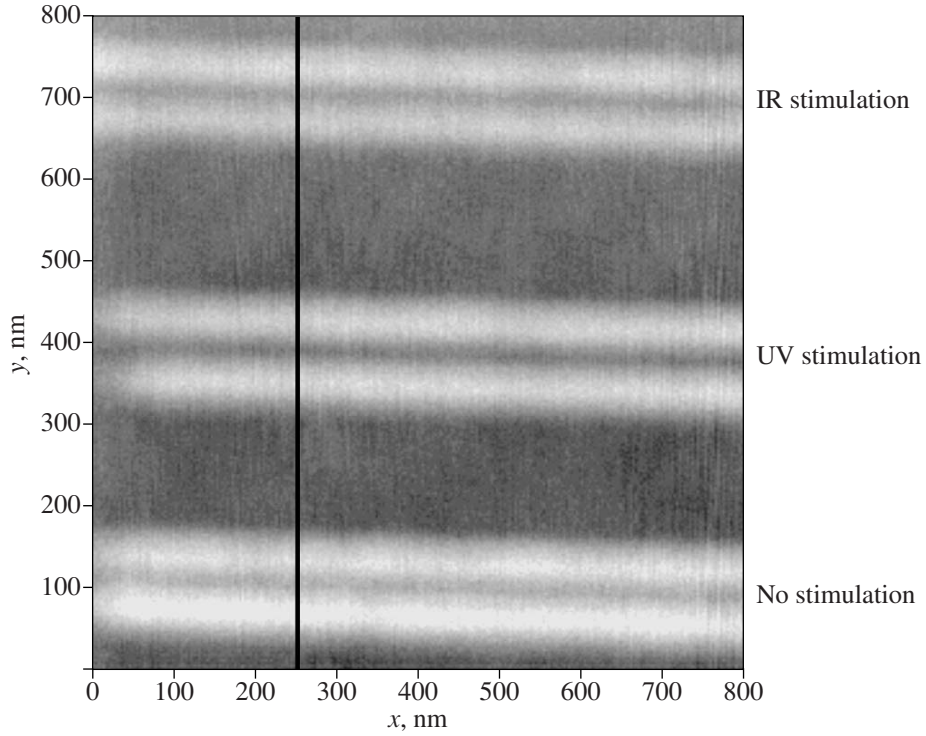

Fig. 4. AFM surface image of a titanium film subjected to local anodic oxidation.

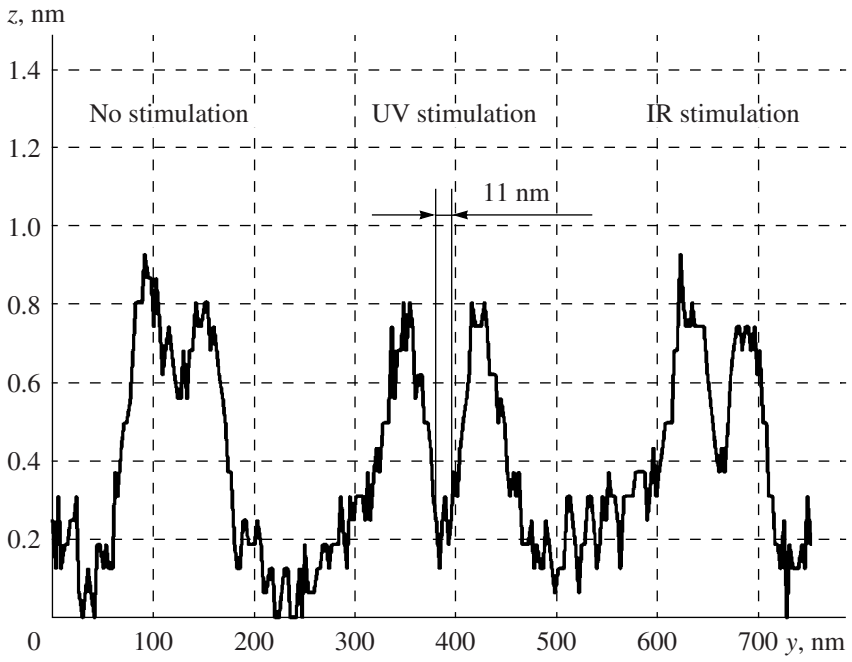

Fig. 5. Surface height profile along the line defined in Fig. 4.

voltage makes Ti^{2+} and $(OH)^-$ ions diffuse through the oxide to form unstable $Ti(OH)_2$ on the surface, which decomposes into TiO_2 and hydrogen [12, 13]. The $(OH)^-$ concentration depends on the humidity of the surrounding medium. Since the humidity was kept constant during this experiment, the decrease in the geometric parameters may be associated with a radiation-induced reduction in $(OH)^-$ concentration.

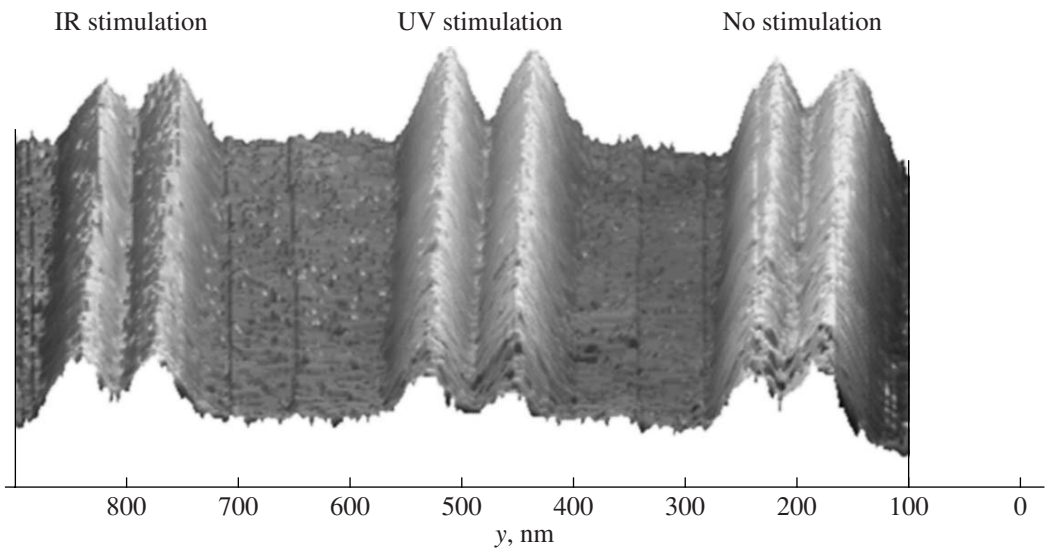

Fig. 6. 3D AFM surface image of a titanium film after LAO.

A second possible mechanism is a change in the magnitude and spatial pattern of the surface charge and related variations in surface potential, in the resistivity of the material in the near-surface layer, and in spreading resistance. These effects should alter the characteristic diameter of the region where charge and mass transport occur in local anodic oxidation [9, 10].

CONCLUSIONS

An experimental investigation has been conducted into the influence of UV or IR irradiation on nanolithography by tip-induced local anodic oxidation as applied to titanium films. Both forms of irradiation are found to reduce the mean values and standard deviations of feature sizes, thus improving the resolution and reproducibility of the lithographic technique.

The results obtained should be of value to those engaged in developing nanoelectronics process technologies based on scanning-probe nanolithography.

This work was supprted by the Russian Foundation for Basic Research, project no. 06-07-81000-Be_a.

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