Optica Applicata, Vol. XLI, No. 2, 2011

Application of AFM technique for creation of patterns in nanoscale

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The lithography is a main technology process which determines the properties of semiconductor devices. The resolution of optical lithography is insufficient for creation of submicrometer patterns, like, *e.g.*, gate electrode in HEMT transistors. Thus, a novel technique that uses AFM technique and common photolithography was proposed. In the paper, the results of nanoscratching lithography were presented and discussed. Also the transmission and root mean square of thin metal films measurements were summarized.

Keywords: nanoscratching, nanoscribing, AFM lithography, lift-off technique.

1. Introduction

The lithography is a basic process which determines the properties of microelectronic devices. The resolution of optical lithography depends on the thickness of a resist layer, wavelength of radiation and method of exposing the resist. The authors of earlier investigations have indicated that the highest possible resolution of classical optical lithography is lower than 500 nm. There are useful methods to create high resolution patterns of electron beam lithography and ion beam lithography. The resolution of these techniques is higher than 50 nm [1, 2]. It is also possible to use optical lithography with a phase-shift mask, and the resolution of this technique is 25 nm [3]. In this method, the phase-shift masks are used, what increases its cost. The application of this method is uneconomic because only few lines with nanometer resolution are fabricated on a substrate. Another technique employed in the creation of patterns in nanoscale is AFM lithography. The resolution of AFM lithography depends on tip geometry and the kind of technique used in experiments [4]. The AFM lithography includes a lot of techniques [4] (*e.g.* dip-pen method, local oxidation of surface, electrostatic deformation of layer) but among these methods only nanoscratching could be applied to create metal paths. In this method, the mechanical mechanism of pattern creation is used, and it is also possible to modify the surface of a semiconductor [5, 6], metal [5, 7] or resist [8, 9]. The resolution of this technique depends on scratching depth, and for lift-off technology it is equal to the thickness of a removed resist or metal layer [8]. A proper removal of the layer requires the optimization of scratching parameters, like the force applied to the tip and the scratching speed. Nanoscratching is a universal technique because it permits to modify the resist surface, what assures the compatibility with optical lithography. The idea of combined AFM and optical lithography assumes the usage of a thin metal film deposited on a resist as a mask for optical lithography. Thus the measurements of the transmission of electromagnetic field through the thin film of metal was indispensable. Obtained results enabled specification of the metal film thickness, impermeable to UV light, proper for application as a mask.

In the paper, the results of mixing optical lithography and nanoscratching are presented. This paper specifies the parameters of technology processes concerning nanometer patterns creation using the system for standard optical lithography.

2. Experiments

2.1. Optical and structural properties of thin film metal

The UV light permeability of a thin metal film used as a mask in photolithography is important because the proposed technique includes exposing step. For the experiments, Ti/Au double-layers were deposited on sapphire substrates in an ultra high vacuum system. The titanium underlayer, 10 nm thick, was evaporated by magnetron sputtering, as an adhesive layer. The gold layer was deposited by using a resistance heater. The thickness of this layer was in the range from 30 nm to 100 nm. The measurements were carried out by a spectrophotometer and the results were referred to sapphire substrate permeability. As an impermeability criterion, the transmission below 0.01 was assumed.

The change in transmission through a thin metal film could be explained by the change in dispersion of light on grain boundaries. The indirect estimation of grain boundaries presence in the layer was specified based on AFM topography scans and evaluation of RMS. The investigations into the RMS of prepared samples were performed by AFM Veeco Multimode V with the use of silicon tips – RTESP [10].

2.2. Scratching

The methodology of investigation into the application of nanoscratching and optical lithography to create high resolution patterns is presented in Fig. 1. The process started with coating of the sample surface with a double-layer of a resist and a thin film of metal (Ti/Au) (Fig. 1**a**). The thicknesses of layers were as follows: resist LOL2000 – 250 nm, resist SPR 700 – 1200 nm and gold – 155 nm. The resists used during

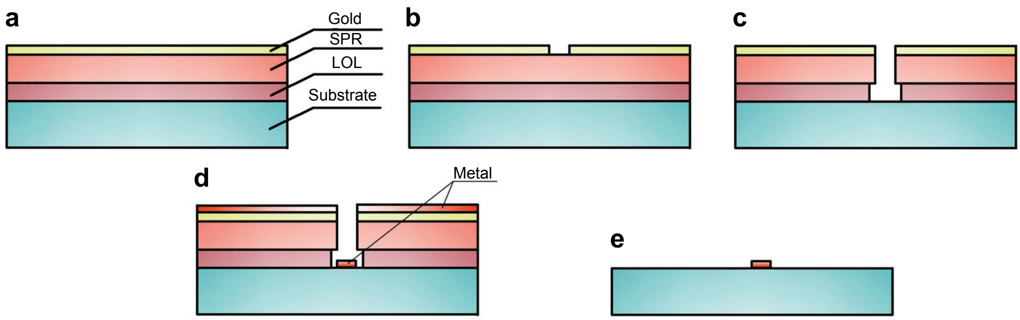

Fig. 1. Idea of investigation into the application of nanoscratching and optical lithography: prepared sample (**a**), substrate after scratching (**b**), sample after exposure and development (**c**), sample after deposition of metal multilayer (**d**), test structure after lift-off process (**e**).

the experiments were commercially available Shipley resists, commonly applied in the conventional lift-off technique. In the next step, the thin film of metal was selectively removed by nanoscratching (Fig. 1b) by the AFM tip. The next operation was the exposition of resists in the MA-56 system by Carl Zuss without a chromium mask. In this step, the thin film of metal was used as a mask for optical lithography. The UV light exposition stage was followed by the development of the resist using a developer (Fig. 1**c**). The next step was the deposition of a metallization multilayer in an ultra high vacuum system (Fig. 1**d**). The last operation was the lift-off in which the resist and metallization used as a mask were removed from the sample surface (Fig. 1**e**).

The AFM system used in the experiments was Veeco Multimode V. The topography scans before and after scratching were made in a tapping mode. The scratching process was carried out in a contact mode. Both studies were performed by using a silicon tip – RTESP – of the nominal force constant 40 N/m and the tip radius of 8 nm [10]. The profiles after development were made by tip AR5-NCHR with the high aspect ratio and the tip radius less than 15 nm [11].

3. Results

3.1. Optical and structural properties of thin film metal

The measurements of transmission through the thin metal layer led to the specification of metal layers thickness that could be used as a mask. In Figure 2**a** the transmission spectra of metal layers with various thicknesses are presented. The dependence of transmission through thin film metal on metal layer thickness is depicted in Fig. 2**b**.

The analysis of presented spectra indicated metal thickness, appropriate for application as a mask in photolithography process, to be 150 nm. The value was obtained based on the extrapolation of the characteristics. A film of this thickness

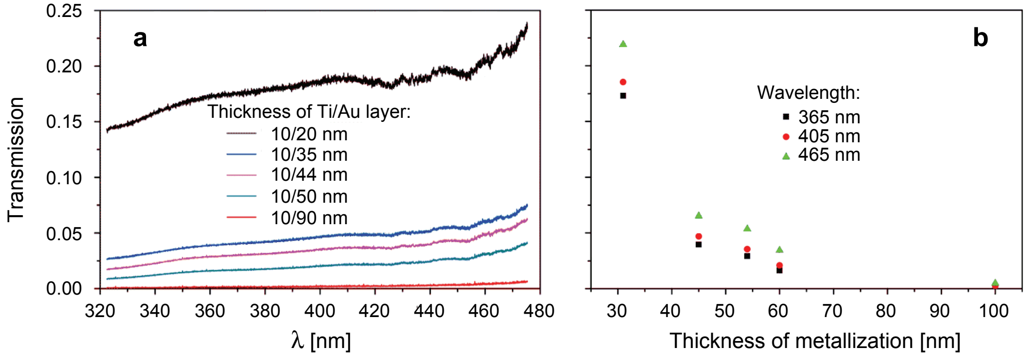

Fig. 2. Transmission through thin film metal: spectral characteristics (**a**), dependence on the thickness of metal mask (**b**).

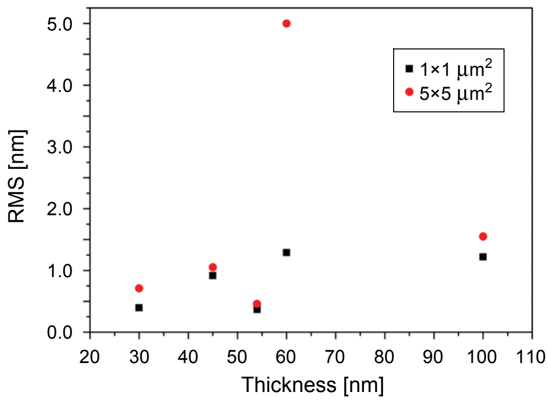

Fig. 3. Dependence of RMS on thickness of a metal layer for two scanning areas (1×1 μm^2 and 5×5 μm^2).

provides the transmission below 0.01. Important is also the fact that the transmission does not exceed 0.1 for layers thicker than 40 nm, what could be preferential in case of further experiments in which thickness lowering of a metal layer will be possible.

The results presented in Fig. 3 show that the trends of RMS alteration with the thickness of metal layer increase were not evident. There are some deviations from the announced trends of changes, which could be remarkable for samples with the thicknesses of 54 nm and 60 nm. Presented results were similar to the results of SLEPICKA *et al*. [12] where the RMS value increased with the thickness of the layer. The differences could be explained by some changes in metal layer deposition process parameters.

3.2. Scratching results

The value of the force applied to the tip determines the scratching depth. Because the thickness of metallization that should be removed was 155 nm, the force used in the experiments was higher than 50 μN. This value was determined in the preliminary investigation. To get full information about occurring phenomena, the topography scans were measured after each step of technology process. For investigated structures, two topography scans were most valuable: after nanoscratching and after lift-off process. After exposing and the development of the resist, the surface scan was made. This scan was performed to extract profiles, which would confirm that the resist was properly developed. Figure 4**a** presents the results of nanoscratching prepared with scratching speed of 10 μm/min and force applied to the tip from 64 μN to 88 μN. The values larger than 70 μN were inappropriate because the edges and scratched paths were ragged. Although this sample confirmed that the shape of a deposited metal was exactly the same as the shape of a pattern created by nanoscratching (Figs. 4**a** and 4**b**).

Figure 5**a** presents the surface topographies after nanoscratching with the force applied to the tip within the range of 52 μN to 64 μN and scratching speed 10 μm/min. The studies for lower values of forces were carried out because of observed insufficient quality of patterns created for a larger value of force. The application of the force from the range of 50 μN to 64 μN allowed for achievement of patterns of good quality and sharp-edged patterns. After exposing and the development of the resist, the surface scans were made. The obtained results confirmed the complete removal of the resist

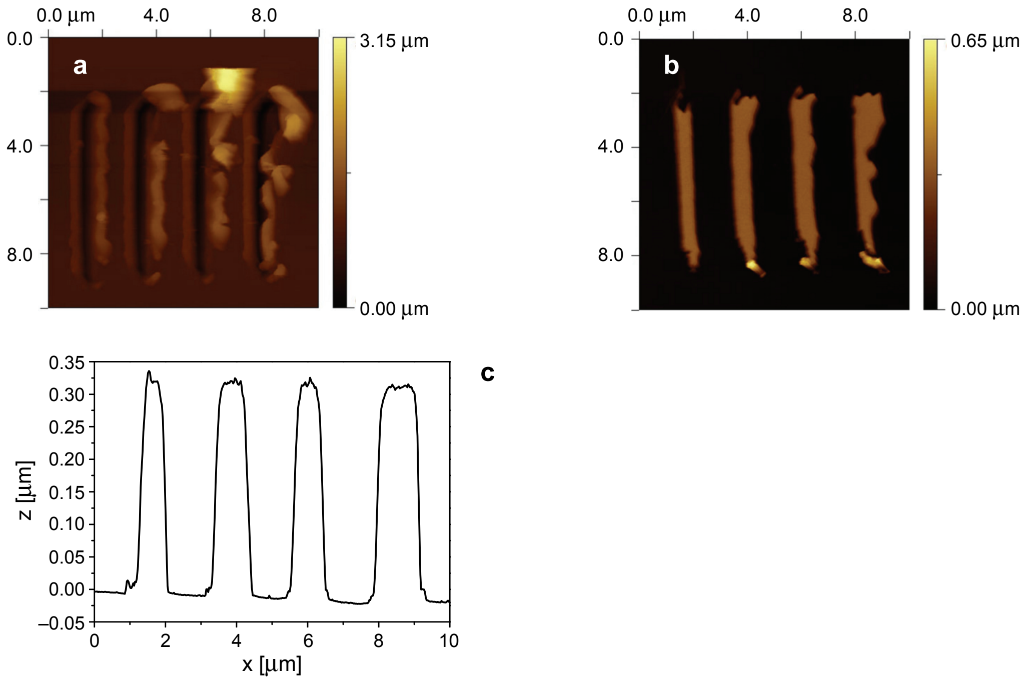

Fig. 4. The AFM map: after scratching with speed 10 μm/min and force applied to the tip from left 64 μN, 72 μN, 80 μN, 88 μN (**a**), test structure after lift-off process (**b**), the profile of metallization (**c**).

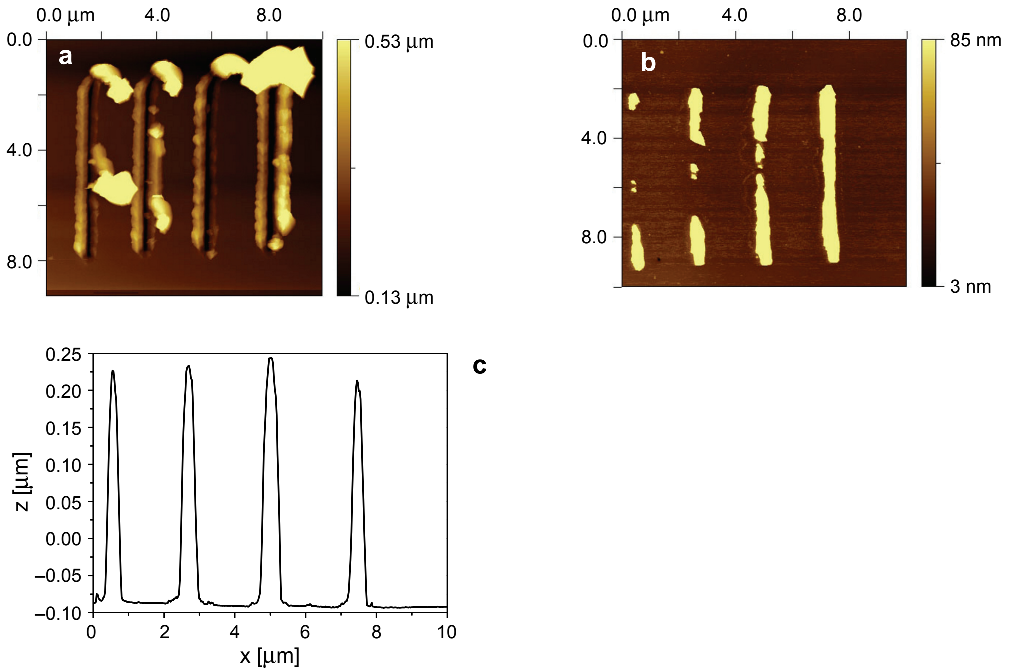

Fig. 5. The AFM map: after scratching with speed 10 µm/min and force applied to the tip from left 52 µN, 56 µN, 60 µN, 64 µN (**a**), test structure after lift-off process (**b**), the profile of metallization (**c**).

from the windows created by nanoscratching. It was concluded basing on the level of profile and the thickness of layers (resists and metal) equality. Figure 5**b** presents the metallization deposited with the application of Au mask. As could be remarked, only the line four (from left) of metallization was continued. This requirement was assumed to be a criterion of selection of the appropriate value of force applied to the AFM tip during mask creation.

The profile of metallization extracted from AFM map and presented in Fig. 5**b** shows that the width of the line four was from 130 nm to 234 nm. The average value of this line permitted to evaluate the resolution of the studied method. The analysis of topography maps profiles allowed to define the resolution to be 150 nm. This value is almost equal to the thickness of a mask layer (155 nm). This value is a result of the shape of the tip and the thickness of the removed layer. The obtained resolution of the proposed method was lower than that reported by YU-JU CHEN *et al.* [8]. Nevertheless, in the work, the thickness of the PMMA resist was 50 nm and, additionally, the layer was not exposed to UV lights. Thus in the presented results, only the resolution of scratching process was evaluated. The scratching is also used to remove a metal layer from the surface. IRMER *et al.* [13] removed 100 nm aluminum layer and the resolution of the scratches was also equal to the thickness of the layer.

4. Conclusions

In the paper, the measurements of light transmission through a thin film layer and the structural characterization of the layer are presented. The results of nanoscratching of the metal layer and the use of the patterns as a mask for optical lithography were studied. The measurements of transmission have shown that the metal layer thicker than 100 nm is not transparent. This property permitted to apply this layer as a mask for exposing the resist layer. The evident trend of RMS changes with the thickness of the metal layer was not clear. The reduction of transmission with increased thickness was observed. It has been proved that the nanoscratching lithography is a useful method to create patterns in a metal layer which could be further used as a mask for optical lithography. The resolution of the elaborated technique was 150 nm and was higher than classical optical lithography. The resolution was calculated based on the metal paths width made by using nanoscratching and optical lithography. The resolution could be increased by the reduction in the thickness of a mask metal layer. This technique could become a powerful tool for fabrication of nanometer patterns like a gate electrode in HEMT transistors.

Acknowledgements – This work has been supported by the fellowship by the European Union Social Found. Researches were also co-financed by the Polish Ministry of Science and Higher Education under grant No. NN 515360436, by the European Union within the European Regional Development Found, through grant Innovative Economy (POIG.01.01.02-00-008/08) and by Wrocław University of Technology statutory grant.

References

[1] VIEU C., CARCENAC F., PEPIN A., CHEN Y., MEJIAS M., LEBIB A., MANIN-FERLAZZO L., COURAUD L., LAUNOIS H., *Electron beam lithography: Resolution limits and applications*, Applied Surface Science **164**(1–4), 2000, pp. 111–117.

[2] ADESIDA I., KRATSCHMER E., WOLF E.D., MURAY A., ISSACSON M., *Ion beam lithography at nanometer dimensions*, Journal of Vacuum Science and Technology B **3**(1), 1985, pp. 45–49.

[3] FRITZE M., TYRRELL B.M., ASTOLFI D.K., LAMBERT R.D., YOST D.-R.W., FORTE A.R., CANN S.G., WHEELER B.D., *Subwavelength optical lithography with phase-shift photomasks*, Lincoln Laboratory Journal **14**(2), 2003, pp. 237–250.

[4] XIE X.N., CHUNG H.J., SOW C.H., WEE A.T.S., *Nanoscale materials patterning and engineering by atomic force microscopy nanolithography*, Materials Science and Engineering R: Reports **54**(1–2), 2006, pp. 1–48.

[5] YAN Y.D., SUN T., DONG S., *Study on effects of tip geometry on AFM nanoscratching tests*, Wear **262**(3–4), 2007, pp. 477–483.

[6] VERSEN M., KLEHN B., KUNZE U., REUTER D., WIECK A.D., *Nanoscale devices fabricated by direct machining of GaAs with an atomic force microscope*, Ultramicroscopy **82**(1–4), 2000, pp. 159–163.

[7] WU TANG, XIAOLONG WENG, LONGJIANG DENG, KEWEI XU, JIAN LU, *Nano-scratch experiments of Au/NiCr multi-layer films for microwave integrated circuits*, Surface and Coatings Technology **201**(9–11), 2007, pp. 5664–5666.

[8] YU-JU CHEN, JU-HUNG HSU, HEH-NAN LIN, *Fabrication of metal nanowires by atomic force microscopy nanoscratching and lift-off process*, Nanotechnology **16**(8), 2005, pp. 1112–1115.

[9] WENDEL M., IRMER B., CORTES J., KAISER R., LORENZ H., KOTTHAUS J.P., LORKE A., WILLIAMS E., *Nanolithography with an atomic force microscope*, Superlattices and Microstructures **20**(3), 1996, pp. 349–356.

[10] http://www.veecoprobes.com/p-3388-rtesp.aspx.

[11] http://nanoandmore.com/AFM-Probe-AR5-NCHR.html.

[12] SLEPICKA P., SVORCIK V., SLOUF M., RYBKA V., SPIRKOVA M., *Characterization of metal nanolayers sputtered on poly(ethyleneterephtalate)*, Optoelectronics and Advanced Materials **2**(3), 2008, pp. 153–160.

[13] IRMER B., BLICK R.H., SIMMEL F., GODEL W., LORENZ H., KOTTHAUS J.P., *Josephson junctions defined by a nanoplough*, Applied Physics Letters **73**(14), 1998, pp. 2051–2053.

Received September 25, 2010