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Submicron Metal Patterns of Arbitrary Geometry Fabricated by Means of Selective Removal of Oxygen Atoms from Molybdenum Oxide

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Abstract—The possibility of manufacturing metal patterns with submicron linear elements on a silicon substrate by means of the selective removal of oxygen atoms from metal oxide is demonstrated for the first time. Structures of 0.35-μm-wide molybdenum stripes with a thickness of 20 nm have been obtained using 3-keV proton irradiation of a molybdenum oxide film on a silicon substrate via an electron-beam resist mask, followed by removal of the resist and the non-reduced oxide regions. The proposed method can be used for the fabrication of submicron metal patterns of arbitrary geometry on various substrates.

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As is well known, lithography is among the technological stages of key importance in the fabrication of integrated circuits and other electronic devices [1]. Moreover, the production of virtually all micro- and nanoelectronic structures involves lithographic operations [2]. Therefore, the improvement of existing and the development of new lithographic techniques is a currently important scientific and technological problem.

The main task of lithography is to obtain a pattern of preset geometry from a desired material on a substrate of different chemical composition. Such a pattern can be either of independent interest or represent an auxiliary structure, in particular, a mask for the subsequent etching of the substrate. Frequently, the final result of a technology involving a lithographic stage is the fabrication of a metal mask on a given substrate [2].

Recently, we have developed [3] a new method for obtaining metal patterns of arbitrary geometry on a substrate, which is based on the selective removal of oxygen atoms from a metal oxide under proton irradiation. The proposed method is principally different from the other known techniques and, in our opinion, offers certain advantages in comparison to the conventionally used lithographic procedures.

The physical essence of the proposed method can be described as follows. When a multicomponent material is irradiated by a beam of accelerated particles, it is possible to select the mass and energy of bombarding particles so that only atoms of a certain kind will be effectively displaced in the surface layers of the target. As a result, atoms of this kind will be selectively removed from the irradiated volume of the material. In particular, during the proton irradiation of metal oxides, special conditions for the removal of oxygen atoms are realized for a proton energy of ≥0.3 keV and above. The thickness of a modified layer, being dependent on the chemical composition of the irradiated material and on the proton energy, can vary within 10–250 nm for the proton energies from 0.5 to 5 keV. We have established that, using proton irradiation of metal oxides, it is possible to ensure the virtually complete removal of oxygen atoms from the irradiated material volume. The thickness of a residual metal layer can vary within 5–100 nm [4].

Thus, by carrying out proton irradiation via a protective mask formed by means of photolithography or electron-beam lithography, it is possible to obtain a metal pattern in the initial oxide matrix. The subsequent removal of the electron-beam resist mask and non-reduced oxide leaves the desired metal pattern on the substrate (Fig. 1).

Previously, we obtained structures consisting of Mo stripes with a width of 2.5 μm [3]. The relatively large lateral size of these patterns was related to a low reso-

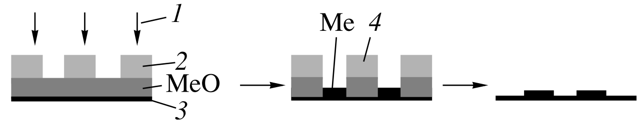

Fig. 1. Schematic diagram of a lithographic process based on the selective removal of atoms: (*1*) proton beam; (*2*) resist mask; (*3*) substrate; (*4*) removal of resist and residual MeO.

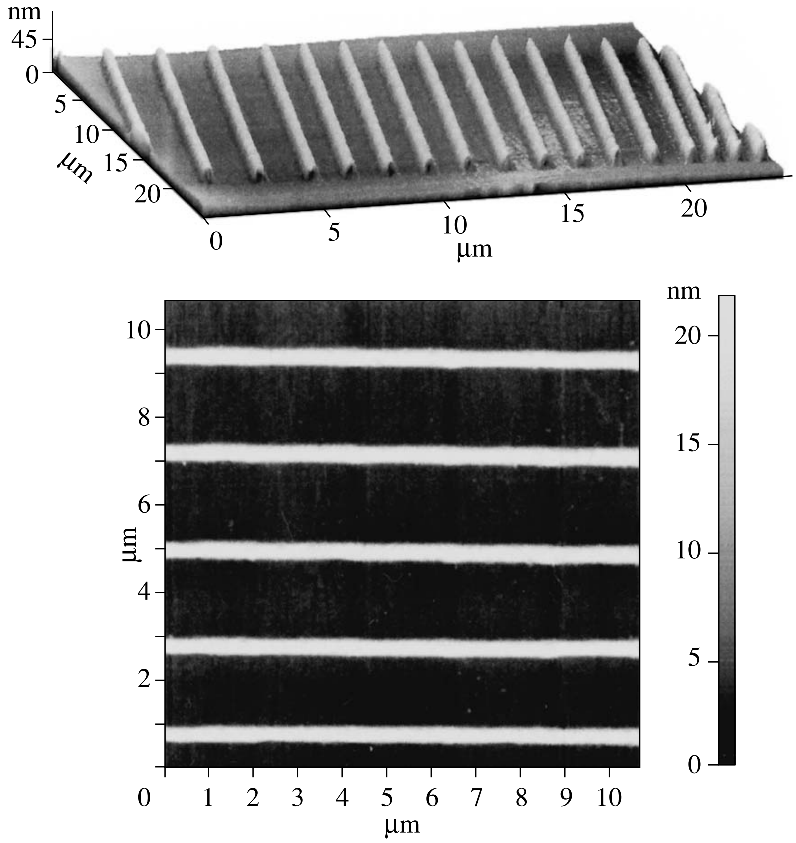

Fig. 2. AFM topographic images of a metal pattern obtained upon removal of the electron resist and residual MoO_3 regions. Bottom right-hand scale refers to the relief height.

lution of the contact photolithography used for the fabrication of masks. In the present Letter, we report for the first time on the formation of metal (molybdenum) patterns with submicron resolution on a silicon substrate, which comprise 0.35-μm-wide metal stripes with variable spacing.

The technology of new patterns was analogous to that described previously [3]. First, a 50-nm-thick film of MoO_3 was deposited onto a silicon single crystal substrate. Subsequently, a 300-nm-thick mask of the ERP-40 electron-beam resist comprising a set of 0.35-μm-thick lines was formed on the oxide surface using electron-beam exposure on a ZBA-21 setup. The width of lines in the electron resist mask was determined only by the maximum resolution that could be achieved with the electron-beam setup employed. It should be noted that use of the ERP-40 electron resist is not optimum, since it has a relatively low stability with respect to radiation and plasma. Then, molybdenum was reduced from its oxide by exposure to 3-keV protons at room temperature to a total dose of 1×10^{18} H^+/cm^2. Finally, the residual electron-beam resist was dissolved in warm (40°C) acetone and the residual MoO_3 oxide regions were removed by dissolving in a 0.5 wt % aqueous KOH solution. The resulting metal pattern was studied using an atomic force microscope (AFM) of the Solver P47 type (NT-MDT, Russia) in a tapping mode.

An analysis of the surface topography images obtained using the AFM showed a perfect coincidence of the final metal pattern obtained using the proton irradiation and the initial resist mask formed by means of electron lithography (Fig. 2). The thickness of metal stripes amounts to ~20 nm, which is in good agreement with theoretical estimates based on a material volume shrinkage as a result of the oxide transformation into metal.

As was noted previously [3], the proposed method offers several advantages in comparison to the lift-off lithography that is most widely used at present. First, the fabrication of a metal pattern using the new method does not require the formation of a resistive mask with a complex wall profile. Second, the proposed method makes possible the formation of thicker metal layers (under otherwise equal conditions) in structures with small (~50 nm and below) linear dimensions. Third, the proposed method is applicable to a broad class of materials. Another interesting feature of the proposed method, which is important for the fabrication of metal–semiconductor type structures, is the possibility to obtain much higher potential barriers at the contact as compared to those provided by the traditional methods based on the deposition of metal films [5]. This is especially important for the fabrication of nano-structures such as Schottky diodes.

Thus, we demonstrated that, using the new lithographic technique proposed previously, it is possible to obtain metal patterns with submicron linear elements. At present, works are in progress aimed at the fabrication of analogous structures with linear elements having dimensions of ~100 nm and below.

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