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Sputtered metal lift-off for grating fabrication on InP based optical devices

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ABSTRACT

Sputtered metal gratings have been realized using lift-off process based on bilayer resist electron beam lithography (EBL). The lithography mask is composed of PMMA (poly(methylmethacrylate)) layer deposited under HSQ (hydrogen silsesquioxane) inorganic resist. EBL is performed in HSQ, whereas PMMA is used to ease final lift-off. We demonstrate the possibility of patterning by lift-off metals with different sputtering yields and deposition conditions. Gratings with period of 200 nm and filling factor of 50% are obtained.

1. Introduction

Optical semiconductor devices for telecommunications are the focus of intensive research especially concerning their integration in photonic circuits. In combination with metallic structures, usual semiconductor devices can presents new interesting properties. As a first example, plasmonic structures have been proposed for highly confined guided mode propagation and transmission [1–3], including metallic Bragg grating [4]. Another example is the use of magneto-optical ferromagnetic metal, like FeCo, for non-reciprocal transmission and realization of integrated isolator [5,6] in InP material system. In both cases, metals become active elements of the device principle, and their nanostructuration is used for advanced control of the propagation, like resonance effects obtained into Bragg gratings [7].

The lift-off process is a straightforward method to fabricate metallic structures with sub-nanometer range. It combines resist lithography and metal deposition. This process is standard in the case of evaporated layers, even for nanostructured thin layers [8]. It is also established that it is not a well adapted method for sputtered metallic layers.

Following deposition conditions and technique, namely evaporation or sputtering, the metallic layers present different material morphologies and thus physical properties. In some cases, it can be necessary to use sputtered metal to obtain suitable physical properties.

In this work we have studied the fabrication of metallic nanostructures by lift-off of sputtered metal. The process is based on PMMA/HSQ bilayer resist electronic lithography [9–11]. Different metals, with various sputtering coefficients, were patterned on InGaAs/InP wafers in order to validate this technology for a wide range of metals.

The paper is organized as follows: the principle of the bilayer process is detailed in the Section 2, the technological parameters adjustment is explained in Section 3. Last section concludes this work.

2. Bilayer resist lift-off technology

The principle of the bilayer e-beam lithography for lift-off process is based on a mask made of two stacked spin-coated resists: in our case poly(methylmethacrylate) PMMA and negative-tone electron sensitive resist HSQ (FOX-12). The upper resist HSQ is used for e-beam lithography whereas the role of PMMA is to allow the lift-off of HSQ (after metal deposition).

The complete process occurs as follows. After spin-coating, the 150 nm thick layer (PMMA) is pre-baked at 175 °C during 15′. In contrast the upper 150 nm thick spin-coated layer (FOX-12) is slowly evaporated at ambient pressure and temperature during 48 h. This contributes to e-beam lithography resolution improvement [12]. The e-beam lithography is performed on the HSQ resist using Raith150 system, a current of 8 pA and an exposure energy of 20 kV. HSQ is developed with MF322 (TMAH), and the pattern is transferred into PMMA layer by RIE (Reactive Ion Etching) in plasma O_2. Then metal is vertically sputtered on the structure. Finally

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the remaining pattern made of the stack metal/HSQ/PMMA is lifted by dissolving PMMA in acetone combined with ultrasounds.

3. Sputtering conditions

We used the bilayer resist lift-off process for two sputtered metals, tungsten (W) and chromium (Cr) which present different sputtering yields in normal incidence [13] as shown in Table 1.

The quality of the lift-off depends on the deposition conditions, which affect the sputtering coefficient of the metal. Higher sputtering coefficient leads to a continuous deposited-film and, consequently compromises the lift-off. This characteristic is stronger when deposition conditions correspond to low rate growth. In order to evaluate ability of bilayer resist process to realize sputtered metal lift-off we have considered two extreme deposition conditions. The first one consists in deposition of W with a rate of 17 Å/s and is expected to allow easiest lift-off. The second one is based on Cr sputtering at 10 Å/s, and should lead to more difficult lift-off. In both cases Ar plasma pressure equals 5×10^{-3} mbar and magnetron source is used with vertical incidence. Source distance equals, respectively 6.5 and 5 cm. Power on the source was kept fixed 300 W.

4. Experimental results

The studied metallic designs are made of a periodic grating, opened in the center of a 3 μm wide ribbon. The grating period is 200 nm and the aimed filling factor equals 50%. Since HSQ resist is negative tone, gratings are patterned with 500 nm wide bars and external pads positioned so that bars are in the center of the 3 μm wide ribbon, as shown in Fig. 1.

Lift-off process has been optimized including variation of lithography electron doses *D*, resist grating apertures *A*, and PMMA RIE etching time. Lithography grating aperture *A* is defined by the width of the open and written bars as follows: a grating with aperture *A* = 110/90 nm is made of remaining resist stripes of 90 nm width and has a period of 200 nm.

First step has consisted in determining respective electron doses required to obtain well-defined grating bars and external pads. Dose has been scanned in the range 50–210 μC/cm^2 for different patterns. As shown in Fig. 1, the best combination is obtained for doses equal to 147 and 60 μC/cm^2, respectively for bars and external pads.

Next step consists in evaluating lift-off process for sputtered W (50 nm) and Cr (30 nm), varying grating aperture and PMMA RIE etch time. This last parameter is used to modify PMMA under-etch and to avoid that metal deposit as a continuous film [10]. With our etching parameters, vertical profile, ie absence of under-etch, is obtained with an etching time of 2 mn. Profile of grating with deposited W and before lift-off is shown in the case of PMMA etching time of 3 mn in Fig. 2. Slight under-etch can be observed at the root of nanostructures.

Lift-off trials have been firstly performed with 50 nm sputtered W, apertures of 110/90 and 90/110 nm, bars electron doses comprised between 126 and 162 μC/cm^2 and PMMA etching times of 6, 4 and 3mn.

Table 1
Ar sputtering yields [13] in normal incidence and for an energy of 500 eV.

Metal	Sputtering yield
Cr	1.131
Fe	1.157
Co	1.248
W	0.664

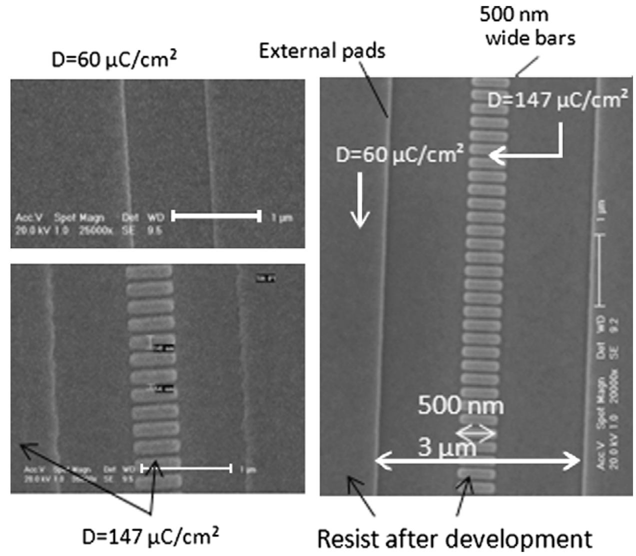

Fig. 1. Bilayer resist patterning before metal deposition for "gratings" and different doses *D*.

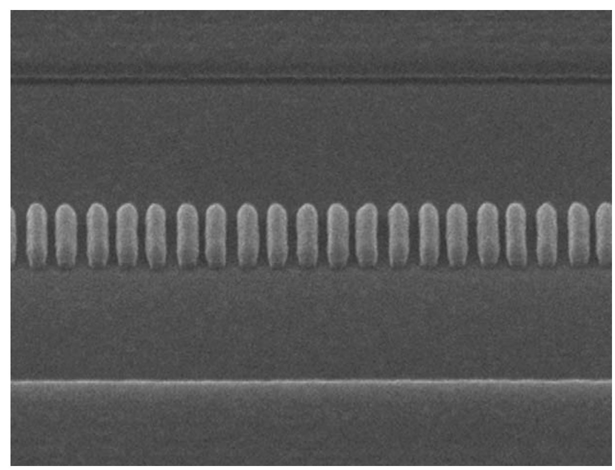

Fig. 2. Profile of the grating bars after W sputtering and before lift-off. PMMA etching time equals 3 mn.

Whatever the initial aperture and the etching time, the best tungsten gratings have been obtained with bars dose of 147 μC/cm^2 in agreement with preliminary dose test. Corresponding pictures are shown in Fig. 3. The indicated aperture is the e-beam written pattern one. For a given initial resist aperture (series (a)–(c), or series (d)–(f)), higher etching time leads to straighter opening of the gratings bars, and resulting grating filling factor near 75%.

Moreover in that case the grating opening edges are not sharp. This is due to the fact that under-etching of PMMA has increased the space between the resist bars. Tungsten was deposited also in these spaces, possibly with no well-defined edges as schematized in Fig. 4. When under-etch is large, the film is ripped down along the edges and let irregular pattern. However by properly choosing process conditions, well-defined nanopatterning can be obtained.

Fig. 3c shows that best grating has been obtained with a PMMA etching time of 3′ and aperture of 90/110 nm, demonstrating that the bilayer resist HSQ/PMMA process allows to realize simultaneous lift-off of small (grating bars) and large (external pads) pattern of low sputtering yield metal.