Microelectronic Engineering 143 (2015) 5–10

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

High contrast 3D proximity correction for electron-beam lithography: An enabling technique for the fabrication of suspended masks for complete device fabrication within an UHV environment

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ARTICLE INFO

Article history:
Received 28 October 2014
Accepted 19 January 2015
Available online 28 January 2015

Keywords:
E-beam lithography
Suspended shadow mask
Angled evaporation
3D-PEC
GenISys BEAMER
Lateral spin valve

ABSTRACT

Many devices, such as lateral spin valves, depend critically on the quality of interfaces formed between different materials, and hence require the entire device to be fabricated within an ultra-high vacuum environment. This is possible using angled deposition with a suspended mask such that, by depositing from specific angles, different patterns form on the substrate beneath. We use a bi-layer of MMA(8.5)-MAA copolymer and PMMA patterned by electron-beam lithography (EBL) to form such a mask. It is necessary, though, to perform proximity effect correction (PEC) in EBL to achieve the correct spatial distribution of electrons, and hence produce the desired pattern in the developed resist. For bi-layer processes this is a three-dimensional (3D) correction since we must optimise for two different critical doses (one for the copolymer, the other for the PMMA) at defined 3D positions within the resist stack. We perform this 3D correction using the commercial software BEAMER produced by GenISys GmbH. We show that by applying manual shape segregation and modulation to the exposure pattern, prior to the "3D-PEC" algorithm, it is possible to achieve much higher contrasts in the spatial distribution of absorbed energy and hence significantly increase the processing window, and yield in the fabrication of suspended masks.

1. Introduction

The performance of many devices, for example lateral spin valves, depend critically on the quality of the interfaces formed between different materials [1,2], and hence requires materials to be grown consecutively within an ultra-high vacuum (UHV) environment. However, to fabricate functional devices, it is often convenient to pattern one material before depositing the next. A commonly adopted approach is to combine a suspended mask structure with angled deposition such that, by changing the angle of deposition, shadowing by the mask forms different patterns on the underlying substrate (Fig. 1). This technique is also used for devices requiring self-aligned structures since multiple layers can be patterned using the same lithographically defined feature.

The angled deposition technique has been applied to the fabrication of lateral spin valves [3], single-electron transistors [4], memristors [5] and Josephson junctions [6], amongst others. One of the earliest, and most widely implemented, suspended mask techniques uses a tri-layer system [7,8]. Here, the top layer is an organic resist which is patterned via electron-, photon- or imprint-lithography. The middle layer forms the mask and is chosen to be chemically different from the organic materials used in the top "resist" and bottom "undercut" layers. Hence, is usually an inorganic material such as aluminium or germanium. The pattern, formed in the resist, is transferred via etching into this middle layer using a method that does not readily degrade the organic layers. For aluminium, a wet etchant, such as mixed phosphoric and nitric acid might be used whilst for germanium, an anisotropic dry etch using CF_4 can lead to more accurate pattern transfer. Finally, the bottom "undercut" layer is selectively removed from beneath the middle layer via isotropic wet or dry etching. Many different implementations of this method have been published including simplified versions requiring only bi-layer systems consisting of pairs of polymers; here, the top resist can be patterned, and the bottom polymer dissolved selectively – e.g. Polymethylglutarimide (PMGI) and PMMA [9].

A significant disadvantage of these approaches is that the degree of undercutting of the mask is equal for all parts of the pattern. Often, it is desirable to define large undercuts in some regions

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http://dx.doi.org/10.1016/j.mee.2015.01.020
0167-9317/

whilst maintaining minimal undercuts in others, since the structural integrity of the suspended mask can be compromised by having large undercuts where they are not required. To achieve this, it is necessary to be able to define the degree of undercutting lithographically. This is possible by utilising two resists possessing significantly different sensitivities and patterning them using electron-beam lithography (EBL). A "high dose" of electrons can be used to expose both resists, whilst a "low dose" can be used to make only the more sensitive resist soluble. If the more sensitive resist is the bottom film within the bi-layer, then the "low dose" can be used to define the regions where undercutting will occur. This method has been implemented previously in both simple bi-layer (MMA(8.5)MAA copolymer and PMMA) [10] – the resist structure we use – and tri-layer schemes (MMA(8.5)MAA copolymer, Ge, PMMA) [11].

In EBL, it is necessary to perform proximity effect correction (PEC) to exposure data in order to achieve the correct spatial distribution of electrons, and hence produce the desired pattern in the developed resist. This correction addresses scattering effects within the resist and substrate that spatially and energetically redistribute the electrons of the incident beam. A PEC algorithm modulates either the relative dose or the shape of an exposure pattern to account for these scattering effects.

In our work, the "high dose" value is determined by the critical dose of the (less sensitive) PMMA top layer while the "low dose" value is determined by the critical dose of the (more sensitive) copolymer bottom layer. The energy density absorbed in "low dose" regions must have an upper and lower bound since it is necessary to make the copolymer soluble whilst not significantly degrading the PMMA layer above. The proximity correction required for such exposure patterns is therefore a 3D problem since it must optimise for two separate doses, defined laterally and vertically, within the resist stack. The commercial software BEAMER (from GenISys GmbH [12]) incorporates a "3D-PEC" algorithm that can be used to solve such a problem.

The PEC algorithms implemented in BEAMER are based on the work of Pavkovich [13] where the energy density absorbed in the resist is modelled as the convolution between the exposure pattern and a point spread function. Furthermore, it is assumed that the developed resist boundary will follow a contour of critical absorbed energy, and hence a simple binary PEC problem can be reduced to considering only the energy density required at the edges of a given pattern. GenISys have modified this basic algorithm and extended its application to 3D-PEC problems [14]. The point spread function (PSF) used in a PEC algorithm is typically a description of the energy density absorbed in the resist as a function of distance from the beam. Such PSFs are usually estimated via Monte Carlo simulation techniques which reasonably describe electron–matter interactions. Other effects such as lateral development, finite resist contrast and process blur can be incorporated into the PSF, however here we shall only consider electron scattering.

We will show that by manually performing shape modulation and segregation of "low dose" parts of the pattern prior to performing the 3D-PEC, it is possible to achieve much higher contrasts in the lateral distribution of absorbed energy and hence significantly increase the processing window and yield in the fabrication of suspended masks. Ultimately, this increase in dynamic range is due to the application of both shape and dose modulations.

2. Resist sensitivity and point spread functions

Suspended mask structures were formed in a resist bi-layer of MMA(8.5)MAA copolymer (500 nm) and PMMA 950 k (200 nm) using 100 kV electron beam lithography with a JEOL JBX-6300FS system (exposure conditions: 100 kV, 500 pA beam current, 6 nm shot pitch). Methyl methacrylate–methacrylic acid copolymer, MMA(8.5)MAA EL11, and polymethylmethacrylate, PMMA 950 k A5, were both purchased from Microchem Corp. Silicon wafers covered with a 100 nm thick oxide film were used as substrates. Fig. 2(a) shows the experimentally measured contrast curves for 50% fill chequer board patterns written in single layers of PMMA and copolymer (each 400 nm thick) developed in 7:3 isopropanol–water for 90 s at 20 °C. The colouration overlaying the graph in Fig. 2(a) correspond directly to those shown in the table, Fig. 2(b), which describes the effects these doses have on the two resists.

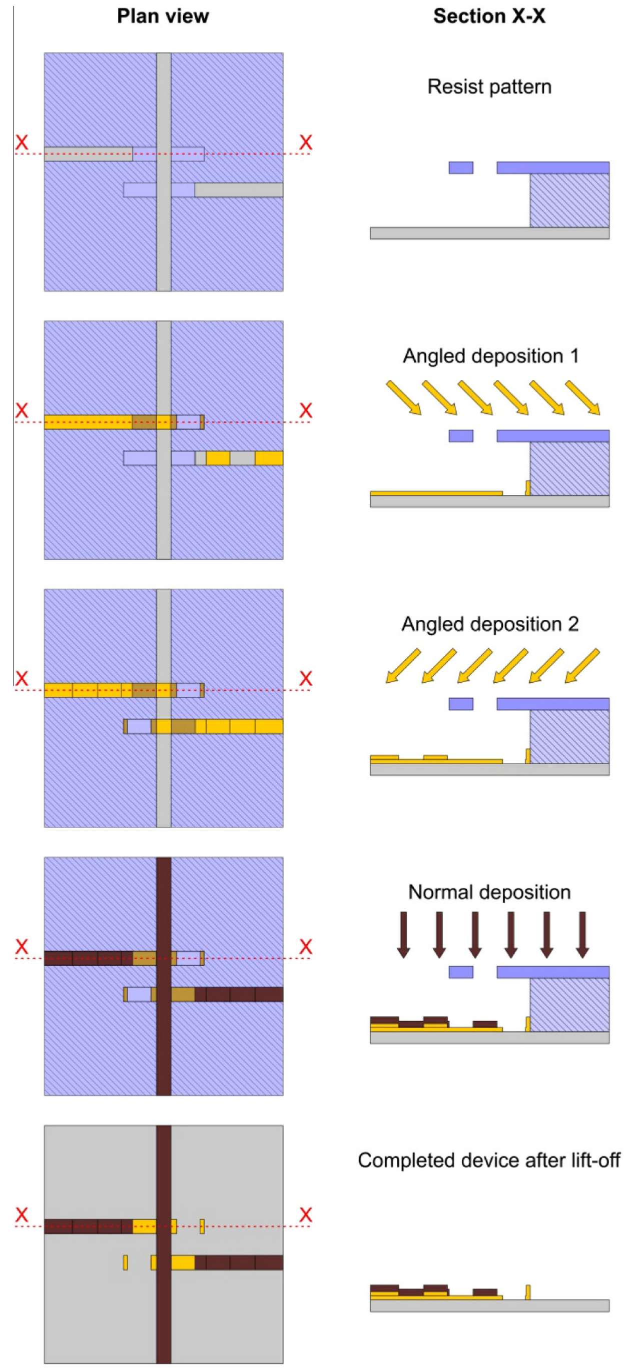

Fig. 1. Schematic showing how different patterns form on a substrate by evaporating materials at specific angles through a suspended mask. Here, grey represents the substrate, hashed blue areas are copolymer and solid blue areas are PMMA. In the plan views, the PMMA has been treated as "transparent" such that the boundaries of the copolymer are visible. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)