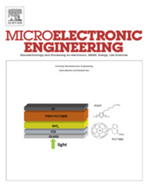
Microelectronic Engineering 130 (2014) 57–61

Contents lists available at ScienceDirect

Microelectronic Engineering

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



Phase-shift lithography for sub-wavelength patterns of varying aspect ratios

Angeline Klemm, Andrew Lyle, Todd Klein, Jonathan Harms, Jian-Ping Wang *

Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455, USA

ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form 30 July 2014
Accepted 28 September 2014
Available online 7 October 2014

Keywords:
Phase-shift lithography
Nanoscale patterning
Mask fabrication

ABSTRACT

A technique for creating phase shift photolithography masks for use with a stepper or mask aligner, as well as how to achieve sub-150 nm features of different aspect ratios is described. The mask utilizes two different regions, one transparent region of only the mask material, and another transparent region of SiO_2, which are overlapped to create the pattern. Patterning was done by use of a Canon Stepper. By adjusting the angle between the two mask regions, the aspect ratio, which is defined as the length:width, of features was controlled. Features below 100 nm were patterned, and aspect ratios were controllably tuned between 1.1 and 2.6. The feature size was also shown to be able to be reduced by 25–30 nm with the use of reactive ion etching.

1. Introduction

The evolution of technology has been continually increasing the demand for patterning nanoscale devices, which have been exploited in a wide range of fields. Optical lithography is a preferred patterning technique compared to other techniques due to its low cost and ease of use to pattern large areas. However, high resolution of feature sizes below the exposure wavelength is difficult to achieve. Patterning of nanoscale devices is traditionally done using electron beam (e-beam) lithography which can resolve features well below 50 nm. However, e-beam lithography is a time consuming and costly process. Furthermore, many research facilities do not have access to an e-beam lithography system.

Optical resolution-enhancement techniques are required in order to continue the scaling of device sizes using optical lithography. One method, phase-shift lithography [1], is an optical lithography process which allows sub wavelength features such as lines and dots to be patterned which are difficult to achieve with regular photolithography masks.

Most previous works on phase-shift lithography have focused on obtaining high resolution patterning [1–5] and controlling the dimensions across a wafer [6–8] in settings such as production or industry research and development. The patterning focuses on rectangular objects and lines used in dense, complex circuit designs. Other advances feature structures can be formed by combining soft-lithography techniques with phase-shift lithography. A phase shift method based on near-field optical nanolithography has been developed which combines aspects of soft-lithography roller techniques with phase-shift photolithography [9]. However, this method requires a set-up designed for roller patterning rather than standard lithography exposure tools. Soft-lithography has also been combined with phase-shift methods to obtain 3D periodic structures [10]. Interference lithography [11,12] and extreme UV interference lithography techniques [13–15] can also be used to obtain various patterns below 100 nm; however, this method can be quite costly and is not available to many smaller companies and research settings. To the best of our knowledge, it has not been systematically shown using phase-shift lithography masks how to achieve various aspect ratios for nanoscale elliptical features, which has strong applications in a variety of topics, including magnetic random access memory (MRAM) and spintronic applications, which are recently of great interest to industry and researchers.

In this study, the phase-shift mask fabrication process, aspect ratio patterning technique, and experimental results from a mask aligner and stepper system will be reported. We have developed a mask design and systematic process for easily and reliably controlling the aspect ratio of patterned dots. Conventional phase-shift lithography masks typically use the entire feature on the mask to create the optical pattern and double exposure techniques are used to define critical and non-critical regions in circuit designs or to trim features. In our design, only the intersection between two phase-shift lithography masks is important to the final feature and is used to define the ellipse. The phase-shift mask fabrication process, aspect ratio patterning technique, and experimental results from a mask aligner and stepper system will be reported.

---

* Corresponding author. Tel.: +1 612 625 9509.
E-mail address: jpwang@umn.edu (J.-P. Wang).

http://dx.doi.org/10.1016/j.mee.2014.09.022
0167-9317/

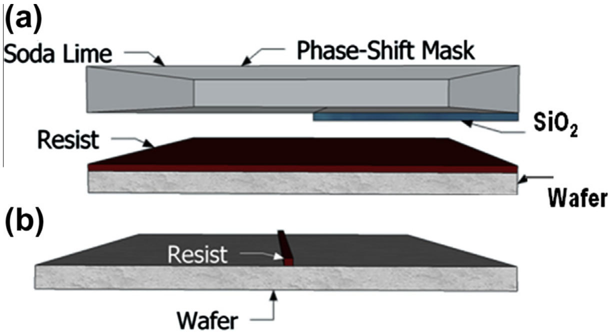


Fig. 1. Working principle for (a) phase-shift lithography and (b) resulting pattern.

Furthermore, we have developed a low-cost mask making process that can be used in a research facility for use with phase-shift photolithography to resolve features down to 100 nm of varying aspect ratios across a four inch wafer which is easy to use and apply. The patterning process described has allowed us to pattern features well beyond the traditional limit of the stepper lithography system used at our facility, which is about 400 nm for feature sizes. This ease of use and versatility should allow a wide range of processes to use phase-shift photolithography and take advantage of the speed of the process. This process can also be used to reliably pattern large substrate areas at one time in a low cost and time effective way, both of which are appealing to academic and industrial applications.

Phase-shift photolithography utilizes a photo mask which has different regions, as shown in Fig. 1(a). One region of the phase-shift mask is fully transparent and only has the mask material, which is typically quartz. The second region has a transparent material on top of the mask, which is silicon dioxide (SiO_2) in our case. The transparent SiO_2 allows the light to pass through; however, there is a difference in refractive index between the SiO_2 and air. By controlling the thickness of the SiO_2 so that the light is phase shifted by 180°, destructive interference occurs between the SiO_2 region and the quartz region of the mask [16]. The destructive interference results in the area near the interfaces receiving a lower exposure dose than the rest of the mask, and sub-wavelength features can be resolved as shown in Fig. 1(b). To pattern circular and elliptical features, a second phase-shift mask is required. The second mask is used to expose parts of the line created from the first mask in order to form circular and elliptical features. By adjusting the angle between the features on the two masks, the aspect ratios of the features can be controlled.

2. Materials and method

2.1. Mask fabrication

The phase-shift masks were fabricated by first thoroughly cleaning the soda lime or quartz in a sulfuric acid bath at 150 °C bath for 1 h. Then silicon dioxide (SiO_2) was deposited on the mask using plasma enhanced chemical vapor deposition (PECVD) at 350 °C. The refractive index for the deposited SiO_2 was approximately 1.46. The thickness of the SiO_2 was set to 436 and was measured using an ellipsometer. A DC sputtering system was used to deposit 100 nm of chromium (Cr) onto the SiO_2. The phase-shift masks were directly patterned using Shipley 1805 photo resist, photolithography masks, and a Karl Suss Mask Aligner. The size of the patterned phase-shift mask features ranged from 7 μm to 40 μm. The Cr was etched using a wet etching technique and then the resist was stripped. The remaining Cr was then used as a hard mask to etch the SiO_2. The SiO_2 was etched using reactive ion etching and then the Cr was removed from the features by wet etching, except for the alignment marks. The step-by-step process for the phase-shift mask fabrication is shown in Fig. 2.

2.2. Phase-shift lithography patterning

Shipley 1805 photo resist was used for all of the photolithography patterning. The samples were prebaked at 115 °C for 2 min and then hexamethyldisilazane (HMDS) was used as an adhesion promoter. The resist was spun on at 4000 rpm which results in a resist thickness of around 460 nm. The sample was soft baked at 105 °C for 1 min. A Canon Stepper was used to pattern the features with a sequence of two phase-shift masks. The pattern was exposed at a wavelength of 365 nm with a total dose of 90 μJ/cm^2. Since two exposure steps were used, the first mask was exposed at half of the total required exposure dose. Then the second mask was exposed at half the required exposure dose, which results in the total required dose for patterning. After patterning, the samples were developed in Microposit 351 developer:DI water. Then the samples were hard baked at 120 °C for 2 min.

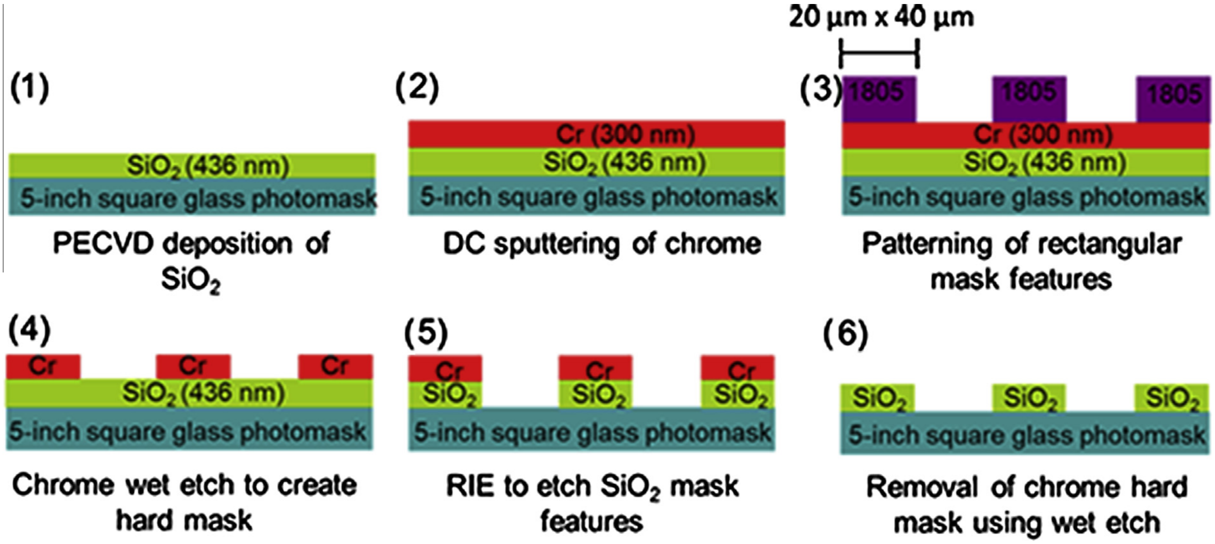


Fig. 2. Process flow for fabrication of phase-shift lithography mask.