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High resolution HSQ nanopillar arrays with low energy electron beam lithography

Y. Guerfi *, F. Carcenac, G. Larrieu

LAAS, CNRS, Univ de Toulouse, 7 avenue du colonel Roche, F-31400 Toulouse, France

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ABSTRACT

Electron beam lithography (EBL) is commonly used for the fabrication of nanostructures by top-down approach with precise control of size, shape, aspect ratio, and location. In this article, we demonstrate the realization of high aspect ratio nanopillars (7.5) with 20 nm diameter in 150 nm Hydrogen SilsesQuioxane (HSQ) thickness based on 20 keV energy exposure. A detailed study of design strategies has been conducted in order to correlate the design of the nanopillars and their practical realization. We describe an original way of scanning for HSQ nanopillar arrays fabrication with almost perfect anisotropic sidewalls (98.5%) and good circularity shape (1.62 nm-1σ) without any residual resist remaining around the nanostructures.

1. Introduction

Following the down-scaling of MOSFETs to the ultimate scale, novel architectures were proposed as tridimensional multigate architecture [1]. In that context, gate all around nanowire transistors [2] present the optimum configuration for electrostatic control of the gate over the channel [3]. The starting point of such a device is the formation of nanowire array with a perfect control of the dimension, location and parasitic contamination. For silicon nanostructure realization, conventional top-down approach is the most used because of its suitability with CMOS fabrication tools and techniques. The definition of the hard mask pattern is the critical step because it determines the form of the final structure. For ultimate scaling, electron beam lithography is one option in order to reach narrow dimension combined with high density.

The high resolution negative tone resist Hydrogen SilsesQuioxane (HSQ), is widely used for EBL processing, because of its capability to perform high resolution nanostructures [4]. The HSQ, being an inorganic resist, has a good resistance to plasma etching and a good mechanical strength [5,6]. Finally, its good sensitivity to electrons permits to apply low doses during electron beam writing.

Outstanding results have been demonstrated using high energy electron beam writers operating at 100 keV [7,8] or 50 keV [9], with dense arrays of 20 nm diameter nanopillars. However, machines enable to work at such voltages are not widely used because of their high total cost of ownership (TCO). Moreover, a longer exposure time is expected when high voltage is used because of the linear dependency of the dose with the energy. To circumvent these potential limitations, nano-patterning of resist at relatively low energy is of prime interest but challenging due to its higher sensibility to the proximity effects. Several studies at low voltages have been conducted [10–13], but exclusively using thin resist thicknesses, which limit their application as etching hard-mask. The results generally show residual resist at the bottom of nanostructures [11] due to the proximity effects, limited aspect ratio or severe size dispersions [12] which should induce variability in the nanostructure-based electronic device. A relevant work have been done at 5 keV with a multi electron beam (13000 beams) from Mapper Company (Netherland) at the CEA LETI (France) but still in thin resist thickness [13].

In this work, a dedicated design strategy has been conducted in order to demonstrate circular shaped nanopillars. Vertical nanostructures with high aspect ratio have been patterned using low energy electron beam lithography, with a good control of proximity effects.

2. Experiments

The HSQ resist is identified with a general formula of $(HSiO_{3/2})n$, based on cage like structure which is transformed into network structure after e-beam exposure by the scission of Si–H bonds and the formation on Si–O–Si bonds (siloxane bonds), as explained by Namatsu et al. [14]. In our experiments, HSQ from Dow Corning (FO*x*-15) have been diluted in Methyl Iso Butyl Keton (MIBK) in 1:1 proportion and spun on Si (100) wafers for 60 s at 5000 rpm, in order to obtain 150 nm HSQ thickness. Then the sample has been softly baked at 80 °C for 1 min in order to evaporate the solvent

* Corresponding author at: LAAS, CNRS, 7 avenue du colonel Roche, F-31400 Toulouse, France. Tel.: +33 (0) 5 61 33 79 84; fax: +33 (0) 5 61 33 62 08.

E-mail addresses: yguerfi@laas.fr (Y. Guerfi), glarrieu@laas.fr (G. Larrieu).

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while avoiding the crosslinking of the resist before e-beam exposure.

The EBL was carried out with a RAITH 150 writer at 20 keV energy exposure with a base dose of 300 $\mu C/cm^2$ and a beam current of 120 pA. Casino simulations [15] were performed to find voltage acceleration suitable to obtain height of nano-pillars sufficient to act as an hard mask in a plasma etching process. For that purpose, it was concluded that 20 keV is the suitable energy exposure to limit electron forward scattering which degrade the side-wall anisotropy of the patterns. The development of the resist after exposure was performed by manual immersion in high concentrated (25%) TetraMethylAmmonium Hydroxide (TMAH) to increase the contrast [16]. Finally the sample was rinsed in deionized water then in methanol solution before a soft dry with nitrogen flux in order to reduce the surface tension and minimize the nanopillar collapse.

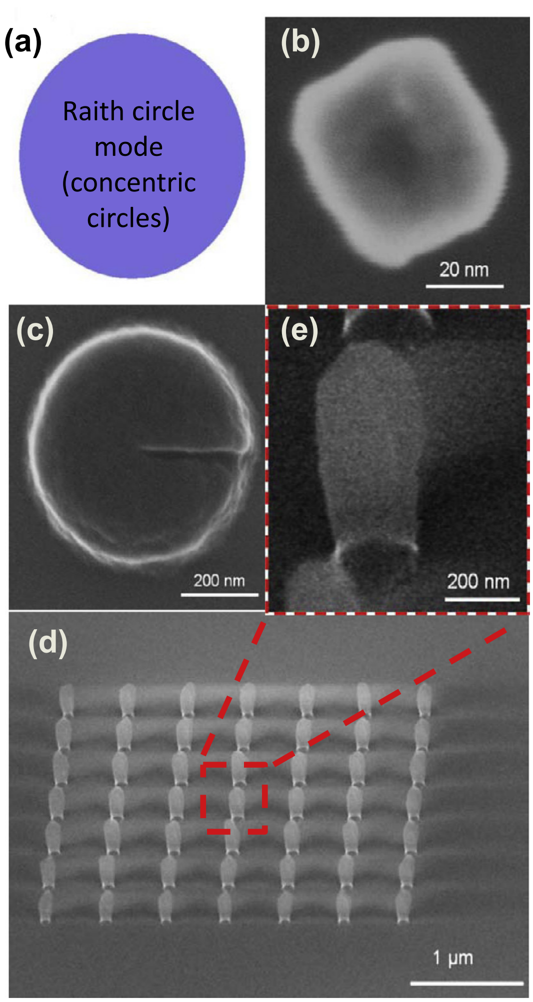

Fig. 1. (a) Illustration of RAITH circle mode design, (b and c) SEM top view of Raith circle mode on HSQ of small and large nanopillars respectively, (d) SEM tilted view of nanopillar array with (e) zoom on a single nanopillar.

3. Design strategy study

To create circular HSQ nanopillars, the first sets of experiments were performed using the RAITH circle mode schematized in Fig. 1a, that supposed to be in concentrically circle mode. When addressing diameter less than 100 nm, the nanostructures showed a square shape (Fig. 1b).Moreover, a stitching defect was clearly noticed when a larger diameter has been patterned (Fig. 1c). We suppose that this defect is issued by the connection of the concentrically circles Raith based mode. From SEM titled view (Fig. 1d), it was observed a bowed sidewalls and the stitching defect mentioned above is transferred along the nanopillars (Fig. 1e). Since the results obtained by the conventional tools available in the RAITH software's equipment give unexpected results, i.e. high dispersion of nanostructures circularity, bowed sidewalls and thus, do not allow a good transfer of the nanostructures to the substrate, a dedicated design strategy studies became a necessity to find out an efficient way for circle design. In this scope, we propose several designs: (i) "concentric circles" which consists in drawing circles one inside another, using the resist resolution (5–10 nm) as the pitch between two circles (Fig. 2a), (ii) "star like" consists in drawing lines starting and finishing at the center of the pattern, with a maximum distance between two adjacent lines is the HSQ resolution (Fig. 2b), and finally (iii) a combination of the two previous designs (Fig. 2c).

4. Results and discussion

Starting with the concentrically circles mode, we firstly decided to tighten the circles in the peripheral region in order to emphasize the effect of the exposure on sidewalls' shape. We obtained circular patterns (Fig. 3a) but the tilted inspection revealed nanostructures with conic shapes (Fig. 3b). A similar result has been obtained when tightening the circles on the center of the designed pattern (not shown). The conic shape obtained is probably due of the superposition of the energy distribution of each designed circle that wraps all the Gaussians distributions into a larger one. Moreover, the combination of concentrically circles and star like designs does not improve the situation where higher dispersion of nanostructure size was obtained coupled with a conic shape, suggested by (Fig. 3c). Finally, the star like design leaded to the most interesting results where nanopillars with better circularity were observed by top SEM inspection with 1.62 nm 1σ dimension dispersion (Fig. 3d). We achieved nanopillars with almost perfect vertical

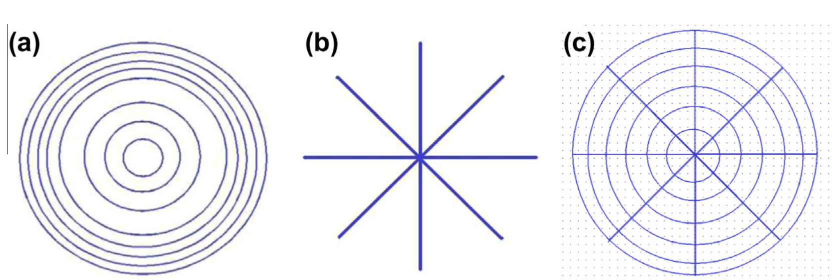

Fig. 2. Circle design strategies: (a) Concentrically circle design, where the circles are designed one inside another, with the HSQ resolution as the pitch between two circles (b) star like design, where the lines start and finish at the center, with a maximum distance between two adjacent lines is the HSQ resolution (c) combination of star like and concentrically circle design.