Microelectronic Engineering 121 (2014) 104–107

Contents lists available at ScienceDirect

Microelectronic Engineering

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

Single-spot e-beam lithography for defining large arrays of nano-holes

Emil Højlund-Nielsen [a], Tine Greibe [b], N. Asger Mortensen [c], Anders Kristensen [a,*]

[a] Department of Micro- and Nanotechnology, Technical University of Denmark, Oersteds Plads, Building 345B, DK-2800 Kgs. Lyngby, Denmark
[b] National Center for Micro- and Nanofabrication, Oersteds Plads, Bygning 347, 2800 Kongens Lyngby, Denmark
[c] Department of Photonics Engineering, Oersteds Plads, Bygning 343, 2800 Kongens Lyngby, Denmark

ARTICLE INFO

Article history:
Received 27 October 2013
Received in revised form 14 March 2014
Accepted 22 March 2014
Available online 3 April 2014

Keywords:
Electron beam lithography
Direct-writing
Single-shot writing
Nanofabrication

ABSTRACT

Efficient nanoscale patterning of large areas is required for sub-wavelength optics. Here we use the single-spot exposure strategy, where electron beam lithography (EBL) with a focused Gaussian beam is used to define shapes directly. The serial technique is optimized on the JEOL JBX-9500FS 100 keV prototype EBL system for speed and pattern fidelity to a minimum writing time of around 30 min/cm^2 for 200 nm periods in 2D lattices. The machine time and feasibility of the method are assessed in terms of the trade-off between high current and large writing field.

1. Introduction

Efficient nanoscale patterning of large areas is required for sub-wavelength optics. For example, photonic crystal applications may require periodic structures with a period of 200 nm or below. Such structures are conveniently fabricated by electron beam lithography. Still, the final product must be made at an economic cost. Here we use a single-spot exposure strategy [1–7], where EBL with a focused Gaussian beam is used to define shapes directly. Conventionally, EBL uses multiple exposures of slightly overlaying spots, see Fig. 1A. As a result, the shape time dominates the beam time, and is the major contributor to the overall writing time. Instead, the single-spot exposure strategy uses the machine as a raster scan tool to write a large rectangle, using a beam step size larger than the spot size, see Fig. 1B. The serial technique is optimized for speed and pattern fidelity to a minimum writing time of around 30 min/cm^2 for 200 nm periods in 2D lattices. The machine time and feasibility are assessed for different topographies and dimensions.

The single-spot electron beam technique discussed in this paper was first described in 1993 by Wendt et al. [1], which used a 6 nm beam-spot with a 5 nm resolution to define holes 50 nm in diameter by etching. This was followed by a more thorough study in 2003 by Kim et al. [4] showing that the single-spot exposure scheme can provide pattern quality similar to the conventional multi-spot exposure approach, but with an order-of-magnitude reduction in the required writing time. For a period of 300 nm and a dose of 30 μC/cm^2 (224 nm spot), writing times were reported to be faster than 1 h/cm^2 depending on the current (up to 44.4 nA). Furthermore, a modified four-spot scheme was also demonstrated for arbitrary shape definition. However, the work of Kim et al. is based on software estimation of the writing time, and it does not investigate small periodic structures with a high filling-ratio. Same year Gadegaard et al. [2] examined the dot diameter as function of dose and the shape diameter as function of the distance to the writing field center, where a writing field side-length of 0.4 mm was found appropriate. Finally, in 2011 Jugessur et al. [5] examined hexagonal patterns with a current of 44 nA. From the literature, it seems that the components of the total writing time has not been examined in detail, which is the focus here.

2. Theory

As a simple model, EBL writing time per area A, t'_{writ}, has four components; beam time, shape time, stage time and calibration time:

$$t'_{\text{writ}} = t'_{\text{beam}} + t'_{\text{stage}} + t'_{\text{shape}} + t'_{\text{cal}} \quad (1)$$

The beam time relates to exposing the resist and is given by dose D and current I as $t'_{\text{beam}} = D/I$ [8]. Stage time, t'_{stage}, is related to the mechanical movement of the stage from writing field to writing field and depends on the writing field area $A_{WF} = \ell_{WF}^2$, with side length ℓ_{WF}, and on the machine parameter τ_{stage} for one average movement of the stage. The stage time can be given as $t'_{\text{stage}} = \tau_{\text{stage}}/A_{WF}$. The shape

* Corresponding author. Tel.: +45 45256331; fax: +45 45887762.
E-mail address: anders.kristensen@nanotech.dtu.dk (A. Kristensen).

http://dx.doi.org/10.1016/j.mee.2014.03.025
0167-9317/

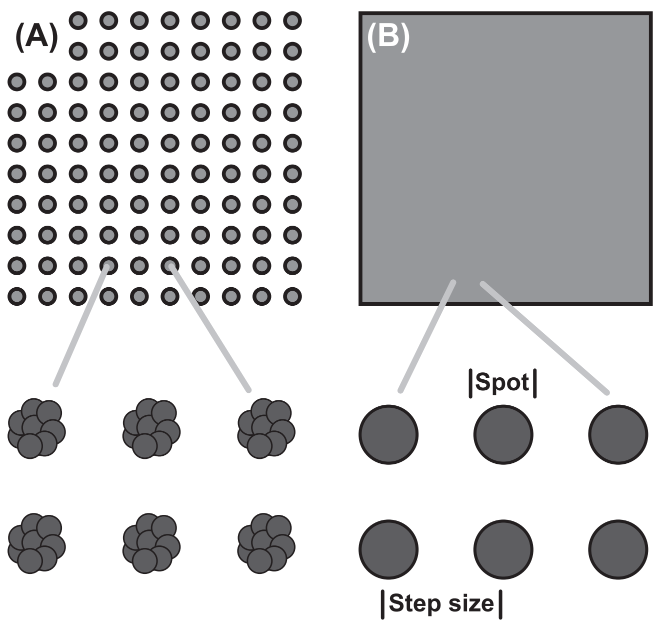

Fig. 1. Illustration of the single-spot exposure strategy. (A) The conventional method for pattern layout is to design an array of circular spots to form the final pattern. (B) Fast-writing patterns are formed directly by a single exposure with a given spot size spaced by the beam step size.

time can be modeled as $t'_{shape} = \tau_{shape} N_{shapes}$, where τ_{shape} is the average time to address each of the N_{shapes} shapes. Shape time is usually negligible using the single-spot exposure strategy, which is the main argument for the method, and will not be discussed further. Calibration is critical for focus [2] and efficient calibration routines in terms of stability and drift compensation become imperative with this method. The calibration can be modeled as a continuous contribution in the form of $t'_{cal} = \tau_{cal}\left(t'_{beam} + t'_{shape} + t'_{stage}\right)/\Delta t_{cal}$ for a Δt_{cal} cyclic calibration interval with time parameter τ_{cal}. Putting all together, the writing time Eq. (1) can be assumed to be a linear function of dose:

$$\begin{aligned} t'_{writ}(D) &= \left(\frac{D}{I} + \frac{\tau_{stage}}{A_{WF}} + \tau_{shape} N\right)\left(\frac{\tau_{cal}}{\Delta t_{cal}} + 1\right) \\ &= \alpha D + \beta, \end{aligned} \quad (2)$$

where α and β are fitting coefficients to be estimated from experiments. From the slope α, we may deduce the calibration time overhead, $\tau_{cal}/\Delta t_{cal} = (\alpha I - 1)$, if the current is assumed constant. Finally by plotting the β coefficients as function of writing field area, we may deduce an expression for stage time:

$$\beta = \left(\frac{\tau_{stage}}{A_{WF}} + \tau_{shape} N\right)\left(\frac{\tau_{cal}}{\Delta t_{cal}} + 1\right) = \gamma \frac{1}{A_{WF}} + \delta, \quad (3)$$

where γ and δ are fitting coefficients. Then the stage time parameter can be deduced as $\tau_{stage} = \gamma/(\tau_{cal}/\Delta t_{cal} + 1)$.

3. Methods

The JEOL JBX-9500FS is a prototype 100 keV spot EBL system. The beam is generated by a ZrO/W emitter and electron-beam scanning speeds up to 100 MHz are available. By optimizing the lens focusing system and using an aperture of 200 μm, stable currents of 29 nA, 42 nA and 61 nA, can be provided with sufficiently small beam diameters, similar to previous reported 44 nA in 2011 [5] and two orders of magnitude higher than previous reported 0.33 nA in 2003 [2].

In terms of initial calibration, the two deflectors (position deflector and scanning deflector) are calibrated. These calibrations correct the gain and rotation deflector errors and determine the height correction coefficient, thereby influencing the homogeneity of the pattern writing over a writing field. The distortion correction values of the electron beam in the writing field are also measured. Prior to each pattern writing, the height of the substrate is measured at different positions, and the focus value of the objective lenses is corrected.

The cyclic calibration includes a current measurement, a drift measurement using a mark on the stage, and a temperature measurement on various positions in the machine. These calibrations are performed on a 5 min basis to ensure identical writing conditions.

Six experiments were carried out in order to test the influence of current and writing field on writing time and pattern quality. The dose was varied from 30 μC/cm^2 to 120 μC/cm^2 in steps of 15 μC/cm^2, yielding a total of 42 areas, each of exposure area 5 mm × 5 mm. The exposure dose interval was loosely estimated based on the clearing dose of the positive ZEP-520A resist (Nippon ZEON Company, Ltd.), which is around 30 μC/cm^2 according to the manufacturer data sheet. First, the current was altered; 29 nA, 42 nA, 61 nA, while keeping the writing field fixed at 0.2 mm and then the writing field was altered; 0.3 mm, 0.4 mm and 1.0 mm, while keeping the current at 29 nA. The outcome of this investigation should be a determination of the machine parameters τ_{cal} and τ_{stage}. For each exposed area the writing time was found by subtracting the end time of the exposure from the start time, both retrieved from the machine log after the exposure. The current was measured as part of the cyclic calibration and the mean current of each experiment was used for the calculations.

Devices were fabricated in silicon by exposure of the resist with thickness 158 nm, development, and reactive-ion etching.

4. Discussion

In Fig. 2, the writing time per cm^2 as function of dose is given for different currents with a writing field side length of 0.2 mm. The writing time is seen to be linear dependent on the dose as expected from Eq. (2) with a large offset due to the 0.2 mm writing field. Still, the writing times are faster than 2 h/cm^2 for the chosen dose interval. By linear fitting, we determine α and β for the three different currents. Based on the fitting, it is given in Table 1 that the beam overhead is around 15 s for 301 s of calibration interval corresponding to 5.5% overhead. Therefore, the effective current, that is the inverse slope in Fig. 2, is 27.6 nA for the 29 nA exposure. From Fig. 2, it is clear that the 61 nA current reduces the beam time. Still the stage time constitutes the main component of the writing time and the writing time remains in the order of 45 min/cm^2.

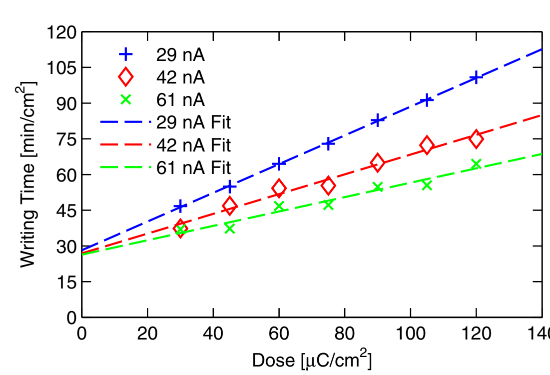

Fig. 2. Measured writing time as function of dose and linear fits (dashed lines) for different currents with array periods of 200 nm and writing field side length of 0.2 mm. Exposure includes calibration. Initial machine calibration not included.