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Intra-level mix and match lithography with electron beam lithography and i-line stepper combined with resolution enhancement for structures below the CD-limit

C. Helke [a,b,*], C.H. Canpolat-Schmidt [a], G. Heldt [a], S. Schermer [a], S. Hartmann [b], A. Voigt [c], D. Reuter [a,b]

[a] Fraunhofer Institute for Electronic Nano Systems (ENAS), Technologie-Campus 3, 09126 Chemnitz, Germany
[b] Technische Universität Chemnitz, Center for Microtechnologies (ZfM), Reichenhainer Str. 70, 09126 Chemnitz, Germany
[c] Micro Resist Technology (MRT) GmbH, Köpenicker Str. 325, 12555 Berlin, Germany

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ABSTRACT

Herein, an Intra-level Mix & Match approach (ILM&M) was investigated to combine electron beam lithography (EBL) and i-line stepper lithography on the same resist layer. This technique allows the combination of the advantages from both technologies. EBL enables the manufacturing of small sub 100 nm structures but has the disadvantage of low writing speed especially for larger structures. The i-line stepper mask- or reticle-based lithography are used for the exposure of larger features with reduced exposure time. Here the negative tone resist ma-N 1402 (from Micro Resist Technology GmbH), an UV and electrone sensitive resist was investigated in EBL and an ILM&M approach. An ILM&M process for both EBL and i-line stepper lithography is performed on the same resist layer followed by one developing step. The inspection of the developed patterns via scanning electron microscopy (SEM) showed dimensions with a 1:1 print for EBL and i-line stepper lithography with respect to the layout. By varying the exposure dose of the i-line stepper, the linear dependency to the structure width is investigated. By this means we achieved structures below the 1:1 print down to 86 nm structure width.

1. Introduction

The fabrication of modern integrated circuits (IC's) or micro-electro-mechanical systems (MEMS) requires more and more complex patterns down to sub-100 nm scale. Electron beam lithography (EBL) is a suitable technology for the fabrication of small structures. It is a very versatile tool due to its mask-less writing technique [1]. But because of the sequential and therefore slow writing speed it is not the favorite technology for large areas or structures. One technique to overcome this problem is the Mix & Match (M&M) approach, where two or more patterning techniques are combined on one wafer [2]. Compared to the M&M approach, the intra-level mix and match (ILM&M) approach, which was investigated in this paper, also combines at least two patterning techniques, but on the same resist layer [3,4]. The advantage of the ILM&M, also known as hybrid lithography [5,6], is that no second layer of resist and only one development is required. The combination of EBL (here with VISTEC SB254, shaped beam with an acceleration voltage of 50 kV) and i-line stepper lithography (here with NIKON NSR 2205i11D with wavelength of 365 nm) allows to unite the advantages of both exposure technologies on one resist layer and to reduce the processing time and therfore saving manufacturing costs.

In [7] we presented first results of an exposure parameter set for both technologies on ma-N 1402 resist. In order to achieve a 1:1 structure print with respect to the layout, the required exposure dose and development process were studied separately first, for both processes. Due to targeted ILM&M approach, finally both exposure technologies were investigated in a combined process on one resist layer followed by one developing step.

In order to overcome the Critical Dimension limit (CD-Limit), i.e. the diffraction limited resolution that can be achieved [8], resolution enhancement techniques (RET) like Double Exposure Technology (DET) or spacer patterning can be used. By application of RET in i-line stepper lithography, smaller structures (e.g. < CD of 350 nm) were achieved, so electron beam lithography isn't even necessary. But RET are complex to integrate that's why alternatives to RET can be used, such as showed by exposing with lower exposure doses as required for the 1:1 structure

* Corresponding author at: Fraunhofer Institute for Electronic Nano Systems (ENAS), Technologie-Campus 3, 09126 Chemnitz, Germany
E-mail address: christian.helke@enas.fraunhofer.de (C. Helke).

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print to realize, structures below the CD-Limit were investigated.

2. Experimental details

For the experiments the negative tone resist ma-N 1402 (from Micro Resist Technology GmbH) with 200 nm thickness is used. The resist is based on a novolac resin and an aromatic bisazide as light sensitive component [9,10] making the resist sensitive to UV light and to electrons. In [7] process parameters such as substrate preparation, the required exposure dose and development time were investigated and determined for both EBL and i-line stepper lithography separately. The resolution limits for both exposure technologies were evaluated with dedicated exposure studies. For EBL 55 nm dots with 200 μC/cm^2 were achieved by exposing a 100 nm layout with a pitch of 300 nm. For i-line stepper lithography the 350 nm CD resolution limit was also investigated. All these experiments were performed on 6″ silicon wafers. The processing conditions for both EBL and i-line stepper lithography are shown in Table 1 for their separate exposure and the combined ILM&M approach.

In detail the process conditions for the IL&M are described in the following. As the standing wave phenomenon causes resist footing when exposing the ma-N 1402 with i-line stepper, a bottom anti-reflective coating (BARC) is used in i-line stepper lithography as well within this ILM&M process here. This coating absorbs the reflected light from the substrate [11,12]. For this purpose, the AZ BARLi II is coated directly underneath the ma-N 1402 layer. In a first step, as substrate pretreatment a dehydration bake at 200 °C for 20 min in a convection oven is applied on the 6″ silicon substrates, followed by spin coating the AZ BARLi II (from Microchemicals GmbH) at 3000 rpm for 60 s for a thickness of 200 nm. The followed baking of 200 °C for 60 s is done on a hot plate. Afterwards ma-N 1402 is spin coated with a resist thickness of about 200 nm at 3000 rpm for 60 s likewise and softbaked at 100 °C for 60s on a hotplate. All these spin coating processes are performed on a semi-automatic spin coater SM-200 (from Sawatec AG). The resist thickness and homogeneity are investigated with a spectroscopic ellipsometer (Sentec SE 850 PV) on 49 datapoints. A highly homogeneous resist film is observed with a thickness between 203 nm to 205 nm for the ma-N 1402 film [7].

EBL is done with the VISTEC SB254 which is a shaped beam writer with an acceleration voltage of 50 kV, whereas for the i-line exposures the NIKON NSR 2205i11D with 365 nm wavelength is used. The development is done by immersion development in a glass beaker with the developer ma-D 532/S for 60 s. Afterwards the wafers were rinsed with deionized water in an automated DI-bath. The inspection is done with an optical microscope from Nikon (Eclipse L300N) and a scanning electron microscope (SEM) from Jeol (JSM-7800F). The SEM allows to measure high-resolution surface and cross-sectional images.

Table 1
Processing conditions of ma-N 1402 for EBL and i-line stepper lithography (adapted from [7]).

Resist	Electron beam lithography separately	i-line stepper lithography separately	ILM&M
Substrate preparation	Dehydration bake: Oven, 20 min at 200 °C		
	Priming HMDS for 120 s at 120 °C	AZ BARLi II 3000 rpm, 60 s, 200 nm / Hot plate, 60 s 200 °C	
Spin-coating, resist	5 ml ma-N 1402 at 3000 rpm, 60 s, 200 nm		
Softbake	Hot plate, 60 s 100 °C		
Exposure	Doses varied, see below		
Development	ma-D 532/S, 30 s bath development, DI rinse	ma-D 532/S, 60 s bath development DI rinse	

3. Results and discussion

3.1. EBL and i-line stepper lithography ILM&M approach

The first step to perform the ILM&M approach is to investigate the ideal exposure dose for the 1:1 structure print of the layout for each patterning technology. Therefore, exposure dose tests for both EBL and i-line stepper lithography were done separately in [7]. In case of the EBL, the exposure dose is varied from 10 μC/cm^2 to 1000 μC/cm^2 in steps of 10 μC/cm^2 at most. Two different structures are investigated with this exposure dose variation, a line array (LA) and a square array (SA). The width of the features is within the range of 25 nm to 500 nm. The pitch of the structures is always double its width, i.e. the line and space ratio is 1:1. In case of the i-line stepper lithography, tuning fork structures are used to evaluate the correct exposure dose and development time. These tuning fork structures have a width between 350 nm and 2 μm. To determine the ideal exposure dose for each structure width, SEM images are taken at various doses. In Fig. 1 a) to d) the EBL exposed SA and LA structures with 500 nm and 100 nm width are shown. Details of the tuning forks (Fig. 1 e) exposed by i-line stepper lithography with a width of 500 nm and 350 nm are shown in Fig. 1 f) and g).

In Fig. 2 the measured structure width in dependence of the exposure dose is shown for the exposure process based on the ILM&M process conditions in Table 1. As expected, a higher exposure dose leads to wider structures. The i-line stepper was used to pattern tuning fork structures with 350 nm and 500 nm width (Fig. 2 a) and b)). There the ideal exposure dose for a 1:1 strucutre print of the layout is 110 mJ/cm^2. Decreasing the exposure dose leads to dramatically smaller structures. How this effect can be used for resolution enhancement is discussed in the next chapter. The widths of the EBL patterned structures are shown in Fig. 2 c) and d). For both layouts, SA and LA, the structures with 100 nm and 500 nm width are investigated. The SA structures are marked in grey, the LA structures in orange. In general, the required exposure dose for 1:1 structure print is lower for LA compared to the SA structures. A possible explanation for this phenomenon is the higher likelihood of back scattered electrons for LA patterns, which reduces the required exposure dose. Due to the larger feature size of the LA (300 μm length), a higher amount of back scattered electrons from surrounding structures is possible. These electron beam exposures were carried out without a proximity effect correction (PEC). Thus, an ideal PEC would eliminate this effect and allows for constant dose settings, independent of the layout. This, however, was not part of this study. The lower required exposure dose for the 100 nm SA and LA structures could be a result of the proximity effect that can occur at 100 nm and sub 100 nm structures.

In order to test the real ILM&M process, a CNT integration layout is used, which is normally used for a CNT integration process flow. Thereby interdigital electrodes are necessary for the integration of the CNTs. As structures below the resolution limit of the i-line stepper are required, this is realized by one EBL layer. For the proof of principle to optimize the writing time of this layout, we divided this layout into an EBL part and an i-line stepper lithography part. The layout of the fabricated device is shown in Fig. 3 a), while the SEM image of the real device is shown in Fig. 3 b). The top and bottom structures are exposed by EBL and the horizontal line has a width of 100 nm. The i-line stepper lithography structure in the middle has a width of 350 nm. The exposure time for a densely packed 6“ Si-wafer with this device would be about 6 hours if the EBL is used for the complete layout. By combining EBL and i-line stepper lithography the exposure time is reduced by ~50% to 3 hours for EBL and 1 minute for i-line stepper lithography for the 6” wafer. This time can be reduced even more by shifting the large contact pads and the large wires from the EBL layer to the i-line stepper layer, too. But then investigations regarding the overlapping area of the resist structures and a high overlay accuracy are necessary.

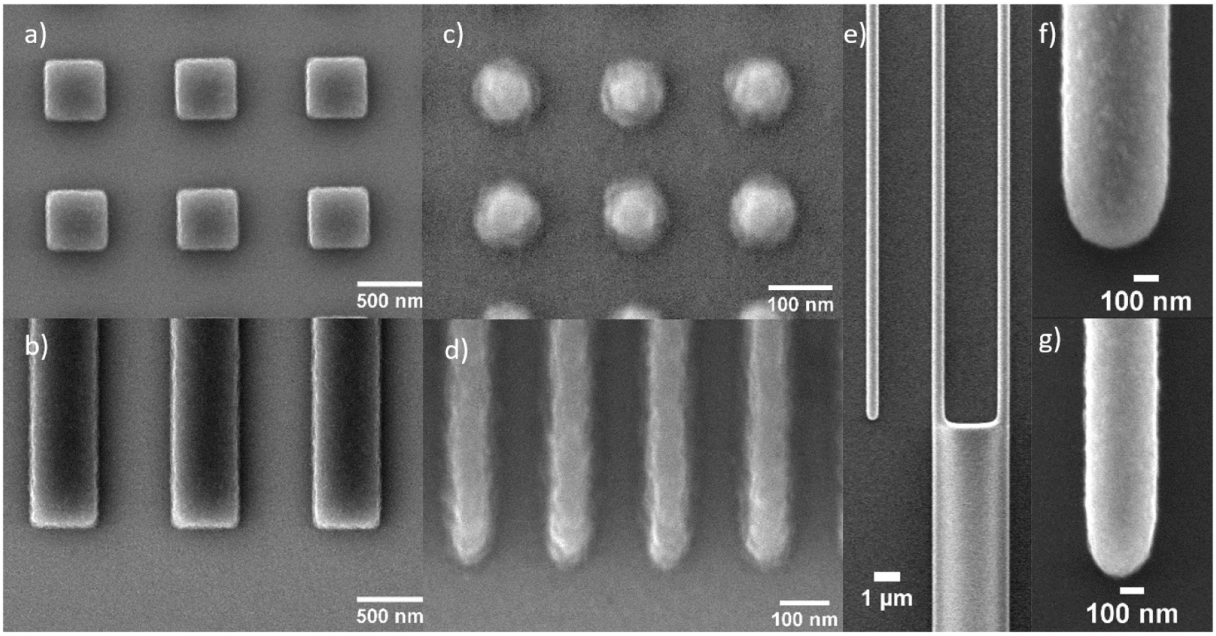

Fig. 1. SEM images of EBL and i-line stepper lithography structures exposed in resist ma-N 1402. a) and b) shows the EBL exposed SA and LA structures with 500 nm width, image c) and d) 100 nm SA and LA structures. Image e) shows the tuning fork structures with 500 nm dimension by i-line stepper lithography. Higher magnification is used for the imaging in f) and g) to demonstrate clear sidewalls on 500 nm and 350 nm structures after exposure of the resist ma-N 1402 while using AZ BARLi II anti reflective coating underneath.

3.2. Resolution enhancement for i-line stepper lithography and ma-N 1402

There are many different options to increase the resolution even below the CD-Limit by using RET such as Double Exposure Technologies (DET) or spacer patterning [8]. The NIKON 2205i11D i-line stepper we are using has a CD-Limit of 350 nm. From a sustainability perspective, improving the CD-Limit of this exposure tool can extend its further usage for high resolution applications. At the same time by improving the CD-Limit, the EBL could be obsolete apart from prototyping for some applications, where the i-line stepper lithography can meet the required resolution in shorter writing time. In this study we reduced the exposure dose below the 1:1 structure print to extend and enhance the resolution capability of the NIKON 2205i11D i-line stepper. Here we used the same process parameters as shown in Table 1 for the ILM&M approach. The 350 nm tuning fork structure is exposed and the results are shown in Fig. 4. By reducing the exposure dose in steps of 5 mJ/cm^2 from 100 mJ/cm^2 down to 50 mJ/cm^2, the structure width is approximately linearly decreasing. A dose of 100 mJ/cm^2 leads to a structure width of 307 nm, while a dose of 50 mJ/cm^2 results in a structure width of 86 nm. The graph and the linear regression are shown in Fig. 4 a). In Fig. 4 b) a SEM image of the 350 nm tuning fork structure exposed with 50 mJ/cm^2 are shown, demonstrating, that the CD-Limit could be reduced by ~75% from 350 nm to 86 nm for this specific resist and exposed structure. Fig. 4 c) to h) show the structures exposed with 50 mJ/cm^2 to 100 mJ/cm^2 in steps of 10 mJ/cm^2 in detail while i) represents the 1:1 printed structures with 110mJ/cm^2 based on the results in Fig. 2 a. This can be achieved due to a massive underexposure of the resist. By decreasing the exposure dose, the area of the resist, which gets enough UV-light for cross-linking the molecules, becomes smaller.

Therefore, smaller structures are possible with the same mask dimensions even without the use of a RET. With the knowledge of the linear fit, structures below the CD-Limit can easily be achieved by using an adapted exposure parameter set. This, however is valid only for the evaluated layout and needs to be studied for each layout individually due to the optical proximity effect, which is not automatically compensated. With this process, not only highly separated single lines may be achieved, but even denser lines are possible. In a first test, a layout with 350 nm lines and spaces is investigated showing the potential of using this i-line stepper approach. More in-depth analysis regarding the dependency and usage for repeatable nanostructure fabrication processes is required here. Nevertheless, this again shows the potential of this process for shrinking the CD-Limit. The downside of this method, exposing with (lower exposure dose than required) is less crosslinking of the resist patterns.

This results in less adhesion – resist patterns are developed away - and reduced resist thickness. The resist thickness, measured with AFM (AFM Series 5600 LS, Model N9610A) with a standard AFM tip (HQ: NSC15/AlBS by SPMTIPS), is reduced to 53 ± 5 nm for the 86 nm lines width in case of the 350 nm line width layout (Fig. 5 (50 mJ/cm^2)). The body of the tuning fork remains at the 180 nm resist thickness, where 200 nm was the design thickness. This deviation is within error bars of the different measurement methods and of the reproducibility from wafer-to-wafer.

4. Conclusion

In this paper, we showed an ILM&M approach using EBL and i-line stepper lithography with the ma-N 1402 negative photoresist. The exposure time of a complex layout generated by EBL and i-line stepper lithography in a combined ILM&M layout is reduced by ~50% from about 6 h to 3 h and 1 min. Besides the ILM&M approach, resolution enhancement for the i-line stepper lithography is investigated. By reducing the exposure dose under the required dose for the 1:1 structure print, smaller structures down to 86 nm are obtained. This reduces the CD-Limit of the used NIKON 2205i11D i-line stepper from 350 nm down to 86 nm (−75%). At the same time the resist thickness is reduced from 200 nm to ~50 nm thickness due to insufficient resist crosslinking degree. Due to the linear dependency of structure width to exposure dose, this process can be used for the deliberate realization of nanostructures below the CD-Limit of such i-line stepper tools.

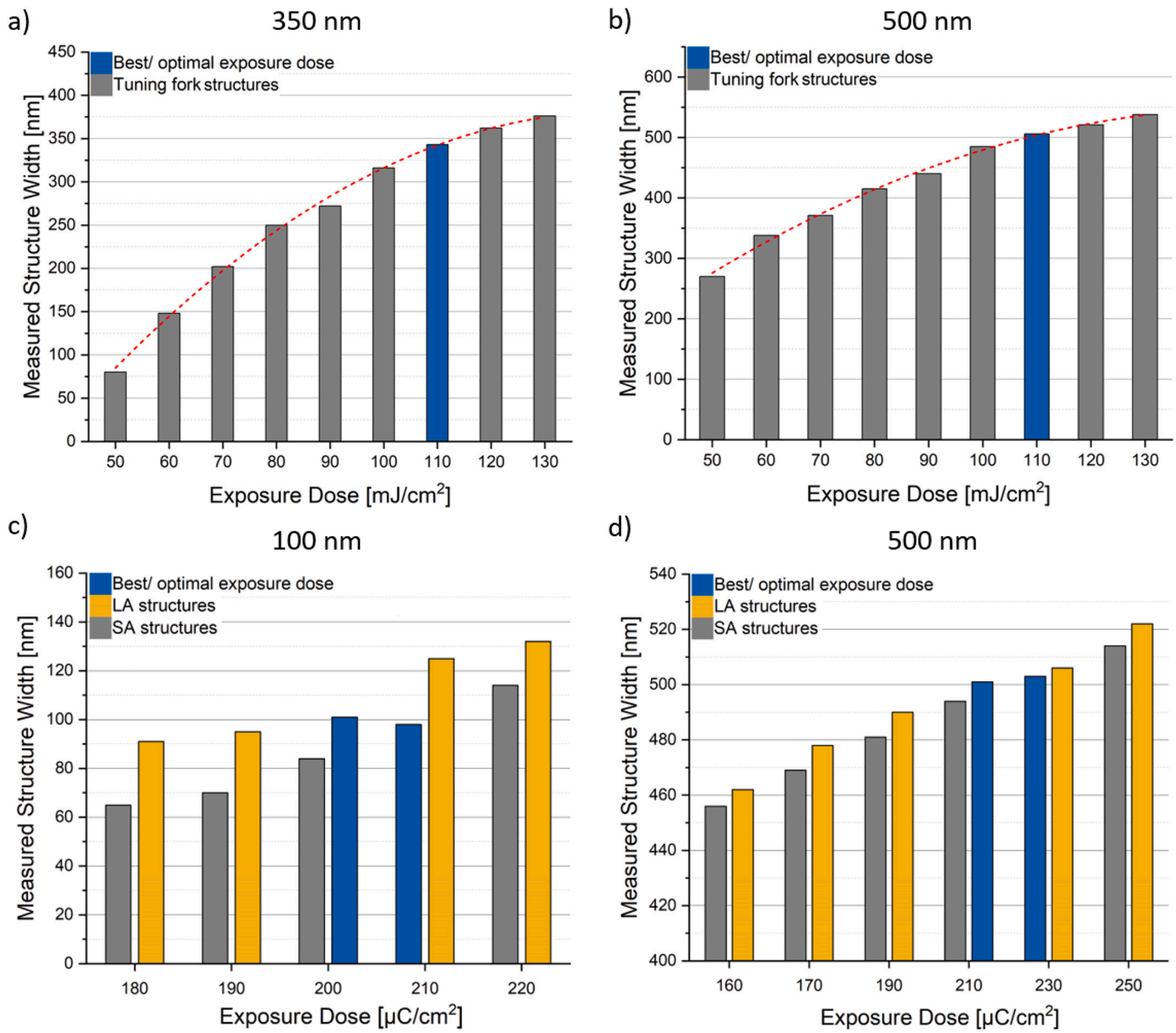

Fig. 2. Structure width in correlation to the exposure dose, a) and b) for the 350 nm and 500 nm tuning fork structures generated by i-line stepper lithography, c) and d) 100 nm and 500 nm SA (grey) and LA (orange) EBL structures. The optimal exposure dose for each layout is marked in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

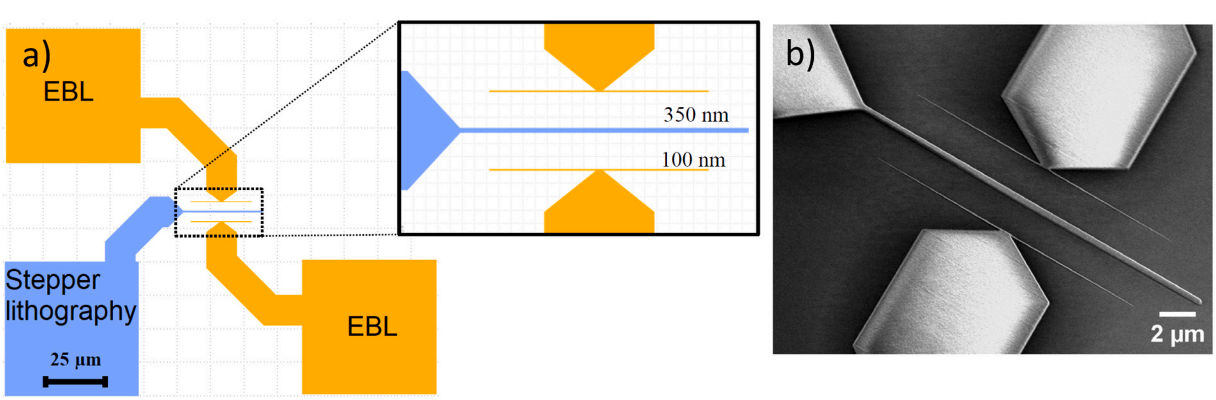

Fig. 3. Device generated by EBL/i-line stepper lithography ILM&M approach. a) Schematic view of the complex ILM&M layout, the orange structures are written with EBL and the blue one with i-line stepper; b) SEM image of the center region of this device rotated by 45°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

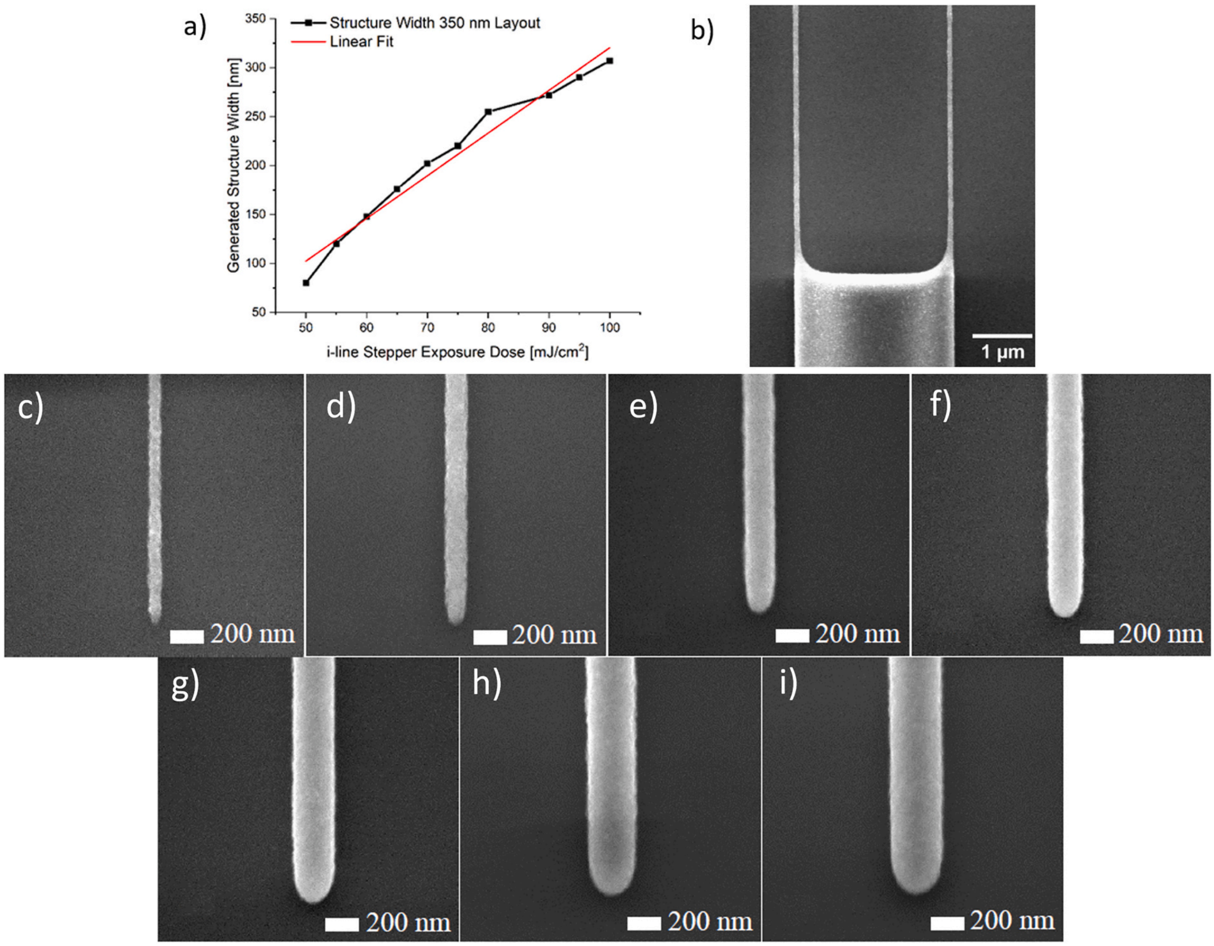

Fig. 4. a) Graph of the generated structure width for the 350 nm tuning fork layout; b) shows SEM images of the 350 nm layout exposed with 50 mJ/cm^2, c) to i) shows the structures exposed with 50 mJ/cm^2 to 110 mJ/cm^2 in steps of 10 mJ/cm^2.

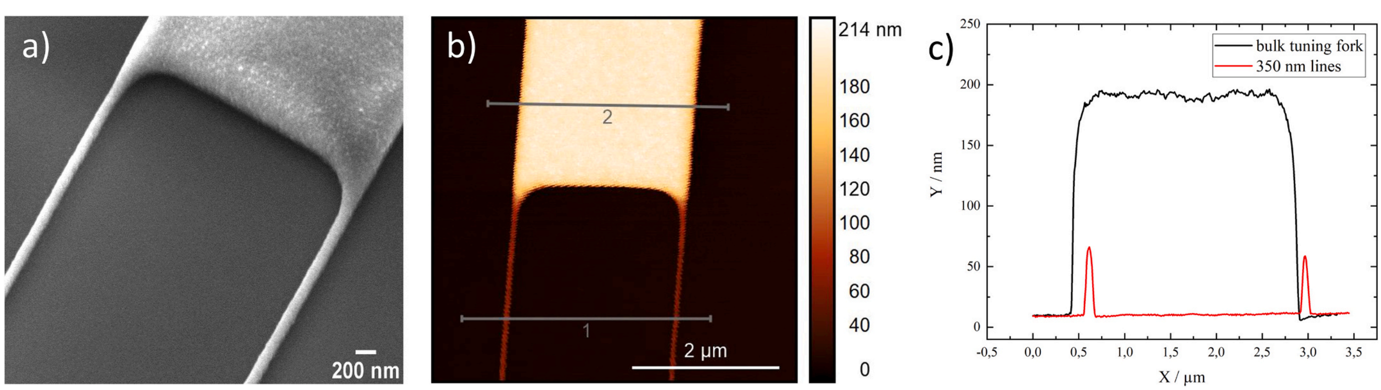

Fig. 5. Tuning fork structure with 350 nm lines, exposed with 50 mJ/cm^2. a) SEM image, b) AFM image and c) corresponding profile as comparison between the bulk tuning fork structures with ~180 nm resist height and the tuning fork ends with 53 ± 5 nm resist height.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

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