High Energy Photon Lithography for Fabrication of Photonic Device.

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Photonic crystals and other photonic devices could be efficiently produced using relatively simple and cheap Plasma Focus Pinch x-ray point sources, similar to the NX2 . With this point x-ray source, it was demonstrated that with a proximity printing scheme, feature sizes less than 100 nm could be reproduced in a 500 nm UV3 CAR layer.

Submicron lithography, x-ray lithography, e-beam lithography, chemically amplified resists, high aspect ratio structures, soft x-ray sources, Plasma Focus Pinch.

1. INTRODUCTION

The development of X-ray lithography was initiated by D.L.Spears and H.I.Smith in 1972 [1,2]. During the next 27 years all the main components of this technology such as powerful soft x-ray sources, long-life and accurate x-ray masks with critical dimensions down to 100 nm and high sensitivity chemically amplified resists were succesfully developed. Nevertheless, for application of this novel technology to commercial production of VLS microelectronic devices, some complicated hence expensive, technical problems, still need to be solved. These are connected mostly with the alignment of layers, requiring an accuracy of 10% of the critical element linewidth over a relatively large area.

However, a recently developed class of photonic devices can be successfully fabricated using existing x-ray lithography technology. This is because a large part of these devices do not need precise alignment of layers. A big number of photonic devices could be built using artificial 2D and 3D photonic crystals with structural dimensions smaller than the wavelength of visible light [3].

Such photonic crystals could be efficiently produced using relatively simple and cheap Plasma Focus Pinch x-ray point sources, similar to the NX2 [4,5]. With this point x-ray source, it was demonstrated that feature sizes less than 100 nm could be produced in a 500 nm UV3 chemically-amplified resist (CAR) layer.

Small size but high accuracy optical elements such as computer generated holograms for a visible and infrared light and Fresnel zone plates have been successfully produced by e-beam and x-ray microlithography technology.

Even micromechanical switch technology for optical fiber devices was recently developed on the basis of high aspect ratio structure microfabrication technology.

Maximum resist thickness of 5 micron could be exposed with 1 nm wavelength soft x-rays from the Plasma Focus operated in neon. The quality of exposure depends on mask contrast and critical feature size since exposure decreases with depth in the resist.

This state of art is good enough for the commercial production of 2D optical crystal. Furthermore, x-ray lithography provides a unique possibility to produce sub-100nm structures with high aspect ratio; for example 70 nm width lines in a 2 micron resist [6]. It is possible to do exposure at an oblique angle to the resist surface.

Therefore modern x-ray lithography techniques could be efficiently used for commercial production of new classes of optical devices based on 2D and 3D artificial crystals, at critical dimensions not achievable with optical wavelengths.

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2. SUBMICRON STRUCTURES FORMATION IN RESIST LAYERS WITH X-RAY LITHOGRAPHY.

One of the most powerful technology which provides structure element dimensions to 100 nm and below with a relatively high output and low cost is conventional proximity x-ray lithography.

At the very beginning of its development it was demonstrated that at small gaps between x-ray mask and wafer exposed the diffraction and shadow blurring of the image transferred could be done much smaller then 100 nm for a precise submicron structures fabrication. PMMA based resists, widely used for demonstration experiments, have the intrinsic resolution better then 10 nm, but a very low sensitivity - of the order of 500 J/cm^3 of absorbed energy. Even simple soft x-ray tubes with electrical power only 300 W and copper anode producing 1.3 nm wavelength irradiation with a very low conversion efficiency of 2×10^{-5} provide a reasonable exposure time of several minutes at a 20 mm distance. To replicate a sub-100 nm elements, mask has to be brought to a close contact with resist to avoid a shadow blurring as the irradiation spot of this x-ray tube has a typical dimension of 1 mm.

This was done by an absorption element fabricated directly onto the resist surface. A half-micron photoresist layer was spun on PMMA, exposed with UV through photomask and developed. Then a heavy absorption material (lead) was evaporated at an oblique angle onto the photoresist structure sidewalls. The thickness of the evaporated layer was only 100 nm and since the walls were vertical, the thickness was also the width of masking element in x-ray exposure. The good test structure exposed in 1.6 micrometer PMMA resist layer to dose 1000 J/cm^3 and developed in 1 : 4 MEK- IPA mixture has been obtained.

Structures produced in resist have near vertical walls. As linewidth is only 70 nm, for 1.6 micron resist height it gives aspect ratio more then 20. This experiment demonstrates that it is easy to get sub-100 nm resolution for single standing lines, if the technology reproducibility and process cost are not under discussion.

For single standing lines it is even possible to vary its width by the proper choice of exposure and development parameters. For instance, for positive resists, overexposure and overdevelopment can lead to linewidth reduction.

The second advantage of x-ray lithography is the possibility to expose a relatively thick resist layer. Submicron resolution could be demonstrated for 5-10 micron resist layers, and structures with several micrometer feature size could be produced even in 200-500 micron resist layers. The main limitations for these thick resist layers exposure are connected with x-ray absorption in resist.

Potentially efficient and cheap x-ray lithography technology for sub-0.1 micrometer feature size devices can be realised already with a powerful plasma focus SXR source for applications not requiring precise alignment of layers. Examples of such devices include artificial optical crystals and single domain magnetic media, and 10-20 micron thick MEMS and micro-optical elements production with sub-micron accuracy to replace inaccurate photolithography.

This simple laboratory equipment (Figure 1) is used for more than 15 years for technology development in x-ray lithography and simple single layer test structures production.

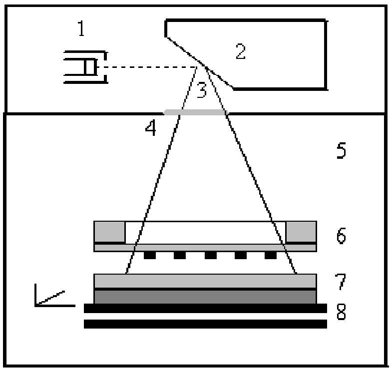

Figure 1. X-ray lithography system . 1- electron gun, 2- anode, 3- x-rays, 4- vacuum window, 5- exposure chamber, 6- x-ray mask, 7- substrate with resist, 8- X-Y-Z stage.

Some results specific to x-ray lithography and very important from different applications point of view were demonstrated using this simple equipment.

X-ray lithography is really the only one technology (except evaporation and ion etching at oblique angles) which gives a possibility to work on an exposed wafer in a direction not perpendicular to its surface. Other submicron lithography technologies such as UV and e-beam do not provide this possibility because of a very small depth of focus.
In the case of x-ray lithography simple tilting of the mask and wafer assembly result in a tilted structure, as shown in Figure 2.

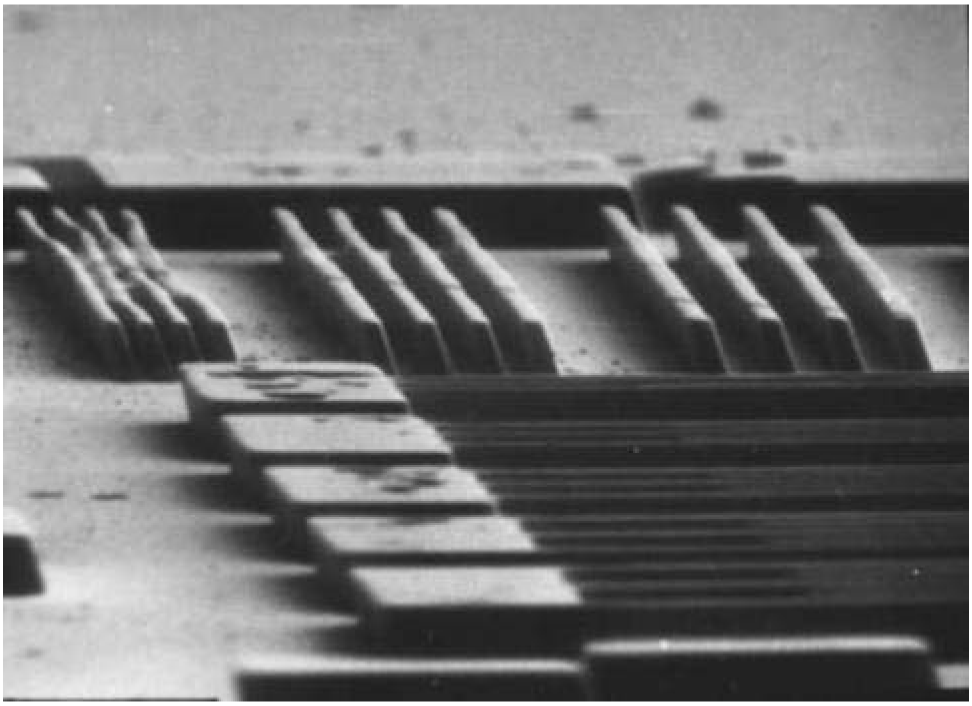

Figure 2. Tilted structures exposed in 3 um PMMA layer with polymer mask providing only 2 UM masking layer – resist gap

Such exposure at an oblique angle could be done with the same resist layer two or three times at different angles, to give a really three-dimensional net in resist bulk during development. As x-ray lithography has a submicron resolution and a very large (10 to 50 micron) depth of focus, this structures could work as an artificial 3D optical crystals. Photons have demonstrated the same behavior in such artificial photonic crystals, as electrons in solid state.

Numerous works were published recently on similar three dimensional structures production technology based on ion etching at oblique angles. But x-ray lithography poses a much higher throughput and so a lower cost. Really this artificial photonic crystals can be one of the main applications for single layer x-ray lithography technology.

A very large (to 5 – 500 micron, depending on wavelength) penetration depth of x-rays in resist gives a possibility to expose thick resist layers and multilayer resist systems. The last gives possibility to produce structures with undercut or slope sidewall profile if resist layers have a different sensitivity.

There is an x-ray lithography technology in which a two different sensitivity resist system is exposed through a special mask with two different pictures, formed in two separate masking layers. In this case different exposure takes place under different mask zones. Mask contrasts and resists sensitivities are chosen in such a manner, that after exposure and development, instead of a binary resist structure, an intermediate height structure is additionally formed.

SEM pictures of test structures produced in 2 and 3 layer resist systems by x-ray exposure are shown in Fig.3.

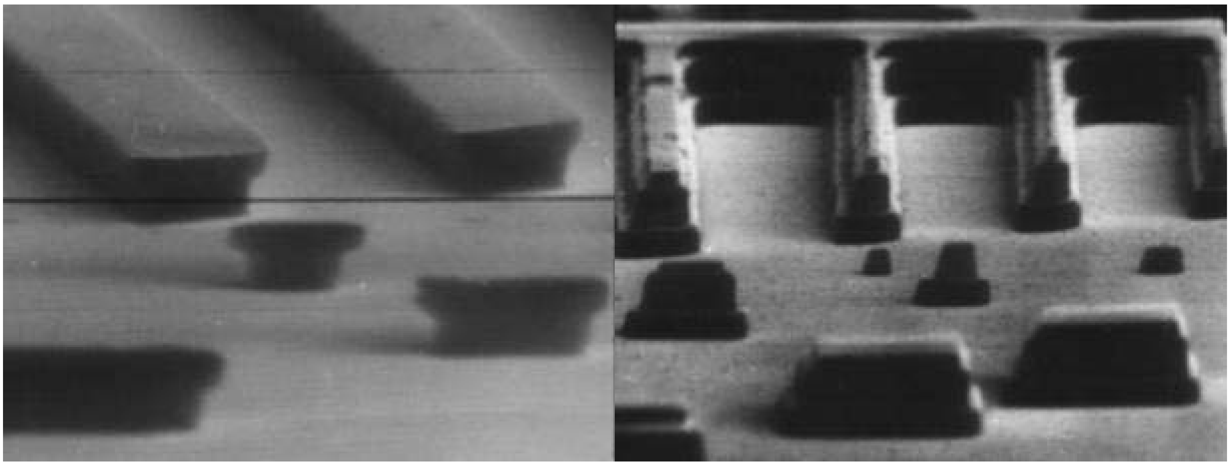

Figure 3 Showing undercut (left) and sidewall profile (right) produced by x-ray exposure in 2 and 3 layer resist systems.

3. X-RAY MASK DESIGN AND TECHNOLOGY

X-ray mask design and technology is still under development. There are numerous technical problems to be solved for practical application of already existing masks for VLSI device production. These problems are connected mostly with alignment accuracy for large area exposure zones. Different kinds of mask distortion caused by tension in its layers during its production and usage, complicate these problems.

However, for single layer devices where high-precision element positioning is not critical, existing masks could be successfully used for a 0.1 micron feature size device fabrication.

Two types of x-ray masks (Figure 4) were used in our experiments. For thick resist layer exposure and for exposures in which we have to be sure that the gap between mask and resist does not exceed 2-3 microns, a polymer membrane with 0.5 –0.8 micron gold masking layer on it was used. At the beginning of exposure, a mask gets an electrical charge because of photoelectrons emission from its surface and attracts to the resist due to electrostatic forces.

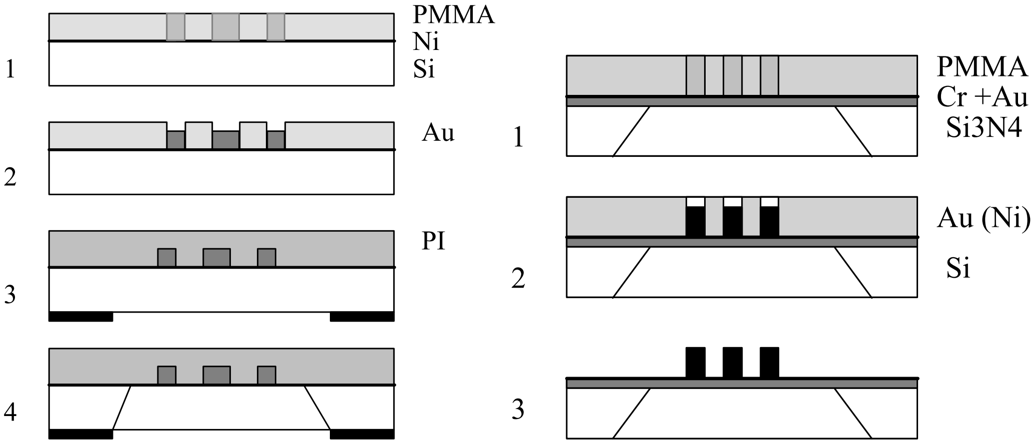

Figure 4. Schematic diagram of Polymer (left) and Si_3N_4 (right) membrane x-ray masks technology

These masks have a several micrometer element positioning run-out, but are cheap, long life and could be useful for some applications. Test structures formed in thick resist layers, including multi-layer resist systems were produced using this type of masks as shown in Figure 5.

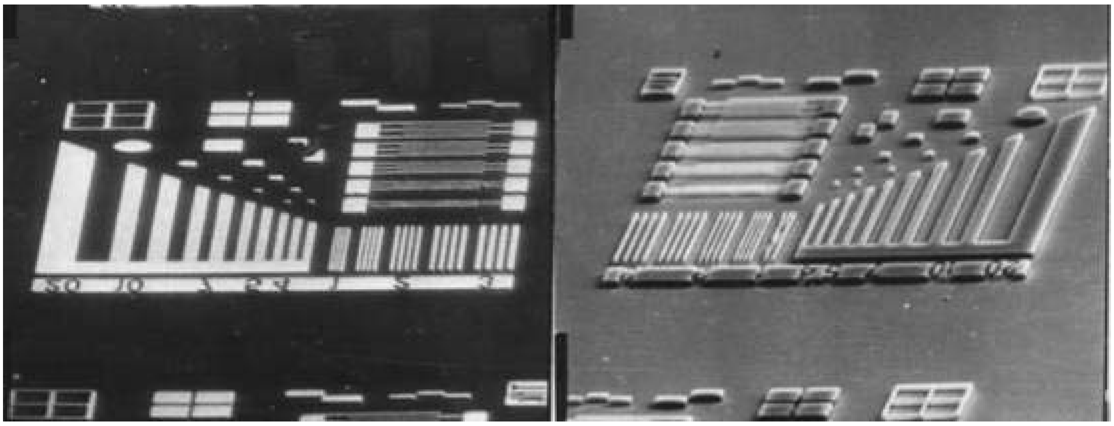

Figure 5. SEM picture of a masking layer for a polymer membrane x-ray mask and its replica in 4 um PMMA layer

Another type of x-ray masks(Figure 4) was employed for high-resolution experiments and was designed in a conventional manner. Silicon wafers with 100 nm Si_3N_4 membrane windows from FASTEC, UK were covered with Cr-Au electroplating base. Positive type PMMA or negative AZPN114 resists were spun on this surface with film thickness from 0.3 to 0.7 micron and structure was exposed with 30 kV electron beam at JEOL 820 SEM modified for e-beam lithography experiments. Then gold was electroplated to thickness 150 – 500 nm using a conventional electroplating technique. SEM pictures of masks with resolution test structure and Frenzel zone plate are given in Fig. 6 .

4. CHEMICALLY AMPLIFIED RESISTS IN X-RAY AND E-BEAM SUBMICRON LITHOGRAPHY.

The main progress in submicron lithography technology development in recent years is the result of Chemically Amplified Resists (CAR) development. These resists provide sub-100 nm resolution and have sensitivity 10-100 times higher then conventional PMMA resists.

CARs have much higher resistance to plasma-chemical etching and good thermal stability. The only one disadvantage of positive CARs is “T”-topping effect, caused by the neutralization of the acid produced during exposure by the airborne contamination in the upper resist layer. For negative CARs the main technological troubles are connected with its poor adhesion to substrate and some swelling during development if exposure is smaller than optimal.

CARs are very flexible from application point of view as could be spun with thickness from 40 nm to 0.5 mm, exposed with UV, e-beam and x-rays. The last makes possible mix-and–match technology application to CARs. Resists have good mechanical properties and could be used for good 3D structures production. Here we mean structures which have a significantly different resist thickness at different areas, of a complicated special profile of structures walls i.e undercut or slope. For micromechanics and optics applications, special self-supporting structures are very important. It was demonstrated that different type of self supporting structures could be easily produced in a relatively thick single layer AZPN114 CAR.

To produce a 3D structure in a single layer resist it is necessary to use two (or more) exposures with agents having a different penetration depth. For example, in experiments described in Ref [7], a 2 micron resist layer was exposed with 30 and 5 kV electron beams. The penetration depth of a 30 kV electron beam is more then 2 microns, so irradiation with this high energy electron beam produces a homogeneous exposure for the all resist depth. On the contrary, 5 kV electrons have a range in the resist or the order of 0.5-0.6 micron only, and with this energy e-beam exposure is produced in the upper resist layer only. After these two exposures, Post Exposure Baking (PEB) and development we get self-supporting structures. SEM pictures of this structures are given in Figure 7.

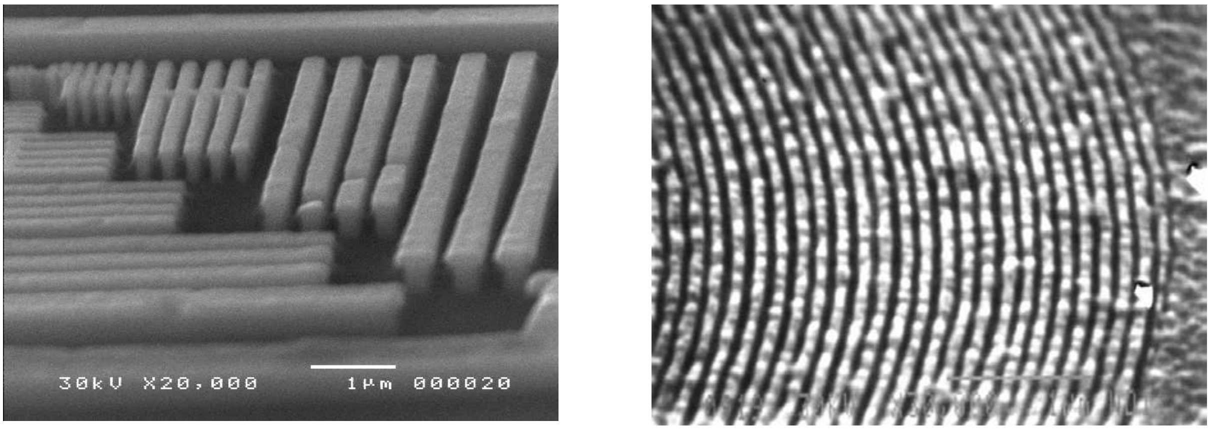

Figure 6. SEM pictures of gold masking structure formed on 100 nm Si_3N_4 membrane, left - resolution test structure with a minimal linewidth to 80 nm, right– zone plate structure with an outer zone width 60 nm.

Self-supporting structures similar to those in the left picture (Figure 7), especially produced in a transparent media like resist, could be used as an optical microfibre or a 3D grating. A relatively large, flat structure connected to the supporting basic structure with its edge only, as it is shown in the right picture(Figure 7), could probably be used as a micromirror array for optical beam deflection or modulation.

This experiment with e-beam exposure just illustrates the general idea, how to produce 3D structures in a single layer resist – two (or more) exposures with different penetration depth are required. If structure has to be produced in a thicker resist layer (more then 5 micron) x-ray lithography has be used for whole thickness layer exposure. Electrons with different energies from 1 to 100 keV could be used for a structure production in the upper resist layer.

Irradiation with soft x-rays (0.8 – 4.4 nm) also could be used for a structure exposure in the upper resist layer. The thickness of the exposed layer will be determined in this case by the x-ray absorption coefficient, dose and resist sensitivity. Varying exposure it will be possible to adjust the thickness of the upper structure layer. This will provide an extra flexibility to the method.

Negative CARs have an additional useful property in optics application. After exposure and postbaking, the resist base is crosslinked. Usually it leads to a polymer free volume reduction and so to the increase of its density. Refractive index increases slightly in this case. For some optical applications this rise could be big enough to change optical properties of the media. Even without development it could be possible to produce some "flat" optical elements similar with lenses, gratings and waveguides.

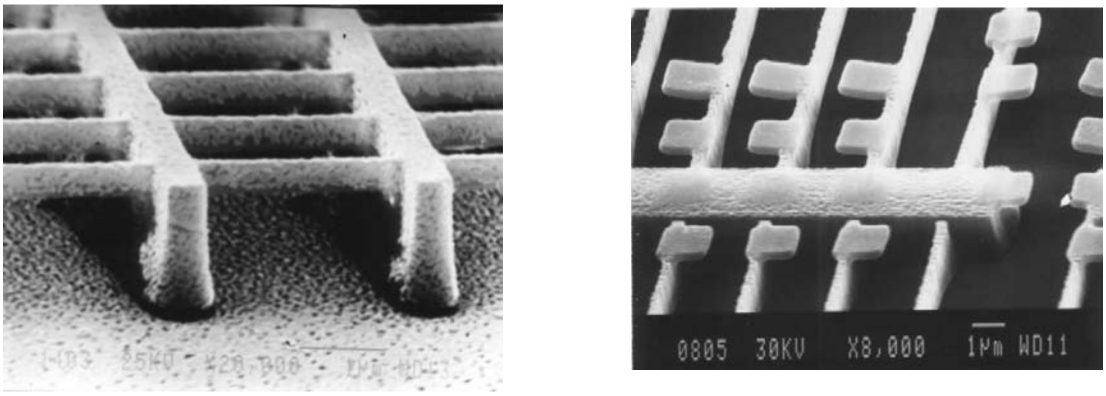

Figure 7. Self-supporting structures, produced in AZPN114 CAR with 5 and 30 kV e-beam exposure

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5. APPLICATION OF PLASMA FOCUS SOFT X-RAY SOURCE TO LITHOGRAPHY TECHNOLOGY.

Soft x-ray tubes, used in simple lithography possibilities demonstration experiments, have a very low x-ray output because of a low electron beam power to x-rays conversion efficiency.
For copper anode and acceleration voltage of 8 kV the efficiency is only 2×10^{-5}. For mask to resist gaps suitable for practical use (from 10 to 20 microns) and resolution better than 100 nm, distance between point x-ray source and mask has to be at least 10 cm. This leads to exposure time of several hours for conventional positive resists.

To put x-ray lithography in practice, it is necessary to use a high sensitivity Chemically Amplified Resists and more powerful soft x-ray sources. In our work we used a plasma focus device for x-ray lithography, and investigate CARs application to soft x-ray lithography.

Experiments were carried out at NTU using a specially designed plasma focus device NX2 [4,5], shown in Figure 8.

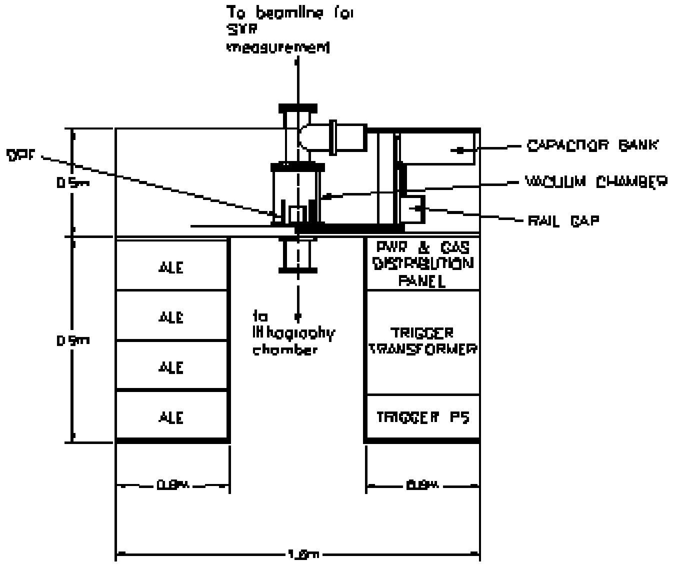

Figure 8. Schematic diagram of the NX2

The NX2 is a plasma focus x-ray source operated in neon gas. The capacitor bank consists of 48 capacitors with a total capacity of 30 µF. The capacitors are charged to a maximum 11.5 kV by ALE model 802 chargers with a total power of 32 kW.

The short circuit rise time is 1 µs. The on-load current peaks at 400 kA at a repetition rate up to 16 shots per second.

The SXR from the plasma focus point source goes through the hole in the bottom of the anode and passes through a magnet trap, which deflects and absorbs the high energy electrons ejected from the pinch. Low energy and scattered electrons and UV radiation are blocked with a 10 µm Be foil located at an entrance aperture of the x-ray mask and wafer holder.

The NX2 produces maximum 20J of SXR per shot at 16 shots per second giving up to 300W of SXR power. For demonstration purposes even operation at the 50W level provides a required exposure dose in a reasonable time and reduces the anode overheating damage problems. The effective radiation source size is less than 0.5 mm. At a working distance from 20 to 40 cm and mask-to-wafer gap of 10 microns the shadow blurring is below 20 nm. Irradiation x-ray spectrum of the neon plasma is shown in Figure 9.

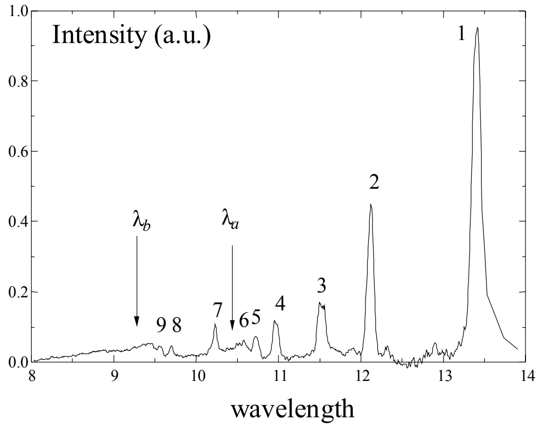

Figure 9. Neon plasma x-ray spectrum.

This wavelength range, 0.8 - 1.4 nm, with the strongest emission lines between 1 and 1.4 nm, provides mask contrast better than 10 for the 0.3 micron gold absorption layer. So, all the main parameters of NX2 such as radiation spectrum, source spot size and SXR power meet the technological requirements of the x-ray lithography for a laboratory application.

For demonstration, our test x-ray masks consist of 0.3 µm Au structure with lines to 0.2 µm and gaps below 0.1 µm electroplated on 0.1 µm Si3N4 membrane with Cr-Au (5 and 20 nm) electroplating base. Exposure was done with close contact between mask and resist, (no special extra spacer was used) to provide the highest possible resolution. Resists soft baking, post exposure baking and development were done in a conventional way [Figure 10]. We used UV3 CAR for this demonstration.

It is well known from experiments in e-beam lithography that both AZPN114 and UV3 have a resolution better then 0.1 µm for 0.3-0.5 µm layers and sensitivity 20 to 50 times higher then conventional PMMA.

The main problems for such high aspect ratio structures formation are the poor adhesion of negative resist and swelling during development, if exposure is not big enough, and a "T"-topping effect for positive resist.

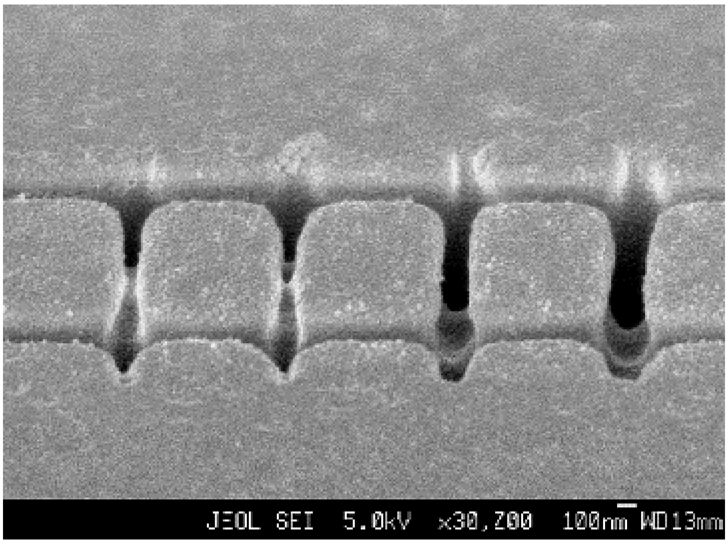

Figure 10. Test structure with sub 0.1 um gaps exposed with x-rays from NX2 in 0.5 um UV3 CAR.

Resist in gaps slightly below 0.1 µm is not removed completely at the groove bottom. It can be explained first of all by the gap dimension dependence of the dissolution mechanism - the narrower the gap, the slower the development of the resist and the slower the motion of the dissolved resist molecules.

But more likely this effect is connected with CAR nature of the resist. During x-ray exposure all lines despite of their width are irradiated with the same dose. Dose-on-linewidth correction is impossible. In our case the width of the exposed line is comparable with a diffusion length of the acid molecules produced during exposure. The concentration of the acid molecules can reduce significantly in the exposed zone because of their drift outside this zone. It leads to a linewidth dependant dissolution rate reduction for lines below 0.1 µm.

So, proximity exposure of thin positive CAR layers with SXR on NX2 plasma focus station provides resolution to 0.1-0.2 µm with a reasonable exposure time.

6. CONCLUSION

Although x-ray lithography is still not widely used for VLSI semiconductor device production, it can be very useful and competitive for a single layer device production. For application in optics this single layer structure could be made 3D even in one resist layer. For commercial applications relatively simple and low cost plasma focus stations could be used for highly efficient soft x-ray production. To increase the throughput, resists with chemical amplification have be used.
A big variety of optical devices could be produced by x-ray lithography – lenses and zone plates, gratings and wavegides, micromechanical optical fibers switches and connectors, flat panel deflectors and modulators.
But the most promising application of the already existing x-ray lithography technology is artificial 3D optical crystals production.

7. REFERENCES

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