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Simulations for printing contacts with near field x-rays

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Abstract

In ultra high resolution lithography, sometimes called near field x-ray lithography, Fresnel diffraction is deliberately used to increase resolution: the contraction in current occurring beyond a clear mask feature has, further, important experimentally beneficial effects that were previously overlooked. All the key features of the technique have, by now, been demonstrated and previously reported. The technique is also an enhancement of the most-developed next generation lithography. The enhancement has fundamental advantages, including an increase in mask–wafer Gap (the Gap scales as the square of the width of a clear mask feature); reduced exposure times; more easily fabricated masks; high density prints by multiple exposures; high contrast; elimination of sidebands; reduction in the effects of mask defects, compact masks, etc. We have, previously reported experimental and simulated prints from lines and more complex flag and bridge structures; here we report simulations for symmetrical contacts. More particularly, in the printing of circular features, it is shown that a demagnification factor around 7 can be routinely used to optimize mask–wafer Gap. Although the Gap is significantly extended by using larger clear mask features, finer prints can still be developed.

1. Introduction

Ultra high resolution lithography (UHRL) [1], sometimes called near field x-ray lithography (NFXRL) [2], is an enhancement of 1X proximity x-ray lithography (1XPXL). This has been on the Roadmap for Semiconductors [3] since next generation lithography (NGL) issues were first addressed. Several demonstrated devices [2], produced in various laboratories, show that x-ray remains the only developed NGL. NFXRL is extensible, beyond other NGLs, to 15 nm [4]. Used as a proximity method, the technique is physically simple and economical: no lenses are used and the only mirrors used are planar, sometimes bent. Throughput is conventional as the broadband sources are bright.

NFXRL is more than just academic: all the key features of NFXRL have been demonstrated [2–8] and simulated [2, 9–11]. The basic concept is that, in Fresnel diffraction, the current passing through a clear mask feature contracts. Prints employ 'demagnification by bias' [7] near the 'sweet spot' [2]. The reader is referred to the earlier work for details. Near the Critical Condition, the contraction is used to make high resolution exposures and prints. Prints have been demonstrated for lines, down to a resolution of 25 nm width, though this is extensible to 15 nm [2]. Typically, broadband, 1–2 kV x-rays, are used to expose a resist.

Many of the resulting features are valuable for lithography. The results follow from the observation that generally, in NGL, the traditional requirement of fiduciality in the reproduction from masks, is now observed by neglect. For a given print size, mask features are enlarged in NFXRL. Mask–wafer Gaps are greatly increased because these depend on the square of the size of the clear mask feature. Exposure times are short because prints are made at peaks of intensity and with broadband radiation. Print densities are high because multiple exposures are used.

Simulations have shown that complex patterns can be printed, including flags [10] and bridges [2]. Various techniques have been devised to eliminate fine irregularities such as 'ripple' and 'bright spots' [2]. The methods include the use of broadband and incoherence produced by carefully shaped masks, as also translation during exposure. In this paper, we consider ways of printing high resolution symmetrical contacts. Experimental arrangements, including the mask–wafer Gap, are compared with requirements for the previously described non-symmetrical patterns.

The technique is valuable for lithographic applications that include semiconductor manufacture and fabrication of micro electromechanical (MEMS) devices.

There have been other attempts (as listed in [4]) to enhance 1XPXL, some of which can, in principle, be employed incrementally with the leap in Near Field to extend further to 15 nm printed features. Other attempts at this have not proved to be competitive enough for high resolution [2] and involve unnecessarily complicated procedures in 1X mask making and in exposure for phase shifting. More significant is the attempt to use shorter wavelength x-rays, about 0.4 nm, with diamond-like mask substrates [13, 14] and modified resists. It is clear that such incremental resolution enhancements can be improved by a large factor of 3 when adapted to Near Field. This is partly due to the larger mask–wafer Gaps that can be employed since the Gap scales as the square of the clear mask feature size: for a ‘demagnification’ of 3 the mask–wafer Gap increases 9 times.

The advances made in NFXRL had been overlooked in both the practice and the theory of 1XPXL. For example, on coming across the profile near the Critical Condition, Cerrina wrote [15] ‘The difference in intensity profiles does not have a significant impact on line width, because the place where they differ is not at the nominal line width position’, thus overlooking the multiple large gains in resolution, increased mask–wafer Gap, ease and economy of mask fabrication, etc, that comes from using the narrow profile with reduced exposure time. He also wrote that a demagnifying mask ‘can be very useful in printing quantum devices which are not densely packed [15]’, overlooking the important advance that comes from using rapid multiple exposures of narrow peaks for dense structures. Subsequently, the same author has acknowledged the novelty of our method as first ‘proposed’ [16].

2. Sweet spot

Figure 1 illustrates terms used in the following simulations and analysis. It is an enhancement of a previous simulation [8] which represents the universal current distribution for radiation transmitted by a clear mask feature. For details showing typical dimensions and the effects of residual transmission of the absorbing mask see [8].

In figure 1, a long ‘Sweet Spot’, occurs where the current is narrow and bright indicating large latitude in what is equivalent to *depth of focus* in projection optics. This feature illustrates the importance, and the necessity, of using the sweet spot when resolution is an issue in the proximity methods.

At the Critical Condition [1, 8] the gap between mask and wafer is $G_c = 4s^2/3\lambda$, where s is the width of the clear mask (line) feature and λ is the wavelength of radiation used, in our case, the x-rays. The Critical Gap is theoretically defined [1, 2, 8] for a one-dimensional slit as the maximum on the corresponding Cornu spiral. This condition provides maximum resolution, maximum intensity and maximum contrast for printing. The Cornu spiral is also known as the vibration curve and it applies to Fresnel diffraction with monochromatic radiation [17]. We have previously adapted the spiral for broadband [2] by using a prior integration for time before the normal integration for the space parallel to the slit.

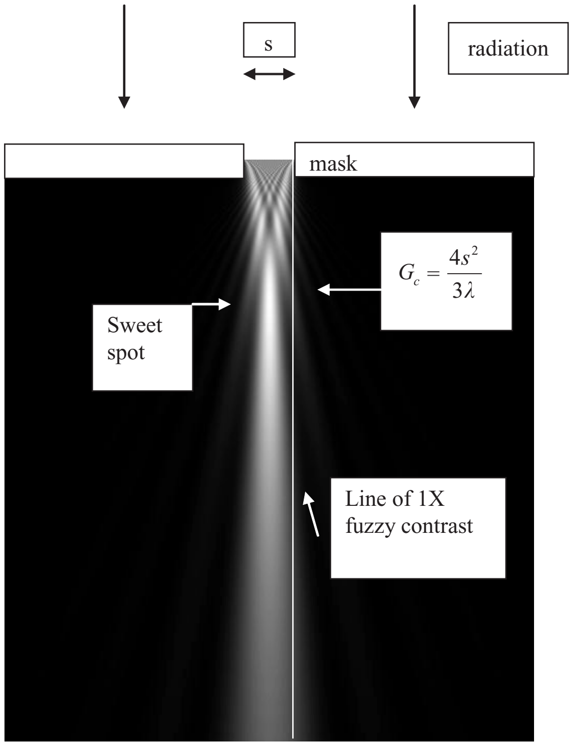

Figure 1. Universal current, or flux distribution, from clear mask feature of width s, simulated in Fresnel diffraction.

In all previous demonstrations of traditional 1XPXL [18], some of which are listed in [2], the line of 1X fuzzy contrast was used. This was done because of the traditional belief that lithography should print fiducial representations of masks. However, in NGL the frequent use of serifs, phase shifting masks, double exposures, etc, shows that fiduciality in reproduction is now old fashioned. Previously, proximity x-ray lithography was shielded by the short wavelengths used; but now that resolution has become an issue, the relegation of a prior requirement for fiduciality has brought about a simple enhancement of considerable power and serviceability.

Moreover, whereas it had been previously thought that non-fiduciality could only be applied to isolated features [15]; it is now clear [4, 18], and demonstrated [2, 10], that multiple exposures of sharp peaks, printed near the Critical Condition, provide prints of dense lines. At this Condition, peaks are intense, exposure is rapid and so also is blind stepping.

So far, we have considered one-dimensional line features. Methods for printing rectangular features and for printing more complex patterns have been previously discussed [2, 8, 9, 10]. In summary,

1. For asymmetric rectangular patterns, the Critical Condition is defined for the shorter dimension.
2. Broadband is used to smear ‘bright spots’ and ‘ripple’, along the longer dimension, which are fine features in Fresnel diffraction.

3. Further reductions and virtual elimination of these effects occur with the use of deviations from ideal mask features by indents, etc (opposite to serifs) [10].
4. Yet further reductions are simulated by the use of double exposures with translation [2], as for example in the printing of bridges.
5. Complex structures, such as flag structures [10] are likewise simulated where some features print under high resolution and others closer to 1X.

3. Demagnification of contacts

Consider next the printing of two-dimensional structures having high symmetry, such as circles. Following a cross-section corresponding to figure 1, the difference between the path length of the axial ray, from the path length of a ray passing from the aperture edge to the wafer axis [2] provides the number of Fresnel half zones, N_F, imaged in the Fresnel pattern [17], since:

$$N_F = \frac{(s/2)^2}{4G\lambda}, \tag{1}$$

where, as before, the Gap G scales as the square of the aperture size of the clear mask feature. Using the SEMPER program [19], aerial images, from 50 nm circular apertures with a 0.62 nm wavelength, were simulated (figure 2) at Gaps corresponding to a series of Fresnel half zones ranging from $N_F = 1$–6. Several features are immediately evident: while, when N_F is even, the centre is vacant; when N_F is odd, the central spot provides a large demagnification of the aperture, the demagnification factor increasing with N_F. However, the increase in N_F corresponds to Gaps decreasing from about 4 μm to less than 1 μm. The largest of these is on the border of practicality for NFXRL. The printing of fine features, therefore, requires an optimization of aperture size in order to increase Gaps. The following profiles were therefore simulated [20] using larger apertures and Gaps as shown in figure 3 with fine variations around the first Fresnel half zone.

The profiles are plotted [20], for various Gaps, in figure 3. From these profiles, typical print resolutions are derived (around three quarters of the peak heights). These profiles are calculated for monochromatic radiation, but the broadening due to broadband can be estimated around 10%, knowing the result for line prints [2,5]. The Gaps and resolutions are shown in table 1, when wavelengths of either 0.8 or 0.4 nm are used.

Notice that the Gap decreases with increasing number of Fresnel half zones, N_F. The minimum occurs about $N_F \sim 1.2$, less than the value of 2.4 noticed earlier [2, 8] in the printing of one-dimensional lines. When $N_F \sim 1.0$, a trading benefit can be obtained by increasing the Gap. This has the added benefit of reducing the background shoulder shown in figure 3 and the benefit is more valuable when print features are denser. However, reducing the number of Fresnel half zones, $N_F < 1.0$, results in a significant loss of resolution. With circular apertures, a large demagnification factor, around 7, can be routinely obtained. Experimental demonstrations of these particular results are underway and are expected to add to the systematic body of demonstrations in both Near Field and proximity x-ray.

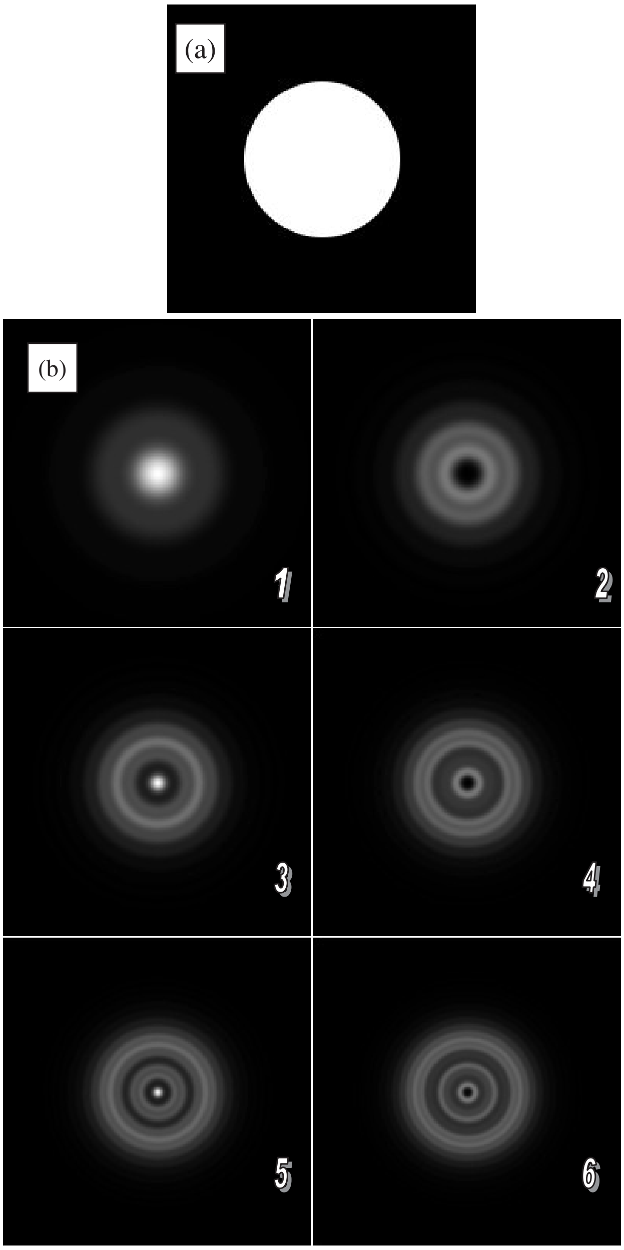

Figure 2. (*a*) Circular aperture and on the same scales and (*b*) simulated aerial images, with 0.62 nm wavelength, at Fresnel half zones ranging from 1 to 6 as inset numbering.

These images and profiles show how small symmetrical features can be printed. Squares are not as easily printed in Near Field as circles. In order to print truly square structures, we have considered the possibility of printing fine structures by using double exposure with double development in negative resists. In principle, two lines crossed, each employing the high contrast that is used in development, would result in truly square prints. Printing squares from 20 nm crossed lines is manageable from considerations of practical Gaps; but the duplication of the development would be a disadvantage.

4. Extensibility and blur

In principle, the resolution of x-ray lithography can be increased by using radiation of shorter wavelength.

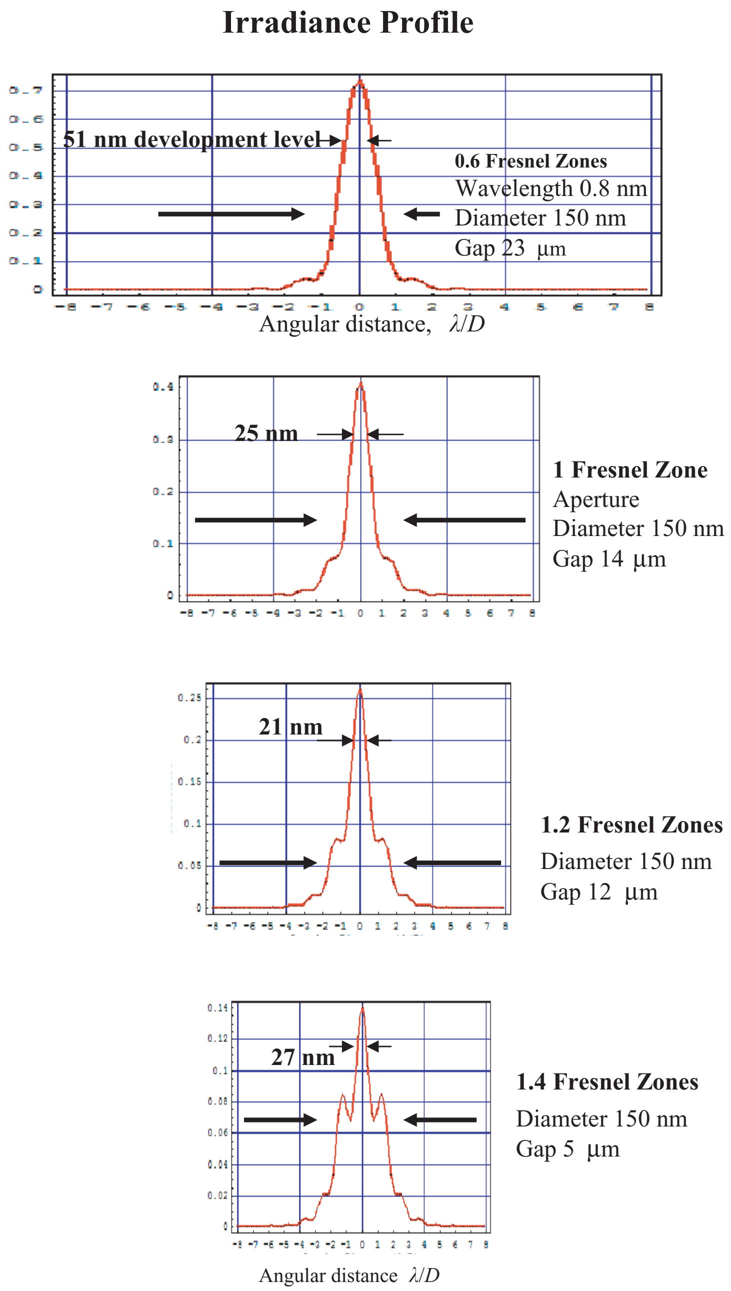

Figure 3. Simulations of profiles of images due to Fresnel diffraction from circular apertures at decreasing Gaps corresponding to 0.6 (top), 1.0, 1.2 and 1.4 (bottom) half zones. By multiplying the non-dimensional angular abscissa scales by G, the profiles are compared with constant aperture size, $\Delta s = 150$ nm at monochromatic $\lambda = 0.8$ nm, as shown in the figure. See corresponding table 1.

(This figure is in colour only in the electronic version)

This principle applies to the printing of symmetric structures as it does to the lines, flags and bridges simulated before. Previously, it was thought [15], that optimum resolution depends on a minimum occurring between photoelectron range, and the diffraction broadening. The former was supposed to increase with incident photon energy; the latter decrease. However, this view is contradicted by various experimental data directly [21, 22], including our own prints at 25 nm [2], and by less direct studies of blur [13, 14]. We now understand that the print resolution depends not on the range of the primary photoelectrons; but on the range of Auger electrons, i.e. independent of the incident photon energy. Meanwhile, in NFXRL, diffraction causes not a broadening, but a contraction in current beyond a clear mask feature. These views are consistent with the experimental data.

In particular, the blur in PMMA (poly methyl methacrylate) produces negligible broadening at 20 nm print resolution when used with 0.8 nm wavelength x-rays incident at the mask and when the printed feature size is dominated by diffraction [2]. Though the primary photoelectron range is comparatively broad, the range of associated Auger electrons is much smaller, typically less than 15 nm. This range changes significantly only with resist composition which can be selected for optimization. Using experimental k-values

Table 1. Comparison of typical resolution (see, e.g. figure 6) and gaps corresponding to various numbers of Fresnel zones in a circular aperture and for two mean wavelengths.

No of Fresnel half zones N_F	Typical resolution when $s = 150$ nm (figure 6)	Gap (μm) mean wavelength, $\lambda = 0.8$ nm	Gap (μm) with $\lambda = 0.4$ nm
1.4	27	5	10
1.2	21	5.9	11.8
1	25	7	14
0.8	38	8.8	19.6
0.6	51	11.7	23.4

(k is the smallest print feature size $(\lambda G)^{-1/2} \sim 0.15$—notice that k is a phenomenological number that is not physically significant, though it has a superficial resemblance to the Rayleigh criterion) obtained using demagnification by bias, we have revised [10] our earlier estimates [4] of the expected blur. Our plots [10] show that at dimensions for 15 nm prints, the Gap approaches an experimental limit around 5 μm, and the printing is facilitated if a restriction to half pitch line width is relaxed. Since PMMA is less sensitive than chemically amplified resists, optimization will benefit from a selection of new resists beyond those currently used in 1XPXL in common with 248 nm optical lithography. It is anticipated that NFXRL will benefit from resist developments in other NGLs.

Moreover, multiple methods have been described [18] for applying magnification corrections to the masks. These corrections can be made at the same time as blur, and run-out are reduced or eliminated [2]. Mask fabrication by well-established methods, involving, at present, comparatively small fields with relatively large features, adds on a further advantage to a well-developed technique.

5. Conclusion

Since Gap is an important system parameter and since this Gap scales with the square of mask feature size, small features are best printed with comparatively large mask features, scaled to the optimum Gap. Demagnification factors of around 7 are routinely available in the printing of circular features for contacts. NFXRL is an enhancement of a well-demonstrated technique that is extensible up to 15 nm and that is conventional in both throughput and manufacturability. There has been considerable interest [18, 23] in extending demonstrations to the 15 nm regions. NFXRL has many advantages including increased Gap width, increased mask feature sizes, small field at the mask, economy in mask fabricability, conventional wafer throughput and magnification control, in addition to the outstanding feature of high resolution. The method opens the way to the manufacture of micromachines and integrated circuits of such small dimensions, whether using modern compact synchrotron light sources [2, 4, 6] or, at a slower rate, point sources [2, 24].

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