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Materials Science in Semiconductor Processing 8 (2005) 483–490
MATERIALS SCIENCE IN SEMICONDUCTOR PROCESSING

Analysis of instability in a critical dimension bar due to focus and exposure

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Available online 7 January 2005

Abstract

In the photolithography processing of semiconductor, the line width becomes smaller and smaller. Therefore, the requirements of process window are stricter than before. Among them, the control of focus and exposure dose is one of the most important factors that may affect the line width. Bad control of focus and exposure may not only affect line width, but also cause the increment of rejects of products. The research mainly explored the effects of focus and exposure dose on line widths of different photo resists. The research obtained related coefficients of exposure dose line width and focus line width by coating photo resist of different components on the surface of the silica wafer. The results of research found that focus may not only change line width but also had a positive–negative symmetric relationship with line width. It also found that there was linear relationship between exposure dose and line width.

Keywords: Line width; Exposure dose; Focus

1. Introduction

Wafer throughput in micro-lithography depends on the sensitivity of the resist film to radiation. A lower exposure time required to produce a latent Image in the resist corresponds to a higher throughput [1]. The focus affects line width: a focus of 0 μm yields the lowest line width, the width increases with the focus distance. Positive and negative foci yield symmetrical results [2]. The line width and the resist thickness curve. The primary factor that dominates the gradient of the exposure/line width relationship is the resist's internal chemical composition [3].

Resist spin coating has been successfully modeled using a detailed non-Newtonian analysis, which allows local fluid viscosity to vary with concentration and shear rate [4]. The cleavage of a butylester is acid-catalyzed and yields carboxcylic acid and isobutene after exposure to the photo active component (PAC) and post-exposure back (PEB) [5]. When an acid generator is present in a CAMP resist formulation, the mechanism for producing a lithographic pattern is simple. The strong acid formed causes deprotection at a relatively low temperature with an activation energy of approximately 11–14 kcal/mol [6]

Resist is a photosensitive material. If exposed to common white light, a chemical reaction occurs and photolithography cannot be performed. The photolithography process is like the development of a photographic film in that it must be performed in a darkroom. The photolithographic process is further limited since a yellow light source does not promote the resist to react chemically. Accordingly, photolithography should be performed in an environment with a yellow light source. The commonly used light sources in the stepper include the G-line, the I-line and deep ultraviolet (DUV). The G-line wavelength is ~436 nm, the I-line

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1369-8001/$ - see front matter
doi:10.1016/j.mssp.2004.10.001

$\lambda = 350-450$ nm, and DUV $\lambda = 100-300$ nm. The wavelength of the I-line changes according to the internal composition and gas pressure of the mercury arc lamp used, varying within 350–450 nm [5]. In this work, the I-line stepper's light source $\lambda = 365$ nm was used. DUV wavelengths differ according to the laser gas composition: KrF $\lambda = 248$ nm, ArF $\lambda = 193$ nm and F_2 $\lambda = 157$ nm [5]. In this work, the DUV stepper's laser light source, KrF $\lambda = 248$ nm, was used.

Photolithographic experiments depend on several kinds of measurement instruments. Moreover, the optical process involved is complex. The main aim is to reduce the line width and make the critical dimension (CD) bar even more stable, which is usually achieved by changing the light source. One method of improvement involves the reticle's zoom ratio. However, a difference between the reticle's zoom ratio that is too large will cause the photolithographic process not to be ideal [8]. In these experiments, the compression ratio applied to the pattern on the reticle and the wafer was 5:1. The compression ratio applied to the DUV was the same as for the I-line.

2. Experimental

2.1. Equipment

(1) The steppers were a Nikon I-line and DUV. The major function of a stepper is to apply the exposure pattern to the surface of a wafer that has already been coated with a layer of resist. The main difference between an I-line stepper and a DUV stepper is that they use different light sources. The light source used by an I-line stepper is a UV lamp $\lambda = 365$ nm, while the light source used by a DUV stepper is a KrF excimer laser $\lambda = 248$ nm. The differences between the wavelengths of these light sources lead to different resolutions. Generally, a shorter wavelength gives a better resolution, and a better resolution enables the line width to be made narrower.

The exposure field used by the I-line stepper was a 6 in/22 mm square of glass material. The lens numerical aperture (LNA) = 0.60 and the input numerical aperture (INA) = 0.38. The numerical apertures (NAs) were fixed.

The exposure field used by the DUV stepper was a 6 in/22 mm square of glass material. LNA = 0.60 and INA = 0.45. The Nikon stepper has two numerical apertures. The INA is the front end of the lens through which the arc lamp or the laser light passes. The INA did not affect the experiment (the INA in the experiment was a fixed type of INA, so the INA had no effect on the experiment). The LNA is a device of aperture in projection LENS. Numerical aperture in this experiment means LNA. Hence, LNA = NA (σ = INA/LNA, I-line and DUV Illumination aperture used conventional types). Generally, the NA of the DUV can be opened wider because the resolution of the resist used with DUV is higher than that used with the I-line.

(2) For scanning electron microscopy (SEM), the microscopes used were a Hitachi S-9200, a KLA_Tencor 8100, and an Applied Materials' SEM Vision. The Hitachi S-9200s primary function was to measure the pattern's line width and the capture a top view of the image. The error correction method involved a standard wafer that, after etching, had a line width of $0.3\,\mu m \pm 10\%$. The line width of this standard wafer was measured and if the result was within $0.3\,\mu m \pm 10\%$, then it was within the scope of our permission. The error between the results obtained by the KLA_Tencor and those obtained by the Hitachi S-9200 was not allowed to exceed $\pm 10\%$.

The Applied Materials SEM Vision was not used to measure line width because its top view measurement was worse than those made with the Hitachi S-9200 or the KLA_Tencor 8100. The Applied Materials SEM Vision was used mainly to view a pattern in three dimensions. This SEM provides the advantage of having an E-beam that measure the wafer's surface at $\pm 45^\circ$ and 0°. This SEM therefore enables a pattern to be observed in three dimensions.

(3) The TEL CLEAN ACT-8 machine was used for spin coating and as a developer. The main functions of the ACT-8 are (1) priming, (2) spin coating, (3) soft baking, and (4) developing. (1) A layer of Hexamethyldislazane (HMDS) is sprayed onto the wafer. HMDS functions as a medium that strengthens the bond between the resist and the wafer surface. After suitable priming, the wafer surface energy can be adjusted to a level similar to the resist surface energy to increase the adhesive strength between the wafer surface and the resist. (2) After dehydration baking and priming, the liquid resist must be evenly applied to the wafer surface. The resist is dripped onto the center of the wafer and distributed over its surface by the centrifugal force due to high-speed rotation. A higher rotation speed yields a thinner and more uniform resist liquid. The resist includes a very volatile organic solvent. After the resist is sprinkled onto the wafer surface, the stickiness of the resist changes with the volatility of the solvent. Failing to complete the coating before the solvent becomes volatile yields poor uniformity. (3) The main purpose of the soft baking is to eliminate the solvent that remains in the resist after spin coating, to transform the resist from a semi-solid to a solid film. (4) The main purpose of developing is to display the pattern that follows the exposure and leaves the required pattern after the developer reacts.

(4) After the coating process is completed, the thickness of the resist must be known. Therefore, a KLA_Tencor PROMETRIX UV-1280SE was used to

measure the thickness of the resist film, by applying optical methods to measure accurately the thickness of the resist from the center of the wafer to the edges of the wafer after the resist has solidified.

3. Experimental

The matrix was exposed by marking off the X (horizontal) and Y (vertical) axes on the surface of the wafer and then changing the focus and the exposure dose to vary the CD bar. Once the resist material was checked, the optimal focus and exposure dose for the resist were determined. Different resists correspond to different optimal focal centers. The focus and exposure dose are two variables that simultaneously influence the line width's cross-sectional pattern. Consequently, a CD-SEM had to be used to measure or observe changes in the pattern. The optimal focus is the center point of the acceptable depth of field (DOF) range. The experiments showed that a focus nearer to zero yielded an image of better quality. The optimal exposure dose is one that—with a fixed focus—makes the pattern on the wafer the same as the pattern on the reticle. Also, a smaller white wall enables more requirements to be met. The best situation involved no white wall. A negative white wall may have caused the CD bar to collapse.

4. Results and discussion

4.1. Symmetrical multiprocessing best focus

Symmetrical multiprocessing focus is that which yields a pattern most similar to that on the reticle. The method for measuring the symmetrical multiprocessing focus was to take a wafer coated with a positive resist (PFI 58 Resist) and to expose 17 sets of patterns on its surface. Each pattern consisted of nine horizontal patterns and nine vertical patterns, each of which included five rhomboids. The length to width ratio of the rhomboids on the reticle was 30:1. However, their shape changed with the focus. The length of each rhombus was measured and the longest one found. The focus on this longest rhombus was the best focus because as the focus changed, all the rhomboid patterns changed shape accordingly due to defocusing and the changing area of exposure. Defocusing can be divided into positive and negative. For a positive resist, the positive defocusing cross-section of a CD-bar is a regular triangle. Severe defocusing causes the sharp cornered pattern to become smoother and rounder. A negative defocusing cross-section CD bar is an undercutting, which, if severe will cause the CD-Bar to collapse and the sharp-cornered pattern to become smoother and rounder. Therefore, when the focus is at zero, the rhombuses are longest, and when the focus shifts to positive or negative, contraction and deformation occur.

The I-line stepper and the DUV stepper in this experiment used the same reticle. However, the differences between the resists used with each stepper caused the I-line stepper to require longer exposure than the DUV stepper. For the I-line stepper, the exposure conditions were exposure dose $= 165\,\mathrm{mJ/cm^2}$ and exposure step $= 0.2\,\mu\mathrm{m}$. The focus variation ranged from $+1.6\,\mu\mathrm{m}$ to $-1.6\,\mu\mathrm{m}$. The Applied Materials' SEM Vision revealed that the best focus for the I-line stepper was $0\,\mu\mathrm{m}$, at which the ratio of length-to-width of the rhombuses was approximately 30:1. Shifting the focus farther from $0\,\mu\mathrm{m}$ caused the rhomboid patterns to become more blurred, contracted and deformed. When the focus was $\pm 1.6\,\mu\mathrm{m}$, the five rhomboid patterns contracted into irregular ellipse forms (Fig. 1) because of the defocusing effect produced on this area. The pattern changes at negative and positive foci were symmetrical (Figs. 2 and 3).

When measuring the best focus for the DUV stepper, SEPR 432 was used as the positive resist. The exposure conditions were exposure dose $=30$ and exposure step $= 0.2\,\mu\mathrm{m}$. The focus variation ranged from $+1.6\,\mu\mathrm{m}$ to $-1.6\,\mu\mathrm{m}$. The Applied Materials SEM Vision was used to observe that that the patterns at negative and positive foci were symmetrical. However, the pattern of the DUV stepper was better than that of the I-line stepper. When the focus was zero, the pattern was a 30:1 rhombus. When the focus was ± 1.6, the five rhomboid patterns contracted into irregular shapes (Fig. 2) because the DUV's defocusing effect is stronger than the I-line's defocusing effect. Consequently, the shapes obtained were smoother and rounder than with the I-line. The patterns at negative and positive foci were symmetrical (Fig. 4).

When the I-line stepper focus was $0\,\mu\mathrm{m}$ and the DUV stepper focus was also $0\,\mu\mathrm{m}$, the two corresponding patterns were expected to be identical. However, in this experiment, the DUV stepper's rhombus pattern was longer than the I-line stepper's because exposure dose impacts pattern length. A longer exposure dose causes the resist to undergo a more intense chemical reaction. However, the difference between the two patterns was satisfactory for this experiment, and the pattern lengths in each of the two cases did not have to be equal. After a long exposure, contact with the developer causes a more intense chemical reaction. Therefore, for both the I-line stepper and the DUV stepper, increased exposure dose yields a shorter pattern.

The focus also affects the length of the pattern. When focus $= 0\,\mu\mathrm{m}$, the pattern is longest, and when the focus is $\pm 1.6\,\mu\mathrm{m}$ the pattern is shortest, because a positive resist was used, the special characteristic of which is that areas of resist that are exposed to light are washed away during the development reaction. The focus was conically distributed, and the negative focus and positive focus were symmetrical. At a focus of $0\,\mu\mathrm{m}$, the exposed

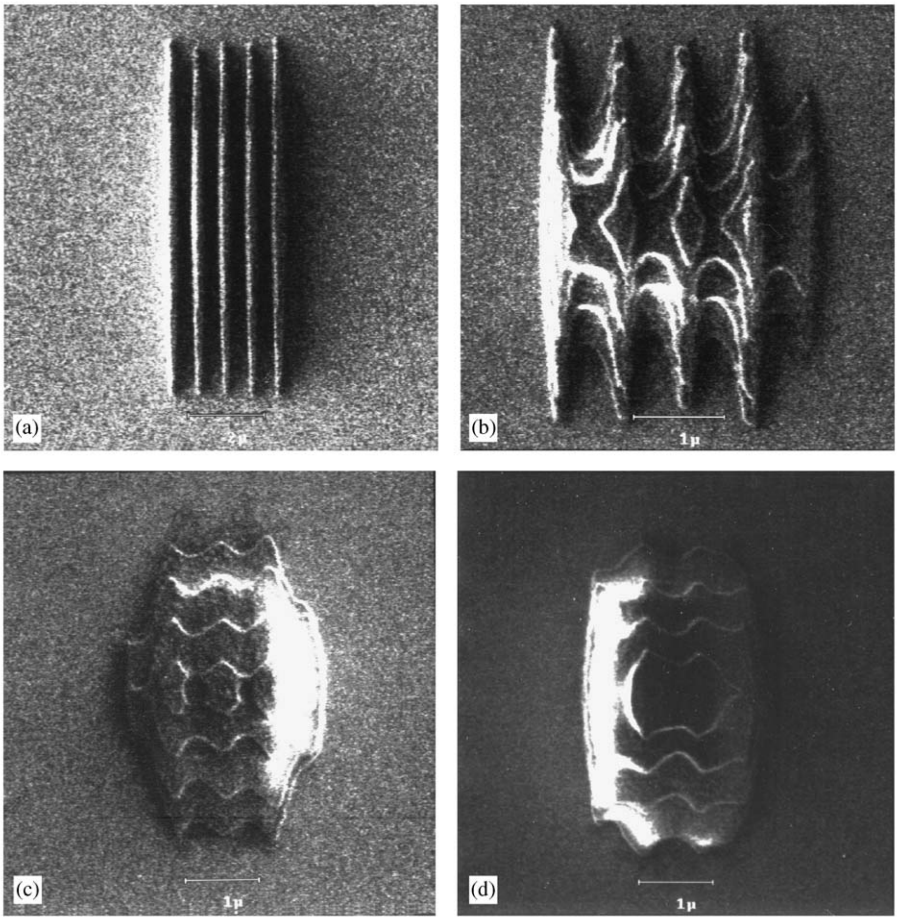

Fig. 1. I-line symmetrical multiprocessing focus. Pattern length changes observed using an Applied Materials SEM Vision. (a) At focus = 0 µm, the pattern had the same shape as that on the reticle; (b) at a focus of −0.8 µm, the pattern was shortened; (c) at focus = −1.2 µm, the pattern was shortened and completely transformed; and (d) at focus = −1.6 µm, the pattern irregularly contracted into a shape that resembled an ellipse.

areas were fewest and no defocusing was observed. At a focus of ±1.6 µm, however, more areas of the positive resist were exposed, and, because of serious defocusing, the pattern was shortened and contracted, becoming irregular.

4.2. Focus

The best focus determines the present, actual focus, which varies with the best focus as standard. According to Preil and Arnold [7], focus influences line width. Their experimental method was to vary the focus from −1.2 to 1.2 µm and observe the changes. They found that at a focus of 0 µm, the line width was smallest; that a longer focus yielded a larger the line width, and that positive and negative foci were symmetrical. In this work, the best focus was used to arrive at results that were the opposite of those obtained by Preil and Arnold because the process latitude smiley curve was different. Restated, a different resist was used herein.

Varying the focus over 1.6 µm revealed that the I-line's best focus curve included clear variations within ±0.4 µm, as shown in Fig. 3. Therefore, the I-line focus was varied within ±0.4 µm and the variation of line width measured. A white wall was observed simultaneously. When focus = 0 µm, a white wall could be observed, see Fig. 5. In theory, focus = 0 µm should not produce a white wall. However, in practice, because the developer liquid contacts the surface of the photo resist during the developer-process for a longer time than it contacts the bottom of photo resist, we may observe a white wall when focus = 0 µm. In Fig. 6, when the focus was varied between ±0.4 µm, a white wall in the shape of a regular triangle appeared regardless of whether the focus was positive or negative, which contradicts theory. With a positive focus the white wall is expected to be a regular triangle, but according to

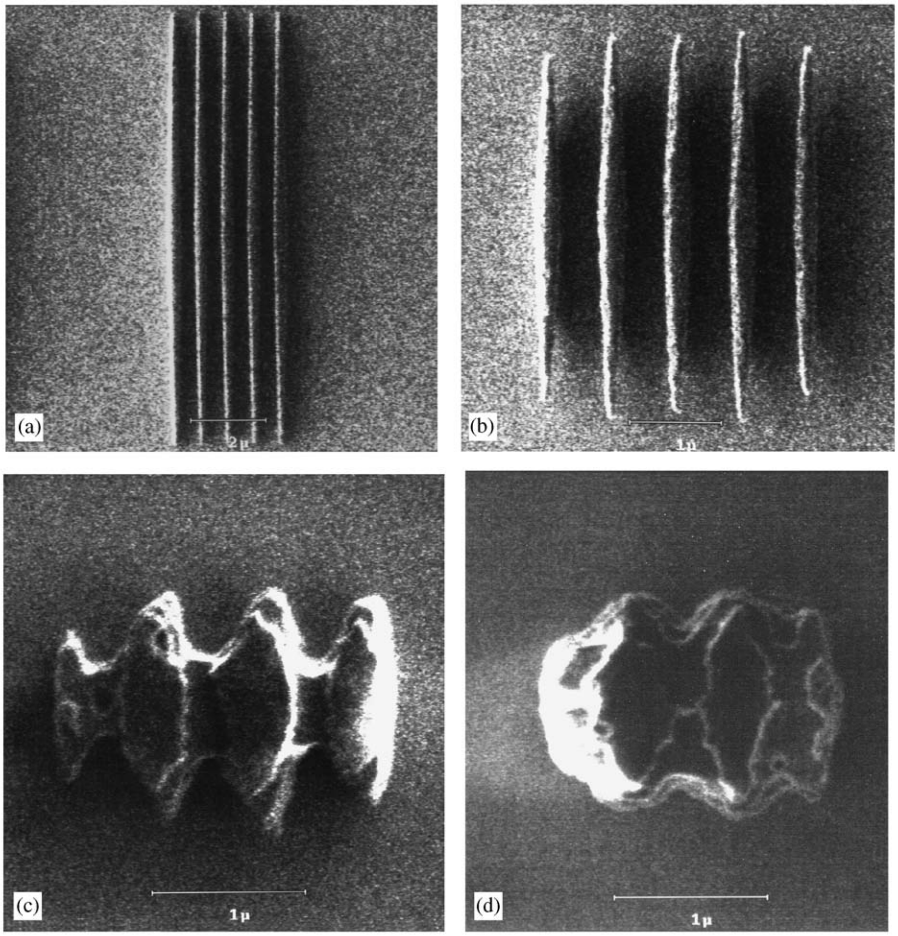

Fig. 2. DUV symmetrical multiprocessing focus. Pattern length changes observed using an Applied Materials SEM Vision: (a) At focus $= 0\,\mu m$, the pattern had the same shape as that on the reticle, but was longer; (b) at focus $= -0.8\,\mu m$, the pattern was shortened; (c) at focus $= -1.2\,\mu m$, the pattern was shortened and completely transformed; and (d) at focus $= -1.6\,\mu m$, the pattern became an irregular shapes.

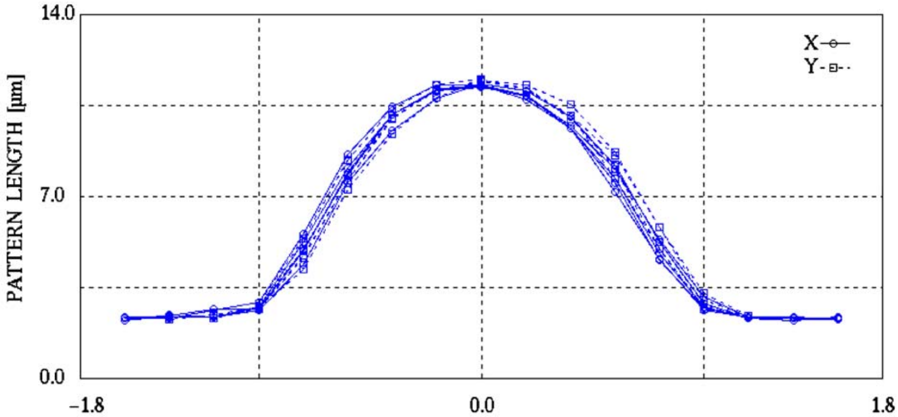

Fig. 3. Process latitude smiley curve of pattern length focus, with an I-line stepper and a positive resist.

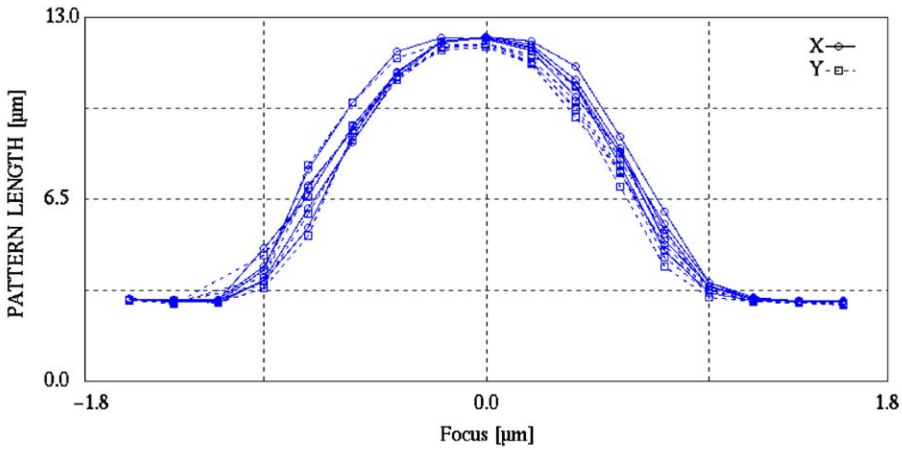

Fig. 4. The process latitude smiley curve pattern length focus, with a DUV stepper and a positive resist.

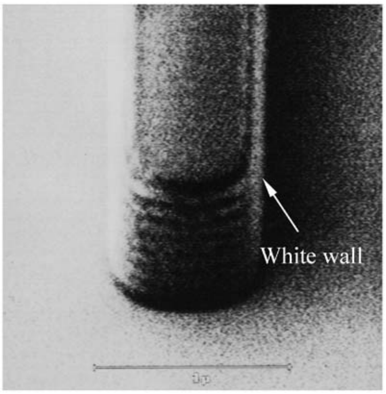

Fig. 5. I-line light source, PFI-58 resist, exposure dose $= 200\,mJ/cm^2$, focus $= 0\,\mu m$: Observed with the Applied Materials SEM at a scanning angle of $+45^{\circ}$: line width $= 0.682\,\mu m$, white wall and three-dimensional picture.

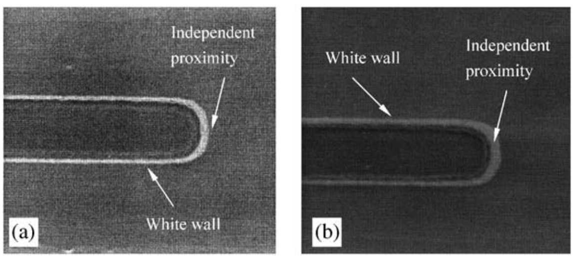

Fig. 6. I-line light source, PFI 58 Resist, Exposure $= 200\,mJ/cm^2$; Figures of white wall and independent proximity when (a) focus $= +0.4\,\mu m$, (b) focus $= -0.4\,\mu m$, under multiplying rate 50 kV of HITACHI S-9200 CD SEM and Line width $= 0.2\,\mu m$. No matter whether it is $\leqslant 0\,\mu m$ or $\geqslant 0\,\mu m$, there is a regular triangular white wall.

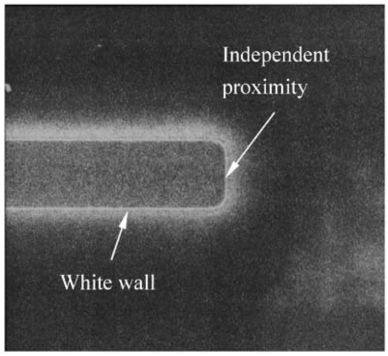

Fig. 7. Deep UV light source, exposure $= 30\,mJ/cm^2$: figures of white wall and independent proximity when focus $= 0$, under multiplying rate 50 kV of HITACHI S-9200 CD SEM and line width $= 0.2\,\mu m$. The independent proximity of Deep UV is smaller than I-line.

theory, at a negative focus, the white wall will be an undercut. However, producing an undercutting with a negative focus was found to be difficult, contrary to expectations, because during the development process, the surface of the water came into contact with the developer for a longer period than did the base, so the chemical reaction took longer at the surface than at the base. Making an undercutting required that a negative focus be continuously maintained. However, a focus nearer to $0\,\mu m$ is generally preferred. Using a negative resist switches the orientation of the white wall.

4.3. Exposure dose

Fig. 8 shows that exposure importantly influences line width. A higher exposure dose corresponds to a smaller

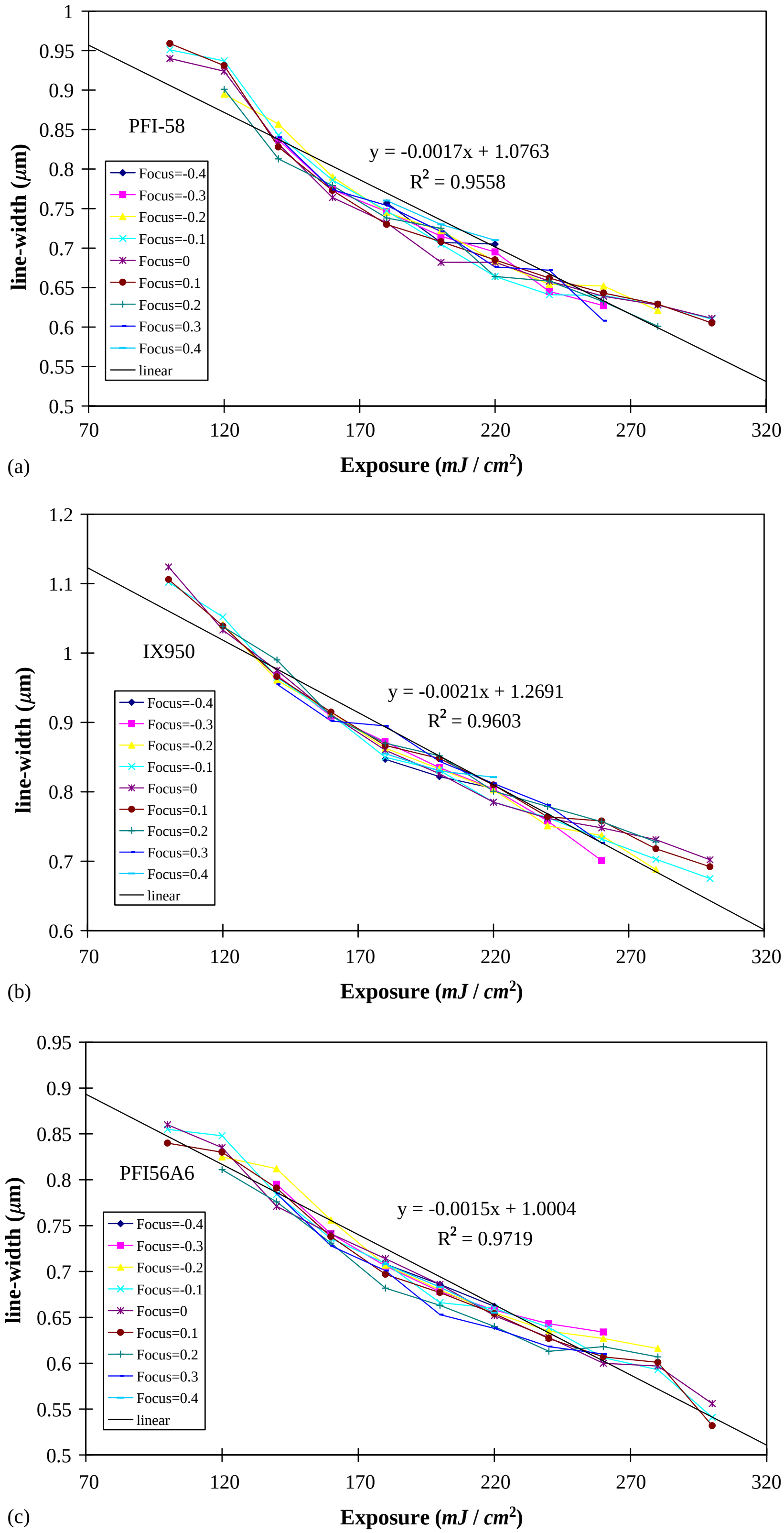

Fig. 8. I-line light source, the figure of linear relationship of (a) PFI-58 resist, (b) IX950 resist and (c) PFI56A6 resist exposure line width.

line width, according to a linear relationship. The experiment revealed that the gradient of the exposure/line width relation did not change with the thickness of the resist. Birol Kuyel and Harry Sewell [6] noticed that line width and the thickness of the resist followed a wave. The main factor that influenced the gradient of the exposure/line width relation was the resist's sensitivity composition. Generally, the extent to which the composition induces a stronger chemical reaction with the developer influences the slope.

Fig. 8 showed that higher the exposure dose corresponds to a smaller line width, mainly because increasing the time for which the resists is exposed increases the force of the chemical reaction between the resist and the developer. Consequently, the developer will remove even more exposed resist, reducing the line width. However, the light source used to obtain Fig. 6 was a UV lamp, while that used to obtain Fig. 7 was a laser, but the line widths are clearly identical (see Fig. 8). The top edge of the CD bar in Fig. 6 is less stable than that in Fig. 7, and the top edge of the CD bar in Fig. 6 is semicircular showing independent proximity. In Fig. 7, the same reticle was used; its borders were found to be more stable than in Fig. 6, and the top edge of the CD bar was almost a right angle, because the wavelength of a UV lamp is higher than that of a lasers, so the resolution is poorer, such that a pattern identical to that on the reticle is harder to obtain.

A better resolution enables a smaller line width to be obtained, such that at the appropriate exposure dose no variations will be produced. Therefore, the line width can be reduced only by improving the resolution. Fig. 1 shows that the resolution ($R = k\lambda/\mathrm{NA}$) was related to NA, λ and k (k is a constant that has relations with materials of photo resist and conditions of manufacturing process are constants that have relations with materials of photo resist and conditions of the manufacturing process). In this experiment, NA was usually set between 0.5 and 0.7, so although the NA was used to control the resolution, the effect was not great. Changing the wavelength and k to adjust the resolution was more effective. The authors' future research will use Light with a shorter wavelength and an electron-beam. However, at present, UV lamps and KrF lasers are our only available light sources. Increasing k will be the simplest method of improving. The current method is to switch to a different resist or to apply an anti-reflection coating (ARC) to the surface of the resist. The goal is to reduce both k and the optical proximity effect. The transmission rate of the ARC material on the surface layer must be increased to allow the light beam to pass through it and fall onto the resist beneath, reducing refraction. However, the addition of a layer of ARC to the surface of the resist is beyond the scope of this work.

5. Conclusions

The focus and exposure of dose in photolithography process is the important condition to determine the figure. It is very hard to determine which is the best focus and exposure dose in photolithography process. In semiconductor plants (Fab), they usually use a frequently used photo resist (PR) as basic standard while other PRs co-work with it. But this method was proved probably wrong. The experiment found that the patterns of focus are symmetrical and process latitude smiley curve will not change because of different elements of PR, but location or figure of best focus will do. Process latitude smiley curve will not change because of different composition in PR while location of best focus and figure may do. The reason why process latitude smiley curve forms a symmetrical curve is that focus distributes in the shape of a circular cone. Under the circumstance of best focus, CD bar will be the longest one because photo resist has minimum contacting area. With changes of focus (changes of distributing locations of the circular cone), the size of CD bar changes accordingly. Exposure dose will change the size of CD Bar, that is, higher exposure dose will make CD bar smaller, but too high an exposure dose will make CD Bar unstable or even cause the collapse of CD Bar. Therefore, it is not correct to use exposure dose to change line width. There is linear relationship between exposure dose and line width. According to the results of our experiment, $R^2 > 0.9$, so their relationship could be considered as a linear relationship ($R^2 > 0.9$ is called high positive correlation in statistics).

Acknowledgement

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 92216E009019.

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