Wet trimming process for critical dimension reduction

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ABSTRACT

Plasma trimming is a method widely used to achieve small feature sizes beyond the capability of photolithography. Plasma processes reduce the dimensions of photoresist, anti-reflective coating, hardmask, or device substrate patterns with varying degrees of anisotropy. The vertical trim rate is higher than or equal to the lateral trim rate. As a result, much of the line-edge roughness from the resist pattern remains. High aspect-ratio resist patterns are subject to necking and collapse during this process. However, by using a developer-soluble hardmask in place of traditional anti-reflective layers, it is possible to achieve controllable, anisotropic trim rates, as well as reduced roughness. Moreover, the process benefits from a very thin resist, or imaging layer, instead of relying on a thicker mask with a high aspect-ratio. The hardmask is patterned during a standard resist develop step, and the resist may be stripped prior to substrate etching due to the high etch resistance of the hardmask. Many other advantages have been discovered from this wet trimming process, including high resolution, extended depth of focus, controllable trim rate, and lower cost than traditional methods.

Keywords: anti-reflective coating, plasma trimming, spin-on hardmask, wet-develop hardmask

1. INTRODUCTION

The three optical and chemical steps in the photolithography process for integrated circuits have not changed in their basic function during the last three decades of semiconductor manufacturing. First, the optical images of the desired patterns are projected onto a photoresist surface to create chemical differences between exposed and unexposed areas. Second, the photoresist with the latent images must undergo chemical reactions with a developer to form three-dimensional features. Third, for anisotropic pattern transfer a plasma etch process transfers the photoresist patterns to the next layer of the substrate, often with a reduction in critical dimension (CD) or sidewall tapering designed to exceed the limits of the first two steps. Each of these three steps has required continuous development. In the first step, to achieve ever smaller dimensions, the wavelength has been reduced from g-line (436 nm) to i-line (365 nm), KrF laser (248 nm) to ArF laser (193 nm), and continuing on to EUV (13.5 nm). Meanwhile, phase shifting masks and optical proximity correction have helped overcome traditional diffraction limits. Recent improvements in the second step, or resist enhancements, have hinged upon chemically amplified resists having sufficient strength to withstand plasma etching, but with acceptable levels of edge roughness in the pattern features. Finally, in the third step, the photoresist must be thick enough for the plasma etch step, which has been refined to lower bias and lower pressure plasma sources to help maximize resist selectivity. Thick photoresist, however, greatly hinders the imaging resolution. Thick photoresist is also susceptible to sidewall standing waves.

The most common method of CD reduction is the plasma trimming process, in which the photoresist, or photoresist and underlying pattern layers, are etched in a semi-isotropic fashion to reduce their dimensions prior to applying the anisotropic substrate etch.[1] The chemistry used for these types of processes includes oxygen, or oxygen mixed with chlorine or another halogen to modulate the trim rate and anisotropy. The most obvious drawback to this approach is that the mask height is reduced by the trimming process, leaving less mask for the substrate etch steps. The line-edge or line-width roughness (LER/LWR) from the photoresist may be reduced somewhat by the trimming process, but pattern distortion often occurs near turns or bends in the pattern of fine features due to stresses within the film.

Several attempts have been made to improve upon plasma CD trimming. Two such methods are the gaseous oxide etch, or chemical oxide removal (COR) process,[2] and the UV trim process.[3] In the former case, an oxide

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hardmask is required and specialized hardware is used to remove the oxide in controlled increments for the CD reduction. This process is time-consuming and expensive to implement. It also requires a separation of the trim and substrate etch steps into different process chambers. In the UV shrink process the resist patterns are heated while applying blanket UV treatment. This process requires dedicated UV shrink equipment, can cause pattern distortion, and the shrink results are resist-formulation dependent.[3]

This investigation seeks to fundamentally disrupt the decades-old three-step patterning process described above by introducing a material with the properties of an anti-reflective layer, CD trimming medium, and etch mask; namely, the spin-on developable hardmask (dHM). The dHM is inserted into the film stack in the place of a traditional anti-reflective layer, and is patterned and trimmed in the developer solution. Rather than requiring a thick photoresist to survive both the trim and substrate etch processes, the trimming of the dHM benefits from a very thin resist layer. The resist serves only as an imaging layer for the wet trimming process, and may be stripped prior to the dry etch steps. This new concept of the photolithography process opens many options for litho performance enhancement and cost savings, but it is not without its own challenges. This report examines hardmask CD trimming processes on the litho track.

2. DEVELOPABLE HARDMASK

The dHM is a spin-on material underlying the imaging layer that can dissolve isotropically in developer with an appropriate rate for CD control. The dHM layers used in this work have dissolution rates in 0.26N tetramethylammonium hydroxide (TMAH) aqueous solution of 0.8 to 4 nm/second. The hardmask materials were designed and engineered for reflectivity control as well. The optical indices of one candidate material are listed in Table 1. The most critical feature of the dHM is its high selectivity in various plasma etch processes used to etch polysilicon or oxide substrates. Using non-optimized etch conditions in a capacitively coupled lab system, the Oxford Plasmalab® 80Plus, selectivity as high as 33:1 was achieved against polysilicon, as illustrated in Fig. 1. The etch process conditions for oxide are 50 mT, 500 W (1.1 W/cm^2), 5 sccm C_4F_8, and 100 sccm Ar. For polysilicon the process conditions are 12 mTorr, 200 W (0.4 W/cm^2), 12.5 sccm Cl_2, 50 sccm HBr, 5 sccm O_2, and 12.5 sccm He. For polysilicon patterning a thickness of less than 10 nm would be sufficient to etch 100 nm thick polysilicon gates.

Table 1. Optical indices for one candidate dHM material/process.

193 nm	n	1.61
	k	0.38
248 nm	n	1.83
	k	0.39
365 nm	n	1.70
	k	0.42
633 nm	n	1.78

3. DEVELOPER TRIMMING PROCESS

The developer trimming process is demonstrated throughout this work with a film stack consisting of a silicon substrate, dHM layer, and imaging layer. The dHM is spun on and thermally cured to withstand the attack from the imaging layer solvents, but remains soluble in developer. The dHM thickness was chosen for minimum reflectivity. The imaging layer is a photosensitive film with high contrast. It can be extremely thin for this application. Thicknesses of 80 nm for i-line and 40 nm for KrF and ArF litho have been tested. The thickness can be further reduced depending on the contrast and integrity of the film. Note that substrate reflectivity has much less impact on the imaging layer when it is very thin. Standing waves would have a period greater than the thickness of the film. The thin imaging layer is removed with organic solvents after the development process. The dHM is the only masking layer for the substrate etch process.

When the film stack is in contact with 0.26N TMAH solution, the exposed areas of the imaging layer dissolve very quickly to form a template. During the remainder of the development time, the developer reacts with the

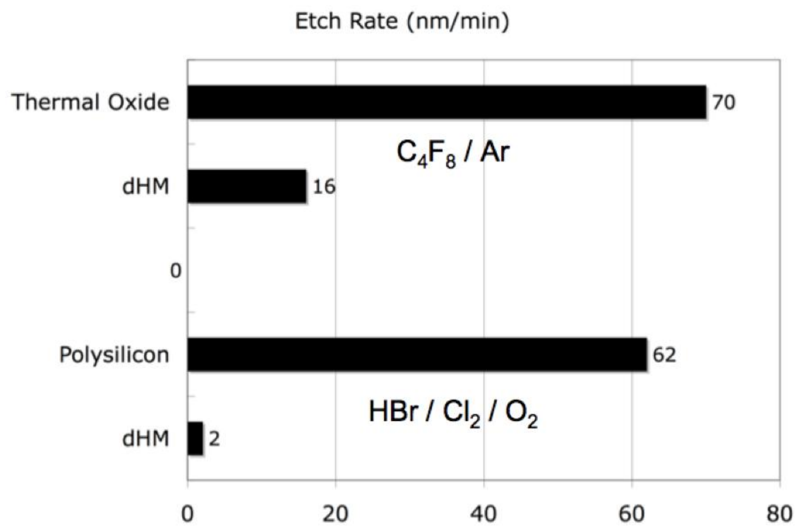

Figure 1. Etch selectivity of dHM for patterning oxide and polysilicon in C_4F_8/O_2 and $Cl_2/HBr/O_2$.

dHM more slowly. The dHM is patterned through the imaging layer template. As soon as the desired CD is reached, the development process is stopped sharply by replacing developer with water. This process is shown in Fig. 2, with an example SEM image taken from a KrF pattern made using an SVGL/ASML Micrascan® III with numerical aperture (NA) of 0.6.

Fig. 2(a) illustrates that the development front proceeds with a gradient in removal rate as soon as the hardmask upper edges start to undercut beneath the imaging layer. The gradient is created due to the balance of localized depletion and diffusion of TMAH molecules. The bottom edges of the hardmask develop faster until the whole development front advances well into the shade of the imaging layer. The end result is vertical sidewalls of the hardmask patterns, shown in Fig. 2(b) as an SEM cross-section image. Fig. 2(c) shows the dissected development zones. In the region labeled AZ1 (anisotropic zone 1), the development is directional due to the contrast of the imaging layer. The removal of the imaging material from this zone creates the pattern template. This portion of the process requires only a few seconds. In the isotropic zone (IZ), the development front propagates in all directions. The bulk of the unmasked dHM is removed from this zone with a moderate speed. This step may take 20-40 seconds depending on how the dHM is engineered and cured. AZ2 (anisotropic zone 2) is the hardmask trimming zone. Developer can only tunnel in one direction under the confinement of the imaging layer. The anisotropic manner of the trimming process in this zone preserves the needed thickness of the hardmask. In contrast, a plasma trimming process can consume the structures vertically as well as horizontally, often with a vertical-to-horizontal etch ratio of 3:1 or higher.

Fig. 3(a) shows the CD trim versus develop time curve for best focus and one focus step above and below best focus, as well as best dose and one step below and above best dose. The development rate is linear for each of the three dose values chosen and within a useful range for process control. The trim rate is 4 nm/second for this example. The SEM cross-sections in Fig. 3(b) help to illustrate the anisotropic trimming behavior. In this particular case the trim rate appears to slow slightly with increasing trim time, a feature that would be valuable to achieve consistent endpointing of the trim process. It is also clear from Fig. 3(b) that hardmask lines can be achieved with the same CD as the imaging layer. This is extremely useful when CD trimming is not desired, although the time window for endpoint determination may not be very large. Future work will examine trim rate for different dHM bake conditions as well as developer concentrations.

An isotropic development rate would be intuitively considered to have a negative impact on through-pitch CD bias. Such intuition is valid for conventional litho processes with a photoresist aspect ratio near 3 or higher. The patterned photoresist layer consists of open areas divided and isolated by tall photoresist lines. Within the isolated open areas, developer molecules depend on diffusion to reach and react with the hardmask. The diffusion

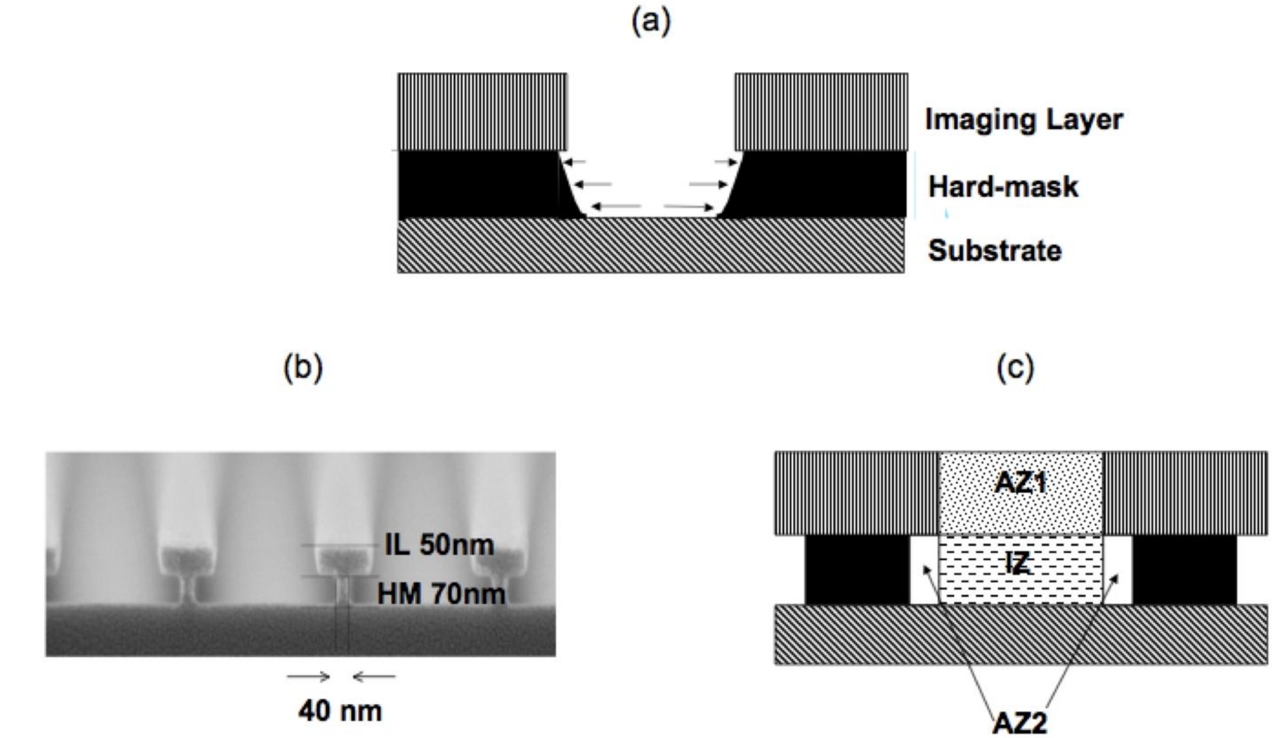

Figure 2. The development and trimming process: (a) Development rate gradient created when dHM starts to undercut. (b) Straight dHM sidewalls formed due to the development rate gradient (KrF exposure on an SVGL/ASML Micrascan® III with 0.6 NA). (c) Illustration of development/trimming zones AZ1, AZ2, and IZ.

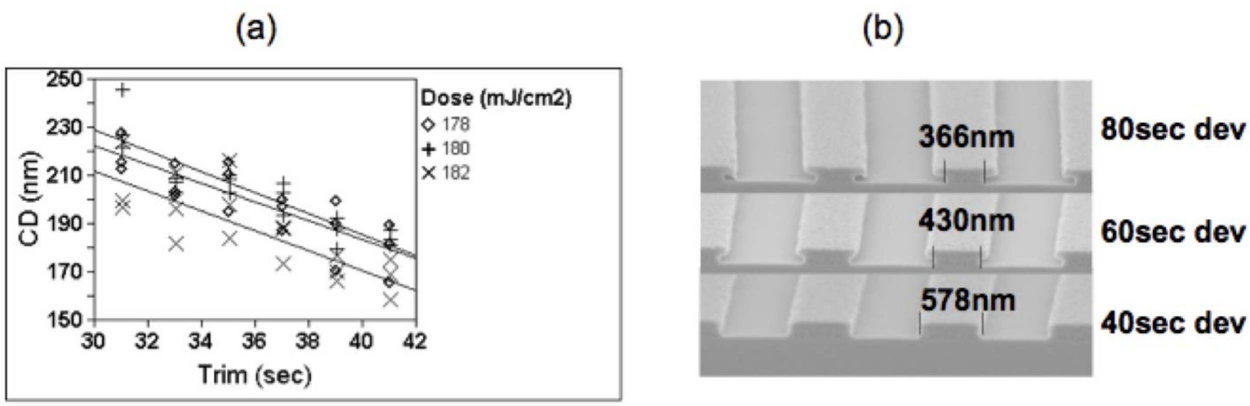

Figure 3. CD trim versus time is shown in (a) for an i-line focus/exposure matrix pattern. Linear fitting is overlaid for a center dose of 180 ± 2 mJ/cm^2 and zero focus offset ± 0.1 μm. The trim rate in this example is 4 nm/second. In (b) cross-section SEM images for different process conditions are shown to illustrate the undercutting process.

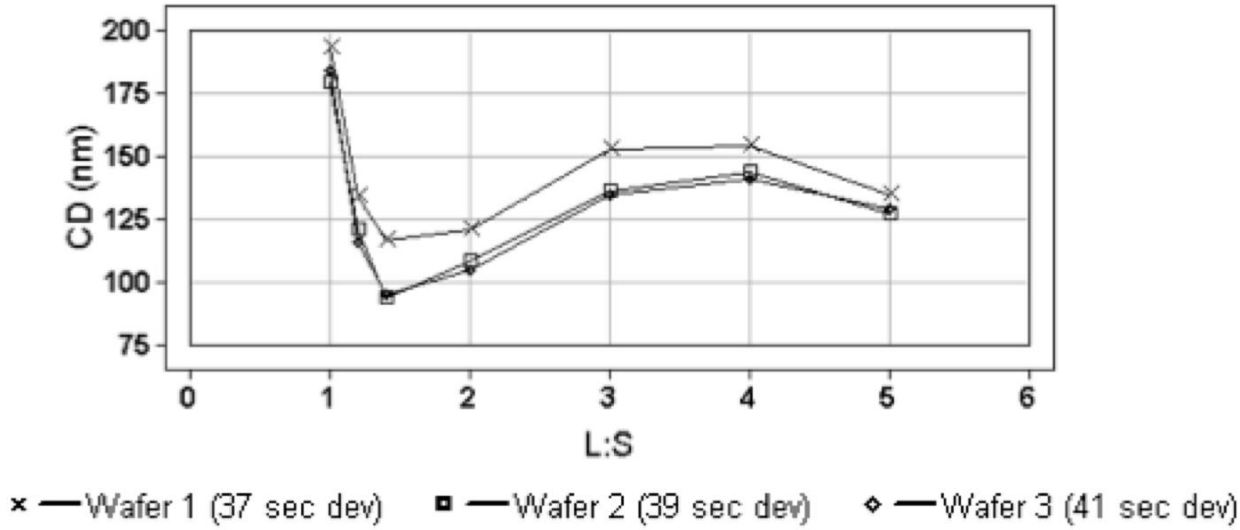

Figure 4. CD through pitch, or line:space (L:S) ratio for three different trim cases. Lithography is i-line on an ASML PAS 5500$^{\mathrm{TM}}$ stepper, using convention illumination, 0.5 sigma, and 0.54 NA. Nominal CD is 300 nm (1:1).

efficiency is obviously a function of the pattern pitch. Therefore the through-pitch CD bias of the hardmask would be greater than that of the photoresist alone. However, these problems are overcome by thinning the resist.

An imaging layer with thickness less than one-quarter of the exposure wavelength reduces pitch dependence, and shifts the process away from these conventional pitfalls. In this new litho process, the aspect ratio of the imaging layer is reduced to unity or less. The line pitch has far less influence on the diffusion efficiency of developer molecules, and hence the trimming rate becomes less pitch-dependent as well. Fig. 4 shows the through pitch CDs of the trimmed hardmask. Lithography was carried out with an imaging layer aspect-ratio of only 0.25. If the trimming rate were slowed by diffusion of developer into the small openings of tighter pitch features, then the CD should be much smaller for isolated lines. In fact, the CD at L:S = 5 is the same as at L:S = 1.2. There is, however, a jump in CD at L:S = 1, but further work is planned to examine if this is due primarily to proximity effects or the trim process. Note that the imaging layer with reduced thickness is especially sensitive to dose swing. With a more relaxed aspect ratio, 0.13 for example, the hardmask CD bias between dense lines, isolated lines, and isolated trenches becomes unnoticeable (see Fig. 5).

The hardmask CD in Fig. 4 swings between 100 nm and 200 nm, with a nominal CD of 300 nm. This represents extraordinarily high resolution for a stepper with 0.54 NA, conventional illumination, and a binary photomask. The resolution enhancement was entirely due to the thickness reduction of the imaging layer. The reduced thickness is desired for extending the depth of focus (DOF) as well. It is not surprising that Fig. 6 shows a flat DOF curve. CD SEM images for some data points are also inserted in Fig. 6. On the other hand, the thin imaging layer is intrinsically sensitive to exposure dose variation. The imaging layer needs to be specifically engineered for such use to maintain a reasonable exposure latitude (EL) window. Fig. 7 shows the process window for an 80 nm thick imaging layer, which is a thinned commercial i-line photoresist. Better data are expected with optimized conditions.

Close examination of the trimmed dHM lines in Fig. 6 reveals that the line edge roughness (LER) is relatively low for CDs that are well beyond the resolving capability of the exposure tool. LER control remains one of the toughest issues for current generation lithography with chemically amplified resists, and although this example employs older technology the benefits have been extended to 193-nm lithography in recent studies. In general, LER is attributed to the diffusion and scarcity of the catalytic acid at photoresist line edges.[4] The

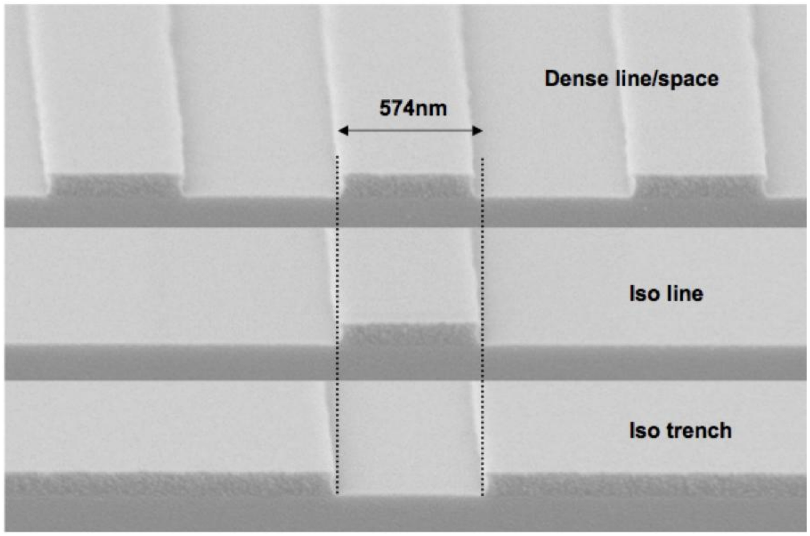

Figure 5. HM isolated trench, isolated lines, and dense lines are shown at 45-second total development time. Lithography is i-line using a GCA Model 3300™ stepper with NA= 0.43, 120 mJ/cm^2. The nominal CD is 600 nm (1:1).

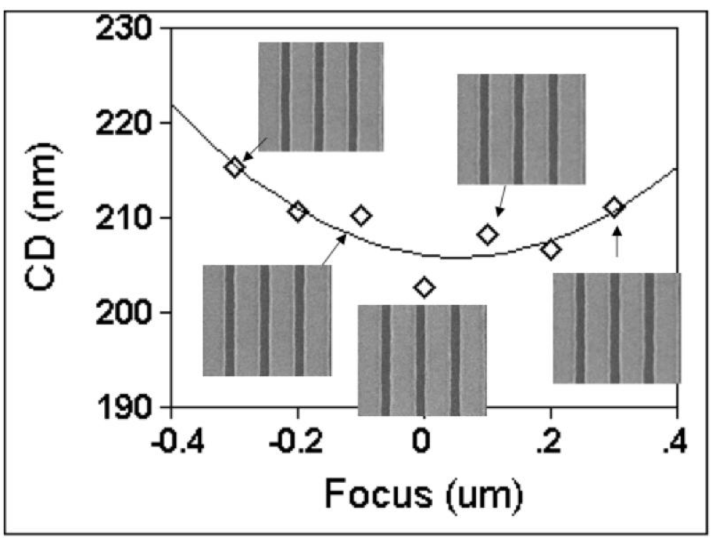

Figure 6. Trimmed CD with defocus. Total development/trimming time is 35 seconds with i-Line exposure on an ASML PAS 5500™ stepper using convention illumination, 0.5 sigma, and 0.54 NA. Nominal CD is 300 nm (1:1).

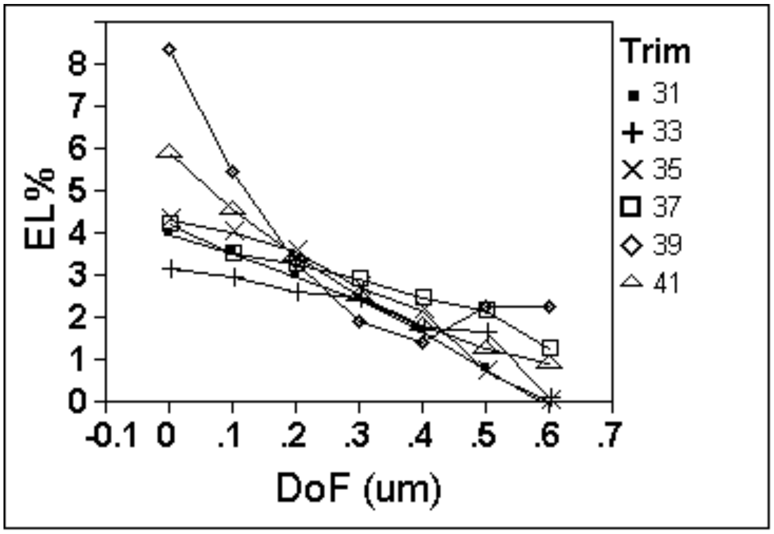

Figure 7. EL/DOF process curve for various develop times with i-Line exposure on an ASML PAS 5500^{TM} stepper using conventional illumination, 0.5 sigma, and 0.54 NA. Nominal CD is 300 nm (1:1).

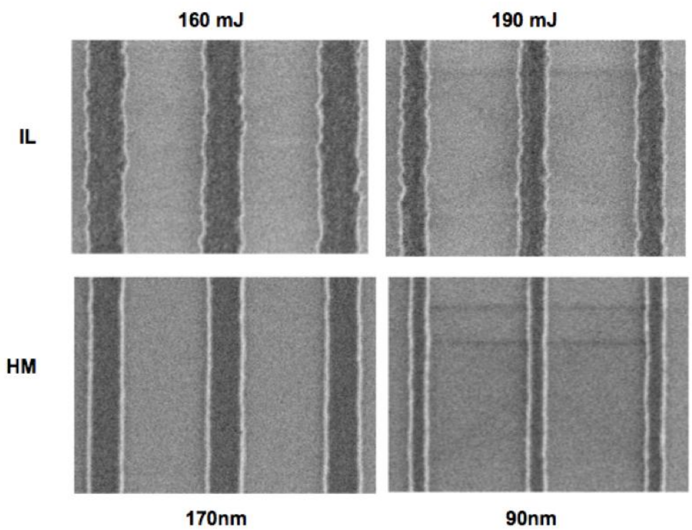

Figure 8. LER of the imaging layer and dHM for a total development/trimming time of 42 seconds. The exposure is i-line on an ASML PAS 5500^{TM} stepper with conventional illumination, 0.5 sigma, and 0.54 NA.

acid distribution profile at the edges defines the LER, because the acid renders the film either soluble or not. However, in this developer trimming process, the dHM does not bear any contrast, meaning all the molecules react with developer in the same manner. The diffusion of abundant developer molecules results in spatially averaged and, therefore, smooth edges. Fig. 8 clearly shows that the dHM lines have much better LER than the imaging layer.

A thin imaging layer in conjunction with a developable underlying layer would be expected to have very poor CD uniformity due to the development rate variation across the wafer, as well as resolution limitations. Therefore, cross-wafer CD uniformity is examined to determine any potential issues. Fig. 9 shows the CD data across two 200-mm wafers trimmed for 33 and 37 seconds. There is surprising CD consistency throughout each wafer, with non-uniformity at just 19% 3-sigma for this early attempt. The uniformity benefits from the high contrast of the imaging layer, the integrity of the hardmask, and low thickness non-uniformity.

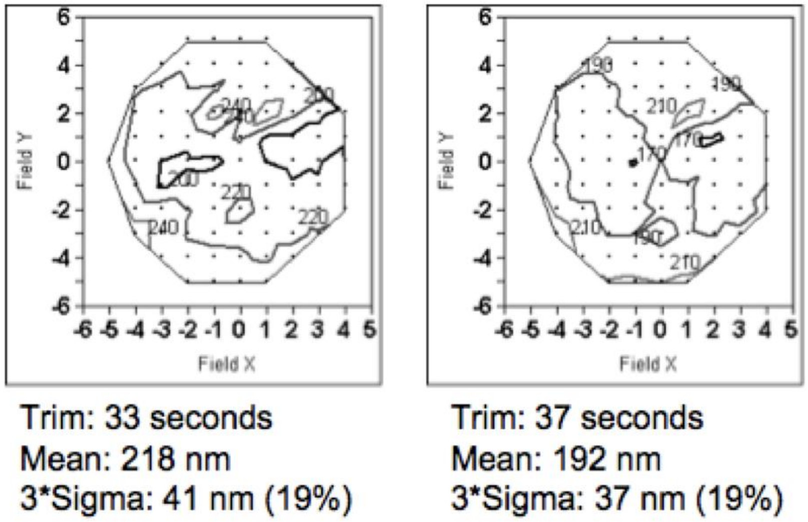

Figure 9. Cross-wafer CD plots for total development/trimming time of 33 and 37 seconds. Dose and focus are 180 mJ/cm^2 and 0.0 μm for the i-line pattern described above.

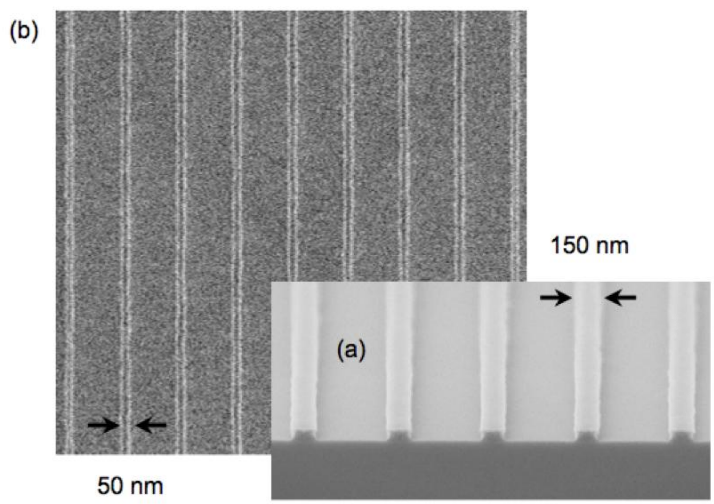

Figure 10. Trimmed HM lines at (a) CD=150 nm with total development/trimming time of 37 seconds and i-line lithography. In (b) the CD has been pushed down to 50 nm with a total development/trimming time of 60 seconds using ArF lithography, dipole illumination, 0.89/0.65 sigma, 0.75 NA, a dose of 20 mJ/cm^2, and 0.0 μm defocus.

Finally, Fig. 10(a) shows how far the wet trimming process can be pushed with i-line lithography while maintaining very smooth lines, while Fig. 10(b) is one of the latest results using ArF lithography and trimming to a final CD of only 50 nm – approaching a CD regime relevant to today's most aggressive technologies. Future work will focus on ArF lithography using resists that are designed for thin application (< 50 nm).

4. PATTERN TRANSFER

The advantages and challenges of the developer trimming process have been discussed. It has been unambiguously demonstrated that a very thin imaging layer is capable of creating robust trim templates for CD reduction of the dHM layer. The next step is to examine whether the dHM patterns can be transferred to the next layer by reactive ion etching (RIE). The feasibility exclusively relies on the etch performance of the hardmask. The next

Table 2. Imaging layer, dHM, and post-etch CD results from top-down SEM. The wafer measurement map is given below.

Field/Step	1	2	3	4	5	6	7	8	9	10	11	Average	Range
IL CD	334	346	346	337	342	345	340	333	351	350	343	342	18
dHM CD	308	315	314	309	308	312	314	306	321	316	318	313	15
Poly CD	301	311	311	303	308	311	306	300	316	315	309	308	16
Etch Bias	7	4	3	6	0	2	8	6	5	1	9	5	9

all values in nm

					4					
		3						11		
					5					
	2				6				10	
		1			7			9		
					8					

layer can be any intermediate film or semiconductor substrate. Polysilicon was chosen for demonstration in this work.

Table 2 shows the polysilicon etch CD results from a Lam 2300 Versys® using a standard poly recipe with HBr, Cl_2, O_2, and CF_4. After the polysilicon steps are completed there is an *in situ* ash to remove any resist residue and re-condition the etch chamber. The 200-mm wafer pattern is i-line with the ASML PAS 5500™ stepper, conventional illumination, 0.5 sigma, and 0.54 NA. The thickness of imaging layer, dHM, and polysilicon were 80 nm, 77 nm, and 100 nm, respectively. The total development and trimming time was 30 seconds for a 30 nm trim. The exposure dose was 17 mJ/cm^2 with no defocus. The nominal CD was 350 nm at L:S = 1:1. The average etch bias is 5 nm across the 11 sites measured per the wafer map included in Table 2. CD uniformity after polysilicon etch is quite good at 5% by range.

The quality of the polysilicon patterns is demonstrated in Fig. 11 with cross-section SEM images for various trim amounts. The sharp edges indicate the high etch selectivity of the dHM over polysilicon. The remaining hardmask on top of each line is still visible. The faceting of the remaining hardmask is due to the stripping step in the plasma etch recipe, which is applicable to photoresist or organic BARC, but not to a hybrid organic/inorganic material. However, successful removal of the dHM after etch exposure is possible using many commercially available strippers.

The lithography for the images in Fig. 11 was carried out on an ASML PAS 5500™ i-line stepper. The hardmask develop/trimming time was 30, 40, and 50 seconds, respectively, for Figures 11(a), (b), and (c), resulting in polysilicon CDs of 324 nm, 280 nm and 260 nm. The nominal CD for the imaging layer is 350 nm. The polysilicon CD was successfully reduced by the trimming process on the track.

Fig. 12 is inserted to further demonstrate the etch performance of the hardmask layer using an ArF pattern. In this example the hardmask was not wet-developed but patterned using a conventional dry-etch approach with a thickness of 35 nm and 120 nm photoresist. The hardmask in this example is the same material that was tested throughout this work but baked at a higher temperature to make it insoluble in developer. The polysilicon lines in this example are 55 nm wide and 100 nm tall. The etch bias is again about 5 nm. So far this hardmask has repeatedly demonstrated excellent etch performance for polysilicon substrates as a spin-on film.

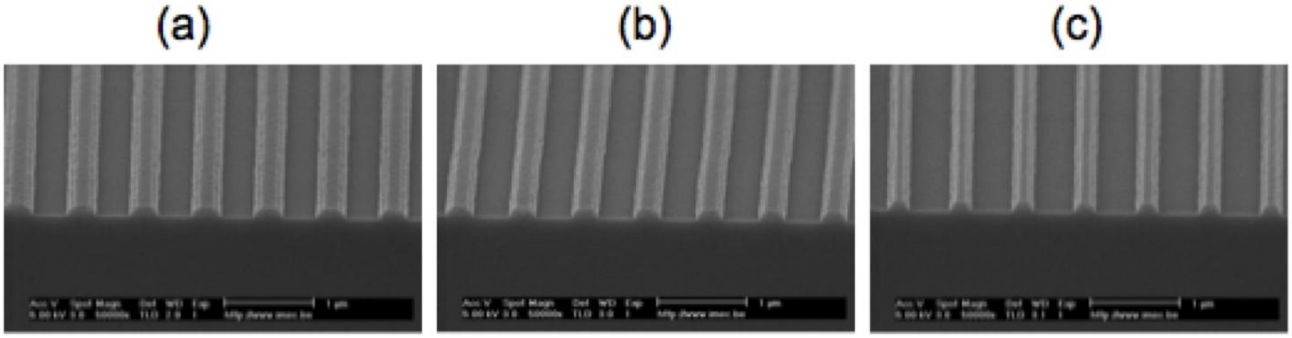

Figure 11. SEM cross-sections of polysilicon lines patterned with dHM using i-line lithography on the ASML PAS 5500™ stepper, conventional illumination, 0.5 sigma, and 0.54 NA. The dose is 170 mJ/cm^2 with 0.0 μm defocus. The nominal CD target is 350 nm at LS=1:1. (a) Total development/trimming time was 30 seconds. (b) Total development/trimming time was 40 seconds. (c) Total development/trimming time was 30 seconds.

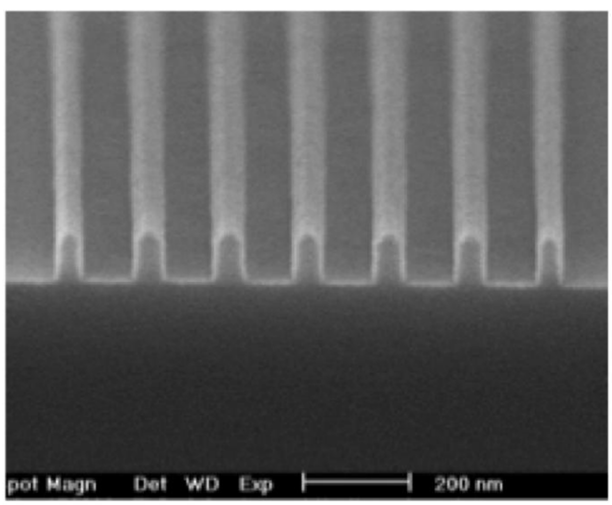

Figure 12. SEM image of polysilicon lines patterned with ArF lithography, dipole illumination, 0.89/0.65 sigma, 0.75 NA, 20 mJ/cm^2, and 0.0 μm defocus.

5. CONCLUSIONS

The dHM process provides aggressive CD trim capability as an alternative to the traditional plasma trim method, which has several drawbacks such as reduced mask height and pattern distortion. The dHM process is also attractive as a less costly method than UV trimming[3] or chemical oxide removal.[2] With this process an on-track wet trimming capability has been presented. The soluble hardmask has also enabled the imaging layer thickness to be less than one quarter of the exposure wavelength. As such, the dHM trimming process shifts the conventional paradigm of lithography away from thicker, tougher resists to an imaging layer template for hardmask trimming. Substrate reflectivity becomes less critical. The k1 factor, defined as $(DR)(NA)/\lambda$, where DR equals design rule, can reach new low values due to resolution enhancement. Process DOF window is improved, and the imaging layer LER is reduced by the lateral isotropic trim of the dHM material. Make no mistake: Each of the areas has new challenges and needs to be thoroughly investigated. Such investigations will comprise our future effort. In addition, we will also investigate the impact of diluted developers to the process outcomes.

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