Defect source analysis of directed self-assembly process (DSA of DSA)

Paulina Rincon Delgadillo1,2,3, Ryota Harukawa4, Mayur Suri4, Stephane Durant4, Andrew Cross4, Venkat R. Nagaswami4, Dieter Van Den Heuvel1, Roel Gronheid1, Paul Nealey3

1 IMEC, Kapeldreef 75, B-3001 Leuven, Belgium
2 Katholieke Universiteit Leuven, Department of Electrical Engineering (ESAT), Kasteelpark Arenberg 10, B-3001, Leuven, Belgium
3 Institute for Molecular Engineering, University of Chicago, 5747 South Ellis Avenue, Jones 217, Chicago, IL 60637, USA
4 KLA-Tencor Corporation, 1 Technology Drive, Milpitas, CA 95035, USA

ABSTRACT

As design rule shrinks, it is essential that the capability to detect smaller and smaller defects should improve. There is considerable effort going on in the industry to enhance Immersion Lithography using DSA for 14 nm design node and below. While the process feasibility is demonstrated with DSA, material issues as well as process control requirements are not fully characterized. The chemical epitaxy process is currently the most-preferred process option for frequency multiplication and it involves new materials at extremely small thickness. The image contrast of the lamellar Line/Space pattern at such small layer thickness is a new challenge for optical inspection tools. In this investigation, the focus is on the capability for optical inspection systems to capture DSA unique defects such as dislocations and disclination clusters over the system and wafer noise. The study is also extended to investigate wafer level data at multiple process steps and determining contribution from each process step and materials using ‘Defect Source Analysis’ methodology. The added defect pareto and spatial distributions of added defects at each process step are discussed.

Keywords: Directed Self Assembly, Defect Source Analysis, DSA Defects, inspection signal, RCWA, defect simulation.

1. INTRODUCTION

Directed self-assembly (DSA) of block copolymers (BCP) has been studied in detail by academia since its initial demonstration, a decade ago. More recently, the potential of this technology for enabling patterning for the semiconductor industry has been suggested. There are, however, various open questions that need to be answered in order to prepare the technology for use in manufacturing, including design decomposition for DSA and pattern placement accuracy. In addition, the capabilities of DSA for low defectivity need to be demonstrated. Achieving high pattern fidelity is crucial for any profitable patterning solution in semiconductor processing. The ability of a thermodynamically driven process (such as DSA) to achieve the required low defect densities has been questioned. Typical random defects that could be expected in a process that uses lamellar phase BCP materials to obtain line/space patterns include dislocations and disclinations. However, initial experimental studies have indicated no fundamental showstoppers. In addition, simulations have indicated that the defect rate may be very low when the boundary conditions for the DSA process are properly optimized.

In previous work, implementation of the UW chemo-epitaxy process (Figure 1) in a 300mm wafer flow has been demonstrated. A thin (~5nm) cross-linkable polystyrene (X-PS) layer is coated on an SiN substrate wafer. Subsequently ArF immersion lithography provides an 84nm pitch pre-pattern targeted at ~38nm CD. Next, a plasma etch step trims the...
CD to ~18nm and simultaneously etches through the uncovered X-PS layer. The resist is selectively stripped using a wet process. Next, an –OH terminated neutral brush is coated over the X-PS pattern. During the subsequent anneal bake, the –OH group grafts to the SiN substrate, but not to the X-PS guide stripes. A solvent rinse is used to remove excess brush material yielding the chemical pre-pattern. A 28nm L₀ lamellar phase poly(styrene-b-methyl methacrylate) BCP material is coated over it and thermally annealed resulting in 28nm pitch line/space structures (3X frequency multiplication). Finally, a dry plasma process affords selective removal of the PMMA blocks from the BCP to give free standing polystyrene (PS) lines.

![Diagram](image)

**Figure 1.** Schematic overview of the UW chemo-epitaxy process flow.

The process aims at constructing a chemical pre-pattern (after the rinse step) with an approach that allows full control over dimensional and surface chemical properties. The dimensional control is obtained by means of the trim etch step, which allows to achieve feature dimensions that are difficult to access through optical lithography on its own. The surface chemistry control is obtained by the ‘neutral brush-last’ approach that avoids chemical modification of sensitive neutral layer during processing. Building on this process, its defect performance has been studied, especially focusing on dislocation defects, which are deemed the most likely DSA specific defects. Main attention in this study has been on 1) setting up the defect metrology such that a maximum sensitivity is obtained for these dislocation defects, 2) determining the defectivity performance of our current process and 3) identification of the root causes for the current defects.

2. EXPERIMENTAL

2.1 Materials

Cross-linkable poly(styrene) (X-PS, AZEMBLY™ NLD128), hydroxyl-terminated poly(styrene-random-methyl methacrylate) (P(S-r-MMA)-OH) brush (AZEMBLY™ NLD127), and poly(styrene-block-methyl methacrylate) (PS-b-PMMA, AZEMBLY™ PME312) BCP with L₀ = 28nm, were synthesized by AZ Electronic Materials and were used as received. ArF immersion photoresist AIM5484, was purchased from JSR Micro. Organic solvent RER600 was purchased from Fujifilm and Orgasolv STR 301 was bought from BASF.

2.2 Process

The process used for this experiment is based on our previously reported method for the fabrication of chemical nanopatterns. All processing was performed at imec on a TEL CLEAN TRACK ACT™12 system. For a 3X feature multiplication process, using a pre-pattern pitch of 84nm, exposures were done on an ASML XT:1950Gi scanner at 1.35NA using quadrupole illumination (XY polarized, NA = 1.35, σ₀=0.87, σᵢ=0.72). An inorganic antireflective coating (ARC) film of SiN, of 14nm, was deposited via chemical vapor deposition (CVD) on 300mm Si wafers. The X-PS film, with thickness of 7-8nm, was spun and annealed at high temperature for 5min under a N₂ atmosphere. After resist coating
and exposure using vendor recommended settings for post-apply bake (PAB), post-exposure bake (PEB), and development, lines and spaces of 84nm pitch and critical dimension (CD) of 38nm were obtained. O₂ and Cl₂ plasma etch was used to trim the resist to target 17nm CD and remove the X-PS exposed to the plasma. The remaining resist was stripped at room temperature with Orgasolv STR 301. The P(S-r-MMA)-OH brush was spun and annealed for 5min at 250°C in a N₂ atmosphere. Non-reacted material was rinsed with RER600. The PS-b- PMMA BCP was coated on the chemical patterns and annealed for 5min at 250°C in a N₂ atmosphere. Defect inspection was done in a KLA-Tencor 2835. Location and imaging of the defects were performed with a review scanning electron microscope (SEM).

2.3 Metrology

For defect inspection and source identification, the tool utilized in this study is a broadband brightfield optical inspection system (2835). This widely adopted tool for both R&D and production monitoring inspection applications was found to be capable for investigating the defect source analysis of the Directed Self Assembly process given the current status of maturity of this next generation lithography contender. In some cases, for new processes techniques and design rule nodes, the initial setup of the tool (wavelength, apertures, modes etc.) can be driven from the results of a proprietary offline simulation methodology from KLA-Tencor which uses a Rigorous Coupled Wave Analysis (RCWA) method to solve the EM simulation. Directed Self Assembly, being a new generation lithography process, the critical defects of interest (such as dislocation and disclination post BCP PMMA removal step) were first studied from simulation to determine the best potential optical setup “recipe” to maximize signal. The recipe was then verified and further optimized to maximize sensitivity to all defects of interest whilst suppressing potential noise sources.

2.4 Defect Source Analysis (DSA) methodology

Defect Source Analysis is a methodology developed by KLA-Tencor to identify the “source” of key defect types in a given semiconductor process. The premise of this methodology depends on the fact that the coordinates of defects captured in an optimized inspection by a tool such as the 2835 can be reported to a very high accuracy (better than a micron). When inspection is carried over multiple process steps, the coordinates of defects reported at each process step can be stacked to separate “added defects” from “previous layer defects.” The “search radius” is a user definable parameter which can be effectively used under different process conditions to discern added defects from previous layer defects.

In the UW chemo-epitaxy process flow described in Fig.1, optimized inspections were set up at seven steps (SiN, X-PS, Exposure Resist, Trimming Resist, Rinse Guide pattern and PMMA removal). Given the engineering nature of this methodology, high sensitivity inspections were set up at each step and the associated slightly higher nuisance rates were acceptable. Defect classification was performed for added defects, example images were captured and paretos were created at each step. At the last step (in this case is PMMA removal) or any other intermediate step, defects found could be tied back to their source. A step-contribution analysis could be conducted to account for and identify the possible sources of the defect types. This provided clear, undisputable, actionable data for defect reduction activities.

3. RESULTS AND DISCUSSION

3.1 Process performance

In order to investigate the contribution of each step of the process to defectivity (density and defect type) generated by materials or processing, defect source analysis of directed self-assembly was performed using the UW flow currently implemented at imec. To this end, a set of 7 samples was defined, as shown on Table 1. After each step of the fabrication of the chemical patterns and BCP anneal, all the samples were inspected using broadband defect inspection. Then, one sample at each step was removed from the flow to perform defect SEM review. In addition, a control sample was added to the flow (as indicated in column 1), which was only inspected after BCP assembly. The purpose of the control wafer was to assess the impact of the inspection on the sample properties.
Using defect source analysis, it is possible to differentiate between common and adder defects at several stages of the fabrication process, by comparing their position on the die/wafer (as explained in Section 2.4). For the UW flow, it was possible not only to follow the progression of defects at each step, but also, to see their evolution and relate them to physical and chemical key parameters of directed self-assembly. Figure 2 shows the overall defect density for each process and the breakdown in its diverse contributors. For example, the SiN deposition did not have a significant impact on the final BCP defectivity, accounting for only 4 defects/cm$^2$ through all the sample fabrication procedure. Defect density increased to about 500 def/cm$^2$ after X-PS coat and anneal, and remained constant along the chemical pattern fabrication. In contrast, the adder defects that were captured from the exposure, trim etch, and strip steps did not contribute to the final density after BCP anneal and PMMA removal. For the brush grafting step, 98% of the defects correspond to particles (data not shown). SEM images do not provide enough information to establish if these particles came from the brush coat or if they were deposited on the surface during the rinse of the un-reacted material. Since the sample was not inspected after brush coating, the root cause for this defect was not identified yet. Finally, after BCP coat and anneal, the defect density was about 564 cm$^{-2}$. These are adder defects and can be related to the BCP material or assembly process.
The main contributors to the final defectivity were, then, X-PS anneal, brush grafting, and BCP coat and anneal. For the X-PS, about 99% of the defects corresponded to bright spots (data not shown). Examples of bright spots are shown on Figure 3. The capture rate of these defects was remarkably constant at each step of the process, except the trim etch. During this step, the SiN was exposed to the surface and the substrate was not uniform. Therefore, the sensitivity of the inspection recipe had to be adjusted to avoid excessive nuisance defects. However, after the strip step, all of the bright spots captured during the X-PS inspection could be captured again. At this point, it was possible to verify that the bright spots will produce an (or multiple) interruption in the guiding stripe. Previous work using programmed defects showed that a gap in the guide stripe may be healed by the BCP in most cases; however, it is possible to generate DSA-specific defects due to this issue.
Directed self-assembly of block copolymers is a thermodynamically equilibrated process that relies on the interaction between the BCP and the surface. In order to achieve zero defectivity, the chemical patterns must provide the necessary conditions to achieve a high degree of order during block copolymer assembly. DSA of DSA has proven to be an effective method to identify the critical parameters during the fabrication of the chemically nano-patterned substrates.

3.2 BCP defect root cause analysis

From the DSA of DSA experiment, it is evident that the white spot defects that are found in the X-PS guide layer are an important contributor to the defectivity that is found in the BCP. A large number (>90%) of the white spots (missing X-PS guide pattern) are repaired by the BCP self-assembly process. As a result the number of X-PS common defects is reduced drastically. However, the larger white spots result in too large an area where there is no guide pattern available and dislocation clusters appear (Figure 4). Note that the circular shape of the X-PS white spots is also somewhat apparent in the BCP dislocation pattern.
Figure 5. Defect maps of the density of white spot defects of in-line coated AZEMBLY™ NLD-128 (left) compared with manually coated AZEMBLY™ NLD-166 (right).

However, most defects in the BCP pattern are not common with the defects from any of the previous processing steps. More detailed analysis shows that the distribution of these defects is not even across wafer and across field. When we first consider the across wafer signature (Figure 6) a clear hot spot of defectivity is seen just right of the wafer center. This hot spot correlates well with the post-trim etch CD signature, but not with the post-litho CD. The trim tech step has so far not been optimized for across wafer CD uniformity. This results in a lower average CD right of the center which is also where the high defect dies are found.

Figure 6. Defect wafer map (left: red: high defect density, green: low defect density) does not correlate with the post-litho CD across wafer (middle), but correlates well with the post-trim etch CD (right).

Interestingly, when a defect map is plotted of any of the high defect dies from the wafer defect map of Figure 6, there is again a distinct signature. Most defects are present near the bottom left corner of the die (Figure 7). Defect maps of the low defect dies show an even distribution of defects across the die area. Also for the intrafield signature there is a clear correlation with the post-trim etch CD. In this case, however, the CD signature stems from the exposure itself. Most likely, there is a reticle signature causing the across field signature. It should be noted that this die CD signature does not automatically lead to high defect numbers. Only when combined with a low average die CD from the trim etch step higher defect density occurs.
Figure 7. Typical defect map of a high defect die (left) shows a clear signature of high defectivity near the bottom left corner. The defects in this region are mainly large dislocations and correlate well with the post-litho and post-trim etch CD signature (right).

The combination of the inter- and intrafield defect and CD signatures demonstrate that the root cause of these signatures is the small CD that results in insufficient guiding of the X-PS stripe, at which point dislocation clusters are formed. This is confirmed by the fact that the majority of the defects in the bottom left die corner are dislocation clusters. The remaining defects that are more evenly distributed across the die are almost exclusively particle defects (see below). It should be noted that the CD variations in the pre-pattern wafers (~6nm) are very large considering the target feature size (~18nm). In that respect the defective area may be regarded as surprisingly small. Proper optimization of the exposure and trim etch process is expected to remove the defect fingerprints and therefore the dislocation fingerprints.

When the dislocation defects from the bottom left corner of the die are removed, the BCP pattern still contains a significant number of defects, but none of those are dislocations or dislocation clusters (outside the X-PS common defects that were discussed earlier). The main contributor on the defect pareto now are small particles. In all cases these particles span less than one pitch in the final DSA pattern. The SEM review (Figure 8) shows some minor topography in the morphology of the defects indicating that these are particles embedded in the BCP material. It is again expected that common filtration optimization will enable removal of this defect type.

Figure 8. Sample SEM images of embedded particles in the BCP patterns.

In summary, our detailed analysis of the defect root causes has revealed no uncontrollable defect sources. When the geometrical and surface chemical properties of the pre-pattern are properly controlled and filtration strategies are further optimized the DSA process defectivity will be driven down by several orders of magnitude.
4. CONCLUSIONS

The critical steps for process and material improvements required to minimize defect formation have been identified by running Defect Source Analysis in the chemo-epitaxy UW directed self-assembly flow. The defect source analysis technique on state-of-the-art defect inspection equipment has proven to be a powerful tool for controlling and understanding defectivity in the DSA process flow.

Root causes for all DSA-specific dislocation defects that have been found are identified as defect types that are commonly known from traditional optical lithography: pinholes, CD control in the pre-pattern and particles. In order to further improve the defect performance of this flow, optimizations of both materials and process will need to be implemented. For the cross-linkable polystyrene mat material, the bright spots (pinholes) after coat and bake need to be eliminated to prevent missing guiding stripes. For the block copolymer material gel particles need to be eliminated since they account for the largest number of defects from the BCP layer. Further optimization to eliminate intra-die and intra-wafer CD non-uniformities generated during the exposure and etching steps, respectively, is necessary to avoid large dislocation clusters. Specifically, the across wafer uniformity of the trim etch step needs to be improved. No uncontrollable defect sources have been identified in our DSA process flow.

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