EUV Research Activity at SEMATECH

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EUV lithography is needed by the semiconductor industry for both its resolution and for the process simplification it provides compared to multiple patterning. However it needs many innovations to make it a success and is an expensive technology to develop. Major areas of concern are source power, defect free mask availability, defect freedom during use and resist performance. Long term it will also need improved mask and material technology for higher NA EUV imaging. SEMATECH is working on mask technology, defects and resist technology for EUV imaging and has developed new mask inspection technology, novel approaches to EUV resist, lower defectivity mask blanks and improved cleaning methods. SEMATECH’s work enables the semiconductor industry to share the cost of developing EUV technology and accelerates the progress of EUV.

Keyword: photoresist, EUV, photo masks, SEMATECH

1. Introduction
EUV lithography promises great resolution improvements over what can be done with ArF immersion lithography. The 2014 ITRS roadmap shows possible manufacturing use in 2016 with contact holes being the most likely application [1]. EUV operates in a vacuum with photons of wavelength 13.5nm. It requires all reflective optics, including reflective multilayer masks. There are exposure tools designed for manufacturing use (but with low throughput) already on the market [2], and throughput adequate for early manufacturing use is scheduled for introduction late in 2014 [3].

SEMATECH’s lithography group focuses on creating the infrastructure needed for successful manufacturing with EUV lithography. We work on mask blank development, mask inspection tool development, mask cleaning technology development and on driving the development of novel resists.

2. EUV Masks
EUV masks have a multilayer structure built on top of a low thermal expansion substrate. Most of the layers are alternating layers of strongly and weakly absorbing EUV materials, typically silicon and molybdenum. On top of the alternating stack is a thick layer of absorber material, plus possibly a passivation layer and/or a bonding layer. A baseline of EUV mask structure is shown in
Figure 1. Standard mask writing techniques are used to write a pattern in photoresist coated on top of the absorber. The absorber is then etched away from the areas without resist and the remaining resist stripped. This provides a patterned absorber. The areas with absorber do not reflect light and the areas without it do reflect light, giving the desired mask function.

Defects in the pattern of the absorber can be detected optically or by SEM measurement. Detecting them is similar to detecting defects in current mask technology except that the critical defect size will still scale with the node. EUV masks will be used for a smaller node than optical masks and so will have tighter defect specifications [4].

The periodicity of the layers is ½ of the wavelength of EUV light, adjusted for the expected incidence angle of the light. So for normally incident light the pitch of the layers for maximum reflectivity is roughly 7nm. Variations in the pitch of this stack or local areas where the regularity of the layers is disturbed will create different phase reflections. These different phase reflections will create interference effects that create unwanted imaging artifacts. These defects can come from particles buried in the multilayer stack as shown in Figure 2. Phase defects can also come from pits or bumps in the substrate that are replicated into the multilayer stack during the deposition process.

Since these defects are buried they often cannot be detected by optical inspection or SEM [5]. Inspection at the actinic wavelength of 13.5nm is required. SEMATECH has organized a consortium to develop an aerial image measurement tool for EUV mask measurement and this tool is expected to be ready for early access in 2014 and customer shipment in 2015 [6].

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To support EUV high volume manufacturing, a reliable supply of low defect EUV mask blanks is needed. SEMATECH has a major effort underway to improve the defect level of EUV mask blanks and has worked on many aspects of mask blank defect reduction. This includes defect characterization [7], reduction of defects during multilayer deposition [8] and cleaning processes to improve substrate quality or clean finished masks [9]. Some recent progress is shown in Figure 3 below. Not only has the overall defect level during deposition dropped by 78%, but now there are a significant fraction of masks (seven out of 24, or roughly 29%) with no adders larger than 100nm and one mask out of 24 with no adders larger than 50nm [10].

Figure 2: Sample EUV mask buried defects

3. Extensions of EUV

With EUV production steppers of 0.33NA now being shipped, research is
needed on the higher NAs that will extend EUV patterning capability to 5 nm and below nodes. SEMATECH has commissioned and is building two 0.5NA lenses to upgrade the existing SEMATECH EUV micro exposure tools (METs). These tools should give a resolution of ~10nm lines and spaces or better. The first one is expected to be available for use sometime late this year [11]. These tools will enable the development of mask and resist technology for imaging smaller features at higher NA.

As mentioned above, the appropriate periodicity of the alternating layers in a mask depends on the expected angle of incidence of the actinic light. As the NA of tool gets bigger the range of expected incidence angles may increase, assuming the mask magnification stays the same. This forces a tradeoff between mask size, exposure field size and exposure tool capability [12]. These factors affect EUV mask design. SEMATECH is working on new capping and absorber layers [13], on new mask designs and on mask technology involving phase shifting for enhanced aerial images [14].

New resists will also be needed for higher NA. Resists have a certain amount of “blur” built into their chemistry. This blur represents the volume of resist where the solubility is changed by one individual photochemical event. Larger blur gives faster photospeed and can average out certain inhomogeneities in the exposure and development process. But the blur also affects the resolution of the resist. So resists are typically optimized for a particular resolution and resist blur in particular is typically optimized for a particular target feature size. Resists currently being used to image 16nm to 22nm lines and spaces are unlikely to be good resists in the resolution range of ≤ 10nm lines and spaces.

4. Novel Resists

Another issue with resists is noisiness. Line width and line edge roughness (LWR and LER) are big concerns because they affect electrical device performance. Contact holes also can have noisiness, characterized by contact hole uniformity (CDU) and contact hole edge roughness (CER). CDU or LWR and LER are present in all chemically amplified resists. This noisiness is due to the random nature of PAG deprotection, acid generation, acid diffusion and development [15]. This noisiness has become a bigger concern over time because it becomes a larger percent of the signal as the feature sizes shrink, while the electrical device requirements require less noise as the dimensions get smaller [16]. EUV has the additional concern of shot noise. Shot noise is the variation in the actual absorbed dose of light in a photoresist due to statistical variation in the number of actual photons absorbed for a given exposure dose. It’s more of a concern for EUV because the high energy of EUV photons mean there are less of them in a given exposure dose than there are for imaging wavelengths already in use.

Figure 4: Sources of noise in EUV resists [17]

Figure 4 shows the contribution of different sources of randomness for 26nm contact holes printed with a state of the art EUV photoresist. The noise in the final CD is larger than the polymer deprotection noise, because there are less events at the edge of the feature where the CD is defined than there are at the center of the feature. At the moment, the shot noise part of the variation is still small, but is expected get larger as feature sizes continue to shrink. Shot noise will also get worse as resists get thinner, since a thinner film absorbs fewer photons. This combination of smaller features and thinner
films drives a need for higher absorbance resist materials [18].

When benchmarking EUV resists, their LWR seems to be limited by a characteristic curve of LWR versus photospeed. This lower limit on LWR as a function of exposure dose is a function of all the sources of randomness in the resist, not just shot noise. Figure 5 shows the data from SEMATECH benchmarking of EUV line and space resists, including our most recent results. Each data point represents a different resist formulation. It’s very clear that faster photospeed makes it harder to get good LWR. EUV throughput and cost are limited by resist photospeed, so this is a big concern. EUV exposure tool throughput is specified assuming a 15mJ/cm² resist, so Figure 4 makes clear that EUV users currently have accepted worse throughput than specified or higher LWR resist formulations.

One area of research is mono-molecular negative tone cross linking resist. If successful, this research should provide a mechanically strong film due to the cross linking. This will enable higher aspect ratios and thicker films. Because the resists are monomolecular and one chemical event is needed per molecule to render it insoluble, we expect this also reduces the intrinsic randomness of the solubility switching mechanism compared to a standard positive tone chemically amplified resist. A recent sample result is shown in Figure 6 [20].

Figure 5: LWR versus photospeed for state of the art EUV line and space photoresists

One can see from Figure 4 that a lot of the noise in resist imaging is driven by the resist chemistry itself, not just by shot noise effects. From Figure 4 one can see that resist developers haven’t made much progress in improving the LWR to photospeed tradeoff in the past year and a half. For this reason, we believe that new resist chemistries with less intrinsic randomness than chemically amplified systems are needed. Non-chemically amplified resists that work with EUV exposure are known, but they are typically very slow [19]. SEMATECH is sponsoring research into three different research areas that hold the promise of new resist materials with different mechanisms from current resists.

The second area of resist research is developing metal oxide nanoparticle based photoresists. The presence of substantial quantities of a metal, for example zirconium or hafnium, provide high EUV absorbance and excellent etch resistance for thin films. These materials have been shown to have fast photospeed and an unusual, non-chemically amplified mechanism. The solubility change after irradiation seems to be related to ligand exchange and possibly also to particle agglomeration [21]. It’s not understood why the photospeed is as fast as it is, but it may related to the ability to change the solubility of one particle by changing only one of the ligands. Given the volume of that particle, typically several nanometers in diameter, this is a lot of solubility change for one chemical event.

Figure 7 shows some imaging results for a zirconium nanoparticle incorporated resist [22]. The photospeed is faster than that of any chemically amplified EUV resists tested by SEMATECH. The lines are rough, but calculations of the Z value [23] for these materials, which assesses progress against the photospeed, resolution and LER tradeoff, shows these materials are competitive in Z with the best chemically amplified materials.
tested [24]. Given the early stage of development of these materials, this is a very promising result.

The third area of EUV resist research that SEMATECH is funding is research into screening metal based compounds for EUV sensitivity and then developing improved materials based on the metal compounds found to have sensitivity. EUV photons are so energetic that there can be many new photosensitivity mechanisms to be discovered with these new materials. These materials have the same potential advantages of high EUV absorbance and good etch resistance that nanoparticles do because of their high metal contents. Since they are systems of soluble materials rather than of nanoparticles, they may have advantages in ultimate resolution, and they could have different novel imaging mechanisms. The results so far have been quite promising; with systems based on several different metals showing good sensitivity and reasonable imaging. Figure 8 shows some recent results with three soluble compounds based on different metals [25].

5. Conclusion

EUV lithography technology is needed by the semiconductor industry but needs improved infrastructure to support high volume manufacturing and development of technology for future extensions of EUV imaging capability. SEMATECH is doing extensive work to improve the EUV infrastructure and to demonstrate new technology that will enable EUV extensions; with work underway on new tools, new mask technology, new inspection and cleaning technology and novel resist technology. Substantial progress has been made and more is expected.

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