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CHARACTERIZATION OF THE IMPACT OF SCATTERED LIGHT AND POWER ILLUMINATION NON UNIFORMITY ON SEMICONDUCTOR PROCESSES

By

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A thesis submitted in fulfillment of

the requirement for the degree of

Master of Electronics (MEng.)

School of Electronic Engineering

Dublin City University

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Academic Supervisor: ***Dr. Stephen Daniels***

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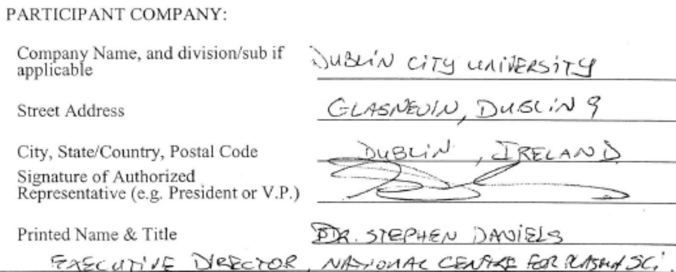
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ABSTRACTS

Over the last number of years, it has become increasingly apparent that lens degradation is a real issue in Semiconductor photolithography equipment. We have seen degradation in many equipment parameter, two major ones are increase in scattered light and degradation in illumination non-uniformity. Scattered Light, or unwanted light scattering, is an increasingly important phenomenon in modern lithography. Control of Scattered Light has been important consideration to achieve good CD control in low k1 lithography. Scattered Light is a key variable for semiconductor process and lithography equipment, it depends on many variables such as degradation of internal optics in PO and illumination paths, deposition on top/bottom lens elements and condenser glass etc.

Very little has been done to understand and characterize the impact of scattered light and illumination non-uniformity degradation despite their significant impact on semiconductor Lithography assets. Therefore, developing a clear understanding of this behavior and its impact on semiconductor processes is key to maintaining effective process control. Constant degradation due to high Scattered Light on a Lithography scanner will ultimately limit the productive life of the equipment, with the consequent impact to factory capacity.

There are real concerns that as the equipment and optics age further, the impact might become much more severe, potentially even reducing company's production capacity. A method of inducing degradation was needed in order to be able to characterize the impact of the scattered light on the actual patterning performance of the photolithography scanner.

An innovative methodology was developed to induce Scattered Light, or light scattering, on any scanner, any technology, and any layer. This methodology has not been used much on the characterization of the impact of scattered light process on several different technologies and several mask layers. It is not easy to determine the priority which process layers are the most sensitive to scattered light, and which etch processes are the least tolerant of degraded patterning.

Thus, there exists a real need to understand and characterize degradation mechanism into current technologies and other mask layers.

I have tried to understand and characterize Scattered Light and illumination non-uniformity for various semiconductor technologies in the 90nm to 65nm nodes. The scope of this work is both 248nm and 193nm wavelength photolithography scanners.

The conclusion of this project is a fundamental characterization of the impact Scattered Light and Illumination non-uniformity degradation on patterning. The result of this will provide an understanding of how much of the process window budget lens degradation will consume in the future. Also, it will provide direction into the need and return on investment of various countermeasures. Some of the countermeasures require significant risk, cost, and/or downtime. The knowledge acquired from this project could also be applied to future semiconductor technologies, where lens degradation is certain to continue to be an issue.

Abbreviations and Symbols

RESIST CD	Develop Check Critical Dimension
ETCHED CD	Final Check Critical Dimension
FC	Final Check
CDSEM	Critical Dimension – Scanning Electron Microscope – a tool to measure CDs at RESIST CD and BE
BE	Back End (Cu interconnection Lines)
FE	Front End (No Cu)
FA	Failure Analysis
BLE	Bottom Lens Element
TLE	Top Lens Element
Flare	Also called as Scattered Light or Stray light or Background light
C-C	Centre to Corner difference
EB	Etch Bias
NA	Numerical Aperture
LNA	Lens Numerical Aperture
iNA	Illumination Numerical Aperture
ITRS	International Technology Roadmap for Semiconductors
NGL	Next Generation Lithography
RET	Resolution Enhancement Techniques
PSM	Phase Shift Mask
OPC	Optical Proximity Correction
EUV	Extreme Ultra Violet
DUV	Deep Ultra Violet
BARC	Bottom Anti-Reflecting Coating
TARC	Top Anti-Reflecting Coating

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Section I

Introduction and Background

Introduction

Lithography technology has been one of the key enablers and drivers for the semiconductor industry for the past several decades. Improvements in lithography are responsible for roughly half of the improvement in cost per function in integrated circuit (IC) technology. Optical Lithography has been the leader ever since the invention of the integrated circuit in 1958. The minimum half pitch has been reduced from 1600nm to 30nm. The underlying reason for the driving force in semiconductor technology has been the ability to keep the cost for printing a silicon wafer roughly constant while dramatically increasing the number of transistors that can be printed per chip.

For nearly 30 years the growth of the semiconductor industry has been tied to Moore's Law which states that the number of devices on a chip doubles every 18 months [1]. There are three main constituents of the technology improvements that have kept the industry on this pace for more than 30 years. These are lithography, increased wafer size, and design. The essence of Moore's law is the ability to give customers faster, more complex products by manufacturing faster, more complex integrated circuits, at a constant or decreasing price.

Today, processors are fabricated using 45-nanometer conventional optical lithography where excimer lasers operate at 193-nanometer wavelength in the ultraviolet range. Lithographers continue to push the limits of optical lithography due to singificant cost involved in developing next generation lithography techniques. As a result lithography has gone thru several advancements and new techniques in recent years. As the feature size continues to decrease lens degradation has become a concern to lithographers. Lens Degradation, optics contamination, and other factors causing light to scatter (Scattered Light) and increase in power illumination non-uniformity. Researchers are continuing tto work hard to understand the impact of scattered light and non-uniformity on patterning and how to control it. Delay in introduction of next generation technologies have pushed optical lithography to beyond its limits and thus different methods like hyper NA tools are being designed and optical lithography is moved to a different technology called Immersion lithography where air is removed by water and other liquid. The next technology is EUV where mirrors and lenses will be used in illumination path to guide EUV light. As future lithography technologies still use lenses and mirrors so ***scattered light*** *and* ***power illumination non-uniformity*** *will be a definite challenge. In this research I am trying to understand the impact of scattered light and illumination power non-uniformity on 248 and 193nm tools involved in manufacturing of 65nm and 90nm semiconductor technology processing node.*

1.1 Basics of Lithography Process.

Optical microlithography is basically a photographic process by which a light sensitive polymer, called a photo-resist, is exposed and developed to form three-dimensional images on the substrate.

Lithography process involves 3 basic steps called as *Coat, Expose* and *Develop*.

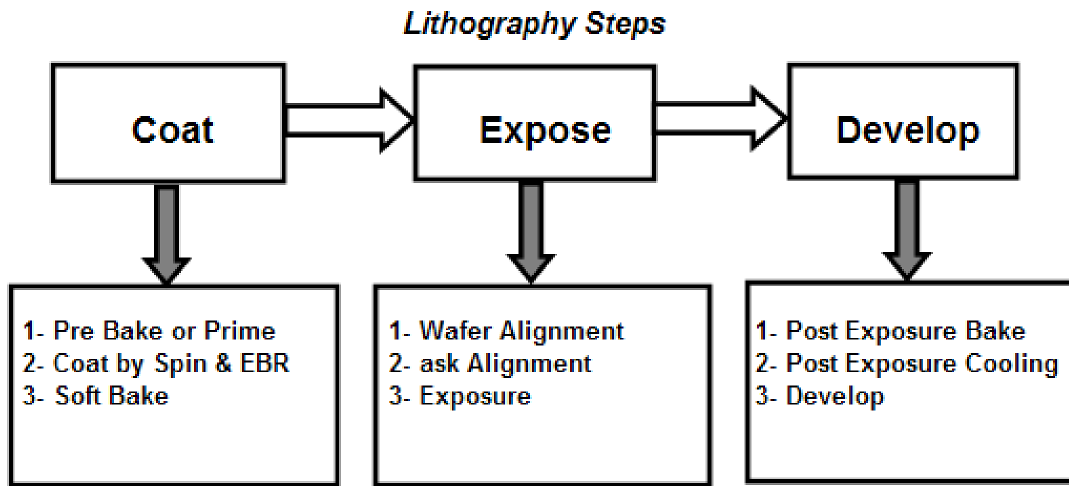


Fig 1.1 Lithography process steps

There are two lithography tools used to complete above three lithography steps. The first one is called a Track which coats and develops photo resist and the second is called a Stepper or Scanner or Step & Scan system which exposes the mask and transfers the image to wafer surface

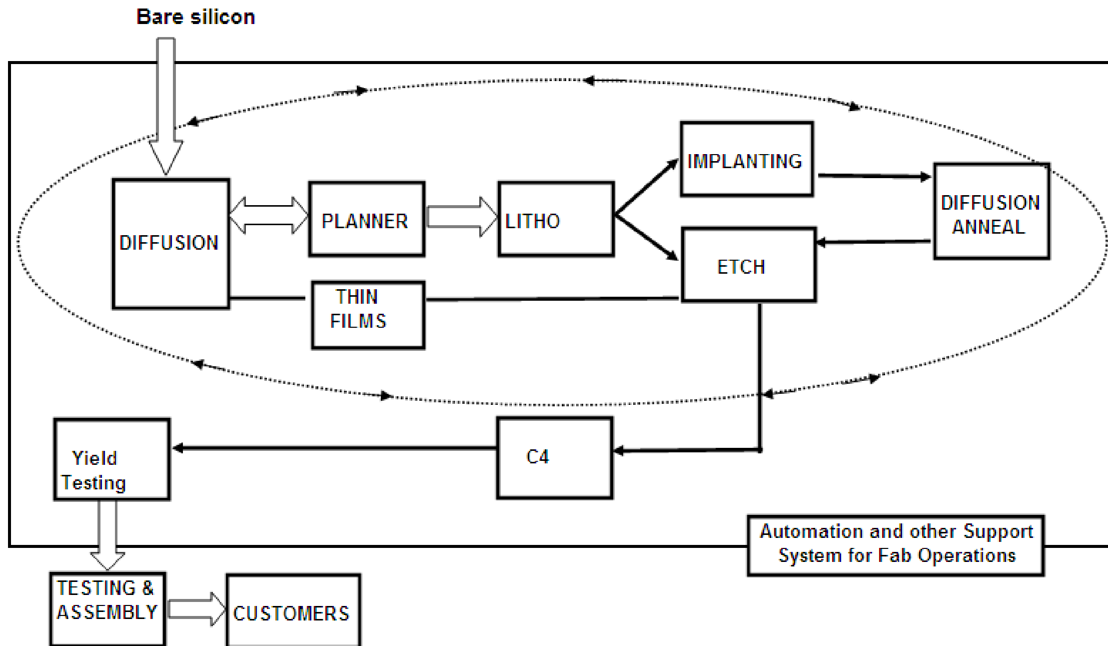


Fig 1.2 Semiconductor manufacturing process

1.1.1 Coat Step

Purpose of Coat step is to spin a temporary layer of photo resist onto the wafer surface.

1.1.1.1 Pre-Bake or Prime

The main function of the Dehydration Bake/Adhesion Promotion process is to prepare the wafer surface so that the resist adheres to it. A hot plate heats the wafers removing excess moisture from their surfaces. Excessive moisture on the wafer surface has a very detrimental effect on resist adhesion, resulting in lifting of the resist, and undercutting during wet etch. Heating causes most of the moisture to evaporate from the surface, leaving only a thin layer of moisture, which aids in adhesion during prime. Dehydrating the wafer surface before priming also helps reduce defects. In the adhesion process Hexamethyldisilizane; (HMDS) is introduced in vapor form into the oven chamber. The HMDS bonds to the wafer surface and prevent the wet etch from penetrating between the resist and the substrate. It displaces moisture to improve adhesion.

1.1.1.2 Coat by Spin & Edge Bead Removal

In preparation for Spin, the wafer moves to a Chill Plate Process Station to cool down from the prebake temperature. By controlling the wafer temperature, the stability and reproducibility of the resist film thickness can be ensured. From the chill-plate, the wafer moves to the Coat Process Station. Resist is then dispensed onto the wafer as it spins at a specified speed for a specified time to achieve the desired resist thickness.

Edge Bead is a pileup of photo resist along the wafer's periphery after spin, caused by the

resist drying before it is spun off. If not removed, the edge bead can break off during subsequent wafer handling and fall back on the wafer as surface contamination. After the resist is spun onto the wafer, chemical or backside chemical wash is performed to remove resist and contaminants from the backside of the wafer and the front edge of the wafer.

1.1.1.3 Soft bake

The wafer then moves to another hotplate for soft bake which drives excess solvent from the resist by baking it. This makes the future patterning of the resist more reliable and reproducible. After soft bake the wafer moves to a chill-plate where it is cooled to room temperature to avoid pattern distortion at expose.

1.1.2 Expose Step

Purpose of Expose or Exposure step is to transfer the mask pattern onto the light sensitive photo resist by exposing the wafer to DUV light through the reticle.

Develop: Purpose of Develop step to clean the exposed resist leaving behind the patterned photo resist. After Spin, the wafer moves to a Stepper or Step and Scan system for Exposure.

There are three stages within Expose: Wafer Alignment, Mask or Reticle Alignment and Exposure.

1.1.2.1 Wafer Alignment

During this step the wafer arrives from a track interface and is placed on a wafer stage. Then, a three-step alignment takes place.

- First, the wafer is pre-aligned with a notch-finder. This is an optical adjustment that aligns the wafer for the subsequent search alignment
- The second adjustment is a search alignment that uses a sensor to coarse aligns the specific alignment marks. The alignment marks of the current layer are lined up to match the alignment targets laid down by the previous layers.
- Third is the fine alignment, which corrects for rotation, wafer expansion and contraction, and wafer orthogonality and centering.

1.1.2.2 Reticle Alignment

The reticle containing the pattern of the specific layer to be patterned is loaded and aligned to the permanent targets on the wafer stage.

1.1.2.3 Expose

At expose the Scanner projects the reticle pattern onto the wafer. Lenses in the Scanner reduce the pattern from the reticle by a factor of four. The photo resist not covered by the

opaque part of the reticle is exposed to a specific amount of light for a specific amount of time. This precise exposure is quantified in terms of laser energy and dose.

1.1.3 Develop Step

After Expose is successfully completed, the wafer is moved back to the Track via the Link interface. The last three steps are Post Exposure Bake, post exposure cooling and then Develop.

1.1.3.1 Post Exposure Bake

Post Expose Bake which takes place within a Low Temperature Hot Plate Process Station, is probably the most critical step in the DUV Litho photo-image reaction. The second step of the photo image reaction takes place at PEB. During Expose, photo-acid generation had taken place in the exposed regions of the resist. PEB results in a chemical reaction causing the exposed resist to become soluble in the developer solution. It is extremely critical that a constant controlled temperature, environment and time delay between expose and PEB is maintained for accurate and repeatable results. PEB also reduces standing waves, which could result in the photo resist sidewalls being wavy. Baking the wafer speeds up the resist pattern deterioration, a result of gradual mixing of exposed/unexposed resist. This makes the process more repeatable and the CDs more consistent.

1.1.3.2 Post Exposure Bake cooling

After PEB, the wafer moves to a chill-plate where it is cooled.

1.1.3.3 Develop

The wafer then moves to the develop chamber. The surface of the wafer is pre-wet with water, and the developer is dispensed while the wafer is rotating slowly. Once enough developer is on the wafer to completely cover it, the rotation stops and the wafer sits with the "puddle" of developer on it. The developer solution (a base) dissolves away the exposed resist (high acid concentration), leaving the pattern of unexposed resist (very low acid concentration) intact. After a prescribed time, the spin resumes and a de-ionized water rinse follows, to ensure that any remaining developer is removed along with the byproducts of the developer and resist reaction. The final step in this chamber is to spin the wafer dry.

1.2 Exposure Methods

Different exposure methods being used for printing and one can categorize these as below.

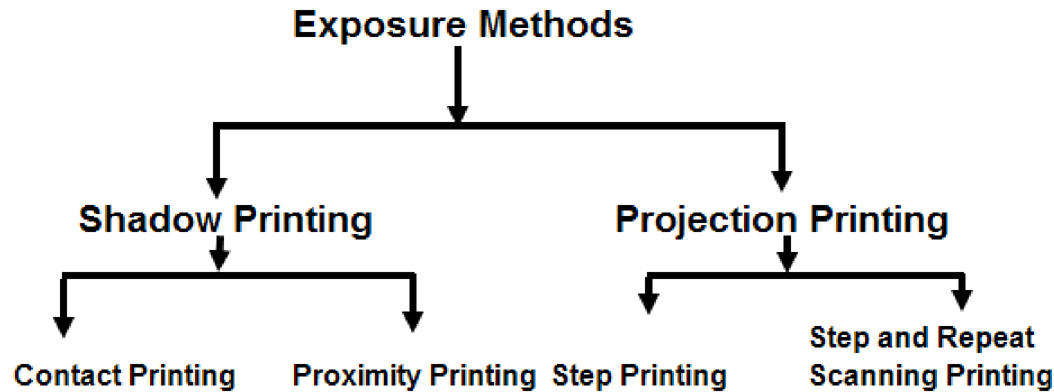


Fig 1.3: Exposure Methods

1.2.1 Contact Printing

This is a very old technique of printing. It involves placing a mask directly on to the wafer and then exposing the mask with light. This form of printing resolved features up to 1um but was abandoned quite quickly due to the fact that it was a non-runner in volume production. However it is still used today to create one of kind microchips and in 200mm C4 processing.

1.2.2 Proximity Printing

To overcome the problems inherent with Contact Printing, the move was made to go to proximity printing. Proximity printing involved raising the mask by a number of microns above the wafer surface. This reduced the defect problem caused by contact printing but the trade off was resolution. Proximity printing only lasted a number of years before it was taken over by projection printing.

1.2.3 Projection Printing

The 3rd iteration of photolithography is projection printing. Projection printing was a vast improvement on manufacturability. Projection printing uses a (reduction) lens between the reticle and the wafer to focus the pattern on to the wafer. Reduction printing allows the reticle to be 4 times larger than the pattern it is printing. This method scans a 26x33mm area (ITRS term is field) of wafers during exposure and then moves to a next 26x33mm area and whole scanning process is repeated until wafer has finished exposing. There are 2 types of projection systems that are commonly in use. They are the stepper and the step and repeat scanning system. The step and repeat scanning system is widely used within several semiconductor companies.

1.3 Lithography Step and Repeat Scanning System

A Lithography Step and Repeat Scanning system *(also called as a Scanner)* prints electronic circuit pattern n wafers with high resolution, high accuracy ad high throughput.

1.3.1 The Step and Repeat Scanning System Overview

The whole system is made of electrical, mechanical and optical modules and components. The main systems components are: Reticle Stage, Wafer Stage, Illumination unit, Projection lens, Auto focus Alignment system, Interferometers, Wafer and Reticle Alignment system, Vibration control system, Arial Image Control system etc.

1.3.2 How wafers are printed by Scan and Step Exposing

The optical system of Scan and Repeat system focuses and projects a small rectangular area of the reticle on the wafer. The reticle stage moves during exposure so that the whole reticle is scanned under the illuminated window. The wafer stage also moves 1/4 times the speed of the reticle stage but in the opposite direction. The sophisticated automatic alignment system aligns the reticle and wafer to ensure accurate overlay of the pattern image. After reticle pattern is exposed on the wafer at one position, wafer stage steps to next position and scanning process is repeated until the whole wafer is printed.

1.3.3 Overlay or Registration Measurement and Alignment

Micro-devices are built-up layer-by-layer, overlay of successive layers relative to previous layers is critical performance criterion of optical lithography align/exposure tool. Overlay in-refers to inaccuracy measured in general pattern placement. An overlay or registration measurement tool is used for this purpose. Alignment refers to the specific spots on the wafer, the alignment marks (course and fine alignment marks) that are used for the alignment procedure. The Alignment target for every layer is zero misalignment. Overlay is affected by Synchronization accuracy of reticle and wafer stages, wafer chuck irregularities, temperature and pressure conditions, lens aberrations, mask pattern misplacement, wafer plane distortion and several other tool related errors and hardware. Registration measured can be broken down into different components to understand its root cause. Below are two ways to break it into wafer level terms and field level terms.

1.3.3.1 Wafer Terms

Wafer terms are the overlay errors at wafer level and only affect field center placement error. This has no impact on overlay errors within fields. There are 6 wafer terms these sometime also called as Grid terms. X/Y- shift is the shifting of pattern in X or Y direction. X/Y scaling is the magnification or compression of whole pattern in X or Y direction. Wafer rotation is the rotation of whole pattern across its center and Wafer Skew is the asymmetric rotation of pattern across its center.

1.3.3.2 Field Terms

Field terms are overlay errors at field levels and have effect on within filed. They have no effect on cross-wafer overlay errors. The following four terms explain field term overlay errors. Field rotation is the rotation of field from its center. Field Skew is the asymmetric

rotation of the field from its center. X/Y Magnification is also called as X/Y field scaling which is either expansion or compression of field size.

1.3.3.2 Non-Linear Errors

This term contains all those errors in overlay which are non-linear and can not fit to the linear models. It is also called as Residual errors. The non-linear behaviour can come from several places like non-synchronized movement between reticle and wafer stages, stepping errors from wafer stage printing of different fields, unstable temperature and pressure conditions inside tool, unstable temperature of wafer, air flow inside scanner exposing area etc.

1.4 Numerical Aperture

The Numerical Aperture of describes the measure of acceptance angle or the number of diffraction order a lens can collect. It's a function of physical dimensions and the refractive index of media. Higher NA means more light is collected by the lenses, better image reconstruction and deliver better CD control.

NA (Numerical Aperture) = n Sin α

Where n is the refractive index of medium. To achieve hyper NA in Immersion lithography water and other liquids are used.

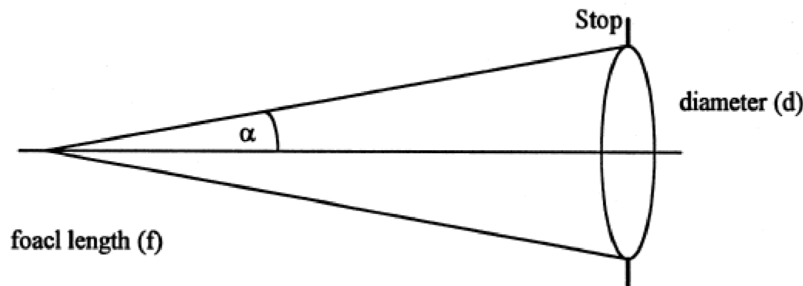


Fig 1.4 Numerical aperture of a lens

1.5 Illumination Sigma σ

The ratio of the illumination optical system's NA to the projection optical system's NA is called illumination Sigma σ.

$$\sigma = \frac{\text{illumination optical system's NA}}{\text{projection optical system's NA}}$$

Assuming NAi is the illumination optical system's NA and that NAr is the projection lens's NA (of the reticle side), each NA is expressed as follows: NAi = sinθi, NAr = sinθr Therefore, the illumination σ is expressed as follows.

$$\sigma = \sin\theta i / \sin\theta r$$

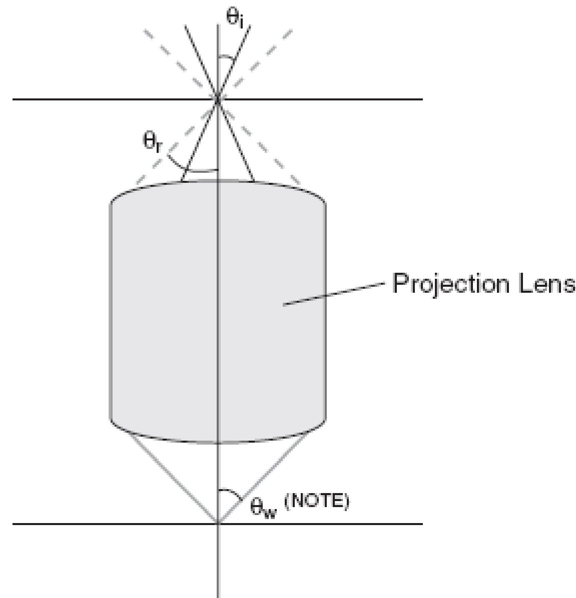


Fig 1.5: Projection lens and Illumination sigma

1.6 Resolution and DOF (Depth of Focus)

The resolution (RES) and depth of focus (DOF) of a lithography system is usually expressed by *Rayleigh equations* in terms of its wavelength and numerical aperture (NA) as;

RES (Resolution) = $k_1 \cdot \lambda / NA$;

DOF (Depth Of Focus) = $k_2 \cdot \lambda / NA^2$

Where k_1 is a litho variable (ranges from 0.5 to 0.8) & k_2 is another litho variable (ranges from 0.8 to 1.0)

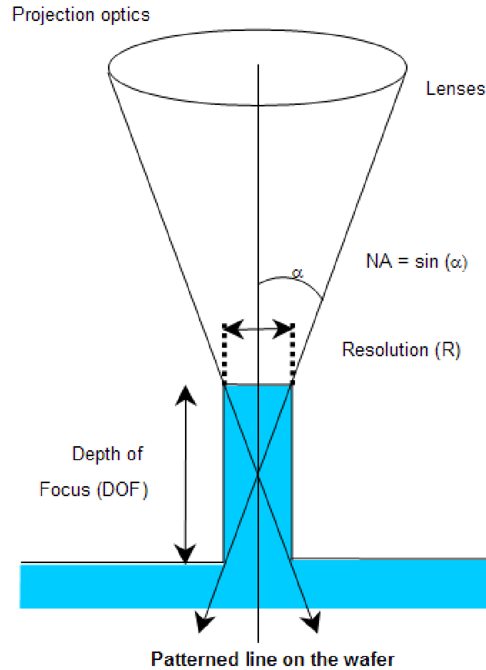


Fig 1.6: Numerical Aperture of a projection lens

The typical rule of thumb is that the smallest features that can be printed are about equal to the wavelength of the light used [2]. The ability to print features significantly less than the wavelength of the exposure radiation can largely be attributed to improvements in the imaging resist materials. These equations clearly show that high NA optical systems must always face the problem of limited depth of focus [3].

1.7 Illumination system

Illumination system is an optical system that guides laser light to the mask surface to project the mask pattern uniformity.

There is an aperture stop at the pupil plane of the projection lens, and this aperture determines the projection lens NA (Numerical Aperture) in the illumination system. There is another aperture stop placed at a location that is conjugate to the projection lens pupil plane. The aperture stop of the illumination system and the aperture stop of the projection lens are both locations where images are formed and the light rays emitted from one point at the illumination system aperture stop in multiple directions will illuminate all places of the mask surface depending on that direction and then collect at one point on the projection lens pupil plane. The distribution of zero-order light on the projection lens pupil plane is determined by the shape of the illumination system aperture stop [4,5,6]

1.7.1 Conventional Illumination

Conventional Illumination (also called as CONV) uses a circular aperture to illuminate the reticle. Conventional illumination use 3 light rays; Zero order light ray and +/- 1st order light ray. As the pitch for features to be resolved is getting smaller, the interval between the Zero order and the 1st order ray has increased, and part of the diffracted light exits outside projection lens aperture stop. Since there is no light to interfere with the Zero order ray, the contrast of the image is decreased and ultimately the image cannot be formed. To resolve this variable illumination shapes are developed.

1.7.2 Variable Illumination

The variable illumination uses various types of aperture styles which illuminates the reticle with exposure light from an angle. They are also called as RET (Resolution Enhancement Techniques). In variable illumination, even if we use same angle of light as in CONV illumination, the zero and 1st order diffracted ray will pass through the projection lens and thus image will be formed by the interference of these two light rays.

1.7.2.1 Annular Illumination

Annular illumination uses a donut shaped aperture centered on the optical axis. Different annular ratios could be used like 2/3 annular or 1/2 annular. This increases depth of focus.

1.7.2.2 Small Sigma Illumination

This is a conventional type aperture centered on the optical axis of the projection lens that is of smaller diameter than the tool is capable of.

1.7.2.3 Four Quadrants Illumination

Four quadrants divides conventional illumination in four quadrants relative to optical axis. An improvement can be seen in Depth of focus and Resolution using this techniques.

1.7.2.4 What is Illumination Settings

Each process condition requires different illumination shape and settings of various optics and other hardware. One typical combination of setting is defined by a number which is known as Illumination Settings. Each illumination shape must have a different Illumination Settings number or designation.

1.8 Current Trends in Lithography

Currently the High Volume Manufacturing (HVM) Lithography industry is in transition from 65nm node to 45nm node. The major companies in Semiconductor Chip manufacturing are Intel, TSM, AMD and IBM. All have already announced their success in developing 45nm process. Intel is the leader in chip manufacturing and it has already started first 45nm production while declaring its rigid plan for 32nm node. Wafers are being printed using 193 and 248nm wavelength. The critical layer where CD size is small and overlay budget is narrow, 193nm light is used. Current lithography techniques are using state of art technologies like Resolution Enhancement Techniques (RET), Optical Proximity Correction (OPC), Phase Shift Mask (PSM), and Off-axis illumination to extend the limit of optical lithography. 32nm node Logic will require patterning at k1=0.38 with 193nm Immersion and k1=0.29 with 193nm 'Dry" Lithography.

1.9 Next Generation Lithography Techniques (NGL)

Tremendous progress has been made in recent years to push the limits of optical lithography by reducing k1 through the use of resolution enhancement technology (RET) such as various phase shift mask (PSM) approaches, off-axis illumination, sub resolution assist features, optical proximity correction (OPC) methods, and many other approaches [3].

The lithography community has been coming to the realization that optical technology is being pushed to its threshold limits of imaging. At some point in time, the costs for pushing optical lithography technology beyond previously conceived limits may exceed the cost of introducing new technologies. This is key driver for development of New Generation Lithography Techniques (NGL) [7-12]

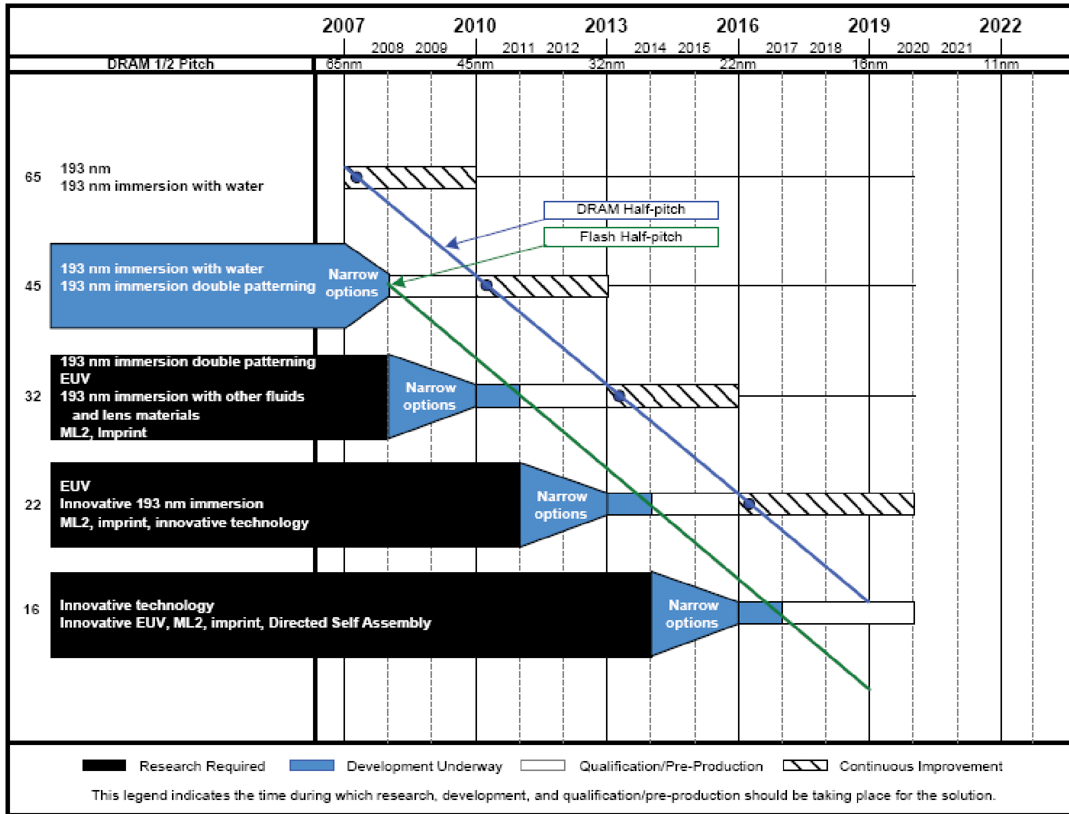


Fig 1.7: ITRS Roadmap 2007: Lithography Exposure Tool Potential Solutions. [13]

Current lithography techniques have been pushed just about as far as they can go, beyond 193nm technology there exist two smaller operating wavelength optical candidates at 157nm and 126nm (shown in Table 2). Although that 157nm and 126nm would provide further optical extension beyond 193nm there is the concern that any gain will only provide a "one generation node" solution. The 126nm technology currently suffers from limitations of not having an optical material that is transparent without being birefringing (e.g. MgF2). Therefore 126nm technology will need to rely on all reflective designs which have been shown to be limited to NA's of only 0.5 or less via modeling. The cost to develop manufacturability systems with limited extension (life span) proves 157nm / 126nm technologies are cost prohibitive. Perhaps 157nm or 126nm will only provide 20nm to 30nm finer resolution over 193nm.

Semiconductor manufacturers are, therefore, at a critical juncture. Soon, they must decide which lithographic horse to back in the race to the next generation of microchip manufacturing. There are currently four possible alternatives: Extreme Ultra Violet (EUV), X-ray proximity, Projection Electron-Beam (SCALPEL), and Ion-Beam Lithography (IPL).

Much attention is therefore being devoted to technologies whose capability would span several SIA generation nodes. These technologies shown in Table 2 are the candidates that the IC manufacturers are keying on to meet post 193nm manufacturing needs. The major differences between any NGL technology and current 248nm or 193nm optical

lithography are deviations toward charged particles (e.g. electrons, protons) or radiation wavelengths and the adoption of membrane or reflective mask technologies.

Parameter	Optical Lithography			Next Generation Lithography			
	Current Optical Lithography	Future Optical Lithography					
	193nm optical	157nm optical	126nm optical	Scalpel	Ion Beam	1X X-Ray	EUV
Effective Wavelength	193nm (ArF laser)	157nm (F2 laser)	126nm (Ar2 lamp)	4 pm (cathode guns)	5 x10^-5 (rf plasma discharge)	~1 nm (synchotron storage ring)	11-14nm (laser plasma discharge)
Exposure Mechanisms	193nm photons	157nm photons	126nm photons	electronics	protons	1nm radiation	11.8 - 13.4nm radiation
Optics	transmission SiO2 or CaF2	transmission CaF2	reflective	electromagnetic	electromagnetic	reflective	Reflective (multilayer)
Typical NA's	up to 0.75	up to 0.75	limited to 0.5	0.001	10 x 10^-5	na	0.10
Reduction (production)	4x	4x	4x	4x	4x	1x	4x
Mask Type	transmissive	transmissive	reflective	membrane transmissive	membrane stencil	membrane transmissive	Reflective (multilayer)
Current Resolution Limits	150nm (k1=0.6) 100nm (k1=0.4)	125nm (k1=0.6) 80nm (k1=0.4)	150nm (k1=0.6) 100nm (k1=0.4)	0.24nm (k1=0.6) 0.16nm* (k1=0.4)	3nm* (k1=0.6) 2nm* (k1=0.4)	30nm (1 um gap)	70nm* (k1=0.6) 45nm (k1=0.4)
Typical Depth of Focus (k2=1.0)*	0.4um	0.28um	0.5um	400 mm	500 um	na	1.1um
Champions (support)	global support	U.S. - MIT/LL Japan - Aset	none identified	Lucent Technologies	Europe - IMS (Vienna) IMS (Stutgart) U.S. - ALG	U.S. - IBM, Motorola Japan - MITI, Aset	EUV-LLC (Intel, Motprala, AMD, LLNL, LBNL, SNL)

Table 1.1 Current and future technology [14]

1.9.1 Extreme Ultra Violet (EUV)

EUV lithography uses radiation with a wavelength of only 13.5 nanometers. The wavelength of choice for EUVL, 13.5 nm, is based on the availability of MoSi multilayer mirrors with excellent reflectivity (Approx. 72%) at this wavelength with a reflectance bandwidth of approximately 0.5 nm. However, this leap in technology represents a greater challenge than any previous move to a new generation because it means developing completely new light sources, optical components and photo resist finishes. Since EUV is absorbed by all materials - including air - the entire lithographical process has to be performed in a vacuum. Conventional optical systems cannot focus light of such short wavelengths, so multi-layer mirrors have to be used. Based on the use of multilayer coated reflective optics, which achieve reflectivities of 70% in the 11-14 nm regions major corporations are now preparing the path for use of extreme ultraviolet lithography in the fabrication of future 20 GHz computer chips in the years 2012 and beyond. EUV lithography technologies can be broken down into three categories: exposure system, multilayer mask, and resist process [15-18].

One of the main obstacles towards the realization of EUV lithography is that no source of EUV radiation is currently available to meet all the specifications for a commercial tool. Several source concepts, all based on hot plasmas, are under intense development [19].

1.9.2 X-rays lithography

The research and development of Proximity X-ray Lithography technology has started earlier than any other NGL and has borne fruits in a wide variety of leading edge circuit fabrication. Soft X-rays, with a wavelength of the order of 0.1 to 10 nm, are interesting in lithography because they are able to define high-resolution images in thick materials. Although it has not yet reached a manufacturing stage, it is a good candidate for an industrial lithography at 0.1 pm and below. An XRL system is composed of an X-ray source, a beam line, a stepper, an X-ray mask, and a resist. Resolution, CD control and overlay accuracy are important measures of lithographic performance [20-22].

1.9.3 Worldwide Next Generation Lithography Development Activities

Below industries are involved in NGL development activities around the world.

Worldwide NGL Development Activities			
EUV	X-Ray	EPL	IPL
EUV LLC	**ASET**	**SCALPEL**	**Medea**
• AMD	• MC	• Lucent	• Infineon
• Intel	• Canon	• Motorola	• IMS
• Micron	• Sumitomo	• Samsung	• ASML
• Motorola	• NTT	• TI	
• ASML		• eLith	
• SVGL		• AMAT	
• USAL		• ASML	
ASET		**PREVAIL**	
• MC		• IBM	
• Nikon		• Nikon	
• Canon			
• European Initiative			
• Zeiss			
• ASML			
• Oxford			
• Infineon			

Table 1.2: Worldwide NGL Development activities [23]

Chapter 2

Scattered Light Theory

2.1 Scattered Light or Flare in Lithography

Flare or Scattered light can be defined simply as “light going to the wrong place". Flare causes rays of light to scatter away from their correct path. In the presence of flare, light is mixed from the bright region into the dark region, and the sharp edge is “softened.” This “softening effect” happens to all images that the lens is trying to form.

Scattered Light is characterized by a range typically measured in microns, and amplitude, typically measured in percent (%). Flare in a projection lens essentially removes light from a bright part of the image and mixes it into a dark part of the image. The amplitude describes the amount of mixed light and the range describes the distance over which the mixing takes place.

Scattered Light or Flare (%) is described as *how much light scattered;* also called as *Flare Max.*

Scattered Light or Flare = E_0/(Dose to clear defined feature)*100

$F_{max} = E_0/(D_{min})*100$

$F_{min} = E_0/(D_{max})*100$

D_{min}= Dose to clear first defined feature i.e. first 2u line
D_{max}= Dose to clear all defined feature i.e. all 2u lines
F_{max} = Flare Max
F_{min} = Flare Min
E_0 = $E_0$is defined as the minimum dose required to completely remove the photo
resist during development for a large open frame exposure.

2.2 Scattered Light Parameters

2.2.1 Scattering Length or Flare Range (um)

Scattered length is described as *how far away it went*. Scattering Length is equal to half the size of the object used in the test, i.e. a 2-μ line allows us to measure flare at 1-μ range (since the flare light comes from both sides of the object at once).

2.2.2 Scattered Light TIR (%)

Scattered Light TIR (%) is the difference between Max and Min flare values. High TIR means higher cross slot Scattered Light. TIR goes up with Bottom Lens contamination build up.

Flare Range TIR = $F_{max} - F_{min}$

2.2.3 Normalization of Scattered Light with E0 (Dose to Clear)

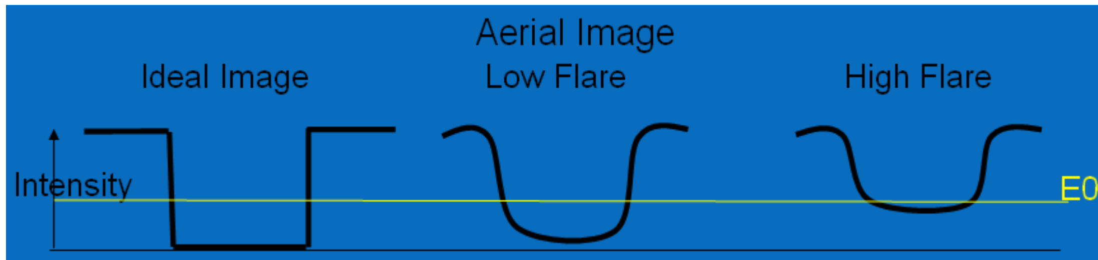


Fig 2.1: Normalization of Scattered Light with E0 (Dose to clear)

2.3 Types of Scattered Light or Flare

Scattered Light spectrum is divided into following 3 types .

Short-range Scattered Light, scattering over a scale of about 1 micron or less, blends into high-order lens aberrations and diffraction effects and has sources similar to local flare.

Local Scattered Light, scattering over a scale of about 2 to 10 microns, measurable by a feature-size-dependent test, affects clearfield-reticle and darkfield-reticle exposures. It comes from scattering from in-homogeneities within the glass and from polishing errors in the surface.

Long-range Scattered Light, scattering over a scale of tens of microns, affects Clearfield reticle exposures. It comes largely from reflections within the projection lens and is affected by choice of lens coating, wafer reflectivity, use of BARC, and contamination.

2.3.2 Importance of Short Range Scattered Light

As pattern size decreases below 100 nm, short-range flare has become more important because short-range affects image degradation and would reduce process margin seriously in low *k1* lithography. For short-range flare process conditions such as photo resist, thickness, and contamination build up on lens elements, substrate film stacks, and even some times photo masks can be important variables of flare. So far the impacts of process variables on flare have mainly been studied on the conditions at wafer level.

2.4 Scattered Light Measurements

The measurement of scattered light was first done by Flagello/Pomerene [24] using a square pad type structure. Then Kirk [25] used similar method to Flagello/Pomerene but he observes the receding edge of a large pad while exposure dose is increased.

2.4.1 Flagello/Pomerene Method

This test used a large feature size square pad (6 microns) which is exposed at gradually increasing doses. The exposed wafer is examined under a microscope and dose E at which the feature is completely removed from wafer is noted. The dose to clear photo resist is calculated separately. Since the only way that exposed light can reach the center of the dark pad feature is via scattered light, so removal of the feature is a direct quantitative indicator of scattering at a range equal to half the feature size.

$$\text{Scattered Light or Flare} = E_0/(\text{Dose to clear defined feature})*100$$
$$F = E_0/Dmax *100$$

2.4.2 Kirk Method

Kirk used an edge measurement technique as a way to remove the short range scattered light contributions. In his test large pad is over exposed as for the standard scattered light test but using dose lower that that needed to clear the pad. Similar square feature but he observes the receding edge of a large pad while exposure dose is increased. However C. Mack [26] commented that Kirk receding edge method assumes that the photo resist has infinite contrast (if a point in the resist receives a dose greater than Eo, it is completely developed away. Lateral development effects will always be present since the development front at the edge of the pad will always be traveling laterally).

2.4.3 Current Method

Currently major lithography tool manufactures are based on Flagello/Pomerene methods but instead of using pad they use line. Line sizes of 1 micron to 10 microns are printed vertically and horizontally with successive dose increments. The dose to clear first 2 micron line (D_{max}) and dose to clear all 2 micron lines (D_{min}) is noted down and then Scattered light is calculated using above formulas. Some Vendor recommends 6 micron line as standard feature to calculate scattered light for 90 and 65nm processes while some semiconductor manufacturer uses 2 micron line. A line size of less than 2 micron feature size or 1 micron scattering length will be affected by diffraction or other effects for low k lithography [27]

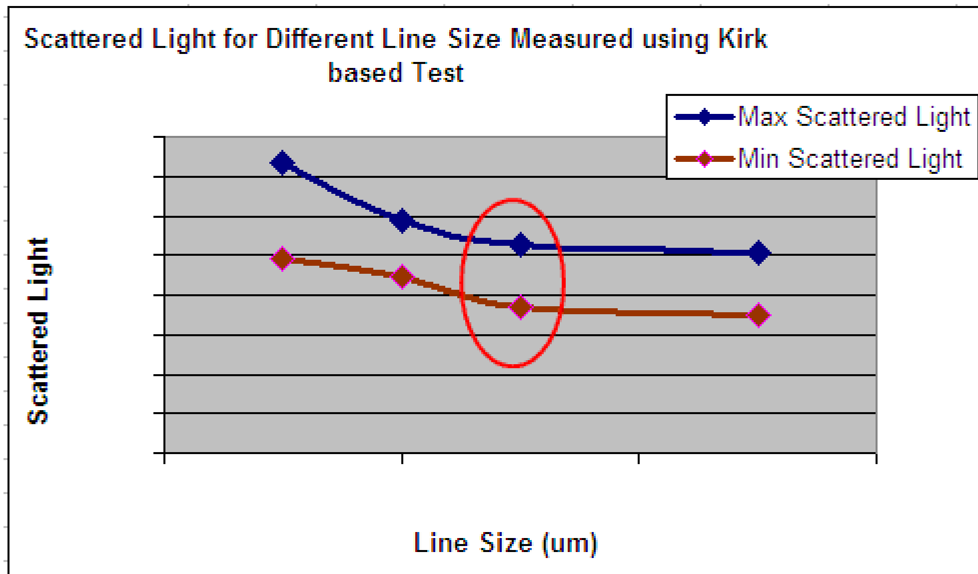


Fig 2.2: Scattered Light at Different Line Sizes using Kirk based test

First Dose to clear Eo is measured by a separate test called Eo test. This test uses rectangular features shot with successive incremental dose starting at very low to high provides a dose to clear photo resist from wafer substrate. Eo is required for calculation of Scattered light.
Ultra flat or BARC wafers are used to coat and expose line pattern for scattered light measurements. Wafers are then measured under a microscope where different sites are measured based on tests used by different vendors. A 2micron is most common choice and less than 1.5micron size is affected by diffraction.

2.5 Point Spread Function of Scattered Light

The point spread function (PSF) of an optical system is the image formed by the system of a point source. Point Spread Function (PSF) of Scattered Light Illustrates of how light scattered by a lens affects the distribution of light intensity around the image of a point source.

- A first point spread function (PSF_{aberr}) describes the spread in the image of a point that can be calculated deterministically from the finite size of the lens and from its aberrations.
- A second point spread function (PSF_{scat}) describes the usually fainter halo of light (flare) that surrounds the image of a point.

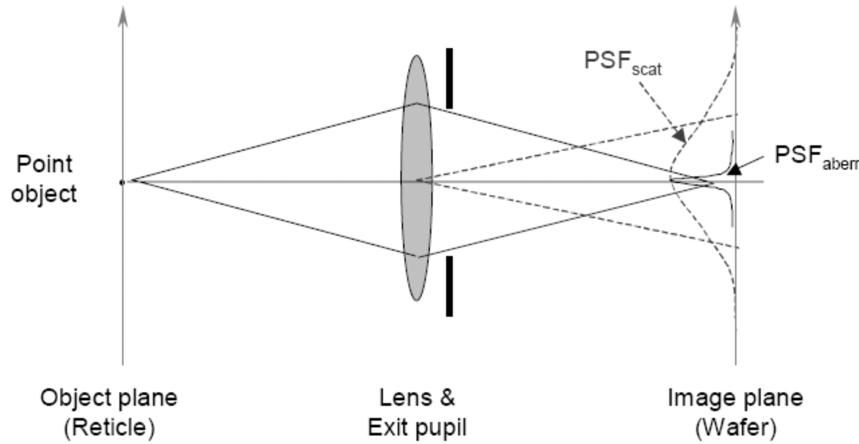


Fig 2.3: How light is scattered by a lens affects te distribution of light intensity around the image of a point [28]

2.5.1 Modelling Scattered light

Scattered Light will cause all light to scatter in equal proportion regardless of its spatial frequency and field position. Scattering will result in a uniform reduction in the energy that coherently interacts to form the image. The fraction of the light energy that scatters and thus does not contribute to the coherent creation of the image called as Scatter Function SF. The final image will be given as below.

$$Image = (1\text{-}SF)\ Io(x, y)$$

If there were no scattering than the resulting image would be Io(x, y).
The scattered light is converted in a background dose and will be added to the aerial image.
Scattering reduces the intensity of the image *locally* while background dose is added *globally*.
So the additional background dose will be equal to the SF multiplied by the total energy passing thru the lens.

$$I(x, y) = SF.IF + (1\text{-}SF)\ Io(x, y)$$

IF is the fraction of intensity of the reticle. IF can also be defined by the ratio of total intensity reaching wafer for this reticle compared to the intensity that would reach the wafer for a perfectly clear reticle.

Total intensity passing thru lens **α** *Clear area of the reticle.*

If CF is the clear area fraction for the field then background flare can be written as below.

$$I(x,y) = SF.CF + (1\text{-}SF)Io(x,y)$$

For any given reticle the clear area fraction CF is a given number. So background flare can be calculated for any reticle once the scatter fraction SF for the lens has been measured.
Above equation does consider the impact of short range scattered light effects as seen in previous equation (xx) The Point spread function can account for short range scattered

light effects. The local scattered light is described as the convolution of the local light intensity (also called the aerial image) with a scattering point spread function, PSF_{scat}.

$$I_{scat}(x,y) = PSF_{scat}(x,y)*Io(x,y)$$

If PSF scattering is a constant then the convolution becomes a calculation of the total energy of the aerial image and the scattered intensity. This will be equal to scatter fraction times the intensity function.

2.6 Sources of Scattered Light

There are several sources of scattered light and major ones are discussed below.

- Pellicle
- Lens Coatings
- Reflection within the projection lens
- In-homogeneities within the glass
- Polishing errors in the glass surface
- Other issues like surface roughness developed by cleaning effects.
- Reflection outside Projection lens and other optics
- Contamination builds up on various Lens Elements in illumination paths
- Wafer Surface, BARC/TARC
- Illumination shape

As the lithography moves to low k1 factor, control of scattered light has become much more critical. The control of scattered light must be done at the time of lens manufacturing. Manufacturer optimizes the number of Calcium Fluoride elements in the projection optics by selecting a novel lens configuration and a very narrow bandwidth laser. To maintain quality control power spectral density (PSD) analysis is performed on each lens surface. Proper polishing methods are used for mid-spatial frequency control to meet the PSD tolerance for each lens element surface. Wave front data measured is measured for the local flare evaluation before integration of the lens [29]

For 193nm and 248nm Lasers sources like pellicle, wafer surface, lens coatings, reflection within the projection lens, glass surface in-homogeneities, polishing errors generally remain a constant as these effects are only seen for a very long run or during manufacturing of lens or pellicle. The illumination shape, wafer surface and contamination build up on lens element are major root cause for scattered light introduction as they change on daily basis [30-34].

2.7 How Lens Element gets contaminated

Photo resists are used to coat wafers. When resist is exposed using laser light it produces some gases and this process is called resist out-gassing. The out-gassing from resist depends on the type of resist and light used for exposure. The main projection lens of

exposure tool contains 30-40 lens elements but only two elements are exposed to outside environment. The last optic of a projection lens is exposed to out-gassing of photo resist and with laser light it produces a large contamination which is deposited on the lens surface cause scattering of light. While top lens contamination is purely due to environmental effect and other gases present inside machine. There is several other optics like Condenser lens which are exposed to environment and also get contaminated.

2.8 Lens Element cleaning

Scattered light rise quickly as the contamination build ups on the lens element. In certain processes scattered light can reach to a significant level in a very short period of time which depends on toolset type, resist used and energy used. Impact of scattered light is seen more on 193nm scanners than 248nm scanners. A lens element cleaning is performed when you hit the upper specification for scattered light after which CD uniformity and other process impacts start appearing which reduce process budged for DOF and resolution capacity. Next section describes these process impacts in details with the help of results. A lens element cleaning is done by a trained specialist. De-Ionized water and vendor recommended Solvent is used for cleaning. As the lens elements are very delicate piece of optics and they are mounted with very sophisticated hardware to compensate for any pressure and temperature changes, so excessive pressure on optics while cleaning can cause a shift in optics position. This will result in shifting lens aberrations profile which requires extensive measurement and correction method to bring back to specifications. Depending on toolset almost 95- 98% of the contaminants are removed by simple solvents wipes but there are occasions where further cleaning methods are used.

Chapter 3

Power Illumination Non-Uniformity Theory

3.1 The Illumination System

The Illumination system is an optical system that guides laser light to the mask surface. Illumination system performs various functions like control of illumination non-uniformity, illumination sigma control, telecentricity control, increased irradiation etc. To realize these functionalities illumination system uses various optical, mechanical, electrical and software technologies.

3.2 Power Illumination non-Uniformity

Laser light used for exposing wafer needs to be highly uniform. Uniformity is a description of the homogeneity of light intensity in the optical train. In the absence of a reticle, the light striking the wafer plane should be highly uniform so that a tool can produce consistent CD's across the field. Illumination non-uniformity is an index to evaluate how much illumination non-uniformity there is in the maximum exposure area when exposing wafer.

3.2.1 Perfect Lens

Illumination intensity distributed equally across the field. Each point on the wafer absorbs an equal amount of laser energy.

3.2.2 Damaged Lens

Illumination intensity distributed unequally across the field; each point on the wafer absorbs a different amount of laser energy.

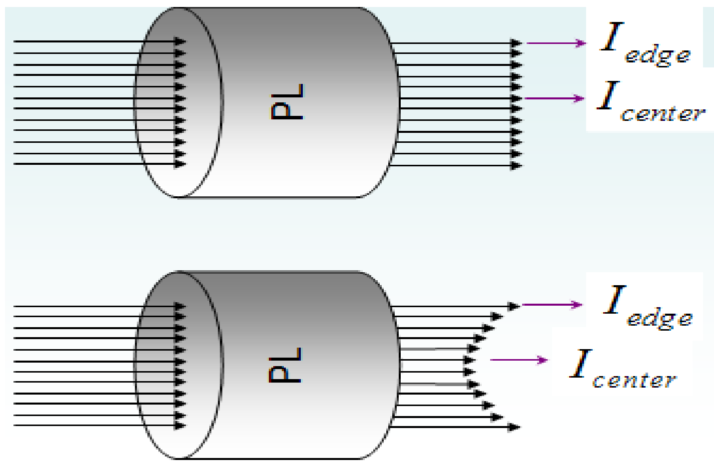


Fig 3.1: Uniformity profiles

3.3 Uniformity Curves

3.3.1 Uniformity – Polynomial

Plotting a chart of Illumination intensity (normalized) over X position yields a curve such as seen in figure 3.2.
The curve may be fit to an nth order polynomial where Ii are constants determined by the fit. Four terms usually suffice, as for the example above. The zero order term is a constant offset. First and third order terms are asymmetric tilts. Most lens damage occurs near the optical axis, thus fourth order terms are of no interest as they dominate near the edges. The second order term remains as the one of interest.

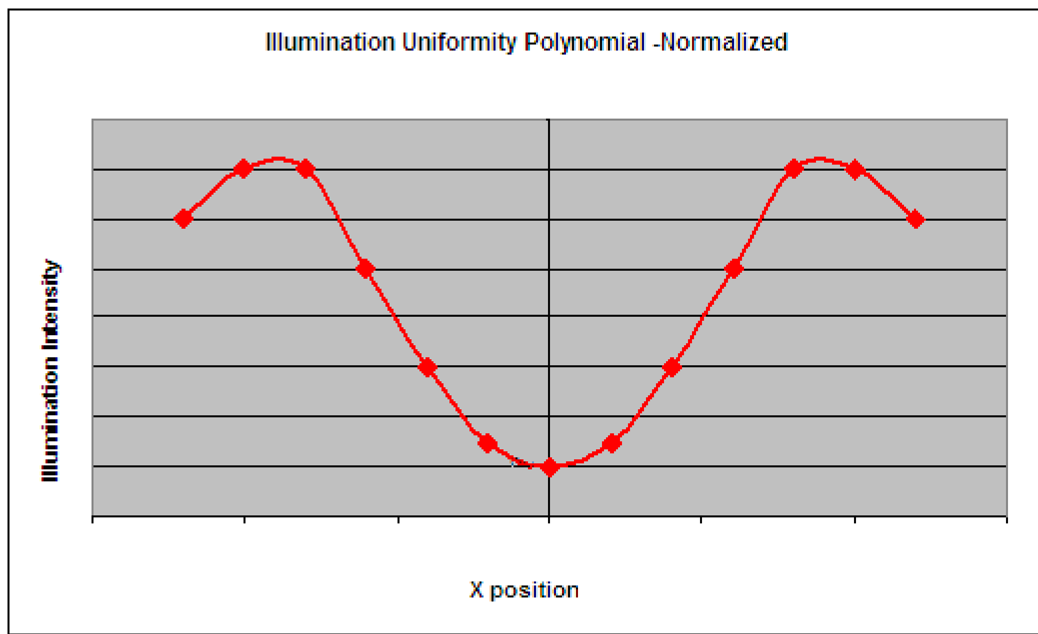


Fig 3.2: Uniformity Polynomial

3.3.2 Uniformity - Second Order

This uniformity is 2nd order uniformity. While the polynomial coefficient could be used alone to describe second order uniformity, a fractional value is used and is commonly referred to simply as "Uniformity."

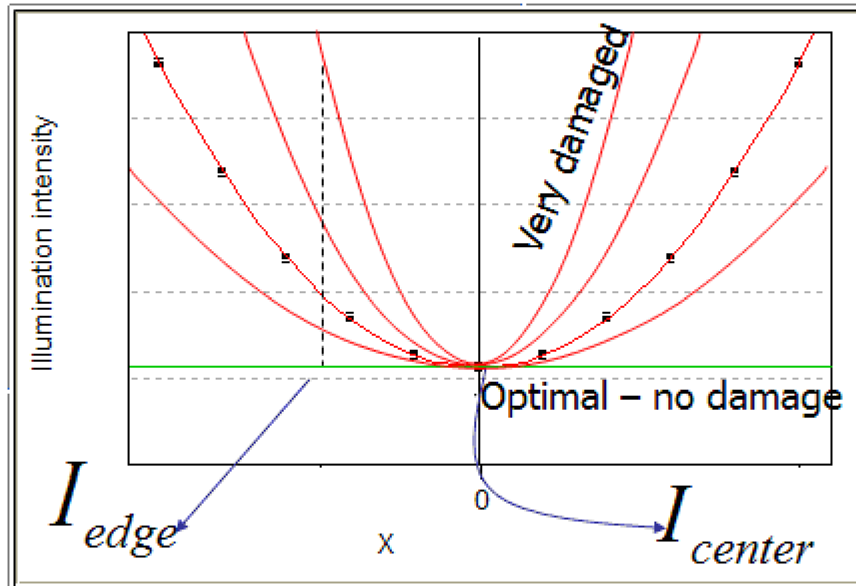


Fig 3.3: Uniformity profiles describing edge and center intensities.

From above figure uniformity can be given as

$$Unf \equiv \left(\frac{I_{edge} - I_{center}}{I_{edge} + I_{center}} \right)$$

Where I_{edge} = Intensity at the edge of lens
I_{center} =Intensity at the center of the lens

The magnitude of this parameter gets larger as uniformity grows worse!
>0 → concave (cold center)
<0 → convex (hot center)

3.4 Illumination Non-Uniformity Measurement

Illumination non-uniformity is an index to evaluate how much illumination non-uniformity there is in the maximum exposure area. The Scanner system has illumination uniformity measurement sensor which measures the non-uniformity for a given set position. This sensor is located on the Wafer stage system.

3.4.1 Static Illumination non-uniformity

Static Illumination non-uniformity is associated with the static exposure which is also called the slit width of scan. The actual size of slit width depends on the vendor specific specs.

3.4.2 Dynamic Illumination non-uniformity

Dynamic illumination non-uniformity is calculated by taking the static illumination uniformity measurement results, integrating along scan axis direction, and producing a one dimension data point for each row. For static uniformity illumination intensity is judged at each point while for dynamic uniformity the integrated illumination for each row is used.

Illumination uniformity is measured by creating a grid of X * Y Grids points in the defined exposure area where pin hole illumination sensor will move with stage and measure each point to measure power.

Then Simpson rule of Integration is applied to calculate along scan direction.

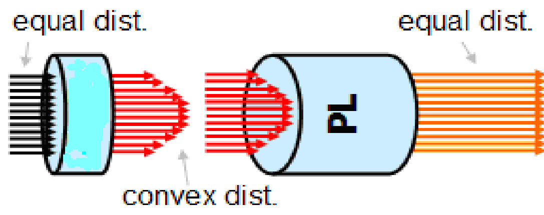
Simpson law

$$\int^{\beta} f(x)dx = \frac{h}{3}[(y_0+y_{2n})+4(y_1 + y_3+ .... + y_{2n-1})+ 2(y_2+ y_4+ .....y_{2n-1})]$$

Uniformity specification varies according to product and layers to be printed. It also depends on the Die size (chip size) i.e. the bigger the chip - higher the non-uniformity. Some layers like Poly Gate are very sensitive for CD control and a high uniformity could easily cause a center to corner Bias issues.

3.5 Uniformity Correction using Filters

The uniformity parameter tends to increase with tool usage (more positive/concave). Uniformity can be corrected with illumination filters. A Variable Uniformity Filter (VUF) is a special filter that corrects the center convex/concave illumination non-uniformity created by previous optics in the illumination paths. VUF is a glass plate with random chrome dots placed upon it. However, these filters only compensate for the damage done to the optics during tool use. Because they are subtractive filters, they contribute to power loss. Increasing filter correction means increasing power loss.



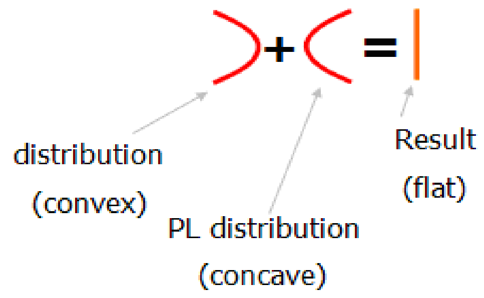


Fig 3.4 Uniformity Variable Filter

Fig 3.5 Convex and Concave Design of filter

Section II

Measurement Techniques and Experiment Setup

Chapter 4

General Measurement Techniques and Experimental Setup

5.1 General Measurement Techniques

Experiment required a lot of setup and pre-work. I have categorized whole setup in below steps.

- Process Layers used and their understanding.
- Measurement Tools and Techniques
- Automation setup
- Cost of Research
- Experimental Techniques - These are the special techniques used for scattered light and uniformity experiments and they will be discussed separately in chapter 5 and 6.

Further details of General Measurement Techniques and Experimental Setup are now removed due to Intellectual Property Restrictions.

Chapter 5

Scattered Light Experimental Techniques

There are few techniques used while running these experiments. This chapter explains key experimental setup and techniques required to run such experiments.

5.1 Scattered Light Induction by Double Flood Exposure Method

An innovative way of Scattered Light induction is available where wafers are double exposed first with standard exposure and then with an additional dose equivalent to induced scattered light. This method only induces Uniform Scattered Light in absence of a reticle. A similar method is described by Chang-Moon Lim, Jung-Ho Song, Soung-Su Woo, Ki-Sung Kwon [37]

Further details of Scattered Light Experimental Techniques are now removed due to Intellectual Property Restrictions.

<u>*Chapter 6*</u>

Power Illumination Non-Uniformity Experimental Techniques

6.1 Setting up illumination Programs for different conditions

Different illumination conditions can be achieved by changing Uniformity Variable Filter settings. This requires a set of procedures to set new positions for Uniformity Variable Filter and then setting up process programs for each illumination conditions.
We setup 15 different Uniformity Variable Filter positions from its neutral position and different tests like scattered light, illumination power and uniformity were run to understand each condition.
9 best Uniformity Variable Filter settings were chosen to simulate power illumination uniformity i.e. 4 on each side of neutral position while keeping all other conditions same.

Further details of Power Illumination Non-Uniformity Experimental Techniques are now removed due to Intellectual Property Restrictions.

Section III

Results

Chapter 7

Impact of Illumination conditions and Silicon Substrate on Scattered Light

7.1 Silicon Substrates and their Impact on Scattered Light

In Lithography light passing through the photo resist material is reflected off the substrate. This reflected light from the wafer interferes with the light wave traveling down. Reflections are caused by a difference in the complex index of refraction of two materials. Lithography processes use different wafer substrate and different stack thickness for patterning. The reflectivity of each substrate and each stack thickness is different from other so it can cause unwanted variations in the resist profile and swing curve effects. It is important to understand the impact of most common substrate type and their impact on scattered light.

7.1.1 Substrate Types

Wafers that are used for patterning use bottom anti reflecting coatings (BARC) to overcome the problem of reflectivity. BARC's in lithography are of the absorbing kind. In this type we have a film thick enough to absorb the light and with an index of refraction close to resist such that the reflectivity is minimized. The other type of wafers used are Ultra flats with no reflecting coating.

7.1.2 Resist Swing Curve

The wafer contribution depends on the substrate reflectivity. Resist swing curve is a sinusoidal variation of resist thickness with dose to clear resist (called as Eo).

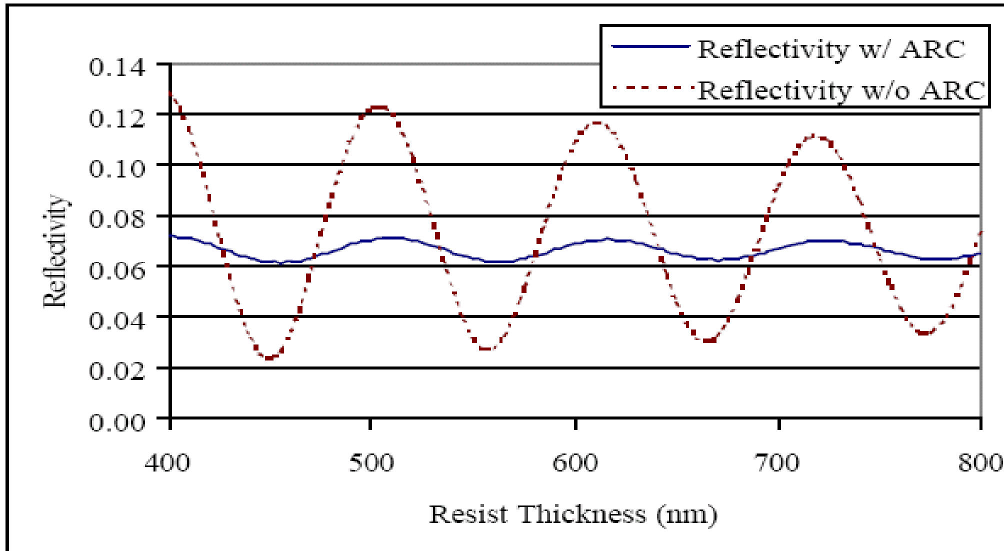


Figure 7.1: Simulation of the swing ratio reduction for Organic ARC thickness for 365 nm [38]

The reflectivity swing curve shows variations in resist thickness result in a sinusoidal variation in the reflectivity of the resist coated wafer. Reflectivity is the ratio of total reflective light intensity divided by the total incident intensity. An increase in reflectivity means more light that does not make it into the resist, which means higher dose, is required i.e. higher Eo. This explains the Eo swing curve. A resist swing curve as described in above figure is required to select the correct dose for exposure. One should select the flat portion of it to avoid sudden change Eo due to thickness change which can come easily from atmospheric pressure variation. Modern track equipments use barometric pressure compensation techniques which adjust spin speed of resist coating module to achieve set thickness. The above figure 6.2 clearly explains how swing ratio decreases with BARC wafers which are ideal for patterning to avoid reflectivity and thus scattering.

7.1.3 Scattered Light Comparison between BARC and Ultra Flat Wafers

Difference in Flare values between different substrate is generally a constant value which linearly varies flare level. To eliminate Wafer contributor one should simulate production conditions and that's why BARCs are preferred for Scattered Light tests.

7.2 Effect of various Illumination Aperture shapes on Scattered Light

The previous work done to understand impact of scattered light was mainly focused on long-range background light. As lithography moves towards 45nm with line size short range scattered light becomes critical. There is lot of work done to understand the impact of scattered light on patterning but very little is being done to understand the impact of illumination conditions. Below result demonstrate how critical it is to understand the impact of illumination conditions.

7.2.1 Results

It can be noticed that the laser beam angle adjusted with NA, modifies the amount of scattered light: Scattered Light decreases when NA increases and NA seems to have low influence. NA has little effect because light is not diffracted by large chrome patterns. The coherence factor makes the incident angle of the light vary; so, when NA increases, more and more light is captured by the edge of the lens where Scattered Light is lower, and then the amount of Scattered Light decreases.

Scattered Light level difference among various Illumination Conditions depends on tool's Scattered Light level. The difference in Scattered Light level from different illumination shape increases with Scattered Light level of a tool.

Scattered Light level difference among various Illumination conditions also depends on different Illumination conditions Type.

1. *Strong co-relation seen between LNA/iNA size and Scattered Light level of a tool. They work opposite to each other.*
2. *Scattered Light level increase when LNA or iNA size decreases.*
3. *Scattered Light level decrease when LNA or iNA size increases.*
4. *This concludes that Annular settings may show low Scattered Light than conventional Settings for same process conditions. This difference increases with Scattered Light level of tool i.e. at low Scattered Light level the difference in Scattered Light level of different Settings may be small or negligible.*

This is a critical piece of information for semiconductor process layers where specifications for maximum scattered light are very tight. The results suggest measurement of scattered light should be based on different illumination conditions.

Chapter 8

Scattered Light Results

In this chapter we will analyze the results and conclusions from scattered light experiments.

- Scattered Light and its effects on imaging
- Scattered Light impact on Semiconductor Processes Failure Analysis and Cross-sectioning Results
- Impact of Scattered Light on Line-Space and hole Critical Dimensions.
- Lens contamination and its impact on Scattered Light & Power Illumination non-uniformity
- Scattered Light and some explanations
- Impact of Power Illumination non-Uniformity on Scattered Light
- Link between Power Illumination Uniformity and Scattered Light.
- Scattered Light Impact on Future Technologies - Immersion and EUV

8.1 Scattered Light and its effects on imaging

A series of experiments were conducted to understand the impact of scattered light on patterning. The results below includes analysis of resist profile, etched profile, end of line E-test and SORT data and cross sectioning profiles.

Experimental data analysis showed following impact of Scattered light on patterning.

1. Cross-field CD variation due to Scattered Light variation across the slot.
2. Scattered Light increase Line Edge Roughness (LER).
3. Line profile changes.
    a) Lines become less vertical.
    b) Slope width increases.
    c) Top of line width decreases.
4. Hole profile Changes.
    a) Holes become trapezoidal.
    b) Corner rounding effect.
5. Scattered Light degrades Image contrast.
6. Cross-field CD variation due to Scattered Light leakage from adjacent fields.
7. Cross-field CD variation due to pattern density changes across the field (that is, features near open areas get a little more dose from scattered light than features near dark areas)
8. Variation in etch bias with Scattered Light, apparently due to changes in resist profile.

8.1.1Cross-field CD variation due to scattered light variation across the slot

As scattered light increases the cross-field CD variation goes higher this is due to scattered light makes field center hot and corners cold for energy. Field center collects more energy due to scattering. Below figure shows clearly how CD uniformity increased linearly with increase in scattered light. This becomes a major concern in production environment where something must be done to fix high scattered light as it consumes a significant portion of process window budget and also reduces DOF. Based on DOF budget for each layer this impact can be evaluated for example far Back end layer will handle higher flare variations due to their high DOF budget while critical layers will have very tight window.

8.1.2 Scattered Light Impact on Line Edge Roughness (LER)

Scattered Light increase Line Edge Roughness (LER). Overall CDs measurement may not be affected but it could lead to other issues.

8.1.3 Line profile changes.

The line size and profile changes with increase in scattered light.

- Lines become trapezoidal in shape and corner rounding effect can be observed.
- Line height decreases with increased in Scattered Light.

Fig 8.1: Simulation of CDs with low and high Scattered Light

8.1.4 Hole profile changes.

The vertical location of the measurement can impact the signal seen pre/post clean

- If measuring at the top, the hole CD might get larger with increasing Scattered Light
- If measuring at the bottom, the hole CD might get smaller with increasing Scattered Light

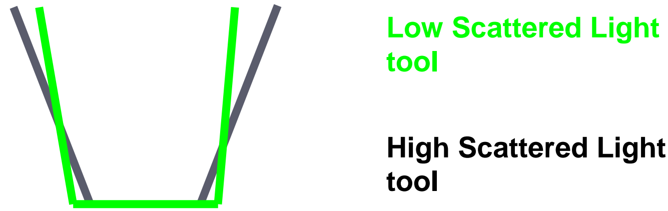


Fig 8.2: Simulation of CDs with low and high Scattered Light

It appears that Scattered Light has very little impact on layers with high chrome density. Contact and VA layers should suffer almost no impact of Scattered Light on CD uniformity. If one has a high Scattered Light tool, keep illumination uniformity under control, and CD variation should be good, even at high Scattered Light levels. Also, Scattered Light will not increase very rapidly, as energy going through the PL will be minimal

8.1.5 Image Contrast Degradation

Scattered Light Degrades the Aerial Image contrast which decrease the process window,. Degradation of Image contrast makes difficult for etch process to handle it.

8.1.6 Cross-field CD variation due to Scattered Light leakage from adjacent fields.

One can see this by patterning isolated fields and comparing them to normally butted fields. Fields butted up to each other closely can actually improve the CD uniformity, by adding scattered light to the field corners – some bleed over is good. Bleed over from adjacent fields can compensate for min flare in the corners as it adds light from neighboring field

8.1.7 Variation in etch bias

Difference between Litho patterned CD and the final Etched CD and can be written as below.

$$Etch\ Bias = CD_{(Resist)} - CD_{(Etched)}$$

Scattered light can cause Etch Bias issue. Scattered Light reduces process marginality which makes difficult for process to cope with any other change at various processing steps. Though experiments conducted on a hole layer did not show etch bias issue as the etch profiles were within tolerance range but this does not mean it will be true for all cases. This depends of etch process and product layer combination printed. The critical layers are more prone to get etch bias issue then non critical layers due to their smaller depth of focus tolerance.

8.2 Scattered Light impact on Semiconductor Processes Failure Analysis and Cross-sectioning Results

Below are the results from experiments conducted on hole layers. Wafers were taken to cross sectioning laboratory to analyze vertical impact on features.

8.2.1 Result comparison for Hole layer with & without Scattered Light induction.

From experimental results following impacts are seen.

- There is a significant CD impact seen due to high induced Scattered Light at resist CD while at etched CD there was no major difference seen between no Scattered Light and high Scattered Light wafers.
- For resist CD, CD profile changes with Scattered Light. With Scattered Light induction hole gets trapezoidal shape while etched CD it was not affected.
- For resist CD Line edge roughness increases with Scattered Light while etched CD showed no change.
- For resist CD Hole CD gets larger with Scattered Light at top. For etched CD, in some cases high Scattered Light helped CDs and CDs are much closer to target.
- For resist CD Gap between nested features gets smaller due to corner rounding effect while no change seen for etched CD.
- There is no noticeable difference seen between center and edge of the field or center and edge field of the wafer for either resist CD or etched CD.
- This clearly indicates that there is a margin to increase Max Scattered Light limit for hole layer 248nm tools as etched CD is not affected significantly by this. There is also a margin to extend the resist CD 3 sigma limits for Scattered Light variation.

8.2.2 Isolated and Nested features

There was no major difference seen between nested and isolated structures while comparing for same conditions between pre & post and within pre or post wafers. For induced Scattered Light conditions the gap between nested features got smaller due to corner rounding effect. It still need to be understood whether this will cause any issue as so far from etched CD data there is no impact seen.

8.2.3 Center vs. Edge of field

There was no noticeable difference seen between center and edge of the fields or center or edge field of the wafer in failure analysis.

8.2.4 Center vs. Edge of Wafer

There was no noticeable difference seen between center and edge of the fields or center or edge field of the wafer in failure analysis.

8.2.5 Impact of Scattered Light on Line-Space and hole Critical Dimensions

The data analysis completed for critical dimensions at Develop check CDs, Final check CDs and Cross sectioning results clearly showed that there is a big difference in impact of scattered light for line space layers and hole layers. The research showed that impact of high scattered light on patterning leads to following;

- Space CDs increases in the field center (vs. corners) for line-space features.
- Hole CDs decreases in the field center for hole layers.

8.3 Lens contamination and its impact on Scattered Light & Power Illumination non-uniformity

Lithography resist out gassing leads to bottom lens element contamination build up. This contamination causes light to scatter and illumination power uniformity to increase. Experimental results show that Scattered Light and illumination uniformity (due to lens degradation) have <u>opposite</u> impact on CDs. This impact is primarily due to the difference in chrome density of reticle i.e. Pattern Density.

- High scattered light makes field center hot, but illumination uniformity makes center cold
- For hole layers, with high chrome density, the impact of scattered light is negligible; illumination uniformity explains the changes in CD variation completely.
- For line-space layers with much lower chrome density, the resulting CD impact is due to the larger contribution from scattered light.
- Post a lens element clean projection lens scattered light reduced significantly. This would make the center of field (A corner) space smaller. Illumination power is hotter in the center than edge of the field post cleaning of lens. Post clean Center of the field increases relative to other corners. The important point which one need to understand here that post lens element clean center of field gets colder due to decrease in scattered light intensity but illumination non-uniformity makes it hotter. Both effect takes place all time but hole layers only see uniformity impact due to most of the light blocked by mask resulting almost negligible light scattering.
- In summary for hole layers there is almost no impact due to scattered light on patterning so if one has a high scattered light on a tool then he can keep running hole layers as long as the illumination non-uniformity is under control. In most cases it is easy to correct illumination non-uniformity by uniformity filters and other optics adjustments in the illumination path.

- We also proved the reverse of above i.e scattered light was measured for a large variation on uniformity for same lens conditions and we saw scattered light remained constant.
- *This became main driver for our next experiment to understand the impact of illumination uniformity on line-space and hole layers.*

8.4 Scattered Light and Discussion

Below are few questions related to scattered light, which we tried to understand and explained from our results.

8.4.1 Max Scattered Light is always at the field center

A point spread function (PSF) can describe the scattered light surrounding the image of each point. Diffraction which is determined by lambda, NA and aberrations, cause light from a point object to spread over a relatively short distance around its geometric image. Random phase errors varying over a short distance at the pupil of the lens cause the light from that same point object to spread over a much larger distance around its geometric image cause Scattered Light.

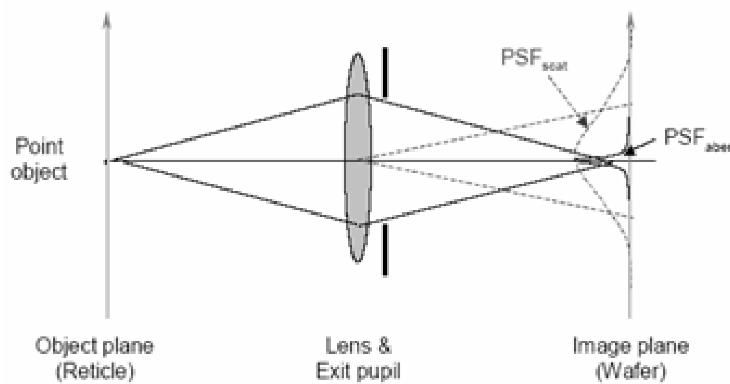


Fig 8.3: Point Spread function [39]

8.4.2 Max Scattered Light lead to center of field being hotter

There is a definite correlation between Flare/TIR test and CD variation within the field. Data clearly showed that max scattered light resulting center of field being hotter i.e. more unwanted light is collected at the center of the lens rather than at the periphery(center of the lens = over expose)

8.5 Scattered Light: New Tool vs Old Tool

Even a new tool will have max Scattered Light in the center, due to intrinsic reflections in the lens, widening the PSFs. As the tools age, the reflections increase and the laser induced chemisorptions increases the reflections in the center resulting in

- Center (maximum) Scattered Light increasing fastest, as most energy goes through here, leading to more contamination.
- Corner (minimum) Scattered Light increasing slowly, as less scattered light gets there, leading to less contamination

8.6 Impact of Power Illumination non-Uniformity on Scattered Light

Lens degradation is one of the primary reasons for increase in scattered light and power illumination non-uniformity. Power uniformity changes due to change in illumination conditions. There are several optics in the illumination path between laser source and when laser light expose reticle surface. Any physical or orientation change in this optics could lead to a change in uniformity variation. The question we must ask whether these uniformity filters, attenuators etc change uniformity but do they change scattered light too.

We ran multiple experiments to understand the impact of illumination non-uniformity on scattered light. Uniformity level was changed with help of Uniformity Variable Filter and scattered light was measured for each change. Results showed that scattered light remains almost unchanged for large uniformity variations. This test was done when lens conditions were exactly same for all uniformity variations. It proves that one can change uniformity without affecting scattered light as the light scattering depends more on the change in lens degradation which changes the shape of lens or contamination build on lens elements.

8.7 Link between Power Illumination Uniformity and Scattered Light

Why typical measurement of light transmission at the wafer plane show a relatively uniform performance for non-uniformity which measurement of scattered light as measured CDs shows that fields to be hotter in the center.

This is due to the pinhole illumination intensity sensor in the scanner.
By design, they do not detect the scattered light

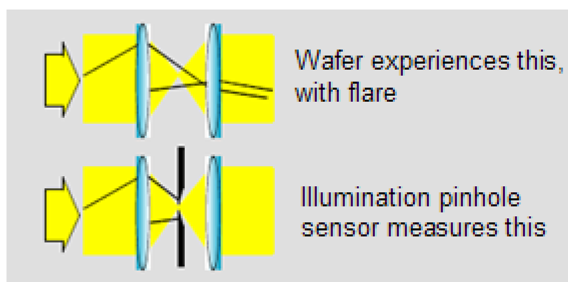


Fig 8.4: Effect of the Illumination pinhole as an ambient light filter (suppression of scattered light) [40]

Stray effects, which possibly occur prior to the excitation light coupling, are effectively suppressed by the illumination pinhole functioning as a spatial filter.

It seems like we could use the pinhole sensor for illumination uniformity measurement, and a larger sensor for Scattered Light measurement. Larger sensor would capture total energy, including scattered light. We could get Scattered Light data during each illumination uniformity measurement.

8.8 Compensating for Scattered Light - by Uniformity Variation

There is a commonly asked question can we allow let the illumination uniformity profile degrade with contamination (causing center to get cooler), while the Scattered Light level increases (causing center to get hotter) to maintain within CDs?

- It can be done only up to a certain limit. The illumination uniformity control is important to maintain the image quality, while the Scattered Light degrades it
- It is effective up to a point and that depends on the process/layer/tool design. One can characterize this for their process/layer/tool.

8.9 Scattered Light Impact on Future Technologies - Immersion and EUV

The two major candidates for future lithography process also suffer from scattered light.

8.9.1 Impact on Immersion Lithography

Immersion can have number of possible scattering mechanism that can occur in a fluid. Scattering from bubbles formation due to out gassing, bubble turbulence, local heating of the liquid or resist surface during exposure, pressure change in bubble, bubble molecular orientation etc. Three major scattering effects due to water bubble are: Raman scattering on molecular vibrations, scattering on gas bubbles in the liquid and scattering due to density fluctuations.

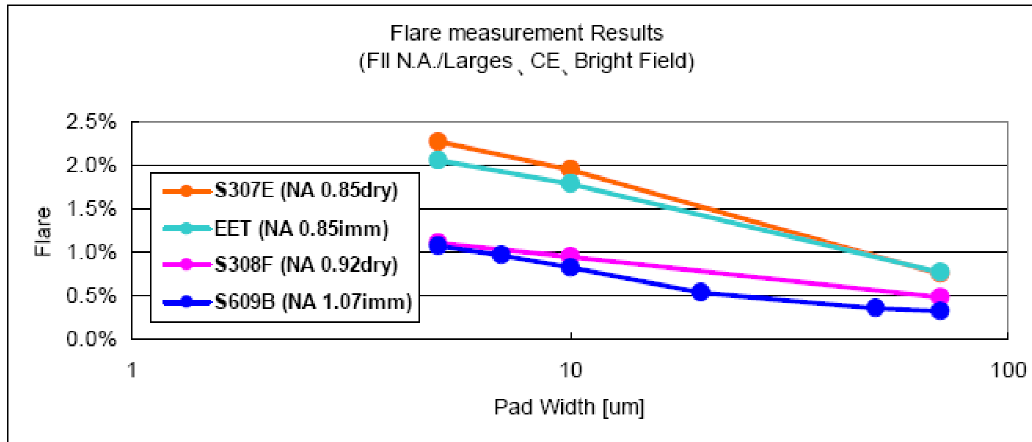


Fig 8.5: Nikon Immersion tool Flare levels. [41]

8.9.2 Impact on EUV Lithography

Scattered Light in EUVL differs from Scattered Light in DUV lithography due to scattering range and underlying mechanisms. Since Scattered Light is proportional to the inverse square of the actinic wavelength, the amount of EUV Scattered Light can be large ~ 10%, which would be 3 - 4 times larger than DUV.

The Source of EUV Scattered Light is mainly arises from roughness of the mirrors in the Projection Optics (PO). EUV Scattered Light is essentially constant over the field due to short scattering range at EUV wavelengths which makes easy prediction of EUV Scattered Light Impact on CDs.

EUV Scattered Light Primarily generated by surface scattering from the mirrors. It can be predicted and calculated from surface roughness characterization of individual mirrors. Thus, Scattered Light is less likely a concern for EUV lithography as long as the amount of open frame Scattered Light is below 10%.

Chapter 9

Power Illumination and Non-Uniformity Results

The illumination system characteristics of a lithography exposure machine can affect various performance metrics and output like resolution, DOF, aberrations, alignment at the wafer and CD uniformity [42, 43]. Power Illumination non-uniformity affects Line width or Critical dimension (CD) which is one of the most critical variables in the lithography process with most direct impact on device performance in integrated circuits. [44, 45]

From our previous experiments we concluded that;

- *High scattered light makes field center hot, but illumination uniformity makes center cold*
- *For hole layers, with high chrome density, the impact of scattered light is negligible; illumination uniformity explains the changes in CD variation completely*

.

When lens element contamination builds up we see rise in scattered light and power illumination non-uniformity. For hole layers where reticle transparency is already very low (high chrome density) the impact of scattered light will be minimal so why do we see hole layers impacted. To find out answer we have tried to understand the impact of power illumination non-uniformity on patterning.

9.1 Power Illumination non-Uniformity Variation with Uniformity Variable Filter

9.1.1 Non-Uniformity Variation

One can achieve desired power illumination non-uniformity level by rotating Uniformity Variable Filter angle. This filter position can typically be changed by software interface and it changes the amount and profile of non-uniformity. Both amount and profile are very important and they react differently. Filter has a neutral position which separates the two uniformity profiles called as *concave (bowl shape)* and *convex (dome shape)*. While Uniformity Variable Filter angle changes from mid position to higher degrees profiles are convex and non-uniformity increases and sometime the degree of order also increases. On other hand when we reduce angle from mid position profile become more and more concave.

Every tool has a different neutral position for Uniformity Variable Filter and this depends on various things like contamination build on projection lens optics, top & bottom lens element contamination build up, illumination optics degradation, illumination optics position and pointing change. During a normal running of a tool the most critical parameter is the contamination build up and top & bottom lens elements of projection system are prone to get this easily as they are exposed to more sources of contamination to outside world. Lens element is closest to wafer and gets much more impacted due to resist out gassing. So Uniformity Variable Filter neutral position changes with time and it differs from tool to tool. Below figure explains a typical change of Uniformity Variable Filter rotation versus uniformity level change.

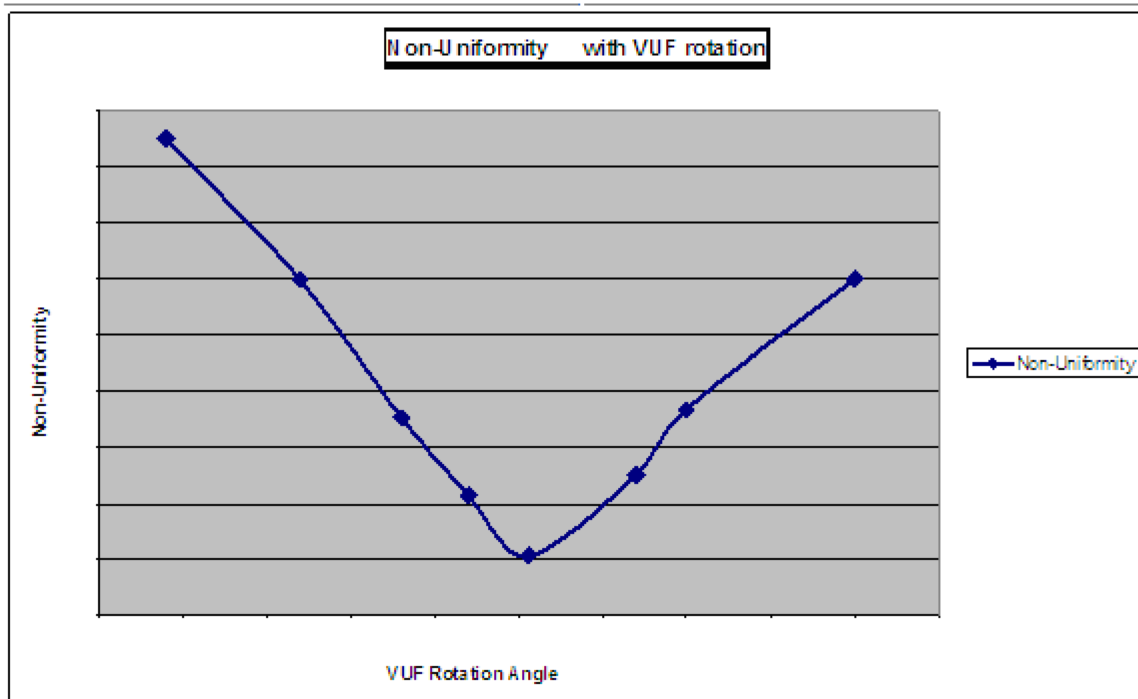


Fig 9.1: Uniformity Variable Filter rotation and power illumination non-uniformity

9.1.2 Non-Uniformity profile shift

As shown in below figure the filter position also changes uniformity profile which is a significant factor in determining actual CD impact. The same level of non-uniformity can be achieved by varying filter position in either direction from its neutral position i.e. a typical dome shape (convex) non-uniformity can be equivalent to a typical bowl shape (concave) non-uniformity level but the actual profile will be completely different. The profile represents the distribution of intensity across the slit in X-direction of lens.

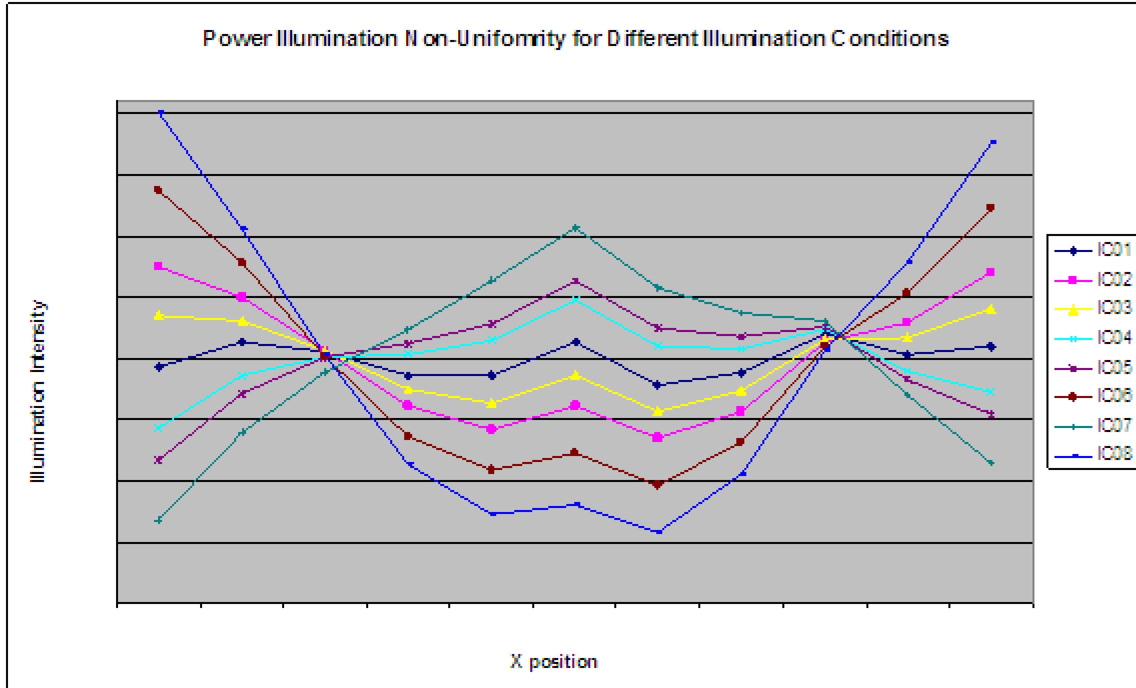


Fig 9.2: Uniformity Variable Filter rotation and power illumination non-uniformity

9.2 Impact of Power illumination non-uniformity on Patterning

The primary impact of Power illumination non-uniformity will be within field. As illumination non-uniformity profile changes the power profile follows which will cause a change in Critical Dimensions across the slot. The Metal lines will become smaller where power is high and vice versa. Similarly hole or space will become bigger where power is high and vice versa. There are several other contributing factors like the impact on different feature size and type. In a normal chip there are different types of features like Isolated and Dense lines and spaces, rectangular features, A Memory cell etc. The major ones are isolated and dense features which have been studied here.

$$\Delta \text{CD} = \text{CD}_{\text{Center}} - \text{CD}_{\text{Corner}}$$

9.2.1 Non-Uniformity and Center – to – Corner Bias Change

The illumination conditions IC02 and IC05 gives almost same uniformity levels but their profile is completely opposite to each other. IC02 gives low intensities at center and high intensities at both corners of lens while IC05 does opposite to IC02. This has a significant impact on CDs between two profiles and this will impact CD size at the center of the field. Like for example if we are printing a line layer then lines will be smaller with IC05 where there is high intensity at center.

When we compare center to corner bias change within the profile then it increases as we move from neutral position of Uniformity Variable Filter. One can see that IC02 and

IC05 have same uniformity level and the absolute magnitude of center to corner intensity is quite near to each other but both have opposite sign which indicates that IC02 intensity at center is much colder then IC05 and this will impact CDs.

9.3 Impact of Power Illumination on Patterning

Uniformity Variable Filter position was changed to set different illumination non-uniformity levels and then wafers were shot on each condition. Below is the analysis and summary of experiment for line patterning.

9.3.1 Center to Corner Difference for RESIST CD

Isolated and Nested space size increases with non-uniformity levels. This means for same uniformity profile, feature size changes between center and corner of the field. Center to Corner difference for RESIST CD decreases with a strong 2nd order polynomial fit. ISO line C-C difference increases with uniformity increase.

9.3.2 Center to Corner Difference for ETCHED CD

Isolated and Nested space size increases with non-uniformity levels. This means for same uniformity profile, feature size changes between center and corner of the field. Center to Corner difference for ETCHED CD decreases with a strong 2nd order polynomial fit. ISO line C-C difference increases with uniformity increase.

9.3.3 Impact on Etch Bias

Isolated space does not show much change in EB while Nested space decreases linearly with uniformity increase. ISO line shows very strong increase in EB with increase in uniformity levels. Lithographers can either control uniformity in strict manner or develop models to correct it for a product/layer conditions.

$$\textit{Etch Bias} = CD_{(Resist)} - CD_{(Etched)}$$

9.4 Failure Analysis Summary

There was a failure analysis cross-sectioning conducted on wafers with standard and high non-uniformity levels. 3-types of features were evaluated for cross-sectioning. Below is the summary of analysis.

9.4.1 Impact on Isolated Features

There was a clear impact of non-uniformity seen on isolated hole features. The holes were bigger with high non-uniformity. The hole opening was bigger with high non-uniformity.

9.4.2 Impact on Nested Hole Features

In comparison to isolated features, nested feature did not show much difference but this could be due to the images taken at Dual Beam Fib tool (Failure analysis machine). There was an impact on whole size and opening them both went bigger. This would alone cause a device performance issue at end of line. The experiment was conducted on layer where layer CDs are quite bigger in size. This indicates that impact of uniformity will be much higher on critical patterning layer, gate layer and first Front end interconnect layer. This could cause shortening of holes for small CDs where gap between two holes smaller.

Section IV

Conclusion & Future Work

Chapter 10

Conclusion

Scattered Light and Illumination Non-Uniformity has significant impact on semiconductor processing. Below are the conclusions from this research.

10.1 Silicon Substrates and their Impact on Scattered Light

Flare varies linearly with substrate reflectivity. To eliminate Wafer contribution one should simulate production conditions. For this reason Bottom Ant-Reflecting Coatings (BARCs) are preferred for Scattered Light tests

10.2 Effect of various Illumination Aperture shapes on Scattered Light

A scattered Light level depends on different Illumination Settings Type. These results suggest measurement of scattered light should be based on different illumination conditions.

- Strong co-relation seen between LNA/iNA size and Scattered Light level of a tool. They work opposite to each other. Scattered Light level increases when LNA or iNA size decreases or vice versa.

- We conclude that Annular Settings may show lower Scattered Light than conventional Settings for same process conditions. This difference increases with Scattered Light level of tool i.e. at low Scattered Light level the effect of changing illumination settings may cause negligible change in scattered light.

10.3 Characterization of the Impact of Scattered Light on Semiconductor Processing

- Scattered light has a significant impact on patterning.
    - As scattered light increases the cross-field CD variation increases, this is due to the fact that scattered light makes field center hot and corners cold for energy.
    - Scattered Light increases Line Edge Roughness (LER). Overall CDs measurements may not be affected but it could lead to other problems.
    - Lines become trapezoidal in shape and corner rounding effect can be observed. Line height decreases with increased in Scattered Light.

  - The hole CD can get larger with increasing Scattered Light. Scattered Light can effect side wall gradient when patterning holes.
  - Scattered Light Degrades the Aerial Image contrast which decrease the process window.
  - Bleed over from adjacent fields can compensate for min flare in the corners as it adds light from neighboring field
  - Scattered light can cause Etch Bias issue. The critical layers are more prone to get etch bias issue then non critical layers due to their smaller depth of focus tolerance.

- In summary the for hole layers there is almost no impact due to scattered light on patterning so if one has a high scattered light on a tool then he can keep running hole layers as long as the illumination non-uniformity is under control. In most cases it is easy to correct illumination non-uniformity by uniformity filters and other optics adjustments in the illumination path.

- Even a new tool will have max Scattered Light in the center, due to intrinsic reflections in the PL, widening the PSFs. As the tools age, Center (maximum) Scattered Light increasing fastest, as most energy goes through here, leading to more contamination. Corner (minimum) Scattered Light increasing slowly, as less scattered light gets there, leading to less contamination

- Impact of Power Illumination non-Uniformity on Scattered Light is minimal as scattered light is modulated more through lens degradation or contamination build up due to change in reflections.

- Scattered Light can be compensated by Illumination non-uniformity change to get uniform CDs. It can be done only up to a certain limit. The illumination uniformity control is important to maintain the image quality, while the Scattered Light degrades it. One can characterize this for their process/layer/tool.

10.4 Characterization of the Impact of Power Illumination Non-Uniformity on Semiconductor Processing

- High scattered light makes field center hot, but illumination uniformity makes center cold. For hole layers, with high chrome density, the impact of scattered light is negligible; illumination uniformity is the primary modulator for CD variation when patterning hole.

- One can achieve desired power illumination non-uniformity level by rotating Uniformity Variable Filter angle.

- Every tool has a different neutral position for Uniformity Variable Filter and this depends on various things like contamination build on projection lens optics, first and & last lens element contamination build up, illumination optics degradation, illumination optics position and pointing change.

- The primary impact of Power illumination non-uniformity will be within field. Center to corner bias changes within the profile then it increases as we move from neutral position of Uniformity Variable Filter.

- The Non-Uniformity profile represents the distribution of light intensity across the slit in X-direction of lens. Same level of non-uniformity can be achieved by varying filter position in either direction from its neutral position i.e. a typical dome shape (convex) non-uniformity can be equivalent to a typical bowl shape (concave) non-uniformity level but the actual profile will be completely different.

In summary the impact of Scattered light and Power illumination Non-uniformity is quite large on processing and lithographers will have to monitor it very closely to control it. This research provides a detailed characterization of the impact on processing and clearly explains that there are various other sources of variation which lithographers need to understand and characterize and only then define the real control limits for Scattered Light and Power Illumination Non-Uniformity for their process.

Chapter 11

Future Work

It is very difficult to characterize the impact of Scattered Light and Power Illumination Non-uniformity for all production conditions but our research showed that Scattered light impact is much more on high chrome density layers so further exploration can be done to understand and characterize different High Chrome density layers.

Due to lack of time resource and money we could not explore mask to open ratio impact which we think is a large contributor and further studies can be done to model this.

There is a real need for measuring scattered light inline so that illumination system can be adjusted to compensate for it. Research can be done to explore this area which will provide real time adjustments of scattered light.

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