MICROLITHOGRAPHY 2004

From
Computer Aided Design (CAD)
to
Patterned Substrate

At the CNF, a number of different options exist for producing a patterned substrate, but deciding which option is best for your application requires considerable *planning* on your part. Choosing the most appropriate lithography tool and technique depends on what you will do one or more steps after you actually perform the exposure. The purpose of this course is to provide you with the information necessary for you to prepare the best plan for achieving the desired results. This portion of the course will be divided into:

Introduction to Nanofabrication

(The technology formerly known as Microfabrication)

A Brief History

Transistors

The first transistor was demonstrated in 1947 at Bell Labs by researchers Bardeen, Brattain, and Shockley. This device was fabricated in Germanium and was rather large by today's standards:

The First Transistor
Courtesy Lucent Technologies

Transistors were manufactured as discrete devices beginning in the 1950's, and continue to be produced and used in that form today. The invention of the transistor revolutionized electronics, enabling smaller, lighter, cooler, and cheaper products to be produced. It was the beginning of the end for vacuum tubes and the birth of personal electronics.

Integrated Circuits

The first integrated circuit was demonstrated in 1959 at Texas Instruments by Jack Kilby.
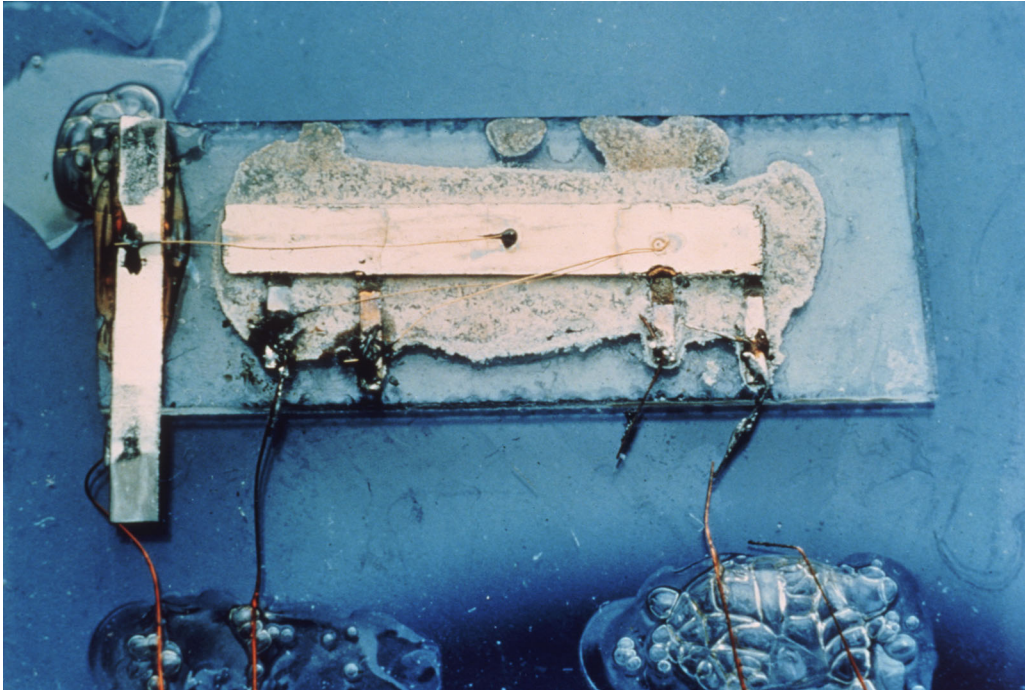
The First Integrated Circuit
Courtesy Texas Instruments

At almost the same time at Fairchild Camera, Robert Noyce was demonstrating a similar device. Noyce's most important contributions to the future of IC fabrication were the use of planar technology, where all structures of the device are flat and in the plane of the substrate, and the use of silicon dioxide as an insulating material on a silicon substrate.

These inventions led to the development of almost all of the electronic products we are familiar with today. Manufacturing of integrated circuits began in the 1960's and continues today.

Automation

The cost-effective manufacturing of modern IC's began in the 1980's with the advent of automated control of processing equipment.

Wafer Manufacturing Facility
Courtesy IBM

Previously, semiconductors were made on a scale reminiscent of laboratory experiments. Large-scale manufacturing was only possible with reproducible computerized automation. As more and more aspects of the fabrication process were controlled, higher yields and efficiencies were achieved; thus cheaper and smaller devices were made possible. This continuous improvement of wafer processing through the statistical controls available with automated systems helps drive the race to higher processing speeds witnessed today.
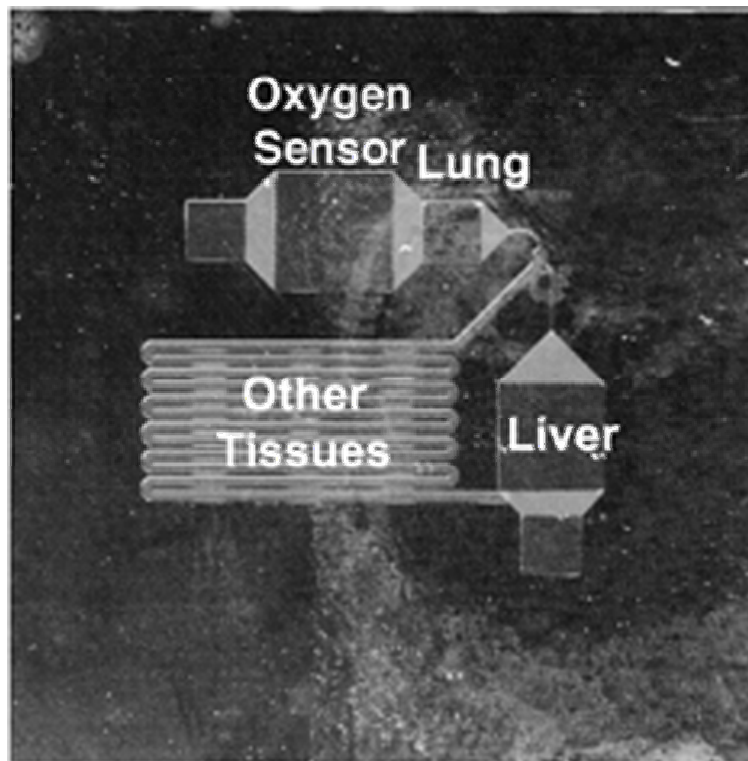
Applications

The international marketplace has driven the demand for faster, smaller, and cheaper devices in several areas. The most visible product is the Personal Computer. While this remains a large customer of IC's, the real growth areas are many: cell phones, PDA's, wireless networks, personal entertainment, and home entertainment to name a few. Even household appliances and automobiles are utilizing more and more electronic devices as size and cost are reduced, and reliability improves.

The Future

What does this mean to Me?

The technology used to produce these devices was developed almost entirely within and for the electronics industry. Only recently have groups outside the realm of electronics considered applying these methods to constructing other devices. One of the most notable has been the biologists, who now are making great strides by applying Nanotechnology to Biology; thus, Nanobiotechnology, which is a booming area of research today.

Courtesy Cornell Nanobiotechnology Center

Other researchers and industries are discovering new applications each year, and the National Science Foundation sees this as a trend worth cultivating. The CNF is now a part of the National Nanotechnology Infrastructure Network (NNIN), which is an integrated partnership of thirteen user facilities, supported by NSF, providing unparalleled opportunities for nanoscience and nanotechnology research.

NNIN Locations

Our purpose is to provide support to researchers using the technologies we make available with state-of-the-art tools and experienced advice. We can teach you to use these tools and apply them to your project, and help to find others who may assist with technology outside of our scope. Our assistance can be as deeply involved or peripheral as you want, and intellectual property is owned by the developer.

What follows is an introduction to working at CNF, and to some of the technologies available here. Much of the discussions are general, with some of it more specific to the tool set currently in the clean room. More information is available from the persons working in a particular area of the facility.

Lithography at CNF
(What is lithography and why do we do it?)

Manufacture of devices depends on selective processes:

Removal of material -- **Etching**

Addition of material -- **Deposition**

Modification of material -- **Implantation, diffusion, etc.**

Defined areas of the substrate must be *protected from* or *exposed to* these processes. These areas make up the pattern.

Pattern definition takes place in the **resist** -- a thin layer of polymeric material that is coated on the substrate.

The resist is modified so that it *remains* in some areas and is *removed* in others. This is a two-step process:

Exposure -- Incident radiation, particles

**Development** -- Selective removal in solvent or base

TYPES OF EXPOSURE

Light -- 436 nm - 157 nm; near UV to Deep UV optical lithography

X-rays -- 5 nm - 0.4 nm; x-ray lithography

Electrons -- 10 keV - 100 keV; electron beam lithography

**Ions** -- 50 keV - 200 keV; focused ion beams

METHODS OF EXPOSURE

Direct Write -- Electrons or ions are focused into a small diameter spot which is scanned *directly* onto the resist; this is a *serial* exposure process.

Masked Exposure -- Light or x-rays are imaged onto the resist through a *mask*; this is a *parallel* exposure process.
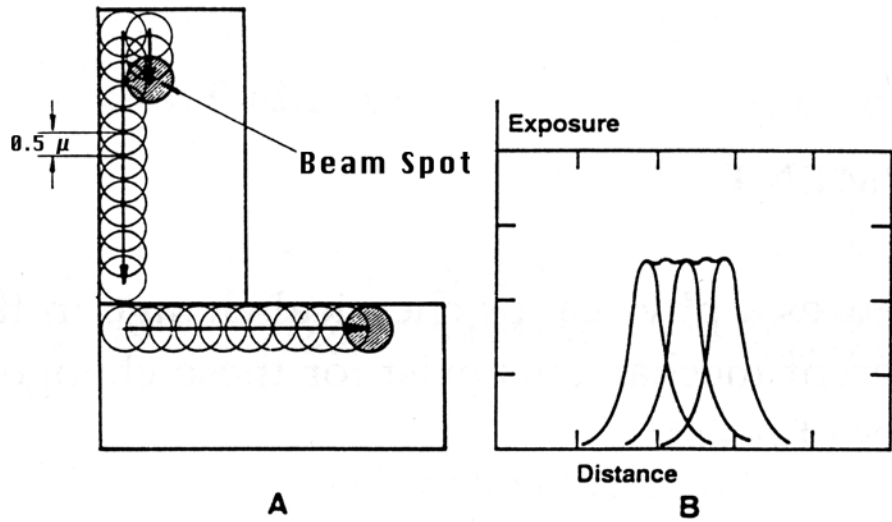
W. Moreau, **Semiconductor Lithography**, Plenum, New York, 1988, p. 423.
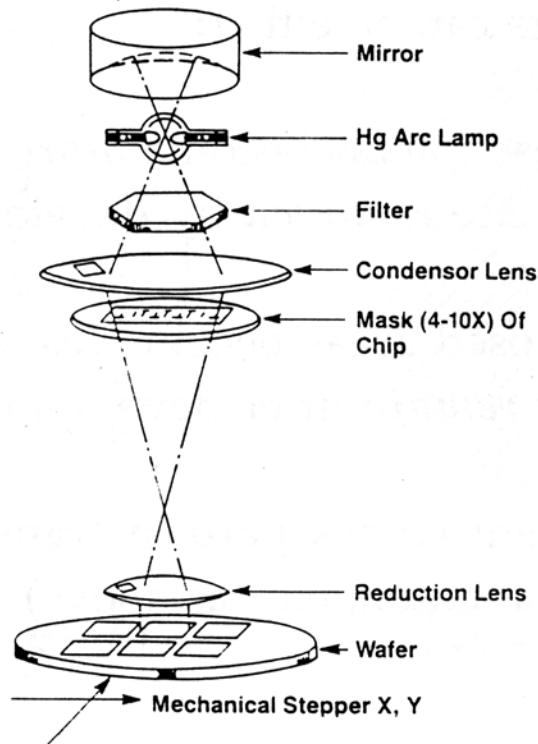
W. Moreau, **Semiconductor Lithography**, Plenum, New York, 1988, p. 363.

DEVELOPMENT

Exposure causes a physical or chemical change in the resist. Different mechanisms exist for these changes for various types of resist.

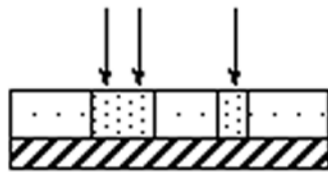Development takes place in a base or solvent, depending on resist type.

In general, resists can be either:

Positive -- exposed areas become *more* soluble in the developer; they are *removed* by development
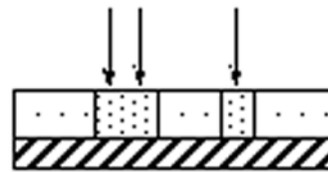
Negative -- exposed areas become *less* soluble in the developer; they *remain* after development

After development comes **pattern transfer** (etching, deposition, implantation, etc., as above).

Lithography at CNF
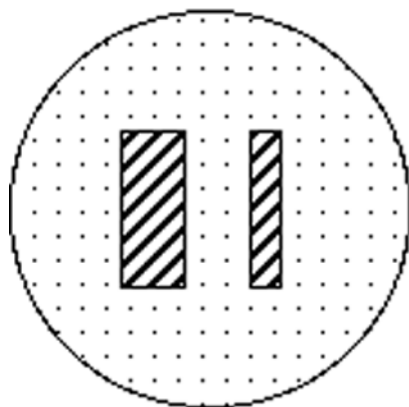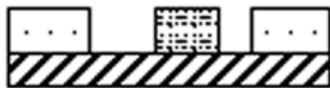
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                          ┌──────────┐
                          │   CAD    │
                          └────┬─────┘
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          ┌──────────┐         │         ┌──────────┐
          │  Direct  ├─────────┴─────────┤   Mask   │
          │  Write   │                   │  Making  │
          └────┬─────┘                   └────┬─────┘
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              │10X     │  5X    │  │  5X    │  │     │ 620 │ MA6  │
              │i-line  │ g-line │  │  i-    │  │     │     │      │
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                6" Steppers         8" Steppers     Contact aligners
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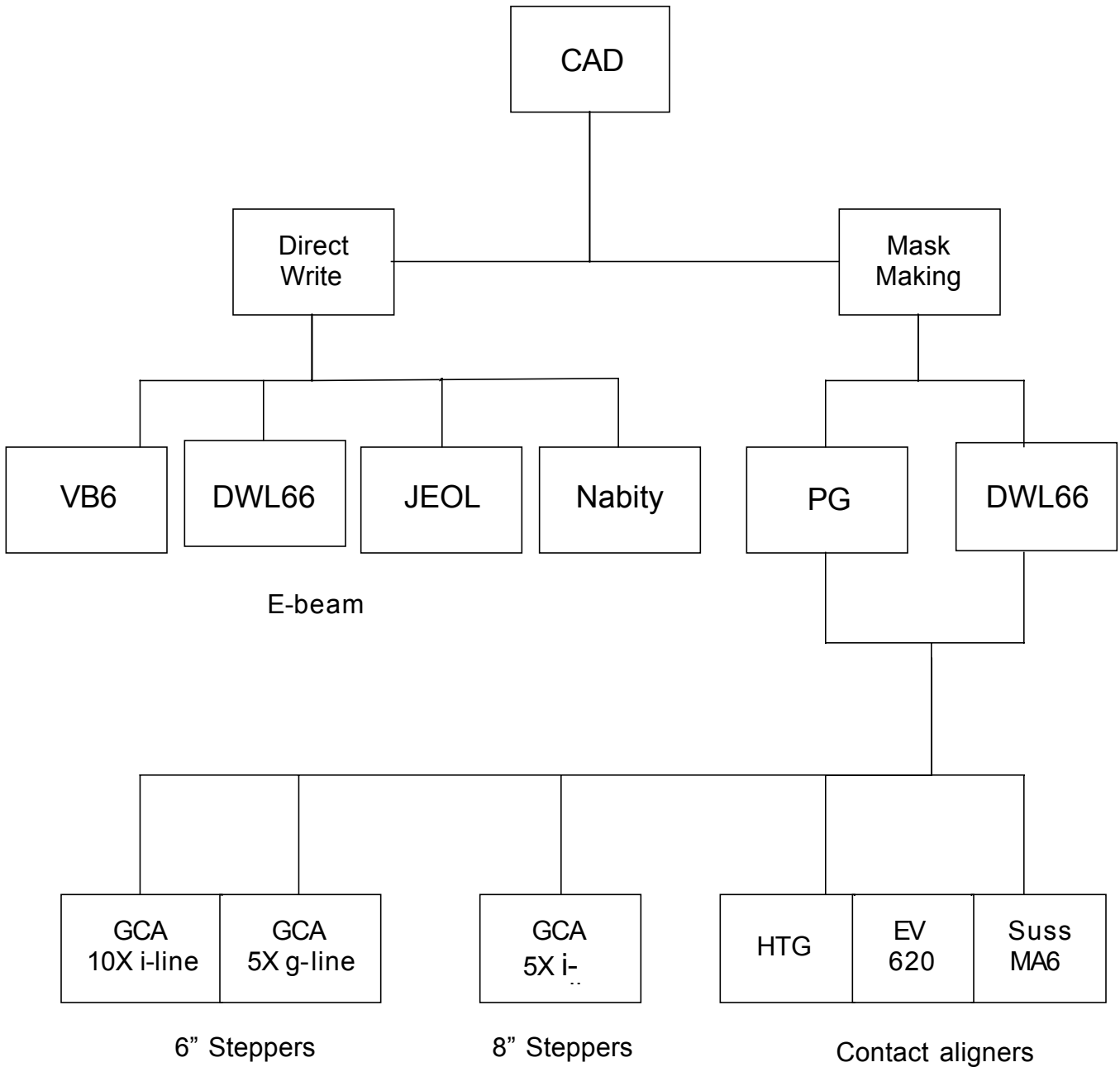
SOME SUGGESTIONS

The most difficult thing about lithography is that you have to *know* what you want to accomplish *before* you do the lithography. In particular, you have to think about:

Your pattern requirements

The requirements of the lithography tool

The requirements of the technique you will use for the pattern transfer

As we go along, we will fill in the details of these requirements.

HERE ARE SOME SUGGESTIONS FOR GETTING STARTED:

1. **Think** about what type of design you want and how to implement it.

2. **Gather information** from this book, staff members and other students about the best tools and techniques to use before you actually sit down and design the pattern.

3. **Design the pattern** using the information you have gathered paying careful attention to the requirements listed above.

4. **Perform** lithography, pattern transfer, etc.

5. **Repeat steps 1 - 4** as many times as necessary to get it right.

HOW CNF WORKS:
(A Staff Member's Perspective)

Your (usually) friendly local CNF staff member is balancing the requirements of local users, outside users, machine maintenance, process characterization, materials supply, and lots of other things. So a few hints are in order:

The more thinking and preparation you do, the more intelligent the questions you ask, and the more time you end up saving the staff member.

The more advance notice you can give about when you would like to talk about your process or be trained on equipment, the better.

The more responsible you can be around the lab, the less we have to clean up after you, and the more time we have for answering your questions.

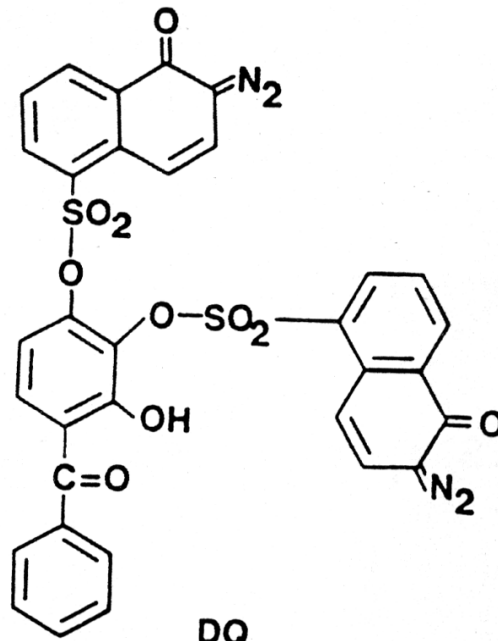**And, last but not least, please be patient!**

OPTICAL LITHOGRAPHY TECHNIQUES

OPTICAL RESISTS

The resist system used almost universally for optical microlithography today is the so-called DNQ system: novolak resin with a diazonaphthoquinone sensitizer. The basic form for the resin and sensitizer are shown below:
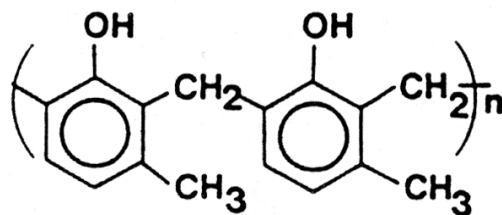

Novolak Resin

DQ

Moreau, p. 32.

The novolak resin is rendered base-insoluble by the addition of the sensitizer, or photoactive compound (PAC). It remains insoluble until photo-exposure transforms the PAC into a base-soluble product. Thus the PAC acts as a dissolution inhibitor until exposure transforms it. The photochemical reaction in the sensitizer is shown below:
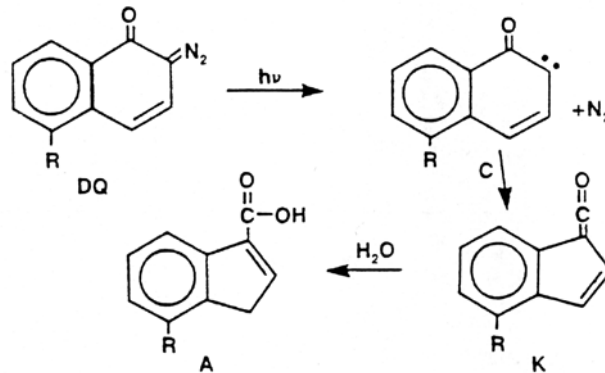
Moreau, p. 35

The reaction product is **indene carboxylic acid**, which will be referred to again later when we discuss image reversal.

The exact composition of resists differs from type to type, and the spectral sensitivity of every resist is different. Normally such data appear in a curve like this:
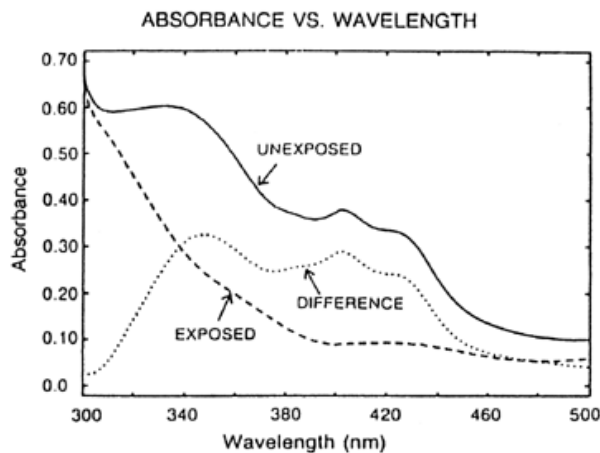

Shipley Product Information

The curve for unexposed resist gives the absorption of the resin plus PAC. This must be high for efficient absorption of the exposing photons. The curve for exposed resist gives the absorption of the resin itself. This should be low, so that once the film is exposed, it is transparent all the way to the substrate. Therefore, the difference between the two curves is an indication of the contrast of the resist.

Every resist is designed to have high contrast over a particular wavelength region. If the resist is exposed with light of an inappropriate wavelength, the higher absorption will result in a sloped sidewall profile, as follows:
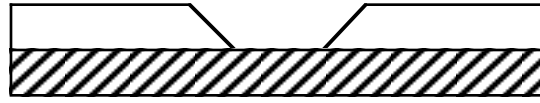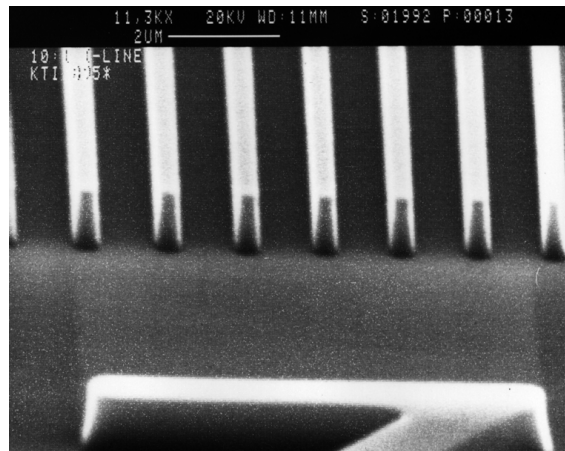

Sloped Resist Profile

Even with an appropriate resist, there will always be some sidewall slope. The following pictures show the effect of using Shipley 1400 resist (designed for g-line) and OCG 895i resist (designed for i-line) with our 10:1 i-line stepper.
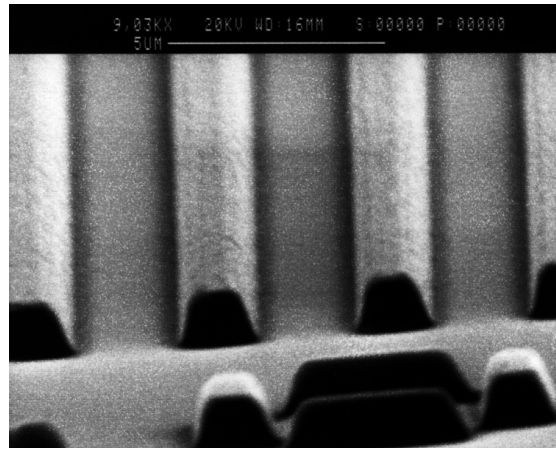
2.0 μm lines and spaces in 1.0 μm Shipley 1400 resist,
exposed with the 10:1 i-line stepper

0.7 μm lines and spaces in 1.0 μm thick OCG 895i resist,
exposed with the 10:1 i-line stepper

RESIST PROCESSING

Cleaning
Cleaning a wafer before coating it may involve removal of the native oxide, or simply cleaning with solvents. A brand new wafer may only require an *isopropyl* or *methanol* rinse. If there is grease on the wafer, *methylene chloride* may be required to remove it. If the wafer has been coated with resist before, this should be stripped before recoating (see stripping, later).
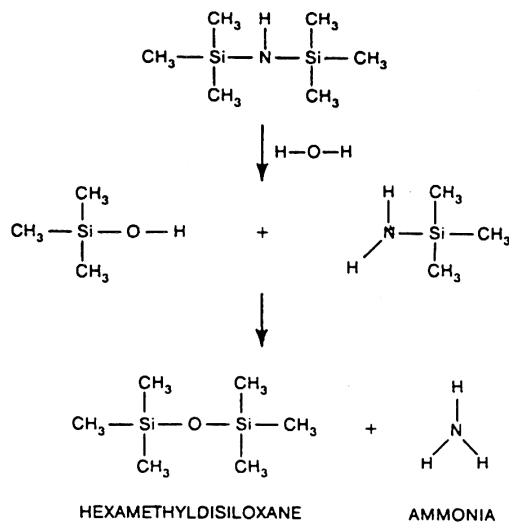
Priming
Unfortunately, the surfaces of many of the materials we want to put resist on oxidize very easily. The surface oxide forms long range hydrogen bonds with water adsorbed from the air. When the resist is spun onto such a surface, it adheres to the water vapor rather than to the surface, and poor adhesion results. Adhesion to a hydrated surface is shown schematically below.
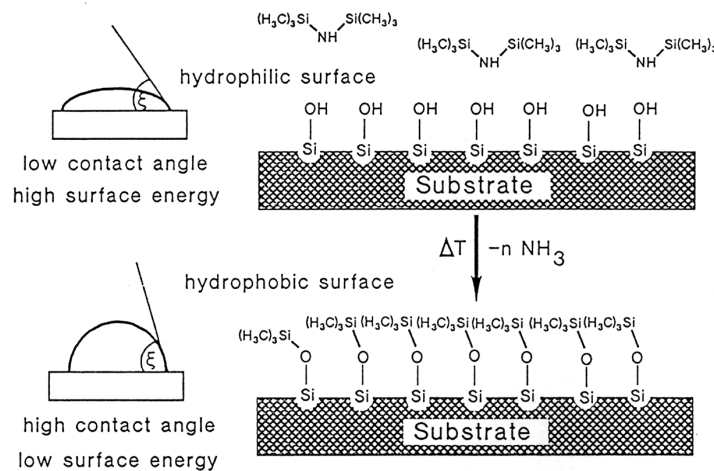
Shipley Tutorial Graphics

SURFACE HYDRATION
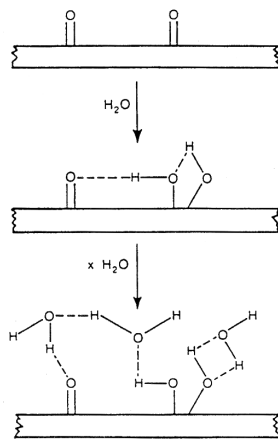
The figure below shows the chemistry of HMDS (hexamethyldisilazane), a primer which acts as an adhesion promoter for photoresist.

HEXAMETHYLDISILOXANE   AMMONIA

The diagram below shows adhesion of resist to a surface silylated with HMDS.


R. Dammel, **Diazonaphthoquinone-based Resists**, SPIE Press, 1993, p. 100.

HMDS may be applied in two ways. **Liquid priming** is the process of spinning HMDS, diluted in solvent, onto a *dehydrated* wafer. We use 20% HMDS in PGMEA, a common resist solvent. This is often effective, but is not as good as **vapor priming**. At CNF we have a **YES Dual-Function Vacuum Oven** in which the samples can be primed. During a 35-minute, pre-programmed cycle, the oven pumps down to dehydrate the samples, and then fills with pure HMDS vapor, resulting in a much more efficient prime than is possible otherwise.

Spinning

Spinning is used to get resist onto the substrate with the required uniform thickness. The physics of spinning is complicated, and depends strongly on the evaporation rate of the solvent used. This is why there are only a few solvent systems in use for resist. The process is simply to spin for a fixed time, usually 30 seconds, at a speed chosen to result in the desired thickness. Spin speed charts allow you to determine what speed to use:
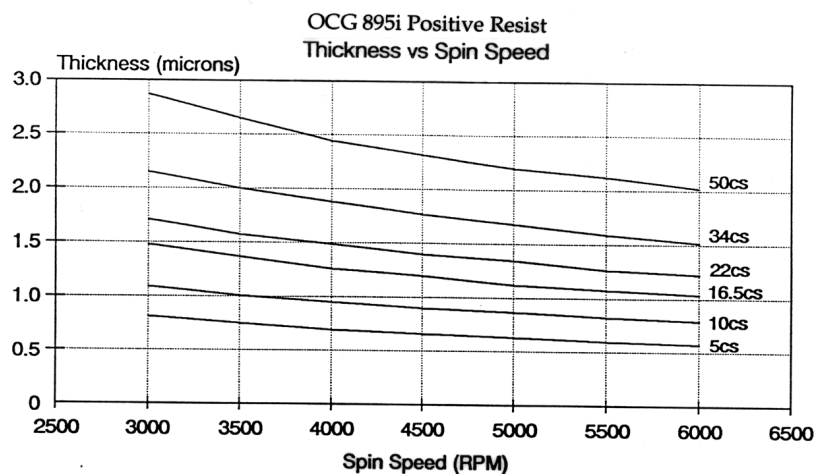

OCG Process Application Note

BAKING

A pre-exposure bake, or *soft bake*, is used to drive the solvent from the resist. This is a critical step in that failure to sufficiently remove the solvent will affect the resist profile, as will excessive baking, which destroys photoactive compound and reduces sensitivity. A typical bake is 1 minute on a 90°C vacuum hot plate or 30 minutes in a 90°C convection oven. Thick resists may benefit from a longer bake time. Consistency is important once you have characterized your exposure for a particular bake.

A post-exposure bake, or *PEB*, is used to reduce standing waves in regular positive resist exposed on the steppers, or to thermally activate chemical processes such as image reversal. It will also affect the resist profile. (See the figure below.) A typical PEB used for OCG 895i is 115°C on the hotplate for one minute.

Calculated   No PEB   PEB, 115°C, 45 sec.
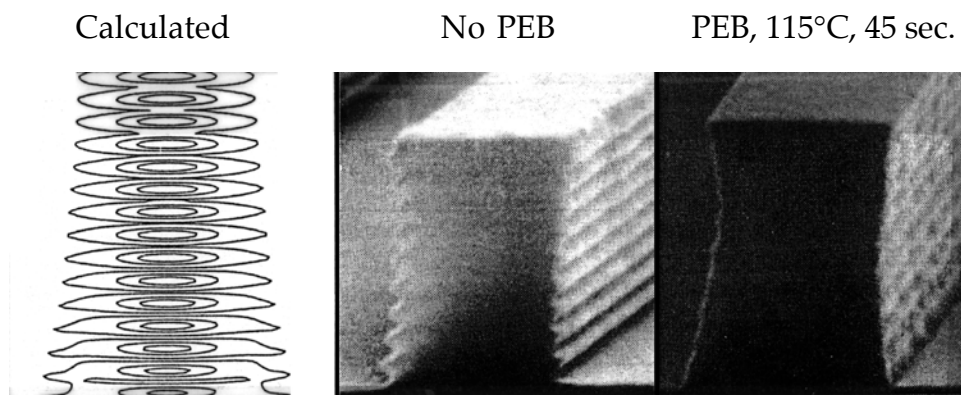
Dammel, p. 110.

A post-develop bake, or *post-bake*, is sometimes used to improve a resist's wet and dry etch resistance by hardening it. It may make the resist more difficult to remove, or easier for aggressive etches. In nearly all cases, temperatures above ~ 130°C will cause the resist to flow, so a DUV curing exposure is performed first to retain the profile.
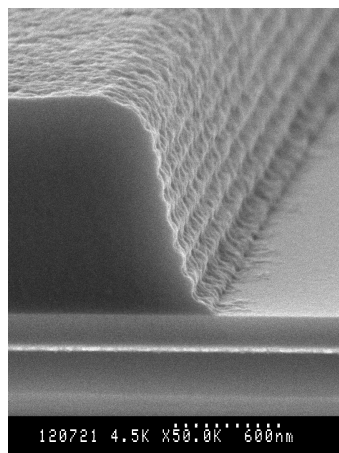
Shipley 1813 no postbake   Shipley 1813 115°C 60 sec. Postbake
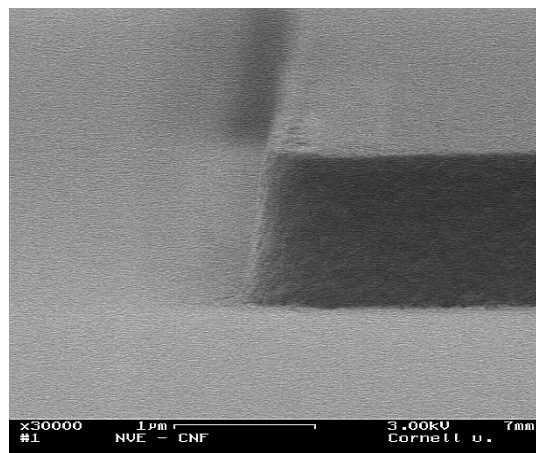
DEVELOPMENT

Development of optical resists takes place in an alkaline solution. Simple solutions of NaOH (Shipley 351), or KOH (Shipley 606) could be used, but because of the possibility of mobile ion contamination in MOS devices, metal ion free developers are often used. These are usually TMAH, tetra-methyl ammonium hydroxide (Shipley CD-26, MF-321, OCG 945). Some developers also contain surfactants to improve wetting properties.

Each developer used has a different dilution, and some require longer development times than others. Developers are generally matched to a type of photoresist. Though they may be interchangeable to some extent, changing the type of developer used in a process will usually change the exposure time necessary to resolve the pattern.

Important Note: All of these developers etch aluminum. In fact, some people prefer to do their aluminum etching in 606, since the etch rate is very high. If you are developing a pattern on aluminum, you may want to consider using Shipley Microposit Developer Concentrate (MDC). This is a mixture of proprietary alkaline salts (mostly phosphates), and it has the slowest aluminum etch rate.

STRIPPING

After pattern transfer it is necessary to remove or **strip** the resist. There are several ways to accomplish this. The simplest is to dissolve the resist away in **acetone** or **Shipley 1165 Remover,** which is often more effective than acetone. Resists can also be removed by **plasma stripping**, which may be done in the **Branson Barrel Asher** or in one of the reactive ion etchers. Sometimes a combination of soaking in remover and plasma stripping is required to remove stubborn resist (in fact, it is usually recommended to follow a wet strip with a brief plasma strip to remove resist residues). If this does not work, you can resort to **Nanostrip**, an acid etch designed for removal of organics. However, Nanostrip will also etch many metals.

IMAGE REVERSAL

The resists used in microlithography today are virtually all positive tone. (Some new negative resists have recently become available, but we do not yet have enough experience to discuss them.) In order to obtain negative tone from our positive resist, we must resort to image reversal. Since we can make masks in either tone at CNF, there is usually no reason to use image reversal simply to give a negative tone. Instead, we use it specifically to generate an undercut profile for *lift-off*.

LIFT-OFF

Suppose you wished to form a metallized pattern on a wafer. If the metal you wanted to use could be etched, you could evaporate or sputter the metal film onto the wafer first, and then pattern the resist.

Process flow for patterning of resist after metal deposition:

Exposure

Mask

Resist
Metal
Substrate

Development

Etching

Result
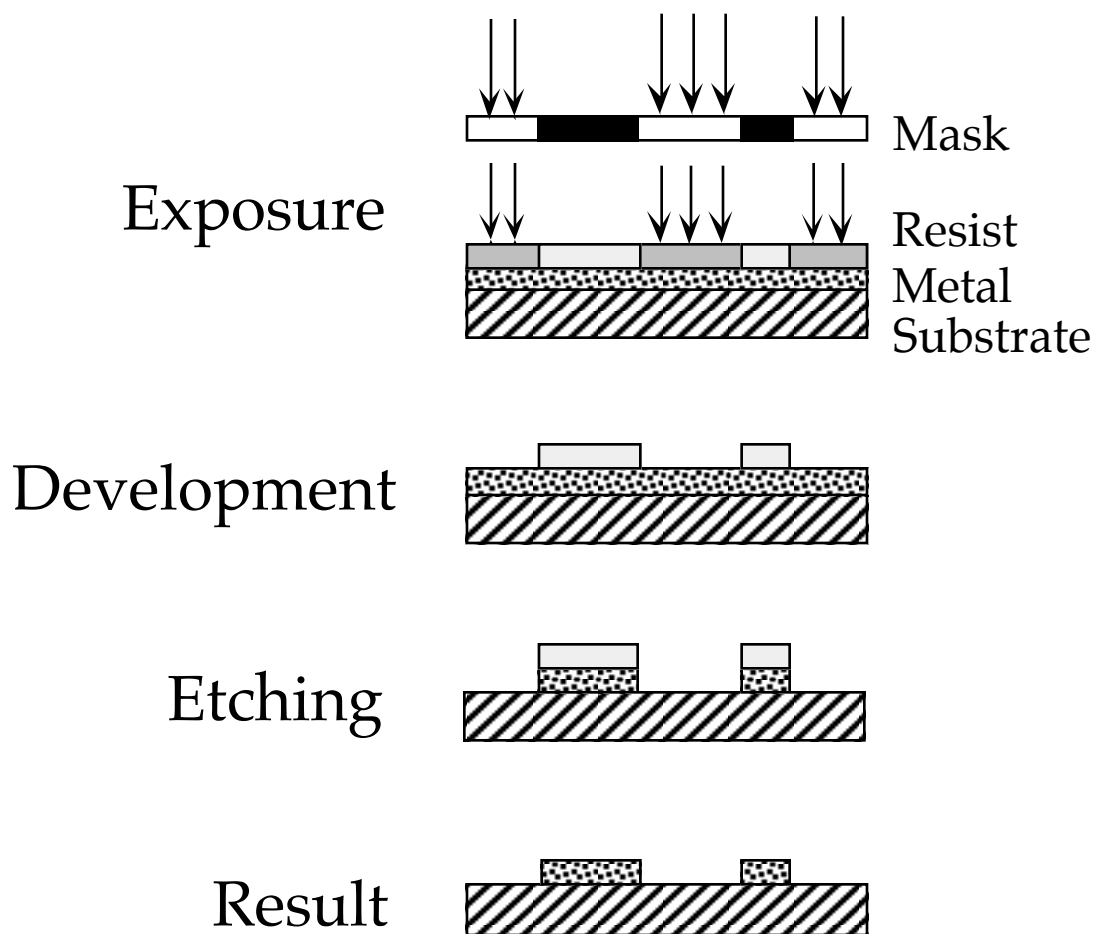
But suppose the metal can't be etched, or only wet etched, which isn't very precise for small features. The preferred technique is *lift-off*. In lift-off, the resist is patterned first, then the metal is evaporated over the resist. The resist is then dissolved away in a solvent, carrying the unwanted metal with it. However, the normal positive resist profile presents a problem. Once again there is the issue of sidewall slope:

After evaporation, the metal would form a continuous film:
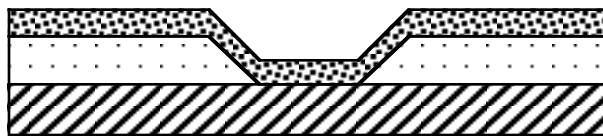
If the resist were removed, the edges of the metal film would tear, or the whole pattern could be torn away.

The solution lies in the use of **image reversal** to create an **undercut profile.** The process flow is as follows:

Process flow for metal lift-off using image reversal:

Exposure

Mask

Resist
Substrate

Reversal

Development

Evaporation

Lift-Off
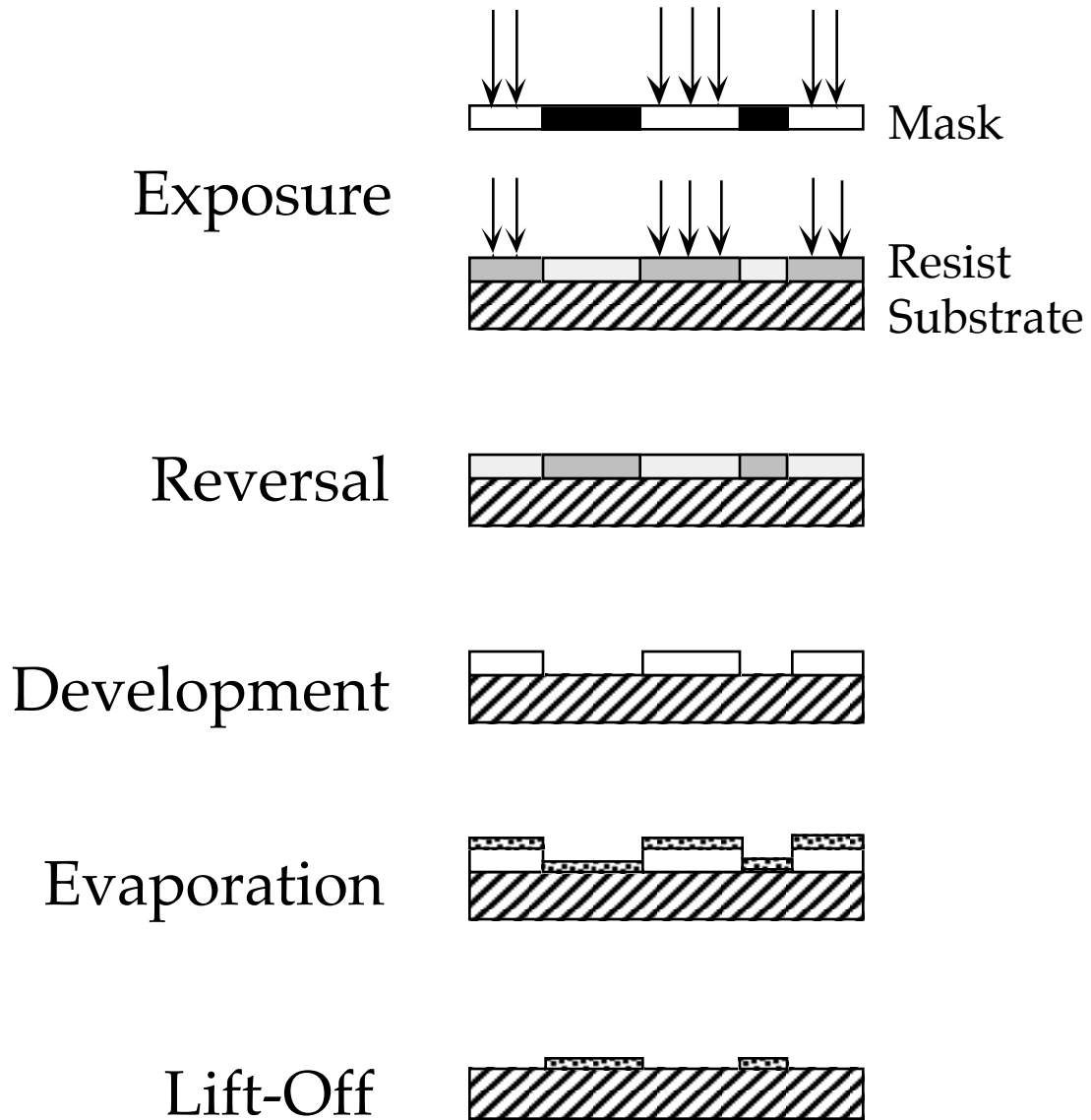
A detailed look at the reversal step reveals why the technique is successful. Instead of exposing the feature where you want the metal, you expose around the feature. This means you use a negative rather than a positive mask.
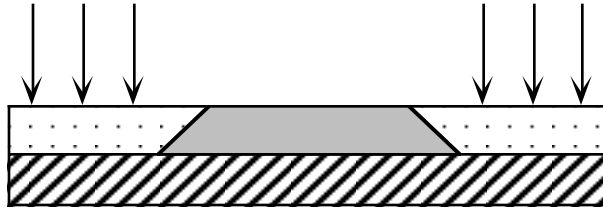
After reversal, the sidewall slope that worked against you in positive tone now forms the undercut profile, which is favorable for lift-off. When the metal is evaporated, the film is discontinuous over the desired features. Now the resist can be removed cleanly, leaving a well-defined metallization pattern behind.
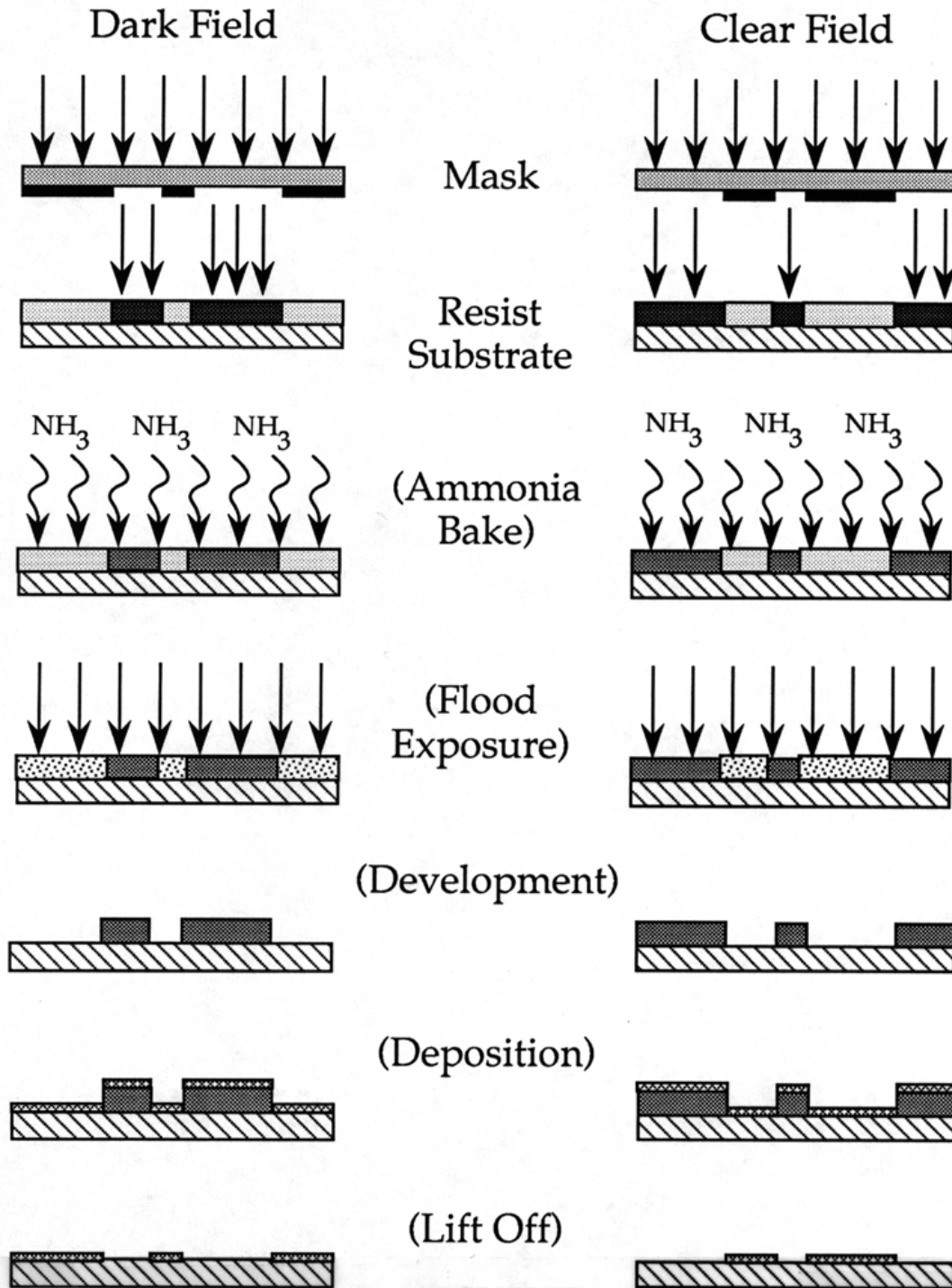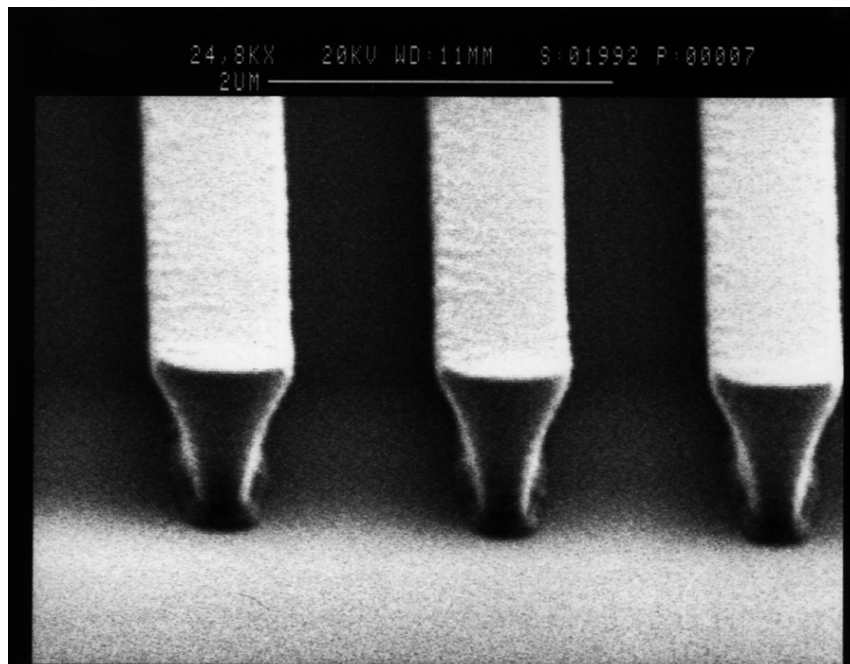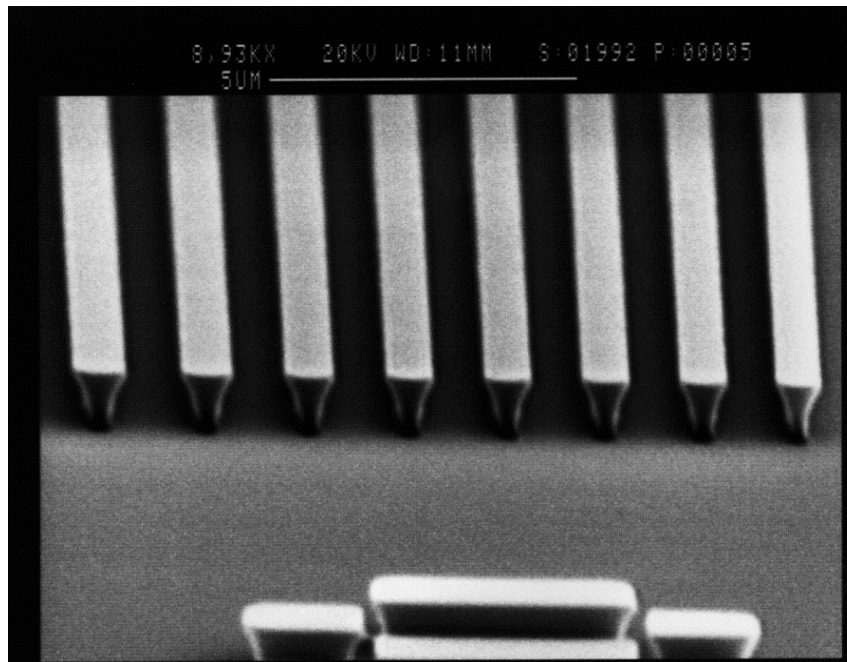
A good rule of thumb is to use a resist layer at least <u>three times</u> the thickness of the metal desired.

Image reversal may be accomplished in two ways at CNF. One way involves the use of the **YES Dual-Function Vacuum Oven**, while the other uses a special photoresist of the AZ 5200 series. The YES Oven method takes longer, but produces superior and more consistent results. The AZ resist is faster and suitable for large feature sizes.

In the YES process, the wafers are placed in the oven after exposure, where an ammonia diffusion bake takes place. The ammonia diffuses into the resist, where it binds to the indene carboxylic acid that has been generated in the exposed areas. The **exposed** areas are now rendered **insoluble**, while the **unexposed** areas are **not affected** by the ammonia. Following the bake, a flood exposure is performed to expose the previously unexposed areas. This is shown schematically on the next page. Photos of image reversed resist are shown on the page after.

IMAGE REVERSAL USING AMMONIA BAKE

Dark Field | | Clear Field

Mask

Resist
Substrate

NH₃   NH₃   NH₃   (Ammonia
Bake)

(Flood
Exposure)

(Development)

(Deposition)

(Lift Off)

Undercut profiles generated in OCG 895i resist using the YES Oven Ammonia Diffusion Process.

In the AZ 5200 process, a post-exposure bake is performed in place of the YES Oven bake. The PEB activates an amine that is already present in the resist. This amine bonds to the photogenerated acid, just as the ammonia does in the YES Oven. A flood exposure and development follows.

Image reversal, using AZ 5200 resist or the YES Oven, is one of the most commonly used processes in the lab. Though complicated, it has been proven effective. It is a very good example of the necessity of *planning* your process before you start the design.

OPTICAL LITHOGRAPHY
EXPOSURE TOOLS

HISTORICAL
PERSPECTIVE

"Optical lithography has been used for over 30 years as the preferred method of image formation in the manufacture of silicon devices and other semiconductor components. Its demise as the premier imaging technology was predicted at about 1 μm feature size by proponents of alternative imaging technologies and others who underestimated the ability of optical tool manufacturers to improve optical and mechanical system performance to the degree necessary to support the production of increasingly complex devices with ever smaller features.

"Nevertheless, optical lithography continues to be the dominant imaging technology used in manufacturing semiconductor components. It is used today for high volume production of products demanding features of less than 1 μm. There is a clear expectation in the industry that it will support several more generations of silicon technology . . . ."

DRAMs are often used to chart the capabilities of optical lithography. The chart below shows the trend in minimum feature size versus time:
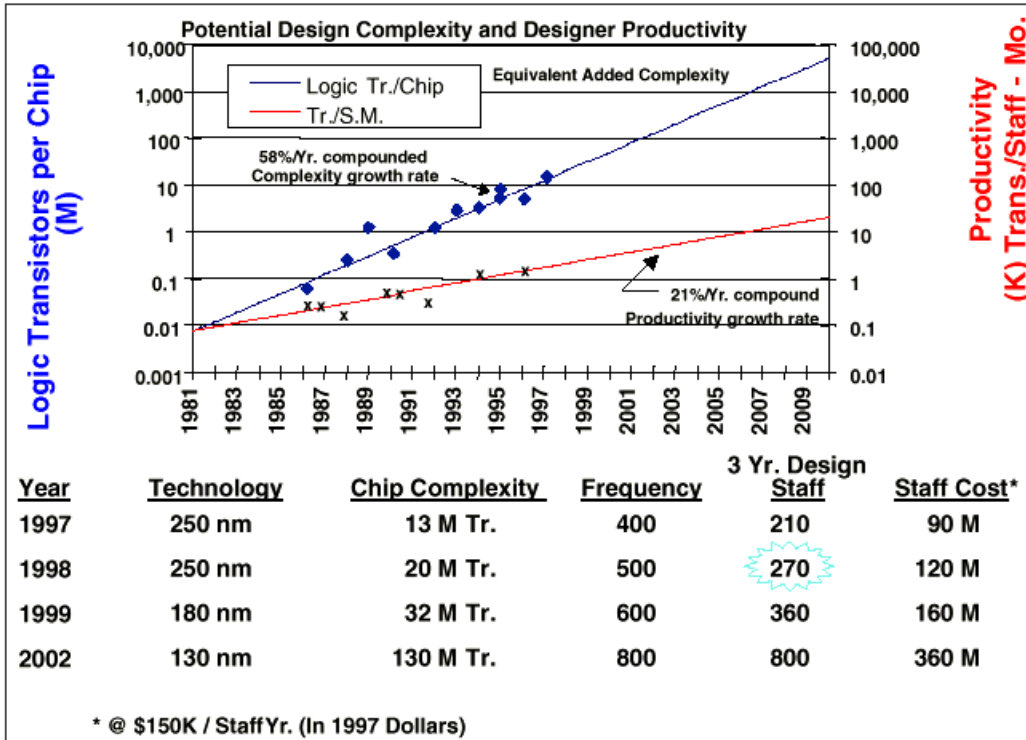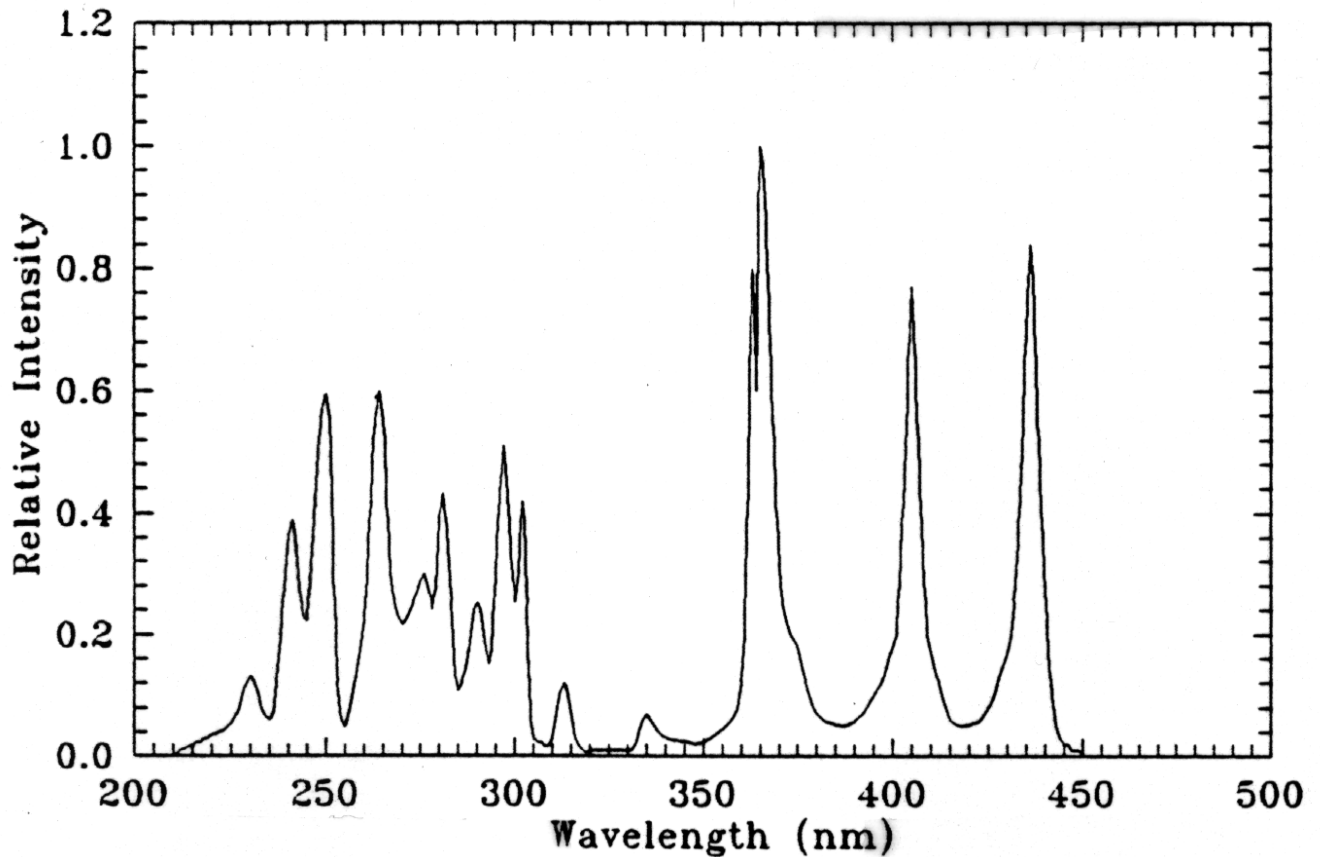
Figure 5   The Design Productivity Gap

SIA Roadmap

LIGHT SOURCE

Nearly all optical exposure tools use high pressure Hg arc lamps. This is because the spectrum of the light output has peaks in the UV. The dominant emission lines are at wavelengths of 365 nm (i-line), 405 nm (h-line), and 436 nm (g-line).

C. A. Mack, **Theory and Techniques in Optical Lithography**,
pre-published short course notes, 1990, p. 1-5

Since resolution scales directly with wavelength, efforts have been made to find higher intensity sources in the mid- and deep-UV. The HTG Contact Aligner (see below) uses a Hg-Xe arc lamp to provide greater output in this wavelength range, though the intensity is still relatively low.

Just to give you an idea of what these lamps look like, here is a picture of one. Keep in mind that these are expensive and delicate: the lamps used in the stepper and PG run at 30 atmospheres internal pressure and have a surface temperature of 700°C.
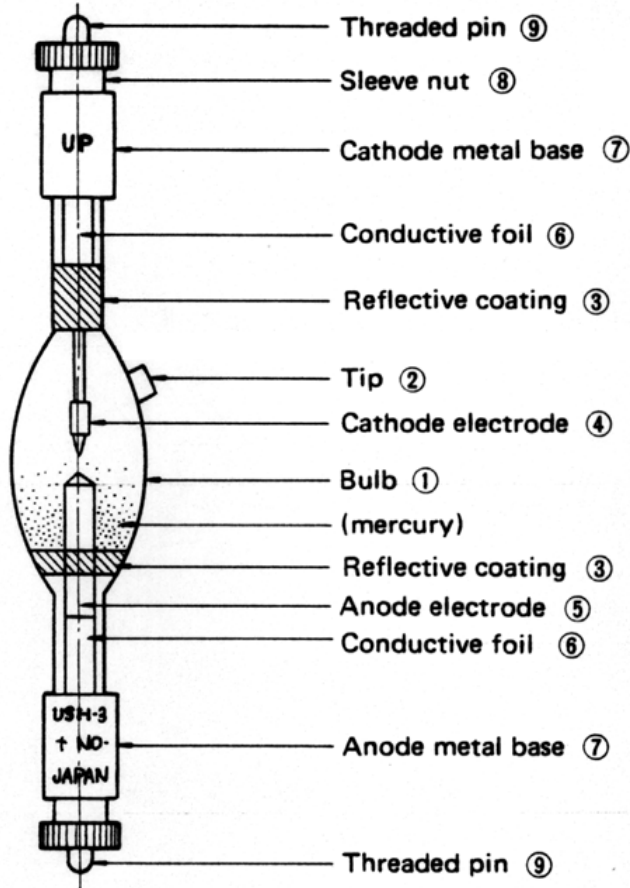
Fig. 1 Lamp Structure (USH-350DP)   Fig. 2 Lamp Dimensions (USH-350DP)

Threaded pin ⑨
Sleeve nut ⑧
Cathode metal base ⑦
Conductive foil ⑥
Reflective coating ③
Tip ②
Cathode electrode ④
Bulb ①
(mercury)
Reflective coating ③
Anode electrode ⑤
Conductive foil ⑥
Anode metal base ⑦
Threaded pin ⑨

Threaded pin
Threaded pin
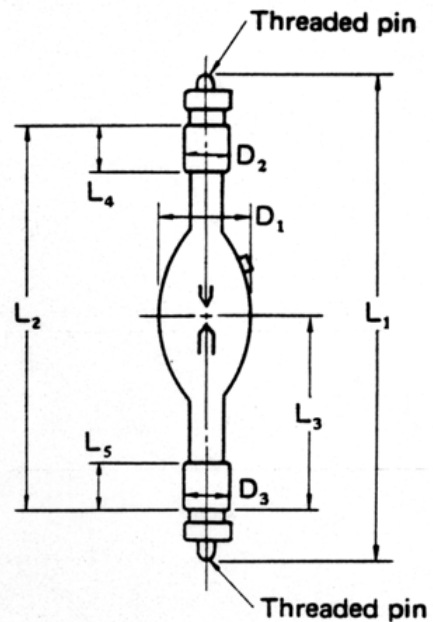
Standard dimensions

L_1	-------	124mm
L_2	-------	101mm
L_3	-------	48mm
D_1	-------	20mm
D_2, D_3	-------	10mm
L_4, L_5	-------	15mm
Threaded pin	-------	No.8 − 32UNC

Ushio Technical Data Sheet

The latest optical tools use **Excimer Lasers** as light sources. KrF excimer lasers can produce 248 nm light at up to 10W @ 2KHz. This is enough power to expose as many as **80** 8" wafers per hour on a stepper. The output bandwidth is very narrow, which is good for lens designers; they only need to correct for one wavelength.

ELS–4000D Typical Laser Spectrum[1]:

ELS–4000D Spectral Profile
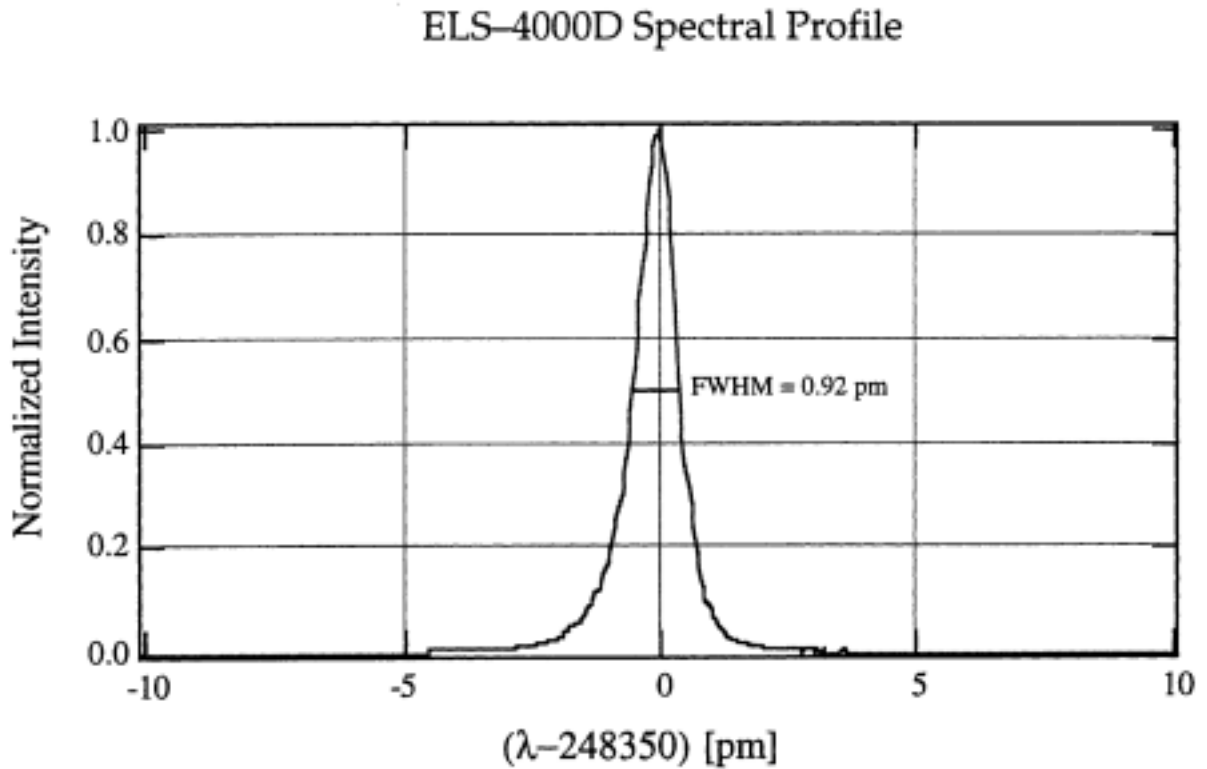
Cymer promotional material

Excimers are also simple, as lasers go, and relatively easy to maintain. This makes them ideal for production facilities where uptime is extremely important. They are expensive, however, and drive the cost of leading edge products up.
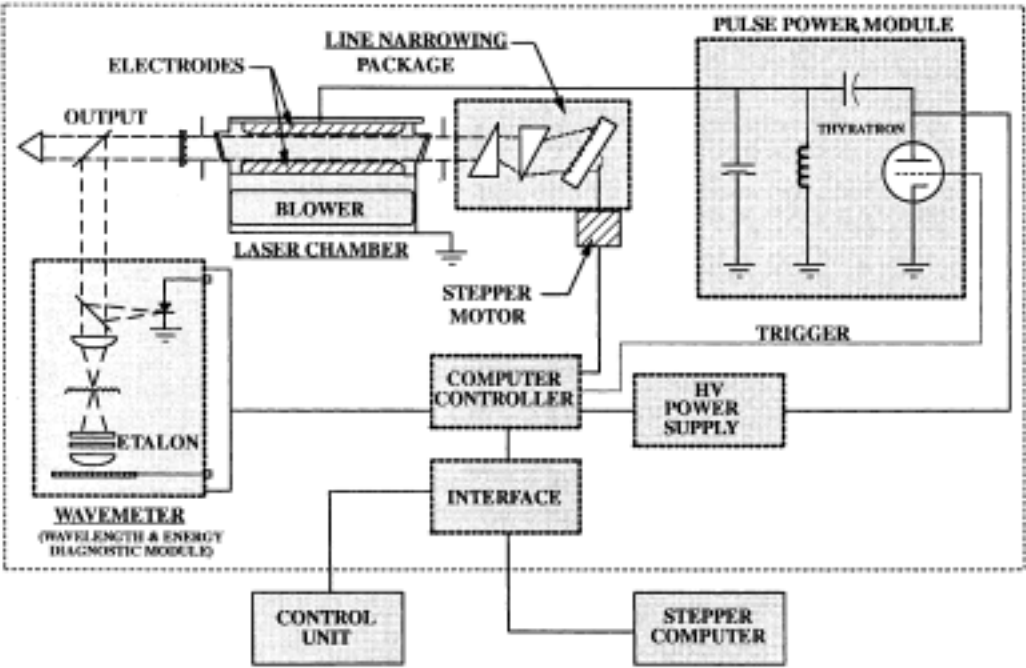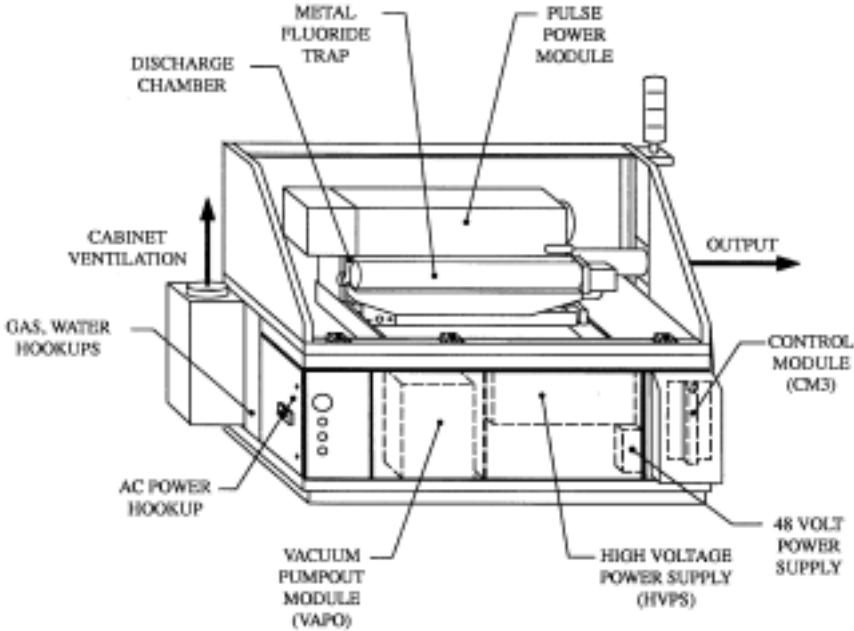
Lithography Laser System Schematic

HPL–100 Laser Major Modules

Cymer promotional material

It should be noted that no optical tools use coherent illumination. While it may seem that coherent light would offer better resolution and control, usually the opposite is true. A combination of limited angles, called **Partial Coherence,** enhances resolution and depth of focus of fine features. This is illustrated below:
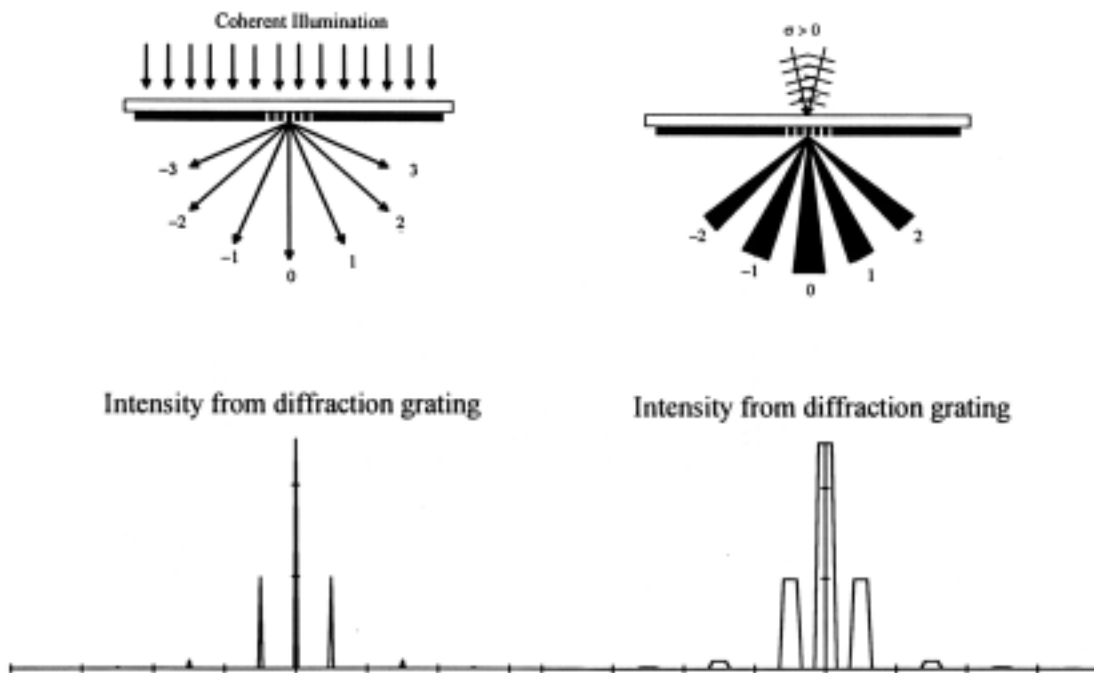
B. W. Smith, PhD; RIT; **The Fundimental Limits of Optical Lithography**; SPIE 1999

The additional spread of angles of the diffracted orders of light allow resolution of features that would otherwise not be printed. Steppers use Köhler illumination, which has become the standard type of partially coherent light source.

CONTACT AND PROXIMITY PRINTING

This is the most straightforward method for exposing a substrate using a mask. Light is directed through the mask and onto the resist-coated substrate, which is held in direct *contact* or close *proximity* to the mask.

The light from the arc lamp must be collimated (made into coherent plane waves) and filtered to pass the desired wavelength(s). At the CNF, we use **HTG System III HR, EV 620**, and **Karl Suss MA6** mask aligners, which look something like this:
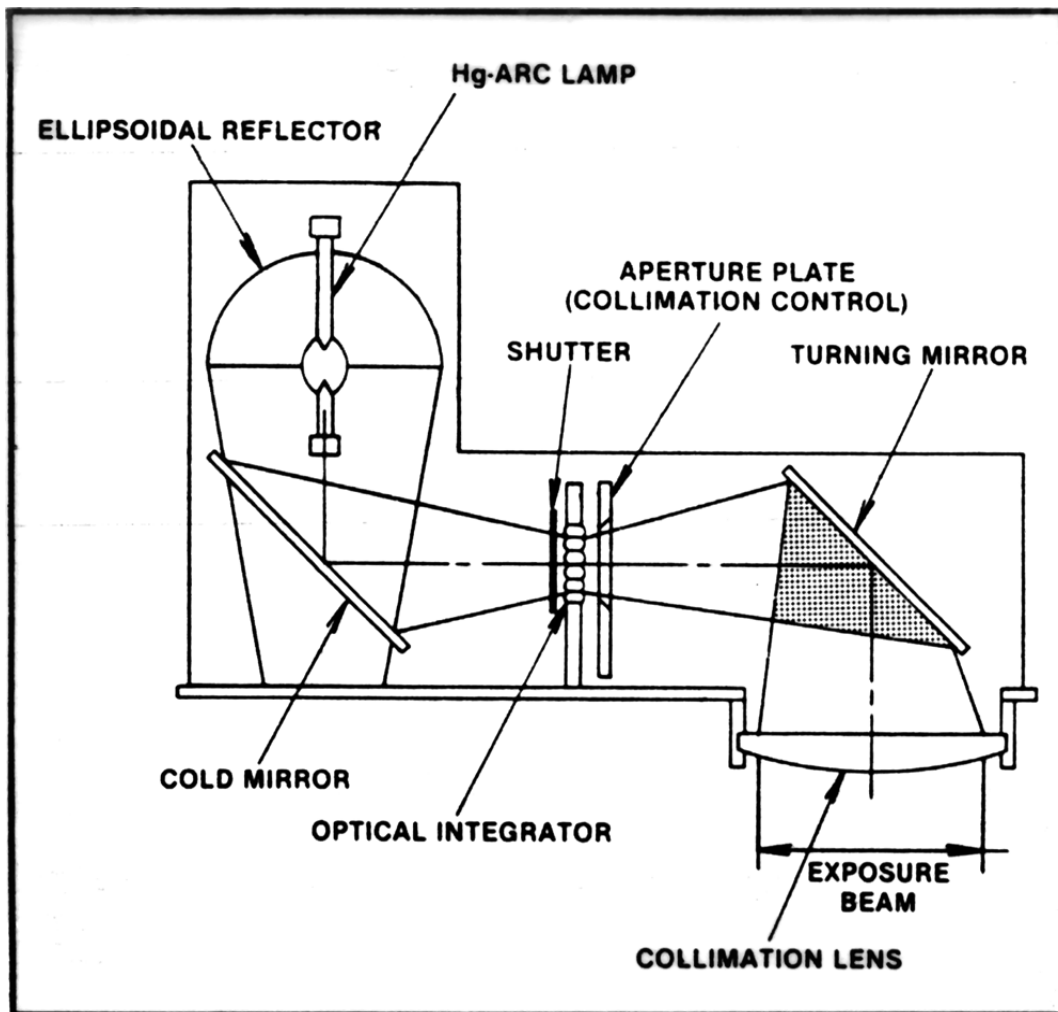
Moreau, p. 379

DIFFRACTION IN
CONTACT LITHOGRAPHY

In contact lithography, the mask pattern is transferred directly into the resist (a 1:1 process). But the transfer isn't perfect. Why not? Because of the fundamental limitation of optical lithography: *diffraction*.

The type of diffraction you usually study in Physics 101 is *Fraunhofer* diffraction (**large** separation between object and image). We will see this when we look at projection lithography. However, for contact lithography, there is a **small** separation between the image and the object. This puts us in the *Fresnel* diffraction regime. To illustrate the difference between the two regimes, consider the classic single slit diffraction pattern:
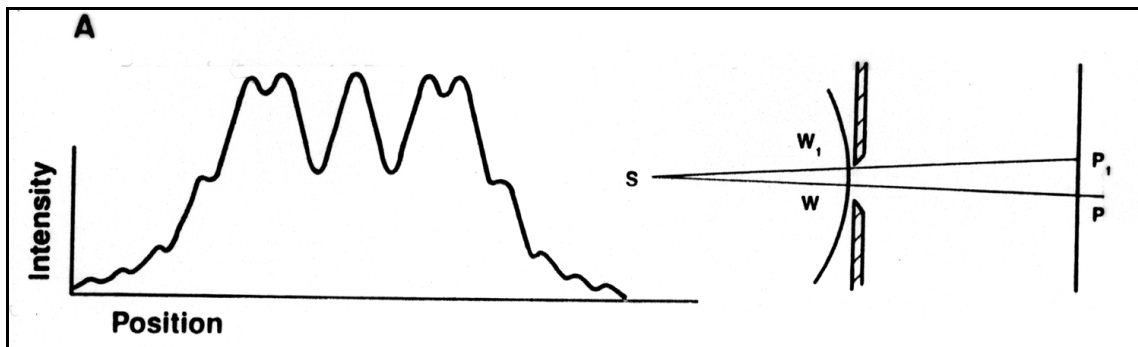
A. Intensity pattern for single-slit Fresnel diffraction
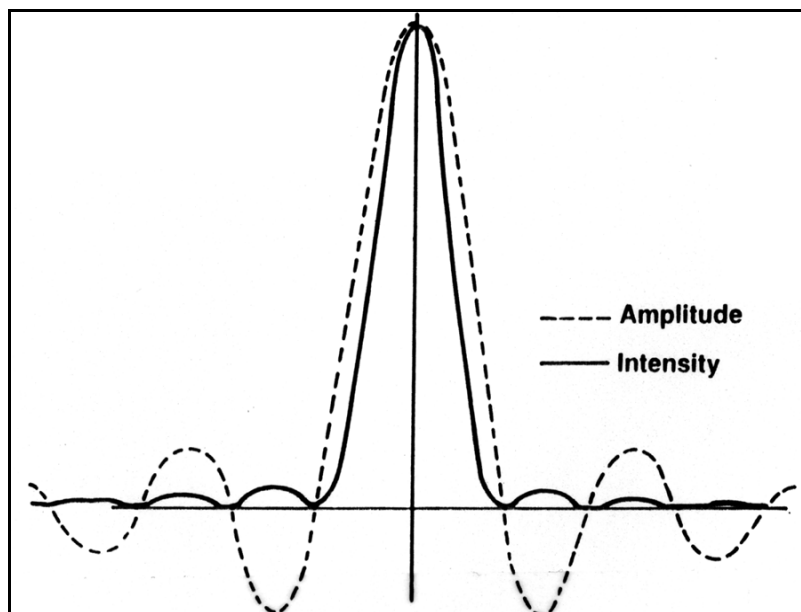
B. Intensity pattern for single-slit Fraunhofer diffraction.

Moreau, p. 376

Consider imaging a pattern of equal lines and spaces of width b onto a substrate. The separation between mask and substrate is s.

Figure with labels:

INCIDENT UV LIGHT ON MASK

MASK PLATE

MASK PATTERN

RESIST

WAFER

IDEAL TRANSFER

ACTUAL TRANSFER

MINIMUM PERIOD TRANSFERABLE:

$$2b_{min} \approx 3\sqrt{s\lambda}$$

INCIDENT INTENSITY ON RESIST

POSITION ON WAFER (ARB UNITS)
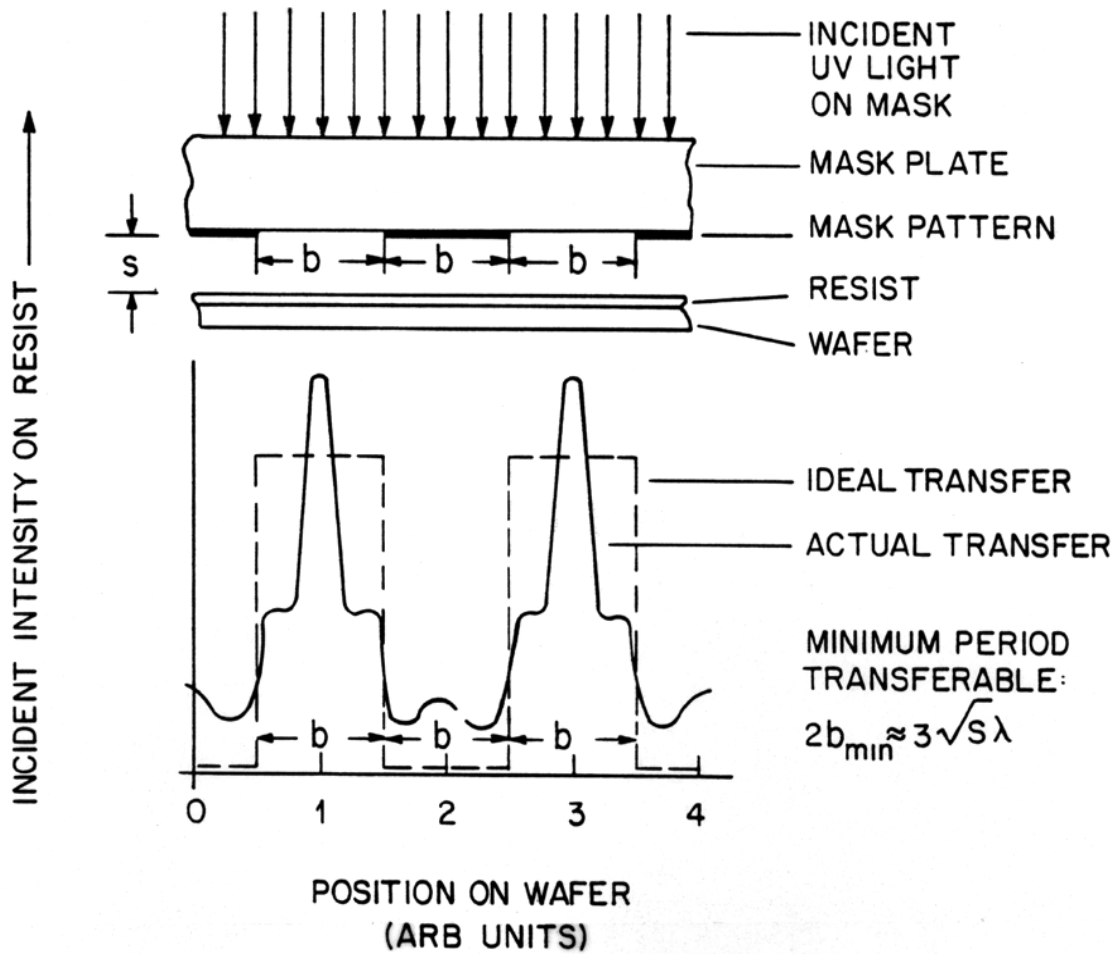
L. F. Thompson, C. G. Wilson and M. J. Bowden, **Introduction to Microlithography**, Amer. Chem. Soc., Washington, 1983, p. 18.

As the figure illustrates, the pattern transfer is not perfect, and will depend to a great extent on the threshold sensitivity of the resist.

The theoretical resolution for a pattern of equal lines and spaces in contact/proximity lithography is given by:

$$2\,b_{min} = 3\,[\,\lambda\,(\,s + 0.5\,d\,)\,]^{1/2}$$

where, $2\,b_{min}$ = grating period,

S = width of gap between mask and resist surface,

d = resist thickness, and

λ = exposure wavelength

Assuming perfect contact, $s = 0$, one obtains:

$$2\,b_{min} = 3\,[\,\lambda\,d\,/\,2\,]^{1/2}$$

Using these equations, we obtain the theoretical limiting resolution for our contact tools, b_{min} :

	$\lambda = 405$ nm	$\lambda = 220$ nm
$d = 1.0\ \mu m$	$0.68\ \mu m$	$0.50\ \mu m$
$d = 0.5\ \mu m$	$0.48\ \mu m$	$0.35\ \mu m$

It is easy to see from the equations that the best resolution can be obtained using *short wavelengths*, *thin resist* and *perfect contact* . Not surprisingly, there are problems that arise when attempting to achieve any of these conditions.

Wavelength -- The HTG has four sets of dichroic mirrors, which allow selection of a desired wavelength range. The four ranges are:

365 - 405 nm

260 - 315 nm

235 - 260 nm

220 - 254 nm

Because of its compatibility with commonly used resists, the default modes for the HTG, EV 620, and MA6 are with the 365 - 405 nm mirrors installed. At shorter wavelengths, the combination of relatively poor sensitivity for most resists and low intensity from the HTG results in long exposure times. For **PMMA** (a frequently used e-beam resist), exposures can be 10 minutes or more.

A plot of the intensities at 4 different wavelengths for each of the mirror sets is shown on the next page.

HTG Intensites
(Alignment Mode)

Legend:
- Mirror Set 220
- Mirror Set 260-235
- Mirror Set 310-260
- Mirror Set 405

Intensity (mW/cm^2)
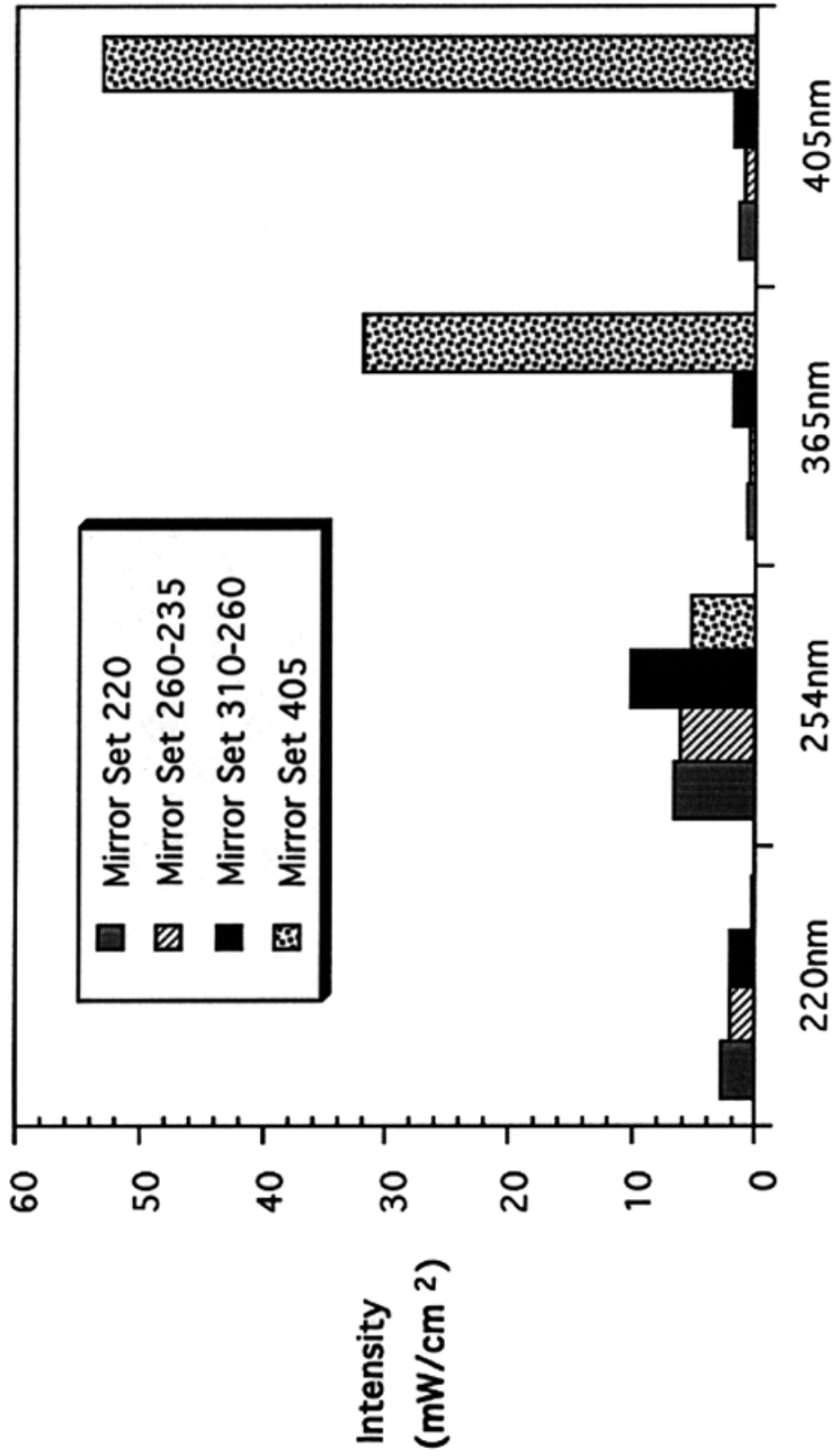
Resist Thickness -- Since the wafer has to come into contact with the mask for best resolution, particulates which find their way between the mask and substrate are forced into the resist. These result in "pinhole" defects. The thinner the resist, the greater the number of such defects. This prevents the use of very thin resists as an aid to resolution in contact lithography. We suggest using a minimum resist thickness of about 1 μm.

Soft Contact, Hard Contact, and Proximity -- Achieving good contact depends on having flat masks and highly polished substrates. These criteria are often met, yet contact is still not perfect. This is primarily because resist edge bead and particulates act as barriers which prevent perfect contact. It is also possible for a small substrate, when used with a large mask, to cause the mask to "bow" and make uneven contact.

On mask aligners, the mode in which the substrate is brought up until it just makes contact with the mask is called *soft contact*. Since soft contact may suffer from the effects mentioned above, the aligners have another mode, called *hard contact*, in which a vacuum seals the substrate to the mask, forcing contact. This mode offers higher resolution, but has the disadvantage that it can result in greater defects in the resist, and greater wear on the mask.

One method for overcoming the disadvantages of mask wear and resist defects is to use *proximity printing*. Here the substrate is brought very close to the mask (about 10 μm), but does not touch it. However, one can see from the resolution equation that any gain in mask life and defect reduction comes at the price of lost resolution.

If the resist thickness is negligible compared to the substrate-mask separation, the equation becomes:

$$2\, b_{min} \sim 3\, [\, \lambda\, s\,]^{1/2}$$

If the gap s = 10 μm, and λ = 405 nm, b_{min} = 3.0 μm. For λ = 220 nm, b_{min} only improves to 2.2 μm.

The effect of increased separation is clearly a large degradation in resolution. This is shown in the next figure, where the image is shown as a function of substrate-mask separation, s, from s = 0 to s = 15 μm.

MASK | | | | | | | | RESIST

h g   f e d c b a

→   15 μm   ←

a

b

c

d

e

f

g

h
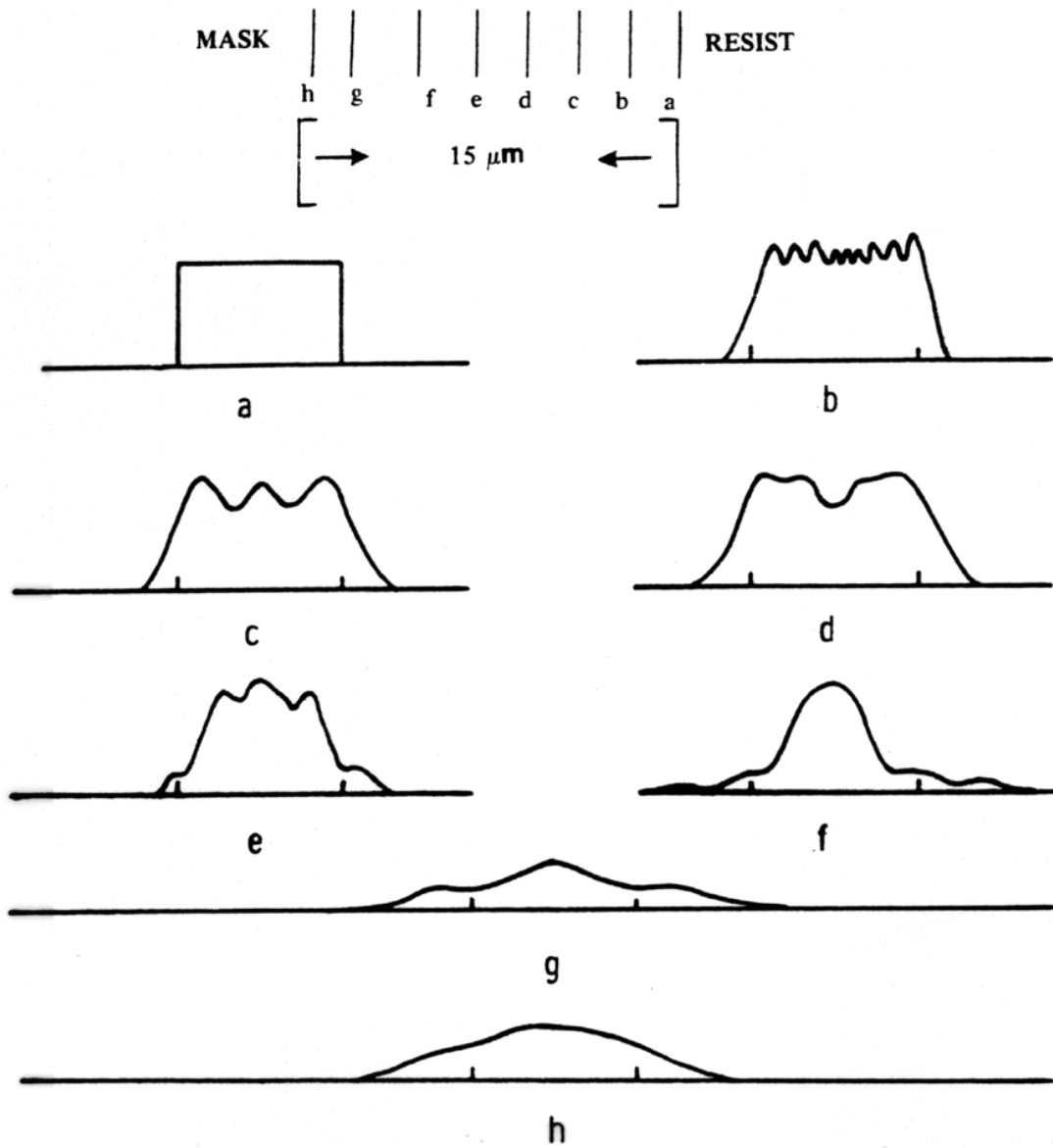
Moreau, p. 377

The decrease in image quality (and hence resolution) noted here affects not just proximity exposure, but also attempts at contact lithography in which particulates or other problems have caused there to be some distance between mask and substrate.

ALIGNMENT USING
CONTACT LITHOGRAPHY

Usually the fabrication of interesting structures requires several levels of lithography. In order to accomplish good registration between all the levels, an alignment scheme must be worked out in the planning stage, before the masks are made. There are several important points to keep in mind:

The pattern placed on the first level mask must be *clearly visible* on the substrate after the initial pattern transfer step. It is this pattern to which other levels of lithography will be aligned.

The marks on higher-level masks must consist of mostly *clear* areas, so that one may see *through* the mask to the mark on the substrate below. This requires careful consideration of the mask tone.

Since those clear areas you look through to see the mark will also allow that area to be *exposed*, a series of marks may be required, one for each alignment step. These examples may be helpful.
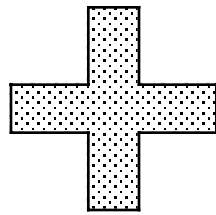
Mark on Substrate
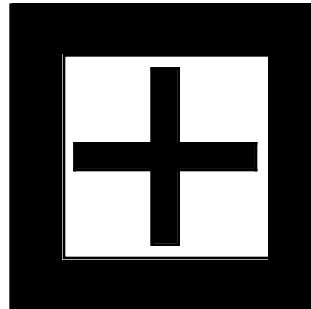
Mark on Second
Level Mask

Marks in Perfect Alignment

Because of the difficulty of maintaining alignment after bringing the mask and substrate into contact, **the mask aligners are limited to a ± 1μm overlay accuracy**. Since the eye is able to detect symmetry very well, alignment to this tolerance is possible using cross patterns of widths 10 μm and 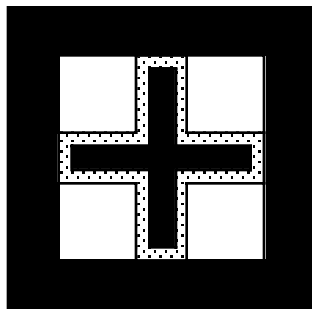20 μm. This leaves 5 μm gaps on either side of the narrow cross, which is sufficient. The length of the arms of the cross is not to scale in the figure; make them quite long, so that the total extent of the clear area on the second level is at least 1 square mm. You can find standard alignment marks by using the macro "**Contactalign**" in Symbad.

A single alignment mark allows for *translational* alignment at that point, but for all parts of the pattern to overlay properly, a pair of marks must be used for *rotational* alignment. The aligners are equipped for split field viewing of two marks simultaneously. The requirement for simultaneous viewing is that the marks have a separation of at least 25 mm for the HTG, and at least 50 mm for the EV 620 and MA6.

ADVANTAGES OF
CONTACT LITHOGRAPHY

1:1 pattern transfer means field size can be large. The HTG can expose wafers up to 4 inches in diameter using 5-inch masks, while the EV 620 and MA6 can expose wafers up to 6 inches in diameter using 7-inch masks.

Substrates of various sizes and thicknesses can be used because there are no focus problems to consider.

Substrates that have non-parallel front and backsides (wedge error) can be used because chucks on the aligners can tilt to planarize the sample.

High resolution can be obtained in DUV mode, or mix and match lithography with e-beam resists can be performed.

Contact lithography is easier to learn than projection.

DISADVANTAGES
OF CONTACT LITHOGRAPHY

Good contact is difficult to achieve because of particulates between mask and substrate, and flatness variations.

As a result of particulate contamination, defects are more numerous than in projection lithography.

Small geometries (< 2 μm) require a mask made on an e-beam system.

DUV exposures require a quartz mask.

Alignment can be time consuming and is not very accurate (especially if the scheme for marks has not been well thought out).

PROJECTION PRINTING

In contrast to contact lithography, projection lithography involves the introduction of extremely complicated lens elements into the optical system. Usually, it also involves a complicated mechanical step-and-repeat stage, along with computer control of the stage motion and the exposures. Despite the introduction of such complexity, there are considerable benefits derived from the use of projection lithography. These are what have made it the dominant form of lithography in industry today.

Multiple images or "die" repeated over the wafer with the desired spacing and exposure.
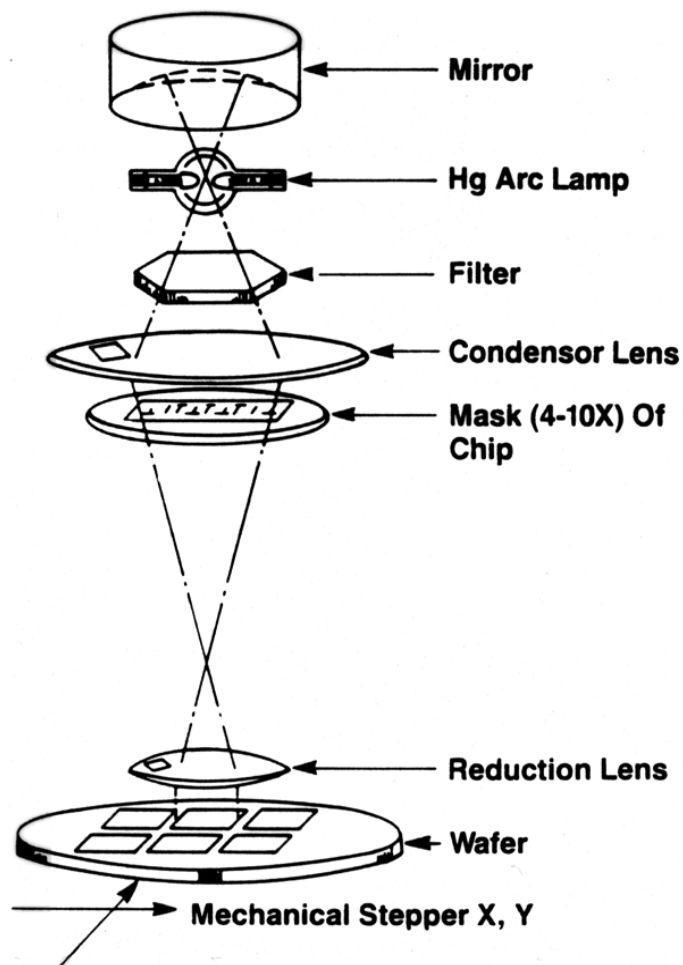
Moreau, p. 363

DIFFRACTION
IN PROJECTION LITHOGRAPHY

As mentioned earlier, Fraunhofer diffraction governs the behavior of the image formed in projection lithography. You may remember that, for a plane wave incident on a grating of period d, the angles θ at which the intensity maxima in the image occur are given by:

$$\sin \theta = N \lambda / d, \quad \text{where } N = 0, 1, 2, \ldots$$

This is shown in the figure below, and in the plots of intensity versus $\sin \theta$ for different numbers of slits.
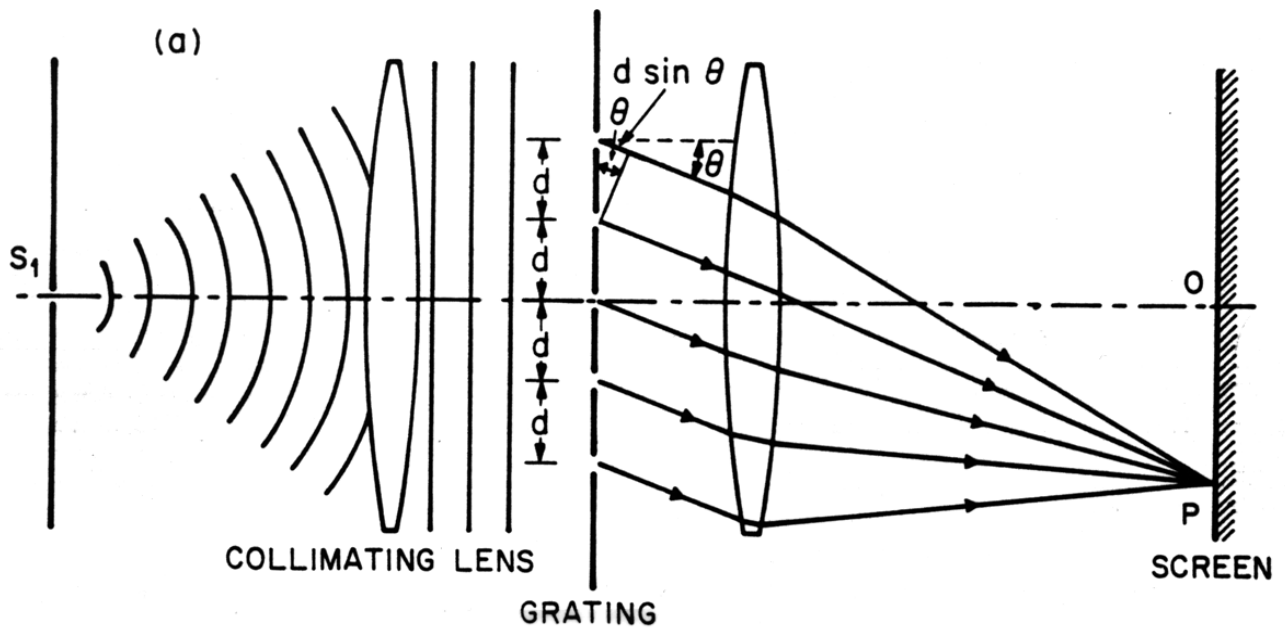
Thompson, Willson, and Bowden, p.33
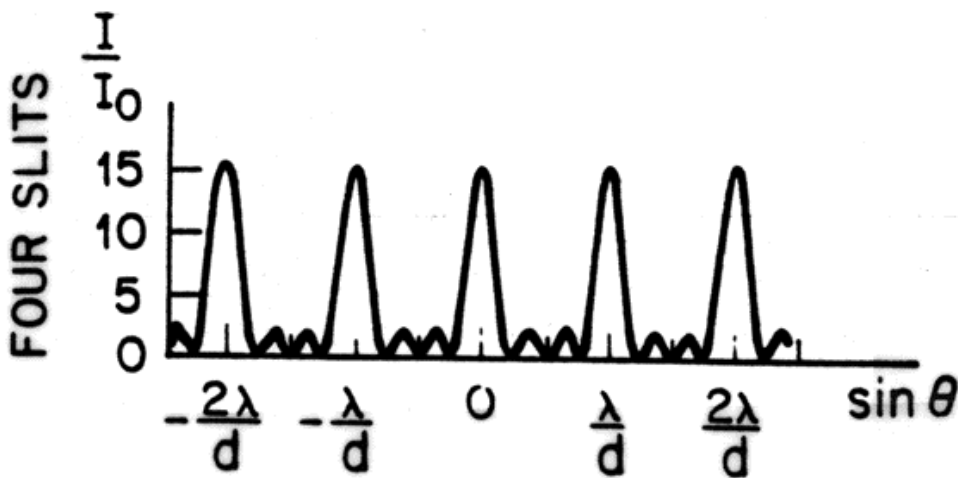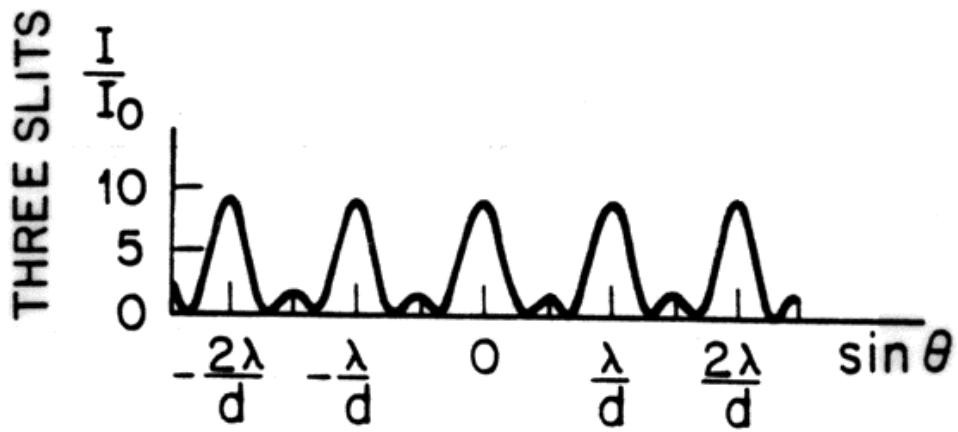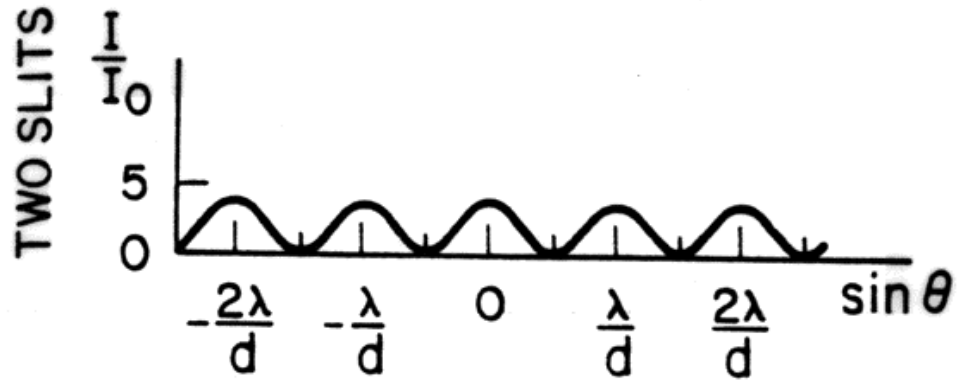
Thompson, Willson, and Bowden, p.33

Now consider what happens when the grating we are discussing is a mask in a projection lithography system, as shown below:
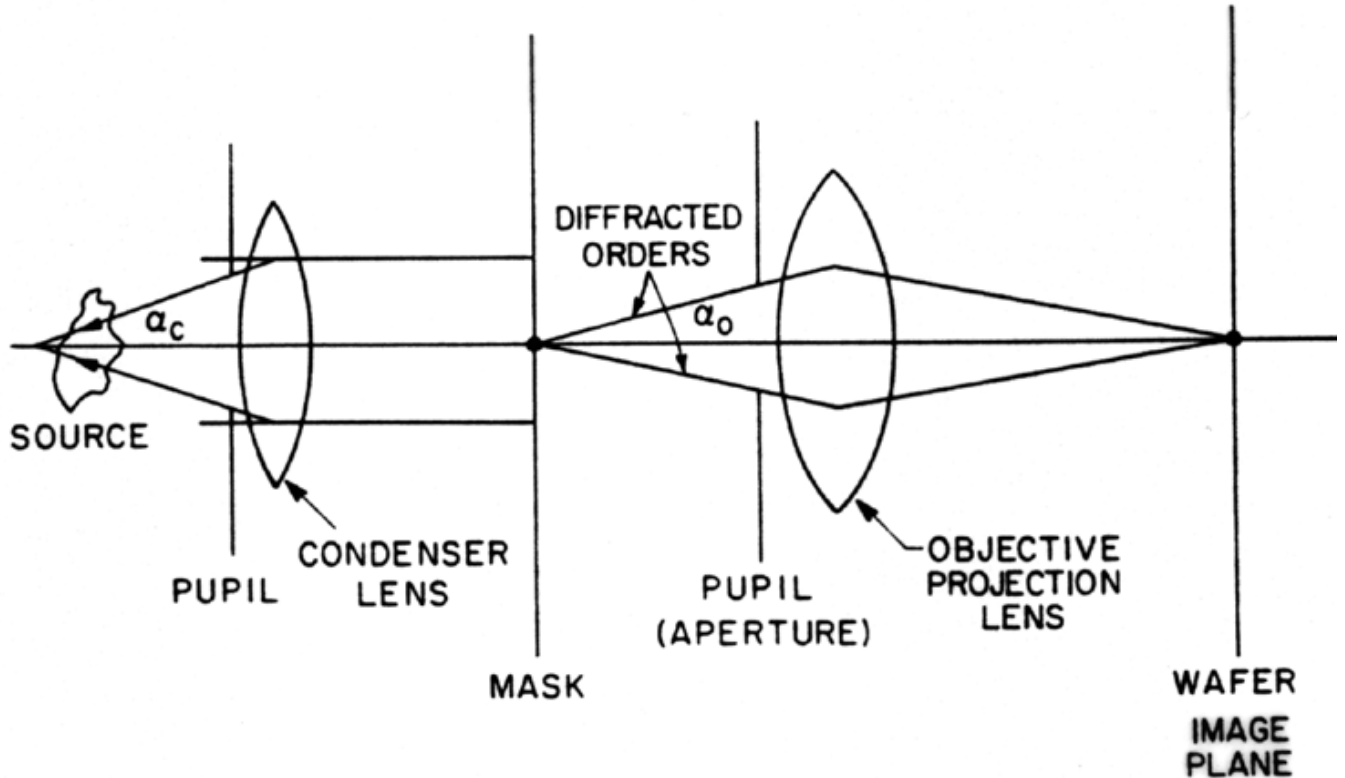
Thompson, Willson, and Bowden, p.34

The angle θ in the figure is the maximum angle for which diffracted light from the mask will be collected for imaging by the lens. With this restriction, we can see that the equation above becomes:

$$\sin\theta = N\,\lambda/d$$

Now, only those values of N for which the term on the right is less than $\sin\theta$ are allowed. Thus, as the period d gets smaller (λ/d gets larger), N gets smaller (i.e. lower diffracted orders). The figure on the following page shows the spread of the diffracted orders for a decrease in relative slit width.

PLANE
LIGHT
WAVES

SLIT

SCREEN
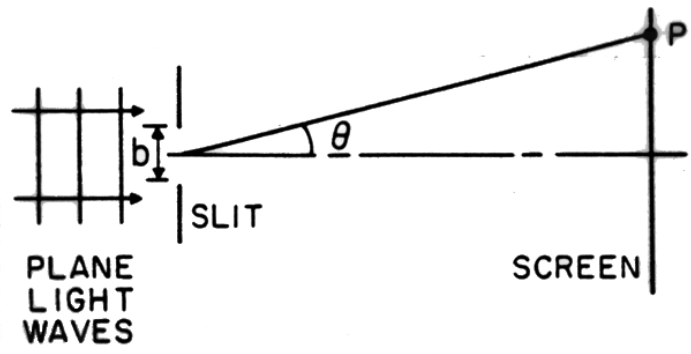
OPTICAL LITHOGRAPHY
MASK MAKING

INTRODUCTION

Before we consider making masks, let's take a more detailed look at the requirements listed in the introduction as they apply to optical lithography specifically.

Your pattern requirements:
  pattern size, feature size, alignment accuracy

The requirements of the lithography tool:
  field size, mask size, mask type, alignment marks

The requirements of the technique you will use for the pattern transfer:
  mask tone, resist type, resist thickness

Most of the items listed here must be considered during the CAD process, and again during the process which follows that: making the mask.

Optical lithography requires the fabrication of a ***mask***. There are two general types of masks in use in the CNF. Both consist of a piece of glass of some type, coated with a film in which the pattern is formed.

Resist-coated chrome masks -- A layer of sputtered Cr about 100 nm thick coats the glass plate. Resist is then spun on the plate, and the exposure is made. After development, the Cr is removed from the unprotected areas with an acid etch, and an image of the pattern is left in the Cr. The exposure can be made with either an optical or an e-beam tool.

Emulsion -- A layer of high-resolution photographic emulsion coats the glass plate. Optical exposure and development causes parts of the emulsion to become opaque, forming an image of the pattern. These types of masks are inexpensive to make, but have poor resolution and are not nearly as robust as Cr masks.

THE PATTERN GENERATOR

The lithography requirements at CNF usually allow you to make a mask faster, cheaper, and more easily optically than with an e-beam tool. There are specific exceptions to this, which will be pointed out as they come up. For optical exposures, we have a **GCA/Mann 3600F Pattern Generator**. Using a data stream containing a fractured data file as input, the PG exposes variably sized rotated rectangles onto the mask blank.

Performance characteristics for the PG are:

> **Data input**: 0.1 μm; this is the least count for object placement

> **Aperture**: 2 μm - 1500 μm in 0.5μm increments

> **Rotation**: 0 - 89.9° in 0.1° increments

> **Image positioning accuracy**: ± 0.6 μm over 150 mm of stage motion -- this is 4 ppm

> **Aperture error**:
> ± 0.35 μm from 2 μm - 125 μm
> ± 0.3 % from 125 μm - 425 μm
> ± 1.25 μm from 425 μm - 1500 μm

The PG is not extremely precise, but it is still used for contact lithography.

Aperture and positioning errors -- The tables below show <u>worst</u> <u>case</u> results for PG errors when used with the optical tools available at CNF.

FEATURE SIZE

Tool	On Mask	On Substrate	Relative Error
Contact (1:1)	2.0 μm	2.0 μm	17.5 %
Stepper (5:1)	5.0 μm	1.0 μm	7.0 %
Stepper (10:1)	6.0 μm	0.6 μm	5.0 %

IMAGE PLACEMENT ERROR

Tool	On Mask	On Substrate
Contact (1:1)	0.6 μm	0.6 μm
Stepper (5:1)	0.6 μm	0.12 μm
Stepper (10:1)	0.6 μm	0.06 μm

There are two things to notice here:

   The errors decrease as the reduction ratio increases. This means that
   masks made for 10:1 lithography are much more precise than masks made
   for 1:1.

   The actual errors are not usually as bad as the worst-case specifications,
   especially those for the smallest aperture sizes.

You will see some examples of the types of errors that can occur as a result of
the way in which Dracula (CAD) fractures the pattern data later. Here are
some pictures that show the effects of aperture errors:

500 μm Circle
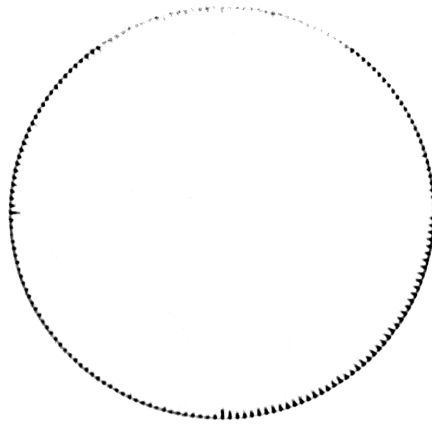
500 μm Circle, Close-up

1500 μm Circle, Close-up

2.5, 7.5 and 10 μm Lines

With good focus and exposure:

Out of focus and underexposed, showing abutments:

2 μm Line Next to Large Feature

With good focus and exposure, showing small height aperture overlap

Out of focus and underexposed, showing "scumming" and sloped sidewalls

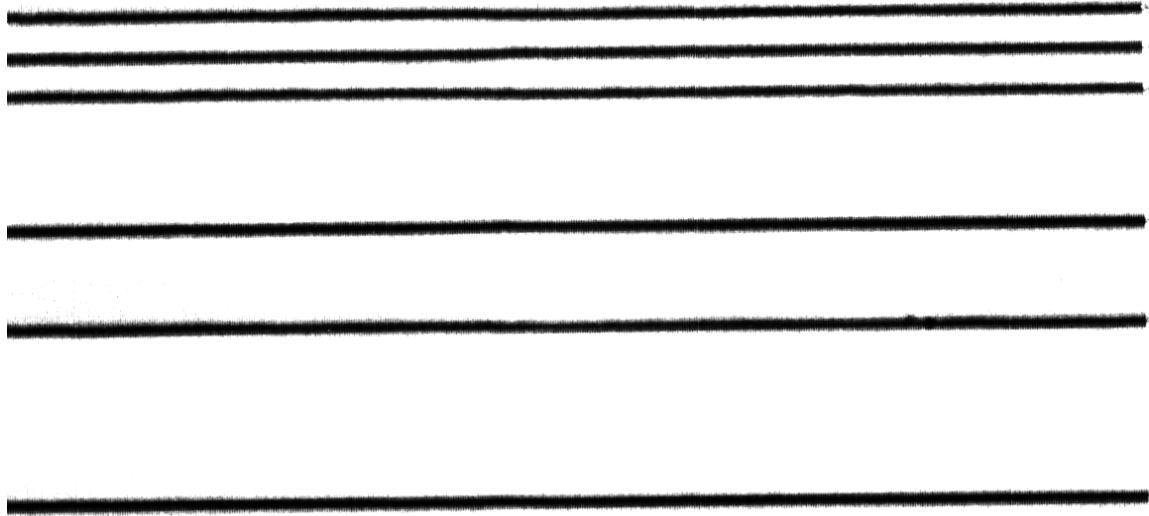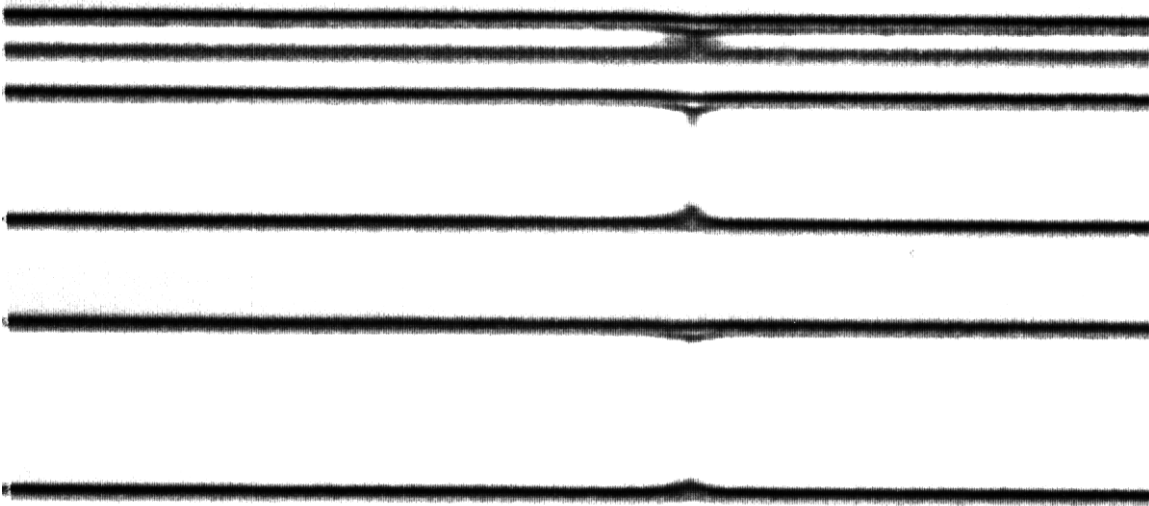There are two **modes of exposure** on the PG. In both cases, the mask plate moves on a stage with laser positioning. When the stage has moved the mask to the proper position, exposure occurs. The two modes are:

Shutter mode -- Uses the 436 nm light from a Hg arc lamp to expose resist-coated chrome-on-glass plates. The stage must stop and settle, then the shutter opens for 100-200 ms. The rate of exposure is somewhat pattern dependent, but is usually in the range of 7000 - 12000 exposures/hour.

Flash mode -- Uses a xenon flash tube to expose emulsion-coated plates. Because the flash is instantaneous, it "freezes" the stage motion. Therefore, the stage can move continuously, resulting in a faster exposure rate, typically 15,000 - 50,000 flashes/hour. We NO LONGER USE emulsion masks at CNF.

Now that you know something about the machine usually used to make masks, let's consider some more details about the masks themselves.

PHOTOMASKS: MASK TONE

This is a topic that always seems to cause great confusion. In the interest of trying to clarify the issue, we'll spend some time on it now.

Masks can be made positive or negative, just like resist. When you draw a pattern on the CAD system, the pattern you have defined is exposed onto the mask. The unexposed, or background area is called the *field*.

A *positive* or *dark field* mask is one on which the pattern is clear with the background dark.

A *negative* or *clear field* mask is one on which the pattern is dark with the background clear.
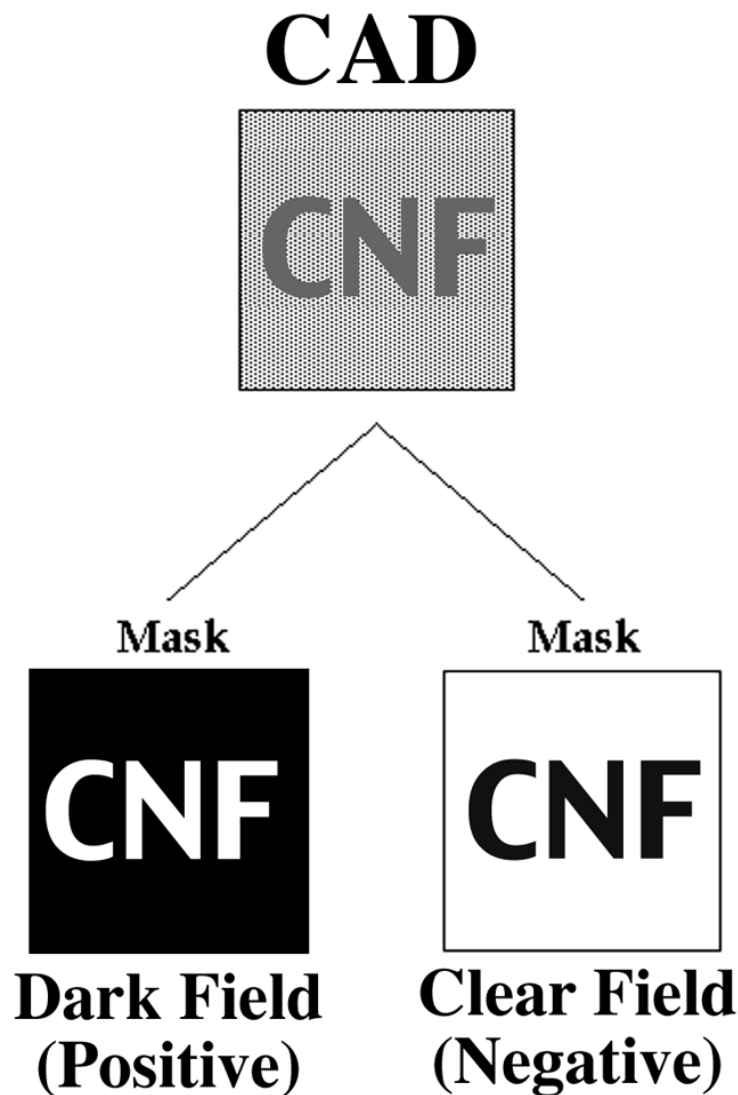
The combination of mask tone and resist tone affects the tone of the final product; so a positive (dark field) mask, used with positive resist, is equivalent to a negative (clear field) mask used with a negative resist, in terms of the pattern outline. <u>But</u>, there are important differences between these two alternatives. These differences have to do with the details of the resist exposure, and the way in which it affects the *sidewall slope* of the resist. This we have shown to be of critical importance when attempting to perform lift-off after metallization.

Clear Field
(Negative)

CNF

Positive
Resist

Negative
Resist
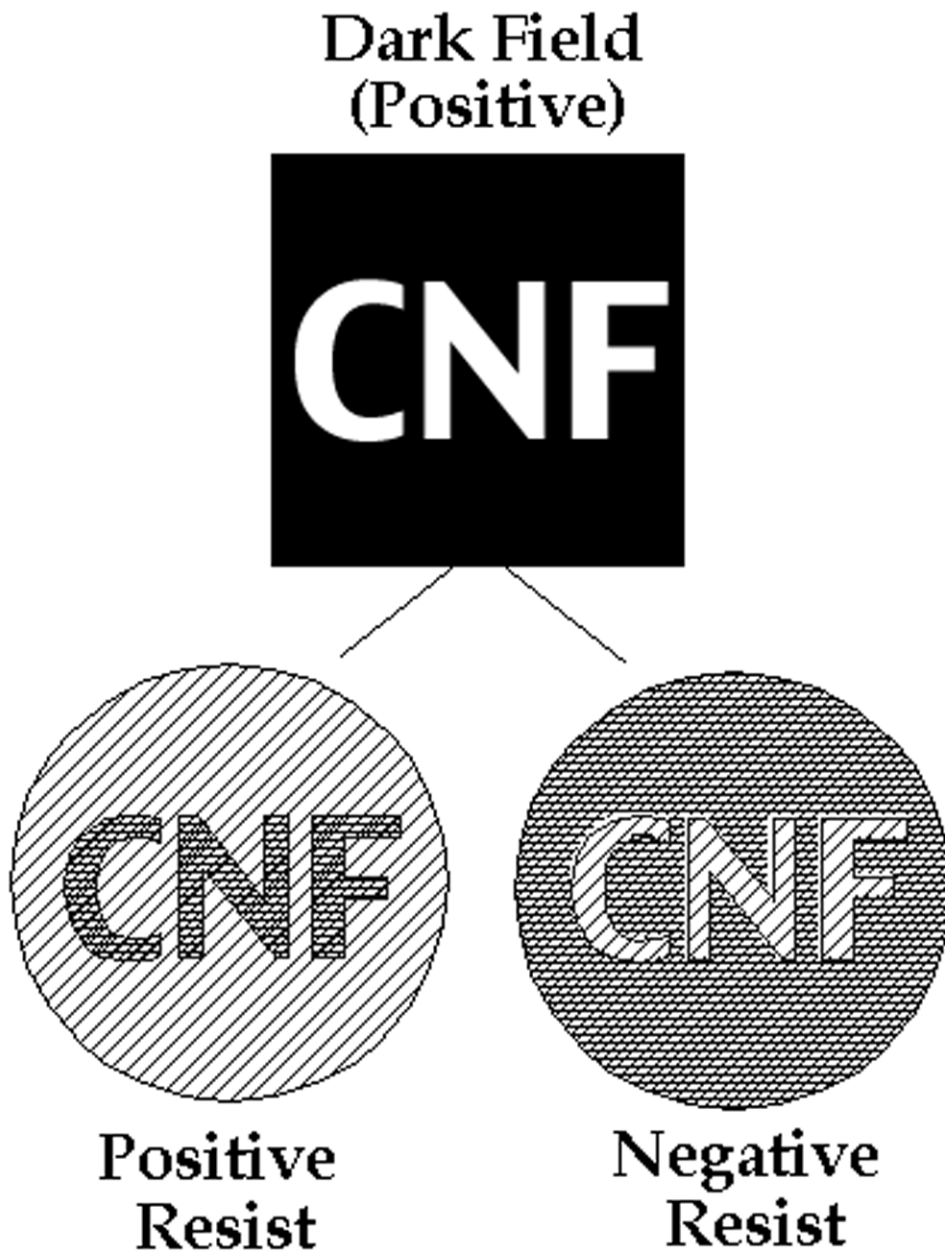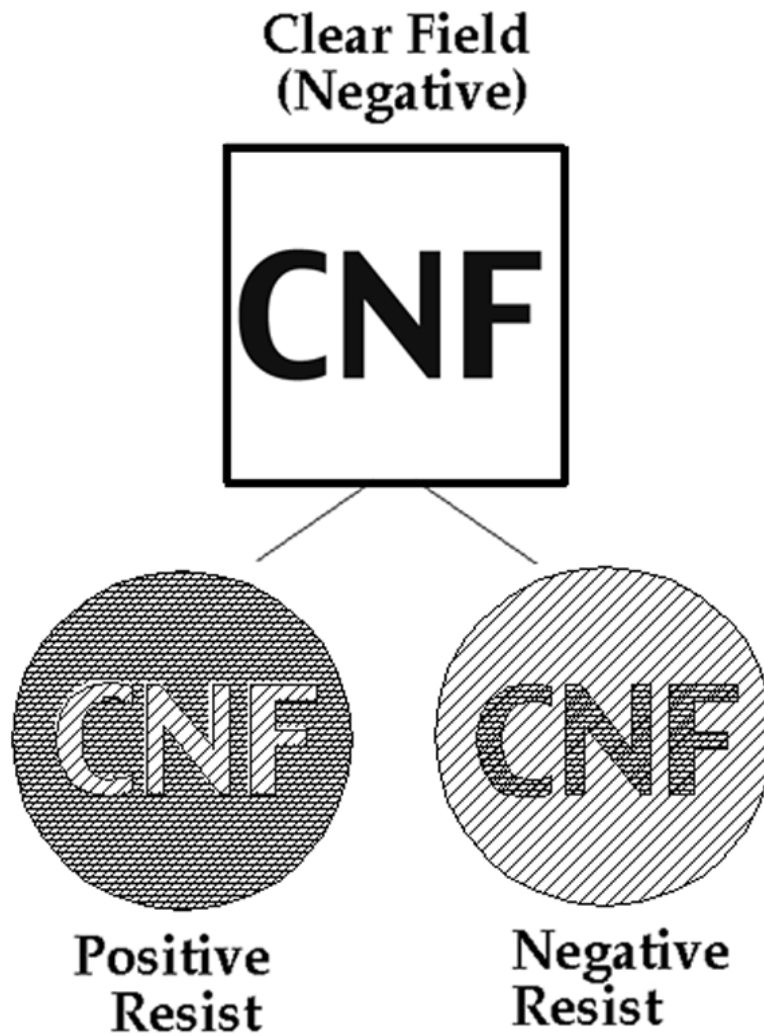
TYPES OF GLASS

One final consideration that is sometimes important is the type of glass out of which the mask is made. There are two considerations here: the *thermal expansion* of the glass and its *transmission* at the exposure wavelength.

Thermal coefficients for different types of glass are:

Soda-lime:	9.3 ppm/°C
Borosilicate:	3.7 ppm/°C
Quartz:	0.5 ppm/°C

The worst case here is **soda-lime glass**, which gives a 1.2 μm change across a 5 inch mask for every 1°C variation in temperature. This is about **twice** the PG image placement error, but we still use soda-lime in most cases because it's much cheaper. Thermal effects are limited because the PG is in an environmental chamber (as are the steppers), and it uses a temperature compensation scheme.

Borosilicate glass is usually used for masks made on e-beam tools. Since the masks are exposed under vacuum, heat is not transferred as readily, so a lower expansion glass is desirable. These masks are about twice as expensive as soda-lime.

Why would you want to use **quartz**? Consider the transmission properties of the various type of glass:
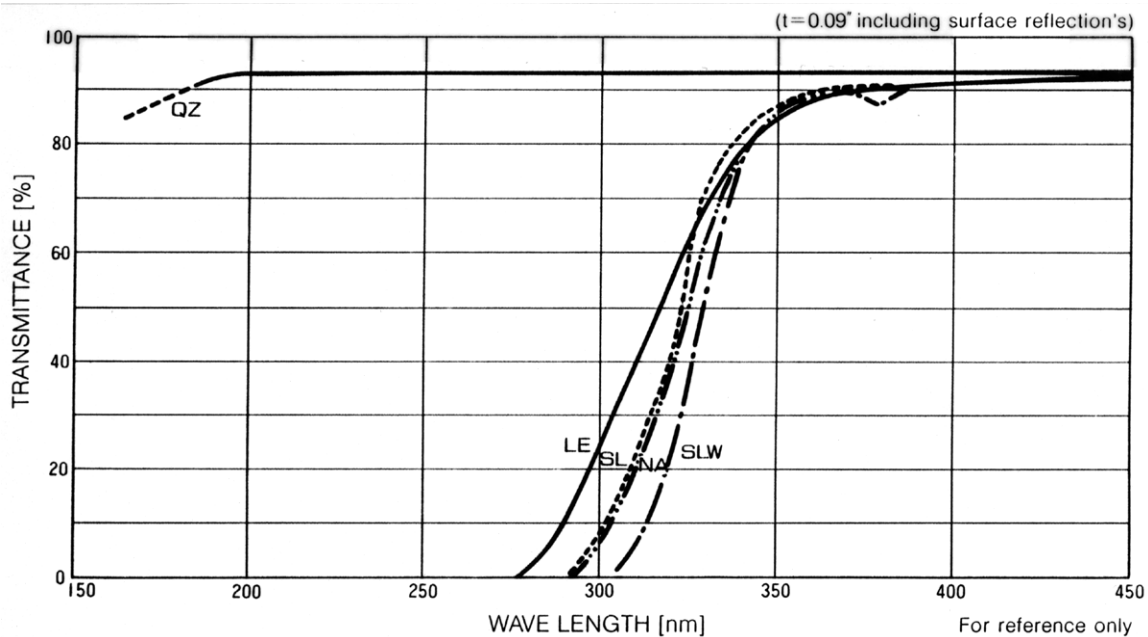
Hoya Product Literature

Deep UV exposures require quartz instead of other types of glass, because glass begins to absorb strongly at wavelengths below about 350 nm. However, quartz masks are several times more expensive than glass.

OTHER MASK-MAKING TECHNIQUES

Heidelberg DWL 66 -- The DWL 66 is a high-resolution direct-write optical imaging system where over half a million dpi is achieved using a 40-nanometer address grid for exposing chrome plates or wafers. The DWL 66 will accommodate substrates up to 8 x 8 inches. Design data is produced in CAD and is converted into a format that is transferred to the DWL 66. There are two write lenses, with a 2 μm or 0.5 μm spot size. The stage resolution is 10 nm, and the system has capability for both front side and backside alignment.

GCA/Mann 6300 in Photorepeater Mode -- Both steppers have a mode in which resist-coated chrome masks can be exposed using a 5:1 or 10:1 "master." This is useful for masks on which an individual pattern is repeated many times across a mask. Good examples are arrays of dots, and large field gratings, which are time-consuming to make full size on the PG. Making a subset of the array on one mask using the PG, and then repeating it in this mode on another mask using the stepper can be much less expensive. See the appropriate staff member for details if you think your pattern fits in this category.

Outside Vendors – Complex data files can be sent to mask making shops for fabrication if necessary.

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Now you have seen enough to begin thinking about that list of requirements shown earlier:

Your pattern requirements:

 pattern size, feature size, alignment accuracy

The requirements of the lithography tool:

 field size, mask size, mask type, alignment marks

The requirements of the technique you will use for the pattern transfer:

 mask tone, resist type, resist thickness

With these in mind, you can begin to plan your process. Notes on resist processes used at CNF follow.

CNF OPTICAL LITHOGRAPHY
PROCESS NOTES

OCG OiR 897i Photoresist

i-line (365 nm) specific photoresist, used with the 10:1 Stepper.

Available as OiR 897-7i, 12i, 21i depending on film thickness desired.

1.a. (Optional) Dehydration bake at 150°C for 30 minutes.

1.b. Liquid prime with P-20 (20% HMDS) primer. Apply primer over entire wafer, allow to remain for 10 seconds, then spin dry (3000-5000 RPM, 30 sec.)

-or-

1. Vapor prime wafer with YES Oven HMDS process.

2. Dispense photoresist in middle of wafer. Spin immediately at desired speed, 20 - 30 seconds (thicker films take a longer time to reach uniformity). You may wish to ramp up to the desired speed for better coverage over topography.

3. Solvent removal bake at 90°C for 1-1/2 minutes on the hot plate or 20 - 30 minutes in the oven. Thicker films benefit from longer baking.

4. Expose. Time will vary depending on resist thickness, bake time, substrate reflectivity, intermediate film thickness, etc. See Sample Processes page for approximate exposure times.

5. Post-exposure bake, 115°C for 1-1/2 minute on hotplate. Post-exposure baking for this resist is **required** for optimum resolution.

6. Develop for 1 minute in AZ 300MIF or Shipley CD26 (no dilution).

7. (Optional) Hard bake at 115°C - 125°C for 1 - 2 minutes on the hot plate, or 20 - 30 minutes in the oven. The hard bake serves to promote adhesion during wet etching or increase selectivity during dry etching.

CNF OPTICAL LITHOGRAPHY PROCESS NOTES

Shipley 1800 Series Photoresist

General purpose broad band (365 nm - 436 nm) resist, best suited for use on the 5X Stepper and HTG Contact Aligner. Not recommended for the 10:1 Stepper.

Available as S1805, S1813, S1818, S1818J (dyed), S1827 (0.5, 1.3, 1.8, 2.7 μm).

1.a. (Optional) Dehydration bake at 150°C for 30 minutes.

1.b. Liquid prime with P-20 (20% HMDS) primer. Apply primer over entire wafer, allow to remain for 10 seconds, then spin dry (3000-5000 RPM, 30 sec.)

-or-

1. Vapor prime wafer with YES Oven HMDS process.

2. Dispense photoresist in middle of wafer. Spin immediately at desired speed, 20 - 30 seconds (thicker films take a longer time to reach uniformity). You may wish to ramp up to the desired speed for better coverage over topography.

3. Solvent removal bake at 90°C - 115°C for 1 - 2 minutes on the hot plate or 20 - 30 minutes in the oven. Thicker films benefit from longer baking.

4. Expose. Time will vary depending on resist thickness, bake time, substrate reflectivity, intermediate film thickness, etc. See Sample Processes page for approximate exposure times.

5. Develop for 1 minute in AZ 300MIF or CD 26. Can also use MF-321 (no dilution), or Microposit Developer Concentrate (MDC) diluted 1:2 (MDC minimizes Al etch rate but is not metal-ion free). <u>USE AGITATION AT END OF DEVELOPMENT TO REMOVE RESIDUES.</u>

6. (Optional) Hard bake at 115°C for 1 minute on the hot plate, or 20 - 30 minutes in the oven. The hard bake serves to promote adhesion during wet etching or increase selectivity during dry etching.

CNF OPTICAL LITHOGRAPHY PROCESS NOTES

Shipley 1000 Series Photoresist

General purpose broad band (365 nm - 436 nm) resist, best suited for use on the 5X Stepper and HTG Contact Aligner. Not recommended for the 10:1 Stepper.

Available as STR1045 and STR1075 (4 – 20 μm).

1.a. (Optional) Dehydration bake at 150°C for 30 minutes.

1.b. Liquid prime with P-20 (20% HMDS) primer. Apply primer over entire wafer, allow to remain for 10 seconds, then spin dry (3000-5000 RPM, 30 sec.)

-or-

1. Vapor prime wafer with YES Oven HMDS process.

2. Dispense photoresist in middle of wafer. Spin immediately at desired speed, 20 - 30 seconds (thicker films take a longer time to reach uniformity). You may wish to ramp up to the desired speed for better coverage over topography.

3. Solvent removal bake at 90°C - 100°C for 1.5 - 3 minutes on the hot plate or 20 - 30 minutes in the oven. Thicker films benefit from longer baking (see product data sheets).

4. Expose. Time will vary depending on resist thickness, bake time, substrate reflectivity, intermediate film thickness, etc. See Sample Processes page for approximate exposure times.

5. Develop for 3 - 6 minutes in AZ 300MIF or CD 26. Can also use Microposit Developer Concentrate (MDC) diluted 1:2 (MDC minimizes Al etch rate but is not metal-ion free).

6. (Optional) Hard bake at 115°C for 1 minute or longer on the hot plate, or 20 - 30 minutes in the oven. The hard bake serves to promote adhesion during wet etching or increase selectivity during dry etching.

CNF OPTICAL LITHOGRAPHY PROCESS NOTES

YES Oven Image Reversal

The YES Oven uses an ammonia diffusion process to reverse the tone of positive photoresists. This process has been developed specifically to generate an undercut profile for lift-off. Good results have been obtained for OCG 895i, 897i, Shipley 1800, Shipley 1000, and AZ4903.

1.a. (Optional) Dehydration bake at 150°C for 30 minutes.

1.b. Liquid prime with P-20 (20% HMDS) primer. Apply primer over entire wafer, allow to remain for 10 seconds, then spin dry (3000-5000 RPM, 30 sec.)

-or-

1. Vapor prime wafer with YES Oven HMDS process.

2. Dispense photoresist in middle of wafer. Spin immediately at desired speed, 20 - 30 seconds (thicker films take a longer time to reach uniformity). You may wish to ramp up to the desired speed for better coverage over topography.

3. Solvent removal bake time and temperature dependent upon the particurlar type and thickness of resist used. Follow normal processing steps.

4. Expose. Time will vary depending on resist thickness, bake time, substrate reflectivity, intermediate film thickness, etc. See Sample Processes page for approximate exposure times.

5. Run YES Oven ammonia diffusion process. See YES Oven operating instructions for details.

6. Flood expose for 60 seconds (more for very thick films) using the HTG.

7. Develop for 1 minute in OCG 945 for OCG 895i, MF-321 (no dilution) for Shipley 1800 and OCG 897i. See staff regarding other resists.

CNF OPTICAL LITHOGRAPHY
PROCESS NOTES

Cr Plate Processing

Development

Develop mask resist side up in AZ 300MIF or CD26 for 2 min. Use slight agitation at end of process to remove residues. Rinse in DI water, blow-dry using N_2. Inspect mask.

Cr Etch

Process plate with resist side up in etch solution with mild agitation. Etch until pattern is completely clear using the hood illumination. Rinse in DI water, blow-dry using N_2. Inspect mask.

Resist Strip

Process plate with resist side down in Shipley 1165 remover for 20+ min. Use periodic agitation until finished. Rinse in DI water, blow-dry using N_2. Inspect mask.

CNF OPTICAL LITHOGRAPHY PROCESS NOTES

OCG OiR 620i Photoresist

i-line (365 nm) specific photoresist, used with the 10:1 Stepper.

Available as OiR 897-7i, 12i, 21i depending on film thickness desired.

1.a. (Optional) Dehydration bake at 150°C for 30 minutes.

1.b. Liquid prime with P-20 (20% HMDS) primer. Apply primer over entire wafer, allow to remain for 10 seconds, then spin dry (3000-5000 RPM, 30 sec.)

-or-

1. Vapor prime wafer with YES Oven HMDS process.

2. Dispense photoresist in middle of wafer. Spin immediately at desired speed, 20 - 30 seconds (thicker films take a longer time to reach uniformity). You may wish to ramp up to the desired speed for better coverage over topography.

3. Solvent removal bake at 90°C for 1-1/2 minutes on the hot plate or 20 - 30 minutes in the oven. Thicker films benefit from longer baking.

4. Expose. Time will vary depending on resist thickness, bake time, substrate reflectivity, intermediate film thickness, etc. See Sample Processes page for approximate exposure times.

5. Post-exposure bake, 115° - 120°C for 1-1/2 minute on hotplate. <u>Post-exposure baking</u> for this resist is **required** for optimum resolution.

6. Develop for 1 minute in AZ 300MIF or Shipley CD26 (no dilution).

7. (Optional) Hard bake at 115°C - 125°C for 1 - 2 minutes on the hot plate, or 20 - 30 minutes in the oven. The hard bake serves to promote adhesion during wet etching or increase selectivity during dry etching.