Highly Coherent Gratings for Optoelectronics:
An Application of Spatial-Phase-Locked Electron Beam Lithography
by
Juan Ferrera
Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degrees of
Master of Science in Electrical Engineering and Computer Science
and
Bachelor of Science in Electrical Engineering
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 1994
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Author............................................................................................................................
Department of Electrical Engineering and Computer Science
May 7, 1994
Certified by ....

............................................
Henry I. Smith
Professor of Electrical Engineering, MIT
Thesis Supervisor
Certified by .................................................................

Stephen A. Rishton
Research Scientist, IBM T. J. Watson Research Center
Thesis Supervisor
Accepted by ....

.................................................................
Frederic R. Morgenthaler
Chairman, Departmental Committee on Graduate Students

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Abstract

The realization of narrowband optical filters and lasers requires periodic structures of submicron dimensions and a high degree of spatial coherence to be fabricated. The versatility of electron beam lithography to pattern arbitrary designs in the nanometer regime makes it the technology of choice. However, this technology suffers from poor pattern placement accuracy, which results in gratings of similarly bad spatial coherence. This thesis describes work done in order to circumvent this difficulty. Coherent gratings produced by the technique of holographic lithography are used as reference to eliminate pattern placement errors. This work can be extended to the fabrication of very large scale integrated circuits in general.

Thesis Supervisor: Henry I. Smith
Title: Professor of Electrical Engineering, MIT

Thesis Supervisor: Stephen A. Rishton
Title: Research Scientist, IBM T. J. Watson Research Center
To the memory of my father, Raúl Ferrera
Acknowledgments

First of all, I would like to thank my advisor, Prof. Henry Smith. I’ve lost count of how many things I have learnt from him. His enthusiasm and vitality are without par. Hank’s door is always open and he devotes lots of time to his students, despite having “gigabytes” of work to do. I consider it an honor to be able to work in his laboratory. I would also like to thank Steve Rishton, who has taught me an enormous amount of interesting things and has always had infinite patience. Working with him is real pleasure. Volker Bögli listens with a smile to [very] occasional complaints about his software and invariably offers to help with any problem. Dieter Kern was the best manager one could ever hope for. I have enjoyed working in his group very much. Erik Anderson is always willing to answer any question or teach one how to do gold plating. I am grateful for the the figures on field distortion that he provided.

It is always fun to talk to Mark Schattenburg about all kinds of ideas, some crazier than others. Hopefully the x-ray telescope will be finished soon, so he will be in the lab more often. I’d like to thank him for the figures about holography that he lent me. All members of the NSL staff deserve many thanks: Jim Carter (a lab manager of superhuman ability and friendly character) for doing holography runs among many other things, Mark Mondol for helping with odd jobs and teaching me a bit of plumbing, Jeanne Porter for always having the right tool for any job, Rich Aucoin for his friendly advice and Bob Sisson for making masks. I’m quite happy to work with Scott Silverman, who is very knowledgeable and has an excellent sense of humour.

I thank all my fellow students for making the NSL such a nice place. I enjoy tremendously my collaboration with Vincent Wong and Jay Damask. Vince’s help has been invaluable to me. He has selflessly done enormous amounts of work and made splendid masks. Jay’s lucid explanations of complicated optics concepts are quite amazing, not to mention his jokes. Thank you both!

Special thanks go to all my friends. I will always be grateful to my family for all their love and support. I hope to be able to repay them some day.
I would like to thank IBM and the 6-A program for giving me the opportunity to work on such a rewarding project, and the Organization of American States for supporting me with a fellowship.
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Chapter 1

Introduction

Modern communications systems are required to handle ever increasing amounts of data, as more sophisticated applications are developed. The concepts of high definition television, video on demand, high fidelity digital sound, etc. will require communications media of remarkable sophistication in order to be implemented successfully. Arguably the most important difficulty to be overcome is the significantly higher data rates that the medium will have to cope with. Fiber optic communication links with extremely broad bandwidths can potentially satisfy these demands, but systems that efficiently utilize the available bandwidth are yet to be implemented.

One possible approach that permits more efficient utilization of the available bandwidth is its division among several narrower channels, onto which electronic devices can modulate signals. Each channel is assigned a center frequency or wavelength. Such a scheme is therefore denominated wavelength division multiplexing/demultiplexing (WDM/WDdM). Modern electronic systems can transmit/receive data at a maximum of several gigahertz, which is equivalent to a fraction of one Å $^1$ at 1.55 μm, a wavelength commonly used in fiber optic transmission systems. This implies that an large number of channels can be carried by a fiber optic link, but their center frequencies must be packed tightly, since the data-rate that a fiber can carry increases with the number of channels.

$^1$1 Å = 10$^{-10}$ meters
In order to achieve this objective, transmitters and receivers whose center wavelength and characteristic linewidth can be controlled with sub-Å accuracy are required. The distributed-feedback laser [1] and the integrated resonant channel-dropping filter [2, 3], can in principle achieve the necessary performance, but fabrication of these devices represents a challenge for current lithography technology.

Both kinds of devices rely on so-called distributed Bragg reflector (DBR) structures. These are made by etching grating corrugations on the top surface of a waveguide. The dimensions of the corrugations are required to be smaller than the wavelength of the light with which they are to interact; the spatial period of the grating is proportional to this wavelength. Two DBR structures appropriately spaced by a quarter wave shift form a resonator. Because of the reflective properties of DBRs, these resonators can yield high quality factors on the order of $10^5$ or greater in a semiconductor material system with less than 1 dB/cm of loss and a resonator length of roughly 0.5 mm, depending on the material properties.

The size of the features that compose these devices requires the use of a high resolution patterning technology. In order to optimize device performance, quarter wave shifts may be introduced at many points along the resonator gratings. The period of individual gratings must be controlled within tight tolerances if different channels are to be assigned center wavelengths that are close to each other. Furthermore, the gratings must remain spatially coherent throughout the length of the resonator for the device to function properly, if at all [4].

Electron-beam lithography (EBL) is capable of writing arbitrary patterns with resolution of tens of nanometers. Due to the aforementioned reasons, it is ideally suited to the fabrication of these filters. However, it suffers from a significant shortcoming: lack of sufficient pattern placement accuracy. A solution to this problem, a global fiducial grid, was proposed by Smith et al. [5, 6] and is the basis for the work described in this thesis. The results have been published in [7].

Chapter 2 lists some of the sources of error in an EBL system. Chapter 3 outlines the fabrication of large-area spatially coherent structures that can be used as references to eliminate placement error. Chapter 4 describes the method of spatial-phase
locking, proposed in order to align written patterns to the reference. Chapter 5 is an account of the process used to produce x-ray masks with spatially coherent gratings that are adequate for the fabrication of high-performance optoelectronic devices.

The EBL system used to develop these techniques is IBM’s VS-6, a vector-scan system used for lithography in the 10 nm - 1 μm regime [8]. Its electron-optic characteristics have been optimized for high resolution and low deflection distortion. It is usually operated at an accelerating potential of 50 kilovolts and is capable of producing an 8 nm spot at the substrate plane. Interference in the form of electronic noise, vibrations, electromagnetic fields, etc. have been reduced to a level that is adequate for nanometer scale lithography [9]. A digital signal processing subsystem has been incorporated to achieve fine overlay between lithographic levels that span the field of view of the system. Mechanical interference has been greatly reduced by the use of a locking stage [10, 11].
Chapter 2

Distortion in electron beam systems

In the 1970’s, it was widely believed that the very fine resolution attained with electron beam lithography (EBL) made it a very likely candidate to replace conventional photolithography in integrated circuit fabrication, once the latter had reached its resolution limit (see for example[12]). However, two significant shortcomings have prevented EBL from becoming a viable manufacturing technology: Low throughput, as well as lack of adequate pattern placement accuracy [13]. The sources of these are described in this chapter.

2.1 Basics of electron beam lithography

2.1.1 The electron-optical system

An EBL system is in essence a scanning electron microscope, modified to perform lithography (see Fig. 2-1). A demagnified image of a source is produced on the surface of a substrate by a set of lenses. Electrons are extracted from the source and accelerated towards the sample by a potential difference. The lenses, which consist of magnetic or electric fields focus the electron beam to a small spot on the substrate. The image can be shifted by applying electric or magnetic fields transversely to the
Figure 2-1: Schematic view of a typical electron beam lithography system.

trajectory of the beam, the magnitude of the field determining the amount of shift. The beam can thus be deflected along a Cartesian coordinate system by means of two orthogonal deflection fields. The beam is blanked by a pair of electrostatic plates that deflect it onto an obstruction, thus preventing it from impinging on the substrate and "turning it off".

By integrating all these elements in an electron optical column, arbitrary patterns can be created on the substrate plane. The sample is coated with a material sensitive to electron irradiation. The beam is turned on and off under computer control, as well as scanned in such a way that areas of any shape can be selectively irradiated,
thus creating the desired image on the substrate.

2.1.2 The stage

It is not possible to deflect the beam more than a few millimeters and keep it focused on the sample plane without running into serious difficulties. Modern integrated circuits can be 1-2 centimeters on the side and are fabricated in large quantities on substrates that can be as large as 20 cm. Therefore, if electron beam lithography is to be of practical use, a different approach has to be taken. In order to be able to pattern large areas, the substrate is put on a movable stage and appropriately small areas, or fields, are exposed. Large area patterns are “stitched” together from small fields. To this end, stage position is typically measured by a laser interferometer. Modern state-of-the-art interferometer position transducers boast resolutions of 5 Å. In principle it should be possible to place features with this accuracy, but in practice several factors severely restrict the pattern placement accuracy of an EBL system. Any deviation from the highly idealized model outlined above is termed distortion.

2.2 Kinds of distortion and their sources

There exist various phenomena, which adversely affect the pattern placement capabilities of an EBL system. They can be classified in two broad categories: those that are intrinsic to the design of the machine and those that are caused by unwanted disturbances in its surrounding environment. It is in principle possible to arbitrarily increase the system’s accuracy by insulating it from its surrounding environment and thereby making it capable of fine positioning, but such an approach will almost certainly make its cost prohibitively expensive. The environmental effects can be lessened by placing the machine in a room whose conditions are carefully controlled, also with great expense.

When a pattern written by EBL is examined to determine pattern placement accuracy, two classes of errors will be apparent.

a. Those that arise from incorrect placement of the substrate with respect to the
Figure 2-2: Example of interfield error: high magnification view of a grating composed of two stitched e-beam fields. At the field boundary, the space between two lines is larger than the others, indicating that a stitching error has occurred.

electron beam column, or equivalently, of the field with respect to the substrate. These imprecisions will manifest themselves as abrupt changes in the position of the features at the boundaries between fields and are denominated **interfield** or "**stitching**" **errors** (see Fig. 2-2).

b. Within one field, feature placement will differ from the ideal. These are called **intrafield errors**.

### 2.2.1 Interfield distortion

The sources of mismatch between field boundaries include the following:

1. Miscalibration of field magnification with respect to the stage coordinate system. If the field size used is larger than the distance that separates two fields,
as measured by the interferometer, there will be an overlap; similarly, if it is smaller, a gap will occur.

2. Rotation of field axes with respect to stage motion axes, which will result in gaps and overlaps at different places along the field boundaries. Rotation and magnification can be calibrated to the coordinate system defined by the laser interferometer and therefore be made small.

3. Errors in the detection of the stage position, with numerous causes. First, the stage will typically be designed to move along two perpendicular axes, namely \(x\) and \(y\). However, movement along other degrees of freedom (\(z\)-translation, roll, pitch and yaw) cannot be completely eliminated and is not usually monitored\(^1\). For example, VS-6 shows considerable yaw, but only monitors displacement along two axes; the errors that result are quite significant. Second, Abbé error: for some mirror geometries, when the sample and the laser beam are not in the same plane, measuring the position of the mirror does not exactly give the position of the sample. Third, the mirrors that act as reference for stage position measurement are not perfectly flat on a fine scale. Optic component manufacturers quote flatness error specifications of \(1/20\)th of the wavelength of light (\(\lambda/20\)) [14], while accuracies as high as \(\lambda/100\) are achieved at the high end [15], numbers which translate to 25 nm and 5 nm respectively, for a wavelength of 500 nm. Pattern placement that relies on the interferometer as a reference cannot be better than the flatness of the mirror, making this item a severe limitation for nanometer placement. Fourth, the laser interferometer has finite resolution, so that it introduces a quantization error; as mentioned above, this error can be made insignificant by utilizing the latest equipment.

4. Thermal expansion (drift): The interferometer elements are held in place by parts that will expand and contract with differences in temperature. For example, if the interferometer beamsplitters are held by the top plate of the chamber,

\(^1\)most new systems monitor yaw by using a 3-axis interferometer system
10 cm away from the polepiece, the distance between them and the polepiece, is given to first order by

$$d = d_0(1 + \alpha T)$$

(2.1)

where $d_0 \approx 10$ cm, $\alpha = 12 \cdot 10^{-6}$/°C for iron and $T$ is the temperature in °C. This distance will therefore have a temperature coefficient of 1.2 µm/°C. Clearly, this is an unacceptable figure for placement of features of sub-µm dimensions; the temperature needs to be controlled to 1/100 °C or better, or materials with much lower thermal expansion coefficients have to be used. Furthermore, the measured stage position is not necessarily equal to the sample position, since the sample is merely fixed onto the stage and is not a part of it. As both objects are not made of the same material, the difference in thermal expansion coefficients can cause the sample position to drift with respect to the stage.

5. Drift of electrical sources, also due to thermal effects.

An experiment to estimate the amount of interfield distortion was carried out with VS-6, which was not designed for absolute pattern placement, but for writing nanometer scale devices over small areas and is not temperature controlled. The position of a small, but distinctive feature was measured repeatedly using the laser interferometer as the reference, during a period of approximately 50 hours. The results are plotted in Fig. 2-3. The extremes differ by as much as 6 µm, but there are no abrupt changes from one measurement to the next, with the exception of the first few, where the sample holder, initially colder than the rest of the elements inside the chamber, was coming into thermal equilibrium. From there on the errors in $x$ and $y$ are almost identical, which suggests uniform expansion and contraction of the different mechanical components of the system with temperature changes. Also, the measured positions can be seen to increase as the temperature of the laboratory rises during the day and to decrease during the night. The plot is not a sinusoid due to the fact that average temperature varies from day to day. These data imply that a
Figure 2-3: Plot of the x and y positions of the same feature, measured as a function of time. The origin is arbitrary.

measured positions can be seen to increase as the temperature of the laboratory rises during the day and to decrease during the night. The plot is not a sinusoid due to the fact that average temperature varies from day to day. These data imply that a large fraction of the field positioning errors are due to thermal drift, to the effect that field position varies slowly and smoothly.

2.2.2 Intrafield distortion

While one particular field is being written, the stage remains stationary and times are relatively short, so mechanical factors have less of an influence, although they remain significant. Mostly, errors are introduced by limitations in the electron-optical system and the electrical sources that drive it. Among the possible sources of error are:
1. Electron-optical distortion, due to aberrations in the lens and deflection fields. Linear deflection of the beam is difficult to achieve except for very small deflection amplitudes. At larger amplitudes, non-linearity of the deflection fields starts to become significant. Also, the aberrations of the focusing lenses can cause an off-axis ray to deviate from its intended destination. From these arguments, it follows that the spot is no longer being moved along a Cartesian coordinate system on the sample, with the discrepancies becoming larger as the beam is deflected more from its axis of travel.

2. Miscalibration of digital-to-analog converters (DACs), which manifests itself as nonlinearity in the output. Instead of a steadily increasing staircase, with steps of the same magnitude, one obtains jumps as more significant bits are engaged, due to the fact that the amount of voltage each bit contributes is different from the appropriate value.

3. Electrostatic charging of column and sample, which produces spurious fields that deflect electrons from their trajectories [16]. As the charge accumulated becomes large, the electric field may break down, removing the charge. Thus, the electron beam will slowly shift away from its intended position and suddenly jump back as spontaneous breakdown occurs. This is clearly undesirable.

4. Thermal expansion and drift, described in the previous section. They can introduce intrafield distortion if the writing time for one field is long.

Fig. 2-4 illustrates intrafield distortion, measured with a high resolution technique [17]. The first plot indicates intrafield distortion of a field measuring 100 μm on the side previous to calibrating the deflection DACs. The errors due to the miscalibration of the DACs are quite obvious, as clear jumps can be seen in the center of the field, most notably in the y-direction. Smaller jumps occur where the next most-significant bit changes, that is, at $x = 25, 75 \, \mu m$ and $y = 25, 75 \, \mu m$. 
Figure 2-4: Distortion maps of a 100 μm field, before calibration of the deflection DACs (a) and after (b). The length of the arrows is proportional to the magnitude of the error. Errors in the most significant bits are easily seen in (a), before the DACs were calibrated. After calibration, intrafield distortion has been significantly reduced.
After having calibrated the DACS, these errors have become quite small, as shown in the second plot, and electron-optical distortion may be starting to become apparent at the edges of the field, although it is mostly absent. Therefore, if high accuracy pattern placement is desired, field sizes smaller than 100 μm should be used to eliminate intrafield errors.

2.3 Error correction: a daunting task

In order to manufacture very large scale integrated circuits with sub-100 nm minimum feature sizes, absolute pattern placement accuracy within a fraction of this figure is required over an area of several cm². This requirement has not been satisfied by an EBL system to date. The fabrication of periodic structures for some optoelectronic devices imposes even stricter absolute placement requirements, although the area that have to be patterned is smaller. These requirements have not been satisfied by an EBL system to date [18, 19, 13].

As has been shown, the identifiable sources of distortion are quite varied. It can be argued that it would be extremely difficult, if not impossible, to account for all sources in a model in order to eliminate the unwanted effects that they give rise to. These difficulties arise because the important parameter, sample-to-beam-displacement, is not monitored directly and one has to rely on secondary referencing by measuring the position of the stage with an interferometer² and try to extrapolate from this measurement the information needed. If the beam can be made to interact with the sample in such a way that information is provided about their relative position, the problem has been solved. An approach that constitutes such a solution is described in subsequent chapters, as well as its application to precision nanofabrication.

²or tertiary, since the position of the stage is not being measured either, but the position of the mirrors attached to it
Chapter 3

Global Fiducial Structures

The problem of beam placement with respect to the sample is solvable if the surface of the latter is modified in such a way that a signal may be obtained, which varies as a function of spot position. This signal can then be processed to extract the appropriate positional information and fed back into the deflection subsystem to correct for any deviations from the intended spot position. In this way, a feedback loop will be put in effect, which will actively correct for any one of the multitude of errors that can arise in such a complex electromechanical system. As long as a reference of the required fidelity can be fabricated on the sample and the position of the beam relative to it can be determined with enough accuracy, the system will be able to satisfy the pattern placement tolerances without making similarly strict demands on the design of the mechanical and electronic components of the system, as well as environmental control.

Some physical phenomena are measured and controlled more easily than others. This has led, for example, to the definition of the standard unit of distance, the meter, in terms of the time and the speed of light: One meter is the distance that light travels in vacuum in 1/299792458 of a second. This is due to the fact that time can be measured much more precisely than distance.\footnote{Time is defined in terms of the resonant frequency of cesium atoms [20].}

Similarly, the construction of a high fidelity reference for precise pattern place-
ment should rely on physical phenomena that can be controlled with a high degree of precision. Such a fabrication process has been developed over many years now [21, 22, 23, 24] and will be briefly described here. This technique, called holographic lithography, provides tight control of the parameters that determine the characteristics of the reference, although it introduces a few artifacts, which can nonetheless be corrected.

It should be pointed out that fabrication of the reference and alignment to it during e-beam writing are independent issues and will be treated separately. Alignment will be discussed in the next chapter.

### 3.1 Holographic lithography

If two mutually coherent waves propagating in opposite directions are superimposed the result is a standing wave, whose peaks and nodes remain stationary in space. If this standing wave can be imprinted on a substrate, a periodic structure (a grating) will result, which can serve as a reference.

This concept has been implemented in the following manner: A beam from an argon ion-laser (λ=351 nm) is split into two beams, which are then directed by a set of mirrors so that they recombine at an angle 2Θ (see Fig. 3-1), producing a lateral standing wave on the surface of the substrate with period \( p \) given by

\[
p = \frac{\lambda}{2\sin\Theta}
\]  \hspace{1cm} (3.1)

In the previous equation, the only parameters to be controlled are the wavelength of the light \( \lambda \) and the half-angle of intersection \( \Theta \). The emission characteristics of a laser can be controlled very accurately and angles can be measured with a precision of a fraction of an arc-second [15], making this an extremely controllable process.

Due to the coherent nature of the laser light used, any spurious reflections and scattered light that reach the substrate will degrade the quality of the resulting grating. To prevent this, a pinhole or spatial filter measuring only a few \( \mu \)m in diameter is inserted in both arms of the system, as shown in Fig. 3-1. Also, the path between
Figure 3-1: Schematic of the system used for holographic lithography. A UV laser beam is split into two arms, which are spatially-filtered and recombined to form a standing wave at the substrate plane. The feedback system described in the text keeps the standing wave pattern stationary despite disturbances.
the spatial filters and the substrates is enclosed by non-reflecting surfaces (not shown in the figure).

Although the standing wave on the substrate is in principle stationary, it is in actuality subject to interference in the form of vibration of the optic elements and local changes in the refractive index of air due to temperature differences, air currents, etc. In order to eliminate this interference, a feedback mechanism has been built that "locks" the standing wave pattern in space. A beamsplitter and two photodiodes are attached to the substrate holder to form an interferometer. The difference in the intensity of light detected by the photodiodes is amplified and fed to an electrostatic modulator (Pockels cell) which changes the phase of one of the arms of the system relative to the other. If a negative feedback loop is set up in such a way that the intensity at both detectors is equal, the standing wave on the substrate is locked in place, thereby greatly improving the quality and repeatability of the grating pattern.

To physically imprint the standing wave onto the substrate, a photosensitive polymer (photoresist) is used, whose dissolution properties in a developer are changed as a function of the intensity of the light is has been exposed to. Conventional photoresist used for ultraviolet photolithography is very well suited for holography.

However, since the refractive indices of the resist and the substrate are not the same in general, the interface will reflect light, causing unwanted vertical standing waves in the bulk of the resist film. Therefore an antireflection layer is put between the resist and the substrate. If the resist film is thin enough the distance between nodes of the vertical standing wave will be much larger than the thickness of the film and the antireflection layer can be eliminated. The process, which is illustrated in Fig. 3-2 produces a resist grating that can serve as a basis for a one-dimensional reference. If a two-dimensional reference is needed, two exposures can be done at right angles. It is necessary for the substrate holder to rotate 90° exactly, as described in [17] if a good orthogonal reference is desired. Examples of a resist grating and a grid are shown in Figs. 3-3 and 3-4.
Figure 3-2: Processing steps used to obtain a thick resist grating (a) and a thin grating (b).
Figure 3-3: Scanning electron micrograph of a typical resist grating.

Figure 3-4: SEM of a grid in resist.
3.2 Distortion of the reference

Unfortunately, a reference grating or grid fabricated by holographic lithography does not form a perfect cartesian reference system. However, any shortcomings found to date can be eliminated or accounted for. These references possess the property of long-range spatial-phase coherence, which implies that the position of any point in the reference structure can be calculated a priori, subject to a few minor constraints.

The wavefronts that originate at the spatial filters are not plane and the standing wave produced by interfering them is not a perfect one-dimensional sinusoid. They can be approximated as spherical waves if each arm of the holographic system is long. As the arms are made longer, the wavefronts interfering at the substrate planes will approach plane waves. Fig. 3-5 shows the calculated distortion of a grating produced by placing the spatial filters 1 m away from the substrate. Each contour indicates the location on the substrate at which the position of the grating lines is off by an integer number of periods.

However, even though the the reference is not perfectly Cartesian, the position of the individual reference features can in principle be determined and a holographic reference can be mapped to a perfect Cartesian system, thanks to the property of long-range spatial-phase coherence. Alternatively, the reference can be made so that it approaches a Cartesian one more closely by making the arms of the system arbitrarily long, by collimating the radiation from the spatial filters by means of lenses or by deforming the substrate so that aberrations are canceled. The question of how to diminish and measure these exceedingly small errors remains open.

3.3 Reference structures

A holographically produced periodic structure, grid or grating, must be fabricated on the substrate so that it provides feedback on the position of the spot during e-beam writing. Many schemes are possible, depending on the nature of the substrate and the signal that is to be collected for feedback purposes. The reference should be
Figure 3-5: Contour map of the distortions introduced by the use of spherical waves instead of plane when fabricating a grating using $\lambda = 351$ nm and $\Theta = 61^\circ$. Each contour indicates the position on the substrate where the calculated grating differs by one period from the ideal grating.
simple to fabricate on the substrate surface and should provide a strong signal, so that long sampling periods are not required in order to acquire a good signal from it. It must be kept in mind that the reference (hereafter referred to as the grid) is sampled during writing, so that the electron-sensitive resist will develop out if exposed with enough dose. In the optimal case, sampling the grid can be effected while keeping the exposure dose below the clearing threshold, so that partially exposed areas will remain unaffected after development. Then, the grid can be sampled before writing a field and corrections made to eliminate inter-field errors. A feedback signal can of course also be collected during writing, and additional corrections made in real time or with little delay. Since the position of a feature is defined by its edges, it is possible to expose the center area of it and sample the reference at the same time. Then, after the beam position has been aligned to the reference, the edges can be defined.

3.3.1 Imaging modes of an EBL system

Scanning electron beam lithography systems generally use three types of methods to image a substrate for the purposes of focusing and registration to already existing features, which are depicted in Fig. 3-6. The finely focused beam is used as a probe and different materials can be distinguished by the effect that the collisions of the highly energetic electrons have on them.

If the material has a high atomic number some electrons will collide with one or more massive nuclei and recoil in a direction roughly opposite to the one they had before the collision with high probability. This produces backscattered electrons, as shown in part (a) of the figure. These electrons can be collected by a detector placed roughly on top of the sample (for this purpose an annular detector is typically mounted on the polepiece of the final lens so that the beam can pass through but a large fraction of backscattered electrons from the sample hit it), which will output a voltage proportional to the backscatter rate and energy of the electrons hitting it.

Regardless of the nuclear mass, there exists the probability that an atom will be stripped of one or more of its electrons by the energetic particle. The electrons that leave the sample in this manner are called secondary electrons and have in general
Figure 3-6: Some methods used for imaging a substrate with a scanning electron beam. Backscattered electrons are collected by a detector placed directly above the substrate. Secondary electrons are collected by an electrostatically biased detector, so that it attracts the low-energy secondaries. Electrons that traverse a thin membrane are collected by a small detector directly under the substrate.
low kinetic energies, so that they cannot travel far through a solid before losing their energy. Therefore, only secondary electrons that originate close to the surface of the sample can be collected by a detector. Different materials yield secondary electrons at specific rates for the same quantity of primary (beam) electrons, so that one can distinguish a change in the signal when the probe traverses the boundary between two features made of different materials. A typical scheme for the detection of secondary electrons is depicted in part (b).

If the primary beam is impinging on a very thin substrate (a membrane), each electron will go through the membrane with high probability. If the electrons go through a region of the membrane where elements of high atomic number have been placed on its surface, scattering events will take place and the beam will spread across a larger angle than it would if the high atomic number material were absent. Thus, if one places a small detector in the line of sight of the beam, it will collect more electrons where the beam is impinging on a region of low atomic number, and less in the contrary case. This method, which has been called Z-contrast, is illustrated in part (c).

The ideal method to collect a signal from the reference grid with a high signal-to-noise ratio depends very much on the application, i.e. the characteristics of the substrate being patterned. Due to the fact that one can only obtain surface information by detecting secondaries, this imaging mode is not used in general when performing registration of one lithographic level to another, since the features from the previous levels are covered with resist at the time of the exposure. The preferred measurement for this purpose is backscatter yield. However, if the fiducial reference is put on the surface of the resist and it is constituted of alternating areas with low and high secondary electron yield, then this measurement will result in high signal to noise ratios, because the yield of materials for this type of signal is generally quite high. If the reference is to be underneath the e-beam resist layer, then it should be made of material with a high average atomic number. Depending on the thickness of the substrate, backscattered or transmitted electrons can be used to sample it. For a thin enough membrane and an adequate detector geometry, transmitted electrons
will result in a higher signal-to-noise ratio.

Fig 3-2 shows how a holographically exposed reference can be placed on substrate for backscattered/transmitted (a) or secondary electron detection (b).

In (a), the substrate is coated with a thin film that will serve as plating base. Next, an antireflection film is put on top of the plating base, followed by photoresist. The resist is exposed in the holographic system and developed, thereby producing a grating. As pointed out before, if a grid is needed, then two orthogonal exposures are required before development. SiO₂ is shadow-evaporated, so that the resist lines are covered with a mask resistant to the subsequent reactive ion etching step, where the antireflection coating is vertically etched away in the regions between the resist, leaving the plating base exposed. The sample is then electropolished in a gold solution using the etched ARC as a mold. Next, SiO₂, resist and ARC are removed, as they are not needed anymore, and the sample is coated with a layer of e-beam resist. For high resolution work poly(methylmethacrylate) (PMMA) is often used. The high atomic number of gold makes it ideal for backscattered or transmitted electron imaging. This process is compatible with the fabrication of absorber patterns on x-ray masks [25]. If secondary electron imaging is chosen, then a process similar to the one outlined in part (b) can be used. The substrate is coated with the e-beam resist and a conductive layer is put on the surface. This conducting layer should be very thin, so as not to disturb the path of the electron beam as it penetrates into the sample. A very thin film of photoresist is put on top of the conducting layer. It is subsequently exposed and developed, leaving a reference on top of the conducting layer. Photoresist, being an insulator, will have a very low secondary electron yield and should produce a high contrast signal in combination with the conducting layer. These are just two possible methods, which are intended to illustrate the flexibility of the holographic patterning technique.
Chapter 4

Spatial Phase Locking

The previous chapter described how global references of high fidelity can be produced. These are structures with periods typically of 0.2 μm. Due to their periodicity, they are only useful if the position of the beam with respect to the sample is known within one half of a period. This is certainly within the capability of any lithography system that is equipped with an interferometer to measure stage position. The method used to accomplish fine alignment to such a structure is now described.

4.1 Signal acquisition

The signal chosen to perform the initial experiments was electron backscattering because, as mentioned before, it is the imaging mode most often used for registration of alignment marks and VS-6 is well set up for it. Moreover, the immediate objective was to fabricate x-ray masks with high quality gratings. A fiducial pattern made from gold was chosen for reference and backscattered electrons were most likely to yield a good signal.

Fig. 4-1 illustrates the signal path used to collect information from the sample. It is the same as was used for previous work on registration [26].

Backscattered electrons penetrate into a large area diode, which is reverse biased or unbiased. The energetic electrons create electron-hole pairs in the depletion region of the diode, which flow out of its terminals and produce a current. Depending on
its energy, a single electron creates many electron-hole pairs and the backscattered electron current is thus "amplified". The current of the diode is fed into a transconductance amplifier, the voltage output of which is further amplified and low-pass filtered. The resulting signal is fed into a Data Translation DT2851 frame grabber. A digital pattern generator, which creates the patterns that the EBL system writes, controls the beam deflection and blanking to sample points of the substrate in a raster scan fashion and provides a sampling clock to the frame-grabber, so that the signal is stored synchronously with the scanning of the beam and an image is formed. The image that this frame grabber collects is 512x512 pixels. An array processor performs image processing operations on the acquired image to extract the desired information from it. This image acquisition system has been used to achieve very fine overlay between different lithographic levels by using alignment marks for registration [26], albeit within a single field. This system is remarkably flexible, because digital image processing has been adopted. A large variety of algorithms can be implemented to extract information from the acquired images, limited almost exclusively by the designer's ingenuity. For this reason, no physical modification was required to implement alignment to a periodic reference; only modifications to the image processing software were needed.
Figure 4-2: Backscattered electron image of a gold plated grating on an x-ray mask membrane. The beam current used was 100 pA.

4.2 Image processing

Fig. 4-2 shows an image sampled from a 250 nm thick, 230 nm period grating fabricated by holographic lithography and gold electroplating on a 1 μm thick SiN_x membrane, identical to the ones used as masks for x-ray lithography. It is obvious to the eye that this reference has slight imperfections, which result in changes in signal intensity and ragged boundaries between lines and spaces. Any reasonable alignment technique should be immune to such “noise”, as well as electrical noise in the signal. Fig. 4-3 depicts a plot of the signal amplitude for a segment of the acquired image.

The two-dimensional Fourier transform may be taken of this image. The transformation is given by
Figure 4-3: Signal amplitudes of the image shown in Fig. 4-2 for $0 < n_1 < 63$, $0 < n_2 < 63$. 
Figure 4-4: Fourier transform of the grating image (magnitude). Sharp peaks corresponding to the DC, fundamental, first and second harmonics can be observed

\[ X(\omega_1, \omega_2) = \sum_{n_1=0}^{N-1} \sum_{n_2=0}^{N-1} x[n_1, n_2] e^{-j\omega_1 n_1} e^{-j\omega_2 n_2} \]  

(4.1)

In this case \( N = 512 \). The magnitude of the Fourier transform for the grating image is shown in part Fig. 4-4. The large peak at \( \omega_1, \omega_2 = 0 \) is due to the fact that all points of the image have a positive magnitude, resulting in a large average, or “DC” component. Discrete peaks can also be seen, corresponding to the Fourier components of the grating image, i.e. the fundamental and its harmonics. Since the image of the grating approximates a square wave in the horizontal, or \( n_1 \) direction, the frequency domain contains peaks along the \( \omega_1 \) axis. Due to the periodicity of the signal, the peaks are sharp and their amplitude is large, while the amplitude for the rest of the components is quite small.

The information needed can be extracted straightforwardly from this transforma-
tion. The spatial period of the grating can be measured by determining the position of the peaks in the magnitude of the Fourier transform, which denotes the spatial frequency of the grating relative to the sampling frequency. The angle of rotation of the grating with respect to the sampling grid can also be determined. Let $(\omega_{1o}, \omega_{2o})$ be the position of the fundamental component in the spatial frequency domain\(^1\). Then the angle $\Theta$ of the grating $k$-vector with respect to the $\omega_1$ axis is given by

$$\Theta = \tan^{-1}\left(\frac{\omega_{1o}}{\omega_{2o}}\right) \quad (4.2)$$

This corresponds to a rotation between the scan field and the reference.

Shift of the sampling grid relative to the reference is calculated from measuring the phase of the FT at the points where the maxima occur. The amount of shift is related to the phase by the delay theorem:

$$x[n_1 - m_1, n_2 - m_2] \xrightarrow{\mathcal{F}} X(\omega_1, \omega_2)e^{-j\omega_1 m_1}e^{-j\omega_2 m_2} \quad (4.3)$$

where $\mathcal{F}$ denotes Fourier transformation. Therefore, the shift of the image $x_s = x_{\text{actual}} - x_{\text{nominal}}$ can be calculated simply from

$$n_s = \omega_o \phi_s \quad (4.4)$$

where $\omega_o$ is the spatial frequency of a particular component. $\omega_o = \sqrt{\omega_{1o}^2 + \omega_{2o}^2}$ and $\phi_s = \phi_{\text{measured}} - \phi_{\text{nominal}}$. Only shifts along the direction of the $k$-vector of the grating are detectable. Also, $n_s$ need not be an integer number; the amount of shift $r$ is related to it by $r = n_s \cdot T_{\text{sampling}}$. This implies that shifts of less than one sampling period are detectable, the resolution being limited by the amount of noise in the signal. The extension to two dimensions (for a grid) is straightforward.

\(^1\)Since the frequency spectrum is symmetric for a real signal, there will also be a peak at $(-\omega_{1o}, -\omega_{2o})$
4.3 Frequency-domain based alignment

The measurements that can be effected by simply analyzing a few components of the detected signal in the frequency domain provide the elements for an alignment scheme that can correct for errors in position, magnification and rotation. The condition of alignment can be specified in terms of parameters obtained from the frequency domain, namely spatial frequency and phase of fundamental and harmonics. Since the phase of a Fourier component is a multiple valued function \((\phi = \phi + 2\pi n; n \text{ integer})\) of the shift, this technique can only detect shifts of less than half a period unambiguously, as was mentioned previously. However, this does not present a serious difficulty.

If the scan field is in the required position with respect to the reference, the phase of the signal components equivalently assumes a definite value. The field must be corrected until the phase assumes this value. Hence the term **spatial phase locking**.

An alignment system based on the principles described in the previous two sections was implemented using the signal acquisition and processing hardware shown in Fig.4.1. Transformation into the frequency domain was accomplished by using a two-dimensional fast Fourier transform (FFT) algorithm. The FFT algorithm is a computationally efficient way of obtaining the discrete Fourier transform of a finite sequence of points

\[
X(k_1, k_2) = \begin{cases} 
\sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} x[n_1, n_2] e^{-j(2\pi/N_1)k_1n_1} e^{-j(2\pi/N_2)k_2n_2} & 0 \leq k_1 \leq N_1 - 1, 0 \leq k_2 \leq N_2 - 1 \\
0 & \text{otherwise}
\end{cases} 
\]

(4.5)

for an \(N_1 \times N_2\) point sequence. The DFT is also a \(N_1 \times N_2\) point sequence where each point \(X(k_1, k_2)\) corresponds to a sample of the Fourier transform of the sequence, according to

\[
X(k_1, k_2) = X(\omega_1, \omega_2) \bigg|_{\omega_1 = \frac{2\pi}{N_1} k_1, \omega_2 = \frac{2\pi}{N_2} k_2}
\]

(4.6)
This limits the resolution in the determination of the spectral peaks to \( \frac{2\pi}{N_1} \) and \( \frac{2\pi}{N_2} \) for \( \omega_1, \omega_2 \) respectively. If there exists a magnification error, such that the peaks occur at locations in the frequency plane other than those sampled by the DFT, this error, combined with the finite extent of the sequence, will result in inaccuracies in the calculation of shift based on the phase [27]. This phenomenon can affect the performance of the algorithm considerably and should be avoided. In order to obtain a preliminary evaluation of an alignment algorithm based on the FFT, a series of experiments was performed.

### 4.4 Experimental data

The intent of these experiments was to determine how fine a shift can be detected by using the proposed alignment scheme, since interfield errors are arguably the most important source of distortion for patterns that span many fields. They can be corrected by shifting the field using the fiducial reference. Therefore, magnification and rotation of the field were not included in the alignment scheme as variables. Instead, they were carefully set so that the spectral peaks occurred at the sampling frequencies\(^2\).

Experiments were done in one dimension with a grating, in two dimensions with a grid and utilizing a sparse sampling technique (moire).

#### 4.4.1 One dimensional phase locking

An array of 256x256 picture elements was scanned. The sampling grid consisted of points separated by one beam step in both dimensions, which is a difference of one least-significant bit of the DACs that deflect the beam; in this case the field covers 16384x16384 beamsteps. The reference used was a holographically generated 250 nm thick gold plated grating on an x-ray mask membrane. The period of the grating was 230 nm, so the magnification of the system was adjusted for this period to be

\(^2\)These parameters were set by a moiré technique, which will be described below
equivalent to 32 beamsteps and the full deflection field measured 117.76 μm on the side. Therefore, the scanned area, or sampling window, measured 1.84 μm. The rotation was set so that the lines were horizontal, parallel to the $n_1$ axis. Once these calibrations had been made, the peak magnitude of the fundamental in the Fourier domain $X(\omega_1, \omega_2)$ was located at $(\omega_1 = \pm \frac{\pi}{16}, \omega_2 = 0)$, which corresponds exactly to $(k_1 = 8, 248; k_2 = 0)$ for the DFT $X(k_1, k_2)$, since $N_1 = N_2 = 256$ in eq. 4.6. The phase of this component was used to determine the shift of the sampling grid with respect to the reference grating and consequently field position. The alignment condition was arbitrarily defined to be when the phase of the fundamental is $\phi_{\text{fundamental}} = -\frac{\pi}{2}$, that is, when the image of the grating that includes only the fundamental can be expressed as $x[n_1, n_2] = \cos(\frac{\pi}{16} n_1 - \frac{\pi}{2}) = \sin(\frac{\pi}{16} n_1)$.

Thus, in order to align the sampling window to the reference, the field must be shifted in the $x$-direction until the condition

$$\angle X(k_1 = 8, k_2 = 0) = -\angle X(k_1 = 248, k_2 = 0) = -\frac{\pi}{2}$$

is met.

When random noise is present the alignment process becomes stochastic and perfect alignment is impossible. In order to quantify the accuracy of alignment, the probability density function (PDF) for this stochastic process is usually estimated, and statistical parameters quoted as a measure. To estimate the PDF that characterizes this particular alignment scheme, repeated measurements were taken with the reference stationary with respect to the electron-optical column. The stage remained locked to the top plate while repeated measurements were taken on the sampling window, and the apparent position of the reference grating was calculated. Unfortunately, as described in Chapter 2, the stage being stationary with respect to the top plate does not imply that the substrate is stationary with respect to the electron-optical system. Due to thermal drift, the apparent position of the reference shifts continuously, an effect which results in an error that grows linearly with time. This error was eliminated by electronically shifting the position of the field to the ideal location.
Figure 4-5: Histogram obtained from many acquisitions of the fiducial grating with the stage stationary. The position of the sampling grid was shifted electronically between each iteration to eliminate the effects of thermal drift as much as possible. The mean has been subtracted.

after each iteration of the measurement. When all measurements were plotted in the form of a histogram, a mean term appeared, which is identified with the amount of drift that occurred between each iteration. The results are shown in Fig. 4-5. The mean term associated with thermal drift has been subtracted from the data. The calculated standard deviation is $\sigma_y = 0.05$ beamsteps (BS) = 0.3 nm, since 1 BS = 7.2 nm. The beam current used for this measurement was 100 pA, which is larger than what is used for high resolution lithography with this system, but is quite adequate for writing patterns in the 100 nm domain. The high beam current, together with the thick gold reference used, which scatters a large portion of the incident electrons back into the detector, provide a high signal-to-noise ratio (SNR). The SNR calculated from a typical image at this beam current is 62 dB. The aspect of the grating image is shown in Fig. 4-2
Table 4.1: 1-D standard deviations measured for different beam currents

<table>
<thead>
<tr>
<th>$I_{\text{beam}}$ (pA)</th>
<th>$\sigma_y$ (beamsteps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>75</td>
<td>0.06</td>
</tr>
<tr>
<td>50</td>
<td>0.07</td>
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<tr>
<td>25</td>
<td>0.08</td>
</tr>
<tr>
<td>10</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Similar measurements were taken at different beam currents, which effectively varied the SNR [28]. At lower beam currents the SNR is also lower, and consequently the accuracy in the detection of the grating position decreases. Table 4.1 shows the standard deviation measured for different beam currents. Even at a very low current of 10 pA the standard deviation is less than 1 nm.

4.4.2 Two dimensional spatial phase locking

The same set of experiments was performed with a holographically generated grid on a silicon substrate, such as the ones used to measure field distortion by Anderson et al. [17]. It had spatial periods $p_x = p_y = 195$ nm, as measured with VS-6. The field correction parameters were adjusted so that the field measured 99.94 μm or the side and its axes were aligned with the grid’s. A sample image of the grid is shown in Fig.4-6

Two fundamental peaks appear in the frequency domain, on the $\omega_1$ and $\omega_2$ axes. The phase of each one of them was used to calculate the shift in the $x$ and $y$ directions respectively. Again, repeated measurements were taken with the stage stationary. The field position was corrected after each iteration to diminish the effects of thermal drift. The resulting mean term was attributed to residual drift occurring between iterations and was subtracted from the data. The resulting distribution for a beam current of 100 pA is shown in Fig. 4-7 Standard deviations calculated for the $x$ and $y$ directions were $\sigma_x = 0.09$ BS $\approx 0.6$ nm, $\sigma_y = 0.07$ BS $\approx 0.4$ nm. The effect of beam current on position detection accuracy is shown in table 4.2
Figure 4-6: Backscattered-electron image of a gold-plated grid on a silicon substrate. A beam current of 100 pA was used.

4.4.3 Moiré spatial phase locking

Moiré techniques are frequently used to study distortion in electron beam systems [29, 30, 31, 32]. The moiré is in this case a sampling artifact. If a periodic structure is sampled at discrete points and the spatial frequency of the sampling grid is close to that of the structure, a beating of low spatial frequency occurs. In other words, the structure is being sampled below the Nyquist limit and aliasing occurs. To illustrate the preceding point, consider the following simple example: A continuous sinusoid of period $T_c$,

$$s(t) = \sin \frac{2\pi}{T_c} t$$  \hspace{1cm} (4.7)
Figure 4-7: Scatter plot of repeated acquisitions in two dimensions (using a grid). The mean terms in the x and y coordinates, attributed to thermal drift, have been subtracted.

Table 4.2: 2-D Standard deviations for different beam currents

<table>
<thead>
<tr>
<th>$I_{beam}$ (pA)</th>
<th>$\sigma_x$ (beamsteps)</th>
<th>$\sigma_y$ (beamsteps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>75</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>10</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>
is sampled at intervals with period $T_{\text{sampling}}$

$$s[n] = s(t) \bigg|_{t = nT_{\text{sampling}}} = \sin \frac{2\pi}{T_c} nT_{\text{sampling}} \ ; \ n \ \text{integer} \quad (4.8)$$

Let the sampling period differ from the continuous period by an amount $\varepsilon$:

$$T_{\text{sampling}} = T_c + \varepsilon \quad (4.9)$$

Then eq. 4.8 becomes

$$s[n] = \sin 2\pi \left(1 + \frac{\varepsilon}{T_c}\right) n = \sin 2\pi \frac{\varepsilon}{T_c} n = \sin 2\pi \frac{1}{T_{\text{moiré}}} n \quad (4.10)$$

The period of the discrete time sinusoid has become $T_{\text{moiré}} = T_c/\varepsilon$, so that if the sampling period is close to the period of the continuous time signal, the period of the moiré can become arbitrarily large.

The measurements discussed in sections 4.4.1 and 4.4.2 involved precise calibration of the sampling grid with respect to the periodic reference. This calibration was achieved by means of a moiré. A sampling grid of 512x512 points separated by 32 beamsteps in both the $x$ and $y$ directions was used. Then, the magnification of the field was adjusted until no variation could be measured across the sampled sequence, so that

$$T_{\text{moiré}} \gg 512 \Rightarrow T_{\text{sampling}} - T_c \ll \frac{T_c}{512}$$

Consequently, the peak of the fundamental was located exactly at the points in the frequency domain that were sampled by the DFT and no error was introduced by using the FFT algorithm to estimate shifts. The moiré technique can be used to obtain an amplification of the spatial period by sampling the periodic reference sparsely. This could also be done by increasing the magnification, but the number of electrons used to obtain a determined signal-to-noise ratio would be concentrated in a smaller area, thus increasing the areal charge dose and, if a sample coated with
e-beam resist is being imaged, the energy dissipated in the resist per unit area. The increase in exposure of the resist is due to the fact that the size of the beam is not infinitesimal, or conversely, that the point exposure distribution function for energy dissipation is not an impulse in space. If one convolves this point exposure distribution function with the impulse array that represents the sampling grid, the advantages of using a sparser sampling grid become apparent. Since the point exposure distribution decreases quite sharply as a function of radius [33], the areal dose practically does not diminish anymore once the sampling grid has been spread beyond a certain limit.

To reiterate, sparse sampling of a periodic structure is quite advantageous, because amplification of the period of the image occurs, while at the same time the areal dose needed to image the structure decreases. Thus, the SNR can be kept constant while the peak exposure dose is decreased and the resolution of the image is increased, which proves to be essential if one wishes to image a global reference without significantly exposing the resist, so that following a low dose sampling operation on the reference, field corrections can be effected and patterns written that are aligned to the reference. The aforementioned point is best clarified by example. Fig. 4-8 shows a two-dimensional moiré that was obtained by finely adjusting the field magnification so that $T_{\text{sampling}} = 195.76$ nm nominally in both $x$ and $y$ directions for a sampling grid of 512x512 points that covered the whole grid (equivalently, the samples were spaced 32 beamsteps apart). The periodic structure imaged was the grid used for the experiments reported in the previous section, with a nominal $T_e = 195$ nm. If equation 4.10 is used, then the moiré is required to have a period $T_{\text{moiré}} = 256$ picture elements, which is indeed the case. Thus, by spacing the sampling points 32 beamsteps and slightly decreasing the magnification, a virtual 8-fold increase in magnification was achieved. Therefore, any shift of the reference with respect to the sampling grid is magnified by a factor of 8.

Since the moiré pattern is also a periodic structure, the same alignment algorithm can be applied to it, as long as the magnification factor is taken into account when calculating shift as a function of phase. To demonstrate the efficacy of this method, experiments like the ones described in the previous sections were performed using the
Figure 4-8: Moiré image of the same grid obtained by sparse sampling. The slight errors introduced by the DACs are quite noticeable as bright vertical lines, due to the virtual magnification increase.
Figure 4-9: Scatter plot of the statistics obtained by spatially-locking the phase of the moiré. The measurements were taken at a beam current of 1 pA, i.e. two orders of magnitude less than for the measurements described previously.

moiré image, but the beam current was decreased to 1 pA. This resulted in standard deviations $\sigma_x = 1.0 \text{ nm}$ and $\sigma_y = 4.1 \text{ nm}$ (Fig. 4-9).

Even though the beam current was decreased by two orders of magnitude relative to the other experiments (and the peak dose by more, because of the sparse sampling), the detectivity of the technique, quantified by the standard deviation, did not suffer much, compared to the numbers in tables 4.1 and 4.2. The larger spread on the y-axis is attributed at the time this thesis is being written to a magnification error in the vertical dimension of the sampling grid, with the deleterious effects described above. No further experiments to prove or disprove this hypothesis have been performed.
4.5 Toward a fabrication technology for high performance optoelectronics components

The experiments reported here were intended to demonstrate that spatial phase locking, a frequency-domain based alignment scheme that is straightforward to implement and at the same time yields a high shift detectivity. Together with a high fidelity reference, this method is expected to be the base of a technology that can be used to fabricate devices that impose remarkably strict pattern placement specifications in one dimension. It has also been shown that the technique may be extended to two dimensions, required for general purpose planar fabrication of systems with very small critical dimensions. The method described in this chapter is by no means optimal, and performance will very likely improve if more sophisticated signal processing and collection mechanisms are used.

The following chapter describes the development of an electron beam patterning technology aimed at the fabrication of distributed-feedback optoelectronic devices.
Chapter 5

X-ray Mask Fabrication

Many types of optoelectronic devices rely on periodic structures that diffract light waves and therefore must have features of sub-μm dimensions. Fabrication of such structures is not feasible with conventional UV lithography technology and one must resort to "nanofabrication techniques". Fabrication of distributed Bragg reflector structures (DBR), the fundamental building block of these devices, using EBL and holography has been reported [34, 35, 36]. Each technique has advantages and disadvantages, when patterning of DBRs is considered. EBL has exceptional flexibility to fabricate arbitrary patterns, which in this case include: many phase shifts on one grating; precise changes in period from one device to another (desirable for the fabrication of wavelength division multiplexing systems). However, EBL lacks the placement accuracy needed to obtain optimum performance from devices such as the integrated resonant channel dropping filter [4], since features must be placed with an accuracy of a small fraction of the desired wavelength over relatively large areas.

Holography provides very good spatial phase coherence over relatively large areas (see chapter 3) and high throughput, but is restrictive in the sense that structures other than simple gratings become quite difficult to fabricate. Phase shifted gratings have been fabricated holographically, but the successful fabrication of abrupt phase shifts has not been found in the literature. Holography also lacks the broad process latitude that other high resolution techniques possess, mainly due to the sinusoidal exposure and the fact that the output of the laser source tends to drift with time.
In ref. [37] a combination of EBL with a high throughput replication step is used to generate a grating pattern, but does not address the problem of pattern placement. A simplified variant of spatial-phase locked EBL using a holographic reference was evaluated to be a possibly satisfactory solution to this problem, as it promised to combine flexibility in pattern generation with long range spatial phase coherence. To obtain high throughput, x-ray lithography, a high resolution mask replication technology [38], was included in the fabrication process.

5.1 Segmented references

If intra-field distortion is treated separately from interfield distortion and corrected, then it is argued that there is no need for a global grid. The following discussion is intended to support this assertion.

Intra-field distortion, as described in chapter 2, has deterministic components that are time invariant and can be eliminated by calibrating the field parameters using a high fidelity reference. Electron-optical distortion can be corrected by generating a distortion map as accomplished before [17] and deriving from it a lookup table so that the position of each feature can be modified when the pattern is designed, taking into account the distortion measured at this location. Subpixel positioning of a feature can be achieved by overlapping two features exposed at a fraction of the total dose in slightly different positions. The remaining time varying components can be considered negligible if their characteristic time constants are much longer than the time it takes to write a single field. If all these conditions are met, then it is only necessary to correct for errors in the placement of the field boundaries, that is, interfield distortion, which can be corrected by using a segmented fiducial pattern. The available area is divided into alignment and writing regions. The alignment regions have a positional reference produced by holographic lithography and therefore retain the property of long range spatial phase coherence. If one is willing to sacrifice the alignment areas then they can be sampled with a high areal dose to obtain a high SNR in the alignment signal. This concept is illustrated in Fig. 5-1
Figure 5-1: Conceptual depiction of the proposed two-dimensional segmented reference. The outlines of two e-beam fields are shown.

The segmented reference is used in the guise of conventional registration marks (see for example [26]). The area that the alignment regions occupy is a minor fraction of the available area. For example, if four alignment marks are used as shown in Fig. 5-1, each 256x256 beamsteps out of a 14 bit deflection field, the area allocated for alignment is 0.02% of the total area. Using a scheme such as the one proposed here, any electron beam system capable of performing mark registration and whose absolute pattern placement accuracy is less than one half of the reference's spatial period will be able to enjoy the benefits of long range spatial phase coherence and place features with high accuracy over large areas.

5.2 Grating fabrication using a segmented grid

The proposed solution for the fabrication of highly coherent gratings for optoelectronic devices is the following:
1. Pattern an x-ray mask membrane by electron beam lithography utilizing spatial phase locking and a segmented, holographically generated grating reference.

2. Replicate the pattern onto the device substrate by means of x-ray lithography

The electron optical properties of VS-6 are so good that after the DACs have been properly calibrated, no field distortion is discernible for a field measuring 100 μm or less. The thermal drift characteristics are such that the errors thus introduced can be neglected if writing of all the features within one field can be done in less than a few seconds, which is in fact the case. Therefore, a grating “stitched together” from many segments less than 100 μm long, using the coherent reference to correct for interfield errors is quite likely to satisfy the requirements for devices of good quality.

5.2.1 The reference

The fiducial regions designed for this one-dimensional problem took the form of horizontal bands, which contained a grating of vertical, gold plated lines. The free areas between the alignment bands are to be patterned with the gratings for the devices. These will hereafter be referred to as the device areas. the fiducial gratings were fabricated by the process described in chapter 3. Initially, the grating was patterned and gold-plated everywhere on the membrane, and the holographic mold removed. Next, a photoresist film was spun on the membrane and the device areas were defined by optical lithography. After the resist was developed, only the alignment regions were covered by a protective layer. The whole mask was then immersed in gold etching solution in order to leave no gold on the device regions. The resist was stripped and a new film of plating base was evaporated on the membrane. This process had many problems, most significant among them the fact that the gold etchant would undercut the protective coat of resist on the fiducial areas and etch the grating lines, as well as causing loss of adhesion, with the consequence that the gratings were very irregular and had little use as fiducial marks for EBL. Also, the number of process steps was quite large. This problem was soon solved by adopting a fabrication scheme that combines holographic exposure and conventional photolithography to pattern gratings on
selected areas only [39]. The process sequence is outlined in Fig. 5-2.

After stripping the SiO₂, resist and ARC, the mask was coated with poly(methylmethacrylate) (PMMA) and was ready for EBL. The thick gold gratings yielded a very high quality backscattered electron signal using VS-6 in imaging mode.

5.3 Electron beam patterning sequence

The alignment configuration used to lock the field to the fiducial reference is the following: four sampling grids of 256x256 beamsteps are defined close to the corners of the deflection field, so that they overlap with the alignment areas that are at the top and bottom of the writing region. The position of the sampling grids was calculated so that when the phase of the signal acquired in each of the sampling grids is locked to the required value, the field boundaries will be in the correct position, thus eliminating stitching error.

To simplify matters, the period of the fiducial grating was designed to be the same as that of the e-beam gratings, or very close to it. Gratings with periods on the order of 200 nm are used for devices made in an InP system. For Silica waveguides the period used is 511 nm. These grating periods are designed to interact with light that has a vacuum wavelength $\lambda = 1.55 \mu m$, widely used for fiber optic communications links.

The alignment procedure is as follows. The field size is adjusted using the laser interferometer as a reference, by looking at a distinctive feature on the membrane, such as a small defect on the gold plating. Then the stage is moved so that the feature moves with respect to the the field, and its apparent position change is compared to the position change of the stage, as measured by the laser interferometer. For example, suppose that when the feature was imaged initially, it was exactly at the center of the field and the fieldsize being calibrated was 100 $\mu m$ (100$\mu m = 16384$ beamsteps). Then the stage moves up and to the right by exactly 25 $\mu m$ as measured by the interferometer. If the field correction parameters are set up correctly, the feature should have shifted by exactly 4096 beamsteps up and to the right. Three
Figure 5-2: Process used for the selective patterning of gratings. After the holographic exposure, the resist is further exposed on the areas where no grating is desired, using a photomask. After development, no resist corrugations are present in these areas, so that they are fully covered by SiO₂, which prevents etching of the ARC layer. The ARC is the used as a mold for gold electroplating, yielding the desired structures.
parameters are corrected for in this way, if enough data points are taken. They are magnification, rotation and orthogonality. This procedure calibrates the axes of deflection so that they are parallel to the mirrors that the interferometer uses to measure stage position. It is very unlikely that, when the mask is mounted on the stage, the grating lines will be perfectly parallel to the deflection axes as calibrated. Therefore, further calibration is needed before patterns can be written. The mask is moved to a large area covered with fiducial grating, which was designed specifically to precalibrate the system before starting execution of a run. The grating is sparsely sampled and a moiré image is thus obtained. The rotation of the field is manually adjusted until the moiré disappears. A minor correction to the magnification may also be necessary. Pattern writing may proceed at this point. The mask is moved to the location where first segment of the pattern is to be written, in the middle of one of the device areas. The alignment areas are sampled at the locations defined by the sampling grids and the four arrays of 256x256 elements collected are stored by the frame grabber as a 512x512 image, which it passes on to the array processor. The phase of the fundamental is calculated for each of the four sub-images and the necessary corrections to the field are computed and applied. Due to inaccuracies in the calculation of the correction parameters, the alignment procedure needs to be performed several times so that the field is aligned as closely as possible. Within 3-5 iterations, no phase error can be detected, except for a small temperature drift component. At this point, the field is considered to be aligned to the reference and the e-beam grating segment is exposed in the center of the field. The mask is shifted by the length of the segment just written and the field is again locked to the reference before the next segment is written. This process is repeated until the whole length of the device grating has been written. The flexibility of the method lies in the fact that the patterns written in the device area can change from segment to segment. Figs. 5-3-5-7 outline this fabrication sequence pictorially.

The above process was used to successfully fabricate long gratings on an x-ray mask.
Figure 5-3: E-beam patterning process: this figure shows the aspect of the substrate previous to exposure. In this case, a test exposure, the substrate is bulk silicon. The alignment areas have been e-beam patterned with a 380 nm period, 300 Å thick gold grating, fabricated by liftoff.
Figure 5-4: The sample was moved for exposure of the first field. The fiducial grating was sampled using sampling grids defined at the four corners of the field. The 512x512 pixel frame contained the four 256x256 pixel images corresponding to each corner.
Figure 5-5: The displacement from the ideal position was calculated for each sampling grid and the rotation and shift of the scan field were corrected to lock the phase of the grating image. The first segment of the grating was then exposed.
Figure 5-6: The stage moved for exposure of the next segment and the alignment areas were scanned at the locations shown.
Figure 5-7: After the field was aligned to the desired position, the next segment of the grating was exposed. The period of the e-beam written grating was 230 nm.
5.4 Metrology

In order to quantify the magnitude of the stitching errors after the pattern was developed and plated two methods were used: a moiré scheme and a frequency domain phase step method.

5.4.1 The moiré method

The finished masks were examined with a Hitachi S800 SEM. This instrument uses a raster scan that is continuous horizontally, but discrete vertically. The mask was placed in the microscope so that the grating lines were horizontally oriented in the image. Then the magnification was adjusted so that the period of the raster scan was approximately equal to the grating period and a moiré resulted. The raster scan was rotated electronically by a small amount, so that the moire lines crossed the e-beam
grating area diagonally. Any phase discontinuity would thus result in a discontinuity in the moiré lines. The ratio between the horizontal period of the moiré and the amount of horizontal shift at the field boundary determines the magnitude of the stitching error. Fig. 5-8 shows the result of a failed attempt at spatial phase locking, a grating with rather obvious stitching errors. There is a discontinuity in the moiré at the field boundary. Fig. 5-9 shows the effect of an intentional 180° phase shift at the midpoint of the grating. This grating is made of 4 segments, and no discontinuity can be seen at the field boundaries. It is estimated that the moiré method can detect a stitching error of approximately 10 nm. Stitching errors in a pattern written by a conventional EBL can be seen by the same method in Ref. [36].

5.4.2 The phase step method

The moiré method does not provide sufficient detectivity to measure the stitching errors that occur when spatial-phase locking is used to diminish inter-field distortion. In order to make an accurate measurement of these errors special structures were incorporated into the written patterns. The stitched fields were made to overlap instead of butting against each other. Then, small gratings were written away from the middle of the field on both sides of the writing area, in such a way that the gratings written for one scan field would be adjacent to the ones written in the previous field. By design, if there is no stitching error, the two “outrigger” gratings will be sitting precisely side by side or, equivalently, their spatial phase will be matched.

The spatial phase of each grating can be measured using the frequency domain methods described previously. After the e-beam pattern was developed and plated, the mask was put in VS-6 and an image of the side-by-side outrigger gratings was sampled.

The accuracy of the spatial phase estimate depends on the sampling frequency. It can be therefore be improved by increasing the sampling rate, which in this case is equivalent to imaging the outrigger gratings with a higher magnification.

The inset in Fig. 5-10 is an 512x512 image of two such gratings, which were made to overlap. The overlap is clearly visible, due to the line broadening as a result of the
Figure 5-9: Illustration of the effect of a 180° phase shift (corresponding to a quarter of the wavelength of the light as it propagates through the device) on the moire of a grating. The grating was composed of 4 segments, but no discontinuity is discernible at the field boundaries.
Figure 5-10: Measurement of the phase of two adjacent outrigger gratings as a function of distance along a direction parallel to the grating lines, as depicted in the inset.

increased dose. Otherwise, no discontinuity is apparent to the eye. The spatial phase of each grating was estimated by taking the 1-dimensional FFT of each column of the image and extracting the phase of the fundamental. These values are plotted in the graph.

The spatial phase can be seen to increase linearly. This is due to the fact that the scan axes were not perfectly aligned to the gratings. Also the phase of the first few columns can be seen to differ from the straight line appreciably. This is attributed to the beam position settling after “fly-back” from the end of one row to the beginning of the other, since the image was sampled in a raster-scan fashion.

The phase step that indicates displacement of one grating with respect to the other is less than the noise, so that it can be claimed that the two gratings are displaced by less than 2 nm. Two straight lines were fitted to the data and superimposed on
the plot.
Chapter 6

Conclusion

The problem of pattern placement on a nanometer scale has been addressed by the work described in this thesis. Specifically, a technique to fabricate long, phase coherent gratings for optoelectronic devices has been developed.

Although the feature dimensions required for these gratings are quite readily achieved, their placement specifications are quite strict. Therefore, if such devices can be successfully made, the techniques developed for their fabrication will be applicable to high-resolution (sub 100 nm) lithography for future integrated circuits.

Preliminary experiments to determine the feasibility of a frequency domain technique in order to align to a holographically produced fiducial structure were performed and yielded promising results. X-ray masks for DBR structures were made and the devices are currently being fabricated.

Many aspects of this novel technology can be developed. To name a few:

1. Signal collection. In order to increase the signal-to-noise ratio, a secondary electron detector may be used. Alternatively the detector geometry can be optimized for backscattered or transmitted electrons. Monte Carlo simulation\(^1\) has shown that significant improvements can be attained [5].

2. Fiducial structure fabrication. As described in chapter 3, a different kind of

\(^{1}\)The simulation program developed by R. Ghanbari [40] was used for this purpose, in slightly modified form
reference is associated with a specific signal. The fabrication parameters need to be studied.

3. Signal processing Better performance can be expected from the use of more sophisticated statistical and signal processing algorithms than the one described here, that is a higher resolution may be attained with a lower signal-to-noise ratio.

4. Metrology. In order to evaluate the quality of the structures fabricated with this technology, new techniques need to be developed to measure absolute placement on a nanometer scale over large areas. One example is the phase-step method, used to quantify inter-field distortion. Another possibility is the comparison of the spatial phase of a periodic diagnostic structure (such as the outrigger gratings) and a subsequent holographic exposure superimposed on the e-beam pattern, with a slightly different spatial period. In this way, the phase of both structures can be measured and compared to an ideal model.

5. Evaluation and correction of distortion due to artifacts introduced by holography.

6. Locking in two dimensions. To fabricate patterns of a more general nature, a two-dimensional reference is needed. The segmented grid proposed in chapter 5 can be readily implemented and might be acceptable for x-ray mask fabrication.

Pattern placement requirements constitute a significant obstacle in the development of future fabrication technologies, which will produce higher device densities than those available today. The fiducial technique [5] that was the basis for the work presented here has been based may be a solution to this problem.
References


