Quantum state control interference lithography and trim double patterning for 32-16 nm lithography

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ABSTRACT

Double patterning has been proposed as a method to extend DUV lithography to 32nm and below. Here, a new form of double, or higher, multiple exposure technique is proposed. This new form of lithography uses a combination of Quantum State Control (QuSC) chemistry, Amplitude Modulation Optical Lithography (AMOL), and multiple micro-stepped exposures, without development between exposures. Further it is proposed to use this form of lithography (called QuSC-litho), to pattern a perfect grating grid, and to trim this grid with an earlier generation lithography tool. QuSC lithography uses short optical pulses to modulate a photochemical pathway while an intermediate is still in a defined vibrational excited state. This is a variation of Stimulated Emission Depletion Microscopy (STED) developed for fluorescence microscopy. With this approach immersion tools that produce 90 nm pitch and 45 nm features should be able to pattern levels with 22 nm features with a 1:1 line-space ratio. This approach is much less sensitive to misalignment than present double patterning approaches. Key to successful deployment of QuSC lithography is defining a resist photochemistry consistent with the QuSC process. There are several approaches to Photo Acid Generator (PAG) - matrix interaction that may be consistent with this approach.

Keywords: Microlithography, nanolithography, double patterning, quantum state control, and interferometric lithography

1. INTRODUCTION

Double patterning is gaining acceptance as a method for extending the resolution of immersion 193 nm Deep Ultra Violet (DUV) lithography to the 32 nm process node[1]. As practiced today double patterning involves splitting the exposure of a process level into two distinct and complementary patterns and performing a complete coat, align, expose, develop and etch process on each partial pattern. Features in each exposure are exposed and etched to produce features that are much less than ½ of the pitch that can be imaged by the numerical aperture of the projection lens. This is a process-intensive protocol that may significantly lower chip throughput. In addition, the overlay requirements for this class of double patterning protocols are significantly tighter than classical single level overlay requirements.

Here we propose a different approach to double exposure that is based upon novel resist exposure chemistry which may eliminate the need for a separate develop, align and coat step between exposures. This may enable higher throughput than previous double patterning protocols. In addition, the double exposure protocol outlined here is shown to relax second level alignment tolerances, potentially resulting in higher process yield levels. In summary, we propose to use a coherent inteferometric exposure to pattern a latent image of a grating in photoresist. Then without development we apply a second exposure, called a trim step, to cut and eliminate grating lines that together result in the definition the specific process level pattern. This approach has previously been proposed[2]. However, our interferometric step is based on a variation of Stimulated Emission Depletion (STED) Microscopy[3] that enables a micro-stepped double exposure of a grating that results in grating with a pitch significantly beyond the diffraction limit of the optics used. In addition, the micro-stepped exposures occur without a development step between

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exposures. As will be shown, the trim step has a relaxed required pitch resolution equal to twice the pitch of the interferometric grid, with double exposure overlay requirement similarly relaxed.

2. QUANTUM STATE CONTROL LITHOGRAPHY

The approach to double patterning described here depends upon controlling the distribution of photo activated initiator at spatial resolution beyond that the diffraction limit of the optics. In this regard we are motivated by a recent advance in Fluorescent microscopy called Stimulated Emission Depletion (STED) microscopy. The STED process uses two laser pulses at two different wavelength bands to provide resolution beyond the diffraction limit[3]. The optical system that enables this is outlined in Figure 1. In the classical case a Gaussian pump beam sets up a population inversion in fluorescent molecules at the diffraction limited focal spot of a microscope. Then a second beam of longer wavelength, called the stimulus depletion beam, is passed through a phase plate which shifts the phase of the central part of the beam to produce an overlapping annular focus at the focus of the microscope. (The phase plate may also be configured with ½ of the beam shifted in phase by pi radians to produce a bi-lobed focus that squeezes central dark node more in one axis than the other.) In the STED microscope the annular beam intensity is used to cause stimulated emission from the donut region around the central dark node. The higher the field in the annulus the closer the encroachment on the dark node and the smaller the central fluorescent region becomes. STED techniques have been shown to yield 16 nm half width fluorescent imaging. The dual wavelength exposure approach with a phase plate producing an annular focus around a Gaussian spot is also used in Amplitude Modulation Optical Lithography (AMOL) where a photochromic top layer is added on top of a photoresist to act as a transient annular apodizer to produce spot exposures in photoresist beyond the diffraction limit[4].

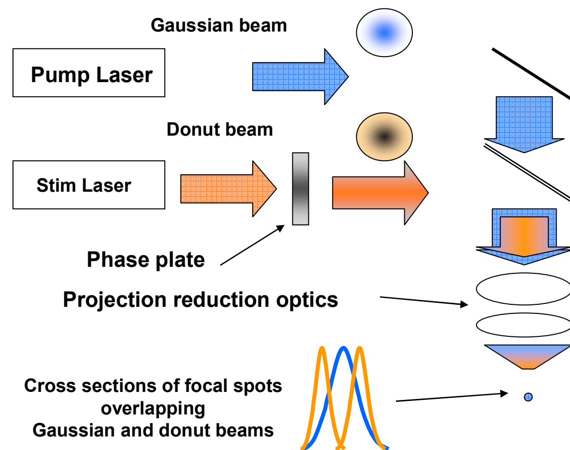

Figure 1. STED microscope optics and laser systems

As presently practiced STED microscopy techniques are not well suited to lithographic applications. Fluorescent molecules differ greatly from photo active initiators. In general molecules are fluorescent if:

– Absorption at a long enough wavelength for no photo dissociation

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– Intra-molecular transfer slow relative to radiative de-excitation
– Geometric factors such as planarity and rigidity limit energy transfer
– Generally there is no bond isomerization, or conformational change
– The molecule is not in intimate contact with energy acceptor molecules to allow intermolecular energy transfer
– Excited state lifetimes are generally greater than nanoseconds
– Fluorescent emission occurs from the lowest energy state in the excited state energy manifold
– The initial molecular structure is preserved after photon emission

In almost all cases these conditions do not apply to initiators in photo resists. Photoresist initiators such as Photo Acid Generators (PAG) in Chemically Amplified Resists (CAR) are designed for rapid irreversible structural conversion to the photochemical active state. This means the intermediates may be present only for 100's of femtoseconds to 10's of picoseconds; initiators are not isolated from there environment; and energy transfers and physical conformational changes are rapid. Although some resists may be fluorescent, the fluorescent quantum yields generally are relatively small. However, that is not to say that the photochemical active excited state cannot be interfered with. In fact, we propose to directly interfere with the photochemical excited state on the sub-picosecond to picosecond time scale. The proposed protocol should work with existing photo resist chemistries. Ultimately photo initiator chemistry may be optimized form the proposed exposure process. In particular we propose to coherently stimulate emission from specific vibrational excited states or an intermediate bottleneck state before photochemcially initiated irreversible structural change has occurred. In general, the techniques we propose fall in the category of vibrational quantum state control, and hence we call this approach Quantum State Control (QuSC) Lithography. Schematically the approach we propose is shown in Figure 2. The photochemistry is similar to the STED process except that specific excited states are excited are stimulated to emit light on a much shorter time scale and into specific ground state vibrational levels. It is also possible to perform direct quantum interference into excited levels, but this approach will not be discussed here. A key attribute of the annular illumination, as shown in Figure 2, is that the annular photons are less energetic than the absorption edge of the photoresist so as not to directly stimulate excited states. In addition, it is required that the energy difference between the exciting photon and depletion photon is equal to the energy of a vibrational state of the molecule. As such the stimulating photon may be called the "Stokes" photon. If multiple reversible intermediates may be depleted then this condition may not apply.

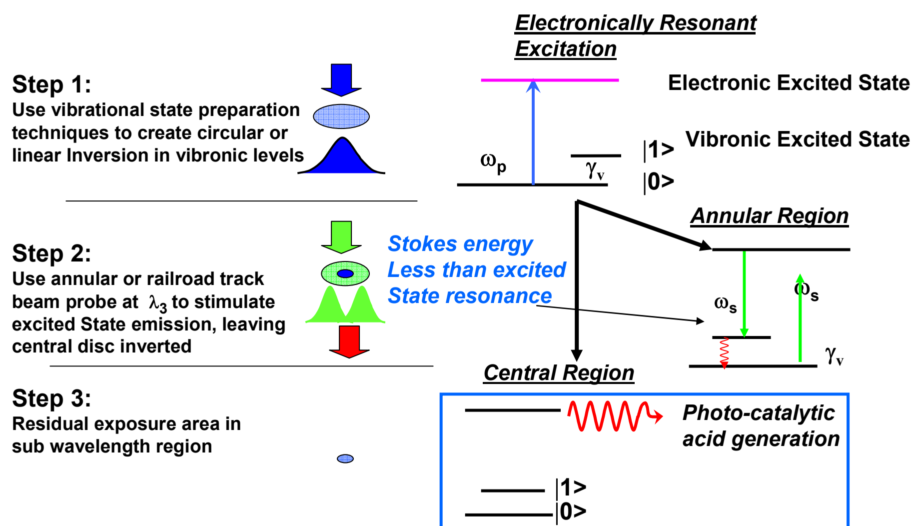

Figure 2. The Quantum State Control (QuSC) lithography process. The annular photons are called Stokes photons due to stimulated emission into an excited vibrational level, or depletion photons, or surround photons

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It is important to further discuss the pulse width and laser bandwidth requirements for the QuSC process and compare and contrast these to those used in STED fluorescent microscopy as well as those used in standard immersion DUV lithography. In STED microscopy nanosecond pulses are often used. As in the case of stimulated emission during dye laser activity, the STED process involves a 3-4 level molecular process. The stimulated emission occurs between the lowest fluorescent excited state and an excited state in the ground state manifold that has a low background population. This enables a significant population inversion. The population inversion in the annulus may be 5-10. The lower vibrational state depopulates in 100's of femtoseconds to picoseconds via the "Kasha" process. Therefore, the ratio of upper lifetime to lower lifetime may be 10^3 or more. Thus an annular optical field can drive the stimulated emission process into saturation and greatly narrow the central excited state flourscent peak. The entire process can occur over nanoseconds.

In QuSC lithography the ratio of excited state and lower level lifetimes may be on the order 1- 100, depending on the photochemistry. Therefore, the depopulation of the photochemical states in the annulus may not be as complete as in STED, as the probability of excitation from the lower state to the upper state may have a significant probability. In the limit the population ratio of these states is 1. The photochemistry of excited states and peak narrowing of photoactive states is shown in Figure 4. Because photoresist development is non-linear, even a worst case of only 50% reduction in photochemical excited states in the surround region, should reduce the latent image enough to enable double exposure with micro stepping, as discussed below. The longer the initial excited state lifetime the more the peak will be narrowed. Certain classes of CAR operate by matrix assisted excitation of the PAG. It is likely that these resist systems will be leading candidates for application of QuSC lithography techniques.

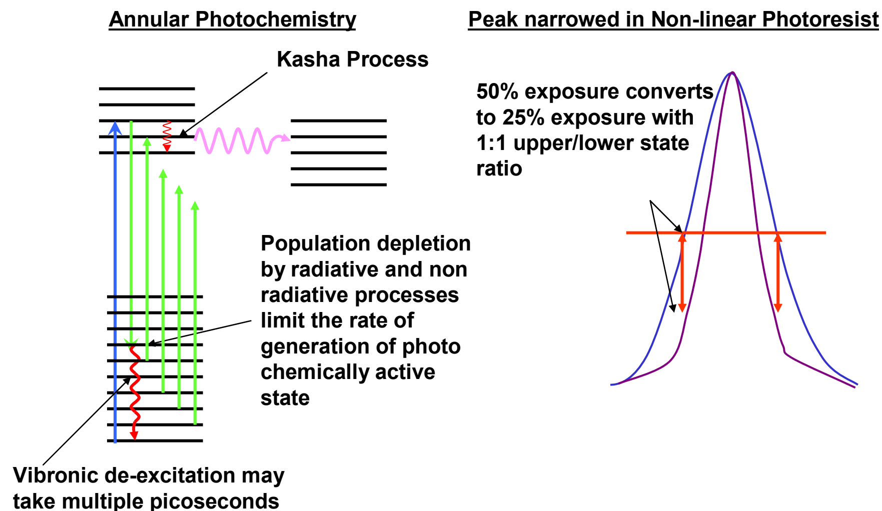

Figure 4. Photochemistry excited states and distribution of photochemical active states after depletion of the surround.

Is it important for excitation and depletion pulses to be of the same time scale as the excited state life time? That is probably not the case. As long as the goal is a 50% reduction in the special extent of photo activated initiator than longer pulses may be used, although ideally pulse widths should be on the same length as the excited state lifetime. Clearly the bandwidth of 0.1-100 picosecond pulses will greatly exceed the bandwidth of 70 nanosecond 0.6pm bandwidth excimer laser pulses that are in use in present DUV

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steppers. QuSC depletion pulses may have bandwidths ranging from 4 - 4000 pm for pulse widths of 100-0.1 picoseconds. These laser bandwidths are clearly larger than can be handled by state-of-the-art fused silica immersion scanner lenses. Therefore, we propose to implement QuSC lithography, in a different way using interferometric lithography with optics composed of Talbot prisms, or achromatic grating pairs[5] as shown in Figure 5B. The achromatic grating system can provide high spatial frequency imaging without the bandwidth constraints of standard projection reduction optics.

An example of a micro-stepped interferometric double exposure process, which is beyond the resolution limit of the interferometric optics, compared to a standard double exposure process as the diffraction limit is outlined in Figure 5A. Here it is assumed, as shown in Figure 5B, that grating interference pattern is laid down by a dual achromatic grating system. The surround or stimulation depletion, light is provided by a separate laser pulse that images to another grating that is π radians phase shifted in the image plane relative to the pump grating. The result of the first two wavelength exposure will be a narrowing of the peaks in the latent image of the center grating. Then the wafer is stepped ½ the period of the gratings and a second dual wavelength, peak narrowing, exposure is performed. After development the result will be a grating with twice the period of the fundamental period of the achromatic printing system. Using 193 nm short pulses, immersion exposure, dense period grating pairs and micro stepping, it should be possible to print 40 nm period gratings with 20 nm, or smaller, features.

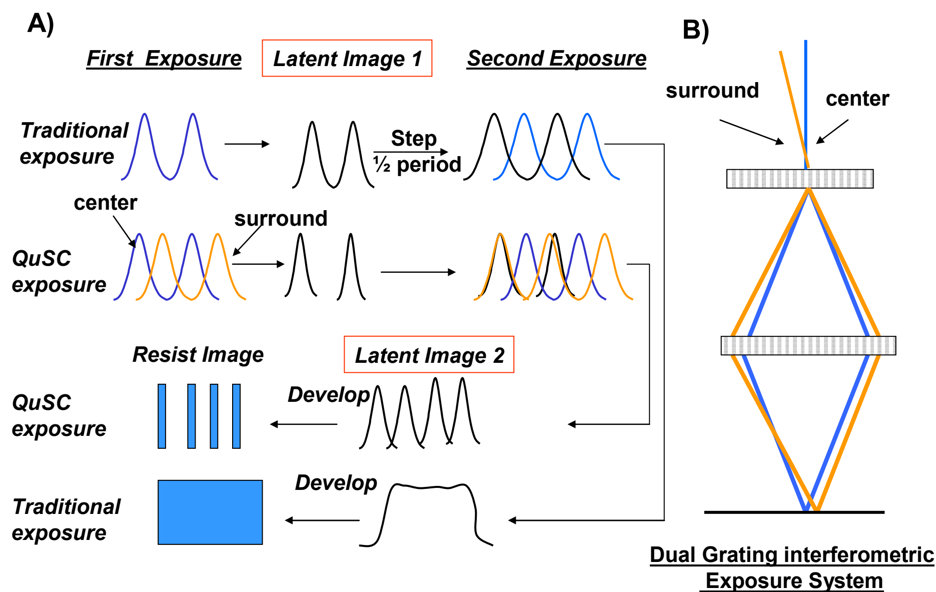

Figure 5. A) Double exposure protocol, B) Achromatic dual grating system

QuSC Lithography should be able to print grating pitches that significantly exceed those of immersion 193 nm lithography. QuSC techniques can also be used to print with diffraction limited spot scanning, as might be required in mask writing or multiple point source parallel exposure technologies in a maskless optical lithography system. It is also possible that photoresist initiator systems may be developed, or exist, that have long excited state that will enable triple or quadruple micro stepping to enable printing of 12 nm lines or less. In the next section we use an inteferometric QuSC lithography in conduction with a lower

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resolution projection reduction scanner to produce a complete process level lithography system capable of sub-32 nm printing.

3. INTERFEROMETRIC EXPOSURE WITH TRIM DOUBLE PATTERNING

As has previously been proposed regular patterns with trim may be used to synthesize complete process level patterns, assuming the levels are designed to be on a Cartesian grid[2]. We assume as process level pitch becomes less than 50 nm and features size falls below 20 nm, design and pattern regularization will become a fundamental design constraint.

Figure 6 shows an overview of a interference lithography with trim mask exposure process. X and y axes are exposed separately, and sequentially, to create a full 2 dimensional pattern. The inteferometric and trim steps may be produced sequentially without development between. This would enable one alignment step to initially align the grating followed by a stage directed blind step to a separate optical column for projection printing. The projection stepper needs to have pitch printing resolution of only ½ the pitch of the micro-stepped, interferometrically patterned grating to correctly trim the first latent image. Using a lower resolution reticle technology provides and cost benefit for this dual patterning approach.

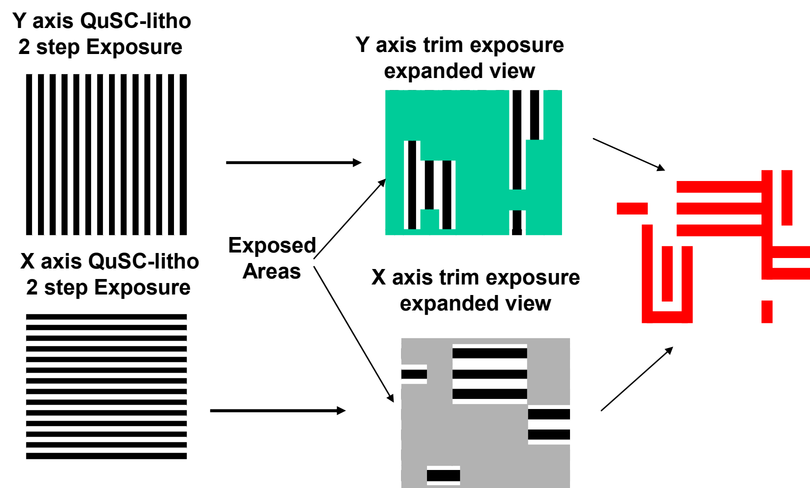

Figure 6. Double patterning process overview using interferometric lithography with trim via generation N+1 projection reduction scanner

Figure 7 shows the proposed process in more detail. Here we propose a double hard mask approach to pattern both axes. In this process there are develop, etch, coat and align steps between patterning of each axis. Dual axis 2-dimensional patterning may not be required if the critical patterning involves only one axis. In this case throughput would not be as compromised as with a double patterning approach which involves develop, coat and align between each exposure. Key to the double hard mask approach is selective etch characteristics for each hard mask.

In the graph in Figure 8 the Critical Dimension (CD) variation for misalignment between the interferometric patterning and the projection reduction trim step is plotted. This calculation was performed

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using a Prolith lithography simulation for 32 nm features. The results show that a 10 nm misalignment between exposures will result in a 3% change in CD. This is a relatively tolerant process, and is much more forgiving than present double exposure protocols.

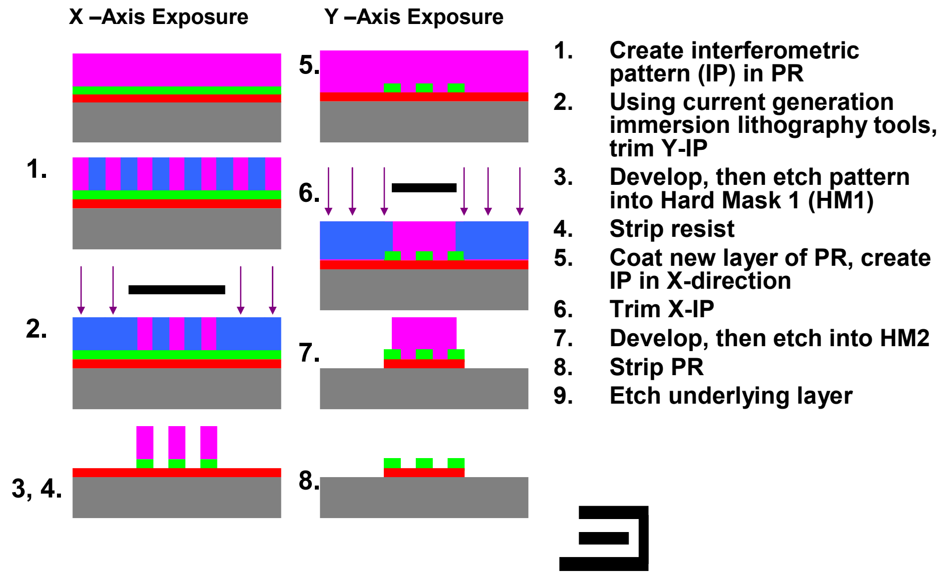

Figure 7. Process involves Double Hard Mask Approach

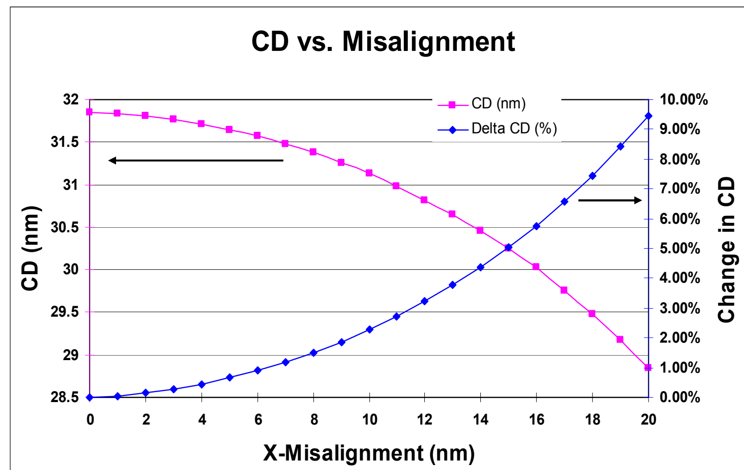

Figure 8. Critical dimension variation for misalignment between the interferometric exposure and the trim step in one axis

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4. SUMMARY

A new form of lithography is proposed called QuSC-lithography. This approach uses vibrational state quantum control concepts with short laser pulses to enable micro-step assisted printing beyond the diffraction limit of optical lithography systems. Specifically, two short laser pulses with different wavelengths are used. The first wavelength (the pump wavelength) produces a photochemical excited state, while the second lower energy photon (the depletion wavelength) causes the excited state to return to the ground state energy manifold. The first wavelength may be at 193nm or 248nm, depending upon the printing requirements, while the second should be beyond the resist absorption edge. Spatially, the first diffraction limited pulse causes photo initiators within the peak field region of the focal volume to move into a photochemical active state and the second diffraction limited pulse is phase engineered to have a dark field node at the peak of the first pulse and high intensity peaks surrounding the feature. The higher the optical field in the surround, the narrower the resultant latent image features become. For a point focus the surround annular energy distribution may be produced with a phase plate, while with a grating stimulated field distribution, the surround may be engineered with a π phase shifted grating at the photochemical depletion wavelength.

It is proposed to use QuSC-lithography in concert with interferometric exposure, and micro-stepping to produce grating latent images in DUV photoresist that are at least 2 times the pitch resolution of the grating forming optics. The latent image is then trimmed, at ½ the pitch of the micro-stepped grating to produce process level features dimensions equal to or less than the ½ pitch of the micro-stepped grating in one axis. After development, selective etch and recoat the orthogonal axis may be patterned with a similar double patterning approach. The result of this process is a complete 2-dimensional process level pattern. It is shown that for 32 nm features, alignment tolerances are relatively relaxed compared to other double patterning approaches.

If the trim step is performed with an advanced 1.55 NA 193nm DUV immersion scanner system, the approach described here is consistent with the production of 16 nm features on 32 nm grid. With appropriate multiple micro stepping and e-beam, or other high resolution trim technology, features and pitches well below this should be able to be produced.

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