LITHOGRAPHY SYSTEM USING QUANTUM ENTANGLED PHOTONS

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This patent is subject to a terminal disclaimer.

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ABSTRACT

A system of etching using quantum entangled particles to get shorter interference fringes. An interferometer is used to obtain an interference fringe. N entangled photons are input to the interferometer. This reduces the distance between interference fringes by n, where again n is the number of entangled photons.

10 Claims, 3 Drawing Sheets
LITHOGRAPHY SYSTEM USING QUANTUM ENTANGLED PHOTONS

This application claims the benefit of the U.S. Provisional Application Ser. No. 60/135,316, filed on May 20, 1999.

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

FIELD OF THE INVENTION

The present application describes a technique of using quantum-entangled particles, e.g., photons, to provide lithographic effect of the photons. For etching features on a computer chip that are smaller than one-quarter of the wavelength of light used in the etching process, by some fraction related to the number of entangled particles.

BACKGROUND

Quantum mechanics tells us that certain unobserved physical systems can have odd behavior. A particle which is decoupled from its environment and which has two possible states will not necessarily be in either of those states, until observed. Putting this in quantum mechanical terms, the particle is simultaneously in a "superposition" of both of those states. However, this only applies while the particle is decoupled from its environment. Any attempt to actually observe the particle couples the particle to its environment, and hence causes the particle to default into one or the other of the eigenstates of the observable operator.

This behavior is part of the superposition principle. The "superposition principle" is illustrated by a famous hypothetical experiment, called the cat paradox. A cat in a box with a vial of poison. The vial containing the poison could equally likely be opened or not opened. If the box/cat/poison is decoupled from its environment, then the cat achieves a state where it is simultaneously dead and not dead. However, any attempt to observe the cat, causes the system to default to dead or alive.

The theory of quantum mechanics predicts that N particles can also exist in such superposition states.

Lithography is a process of etching features on a substrate. Photolithography uses light to etch these features. Each spot can be etched, or not etched, to form a desired feature. In general, it is desirable to make the features as small as possible.

In the prior art, called Classical Optical Interferometric Lithography, a lithographic pattern is etched on a photosensitive material using a combination of phase shifters, substrate rotators, and a Mach-Zehnder or other optical interferometer. The minimum sized feature that can be produced in this fashion is on the order of one-quarter of the optical wavelength [Brueck 98]. The only way to improve on this resolution classically is to decrease the physical wavelength of the light used in the etching process.

This can come at a tremendous commercial expense. Optical sources and imaging elements are not readily available at very short wavelengths, such as hard UV or soft x-ray.

SUMMARY

The present system uses a plurality of entangled particles, e.g., photons, in a lithographic system to change the lithographic effect of the photons.
a number of quantum-entangled particles, photons, electrons, atoms or the like. This will obtain the increased resolution, and reduction of feature size without shortening the physical wavelength. This system uses quantum entanglement effects to produce the same result as that previously obtained by using a shorter wavelength.

For example, if the uncorrelated classical stream of photons is replaced by sets of n entangled photons, then the interference pattern has the form \((1 + \cos(2\phi))\) with \(\phi = kx\) being the phase shift in one arm of the interferometer, and \(k = 2\pi/\lambda\) being the wave number. Consequently, the peak to peak distance in the interference pattern now becomes \(\lambda/2n\). This is substantially smaller than the original peak to peak spacing of \(\lambda/2\) and, in fact, increases the linear solution by a factor of \(n\). So even though the optical source and imaging is done with a relatively long wavelength \(\lambda\), the effective wavelength of the interference pattern is \(\lambda/n\).

Therefore, the resolution increases by a factor of \(n\).

Analog classical optics operate according to the so-called Rayleigh diffraction limit which imposes a restriction on minimum feature size that can be etched by a photon or other particle. This minimum feature size cannot be smaller than half a wavelength. The minimum size lines are on the order of \(\lambda/2\) where \(\lambda\) is the optical wavelength used for the exposure. This limit on line sizes generally holds whenever classical optics and lenses are used for interferometric lithographic etching [Brueck 98].

Put mathematically, the prior art classical device lays down a series of interferometrically-produced lines which obey the function form \(1 + \cos(2\phi)\) where \(k = 2\pi/\lambda\) is the wave number, and \(\lambda\) is the optical wavelength, where 1 is the optical intensity and \(k = 2\pi/\lambda\) is the wave number, and \(\lambda\) is the optical wavelength.

Quantum entangled photons are used in this application for reducing the size of the features. In a classical stream of photons used for interferometric lithography, the minimum size feature is on the order of one-half the optical wavelength. For a stream of \(n\) entangled photons, the interference pattern has the form \((1 + \cos(2\phi))\) with \(\phi = kx\), and \(k = 2\pi/\lambda\), resulting in an effective resolution of the interference pattern that scales linearly with \(n\). The size of the feature is a function of the number of entangled photons \(n\). Thus, for a given wavelength of photon, the resolution for entangled photons increases by \(n\) over the non-entangled classical system along one dimension. Etching in two dimensions can increase the resolution by \(n^2\).

A single photon can be downconverted into two photons of lower wavelength. The polarization, energy and position of the resulting two photons are correlated because of conservation principles. In this particular case, the polarization correlation provides scaling properties. The ability to produce these entangled photons is well understood.

The present system uses particle beams which are quantum in nature to carry out this operation. These beams are composed of streams of single photons, each of which is an individual quantum particle that is decoupled from the system around it. The correlated particles are made to behave in a way that is non-locally correlated. In accordance with quantum mechanical theory, the position, direction of motion, and frequency of each photon depends on the other photon(s).

In the quantum optics community, it has been known for many years that light can exist in an entirely nonclassical state called a number state or a Fock state. This is described by Scully. The number state has no classical analog, as the coherent state does. In particular, the number state \(|n>\) has a precise and fixed number of photons in it. This is in contrast to the classical-like coherent state, which can only be determined to have a mean number of photons \(n_{mean} = |\langle n|\rangle\) due to the quantum fluctuation factor \(\Delta n\). The number state \(|n>\) has no intensity fluctuations, \(\Delta N = 0\). This is a remarkable fact that gives the number state a digital quality; one can have either 0, 1, 2, etc., photons in a single number-state mode. Particles in number states can be produced en masse by a process called Parametric downconversion. Number states have, however, somewhat paradoxical and non-intuitive properties.

FIG. 1 shows a block diagram of the overall quantum lithographic etching system. A single photon 101 of specified frequency is output from laser 99. This photon is sent to a downconverter 100.

A downconverter of this type receives a high-frequency photon into a nonlinear optical crystal of a material such as KTP. A nonlinear interaction in the crystal generates a pair of daughter photons. If the original photon has frequency \(\omega_0\) and vector wave number \(k_0\), then the daughter photons have the same quantities, \(\omega_1, \omega_2, k_1, k_2\). The particles obey the laws of conservation of energy and momentum in the form, \(\omega_0 = \omega_1 + \omega_2\), \(k_0 = k_1 + k_2\), which entangles or correlates the photons in terms of energy and wave number. This correlation is the basis for many interesting experiments where the two daughter photons can be treated as number states in particular photon modes in an interferometer.

The schematic for the down-conversion process is shown in FIG. 2. Incoming high frequency photons from the left are down-converted in a nonlinear crystal and produce two daughter photons that are correlated in both momentum and frequency. The vector wave number conservation condition, Eq. (1b), is degenerate in azimuthal angle about the initial photon propagation axis, generating a typically circular pattern of photons.

A typical spectral pattern is shown in FIG. 3. Choosing two points equidistant apart, as illustrated by the crosses in the FIG. 3, identifies by angular separation a particular down converted pair.

"Parametric" down conversion imposes the additional restriction that \(\omega_1 = \omega_2\) and \(k_1 = k_2\), which selects photon pairs symmetrically placed about the center of the spectrum in FIG. 2. By choosing appropriate angular deflections in the optics, these particular pairs can be captured.

The correlated photon particles are coupled through a coupler system 110 to beam splitter 122. This is the input beam splitter to a partial Mach-Zehnder interferometer with beam splitter 122, mirrors 126 and 128 and a phase shifter 130. The Interferometer produces parallel lines as its output. It has been demonstrated in Brueck, 98, "Interferometric lithography—from Periodic Arrays to Arbitrary Patterns", Microelectronic Eng 42: 145–148 March 1998, that etching a series of parallel lines can be generalized in the lithographic domain into forming any desired feature.

The correlations between the photons are quantum in nature, and the angular relation allows selection of a particular photon moving in a particular path, generating desired nonclassical number states of the form \(|n>\).

A more detailed schematic of the Mach-Zehnder interferometer (MZI) is shown in FIG. 4. First and second correlated input photons 1 and 2 are input to both ports A and B.

Neglecting losses in the interferometer for this discussion, if the input optical intensity is some constant \(I_0\), then for a
where each photon in the correlated pair contributes one port gives the standard classical results, which can then be obtained. The first term accounts for noise sources in the interferometer. The physics can be understood with reference to the case of entangled photons. The number of entangled photons is given by the intensity minimum-to-maximum condition $Nk\Delta x=\pi$, or equivalently $\Delta x=\lambda/(2N)$, as noted above. This is a factor of $N$ below the usual limit of $\Delta x=h/2$. This is used to write an arbitrary pattern of N=3, for example. If the photons were not entangled or correlated, then at the first beam splitter in FIG. 4, they would generate a simple linear matrix relationship between the interferometers. More phase shifters, beam splitters, mirrors, etc., make a more complex matrix. Nevertheless, it is still linear and it is a straightforward problem to translate any arbitrary two-port interferometric system into an appropriate two-by-two transfer matrix. This matrix, can also include complex terms that account for noise sources in the interferometer. These noise sources could otherwise lead to photon loss or the loss of the quantum correlations.

One can think of the entire interferometer as a simple quantum circuit with two inputs and two outputs. This allows the interferometer to be handled in the recently well-developed formalism of quantum circuit theory. Additional photon circuits can be added in parallel to the lithographic circuit in order to apply fault-tolerant quantum error correction techniques in order to minimize the effect of noise sources, allowing maximum resolution and contrast in the lithographic exposure.
the quantum input state can be used to image the sub-
wavelength image at the output. The number of states can be
chosen to be entangled or correlated in a large number of
different ways in the simulation. Some of these choices are
the natural output of a nonlinear photon down converter or
a parametric oscillator, and others can be generated in
preprocessing step with linear optical elements.

For example, it is well known that a simple optical beam
splitter can take an unentangled number direct-product state
and convert it into a nonseparable entangled number-state
output, of the form of Eq. (4), needed for this device.

According to the first disclosed mode, correlated photon
pairs \( (N=2) \) are used. This makes it possible to etch features
on the order of size \( x=\lambda/4 \). For example, light of wavelength
200 nanometers could be used to etch features of size \( x=25 \)
nanometers using a stream of two entangled photons corre-
lated photons. These photons are relatively easy to produce
using the optical process of photon down conversion.
Moreover, these photons produce the surface damage of a
200 nm photon, even though they have the resolution of a
100 nm photon.

Another mode uses correlated photon triplets \( (N=3) \). This
etches features on the order of \( x=\lambda/6 \) in three-photon absorp-
tion.

In fact, there is no theoretical limit on the number of
25 correlated photons that could be produced, and hence no
limit the amount of division below the Rayleigh-limited
value.

Another important advantage is beating the damage cri-
terion that is caused by etching in classical physics. Each
30 photon carries an energy \( c=hc/\lambda \) which is \( c=hc/\lambda \) per photon.
Hence the energy of the photons rise inversely with decreasing
wavelengths.

This can cause undesired resist damage to the material
35 being etched. In addition, statistical fluctuations, called shot
noise, can cause clumping of the arriving high frequency
photons and hence lead to irregularities in the etch. This
system allows etching features that have a better resolution
without correspondingly increasing the damage potential.

Specifically classical systems have a linear ratio of energy
(damage potential) to feature size. The present system
improves this ratio by a factor of the number of entangled
particles.

The laser used herein is a titanium sapphire laser, pro-
cucing an output wave on the order of 100 to 200 nanom-
eters. The optically nonlinear crystal is a KDP crystal doped
with LiIO3.

Any kind of interferometer could be used. While the
present specification describes a Mach Zehnder
Interferometer, any other kind can be used with these
35 teachings.

Although only a few embodiments have been disclosed in
detail above, those with ordinary skill in the art certainly
understand that modifications are possible in the preferred
embodiment and that such modifications are intended to be
encompassed within the following claims, in which

What is claimed is:
1. A quantum mechanically entangled lithographic etch-
ing device, comprising:
a source of quantum mechanically-entangled particles
with a wavelength \( \lambda \); and
an interferometer which produces an interference pattern
by producing a phase shift between \( n \) of said entangled
particles, where \( n>1 \), and using said phase shift to
produce an interference fringe, where said interference
fringe has bright spots and dark spots, an adjacent
bright spot being spaced from one another by less than
\( \lambda/2 \); and
a lithographic etching device, producing a lithographic
etch in a target using said interference pattern.
2. A device as in claim 1 wherein said interferometer is
Mach-Zender interferometer.
3. A device as in claim 1 wherein said source includes a
nonlinear optical element for producing entangled photons.
4. A device as in claim 1 wherein there are two of said
particles, and wherein the interference fringes are spaced by
\( \lambda/8 \) times a constant.
5. A device as in claim 1 wherein there are three of said
photons and said photons are spaced by \( \lambda/12 \) times a constant.
6. A lithography method, comprising:
producing a plurality of entangled particles with a
wavelength \( \lambda \);
inputting said entangled particles into an interferometric
device which produces a phase shift between different
paths;
 obtening an output of said interferometric device having
a pattern spacing between parts of said pattern propor-
tional to \( \lambda \) over \( 4N \) where \( N \) is the number of entangled
particles; and
using said output for lithography.
7. A method as in claim 6 wherein said particles are
photons.
8. A method as in claim 7 wherein there are two of said
photons.
9. A method as in claim 8 wherein there are three of said
photons.
10. A method of carrying out quantum lithography, com-
prising:
obtaining a plurality of entangled particles, which are
quantum entangled with one another;
establishing an interferometer system which is decoupled
to its environment, and applying said entangled par-
ticles into said interferometer system to cause interfer-
ence there, between to form interference fringes spaced
from one another by \( \lambda \) over \( 4N \) where \( N \) is a number of
decoupled photons; and
using said interference fringes for lithography.

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