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(54) Title: SINGLE AXIS LIGHT PIPE FOR HOMOGENIZING ONE AXIS OF ILLUMINATION SYSTEMS BASED ON LASER DIODES
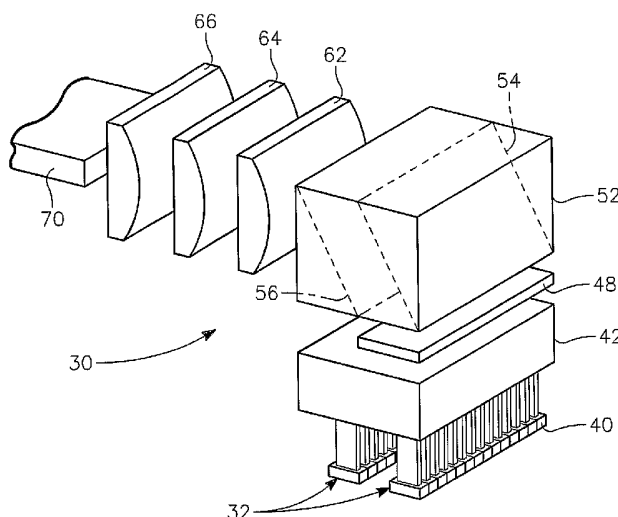
(57) Abstract: Apparatus for thermally processing a semiconductor wafer includes an array of semiconductor laser emitters ar-
ranged in plural parallel rows extending along a slow axis, plural respective cylindrical lenses overlying respective ones of the rows
of laser emitters for collimating light from the respective rows along a fast axis generally perpendicular to the slow axis, a homog-
enizing light pipe having an input face at a first end for receiving light from the plural cylindrical lenses and an output face at an
opposite end, the light pipe comprising a. pair of reflective walls extending between the input and output faces and separated from
one another along the direction of the slow axis, and scanning apparatus for scanning light emitted from the homogenizing light pipe
across the wafer in a scanning direction parallel to the fast axis.

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SINGLE AXIS LIGHT PIPE FOR HOMOGENIZING ONE AXIS OF ILLUMINATION SYSTEMS BASED ON LASER DIODES

CROSS REFERENCE TO RELATED APPLICATIONS

[001]   This application claims the benefit of U.S. Provisional Application No. 60/627,238, filed November 12, 2004.

BACKGROUND OF THE INVENTION

Field of the Invention:

[002]   The invention relates generally to thermal processing of semiconductor substrates. In particular, the invention relates to laser thermal processing of semiconductor substrates.

Background Art:

[003]   Thermal processing is required in the fabrication of silicon and other semiconductor integrated circuits formed in silicon wafers or other substrates such as glass panels for displays. The required temperatures may range from relatively low temperatures of less than 250°C to greater than 1000°, 1200°, or even 1400°C and may be used for a variety of processes such as dopant implant annealing, crystallization, oxidation, nitridation, silicidation, and chemical vapor deposition as well as others.

[004]   For the very shallow circuit features required for advanced integrated circuits, it is greatly desired

to reduce the total thermal budget in achieving the
required thermal processing. The thermal budget may be
considered as the total time at high temperatures
necessary to achieve the desired processing temperature.
 The time that the wafer needs to stay at the highest
temperature can be very short.

[005]   Rapid thermal processing (RTP) uses radiant
lamps which can be very quickly turned on and off to heat
only the wafer and not the rest of the chamber. Pulsed
laser annealing using very short (about 20ns) laser
pulses is effective at heating only the surface layer and
not the underlying wafer, thus allowing very short ramp
up and ramp down rates.

[006]   A more recently developed approach in various
forms, sometimes called thermal flux laser annealing or
dynamic surface annealing (DSA), is described by Jennings
et al. in PCT/2003/00196966 based upon U.S. Patent
Application 10/325,497, filed December 18, 2002 and
incorporated herein by reference in its entirety. Markle
describes a different form in U.S. Patent 6,531,681 and
Talwar yet a further version in U.S. Patent 6,747,245.

[007]   The Jennings and Markle versions use CW diode
lasers to produce very intense beams of light that
strikes the wafer as a thin long line of radiation. The
line is then scanned over the surface of the wafer in a
direction perpendicular to the long dimension of the line
beam.

SUMMARY OF THE INVENTION

[008]   Apparatus for thermally processing a
semiconductor wafer includes an array of semiconductor
laser emitters arranged in plural parallel rows extending
along a slow axis, plural respective cylindrical lenses

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overlying respective ones of the rows of laser emitters for collimating light from the respective rows along a fast axis generally perpendicular to the slow axis, a homogenizing light pipe having an input face at a first end for receiving light from the plural cylindrical lenses and an output face at an opposite end, the light pipe comprising a pair of reflective walls extending between the input and output faces and separated from one another along the direction of the slow axis, and scanning apparatus for scanning light emitted from the homogenizing light pipe across the wafer in a scanning direction parallel to the fast axis. Lenses focus light derived from the output face of the light pipe into a line of light on the wafer, the line of light having an elongate dimension along the slow axis and a narrow dimension along the fast axis, wherein the scanning apparatus scans the line of light across the wafer along the fast axis. The reflective walls of the light pipe are sufficiently close to one another to facilitate multiple reflections across the slow axis.

BRIEF DESCRIPTION OF THE DRAWINGS

[009]   FIG. 1 is an orthographic representation of a thermal flux laser annealing apparatus employed in the present invention.

[0010]   FIGS. 2 and 3 are orthographic views from different perspectives of optical components of the apparatus of FIG. 1.

[0011]   FIG. 4 is an end plan view of a portion of a semiconductor laser array in the apparatus of FIG. 1.

[0012]   FIG. 5 is an orthographic view of a homogenizing light pipe for the apparatus of FIG. 1.

[0013]   FIG. 6 is a perspective view of the light pipe

of FIG. 5 and of the lens assemblies at its input and output faces.

[0014]   FIG. 7 is a top view of the light pipe of FIG. 6 along the fast axis.

[0015]   FIG. 8 is a side view of the light pipe of FIG. 6 along the slow axis.

[0016]   FIG .9 is an orthographic view of an embodiment of the light pipe of FIG. 5 formed as a truncated wedge having decreasing cross-sectional area along the optical axis.

[0017]   FIG. 10 is an orthographic view of an embodiment of the light pipe of FIG. 5 formed as a truncated wedge having increasing cross-sectional area along the optical axis.

[0018]   FIG. 11 is diagram of multiple reflections inside the light pipe of FIG. 10, illustrating the effects of a beam diverging lens at the input of the light pipe.

                DETAILED DESCRIPTION OF THE INVENTION

[0019]   One embodiment of the apparatus described in the above-referenced application by Jennings et al. is illustrated in the schematic orthographic representation of FIG. 1. A gantry structure 10 for two-dimensional scanning includes a pair of fixed parallel rails 12, 14. Two parallel gantry beams 16, 18 are fixed together a set distance apart and supported on the fixed rails 12, 14 and are controlled by an unillustrated motor and drive mechanism to slide on rollers or ball bearings together along the fixed rails 12, 14. A beam source 20 is slidably supported on the gantry beams 16, 18, and may be suspended below the beams 16, 18 which are controlled by unillustrated motors and drive mechanisms to slide along

them. A silicon wafer 22 or other substrate is
stationarily supported below the gantry structure 10. The
beam source 20 includes a laser light source and optics
to produce a downwardly directed fan-shaped beam 24 that
strikes the wafer 22 as a line beam 26 extending
generally parallel to the fixed rails 12, 14, in what is
conveniently called the slow direction. Although not
illustrated here, the gantry structure further includes a
Z-axis stage for moving the laser light source and optics
in a direction generally parallel to the fan-shaped beam
24 to thereby controllably vary the distance between the
beam source 20 and the wafer 22 and thus control the
focusing of the line beam 26 on the wafer 22. Exemplary
dimensions of the line beam 26 include a length of 1cm
and a width of 66 microns with an exemplary power density
of 220kW/cm^2. Alternatively, the beam source and
associated optics may be stationary while the wafer is
supported on a stage which scans it in two dimensions.

[0020]   In typical operation, the gantry beams 16, 18
are set at a particular position along the fixed rails
12, 14 and the beam source 20 is moved at a uniform speed
along the gantry beams 16, 18 to scan the line beam 26
perpendicularly to its long dimension in a direction
conveniently called the fast direction. The line beam 26
is thereby scanned from one side of the wafer 22 to the
other to irradiate a 1cm swath of the wafer 22. The line
beam 26 is narrow enough and the scanning speed in the
fast direction fast enough that a particular area of the
wafer is only momentarily exposed to the optical
radiation of the line beam 26 but the intensity at the
peak of the line beam is enough to heat the surface
region to very high temperatures. However, the deeper
portions of the wafer 22 are not significantly heated and

further act as a heat sink to quickly cool the surface
region. Once the fast scan has been completed, the
gantry beams 16, 18 are moved along the fixed rails 12,
14 to a new position such that the line beam 26 is moved
along its long dimension extending along the slow axis.
The fast scanning is then performed to irradiate a
neighboring swath of the wafer 22. The alternating fast
and slow scanning are repeated, perhaps in a serpentine
path of the beam source 20, until the entire wafer 22 has
been thermally processed.

[0021]   The optics beam source 20 includes an array of
lasers. An example is orthographically illustrated in
FIGS. 2 and 3, in which laser radiation at about 810nm is
produced in an optical system 30 from two laser bar
stacks 32, one of which is illustrated in end plan view
in FIG. 4. Each laser bar stack 32 includes 14 parallel
bars 34, generally corresponding to a vertical p-n
junction in a GaAs semiconductor structure, extending
laterally about 1cm and separated by about 0.9mm.
Typically, water cooling layers are disposed between the
bars 34. In each bar 34 are formed 49 emitters 36, each
constituting a separate GaAs laser emitting respective
beams having different divergence angles in orthogonal
directions. The illustrated bars 34 are positioned with
their long dimension extending over multiple emitters 36
and aligned along the slow axis and their short dimension
corresponding to the less than 1-micron p-n depletion
layer aligned along the fast axis. The small source size
along the fast axis allows effective collimation along
the fast axis. The divergence angle is large along the
fast axis and relatively small along the slow axis.

[0022]   Returning to FIGS. 2 and 3 two arrays of
cylindrical lenslets 40 are positioned along the laser

bars 34 to collimate the laser light in a narrow beam along the fast axis. They may be bonded with adhesive on the laser stacks 32 and aligned with the bars 34 to extend over the emitting areas 36.

[0023]   The optics beam source 20 can further include conventional optical elements. Such conventional optical elements can include an interleaver and a polarization multiplexer, although the selection by the skilled worker of such elements is not limited to such an example. In the example of FIGS. 2 and 3, the two sets of beams from the two bar stacks 32 are input to an interleaver 42, which has a multiple beam splitter type of structure and having specified coatings on two internal diagonal faces, e.g., reflective parallel bands, to selectively reflect and transmit light. Such interleavers are commercially available from Research Electro Optics (REO). In the interleaver 42, patterned metallic reflector bands are formed in angled surfaces for each set of beams from the two bar stacks 32 such that beams from bars 34 on one side of the stack 32 are alternatively reflected or transmitted and thereby interleaved with beams from bars 34 on the other side of the stack 32 which undergo corresponding selective transmission/reflection, thereby filling in the otherwise spaced radiation profile from the separated emitters 36.

[0024]   A first set of interleaved beams is passed through a quarter-wave plate 48 to rotate its polarization relative to that of the second set of interleaved beams. Both sets of interleaved beams are input to a polarization multiplexer (PMUX) 52 having a structure of a double polarization beam splitter. Such a PMUX is commercially available from Research Electro Optics. First and second diagonal interface layers 54,

56 cause the two sets of interleaved beams to be
reflected along a common axis from their front faces. The
first interface 54 is typically implemented as a
dielectric interference filter designed as a hard
reflector (HR) while the second interface 56 is
implemented as a dielectric interference filter designed
as a polarization beam splitter (PBS) at the laser
wavelength. As a result, the first set of interleaved
beams reflected from the first interface layer 54 strikes
the back of the second interface layer 56. Because of
the polarization rotation introduced by the quarter-wave
plate 48, the first set of interleaved beams passes
through the second interface layer 56. The intensity of
a source beam 58 output by the PMUX 52 is doubled from
that of the either of the two sets of interleaved beams.

[0025]   Although shown separated in the drawings, the
interleaver 42, the quarter-wave plate 48, and the PMUX
52 and its interfaces 54, 56, as well as additional
filters that may be attached to input and output faces
are typically joined together by a plastic encapsulant,
such as a UV curable epoxy, to provide a rigid optical
system. An important interface is the plastic bonding of
the lenslets 40 to the laser stacks 32, on which they
must be aligned to the bars 34. The source beam 58 is
passed through a set of cylindrical lenses 62, 64, 66 to
focus the source beam 58 along the slow axis.

[0026]   A one-dimensional light pipe 70 homogenizes
the source beam along the slow axis. The source beam,
focused by the cylindrical lenses 62, 64, 66, enters the
light pipe 70 with a finite convergence angle along the
slow axis but substantially collimated along the fast
axis. The light pipe 70, more clearly illustrated in the
orthographic view of FIG. 5, acts as a beam homogenizer

to reduce the beam structure along the slow axis
introduced by the multiple emitters 36 in the bar stack
32 spaced apart on the slow axis. The light pipe 70 may
be implemented as a rectangular slab 72 of optical glass
having a sufficiently high index of refraction to produce
total internal reflection. It has a short dimension
along the slow axis and a longer dimension along the fast
axis. The slab 72 extends a substantial distance along
an axis 74 of the source beam 58 converging along the
slow axis on an input face 76. The source beam 58 is
internally reflected several times from the top and
bottom surfaces of the slab 72, thereby removing much of
the texturing along the slow axis and homogenizing the
beam along the slow axis when it exits on an output face
78. The source beam 58, however, is already well
collimated along the fast axis (by the cylindrical
lensets 40) and the slab 72 is wide enough that the
source beam 58 is not internally reflected on the side
surfaces of the slab 72 but maintains its collimation
along the fast axis. The light pipe 70 may be tapered
along its axial direction to control the entrance and
exit apertures and beam convergence and divergence. The
one-dimensional light pipe can alternatively be
implemented as two parallel reflective surfaces
corresponding generally to the upper and lower faces of
the slab 72 with the source beam passing between them.

[0027]   The source beam output by the light pipe 70 is
generally uniform. As further illustrated in the
schematic view of FIG. 6, further anamorphic lens set or
optics 80 that includes cylindrical lenses 81, 82,
expands the output beam in the slow axis, and further
includes a generally spherical lens 83 to project the
desired line beam 26 on the wafer 22. The anamorphic

optics 80 shape the source beam in two dimensions to produce a narrow line beam of limited length. In the direction of the fast axis, the output optics have an infinite conjugate for the source at the output of the light pipe (although systems may be designed with a finite source conjugate) and a finite conjugate at the image plane of the wafer 22 while, in the direction of the slow axis, the output optics has a finite conjugate at the source at the output of the light pipe 70 and a finite conjugate at the image plane. Further, in the direction of the slow axis, the nonuniform radiation from the multiple laser diodes of the laser bars is homogenized by the light pipe 70. The ability of the light pipe 70 to homogenize strongly depends on the number of times the light is reflected traversing the light pipe 70. This number is determined by the length of the light pipe 70, the direction of the taper if any, the size of the entrance and exit apertures as well as the launch angle into the light pipe 70. The output optics 80 focus the source beam into the line beam of desired dimensions on the surface of the wafer 22.

[0028]   Figures 7 and 8 are perpendicularly arranged side views along the fast and slow axes respectively showing the light pipe 70 and some associated optics. In the direction of the fast axis, the beam from the lasers bars 32 is well collimated and not affected by the light pipe 70 or anamorphic optics. On the other hand, in the direction of the slow axis, the input anamorphic optics 62, 64, 66 condense and converge the beam into the input end of the light pipe 70. The beam exits the light pipe 70 with substantially uniform intensity along the slow axis but with a substantial divergence. The output anamorphic optics 80 expand and collimate the output beam

along the slow axis.

[0029]   The light pipe 70 described above has a
uniform rectangular cross section along the optical axis
74. However, tapered profiles with cross sections
tapering along the optical axis 74 may be advantageously
used in combination with the subsequent optics. In
particular, a tapered light pipe increases the number of
reflections occurring over a fixed length of the light
pipe. A dielectric light pipe 90 illustrated
orthographically in FIG. 9 is formed from a truncated
wedge 92 of optical glass with a uniformly decreasing
rectangular cross section along the optical axis 74 from
an input face 94 to an output face 96. That is, the
aspect ratio of the light pipe 90 is continually
increasing, for example, from 5:1 to 10:1, producing a
ratio of aspect ratios, for example, of at least 2. In
particular, the dimension along the slow axis is
decreasing and the dimension along the fast axis may be
maintained constant. The advantage of the narrow output
face 96 is that its numerical aperture (NA) is higher,
that is, the output beam divergence is greater.

[0030]   A complementary configuration is a dielectric
light pipe 100 illustrated orthographically in FIG. 10
formed of a truncated wedge 102 of optical glass with a
uniformly increasing rectangular cross section along the
optical axis from an input face 104 to an output face 106
so that the aspect ratio of the wedge 102 is continually
decreasing, for example, by ratios reverse to those of
the previous embodiment. In particular, the dimension
along the slow axis is increasing and the dimension along
the fast axis may be maintained constant. This
configuration has the advantage that the NA of the wide
output face 106 is lower and the output beam divergence

is less. Advantageously a cylindrical lens 108 placed
near the input face and extending along the long lateral
direction of the light pipe 100 focuses a somewhat
collimated input beam 112 into a sharply converging beam
at the input face 104. As illustrated in the side cross
sectional view of FIG. 11, lateral beam components 114 at
the ends of the slow direction bounce many times near the
small end of the tapered light pipe 100 and are gradually
brought closer to be parallel to the optical axis. As a
result, the output beam has a small NA and relatively
large size along the slow axis.

[0031]   It is appreciated that the lateral side walls
of the dielectric light pipes 70, 90, 100 do not really
participate in the action of the light pipe such that a
single-axis light pipe is obtained in which no reflecting
or homogenizing is obtained in along the long lateral
direction of the pipe. Hence, it is not required that
those laterals walls be parallel although such parallel
walls ease fabrication.

[0032]   The one-dimensional light pipe can
alternatively be implemented as two parallel or slightly
inclined reflective surfaces corresponding generally to
the upper and lower faces of the slab 72 or wedges 92,
102 with the source beam passing between them. The
reflective surfaces can be formed as free-standing
mirrors or as coatings on a transparent member not
providing total internal reflection. It may be possible
to carry out the invention without either the interleaver
42 or the polarization multiplexer 52 or without both of
them.

[0033]   While the invention has been described in
detail by specific reference to preferred embodiments, it
is understood that variations and modifications thereof

may be made without departing from the true spirit and
scope of the invention.

What is claimed is:

1.   A thermal processing system, comprising:
        a source of laser radiation emitting at a laser
wavelength and comprising a plurality of laser diodes
formed in a substrate and emitting along an optical axis
from emitter areas arranged along a first axis; and
        a single axis light pipe having reflective
walls separated along said first axis with respect to
said optical axis, wherein said optical axis passes
between said reflective walls.

2.   The system of claim 1, further comprising at
least one anamorphic lens over said emitter areas of said
laser diodes and extending along said first axis to
substantially collimate radiation from said laser diodes
along a second axis perpendicular to said first axis.

3.   The system of claim 2, wherein said light pipe
does not reflect said radiation with respect to said
second axis.

4.   The system of claim 2, wherein said first axis
is a slow axis of a line beam scanning apparatus and said
second axis is a fast axis thereof.

5.   The system of claim 1, wherein said light pipe
is tapered along said first axis.

6.   The system of claim 5, wherein said light pipe
has an expanding taper along said optical axis from said
source.

7. The system of Claim 5, wherein said light pipe has a contracting taper along said optical axis from said source.

8. The system of Claim 4 further comprising scanning apparatus for producing relative motion along said fast axis between said optical axis and a workpiece.

9. The system of Claim 1 wherein said reflective walls are spaced from one another by a sufficiently short distance across said first axis to afford multiple reflections across said first axis of light between said reflective walls from said source of laser radiation.

10. The system of Claim 9 further comprising a pair of support walls coupled to said reflective walls, said support walls separated from one another across said second axis by a sufficiently large distance to prevent reflection across said second axis between said support walls.

11. The system of Claim 10 further comprising respective cylindrical lenses axially extending along said first axis and resting on respective rows of the emitter areas for collimating light from said laser source along said second axis.

12. The system of Claim 9 wherein said light pipe is tapered to have increased spacing between said reflective surfaces along said optical axis from an input face to an output face of said light pipe.

13. The system of Claim 9 wherein said light pipe

is tapered to have decreased spacing between said
reflective surfaces along said optical axis from an input
face to an output face of said light pipe.

14. Apparatus for processing a semiconductor wafer,
comprising:

an array of semiconductor laser emitters
arranged in plural parallel rows extending along a slow
axis;

plural respective cylindrical lenses overlying
respective ones of said rows of laser emitters for
collimating light from the respective rows along a fast
axis generally perpendicular to said slow axis;

a homogenizing light pipe having an input face
at a first end for receiving light collimated by said
plural cylindrical lenses and an output face at an
opposite end, said light pipe comprising a pair of
reflective surfaces extending between said input and
output faces and separated from one another along the
direction of said slow axis; and

scanning apparatus for scanning light emitted
from said homogenizing light pipe across the wafer in a
scanning direction parallel to said fast axis.

15. The apparatus of Claim 14 further comprising
optics for focusing light derived from the output face of
said light pipe into a line of light on said wafer, said
line of light having an elongate dimension along said
slow axis and a narrow dimension along said fast axis,
wherein said scanning apparatus scans said line of light
across said wafer along said fast axis.

16. The apparatus of Claim 14 wherein said

reflective surfaces are sufficiently close to one another
to facilitate multiple reflections across said slow axis.

17. The apparatus of Claim 16 further comprising a
pair of support surfaces coupled to said pair of
reflective surfaces and being separated from one another
along the direction of said fast axis by a sufficiently
large distance to prevent multiple reflections between
them along said fast axis.

18. The apparatus of Claim 14 wherein said
reflective surfaces define a truncated wedge shape, said
apparatus further comprising a lens at said input face of
said light pipe for increasing beam divergence along said
slow axis.

19. The apparatus of Claim 18 wherein said
truncated wedge shape has a decreasing cross-sectional
area along the direction of light propagation.

20. A method of annealing a workpiece, comprising:
        emitting plural light beams from an array of
semiconductor laser emitters arranged in plural parallel
rows extending along a slow axis;
        collimating, along a fast axis generally
perpendicular to said slow axis, the light beams from
each respective row of laser emitters in respective
cylindrical lenses overlying respective ones of said rows
of laser emitters;
        making multiple reflections across said slow
axis in a light pipe of the light from said plural
cylindrical lenses between a pair of reflective surfaces

separated from one another along the direction of said slow axis to produce a light beam homogenized along said slow axis;

focusing said homogenized light beam onto said workpiece as line of light having a broad dimension along said slow axis and a narrow dimension along said fast axis; and

scanning said line of light across the workpiece in a scanning direction parallel to said fast axis.
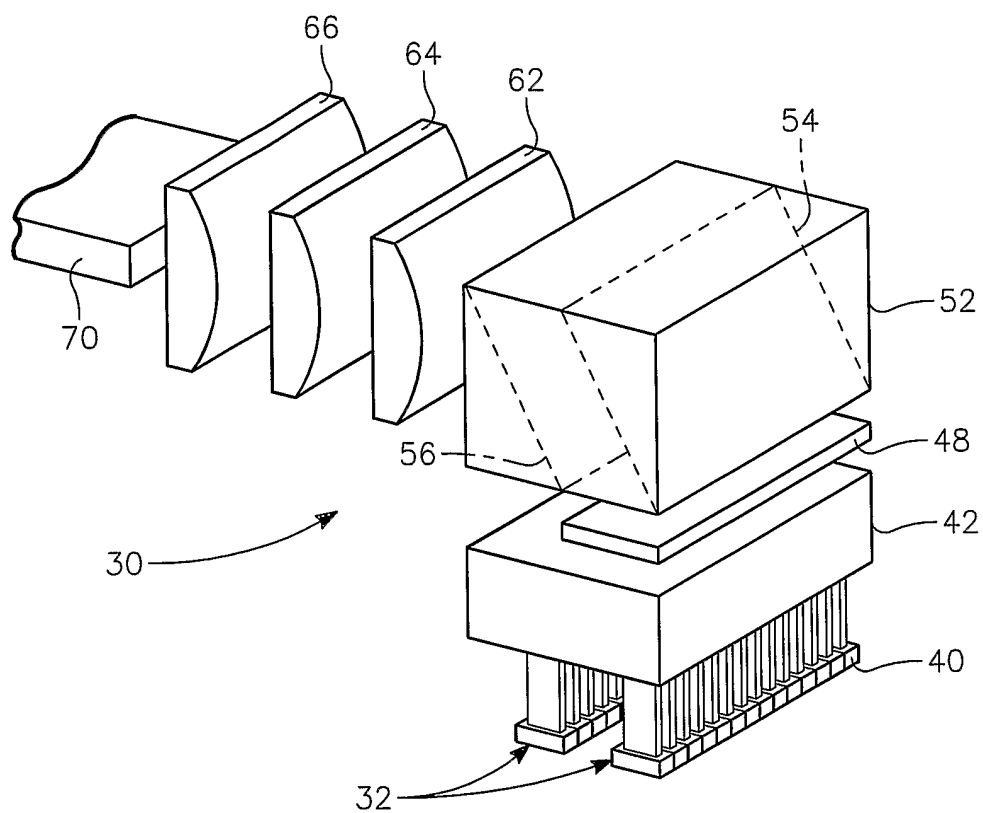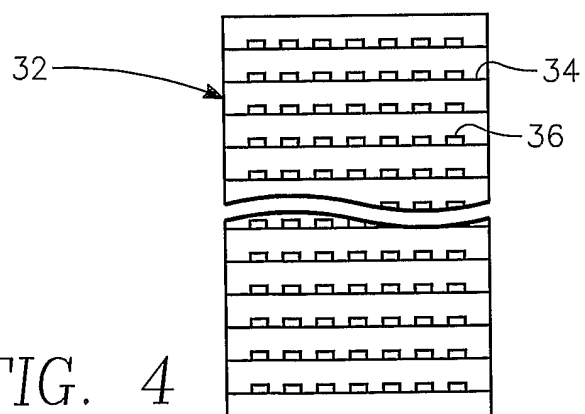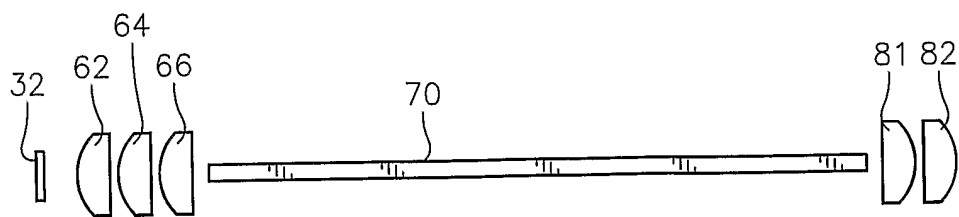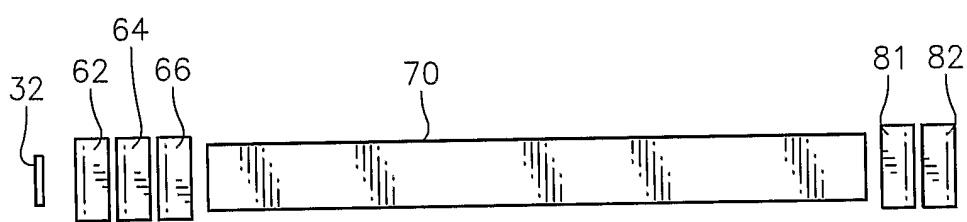
FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8
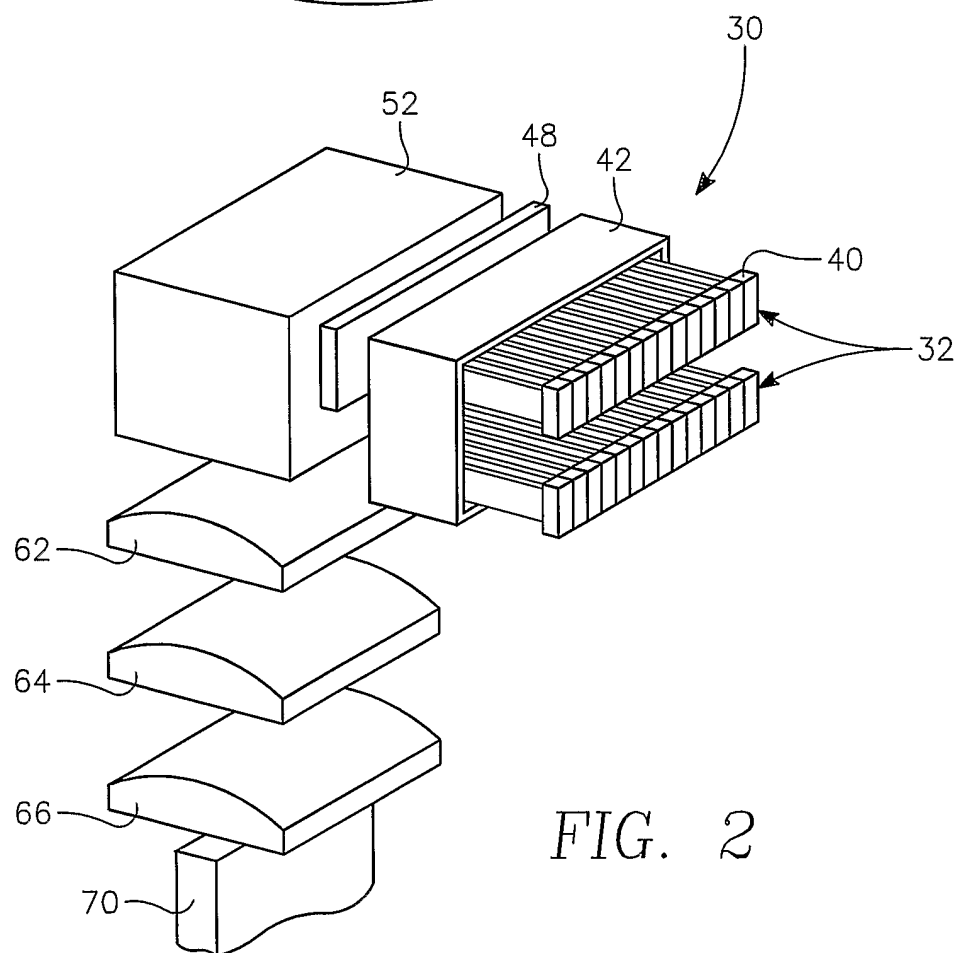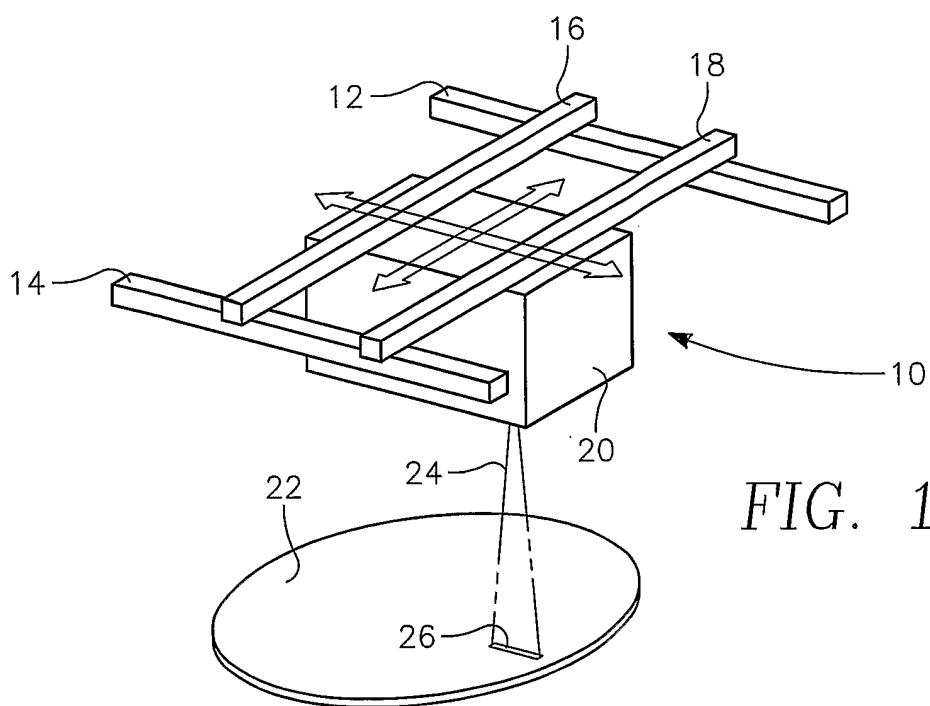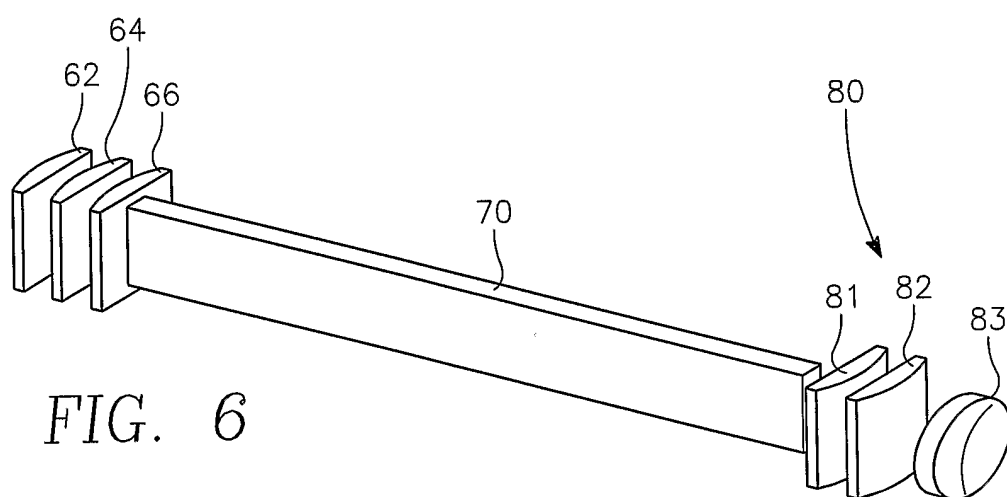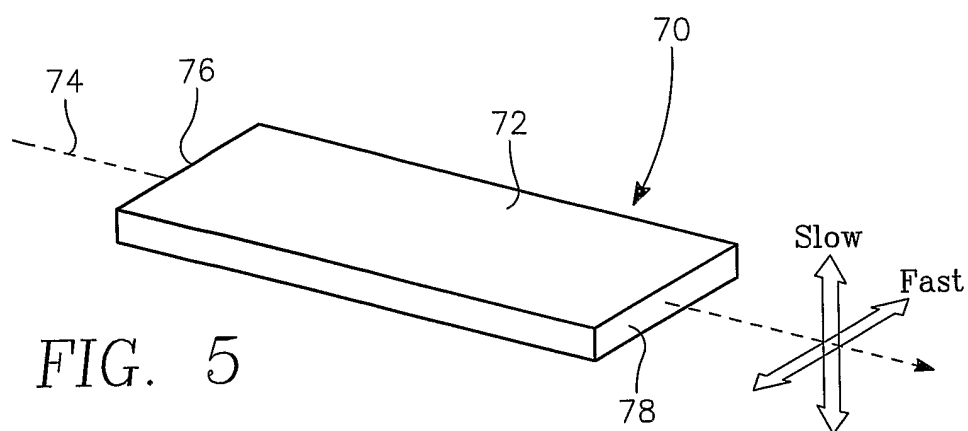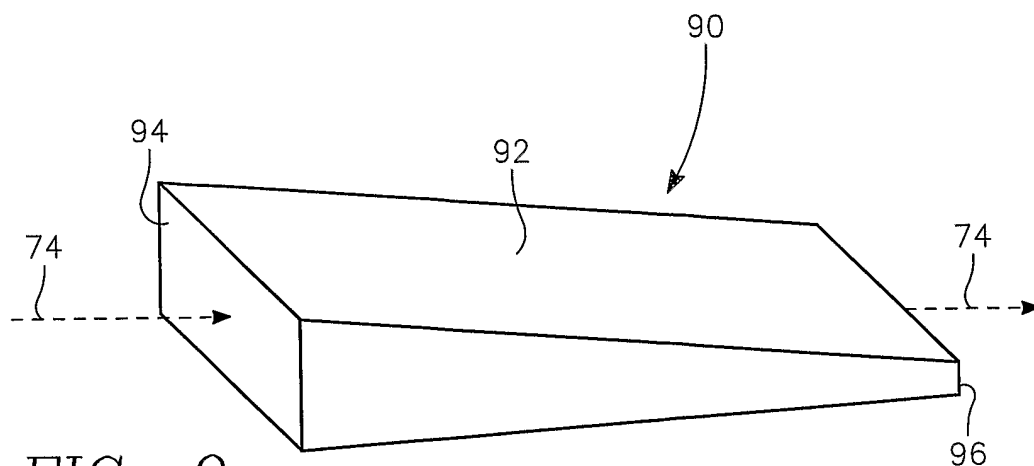
FIG. 9
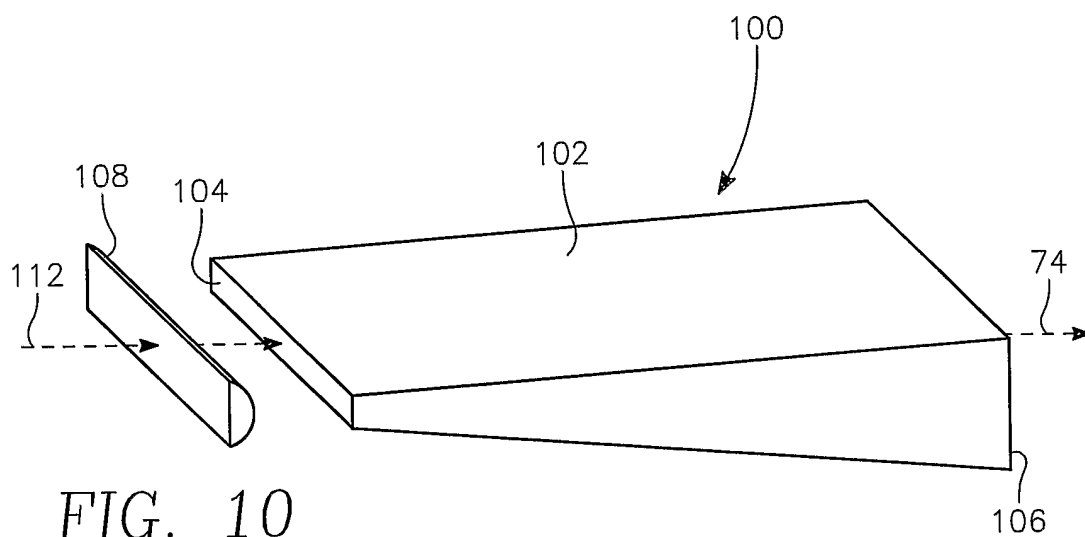
FIG. 10

FIG. 11

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
G02B6/00   H01L21/324   H01L21/268

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02B   H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 03/089184 A (APPLIED MATERIALS, INC) 30 October 2003 (2003-10-30) paragraph '0074!; figures 2a,3,9a,9b,11	1,2,4,5, 7-9, 13-16,20
Y	US 2004/198028 A1 (TANAKA KOICHIRO ET AL) 7 October 2004 (2004-10-07) paragraph '0073!; figures 2-4,b	1,2,4,5, 7-9, 13-16,20
A	US 4 305 640 A (CULLIS ET AL) 15 December 1981 (1981-12-15) column 3, line 34 - line 36; figures 1,2	5,7,13
A	EP 0 231 794 A (INTERNATIONAL BUSINESS MACHINES CORPORATION) 12 August 1987 (1987-08-12) column 2; figure 2	1,14,20

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| X | Further documents are listed in the continuation of Box C. | X | See patent family annex. |

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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