

HIGH POWER GAS DISCHARGE LASER WITH HELIUM PURGED LINE NARROWING UNIT

This invention relates to lasers and in particular to high power gas discharge lasers with a grating based line narrowing unit. This invention is a continuation-in-part of Serial No. 09/451,407, filed November 30, 1999.

BACKGROUND OF THE INVENTION

Narrow Band Gas Discharge Lasers

Gas discharge ultraviolet lasers used as a light source for integrated circuit lithography typically are line narrowed. A preferred line narrowing prior art technique is to use a grating based line narrowing unit along with an output coupler to form the laser resonance cavity. The gain medium within this cavity is produced by electrical discharges into a circulating laser gas such as krypton, fluorine and neon (for a KrF laser); argon, fluorine and neon (for an ArF laser); or fluorine and helium and/or neon (for an F₂ laser).

Prior Art Line-Narrowing Technique

A sketch of such a prior art system is shown in FIG. 1 which is extracted from Japan Patent No. 2,696,285. The system shown includes output coupler (or front mirror) 4, laser chamber 3, chamber windows 11, and a grating based line narrowing unit 7. The line narrowing unit 7 is typically provided on a lithography laser system as an easily replaceable unit and is sometimes called a "line narrowing package" or "LNP" for short. This unit includes two beam expanding prisms 27 and 29 and a grating 16 disposed in a Litrow configuration. Gratings used in these systems are extremely sensitive optical devices and deteriorate rapidly under ultraviolet radiation in the presence of oxygen in standard air. For this reason, the optical components of line narrowing units for lithography lasers are typically purged continuously during operation with nitrogen.

For many years, designers for line narrowed lasers have believed that distortions of the laser beam could be caused by gas flow near the face of the grating. Therefore,

laser designers in the past have made special efforts to keep the purge nitrogen from flowing directly on the face of the grating. Several examples of these efforts are described in the Japan Patent 2,696,285 referred to above. In the example shown in extracted FIG. 1, the purge flow is directed from N₂ gas bottle 44 toward the back side of grating 16 through port 46.

The Grating Formula

Another prior art excimer laser system utilizing a diffraction grating for spectrum line selection is shown in FIG. 2. The cavity of the laser is created by an output coupler 4 and a grating 16, which works as a reflector and a spectral selective element. Output coupler 4 reflects a portion of the light back to the laser and transmits the other portion 6 which is the output of the laser. Prisms 8, 10 and 12 form a beam expander, which expands the beam before it heats the grating. A mirror 14 is used to steer the beam as it propagates towards the grating, thus controlling the angle of incidence. The laser central wavelength is normally changed by tuning that mirror 14. A gain generation is created in chamber 3.

Diffraction grating provides the wavelength selection by reflecting light with different wavelengths at different angles. Because of that only those light rays, which are reflected back to the laser, will be amplified by the laser gain media, while all other light with different wavelengths will be lost.

The diffraction grating in this prior art laser works in a so-called Littrow configuration, when it reflects light exactly back. For this configuration, the incident (diffracted) angle and the wavelength are related through the formula:

$$2d n \sin \alpha = m\lambda \quad (1)$$

where α is the incidence (diffracted) angle on the grating, m is the diffraction order, n is refractive index of gas, and d is the period of the grating.

Because the microlithography exposure lens is very sensitive to chromatic aberrations of the light source, it is required that the laser produce light with very narrow spectrum line width. For example, state of the art excimer lasers are now produce spectral linewidth on the order of 0.5 pm as measured at Full Width at half

maximum values and with 95% of the light energy concentrated in the range of about 1.5 pm. New generations of microlithography exposure tools will require even tighter spectral requirements. In addition, it is very important that the laser central wavelength be maintained to very high accuracy as well. In practice, it is required that the central wavelength is maintained to better than 0.05 – 0.1 pm stability. The state of the art microlithography excimer laser does have an onboard spectrometer, which can control the laser wavelength to the required accuracy. The problem is, however, that in order for that spectrometer to work, the laser must be firing pulses. Therefore, when the laser is continuously exposing the wafers, its spectrometer can control the wavelength to the required accuracy. The problem arises, when the exposure process is stopped, such as for wafers replacement. The wafer replacement may take a minute or two, and during that time the laser is not allowed to fire pulses. When the laser is firing, it produces a lot of heat. When the laser is not firing, it cools down. This cooling down can change the laser wavelength due to thermal drifts. One of the possible causes for the drift is change in the refractive index n of the gas with temperature, according to the above equation. This change in n will cause change in Littrow wavelength of the grating, and therefore, change the laser operating central wavelength. Therefore, the first several pulses after the laser resumes firing will often be at a different wavelength than required. If these pulses are used to expose wafers, the chromatic aberration will cause the quality of the image to degrade. That in turn may cause severe yield issues. One solution to the problem is not to use these first few pulses for wafer exposure. This can be done by closing the mechanical shutter of the laser during the first pulses. Unfortunately, because closing and opening of the mechanical shutter takes time, it will cause the throughput reduction. The lithography laser works in tandem with a number of very expensive tools in a semiconductor fab. Therefore, even a 1% reduction in the throughput of the laser will bear a substantial price tag.

Increased Repetition Rates

Line narrowed ultraviolet laser light sources currently in use in the integrated circuit industry typically produce about 10 mJ per pulse at repetition rates of about 2000 Hz and duty factors of about 20 percent. Increased integrated circuit production can be achieved at higher repetition rates and greater duty cycles. Applicants and their

fellow workers have designed and tested a 4000 Hz gas discharge lithography laser. Applicants are now experimenting with even higher repetition rates and are attempting to minimize laser center wavelength drifts. Applicants have experienced difficulties maintaining consistent narrow bandwidths at these higher repetition rates and duty cycles.

A need exists for reliable line narrowing devices and techniques for high repetition rate, high duty cycle gas discharge lasers.

SUMMARY OF THE INVENTION

The present invention provides helium purge for a grating based line narrowing device for minimizing thermal distortions in line narrowed lasers producing high energy laser beams at high repetition rates. Applicants have shown substantial improvement in performance with the use of helium purge as compared to prior art nitrogen purges.

In preferred embodiments a stream of helium gas is directed across the face of the grating. In other embodiments the purge gas pressure is reduced to reduce the optical effects of the hot gas layer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a first prior art line narrowed laser system.

FIG. 2 shows a second prior art line narrowed laser system.

FIG. 3 shows adverse effects on bandwidth of a hot gas layer on the face of a line narrowing grating.

FIG. 4A and 4B show a preferred embodiment of the present invention.

FIG. 5A shows bandwidth traces at various rep rates with prior art purging.

FIG. 5B shows bandwidth traces at various rep rates with purging in accordance with the present invention.

FIGS. 6A, 6B and 6C show alternate embodiments of the present invention.

FIGS. 7, 8 and 8A-D show LNP's equipped for fast feedback control.

FIG. 9 shows the heating of the gas layer on the grating surface.

FIG. 10 shows a technique for reducing the purge gas pressure.

FIG. 11 shows a preferred embodiment of the present invention.

FIG. 12 is a graph comparing a nitrogen purge with a helium purge.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Laser Performance at High Average Power

A prior art line narrowed KrF excimer laser operating at relatively low average power, typically less than 5W will produce a laser beam centered at about 248 nm with a bandwidth of less than 0.6 pm. The laser can run at high rep rate, up to 2000 Hz and even above that as long as average power is below 5W. A typical lithography KrF excimer laser has a pulse energy of 10 mJ. Therefore, in order to keep the average power low, it has to be operated with a relatively low duty cycle. For example, it can be run at 2 kHz in bursts of 200 pulses with pause between bursts of about 0.45. Such an operation will produce an average power of :

$$P_{ave} = \frac{10mJ \cdot 200 pulses}{0.5 sec} = 4W \quad (2)$$

Problems with bandwidth control start to appear when the average power is increased. This happens, for example, when the interburst delay is decreased. For example, laser running the same 200 pulse bursts with 0.1 second interburst delay will have an average power of :

$$P_{ave} = \frac{10mJ \cdot 200 pulses}{0.2 sec} = 10W \quad (3)$$

At maximum, the laser is run in continuous mode which at 2000 Hz and 10 mJ pulse energy is equivalent to 20W average power.

When the prior art laser system is run with high average power, the bandwidth increases gradually over a period of about 5 to 20 minutes from initial bandwidth of less than 0.6 pm, and remains substantially higher than 0.6 pm. Such an increase in bandwidth should be avoided in microlithography production runs, because it will cause images to blur due to chromatic alterations of projection lenses. Another important application is when the laser is used to test thermal properties at high duty cycles of other lithography components, such as the projection lens itself. In this application, the laser is supposed to maintain its bandwidth and other parameters within the specification during the duration of the test.

The bandwidth transient can be corrected somewhat using a special bandwidth control device.

FIG. 2 is a sketch showing a prior art line narrowing unit fabricated by Applicants' employer, Cymer, Inc., as a part of a prior art line narrowed lithography KrF laser system incorporating such a device. The unit includes three beams expanding prisms 8, 10 and 12, a tuning mirror 14 and a grating 16. Note that the nitrogen purge from bottle 44 enters the unit on the back side of the tuning mirror 46 to avoid purge flow directly on the grating face. In this system the wavelength of the laser beam 6 is controlled in a feedback arrangement in which the wavelength of the beam is measured by monitor 22 and computer controller 24 uses the wavelength information to adjust the angular position of tuning mirror 14 to control the wavelength to a desired value. The bandwidth control device 20 is used to mechanically bend grating 16 to make it slightly concave, for example. This device is described in detail in U.S. Patent No. 5,095,492 assigned to Cymer. Use of this device permits reduction of the bandwidth somewhat, but it still goes out of specification when the laser is run at high duty cycle.

FIG. 3 shows one of such examples, when the bandwidth goes out of specification in prior art laser run at 20W average power (10 mJ, 2000 Hz continuous operation). Also, the bandwidth control device can be optimized for one specific mode of

operation, but lithography lasers must be able to be run in several different modes. For example, a typical operating mode might be as follows:

- (1) a burst of 600 pulses 10 mJ pulses at 2000 Hz for 0.3 seconds,
- (2) idle for 0.3 seconds
- (3) repeat (1) and (2) for 85 bursts and
- (4) idle for 9 seconds.

Hot Purge Gas Layer

Applicants have determined that the poor performance at higher repetition rates as shown in FIG. 3 is the result of the development of a hot layer of nitrogen which builds up over a period of about 5 minutes on the face of the grating 48.

This hot gas is heated by the grating surface, which in turn is heated by absorbing a portion of incident laser beam. Typically, as much as 15 to 20% of incident light might be absorbed by grating surface. The surface temperature of the grating might rise to 10 to 15°C. This temperature increase is non-uniform, it is higher in the middle of the grating and lower at the ends as shown in FIG. 9. Therefore, the air in front of the middle portion of the grating is hotter than the air in front of the edges. Therefore, when the laser beam 80 incidents on the grating surface 86 it goes through this boundary layer 82. Because this air has the same pressure, the hotter the air, the less its density is. So, the air near the center of the grating is less dense, than the air near the edges. Because of that, the laser beam 80 will have different phase shifts when it goes to the middle portion of the grating and edges. So, the incoming beam with parallel wavefront 88 will have a curved wavefront 90, corresponding to divergent beam. This happens even if grating 16 is perfectly flat.

Applicants have developed preferred modifications to the line narrowing unit to substantially eliminate this hot nitrogen layer.

Flow Across Grating Face

A first preferred embodiment of the present invention is shown in FIGS. 4A and 4B. In this case the nitrogen purge of about 2 liters per minute is flowed upward through approximately 1 mm diameter holes spaced at ¼ inch in a 10 inch long 3/8 inch ID tube functioning as a purge gas manifold. Barrier plate 60 and barrier cover 62 force

most of the nitrogen purge flow in the direction shown by the arrows in FIG. 4B. This arrangement has produced excellent results as shown by the chart in FIG. 5. In this case, an increase in the output average power from 0.1W to 20W resulted in variations within 0.4 to 0.5 pm. It is interesting to note that at 10W average power, the bandwidth is actually slightly smaller than at 0.1W.

It is important that the purge flow across the face of the grating be carefully controlled to avoid flow related distortions. Applicants have tested various flow rates and have determined that excessive flow can do more harm than good. For example, a flow rate of 20 liters per minute produced very poor results. Recommended flow rates are in the range of about 0.5 liters per minute to about 10 liters per minute.

It is also important to note, that this purge does not substantially reduce the temperature of the grating. The grating remains hot. What the purge does is to rather continuously displace air in front of the grating, so it does not have time to heat up by the grating. Very small flow rate and, correspondingly, gas velocity prevents any air distortions caused by the flow itself from affecting laser operation.

Other Purge Arrangements

There are many potential arrangements to provide gas flow across the face of the grating to prevent the buildup of the thermal layer which causes the problem shown in FIG. 3. For example, a narrow slit of about 0.5 mm running the length of the manifold could be used instead of the small holes. Also smoother flow could be provided with a slit type nozzle such as shown in cross section in FIG. 6A or slit nozzles could be provided both at the top and bottom of the grating as shown in FIG. 6B. Also, flow across the grating face could be provided with a very small fan in a semi-closed system as shown in FIG. 6C. In this case, the regular nitrogen purge could be provided as in the prior art as shown in FIG. 2. In the FIG. 6C embodiment, the cavity between the grating and the barrier is not sealed and purge gas is permitted to circulate into and out of the cavity as shown at 64 and 66. The tubes 68 leading to and from fan 70 connect near the center of slitted tubes 72 and 74 which is just above and below the hottest area on grating 16.

Reduced Gas Pressure

A second solution to the hot gas layers problem is to reduce the gas pressure in the line narrowing package.

Gas convection modulates the gas density spatially, causing an inhomogeneous distribution of the refractive index, which in turn leads to phase front aberration. The magnitude of any aberration caused by gas density fluctuations, which are due to the gas convection close to the heated grating surface, is approximately linearly dependant on the nominal value of the susceptibility or the refractive index and thus the gas density.

Convective cooling of the surface of the grating and other optical components is not substantially reduced so long as the mean free path of the gas molecules is not less than distances between the “hot” and “cold” surfaces in the LNP. If we assume these distances are about 10 cm then as a rule of thumb we would say that the gas pressure should not be reduced beyond the pressure where the mean free path length is about 10 cm. That pressure is in the range of about 1 to 10 millibar so that the density of the gas in the LNP is about 0.1 to 1.0 percent the density at atmospheric conditions.

FIG. 10 is a sketch showing a system for maintaining a controlled pressure in the LNP at about 1 to 10 millibar. The nitrogen enters sealed LNP 7 through orifice 90. Vacuum pump 92 is used to create the vacuum in the LNP and the desired vacuum is maintained by controller 94 using a feedback signal from pressure sensor 96 to control needle valve 98. Since LNP is a sealed system and the pressure is approximately at equilibrium, sensor 96 may be thermocoupled.

Purge With Helium

Another solution to reduce the hot layer effect is to purge the LNP with helium. Helium has a smaller differential refractive index so that a hot layer will cause less distortion. In addition, helium has much better heat transfer properties than nitrogen. Argon may also be used with the same advantages. Helium, however, is much more expensive than nitrogen.

The equation for the Littrow wavelength (see equation (1) in the Background section) has potentially two components which can change with temperature d (the period of the grating) and n (the refractive index of gas). State of the art microlithography excimer lasers usually have an eschelle diffraction grating. The substrate of that grating is usually made out of very low thermally expanding material, such as ULE zero expansion glass made by Corning. The coefficient of thermal expansion (CTE) of this material is very small, typically on the order of 10^{-8} $1/^\circ\text{C}$; therefore, changes in d are very small. On the other hand, refractive index n of gas has a dependence on temperature which is described by the following equation:

$$n = 1 + kT/300 \quad (4)$$

where T is the temperature in $^\circ\text{C}$, k is the proportionally coefficient. For nitrogen and for 248 nm light $k = 3 \cdot 10^{-4}$. Therefore, for nitrogen we have $\Delta n = 1 \cdot 10^{-6}$ for a $\Delta T = 1^\circ\text{C}$. According to the equation (1), this Δn will lead to $\Delta \lambda = 0.25$ pm (per $^\circ\text{C}$) for 193 nm light. This is a very strong temperature dependence and it means that the temperature of the gas in the LNP should be maintained to better than 0.2 degrees C if we want the drift to be less than 0.05 pm. This is a very technically difficult task.

A laser of the preferred embodiment is shown in FIG. 11. In this laser, the beam expander prisms 8, 10 and 12; mirror 14; and grating 16 are placed in a tightly sealed housing 34. The housing has one gas input and one gas output. This enclosure is filled with helium. A window 30 is placed to seal the housing in the path of the beam 20. An aperture 36 is placed near the window 30. The exit port is a long thin tube to prevent back diffusion of air molecules.

For helium, the k coefficient is about $k = 3.8 \cdot 10^{-5}$ or about 8 times smaller than that of nitrogen. Therefore, for helium we have $\Delta n = 1.25 \cdot 10^{-7}$ for a $\Delta T = 1^\circ\text{C}$. According to the equation (1), this Δn will lead to $\Delta \lambda = 0.03$ pm (per $^\circ\text{C}$) for 248 nm light and to approximately 0.025 pm (per $^\circ\text{C}$) for 193 nm light. Now one has to maintain the temperature inside the LNP to within about 2 degrees, which is much more manageable problem. In fact, the thermal mass of the LNP, which in the preferred embodiment weighs about 5 – 10 pounds is sufficient to hold the

temperature within that range for several minutes. Because helium has so much different properties than nitrogen and the air, the LNP housing should be sealed very well and should have one entrance gas port and one or more exit ports for helium purge. The exit port should have a long pigtail tube attached to it as to prevent the back stream of outside air into the LNP.

FIG. 12 shows comparison of the line center drifts measured for nitrogen and helium purged LNPs.

Persons skilled in the art will recognize that in addition to the above-described specific embodiments of the present invention, there are many other embodiments possible to deal with distortions caused by the hot gas layer. Another technique for dealing with the hot gas layer is to provide active bandwidth control to correct for the adverse effects of the hot gas layer. Techniques for substantially real time control of several wavelength parameters are described in a United States patent application filed September 3, 1999, Serial No. 09/390,579 and in a United States patent application filed October 31, 2000, Serial No. 09/703,317 which are incorporated by reference herein. These techniques include fast feedback control of the position of the beam expanding prisms, grating curvature and tuning mirror position. Control of the position of the laser chamber is also provided. FIG. 7 is a combination block diagram schematic drawing of the entire laser system and FIG. 8A and 8B are drawings of the LNP with the added feedback control features. In the FIG. 8 embodiment, the curvature of the grating is controlled by grating curvature stepper motor 30 to compensate for the distortion caused by the hot gas layer on the face of the grating. In the FIGS. 8A-D embodiment, the curvature of grating 82 is controlled with seven piezoelectric devices 86 acting through seven invar rods 84 against backing block 88 and compression spring 90. This embodiment provides very fast adjustment of the curvature of the grating face.

The scope of the present invention should be determined by the appended claims and their legal equivalents.

CLAIMS

WE CLAIM:

1. A grating based line narrowing device for line narrowing a laser producing high energy laser beams, said device comprising:
 - (A) a grating defining a grating face,
 - (B) a chamber for housing at least said grating,
 - (C) a helium source for providing a helium purge for purging said chamber,
 - (D) a beam expanding means for expanding a beam from said laser to produce an expanded beam,
 - (E) a tuning means for directing said expanded beam onto the grating face in order to select from said expanded beam a desired range of wavelengths.
2. A device as in Claim 1 wherein said expanded beam heats said grating face producing a temperature increase in said grating face which in turn heats purge gas in a hot purge gas layer adjacent to said grating face, and a heat removal means for removing heat from said purge gas layer to reduce optical distortion caused by said hot purge gas layer.
3. A device as in Claim 2 wherein said heat removal means comprises a purge gas manifold having a plurality of small ports for directing purge gas across the grating face.
4. A device as in Claim 3 wherein said heat removal means comprises a grating purge gas flow control means for controlling purge gas flow across the grating face.
5. A device as in Claim 4 wherein said purge gas flow control means comprises structures defining a flow path across said grating face and then away from said grating face.

6. A device as in Claim 2 wherein said heat removal means comprises a purge gas manifold having at least one long very narrow slot.
7. A device as in Claim 6 wherein said slot is in the form of a long rectangular shaped nozzle.
8. A device as in Claim 3 wherein said helium purge gas flow through said manifold is less than 20 liters per minute.
9. A device as in Claim 1 wherein said helium purge gas flow is about 2 liters per minute.
10. A device as in Claim 1 and further comprising a vacuum pump for creating a vacuum in said chamber.
11. A device as in Claim 10 wherein said vacuum is a pressure of about 1 to 10 millibars.
12. A device as in Claim 10 wherein said vacuum is chosen so that gas molecules inside said chamber have a mean free path of between 5 cm and 30 cm.
13. A device as in Claim 1 and further comprising a feedback grating curvature control mechanism for providing active control of curvature of said grating face.
14. A device as in Claim 1 and further comprising a fan and at least one manifold configured to force a flow of helium gas across the grating face.
15. A method of bandwidth control of a narrow band gas discharge laser having a grating based line narrowing unit with a grating defining a grating face comprising the step of forcing a flow of gas across said grating face.
16. The method as in Claim 1 wherein said gas flow is less than 20 liters per minute.

17. The method as in Claim 16 wherein said gas flow is between 1 and 8 liters per minute.