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Power scaling of an extreme ultraviolet light source for future lithography

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Abstract

For future lithography applications, high-power extreme ultraviolet (EUV) light sources are needed at a central wavelength of 13.5 nm within 2% bandwidth. We have demonstrated that from a physics point of view the Philips alpha-prototype source concept is scalable up to the power levels required for high-volume manufacturing (HVM) purposes. Scalability is shown both in frequency, up to 100 kHz, and pulse energy, up to 55 mJ collectable EUV per pulse, which allows us to find an optimal working point for future HVM sources within a wide parameter space.

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In semiconductor industry there is an ongoing effort to produce smaller and cheaper printable structures. For more than half a century, these advances are driven by Moore's law, which states that the number of transistors on an integrated circuit doubles every two years [1]. To continue Moore's exponential development, structures as small as 22 nm half-pitch have to be realised by 2011. To achieve this with the current 193-nm-immersion lithography is technically challenging and economically not viable. Therefore, an alternative technique is needed and extreme ultraviolet (EUV) lithography is by far the most promising candidate [2].

An example of an EUV lithography scanner is shown in Figure 1. An EUV light source, operating under moderate vacuum conditions, produces EUV light at a central wavelength of 13.5 nm within 2% bandwidth. A large fraction of the light is reflected by a collector mirror and directed towards the intermediate focus (IF) point. A debris mitigation system is placed between the source and the collector to protect the mirrors against 'debris', such as droplets, produced by the plasma. Multiple multilayer mirrors direct the EUV light beam from the IF to the reticle (or mask), which is imaged on the wafer. The EUV power requirements for lithography scanners are normally defined for the IF and for high-volume manufacturing (HVM) purposes an EUV power of >200 W is needed. Taking into account the transmission of the debris mitigation and collector systems, this corresponds roughly to an EUV source capable of delivering >1000 W/2πsr in-band EUV light within the etendue of the scanner (so-called collectable light).

EUV light can efficiently be produced using a highly-ionized plasma. To generate such plasmas, there are currently two options under investigation: discharge-produced plasmas (DPP) and laser-produced plasmas (LPP). In the first an electrical gas discharge is used, in the second the plasma is created by a high-power laser [3]. At the moment the DPP concept is more mature since the prototype 'alpha' scanners of both ASML and Nikon are using DPP sources [4, 5]. The experiences from these prototype scanners, in combination with the ongoing development of the sources, show that the next step in the development, a 'beta'-pre-production scanner in 2009, is timely possible with a DPP source.

However, for HVM production in 2011 a further scaling of EUV output power is necessary and feasibilty of EUV sources (DPP or LPP) capable of HVM power levels has not been shown so far. Therefore, the scalability of any EUV source up to the required HVM level has been questioned. The consequence is that without a suitable EUV source there will not be EUV lithography which would mean the end of Moore's scaling law. In this Letter we present investigations of the scalabilty of the Philips DPP source and EUV output power at HVM level (>1000 W/2πsr collectable in-band EUV light).

The Philips EUV source, schematically shown in Figure 2, is a pulsed gas discharge in tin vapor [6]. It consists of two circular electrodes which rotate through baths of liquid tin, covering the electrodes with a thin layer of liquid tin. A pulsed laser triggers the discharge by evaporating a small amount of tin from the liquid surface between the two electrodes. Subsequently, a capacitor bank is discharged through the tin vapor, creating a high-current pinch discharge. Due to the low inductance of the system, a high peak power is dissipated in the plasma and highly ionized tin species (Sn^{10+}-Sn^{12+}) are created. These ions emit EUV line radiation in a quasi-continuum. More details can be found in [3, 6].

Power scaling of Philips' DPP source concept will follow (a combination of) three directions. First, an increase of the conversion efficiency (CE) of the plasma, producing more EUV at the same input energy. Second, increasing repetion frequency resulting in increasing average power. And finally, increasing the electrical input energy per pulse, leading to more EUV output per pulse. In this Letter we investigated the feasibility and limits of the last two scaling directions, frequency and pulse energy. The first direction, efficiency is expected to also contribute to the power scaling of our source, but these investigations are beyond the scope of this Letter.

A possible limitation for the repetition frequency is the presence of plasma remnants of the previous pulse. These remnants could negatively influence the conversion efficiency and size of the plasma of the next pulse. This possible effect is investigated using a modified alpha product source (the standard source is described in more detail in [6]). The repetition frequency of the standard alpha sources is currently not limited by plasma physics, as described above, but by the laser and power supply modules. Improvement of these modules for future generations of sources is not a technical limitation and currently under development. For the current frequency scaling experiments we equipped an alpha source with two lasers and upgraded the power supply module.

The two lasers could generate two pulse trains with variable time (Δt) between the lasers. To ensure a fresh and stable tin surface for every pulse in this specific experiment, the two laser beams are directed to slightly different positions on the electrode (in the direction of the wheel rotation). It should be noted that in future HVM product sources the laser will be on a fixed position on the wheel for every pulse; the fresh tin surface is ensured by fast rotation of the wheels. Figure 3 schematically shows the timing of the two laser pulse trains and the positions on the electrode. With this system we effectively created a series of double pulses of which the second pulse is equivalent to 'high-frequency' operation of the source and the first resembles 'low-frequency' operation. The second pulses of the double pulse are used to mimic high-frequency operation of our EUV source and investigate the frequency scaling of our source concept.

Additionally, the power supply must be able to operate at the same double pulse timing scheme as the laser pulses. For this end we used an improved power supply which achieves capacitor bank charging times as short as 4 μs, enabling shorter times (Δt) between two EUV discharge pulses. Figure 4 presents the charging voltage and EUV signal measured at the source operated with Δt=9.8 μs, which corresponds to 102 kHz. It should be noted that the EUV signal in the figure is much longer than the actual EUV pulse due to the slow response time of the measurement equipment.

For 256 consecutive discharge pulses, the discharge voltage and the in-band EUV energy are measured for every pulse separately. The measured values of only the second pulses of the double pulse are averaged, giving EUV energy of the high-frequency pulses only. Additionally, time-integrated EUV pinhole images are made. The camera system was not fast enough to capture single discharge pulses. Therefore, the images are a superposition of low-frequency and high-frequency pulses. From these images the total collection efficiency (fraction of EUV light emitted within the scanner etendue) was calculated using a typical collection volume with 1.3 mm diameter [3]. Since the two pulses are spatially separated, the resulting image shows a broader pinch than normal. Therefore, the calculated collection efficiency is a lower limit for the real collection efficiency of the high-frequency pulses. Figure 5 presents the results of the frequency scaling experiments; EUV output as function of frequency and a pinch image showing a superposition of 25 double pulses at 100 kHz. The results in Figure 5 show that the intrinsic CE and collection efficiency are constant over the entire frequency range, respectively 2% and 65%. This results in up to 3000 W/2πsr in-band EUV at 100 kHz of which 2000 W/2πsr is collectable. It also shows that the plasma remnants from the previous pulse decay within 10 μs (Δt=1/f$_{max}$) to sufficiently low levels not to disturb the next discharge since the EUV output energy per pulse of the high-frequency pulses is the same as for the low-frequency pulses (about 20 mJ collectable).

The second part of the power scaling investigations consists of increasing the EUV output energy per pulse by increasing the electrical input pulse energy. For this experiment, the electrical insulation of a standard alpha source is upgraded to enable operation up to 6.3 J pulse energy (at low repetition rates). Again, EUV in-band output energy and EUV pinch images are recorded. The results are shown in Figure 6. These experiments show that operation up to 6.3 J pulse energy is feasible, resulting in over 80 mJ EUV energy per pulse of which 55 mJ is collectable. This is over a factor 2.5 more collectable energy per pulse, compared to the pulse energies used for the frequency scaling experiments.

The experiments presented in this Letter show for the first time measurements of power levels required for HVM scanners. Additionally, we have shown that power scaling of our DPP source concept is straightforward from a physics point of view. Finally, we have established that scaling of our source is not limited to a single parameter; both frequency (currently up to 100 kHz) and pulse energy scaling (currently up to 55 mJ collectable per pulse) can be used in the future. This gives us a whole parameter space in which to find an optimal working point in frequency and pulse energy for future EUV sources at power levels ($>$1000 W/2πsr) enabling HVM chip production and extention of Moore's law further in to the future.

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FIG. 1. Schematic diagram of an EUV wafer scanner. Adapted from [3].

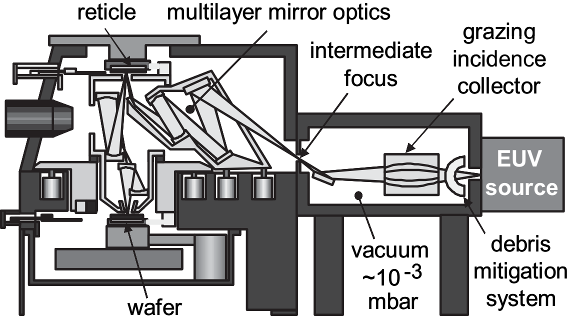
FIG. 2. Schematic diagram of the Philips EUV source.

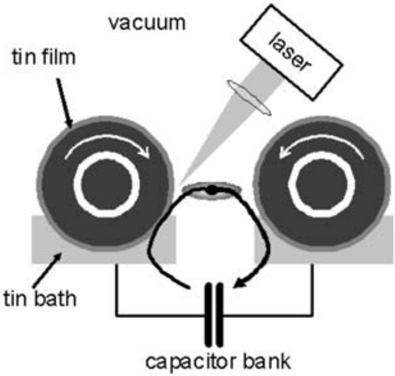
FIG. 3. Experimental arrangement for the frequency scaling experiments. The two lasers operate at the same, fixed repetition rate (rep. rate = $1/\Delta$T), while the relative timing between the pulse trains, Δt, can be varied. For all experiments $\Delta t \ll \Delta T$, which means that effectively a series of double pulses is generated. The discharge that is triggered by the second pulse (laser 2) is made under equivalent conditions as source operation at frequencies $f=1/\Delta t$. In this way, high frequency operation of the source can be mimicked by choosing Δt small.

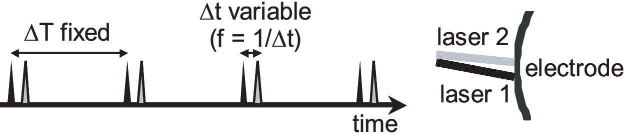
FIG. 4. Oscilloscope image measured during a frequency scaling experiment at effectively 102 kHz. The upper signal is the voltage on the capacitor bank, the lower signal the produced in-band EUV, measured with a (slow) photodiode.

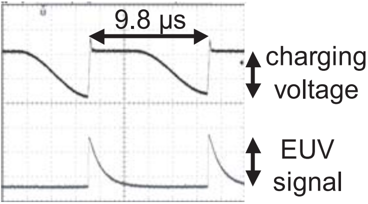
FIG. 5. Results of frequency scaling experiments. Left: Measured EUV output power in 2πsr of high-frequency pulses, with and without etendue correction. Right: EUV pinhole image showing a superposition of 25 double pulse discharges at effectively 100 kHz.

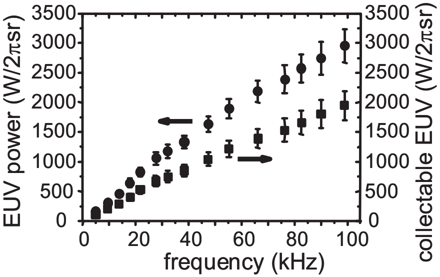
FIG. 6. Results of pulse energy scaling experiments. Left: The measured EUV output energy in 2πsr per pulse (128-pulse average), with and without an etendue correction. Right: EUV pinhole image measured at 6.3 J input pulse energy.

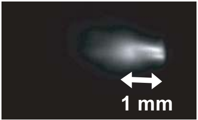

reticle
multilayer mirror optics
intermediate focus
grazing incidence collector
EUV source
vacuum ~10 -3 mbar
debris mitigation system
wafer

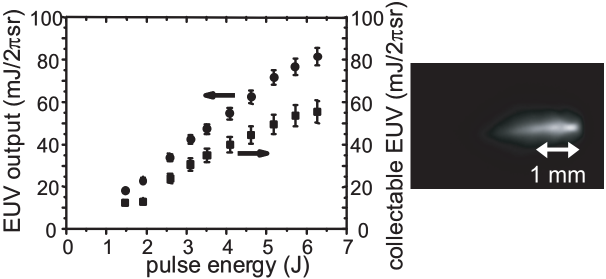

vacuum
laser
tin film
tin bath
capacitor bank


ΔT fixed
Δt variable
(f = 1/Δt)
time
laser 2
laser 1
electrode


9.8 µs
charging voltage
EUV signal


EUV power (W/2πsr)
collectable EUV (W/2πsr)
frequency (kHz)
0
500
1000
1500
2000
2500
3000
3500
0
20
40
60
80
100


1 mm


EUV output (mJ/2πsr)
collectable EUV (mJ/2πsr)
pulse energy (J)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
0
20
40
60
80
100
1 mm