EUV Sources for Lithographic Applications

EUV Technology Enables Future Semiconductor Manufacturing

- Semiconductor device manufacturing is currently using excimer lasers as the light source for lithographic structuring. The wavelength of these ArF lasers is 193 nm and the high volume manufacturing of structures with 45 nm has started already. To further shrink the structure size to 32 nm and beyond, a reduction of the used wavelength is required for physical reasons. The next technology will be the extreme ultraviolet (EUV) lithography using light with 13.5 nm wavelength. Efficient optical elements like multi layer optics were developed in the last years using improvements in thin film technology on large area substrates with roughness in the sub-nanometer range. Sources for such light are plasma based sources in which the plasmas are generated either by electrical gas discharges or by pulsed laser radiation. In this paper we describe the discharge produced plasma (DPP) sources only because of their advantages concerning efficiency, simplicity, reliability and maturity.

Requirements

For industrial EUV lithography applications high power extreme ultraviolet (EUV) light sources are needed at a central wavelength of 13.5 nm. For the economical operation of the scanners, a throughput of up to 100 wafers per hour is needed. Depending on resist sensitivity and the throughput of the rest of the scanner, this pushes the requirements on the source to an output power of up to 500 W in the so called intermediate focus (IF) which is the interface between the source unit and the scanner and is defined after the first collection mirror. The EUV is emitted nearly isotropically by the plasma, so that the collector optics is collecting only a part of it. Including other losses, the efficiency of the transmission from power in $2\pi$ sr to the IF is in the range of 10–15%.

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Guido Schriever received his diploma in Physics from the Technical University of Aachen, Germany, in 1994. His PhD thesis at the department for laser technology of the RWTH Aachen, Germany, dealt with fundamental investigations on the generation of extreme ultraviolet radiation using laser produced plasmas. He is one of the inventors of the gas discharge based Hollow Cathode Triggered Pinch EUV source. He joined Lambda Physik in Göttingen, Germany, by the end of 1999 as project leader for the EUV source development. In 2001 he changed to the new founded company XTREME technologies in Göttingen, Germany, where he is now director for research and development.

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FIGURE 1: Static arrangement for the generation of hot dense plasmas by electrical discharges of gases.
In addition to that, the multi layer optics used inside the scanner limits the bandwidth of useable light. This narrow region of 13.5 nm +/- 1 % is called in-band EUV and limits the efficiency of the light generation by hot dense plasmas to only a few percent compared to the electrical power put into the plasma. That means the electrical input power into the light generation will be in the multiple 10 kW range, which is a big technical challenge concerning cooling of modules including source parts and collector optics.

Physical Principles

Well known and efficient methods of plasma generation are electrical gas discharges for example as spark or flash. Unfortunately, the densities and temperatures of conventional gas discharges are not sufficient for the generation of EUV radiation. However, magnetic fields can compress relatively cold plasma with low density to hot, dense plasma with maximum intensity at an emission wavelength of 13.5 nm. The azimuthal magnetic field generated by the axial discharge current can be used to self-compress cylindrical plasma. This effect has been described as the pinch-effect [1]. In Figure 1 you see one possible geometrical arrangement for the plasma generation – other geometries were considered as well [2].

Initial experiments with the emitter gas xenon have been made to generate 13.5 nm radiation with gas discharge produced plasma sources [3]. From the above relation and the requirements for EUV sources for lithography (plasma diameter about 1 mm, almost spherical) an electrical current of approximately 20 kilo amperes for gases like xenon is necessary to generate a plasma temperature of 20 eV (which is equivalent to around 230'000 K). The magnetic field is about 20 Tesla and compresses the plasma cylinder to approximately 2000 bar pressure. The total energy in the magnetic field, plasma and external circuit can be estimated to 5 – 10 Joules per pulse. A stable plasma cylinder would possess a resistance of some 10^7 Watt. The current decreases significantly after several hundred nanoseconds due to the electrical properties of the generated hot and dense plasma. A pulsed regime is necessary to operate the discharge.

To increase the efficiency of these sources, other fuels are in use. Former experiments showed that tin increases the conversion efficiency by a factor of 3 – 4 compared to xenon. This is mainly due to the better wavelength matching of the tin emission.

The two German companies have been developing high power Extreme ultraviolet (EUV) sources based on gas discharge technologies. Several sources have been sold to leading semiconductor supplier companies that are using them in wafer scanners for semiconductor device manufacturing. All EUV lithography steppers and scanners worldwide are equipped with EUV sources from either XTREME technologies or Philips Extreme UV. For the future both companies announced the intention to cooperate to accelerate the development of EUV sources.
spectrum to the targeted 13.5 nm whereas tin requires higher efforts on source engineering.

The physical principle is quite similar compared to xenon based sources. In Figure 2 the production of highly ionized tin plasma is shown — it is produced in between two rotating electrode wheels, covered with a thin tin layer. A tiny tin cloud is generated by laser ablation from one of the electrode wheels. If this cloud reaches the second electrode, a conductive channel is created. At this moment a capacitor bank with a stored electrical energy of several Joules is discharged which leads to a high current between the electrodes of up to 20 kA. A highly ionized (around tenfold) tin pinch plasma is created, that emits the EUV radiation. In normal operation the source runs at several kilohertz repetition rate.

Figure 2 illustrates the principles of the tin DPP source schematically. Jonkers [4] and Pankert [5] described the tin DPP sources more detailed.

Besides feeding the tin to the discharge region, the rotating tin covered wheels have three main advantages. The tin layer is permanently renewed, which principally solves the lifetime limitations due to electrode erosion. Additionally, the liquid tin serves as very efficient cooling liquid to remove the heat from the discharge region. Finally, the liquid tin guarantees a good electrical contact between the rotating wheels and the capacitor bank.

Achieved Results

In the currently operational EUV steppers and scanners worldwide only discharge produced plasma sources from XTREME technologies and Philips Extreme UV are integrated. This demonstrates the very good results achieved with discharge plasmas during the last years in comparison to alternative ways to generate EUV [4]. Starting with the micro exposure tool technology in 2003, the source power in the intermediate focus was well below 1 W. By improvements of the output power, in 2004 and 2005 first sources with up to 2 W were delivered to customers. In 2006 and 2007 the output power could be increased again to the current level of up to 10 W. On the actual power level both fuels (xenon and tin) can match the requirements.

By developing xenon based sources XTREME technologies put large efforts on the improvement of the stability and reliability. Important for the applicant is e.g. the stability of the output power over the component lifetime (Fig. 3). This enables constant exposure conditions for the scanner between the maintenance procedures.

Already in 2003 the development status of xenon fueled sources enabled the integration of these sources into the first commercial EUV stepper from Exitech, UK, (Fig. 4). Using these micro exposure tools, the feasibility of EUV lithography was demonstrated early and the systems are still running with high duty cycle. Intel Corp. in Hillsbo-
An upgrade of the Xenon fueled source was developed for the integration into the EUV1 scanner from Nikon (Fig. 5). These sources are currently under integration into the scanner. First structures printed with these machines have been presented recently and demonstrate very good results [6]. The output power could be increased by a factor of more than ten, compared to the Micro exposure tool sources. Compared to the former source generation, the component lifetime was extended by a factor of more than ten as well. The current source generation belongs to the so called alpha generation.

ASML (The Netherlands) shipped already two scanners on alpha level to the customers IMEC in Leuven, Belgium, and CSNE in Albany, USA. In these scanners tin based sources are integrated which were developed by Philips Extreme UV (Fig. 6). These devices exposed pre-scanned images – recently the first test chip was presented by AMD, in which EUV lithography was used to manufacture one critical layer [7].

Outlook

For all alpha sources, xenon and tin fueled, power upgrades are planned around the 10 W level at IF (intermediate focus) within 2008. For the delivery of beta sources in 2009, a power level above 50 W in the intermediate focus is targeted. Further upgrades to 200 W power are expected until 2010. For high volume manufacturing (HVM), a power upgrade to approx. 500 W until 2013 (Fig. 7) will be necessary.

For this development work, XTREME technologies and Philips Extreme UV want to join their forces. The long year experiences of both companies ensures even faster progress and shall be combined for the upcoming development.

The tin based source concept has been selected for the technology of choice as the future source concept. It is more efficient, deals with higher input powers and is resistant against electrode erosion. Compared to the current status, the repetition rate as well as the energy per pulse needs further improvements to achieve the higher power level (Fig. 8). Test experiments for both approaches have been already performed. In-band EUV pulse energies up to 80 mJ were demonstrated as well as repetition rates up to 100 kHz. The scaling of the pulse energy as well as the scaling of the repetition frequency can be realized without losses of the plasma efficiency nor other important plasma parameters like the size of the pinch. This has been shown in proof of principle experiments. The yellow star in Figure 8 depicts the highest power already demonstrated in combination of high in-band EUV pulse energy and high repetition rate. You can find more details in [8, 9].

The main challenge now is to solve the related engineering tasks like cooling capability, component lifetime and system reliability.

Summary

The feasibility of EUV lithography could be demonstrated during the last years. The work on discharge plasma sources resulted in tremendous progress and power improvements from initially <1 W power level five years ago into the current 10 W region. It is still a long way to the targeted 500 W source power level, but former experiments already demonstrated that no physical limits will block increasing the source power up to this level. Development and engineering work will need significant effort to reach this aim step by step.

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References