Making extreme-UV light sources a reality

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Scalable and highly stable at 13.5nm, laser-produced discharge plasma is a viable means of generating extreme-UV photons to power the next generation of lithography exposure tools.

To sustain this century’s information and communication revolution, optical lithography—the core technology that allows the printing of ever more powerful, smaller, and faster electronics—will have to continue to deliver productivity gains at the pace described by Moore’s law. However, the economic viability of next-generation optical lithography (extreme-UV, or EUV) in a high-volume manufacturing environment will require appropriate exposure tools (‘scanners’) to achieve high-throughput and high-yield operation. Consequently, EUV light sources must be able not only to generate and deliver powerful, stable, and ‘clean’ EUV photons at 13.5nm (see Table 1) but also to do so consistently and reliably.

Many ideas for EUV sources have been explored over the years. The technology now centers on two concepts: laser-produced plasma—LPP (see Figure 1, left)—and laser-enabled-discharge-produced plasma: LDP (see Figure 1, right). Though each of these approaches generates hot, dense plasmas (at temperatures close to 200,000°C) and emits EUV radiation efficiently as a black body (i.e., at all frequencies), how they do it differs greatly.

In the case of LPP, microscopic droplets (diameter ~ 20μm) of molten tin at a temperature in excess of 232°C are fired through a vacuum chamber, individually tracked, vaporized by a pre-pulse laser, and eventually irradiated by a pulsed high-power IR CO₂ laser at 50–100kHz. When the highly excited electrons relax to lower energy levels, the tin plasma generated radiates EUV photons.

Though seemingly simple, the LPP concept is, unfortunately, inherently unstable due to the discrete nature of tin delivery and the challenge of spatially synchronizing and focusing (from some 50m away) the laser beam on the microscopic droplets. CO₂ laser instabilities coupled with droplet instabilities further constrain the ability of LPP to consistently achieve a high average energy-conversion efficiency. The primary contributors to short- and long-term laser instabilities are pulse-to-pulse energy variability, timing jitters, beam defocusing due to thermal lensing, and various power loss mechanisms (e.g., beam widening and clipping by apertures when operating at a high duty cycle, gradual coating of laser optics with tin, and filtering of IR radiation from the EUV beam).

Droplet variability stems from difficulty in consistently generating identical droplets at a high rate, instabilities in droplet position, velocity, and spacing, interactions of the plasma and...
shock waves with other droplets, collisions between droplets, and missing droplets. Moreover, the high level of debris produced at high power severely limits collector mirror lifetime. The indirect energy-conversion scheme of LPP (electrical → laser light → EUV) also makes this approach inefficient. As LPP scales in power, an unacceptable strain (~1MW per source) on the electrical power supply of the fabrication facility would severely limit the economic viability of the technology. Finally, LPP costs increase linearly with the number of amplification stages required by the architecture.

Acknowledging these challenges and tight constraints early on, we abandoned LPP in favor of developing LDP. With LDP,\textsuperscript{4,5} the plasma is generated between two rotating discs. The discs are partially immersed in a bath filled with liquid tin, which coats the discs in a thin layer. A pulsed laser beam focused on one of the discs evaporates a small amount of tin and generates a tin cloud between the two discs. Next, a capacitor bank connected to the discs through the liquid tin discharges and converts the tin cloud into a plasma heated to 200,000°C. Pinched by the high current, the plasma emits EUV radiation. This process is repeated several thousand times per second. The resulting heat load is cooled away by the liquid tin, which is kept at constant temperature by an external cooler. Debris is captured by a foil trap, substantially extending the life of the collector mirror.\textsuperscript{6}

Because high throughput without stability would be tantamount merely to printing defective semiconductor devices at high speed, we have striven to increase EUV power without compromising dose stability. The objective is to ensure consistent dimensional uniformity of the printed features and, consequently, the performance of the chips. To date, we have experimentally demonstrated 73W of clean EUV power after intermediate focus (IF, the interface source scanner), while maintaining exposure dose stability well within the specifications (3σ ≤ 0.2%). At lower power level, light sources in the field are also maturing and now exhibit high availability in excess of 70% and as high as 95%.

To achieve higher EUV output power (250W of stable EUV clean power after IF), the pulse energy and repetition rate—i.e., the frequency of the source operation—and the intrinsic conversion efficiency (electrical → EUV) must be increased.\textsuperscript{7}

In summary, the challenges of LPP (e.g., power scaling vs. debris mitigation/mirror lifetime, laser frequency scaling vs. droplet minimum stable distance, stability vs. reflection on secondary droplets, droplet breakdown/expansion/evaporation, droplet tracking and targeting) are still not solved and are primarily challenges of physics. In contrast, the challenges of LDP are those of engineering (spatial tolerances, heat removal, and module lifetime) whose solutions we are already beginning to address.

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