Boxing with tin droplets

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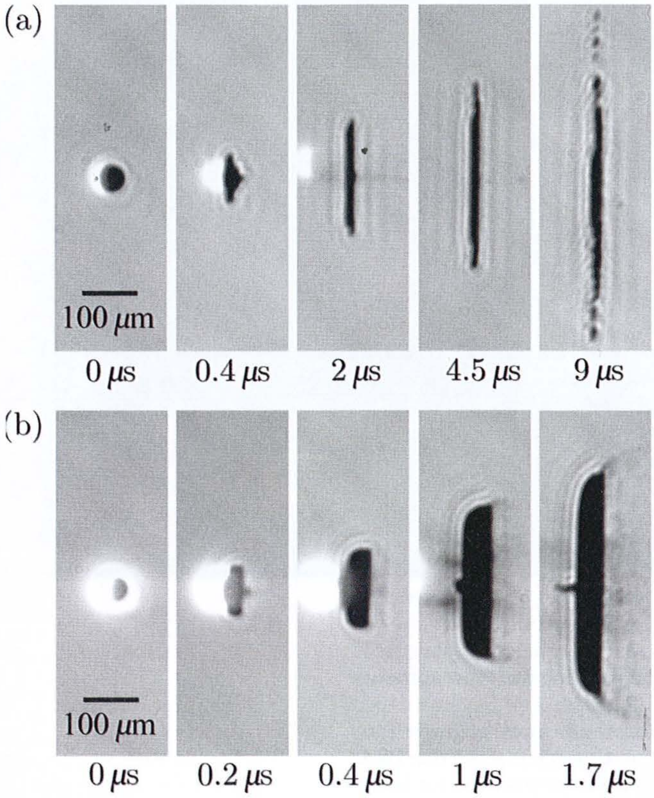

↙ Figure
Shadowgraph images, taken at various times, of a tin droplet (seen from the side) being hit by a (a) low-energy and (b) high-energy laser pulse impinging from the left. The laser pulse induces a plasma, which expands and pushes the drop away from the laser. This deforms the droplet into a flat pancake.

→ Moore's law predicts that the number of transistors on computer chips doubles every two years. This prediction, made in 1965 by Gordon Moore, has impressively held for over 50 years and has driven the semiconductor industry. However, fitting more transistors onto chips is challenging. 'Chip-making' photolithography systems use light to 'print' extremely small structures onto chips. The shorter the wavelength of light, the smaller the structures that can be printed, so the latest generation of these systems uses very short-wavelength, 'extreme ultraviolet' (EUV), light.

One way to produce this light is to heat a droplet of fluid metal (tin) with a laser beam, so that it disintegrates into independent electrons and ions, thereby forming an extremely hot fourth state of matter – plasma – which emits EUV light. Simply put, the plasma glows because of its high temperature, much like an old-fashioned incandescent light bulb, in which a filament is heated to temperatures similar to that of the sun. In our ARCNL set-up, a much hotter plasma is produced, exciting highly charged tin ions, which radiate light when they spontaneously decay. The atomic structure of tin ensures that most of this light is emitted as useful EUV light with a wavelength around 13.5 nanometres. This is about 15 times shorter than the 193-nanometre-wavelength light used by conventional photolithography. The formation of such a laser-produced plasma happens in two steps. A first laser pulse hits the molten tin droplet, creating a small plasma, which quickly expands and pushes on the droplet, causing it to accelerate. This acceleration is so powerful that the droplet deforms radically. The deformation happens at a much longer timescale of several microseconds, after which the droplet looks like a thin pancake. This shape was found to be optimal for the production of EUV light. To obtain this light, a second, more powerful laser pulse ensures the knock-out: the deformed droplet changes into an EUV-emitting plasma. The efficiency of the entire process is dependent on the effectiveness of the first pulse in optimally deforming the target.

> **"A droplet of tin is heated with a laser beam, thereby forming an extremely hot plasma, which emits extreme ultraviolet light."**

At ARCNL, we designed an experiment with tin droplets and laser systems that imitates an industrial lithography system as accurately as possible, while still allowing us to study the physics underlying the propulsion and deformation of tin droplets in detail. In this work, we looked at the microscopically small droplets (about the thickness of a human hair) using long-distance microscopes and pulsed laser light to make high-resolution, negative images of the droplets. There are two types of physics at play: in the first few nanoseconds, *plasma physics* describes the plasma that propels and deforms the droplet. The deformation is described by *physics of fluids*.

We collaborated with Dr. Hanneke Gelderblom and her team at the University of Twente and ASML to demonstrate that the deformation of tin droplets is very similar to the deformation of a water droplet under the influence of laser light, and that it can be described by a recently developed analytical model. Although the physics of the acceleration differs, the fluid dynamics are completely scalable from water to tin. We also found that the velocity of the accelerated tin droplet exhibits an interesting dependence on the energy of the laser pulse, which can be understood from basic momentum conservation. This dependence has two features. First, we demonstrated and explained that a minimum laser-pulse energy is required before anything happens at all: below this threshold energy, no plasma is created. Above the threshold, we find that there is an extremely 'simple' relation between the droplet's velocity and the laser-pulse energy over a very large range of energies. This simple relation provides a very sensitive test of the most recent developments in plasma theory, which underpin state-of-the-art modelling of plasma EUV sources. Our results contribute to understanding the first step in the formation of laser-produced plasma for EUV light and led to the first scientific publication of the ARCNL.

ARCNL was established in January 2014 and forms a public-private partnership between the Netherlands Organisation for Scientific Research (NWO), the University of Amsterdam (UvA), the VU Amsterdam and semiconductor equipment manufacturer ASML. Ω

→ Reference

D. Kurilovich *et al.*, Plasma Propulsion of a Metallic Microdroplet and its Deformation upon Laser Impact, *Physical Review Applied* 6, (2016) https://doi.org/10.1103/PhysRevApplied.6.014018