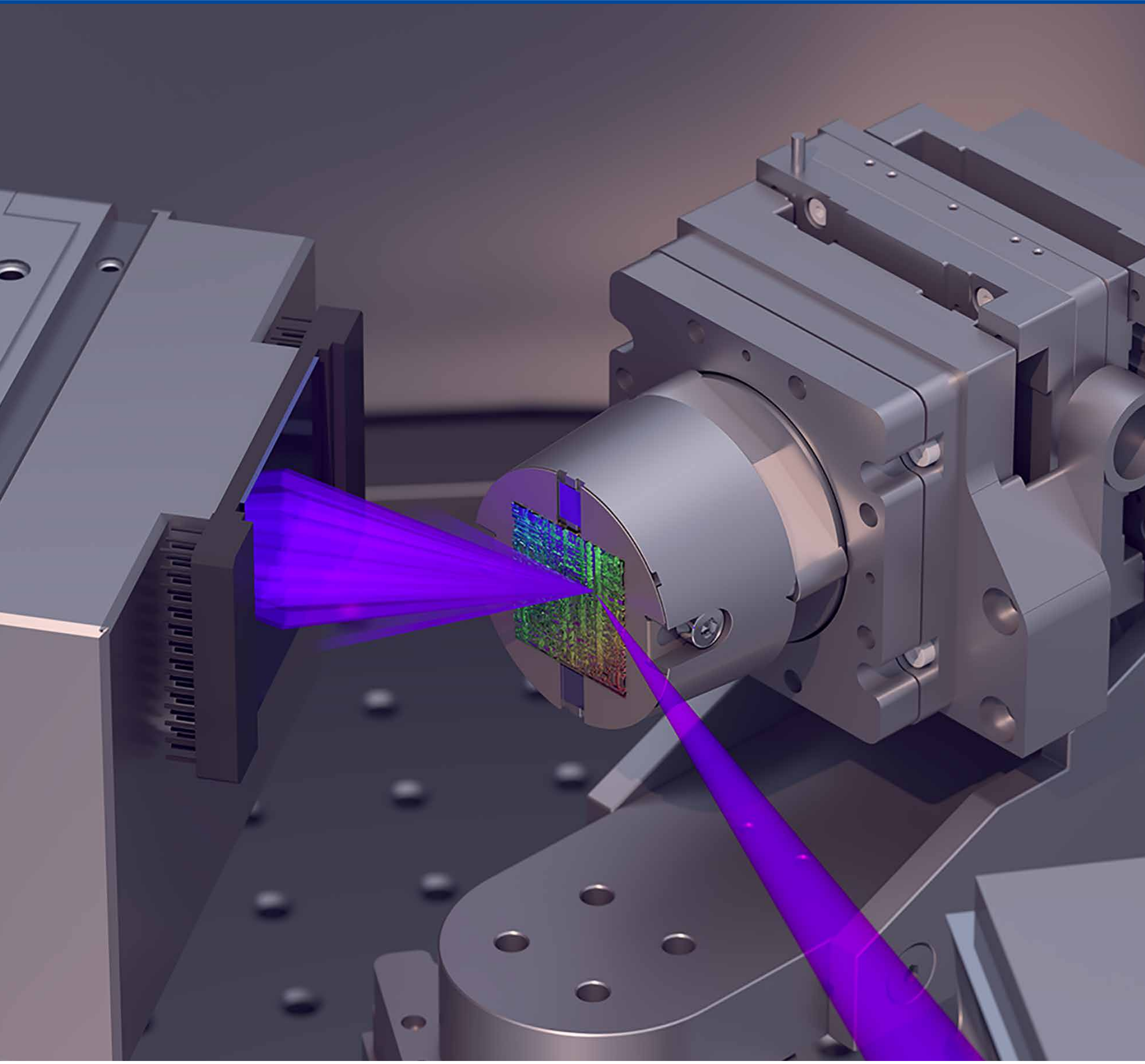
DSPE MIKRONIEK
2022 (VOL. 62) ISSUE 4
PROFESSIONAL JOURNAL ON PRECISION ENGINEERING



- THEME: METROLOGY & TIMEKEEPING
- A LENSLESS APPROACH TO EUV AND SOFT X-RAY MICROSCOPY
- A COMMUNITY REJOICING AT EUSPEN'S NON-VIRTUAL CONFERENCE
- PRECISION CLEANING OF INDUSTRIAL PARTS AND SURFACES

MIKRONIEK IS A PUBLICATION OF THE DUTCH SOCIETY FOR PRECISION ENGINEERING – WWW.DSPE.NL

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics. The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

DSPE
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Publisher
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Subscription
Mikroniek is for DSPE members only.
DSPE membership is open to institutes, companies, self-employed professionals and private persons, and starts at € 80.00 (excl. VAT) per year.

Mikroniek appears six times a year.

ISSN 0026-3699

The cover image (featuring the sample stage of a lensless microscope) is courtesy of Sven Weerdenburg (TU Delft). Read the article on page 5 ff.

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THEME: METROLOGY & TIMEKEEPING

FEATURES

METROLOGY TRENDS IN PRECISION MANUFACTURING

(Photo: Nicole Minneboo)

It can be argued that the story of precision is an arc driven by a search for perfection and the need for interchangeable parts to drive manufacturing volumes. With that comes accuracy and tolerance needs that must be met by measurement innovations. Metrology, from the ancient Greek metron (measure) and logos (study of), is the science of measurement. As precision engineers we understand that a scientific approach to measurement is critical to assure precision outcomes.

It has been reported that there are now more transistors in the world than leaves on all the trees. As metrologists we would say this must be proven, but what is certain is that when it comes to semiconductor fabrication equipment, such as lithography machines, the hunger for precision does not stop. For integrated circuit production typical layer-to-layer accuracy (overlay) during fabrication is now at 1.5 nanometer. And the mirrors integrated in the latest generation of lithography machines require a form accuracy one hundred times smaller again.

As the targeted precision increases, so too does the skill required to control potential disturbances. Unwanted temperature gradients, for example, or unintended vibrations at extremely low levels, can have significant impacts on performance and must be managed. As each functional part of a machine becomes more complex, the measurement strategy needed to achieve precision also becomes more challenging. This strategy must take into consideration each of the parts and their interrelationships.

Printing has required precision for many decades as the human eye is very sensitive to accurate registration of colours. Today however, large cylindrical printing equipment parts must achieve sub-micron ($< 10^{-6}$ m) level accuracy over ~5 m. With advanced printing technologies, not only visuals are printed but also devices such as electronics. This requires control of the substrate during the printing process with sub-micron accuracy, whether the substrate is thin (glass) or flexible (plastic foils). In-line inspection interferometers can be applied to verify these accuracies.

Moving from 2D to 3D printing, these accuracy requirements become spatial. Here, precision motion components are key to achieve the required volumetric repeatability. The latest 3D (polymer) printers have the capability for sub-micron feature printing. For production this requires extremely accurate x-, y- and z-stages. Air bearings allow to move without friction at high speed, essential to achieve both accuracy and productivity.

In the area of machine tools, demands grow for complex shapes such as turbine blades, impellors and medical protheses. Today, 5-axis machine qualification demands sub-micron measurement of the kinematic accuracy over the full machine working volume in under a minute. Further, the trend is moving from only measurement and correction to prediction and intervention.

Precision timekeeping is inescapably linked to precision instruments. Today's official standard of time is generated by hundreds of caesium atomic clocks around the world operating at microwave frequencies. Progress with optical clocks in the last decades has reached accuracies of one part in 10^{+18}; this value corresponds to losing less than a second over the age of the Universe. This progress has been achieved through precision components and in turn feeds the precision timing needs of tomorrow's complex machines.

IBS has been part of this precision ecosystem for 30 years. We now design to the picometer. Making virtual machines has become the norm. And big data strategies have become a standard requirement as machines become more intelligent. In the field of precision engineering, the challenges never stop. Luckily, neither does the ingenuity of the engineers who love to meet these challenges.

Henny Spaan
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COHERENT DIFFRACTIVE IMAGING

Semiconductor features such as transistors used in computer chips have reached the nanometer scale, yet metrology tools still have to follow the advances in the industry to study this new generation of chips. Short-wavelength microscopy using extreme ultraviolet (EUV) light or soft X-rays could offer a solution, but it is not compatible with conventional imaging optics. Researchers from Delft University of Technology have built a lensless microscope that uses coherent EUV light to make an image at the scale of 100 nm. With further refining of this technique, they expect to drastically improve the resolution, possibly down to wavelength scales.

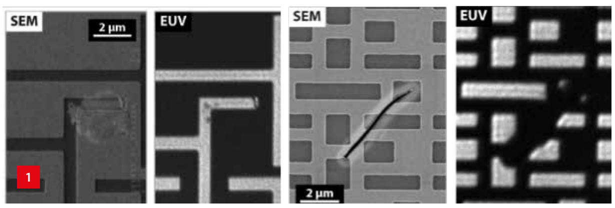
SVEN WEERDENBURG

Introduction

The quest for lensless microscopy with extreme ultraviolet (EUV) and soft X-rays (SXR) originated from the need for short-wavelength (roughly below 20 nm) microscopy. A conventional microscope uses a set of lenses, arranged in such a way that they can magnify extremely small objects. The smallest feature one can observe with such a device is typically defined by the quality of the lenses and the wavelength of the light used to illuminate the sample. This is the so-called diffraction limit or Abbe limit, which is defined as $d = \lambda/(2 \cdot NA)$, where d is the resolution, λ is the wavelength and NA (numerical aperture) indicates the quality of the optics.

Improving the resolution is obviously of interest for many applications, but in particular for optical metrology in the semiconductor industry. The continuous innovation in this industry reduces the dimensions of structures in next-gen chips and thus increases the resolution requirements for metrology tools. Consequently, this wavelength-dependent diffraction limit is obviously a good reason to use shorter wavelengths.

If resolution is the main driver, then why not use electron microscopy, as this is an already well-adopted and matured tool? Besides resolution, optical contrast is of importance, especially for lithography mask metrology, for example. The masks involved are exposed to EUV light (13.5 nm) in advanced lithography scanners and project the structures in the mask onto a wafer. If they contain defects, these are transferred via the EUV light to the wafer and could potentially ruin the product. Therefore, one would ideally like to know what the defects look like under EUV light, so-called actinic metrology, as they can look vastly different in different metrology tools; see Figure 1.



Defects in semiconductor samples can look vastly different depending on which metrology tool is used. (Image source: [1])

So, why not use the smallest wavelength possible and go all the way down to EUV, X-rays or gamma rays for high-end microscopy? Unfortunately, fabricating optics for these wavelengths is quite a challenge. Conventional refractive optics do not exist in this regime (with some exceptions [2]), so we have to resort to other types of optics. Diffractive optics, such as Fresnel zone plates, and reflective optics can be used, but are exceptionally hard to manufacture in a high-*NA* version.

As an indication, the advanced optical system of ASML's EUV scanners is based on a set of mirrors with an *NA* of 0.33 (which will be improved to 0.55 [3]). While ASML's deep-UV immersion scanner, which still works with refractive lenses, has an *NA* of 1.35. Although these are not metrology tools, it does demonstrate that reaching a high *NA* with EUV is a major challenge.

Lensless imaging, particularly ptychography (see below), can be an exciting approach to bypass this issue for next-generation metrology tools and extract the potential that EUV and SXR light can offer to the industry.

Lensless imaging

In a conventional microscope, an object of interest is illuminated with a light probe and part of the light is

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Sven Weerdenburg is a Ph.D. candidate in the Optics Research Group at Delft University of Technology. The research presented in this article is the result of a collaboration between five Dutch universities (Amsterdam (VU), Utrecht, Eindhoven, Twente, and Delft) and several industrial partners in the NWO-TTW perspective programme P16-08, LINX (Lensless Imaging of 3D Nanostructures with soft X-rays). LINX provided funding for this project.

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reflected and diffracted by the sample. This light is captured by a set of lenses (or mirrors) and transformed into an image on a camera or an observer's eye. Now if this were repeated without any lenses, the electric field E of the light beam would freely propagate towards the camera; see Figure 2. This propagation of the electric field can be described as:

$$E(x, y, z) = \iint \frac{1}{i\lambda} \frac{e^{ikr}}{r} E_0(x_0, y_0, z_0) dxdy$$

Here, E_0 refers to the electric field at the sample and r is the observation location in x,y,z space, i.e. the location of the camera:

$$r = \sqrt{(z - z_0)^2 + (x - x_0)^2 + (y - y_0)^2}$$

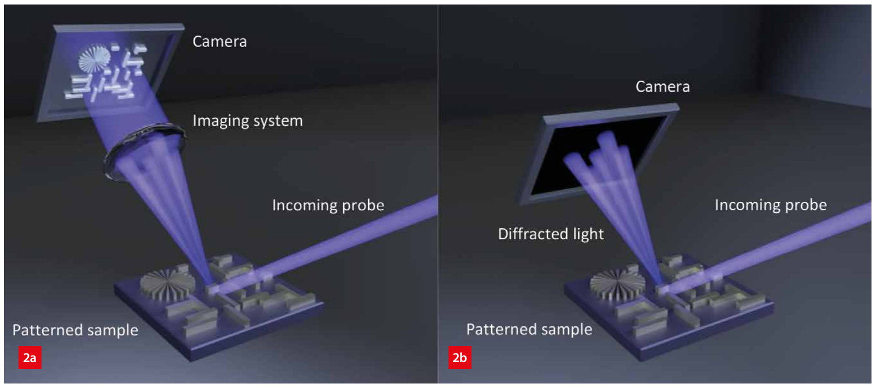
If the camera is sufficiently far away from the sample, meaning z becomes sufficiently large, these equations approach a 2D Fourier transform of the light that originated from the sample.

The diffraction patterns contain amplitude and phase information, both of which are needed to be able to perform an inverse Fourier transform and resolve the sample. However, cameras can only register intensity, so that the phase information is lost. It has been shown previously [4] that the phase can be retrieved via an iterative phase-retrieval algorithm. Loosely said, a suitable phase is found by fitting/optimising via iterations between Fourier space and real space. Imaging methods based on this concept are often referred to as coherent diffractive imaging (CDI).

CDI can be extended by scanning the probe across the sample and acquiring multiple diffraction patterns. By overlapping the probe at different scanning locations, we ensure that diffraction patterns acquired at neighbouring locations share information. This results in ambiguities, which reduce the number of solutions in the optimisation algorithm and make the reconstruction more robust. This approach is commonly known as ptychography and it has shown great potential in recent publications [5]. We have developed our own ptychography reconstruction algorithm, which is outside the scope of this article.

High harmonic generation

In order to perform ptychography and capture sets of diffraction patterns, the sample has to be illuminated with spatially and temporally coherent EUV light. Typically, researchers resort to large facilities such as synchrotrons or free-electron lasers (FELs) for obtaining laser-like EUV



Two ways of capturing diffracted light.
(a) Conventional imaging: using an optical (imaging) system to create an image on a camera.
(b) Lensless imaging: the optical system is removed and the diffracted light is captured directly.

light. Unfortunately, this is out of reach for many research or industry applications. However, enormous advances in table-top coherent EUV sources have made them commercially available, making it a viable solution for most applications with these requirements.

The sources are based on high harmonic generation (HHG), which is achieved by focusing a high-power laser with pulses of a few femtoseconds (fs) on a gas jet. The electric field in the focus is sufficiently large to distort the potential well of these noble-gas atoms to such an extent that electrons can tunnel out of this well and the atom is essentially ionised. The electric field accelerates the electron away from the parent ion. Eventually, the electric field of the light pulse flips and the electron starts to decelerate and then accelerate again back towards the parent ion with considerable additional kinetic energy.

If the electron recombines with the ion, it releases this additional energy in the form of light. This light contains multiple harmonics of the fundamental drive-laser frequency, leading to a frequency-comb-like response of odd harmonics (i.e. $n = 1, 3, 5, 7$, etc.). By combining the individual responses of a collective of atoms, it becomes possible to generate coherent light through phase matching.

The EUV system is driven by a 1,030-nm infrared (IR) Ytterbium fibre laser (Active Fiber Systems) with an average power of 100 W running at a repetition rate of 600 kHz and a pulse length of 300 fs. These pulses are compressed to ~30 fs with an efficiency of 70% and focused onto a pressurised noble-gas jet (Figure 3). Higher harmonics are generated (depending on the drive gas) up to 140 eV (~9 nm). The wavelengths of interest for our applications are 68 eV (18 nm) and 92 eV (13.5 nm), with photon fluxes of $1 \cdot 10^{11}$ and $0.5 \cdot 10^{9}$ photons per second, respectively.

THE TIMES THEY ARE CHANGING

What time is it? What is time? Time keeps running, but how can you keep up? Although the position of the earth with respect to the sun or other celestial objects is still a useful indicator for the time of day, modern timekeeping with the highest accuracy can only be done by using atomic clocks. This article discusses the past, present and future of accurate timekeeping and some of its applications.

ERIK DIERIKX

Past

In 1967, the international organisation coordinating the use of all measurement units, the *Bureau International des Poids et Mesures* (BIPM), proposed the definition of the unit of time interval, the second, based on the cesium atom. The definition of the second (after the last revision in 2020) is as follows:

> The unit resulting from the fixed numerical value of the cesium frequency $\Delta\nu_{Cs}$, the frequency of the undisturbed hyperfine transition of the cesium-133 atom in the ground state, which is fixed at 9 192 631 770, expressed in the unit Hz, which is equal to s^{-1}.

In addition to this definition of the second, a common internationally accepted time scale is also important for many practical matters. By means of radio transmissions of time signals, coordinated by the International Telecom Union (ITU), the first international comparisons of atomic clocks (see the text box on the next page) were carried out about 52 years ago. Based on this, BIPM started calculating the International Atomic Timescale (TAI).

The TAI is much more accurate than the former universal time (UT1) based on the rotation of the earth. However, over time it was seen that the TAI and the UT1 were starting to diverge. Therefore, the ITU proposed a universal coordinated time (UTC) running at the same pace as TAI and in which a step of 1 second is introduced occasionally to remain close to UT1. We call these correction steps 'leap seconds'. At first this seemed like a good compromise, but because practical implementation proves difficult in time-critical systems, the leap second has been under discussion for quite some time.

Present

Currently, there are about 90 time laboratories around the world that together have more than 400 atomic clocks. These clocks are compared with each other continuously, day and night, mostly by means of microwave measurement techniques using satellites. All measurement data from these laboratories is collected at BIPM and once a month, based on this data, the official UTC from the previous month is computed. Since this delay of more than a month is undesirable for certain applications, an unofficial "UTC rapid" (UTCr) was introduced several years ago, which is computed every week. In the monthly "Circular T", BIPM reports to all time laboratories in 5-day intervals how much the timescale realisation of laboratory *k*, denoted by UTC(*k*), deviated from the computed UTC. And similarly, a weekly report is published that shows the differences between the UTC(*k*) and UTCr at 1-day intervals.

In the computation of the UTC, there is a distinction in the types of atomic clocks. Most of the clocks included in the UTC calculation are first-generation atomic clocks, which have already been commercially available for a long time. These are cesium-beam clocks and hydrogen masers. They generate a very stable (precision) frequency, but because the atoms are not completely brought into their ground state first, they still have a small deviation from the definition of the second (accuracy). In addition, there are several dozen second-generation atomic clocks worldwide; cesium or rubidium fountain clocks (in which atoms are launched upwards; while weightless, they are measured to set the frequency). In these clocks, the atoms are first brought to their ground state by means of laser cooling. As a result, the frequency coming from these clocks is not only extremely precise, but also accurate to the definition of the second.

For the computation of International Atomic Time (TAI), the clocks of the first generation are like a large flywheel of frequency standards, each of which has a stable deviation from the group mean. This group mean is a weighted mean in which the weight of each clock is determined by the stability of the individual clock relative to the mean of the

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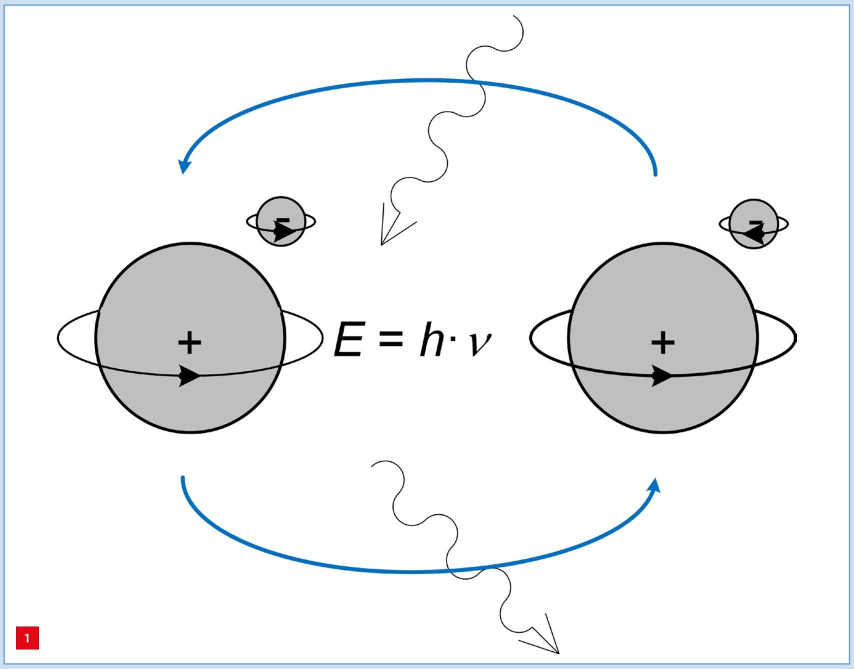
Principle of an atomic clock

Atomic clocks often work with atoms that have just one electron in the outer valence band. ^{1}H, ^{85}Rb and ^{133}Cs atoms are the most well-known elements used in microwave atomic clocks. The atom can be in two energy states. In one case (low energy), the electron spin is opposite to the nuclear spin, and in the other case (high energy), the electron spin is in the same direction as the nuclear spin. To get from the low state to the high state, the atom must absorb energy, and when the atom falls back from the high state, energy is released (Figure 1). The difference in energy can be directly linked via Planck's constant, h, to the frequency, ν, of the electromagnetic (EM) radiation that is released when the atom falls back to its low-energy state. Conversely, radiation of the same frequency must be added to return the atom to its high-energy state.

In a Cs-tube clock, the atoms in the low-energy state are separated from the atoms in the high-energy state by means of a magnetic field. The atoms in the low-energy state are exposed to an EM-field, with a frequency that is as close as possible to a frequency to which the atom is sensitive. This field is generated with a very stable crystal oscillator, the frequency of which can be adjusted. The atoms coming out of the EM-field are separated again into low- and high-energy-state atoms. The ratio of high- to low-energy-state atoms shows how close the generator is to the optimal frequency – the higher the ratio, the closer.



Transition of an atom between two hyperfine levels, in which electromagnetic radiation is absorbed or emitted. On the left, the high-energy state (nucleus and electron have the same spin direction); on the right, the low-energy state (opposite spins).

The generator is automatically adjusted to the optimum point via a feedback mechanism. The output frequency of the generator in a Cs clock is 9 192 631 770 Hz. Since this is not a useful value for many practical applications, this signal is converted via frequency dividers to signals of 10 MHz and 1 pulse per second. These signals are used as frequency and time references.

rest of the group. We call this weighted average of first-generation atomic clocks the "free atomic timescale" (*Échelle Atomique Libre*, EAL). Daily, the mean frequency deviation of this EAL is determined with respect to the second generation of atomic clocks.

Due to the complexity of second-generation clocks, it is difficult to keep them running continuously, but because of the stability of the EAL's flywheel, a continuous comparison of individual second-generation clocks with respect to the flywheel is not necessary, as long as there is sufficient data to monitor the average frequency of the EAL. The TAI calculation is based on the EAL corrected with the integrated frequency offset with respect to the second-generation atomic clocks. Finally, the TAI is corrected with leap seconds to get the coordinated universal time, UTC.

The Dutch national timescale

In the Netherlands, the National Metrology Institute, VSL, has been appointed by the government for the centralised maintenance of national measurement standards, including the standard for absolute time, time interval and frequency. VSL is one of about 90 time laboratories in the world with atomic clocks contributing to the computation of UTC. For this purpose, VSL has four first-generation atomic clocks that contribute to the EAL flywheel. From the monthly Circular T produced by BIPM, VSL knows the small deviations of its clocks and corrects for this deviation with a frequency offset generator. We call this corrected frequency and time UTC(VSL) – it is the physical realisation of Dutch time.

Comparing atomic clocks over large distances

For determining the difference between the calculated UTC and the realisation of UTC(VSL) as accurately as possible, VSL has always been at the forefront in developing measurement methods for comparing clocks over long distances. Two techniques are currently used at VSL for (semi-)continuous international clock comparisons.