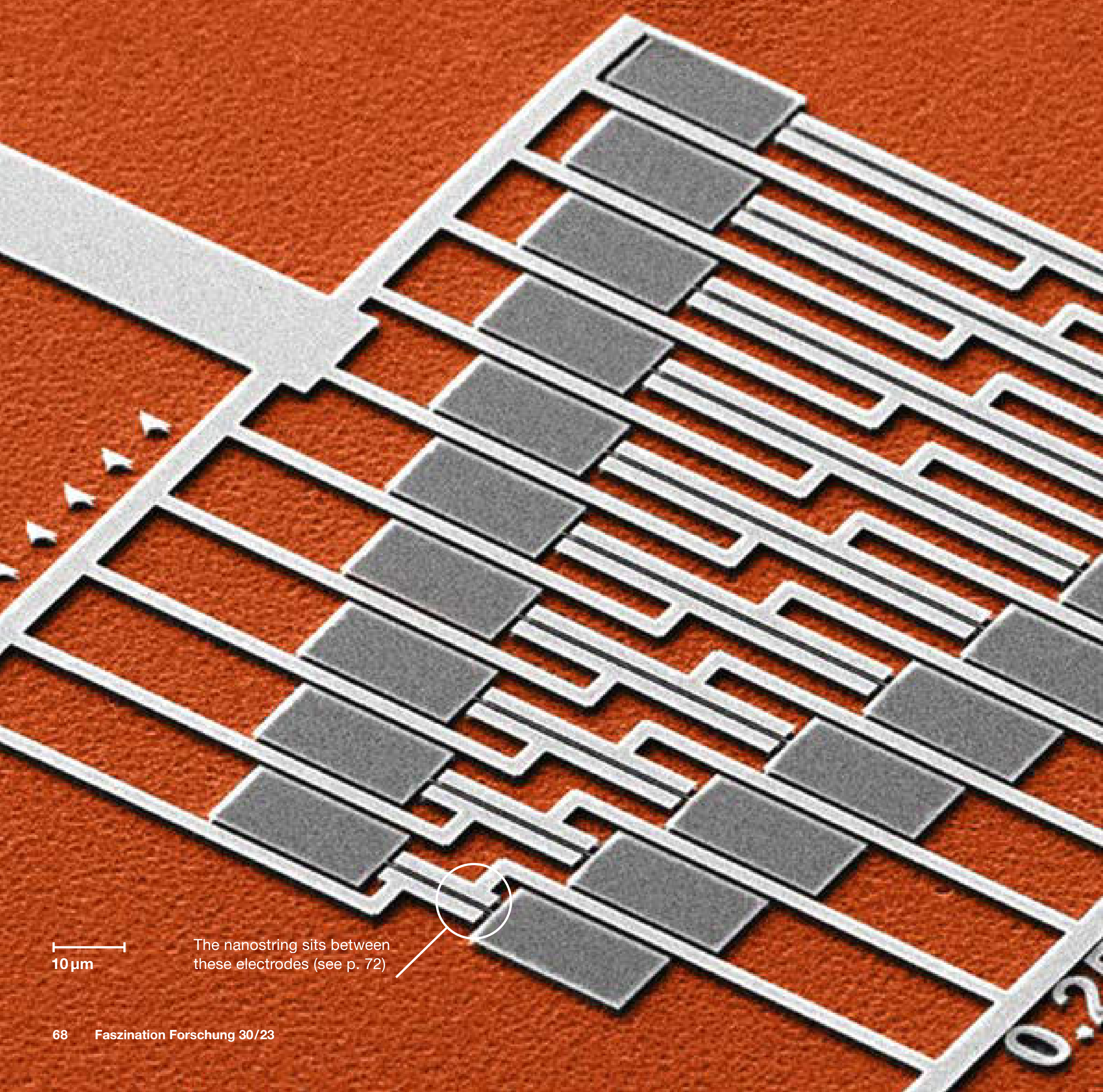
The World's Largest **Quantum Objects**



10 µm

The nanostring sits between these electrodes (see p. 72)

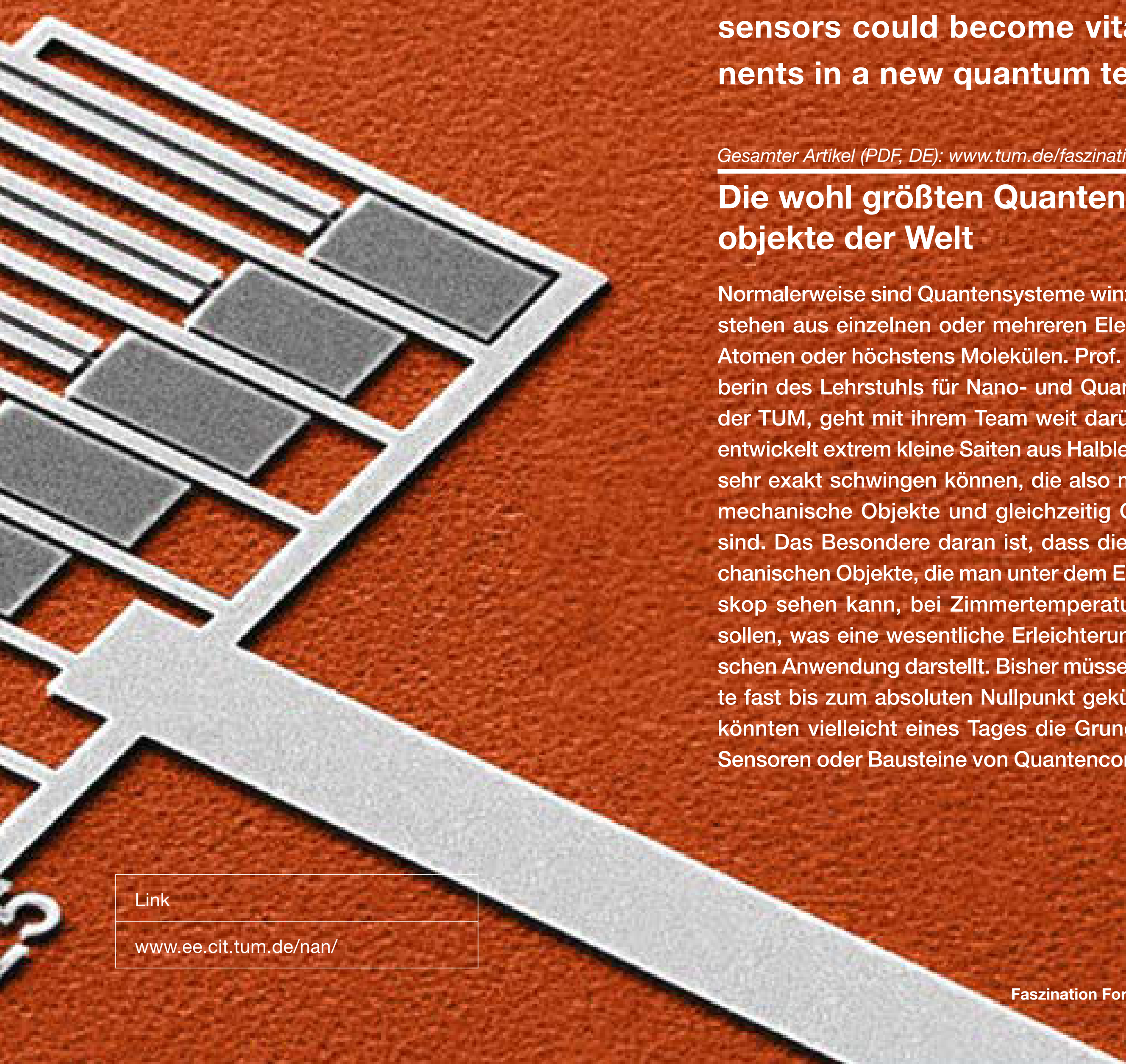
Picture credit: Y. Klaß & E. Weig (TUM)

In the quantum world, the very smallest scale of existence, being the largest object should hardly pose a challenge. However, complying with normal laws in this minute world at the same time is virtually impossible. Yet, Prof. Eva Weig and her team of researchers are striving to do exactly that – by creating mechanical quantum sensors large enough to be visible under an electron microscope. One day, these sensors could become vital components in a new quantum technology.

Gesamter Artikel (PDF, DE): www.tum.de/faszination-forschung-30

Die wohl größten Quantenobjekte der Welt

Normalerweise sind Quantensysteme winzig klein, sie bestehen aus einzelnen oder mehreren Elementarteilchen, Atomen oder höchstens Molekülen. Prof. Eva Weig, Inhaberin des Lehrstuhls für Nano- und Quantensensorik an der TUM, geht mit ihrem Team weit darüber hinaus: Sie entwickelt extrem kleine Saiten aus Halbleitermaterial, die sehr exakt schwingen können, die also makroskopische mechanische Objekte und gleichzeitig Quantenobjekte sind. Das Besondere daran ist, dass diese quantenmechanischen Objekte, die man unter dem Elektronenmikroskop sehen kann, bei Zimmertemperatur funktionieren sollen, was eine wesentliche Erleichterung in der praktischen Anwendung darstellt. Bisher müssen solche Objekte fast bis zum absoluten Nullpunkt gekühlt werden. Sie könnten vielleicht eines Tages die Grundlage wichtiger Sensoren oder Bausteine von Quantencomputern sein. □



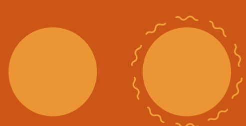
Link

www.ee.cit.tum.de/nan/

When is an object a quantum object?

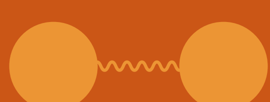
In the quantum world, the world on the smallest scale, there are objects with properties that completely contradict our natural sensibilities and cannot be explained by classical physics:

While we can measure their energy and identify their position, we cannot do both at the same time. This phenomenon is known as Heisenberg's Uncertainty Principle.



They can only take on very specific energy states. There is no continuous transition between these states, only quantum jumps – hence their name, "quantum objects".

They can, however, exist in multiple states at once through a principle called superposition. It is only when we measure their energy that we can attribute a specific state to them. This property is used, for example, in quantum computers.



They can also become entangled with other quantum objects, a phenomenon Einstein described as "spooky action at a distance". If one object changes state, the other objects entangled with it do the same. As a result, quantum objects are also able to teleport.

If an object displays one or more of these properties, it is described as a quantum object.

To ordinary people with a healthy dose of common sense, the processes at work in the quantum world sound more like a fairytale than reality. Particles that change into waves and back again, and even communicate through telepathy; cats that are simultaneously dead and alive, and objects present in two different locations simultaneously. These are not fairytales, though – they are the very foundations of our modern world. Without these astonishing phenomena we would not have computers, lasers or magnetic resonance imaging, not even a common television. So, although the underlying principles might appear inexplicable and mysterious to ordinary people, they have been proven in practice millions of times over.
Their development is progressing at pace: the properties of the quantum world, which still appear so peculiar to us, might soon become the basis of a new quantum technology that we come to take for granted, just as we do electricity and semiconductor technology today. This technology will not only use these phenomena behind the scenes but will instead make conscious, deliberate use of them. However, scientists are only now starting to develop technical components for this new quantum world. They capture atoms and ions in traps, integrate designer atoms into solids, and create ultra-fine electrical junctions in superconductors. Also included are devices that can connect, activate and deactivate these elements.

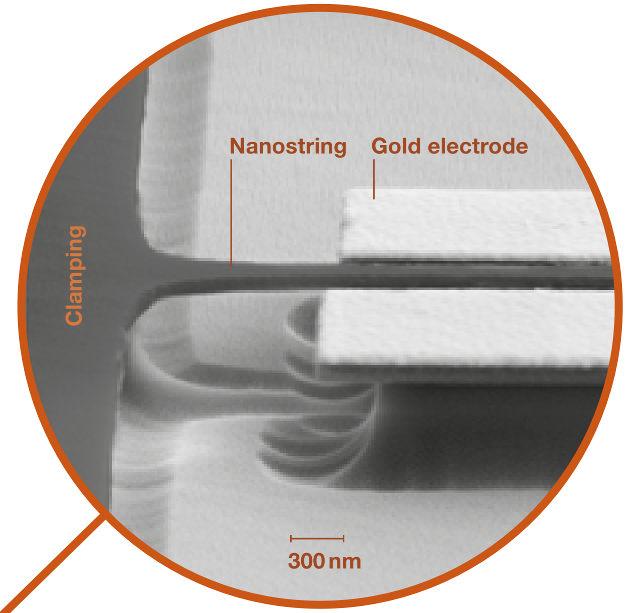
Vibrating nanostrings

Normally, quantum systems comprise one or several elementary particles, atoms or at most molecules. Eva Weig and her team, however, are pursuing a very different path. The researchers at her Chair of Nano and Quantum Sensors are working to create extremely fine strings made from ceramic and semiconductor materials, which are still macroscopic objects, containing around a billion (10^{12}) atoms. But can a system like this serve as a quantum component? It might sound quite outlandish – and, in truth, it is – but this approach offers a series of advantages. "Our objects can be compared with nanoscale guitar strings, which vibrate when plucked," explains Weig. "And, under certain conditions, these objects behave like quantum-mechanical systems. This means they can take on states that can be stored, transferred and even entangled with others. I find that fascinating." Measuring up to 50 micrometers in length, these nanostrings are now among the largest quantum-mechanical systems on the planet.

Picture credit: Magdalena Jooss; Graphics: ediundsepp

Prof. Eva Maria Weig

never lost her love of Munich. Born in the city, she studied physics at LMU, where she received her doctorate in 2004 at the Chair of Solid State Physics. And, although she took up a postdoctoral research position in Santa Barbara in California, she returned to Munich in 2008, working as a Senior Researcher from 2007 to 2012 and a Substitute Professor at her old institute at LMU from 2008 to 2009. As a professor at the University of Konstanz, she headed up the Nanomechanical Systems working group at the Department of Physics. She accepted a professorship and joined TUM on October 1, 2020, where she has held the Chair of Nano and Quantum Sensors ever since. Eva Weig is also director of the TUM Center for QuantumEngineering (ZQE).



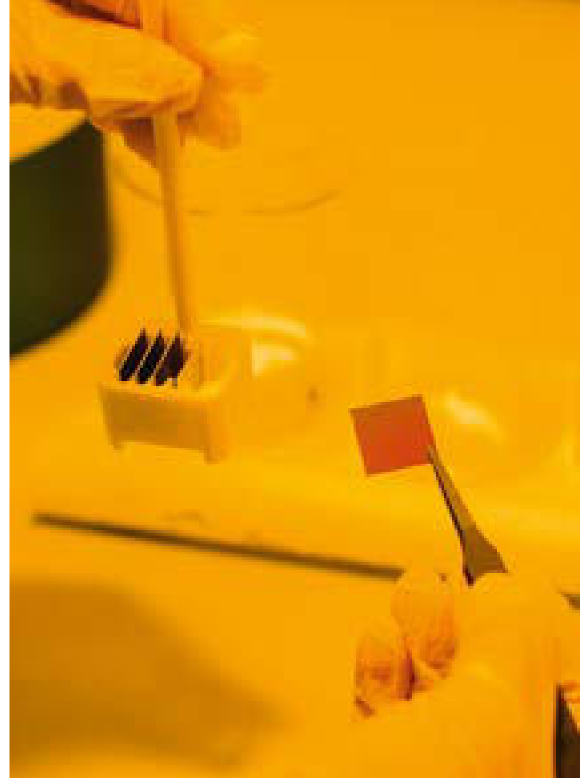
“Producing our prototypes is still highly complex at present.”

Eva Weig

Picture credit: Magdalena Jooss

△ **Top: Scanning electron micrograph of a nanostring** between two gold electrodes.

△ **Bottom: In the course of her career as a researcher,** Eva Weig has spent countless days and weeks in the cleanroom. Today, as a professor, she only dons the cleanroom suit on special occasions.



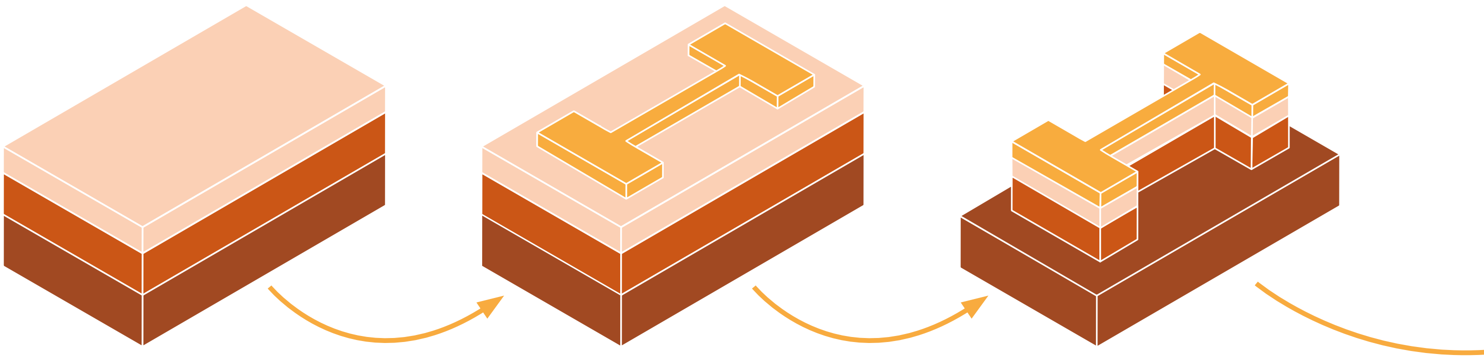
△ **Chip processing in the cleanroom:** Under the fume hood, resist is coated on the sample to prepare for lithography and developed after exposure.

This is still an emerging field: in early 2010, 29-year-old Aaron D. O'Connell made waves around the world with his doctoral dissertation at the University of California, Santa Barbara. Under the tutelage of his supervisor Andrew N. Cleland, O'Connell linked a superconducting quantum bit – a component used in quantum computers – with a vibrating, macroscopic mechanical resonator. He achieved this using a superconducting circuit. The ingenious part was using a resonator made from piezoelectric materials, which deform when subjected to electrical voltage and generate electrical voltage when subjected to mechanical stress. This experiment achieved a world first, namely establishing a connection between the minute quantum world and our "normal" macroworld. The journal *Science* named his accomplishment "Breakthrough of the Year 2010", calling the structure "the first quantum machine".

This breakthrough was only possible because the vibrating object was shielded against all external influences, given that it was supercooled, in darkness and in a vacuum chamber. Several groups around the world have achieved similar successes since O'Connell's initial breakthrough, but only by working at extremely low temperatures.

Making supercooling superfluous

The nanostrings developed by Eva Weig, however, are significantly finer than O'Connell's system. Together with her ten-strong team, Weig is now striving to create a quantum-mechanical system at room temperature. This would open up new uses for such systems and simplify their use in existing applications. The researchers produce their nanostrings in cleanrooms, relying on electron beam lithography for the laborious, painstaking process of applying layer upon layer on a silicon wafer, corroding and burning off sections at specific points. The result is a miniature masterpiece: each string is typically 30 to 50 micrometers in length and less than 100 nanometers wide. "Producing our prototypes is still highly complex at present," says Weig. "Our Master's students spend around half their working hours on that step alone but, with appropriate process controls, we'll be able to produce industrial quantities at some point." The strings are then transferred to a vacuum chamber, where they are precisely measured for the first time. It is vital that the strings do not come into contact with the air because collisions with air molecules would immediately dampen them, just as the wind can disrupt waves of water in the sea. The strings are "plucked" by means of laser light, electrical fields or even acoustic waves. ▷

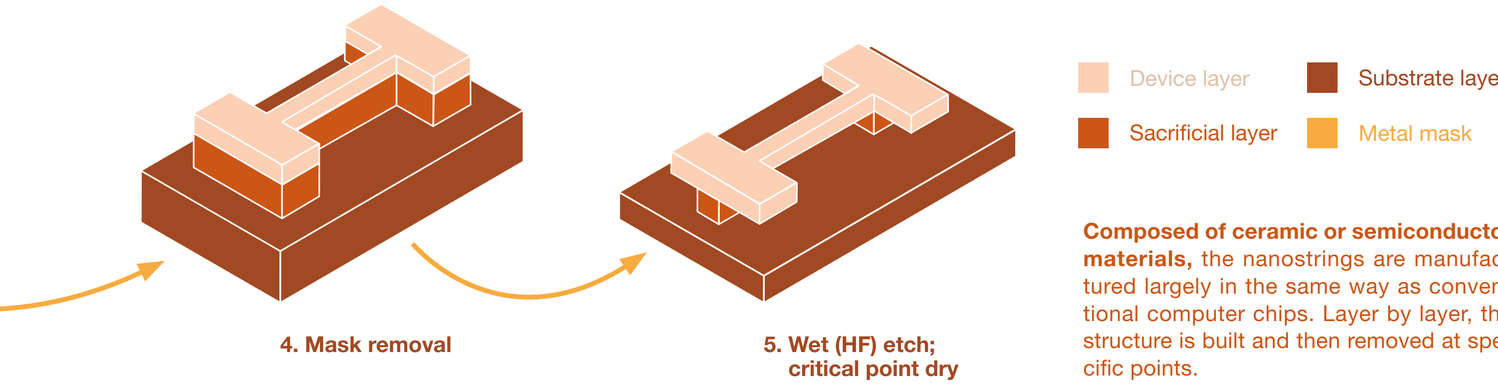


▷ **Left: The nanostrings are measured at room temperature** inside a vaccuum chamber. The lab has various measurement set-ups.

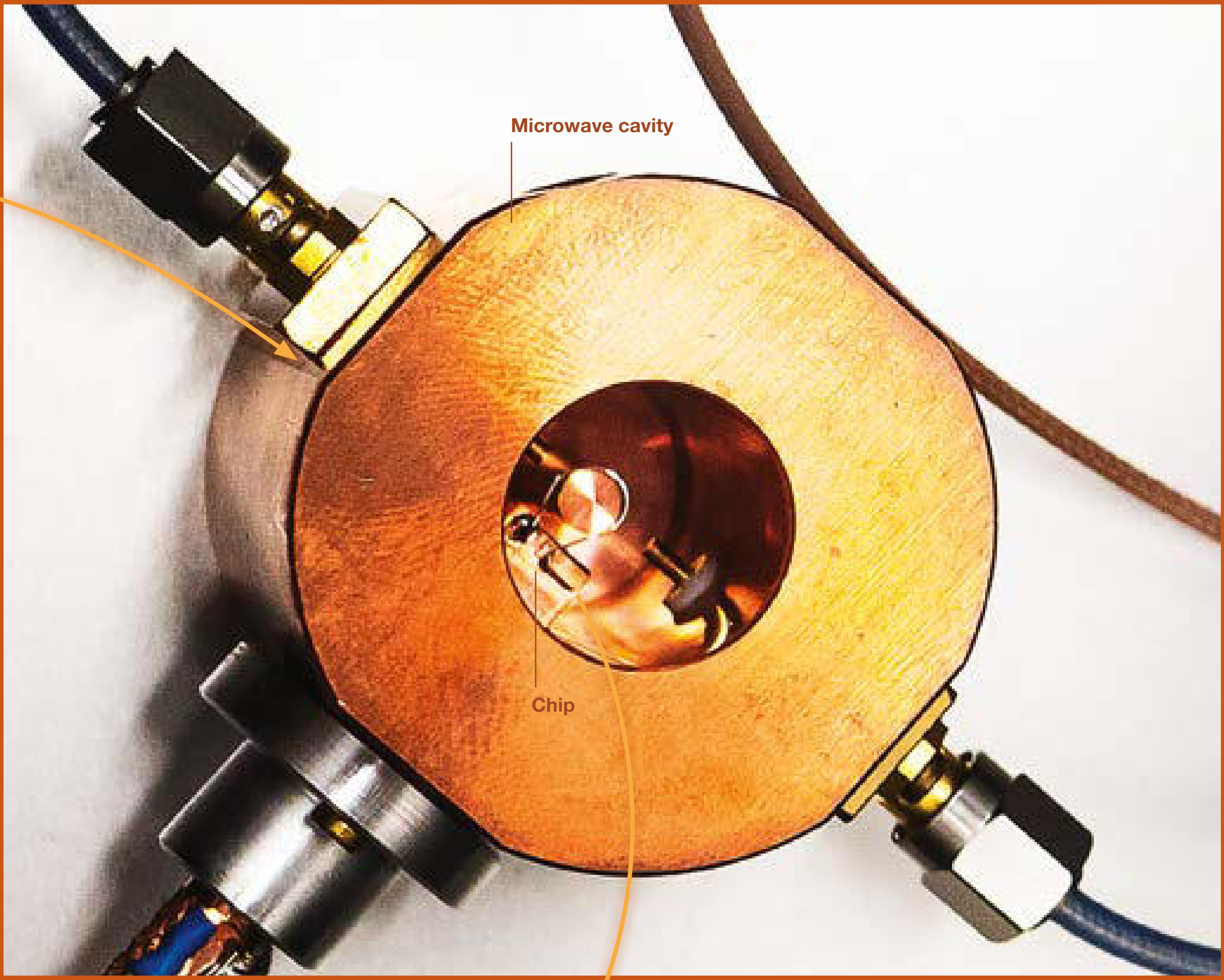
Right: A look from the top into a chamber with a microwave cavity for measuring the string's vibration. The transparent chip contains the nanostring, invisible to the human eye.

These nanostrings have an extraordinary quality factor: Eva Weig and her team have continuously refined them, so much so that some of these strings can be made to vibrate with the same frequency for a few milliseconds. It might not sound like much but, in terms of quantum mechanics, this is a vast period of time. Translating this to the macroworld, it would mean ordinary guitar strings vibrating in the same tone for around an hour. "It's truly spectacular," the physicist explains, "because this ability could enable us to use such systems as a temporary storage of quantum-mechanical information, such as to park qubits in quantum computers." This has not been possible to date. There are various options for transmission, either using a similar approach to O'Connell's experiment or using lasers.

Until now, the vibrating nanostrings were only able to maintain a constant frequency for long periods when cooled to extremely low temperatures. The newly produced prototypes, however, have achieved this at room temperature because the string only emits a tiny quantity of energy to its surroundings. Having said this, the strings are particularly sensitive to any kind of external disruption – though this sensitivity can be leveraged with targeted "disruptions". The strings can therefore be connected



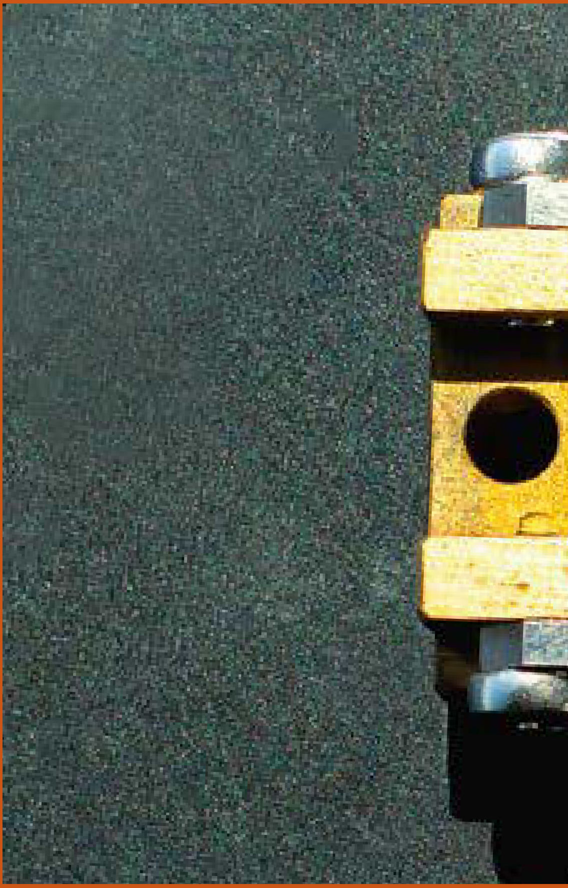
Composed of ceramic or semiconductor materials, the nanostrings are manufactured largely in the same way as conventional computer chips. Layer by layer, the structure is built and then removed at specific points.



Picture credit: Magdalena Jooss; Graphics: ediundsepp (source: TUM)

"It's still basic research, but initial applications are already emerging."

Eva Weig



to other systems, either to control the strings or to use them as detectors. "This field fascinates me," says Eva Weig. "It's still basic research, but initial applications are already emerging. In ten years' time, we will certainly be seeing applications."

The underlying principle of these applications always relies on how the string interacts with what is to be measured. This is supported by a quantum-mechanical property of the string: in addition to its basic state, it can also take on excited energy states. These states are precisely determined by the laws of quantum mechanics. So, by linking it to a measured value, the string can be made to jump back and forth between two states – the very property required for a quantum sensor. Eva Weig's team has already constructed a series of test platforms for exactly this purpose. "Our aim is effectively to develop a quantum sensor that works at room temperature," explains Weig. "It would enable us to detect tiny magnetic fields and forces, perhaps even spin effects."

The Chair led by Eva Weig will soon move into new laboratories on the Garching research campus. Its current facilities are not entirely suitable for these experiments, as they cannot be sufficiently shielded against external influences, such as vibrations. The projects then continue in many directions. For instance, the researchers strive to achieve their systems' basic state. Although they have not managed this to date, it would be of considerable interest for basic research. Another avenue focuses on other forms, because the principle of using mechanical vibrations as a quantum object is not limited to a single string. The Garching-based researchers are also examining carbon nanotubes, which grow like a blade of grass on a substrate, nanomembranes that look like a tiny drumhead, and nano-sized colonnades with tiny heads evenly oscillating back and forth. Further experiments will show which methods ultimately work best in practice. ■

Brigitte Röthlein

Picture credit: Magdalena Jooss, Y. Klaß & E. Weig (TUM)

◁ **Integrated platform to control nanostrings.** The 5 x 5 mm sized chip containing the nanostrings is located in the center. To its left, a microwave cavity connects via bond wire to the gold electrodes, which create an electric field around the nanostring. The circuit board on the right-hand side provides the connection to the measurement system.

▽ **The transparent chip** made of ceramic material contains a set of 12 nanostrings of different lengths, each between two gold electrodes, as shown in this scanning electron micrograph. Each string can be controlled and measured individually.