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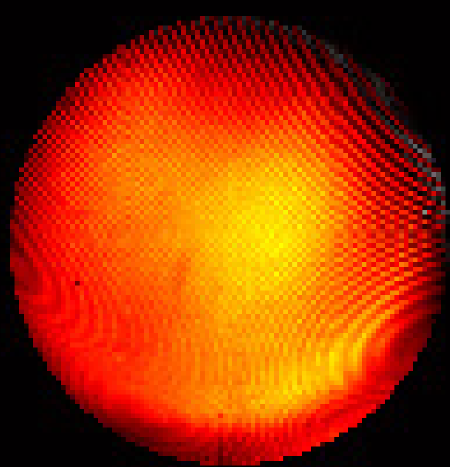

FOCUS ON:

↗ Quantum Science and Technology

NO. 21

Materials Research Department

MRD

MATERIALS RESEARCH DEPARTMENT

FOCUS ON:
QUANTUM SCIENCE AND TECHNOLOGY

The rapidly evolving field of quantum science and technology is transforming our understanding of matter, energy, and information at the most fundamental level. Harnessing quantum effects enables breakthroughs in computing, communication, and sensing–offering unprecedented precision and power beyond classical limits.

In this edition of the MRD Newsletter, we highlight current research activities, collaborations and innovations exploring the quantum science and technology.

This issue, like all previous ones, is available on the MRD website: www.mrd.rub.de. We welcome your ideas and feedback for future editions.

Enjoy reading,

Ralf Drautz and Tong Li
MRD Speakers
Denisa Voicu
MRD Science Manager

CONTENT

On the cover: Photoluminescence intensity map of periodically ordered quantum dots (authors: Nikolai Bart and Arne Ludwig).

QUANTUM SIMULATIONS OF CORRELATED ELECTRONIC SYSTEMS WITH QUBITS NETWORKS

Hunting for novel quantum matters with Josephson junction networks

A central challenge in modern physics, quantum chemistry, and materials science is the quantitative modeling of strongly correlated electron systems, including superconductors, magnetically frustrated materials, interacting molecular clusters, and Mott insulators. These systems exhibit a wide variety of collective quantum phases that emerge from strong electron–electron interactions [1-3]. Although combining symmetry analysis of atomic and electronic structures with ab initio density functional theory (DFT) enables the derivation of interacting spin Hamiltonians for many correlated systems, achieving a quantitative understanding of their complex quantum behavior remains a formidable task.

Analytical solutions exist only for a few paradigmatic models, while exact diagonalization methods on classical computers are restricted to small spin clusters. Numerical techniques such as the Density Matrix Renormalization Group (DMRG) or Quantum Monte Carlo (QMC) also face significant limitations when applied to large or highly frustrated spin networks. In recent years, significant progress has been achieved in the fabrication and control of artificial quantum systems that exhibit coherent quantum dynamics on macroscopic scales. These systems, composed of thousands of interacting macroscopic two-level elements (qubits), are effectively described by interacting spin Hamiltonians and thus provide a promising platform for Analog Quantum Simulation (AQS) [4-5]. Among various architectures, networks of Josephson junctions stand out as particularly suitable experimental systems. They allow the implementation of complex spin Hamiltonians with tunable spin–spin couplings and offer opportunities for detailed studies of quantum coherent phenomena on a macroscopic level, thereby realizing practical AQS [5-6].

In our group, we predicted and analyzed the emergence of collective quantum phases in frustrated Josephson-junction networks [7-8]. The frustration arises from a periodic arrangement of 0- and π-Josephson junctions. The fundamental unit of the system—a triangular superconducting cell—contains two 0-junctions and one π-junction. The quantum dynamics of each cell are governed by clockwise or counterclockwise persistent currents (vortex and antivortex states), forming an effective flux qubit [7-9].

We investigated two representative qubit network geometries: sawtooth chains (Figure 1a) [7] and Kagome lattices (Figure 2a) [8]. In the sawtooth configuration, direct embedding of π-junctions in a low-dissipative transmission line enables interactions between vortices and antivortices in distant cells. Mapping the superconducting circuit Hamiltonian onto an effective XX spin model with exchange interactions and a transverse field (representing coherent tunneling between vortex and antivortex states) reveals three distinct collective quantum phases: paramagnetic (P), compressible superfluid (CS), and weakly compressible superfluid (w-CS) (Figure 1b) [7].

In Kagome-lattice networks, topological constraints arising from flux quantization in hexagonal loops induce highly anisotropic and long-range Ising-type interactions between distant vortices and antivortices. The interplay between macroscopic tunneling in individual superconducting triangles and these long-range interactions leads to (i) a temperature-dependent crossover between ordered and disordered vortex/antivortex states (Figure 2b), and (ii) lifting of ground-state degeneracy accompanied by the formation of highly entangled collective states [8].

These results demonstrate that Josephson-junction networks provide a versatile and controllable platform for exploring collective quantum phenomena in strongly correlated systems, offering key insights for the realization of large-scale analog quantum simulators.

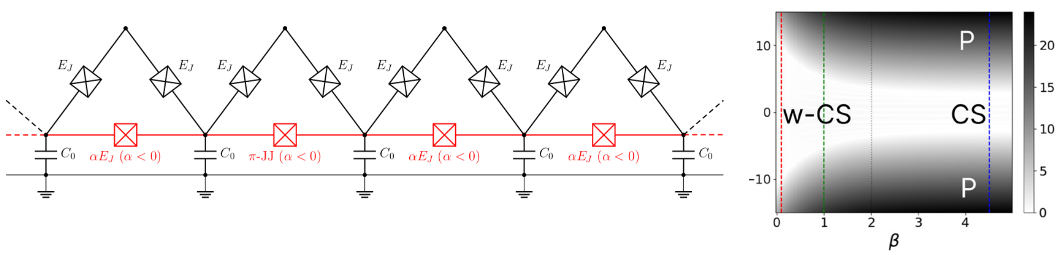

Figure 1: (From [7]) Schematics of a frustrated sawtooth chain of Josephson junctions directly embedded in a dissipationless transmission line (a). The color plot shows the dependence of the minimal gap in the energy spectrum on the parameters of the effective Hamiltonian. The various collective quantum phases are indicated (b).

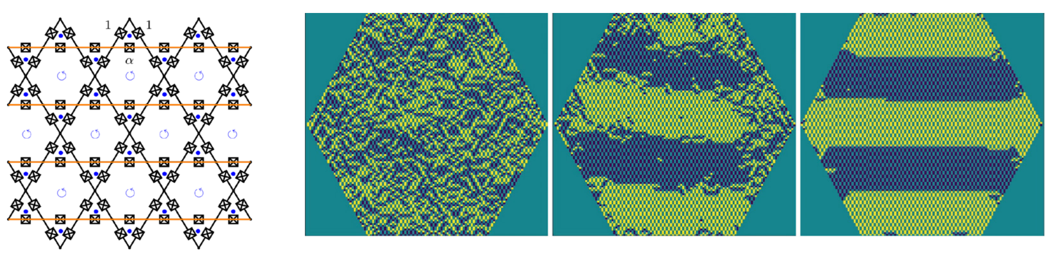

Figure 2: (From [8]) Schematic structure of a frustrated Kagome lattice of quantum Josephson junctions (a). Typical vortex/antivortex patterns obtained in large frustrated Kagome lattices of Josephson junctions for different temperatures: k_BT/E_J (α) = 0.2 (left); k_BT/E_J (α) = 0.19 (middle); and k_BT/E_J (α) = 0.12 (right) (b).

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ALTERNATIVE RESONANCES IN SEMICONDUCTOR LASERS

From polarization dynamics to coupled-cavity photonic resonators

Semiconductor lasers are at the heart of modern data links, yet their speed is traditionally limited by the photon–carrier relaxation oscillation. At the same time, global traffic continues to surge, which demands from networks to deliver much higher bandwidths with lower energy per bit [1]. Thus, the limited speed of traditional lasers becomes a bottleneck in modern communication systems as, for example, in data centers. Spin-lasers address this challenge by exploiting spin-polarized carriers in vertical-cavity surface-emitting lasers (VCSELs) to control the light's polarization at ultrafast rates. The key idea is to shift from intensity modulation to polarization dynamics, thereby tapping a different, much faster resonance inside the laser.

In our demonstration of ultrafast spin-lasers, polarization oscillations tied to the carrier spin dynamics were shown to reach far beyond conventional relaxation frequencies (ROF) f_R, opening a route to sub-picosecond control and, in principle, hundreds-of-gigahertz operation [2]. Conceptually, these lasers can be well theoretically described with the so-called spin-flip model that augments standard rate equations with coupled equations for spin-up and spin-down carrier populations and their exchange via spin-flip scattering. When the spin-flip rate and cavity anisotropies are chosen properly, the resulting polarization resonance can dominate the small-signal response and enable ultrafast modulation at low drive currents, i.e., with high energy efficiency [2].

A central lever to engineer this resonance is the cavity birefringence, resulting in the refractive indices $n_{x,y,}$ which differ along the corresponding spacial axes in the VCSEL depicted in Figure 1(a). Instead of the conventional ROF, depicted in Figure 1(b), the birefringence determines the polarization dynamics resonance $\tilde{f}_R$ as depicted in Figure 1(c). Recent devices integrate surface gratings to control the birefringence splitting, thereby defining the polarization resonance frequency. Crucially, these gratings can pin the static polarization while still allowing strong polarization oscillations, with measured dynamics up to ~68 GHz and resonance frequencies that scale with the induced splitting [3]. These results validate a fabrication-ready pathway to polarization-based high-speed operation compatible with standard VCSEL processes [3].

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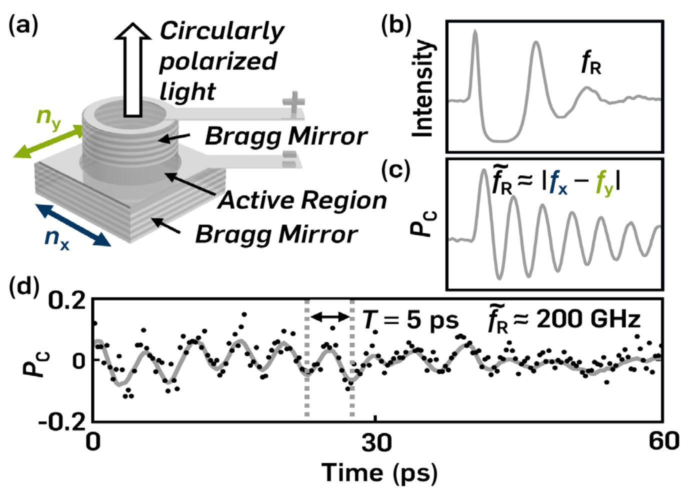

Figure 1: Conceptual schematic of a spin-laser indicating birefringence represented by the difference between n_x and n_y (a). Intensity relaxation oscillation frequency, representing the impulse response of conventional laser dynamics oscillating at f_R (b). Polarization oscillations in the circular polarization degree P_C after pulsed spin-injection, representing the impulse response of the polarization dynamics, oscillating at the difference frequency $|f_x - f_y|$ of the two orthogonally polarized modes (c). Measured polarization oscillations (d).

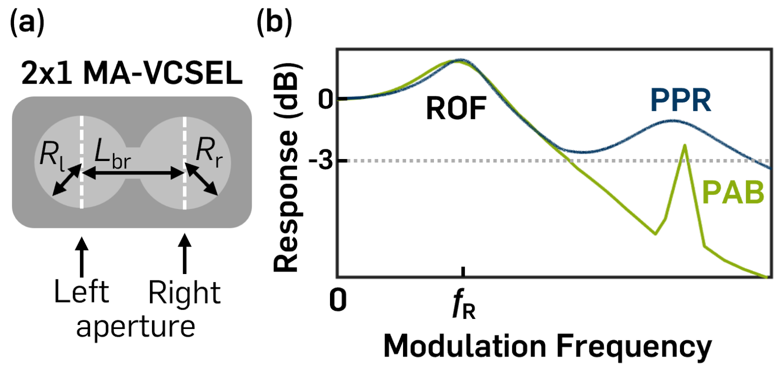

Figure 2: A 2x1 mini-array VCSEL with transverse-coupled-cavities. The apertures have small radius $R_{l,r}$ in the range of 1.5µm and a bridge length in the range of 5µm (a). Representative modulation responses of coupled-cavity VCSELs, showing the conventional ROF and additional resonant features: A narrow PAB peak in WCR and a broader PPR in SIL, which can extend the modulation bandwidth (b).

Even faster dynamics were demonstrateda at $\tilde{f}_R \approx 200$ GHz in a laboratory environment by optical pulsed spin-injection [2], as depicted in Figure 1(d), pointing out the huge potential for future data transmission systems based on spin-lasers, if electrical spin-injection can be realized.

Beyond the spin degree of freedom, alternative resonances can be introduced through photonic coupling. Laterally coupled (transverse-coupled-cavity) VCSELs, as depicted in Figure 2(a) in top view, form optical supermodes whose frequency separation and phase relation add extra resonant features to the modulation response. Two operational regimes emerge: a weakly coupled regime (WCR) where both supermodes lase and produce a narrow, tunable plasma-assisted beating (PAB) peak, and a self-injection-locked (SIL) regime where one supermode dominates and a broader photon–photon resonance (PPR) enhances bandwidth [4,5], as shown in Figure 2(b). Experiments on oxide-confined mini-arrays with a single common contact confirm switching between WCR and SIL via the bias current. This is connected to anti-phase and in-phase aperture dynamics as well as narrow and broad response features. In a recent work we measured WCR and SIL dynamics up to 70 GHz with excellent agreement to distributed rate-equation modeling [4]. The photonic-coupling route is technologically attractive because it relies on standard VCSEL manufacturing and simple operation given by the single contact [4,5].

The two concepts of spin-controlled polarization dynamics and cavity-coupling-induced supermode dynamics are closely related. Both introduce additional internal degrees of freedom that decouple the usable resonance from the conventional limitations given by the intrinsic resonance of the ROF, broadening the design space for high-speed, low-energy links. Hybrid devices that combine engineered birefringence for polarization control with controlled lateral coupling for supermode control could enable on-chip switching between narrow, tunable and broad, bandwidth-extending resonances, or even multi-resonant responses tailored to application needs [2-5].

Applications extend beyond data communications. Coupled-cavity VCSELs provide electrically simple, compact dual-frequency sources whose optical beat can be converted into continuous-wave terahertz (THz) radiation. Using a 2×1 mini-array VCSEL (MA-VCSEL), coherent photomixing with lock-in detection has demonstrated tunable beat notes from ~50 to 300 GHz, which are suitable for spectroscopy and frequency-modulated continuous-wave radar, while preserving the low-power, low-cost advantages of VCSEL technology [6]. Such sources offer a practical bridge between photonics and THz systems.

Spin-VCSELs themselves continue to diversify. Beyond single-mode operation with engineered birefringence, emerging multimode spin-VCSEL concepts explore how multiple transverse or polarization modes can participate in the dynamics. By distributing gain and spin interactions across several modes, these devices may realize additional, controllable resonances that further extend usable bandwidths or enable new modulation formats. Our recently published study on multimode spin-VCSELs reports broadened dynamical responses consistent with this vision [7].

Taken together, these advances reframe the VCSEL from a single-resonance light source into a programmable photonic oscillator. By harnessing polarization and supermode dynamics individually or jointly, future devices can achieve higher symbol rates at lower drive currents, aligning with the pressing need for scalable, energy-efficient bandwidth in next-generation networks [1-6]. While the laterally coupled VCSELs are based on standard VCSEL manufacturing technology, the implementation of electrically controlled spin-lasers requires to change standard fabrication technologies and thus imposes new directions in materials research and device processing.

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FeSe – A MODERN CLASSIC IN QUANTUM MATERIALS

Featuring unconventional superconductivity, nematicity, elusive magnetism, quantum criticality, non-trivial topology, and more

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The term quantum materials is used to characterize materials whose properties are dominated by non-trivial quantum effects, such as entanglement of electronic wave functions. FeSe offers a particularly fascinating example for a quantum material with multiple competing electronic states. Though being structurally rather simple, its physical properties are intriguingly complex and keep surprising researchers even in the second decade after the discovery of superconductivity in FeSe [1]. It is indeed the structurally simplest member of the family of iron-based superconductors, which is often called the second class of high-temperature superconductors after the copper-oxides.

The vast majority of iron-based superconductors host three different quantum phases: superconductivity, antiferromagnetic order and so-called nematic order. Nematic order denotes the breaking of a rotational symmetry of the crystal by an electronic mechanism. In iron-based superconductors, this mechanism has most often been linked to antiferromagnetic fluctuations. One of the first intriguing aspects of FeSe was the realization that FeSe features nematic order below 90 K and superconductivity below 8 K – but no antiferromagnetic order. The nematic order indeed forms in the presence of much weaker antiferromagnetic fluctuations than any other iron-based superconductor. Further, the investigation of the Fermi surface of FeSe in the nematic state has revealed the puzzling "disappearance" of a Fermi surface pocket inside the nematic state. Indeed, multiple theoretical models different from the magnetic-fluctuation mechanism have been put forward to explain nematic order in FeSe [2].

However, there is a way to drive FeSe into antiferromagnetic order. Namely, if FeSe samples are confined in a pressure cell, nematic order can be suppressed and an antiferromagnetic state can be

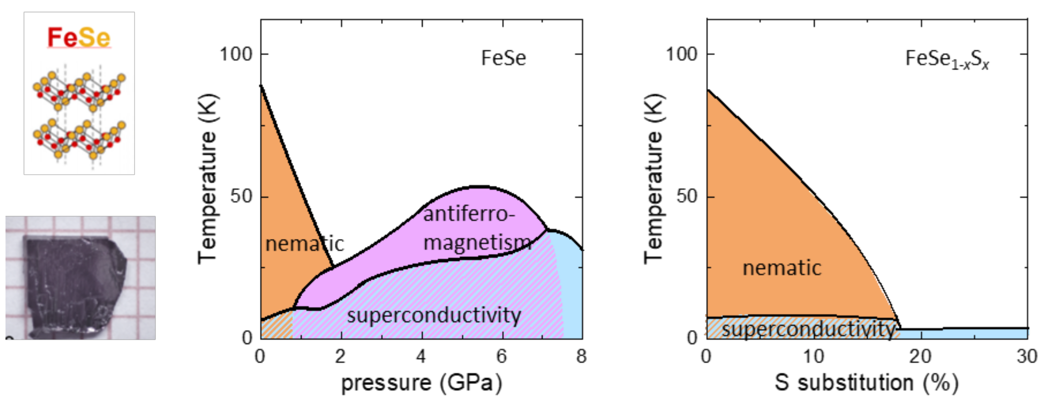

Figure 1: Crystal structure of FeSe and photograph of an FeSe single crystal (left). Phase diagrams of FeSe as a function of pressure and sulfur substitution (right).

experimentally proven in the pressure range of 1 - 6 GPa (10 000 – 60 000 atmospheres) [3]. In antiferromagnets, one important question is the propagation vector of the magnetization – the ordering pattern of “up” and “down” magnetic moments. Despite large experimental effort, the unambiguous determination of this ordering pattern in FeSe has eluded discovery so far. Interestingly, the application of pressure also enhances the superconducting transition temperature of FeSe more than fourfold, to almost 40 K right at the pressure of 6 GPa where antiferromagnetic order disappears again.

Many techniques cannot be applied if the sample is confined in a pressure cell, limiting experimental studies. Fortunately, there is a different way to suppress nematic order and study the evolution of superconductivity in FeSe. This is the partial chemical substitution of selenium by other elements. Sulfur and tellurium have proven to be particularly interesting. Both suppress nematic order and lead to a modification of the superconducting state, though the enhancement of the superconducting transition temperature is much more modest. Notably, a situation called ‘quantum criticality’ has been observed around the point where nematic order is suppressed to zero temperature via sulfur substitution in $FeSe_{1-x}S_x$. A quantum critical point refers to a second order phase transition that is suppressed to zero temperature. Here, the transition can no longer be driven via thermal fluctuations but is driven by quantum fluctuations and the characteristic energy scale of the order vanishes. Notably, this leads to unusual properties even at finite temperatures, such as an unusal temperature dependence of the electrical resistivity.

The superconductivity of $FeSe_{1-x}S_x$ is highly unsual. The characteristic order parameter of a superconductor is its gap function, whose magnitude indicates the excitation gap for an electron at a particular point on the Fermi surface. In most metals, the gap value is only a tiny fraction of the Fermi energy (the difference between the energy of the topmost filled electron state and the bottom of the conduction band standard metal). However, in FeSe, the gap value is of the order of 10% of this energy, which means that the superconducting transition in FeSe might be better described by a Bose-Einstein condensation than by the standard BCS mechanism of superconductivity [4]. As a quantum mechanical function, the gap function also has a phase. In $FeSe_{1-x}S_x$ the gap function has been shown to change sign between different parts of the Fermi surface, and also vanishes along particular lines of the Fermi surface [5]. However, there is evidence that the excitation gap indeed vanishes on extended sections of the Fermi surface in a certain range of sulfur substitution, with no clear explanation to date.

Finally, topological properties of the band structure of metals have recently received enormous attention. Non-trivial topological states lead to special electronic states on the surface of a sample. Interestingly, $FeSe_{0.45}Te_{0.55}$ shows indications for such a non-trivial topological state. Being also a superconductor, this leads to exciting possibilities for exotic quantum properties.

To summarize, FeSe is a gift that keeps on giving. This structurally simple material features indeed a broad range of major phenomena in quantum materials. Thus, FeSe deserves a place in the canon of classic quantum materials.

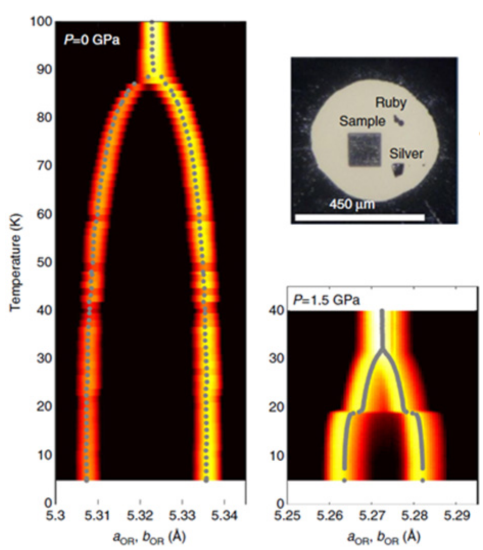

Figure 2: X-ray diffraction intensity showing the evolution of the lattice parameters of FeSe on cooling through different phase transitions. The nematic transition, which occurs at 90 K at zero pressure is indicated by a splitting of lattice parameters *a*OR and *b*OR. At a pressure of 1.5 GPa, this nematic transition occurs only at 30 K. However, the second transition at 20 K is caused by the emergence of antiferromagnetic order (left and bottom right). Photograph of the inside of a pressure cell, in which an FeSe single crystal sample is compressed. The simultaneously measured properties of ruby and silver are used to determine the exact pressure value (top right). Figure reproduced from Ref. [3].

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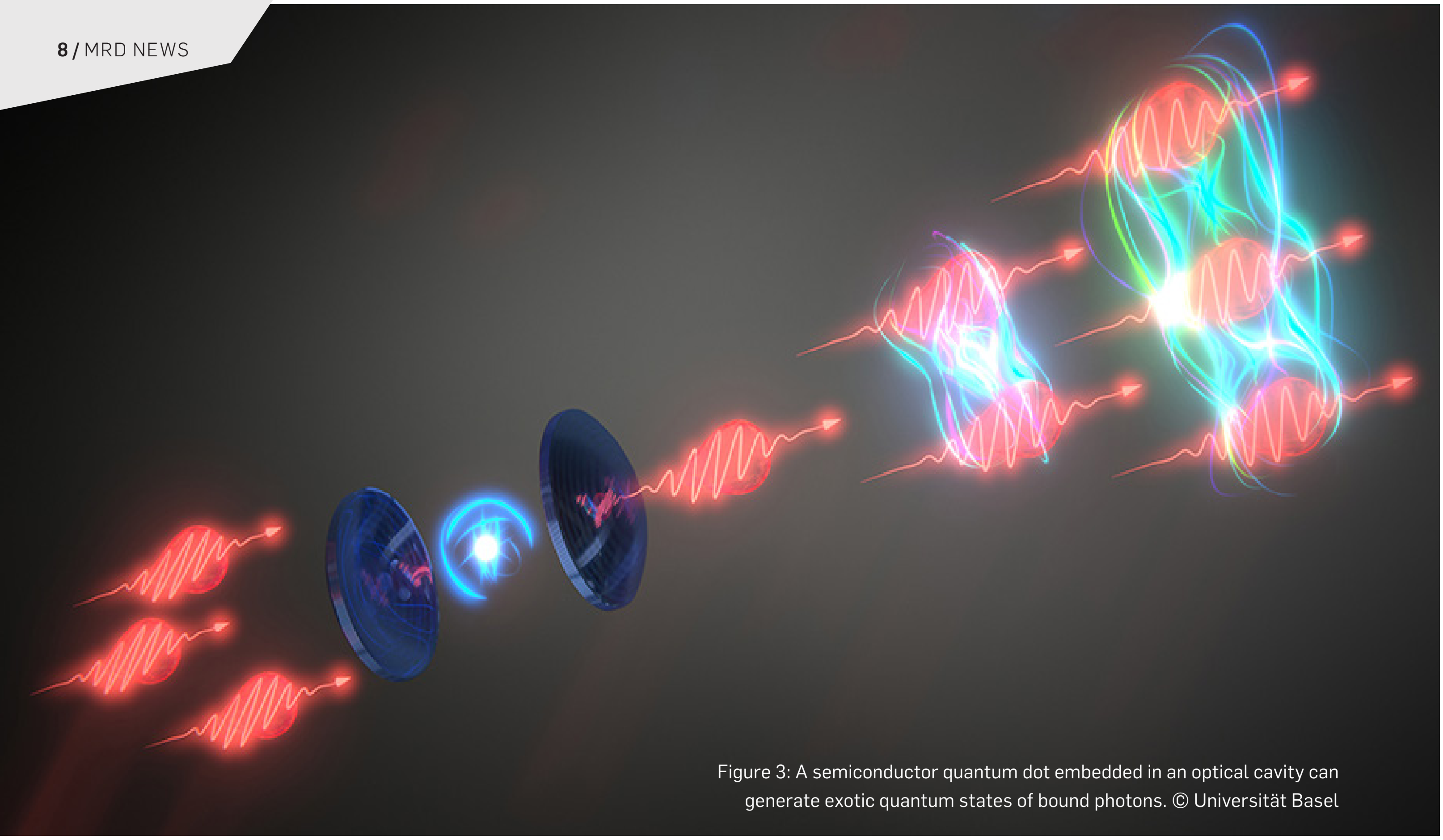

Figure 3: A semiconductor quantum dot embedded in an optical cavity can generate exotic quantum states of bound photons. © Universität Basel

HOW TO SCALE QUANTUM TECHNOLOGIES?

Quantum dots for a scalable photonic quantum technology

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Quantum technology is transforming our understanding of nature, with quantum dots playing a pivotal role in the pursuit of scalable photonic quantum systems. By harnessing the remarkable coherence properties of photons emitted from semiconductor quantum dots, researchers are bringing large-scale quantum information processing within reach. This newsletter article presents current advances in quantum dot growth and patterning—progress that may redefine the architecture of future quantum hardware.

Quantum theory stands as the most advanced framework describing the nature of reality—a theory regularly tested through the rapidly evolving field of quantum science. The surprising and sometimes counterintuitive implications of quantum phenomena continue to inspire new lines of research, making this area one of the most vibrant in all of physics. The quest to transform quantum theory into practical tools is at the heart of quantum technology, which is already improving lives—consider the advances in quantum sensing and imaging as applied in magnetic resonance tomography scanners. Such instruments allow for precise, non-destructive imaging and exemplify the tangible benefits of quantum innovations.

Semiconductor devices such as LEDs, lasers, cameras, and solar cells have long shaped modern life. Transistors, the cornerstone of microchip technology, represent one of humanity's greatest technological achievements, still advancing at remarkable speed. Their operation depends on the quantum behavior of electrons and photons. Electrons traverse the semiconductors crystal matrix as waves, yet they emit energy in discrete quanta, giving rise to light in LEDs and lasers. In solar cells, photons prompt the creation of electron-hole pairs, converting sunlight into electricity, while digital cameras exploit quantum transitions to capture images. These applications demonstrate how quantum mechanics underpins technologies already essential to modern society.

Yet, quantum technology today seeks finer control—the manipulation of *coherent quantum properties* at the level of individual systems. These systems, called quantum bits or *qubits*, are the fundamental units for quantum information processing. Building a quantum computer demands the ability to entangle and coordinate many qubits, presenting a major scaling challenge that dominates current research. The promise is immense: quantum processors should, in principle, require far fewer qubits than classical bits to tackle problems that classical computers—regardless of their power—cannot solve. But this promise depends on taming a formidable obstacle: the fragility of quantum coherence.

Qubit coherence is acutely sensitive to environmental noise. Errors arise quickly, and if left unchecked, render quantum computations unreliable. Therefore, quantum science increasingly focuses on developing qubits robust against decoherence. Prominent candidates include engineered states in special materials and devices as superconducting Josephson junctions (transmons) and laser-cooled ions and atoms. Even with cooling close to absolute zero and remarkable experimental progress, these systems remain vulnerable. Quantum error correction could help, but the approach typically requires many "noisy" qubits to support just a few robust logical qubits, complicating efforts to scale to practical quantum computer sizes. Thus, while superconducting and atomic platforms are promising, scalability limits remain substantial. Semiconductors—a proven pathway for classical scaling—attract interest, but their qubits often suffer from strong coupling to the environment, which increases decoherence.

Against this background, photons offer compelling advantages. Because they interact weakly with their environment, photons can overlap, travel at the speed of light, and connect quantum devices as for instance quantum nodes in a quantum network over vast distances. Quantum coherence in light is tangible: it appears naturally at ambient conditions, as in the shimmering colours visible on the surface of a soap bubble (Figure 1). Photons routinely carry enormous volumes of classical information across continents through optical fibres. However, using photons for quantum computation requires exact control over single photons—creating photon qubits and establishing quantum entanglement between them.

Semiconductor quantum dots (QDs) have emerged as exceptionally efficient and pure sources of single and entangled photons. In one landmark demonstration, a coupling efficiency of approximately 60% into an optical fiber was achieved. To realize such performance, the surrounding semiconductor matrix must be of outstanding quality: it must be clean, low-noise, and virtually free of charge fluctuations. Once achieved, quantum dots can emit photons with no measurable quality degradation—reliably, and over thousands of consecutive emissions [1]. If tunable and exceptionally stable, QDs can even generate high fidelity pairs of entangled photons [2]. This line of research paves the way toward robust, scalable, on-demand entangled photon sources for the quantum internet and integrated quantum optical circuits.

The ultimate test of QD stability is achieved by using photons from physically separate quantum dots. In such experiments, remote QDs can be entangled or used to implement elementary quantum logic gates. At Ruhr University Bochum, we have demonstrated that GaAs quantum dots constitute interconnectable sources of indistinguishable single photons, achieving near-unity mutual coherence between photons emitted from separate sources [3]. This advance shows promise for future quantum applications, where multiple QD sources can work together. Figure 2 illustrates how three quantum dots of differing physical sizes and shapes are engineered to emit photons that are functionally indistinguishable—critical for scalable optical quantum computing.

Recent progress allowed the development of charge-tunable GaAs QDs with ultra-low charge noise by molecular beam epitaxy [4]. Materials advances—such as a new diode structure hosting GaAs QDs with all doping contained in layers of low aluminium concentration—prevent the occupation of DX centres and render AlGaAs layers conductive at low temperatures. A low-strain environment surrounding the QDs also promises to prolong electron spin coherence, another crucial milestone.

Figure 1: A soap bubble. The shimmering colours originate from quantum interference of light.

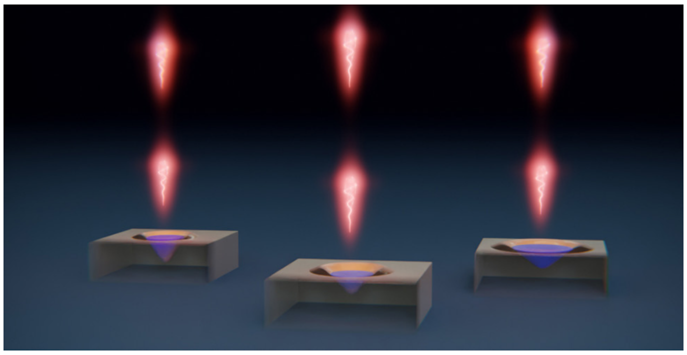

Figure 2: Quantum dots of different origins and sizes emit spectrally identical, indistinguishable photons. © Universität Basel

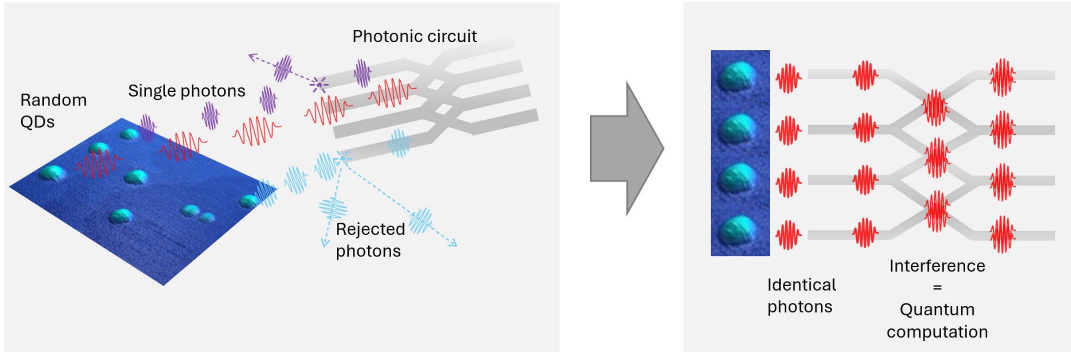

Figure 4: From randomly nucleated quantum dots with varying emission wavelengths (left) toward ordered arrays of identical dots—enabling photonic quantum computing with standard foundry photonic integrated circuits (right).

From the quantum photonics perspective, this work opens the door to bright, low-noise single photon sources.

For us, the foundation for scalable quantum photonics is now clearly defined: developing arrays of quantum emitters that together produce uniform quantum light. Such arrays may be orchestrated to generate complex, high-dimensional entangled states. Our single QDs have already shown potential for quantum advantage over classical light sources [5]. They can even create more elaborate multi-qubit entangled states [6] and enable quantum-secure data communication [7].

Beyond applications, quantum dots are celebrated platforms for exploring quantum optics. They can be used to produce exotic states of light [8], as illustrated in Figure 3. The identification and manipulation of highly correlated photonic states in time have been demonstrated, providing new insights into stimulated emission—the fundamental process underlying lasers and quantum amplification. Stimulated emission at the level of a single quantum emitter and single photons marks a milestone and underpins future quantum technologies: photon sorting, photon-number-resolving detectors, and Bell measurements are enabled by these advances. Revealing two-photon bound states in interaction with a single atom presents new resources for high-fidelity, two-qubit photonic gates and controlled-phase operations. These phenomena enable quantum-enhanced metrology, advanced microscopy, and lithography.

In a previous newsletter [9], we detailed the progress in QD synthesis. While self-assembly has yielded high-quality QDs, it naturally generates random positions and emission wavelengths—an obstacle for photonic integration at scale (Figure 4). The pathway forward is the creation of ordered arrays of identical dots, which would make scalable photonic quantum computing with existing foundry techniques feasible.

Epitaxial layer-by-layer crystal growth enables unprecedented control over the self-assembly of quantum dots, allowing researchers to engineer ordered arrays with tailored density modulation across a wafer. By introducing carefully designed thickness gradients during growth, the surface roughness evolves periodically, profoundly influencing where quantum dots nucleate. This method produces regular patterns of high and low QD density—how many dots are found per area—which can be precisely tuned according to device requirements; such spatial control is ideal for both fundamental studies and the fabrication of quantum optoelectronic devices with specific density demands [10].

The periodic modulation originates in the dynamics of the epitaxial growth process, specifically the evolution between atomically smooth regions and sites with increased roughness or missing atomic layers. These engineered density patterns are vividly displayed in the false-color photoluminescence intensity maps shown on the cover of the newsletter and in Figure 5. Here, regions of high dot density appear bright, while low-density zones are dark. In the full-wafer scan at limited resolution (left), a Moiré pattern emerges as an aliasing artifact due to insufficient spatial

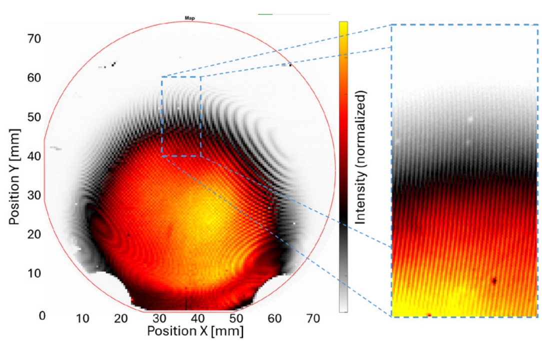

Figure 5: Photoluminescence intensity map of QDs arranged in a density-modulated pattern. The left panel shows a full-wafer scan, where coarse sampling generates a Moiré pattern that obscures the true modulation. In contrast, the magnified high-resolution scan on the right reveals the actual periodic variation in quantum dot density, vividly distinguishing regions of high and low photoluminescence intensity.

sampling. Only in the high-resolution inset (right) does the true periodic density modulation become apparent, clearly distinguishing the engineered pattern from imaging effects. Combining this density modulation approach with laser-based patterning (Figures 6 and 7) enables directed formation of QDs, paving the way for highly coherent, ordered multi-emitter sources that integrate seamlessly with photonic circuits—essential for large-scale quantum hardware.

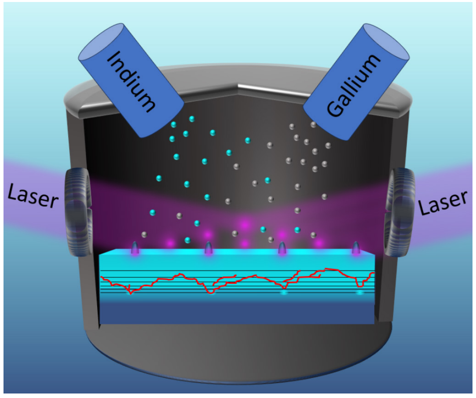

Figure 6: Schematic of a molecular beam epitaxy system growing semiconductor heterostructures. Laser interference patterns on the substrate create controlled thermal gradients that guide the formation of ordered QD arrays.

This research effort unites experts in solid-state physics, quantum optics, and quantum information science. In a new project funded by the European Research Council, the team works to harness entangled photons from quantum dots as scalable resources for quantum information technology. By controlling the QDs via laser fields and collecting emitted photons through optical nanostructures, highly entangled photonic states can be engineered and deployed for quantum information processing. A distinctive advantage of this approach is its inherent scalability: once sources of sufficiently high quality are realized, the technology readily extends to larger quantum processors simply by integrating more emitters.

The project confronts the challenge of creating advanced photonic resource states. Achieving this goal requires quantum dots of unprecedented quality and novel functionalities, including sources engineered for entangled emission of up to ten photons. As proof-of-principle experiments progress, the field draws closer to fully operational quantum information processors, laying critical groundwork for future photonic-based quantum technologies.

Continued advances in quantum dot synthesis, patterning, and characterization are paving the way for the next generation of scalable photonic quantum technologies. As semiconductor quantum dots achieve higher uniformity, tunability, and coherence, the seamless integration of deterministic photon sources into photonic circuits becomes increasingly feasible. These breakthroughs not only accelerate the realization of practical quantum computers and networks, but also further position quantum dots as a cornerstone of quantum science and engineering.

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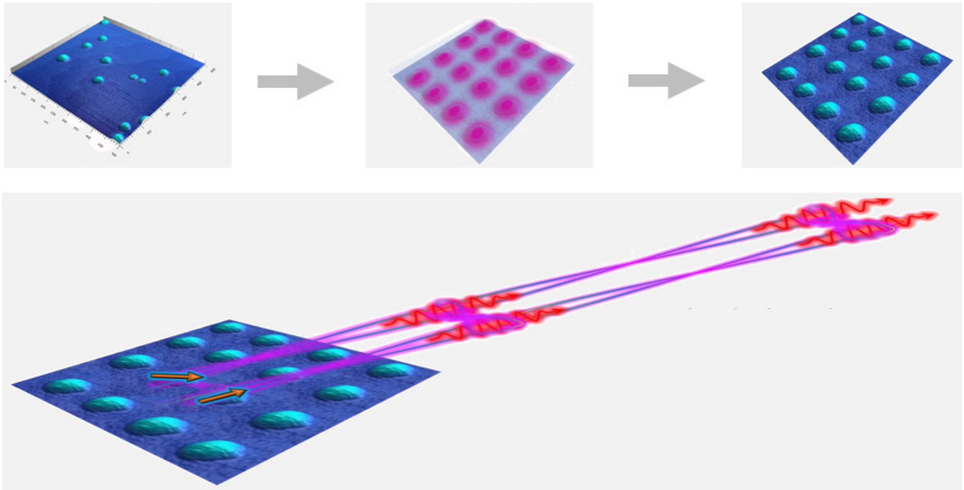

Figure 7: Light-assisted self-assembly transforms random QD nucleation into well-ordered arrays of near identical QDs (top row). Coupled QD spins and photons generate entangled photonic cluster states—cornerstones of future quantum information networks (bottom image).

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QUANTUM SCIENCE AT CHURCH

Saturday Morning Physics brings research to the public

"Saturday Morning Physics" is an event series organized by the Faculty of Physics and Astronomy. On several Saturdays during the winter semester, researchers unravel the mysteries of the world with the help of physics—with contagious enthusiasm for their topics and in a way that is understandable to everyone. The series brings science to the heart of Bochum city, specifically to the Pauluskirche. It thus offers a unique platform for making complex physics topics accessible to a broad audience. In 2025, the focus is on quantum science. Researchers from the Materials Research Department are also presenting their research.

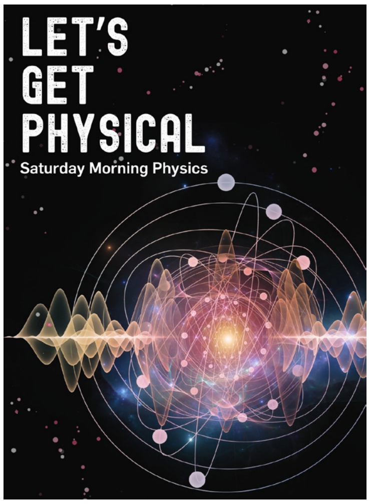
In January, Prof. Anna Böhmer offered insights into her studies on superconductors as well as a hands-on introduction to quantum physics. She provided a lively illustration of the significance of quantum physics for the unique characteristics of superconductors, such as their lack of electrical resistance and special magnetic properties. The audience was particularly fascinated by the demonstration of a very special characteristic of superconductors: when cooled to minus 200°C, they abruptly change their physical properties and completely displace an applied magnetic field. The repulsive force causes a magnet to float above the superconductor as if by magic.

Dr. Arne Ludwig also took the audience on a journey into the world of quantum physics in March. A whole series of experiments shed light on questions such as: does light behave like waves or particles? What role do quantum mechanical phenomena play in semiconductors, which form the perfect basis for modern electronics? Together with the audience, Dr. Ludwig took a closer look at tiny semiconductor crystals, known as quantum dots, and showed how they can be used to generate light. The lecture impressively revealed how complex quantum mechanical phenomena are applied in practice.

Next up is a talk by Prof. Anna Grünebohm on November 29: "From quantum mechanics to the refrigerator of the future—insights into theoretical materials science." In her presentation, she will show how theoretical materials science is shaping the technologies of tomorrow and provide exciting insights into everyday applications of quantum science.

Saturday Morning Physics has proven to be an excellent way to make scientific research on quantum topics accessible to a broad audience. Its popularity is testament to the public's keen interest in the topic: the Pauluskirche is usually only this full for Christmas!

Further information at physik.rub.de/veranstaltungen/smp.



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