Christian Schneider

Can atomically thin crystals light up our future?

Finding ways to efficiently generate light in solids has always been a central task in material engineering. What started with a glowing wire in Edison's lab has meanwhile turned into highly advanced crystallography and solid-state physics. The prime example are semiconductor heterostructures, first developed approximately five decades ago: A modern light emitting diode consists of a complex semiconductor heterostructure (mostly based on GaN and InGaN compound semiconductors), which is embedded in a matrix which converts the monochromatic blue- or even ultra-violet light output of the semiconductor crystal into cozy white light. The invention and development of thin layer semiconductors have not only yielded the modern LED technology, but also led to the development of semiconductor lasers and amplifiers: the core workhorses of modern communication society. Without highly efficient lasers, long distance data transmission in fibers, as we know it today, is unthinkable.

Less than two decades ago, the quantum material community was confronted with another paradigmatic development: A. Geim and K. Novoselov demonstrated not only the method to isolate a monoatomically thin layer of Carbon atoms (dubbed 'Graphene'), neatly arranged in a hexagonal (so called Honeycomb) lattice, but the two researchers clearly verified a fundamental modification of the most principal material properties in this monolayer [1]: Most notably, if properly prepared, an electron can propagate in such a sheet of graphene with almost unprecendented mobility, since the bandstructure of the material mimics the behavior of massless particles. In other words, the electron behaves rather like a particle of light. As a direct consequence, macroscopic quantum effects, such as the quantum Hall effect and the fractional quantum Hall effect revealed themselves in Graphene with ease [2]. However, the wonder material had a downside: Applications in photonics and optoelectronics were sparse since the semi-metallic two-dimensional crystal is a very poor light emitter.

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Shiny new flatland

In 2010, everything changed. A team of researchers from Columbia University realized that, like Graphene, the Transition Metal Dichalcogenide MoS_2 could be prepared as a monolayer via the same simple technique: Utilizing Scotch tape, single crystal layers can be peeled off the bulk crystal, by tearing and subsequent stamping onto carrier substrates [3]. More amazing, what used to be a rather dim material with practically no capabilities to emit light, and which was mostly used as an industrial lubricant, turned into a monolayer with highly efficient luminescence. This surprise is rooted in the transition from an indirect- to a direct band semiconductor bandstructure as the monolayer limit is reached in MoS_2 crystals [3]. Shortly afterwards, more TMDC materials were discovered which display similar behavior, and which can now cover a wide spectral range, from the visible well into the near infrared spectral range. With these discoveries, the golden era of Transition Metal Dichalcogenide research was initiated, and meanwhile, hundreds of research groups have set up dedicated programs targeting their investigation and application in light-matter coupling. This is not only a consequence of the monolayers being efficient light emitters and absorbers, but also because they emit and absorb light in "special" ways: Because these materials are ultimately thin, the most elementary interactions in solids are particularly pronounced. The prime example is the exciton (see Fig. 1), which is a "quasi-particle", that has been studied in all kinds of configuration since the beginning of semiconductor optics. Such an exciton is created in a crystal, when an electron is excited into a higher state (e.g. the conduction band), and under the condition that the coulomb interactions are strong enough to bind this electron to the residing hole (the empty state, which the electron leaves behind) in the valence band. Usually, excitons in solids manifest at cryogenic temperatures, and as such, have little relevance in real-world applications. In turn, in TMDC crystals, they dominate the optical response even at room temperature, and as such become highly relevant [4, 5].

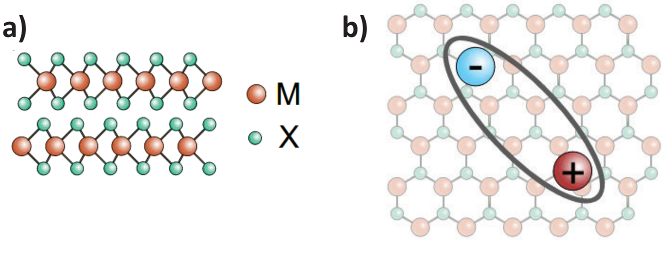

Fig. 1: Schematic drawing of a two dimensional crystal structure, which hosts an exciton (a bound electron-hole pair). The exciton causes efficient light emission and absorption in the material.

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Can lasers go 2D?

Since TMDC monolayers have quickly exhibited their capability to efficiently emit light, first attempts towards their implementation in light emitting diodes were made early on. Yet, researchers were confronted with a problem: Since, up to now, there is no monolayer semiconductor which can emit light in the blue and UV with ultra-high quantum efficiencies, the implementation of user-friendly white LEDs is still a goal lying far ahead in the future. In addition, despite impressive efforts that were reported in the last years towards large area synthesis of monolayer crystals, it still remains a great challenge to produce macroscopically large monolayers. The question whether monolayers can provide enough light to even fuel a laser, has been even more open to the research community. A laser, which can be driven by no more but a single layer of atoms is not only a scientific curiosity. Essentially, reaching this limit should inherently come along with minimal energy consumption when the device is operated, and production costs may be minimized.

The quest for a reliable implementation and for solidifying an understanding of the physics of lasers based on 2D materials (see Fig. 2a) is still ongoing: While initial reports indicated laser threshold transitions in nanophotonic cavity structures with embedded two-dimensional layers even at room temperature [6], many of the initial reports could not clearly demonstrate “coherence” of the emitted radiation, even though it is the central property that distinguishes a laser from a simple, conventional light emitter. Studies with a stronger emphasize of this central property were just recently discussed in the literature: To date, it seems that the most reliable method to generate coherent light emission using a two dimensional material is harnessing not the process of stimulated emission (which takes place in a normal laser), but the intriguing effect of Bose-condensation of light, which is strongly coupled to the excitons in the TMDCs [7, 8]. This phenomenon is also known as polariton condensation or polariton lasing. Hence, TMDC lasers are again very special: They may constitute a case, where the polariton condensation could be of higher application relevance than the standard laser oscillation [9] based on stimulated emission of radiation!

The quantum perspective

While a laser is a strictly non-classical light source (non-classical means non-thermal here), the second non-classical type of light sources are devices, which have the capability to emit well-quantized packets of radiation energy with a distinct time ordering. In this extreme case, wave packets contain exactly one - and only one - single photon, as the minimum quantum of energy. Such a device is usually referred to as a single photon source (see Fig. 2b). It is one of the most important building blocks in quantum photonic networks specifically, and in quantum applications in general. In particular in the next generation of communication, single photon sources could play a pivotal role by enhancing information and communication security, e.g. via quantum cryptography. Single photon sources are notoriously difficult and expensive to produce. A rather surprising experimental series in 2015 has, however, revealed, that TMDC monolayers show all the fundamental features to enable the engineering of single photon sources [10, 11, 12, 13]. Ever since, researchers around the globe are working on reliable and cost-effective schemes to improve the performance of monolayer-based single photon sources, possibly produced via Scotch tape exfoliation. The latest developments are very promising: Advanced implementation schemes boosted the performance to a degree that the performance of TMDC- or hexagonal Boron Nitride (another 2D material) based single photon sources do not only approach the performance of more conventional (and expensive) semiconductor single photon emitting devices [14], but also have started to be tested in real-world communication testbeds [15, 16]!

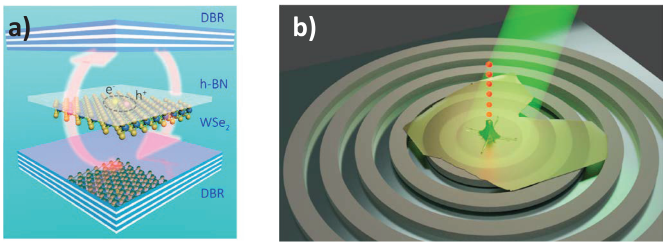

Fig. 2: a) Schematics of a Polariton laser using a 2D material. Adapted from (Shan et al. Nature communications 13.1 (2022): 3001) b) Schematics of a single photon source based on a 2D crystal.

The van der Waals era: The twist of the story

Graphene, two dimensional TMDC semiconductors and hexagonal boron Nitrite (a 2D insulator) come in very handy, not only because of the ease of fabrication, but also because they can be arbitrarily combined with other materials. Take, for instance, conventional semiconductors: here, only those crystals can be combined into defect-free, high quality heterostructures, which share a more or less identical lattice constant, which is a dramatic limitation in material engineering. 2D materials do not share this restriction. Because all chemical bonds are saturated, only van der Waals forces remain to bind the 2D layer to its environment. As a result, pretty much any 2D layer can be combined (stacked) on top of another 2D layer- or any kind

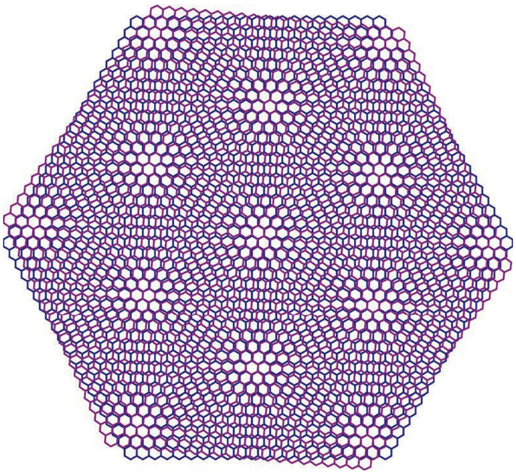

Fig. 3: a) Drawing of a heterostructure composed of two twisted monolayers, forming a so-called Moiré pattern in top-view.

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of substrate. It becomes even better: in contrast to any other semiconductor multilayer system, multilayers of van der Waals stacked materials can even be twisted between the layers. We have only explored the tip of the iceberg of the most fundamental effects, which can result from this twist engineering. Thus far, the prime example is the emergence of superconductivity (the complete loss of electrical resistivity below a characteristic temperature) in two layers of Graphene, which are rotated by a so-called 'magic angle' with respect to each other [18]. So clearly, it is left to the imagination of the scientists and engineers to explore the limits of this novel engineering approach [19].

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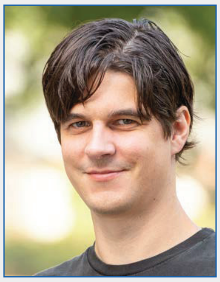

Prof. Dr. Christian Schneider

Christian Schneider leads the Quantum Materials group at the Institute of Physics, University of Oldenburg, Germany. Before he became professor in 2020, he was in charge of the optical spectroscopy activities at the Chair of Technische Physik at the University of Würzburg. In 2016, he was awarded with an ERC Starting grant. C. Schneider has authored and co-authored more than 250 journal publications, his H-index is 62.

The research interests of Christian Schneider focus on fundamentals of light-matter coupling in quantum materials, quantum photonics, novel laser concepts including Bose condensates of quasi-particles and 2D materials.

ZITATBOX

Albert Einstein (1879 - 1955)

„Zwei Dinge sind zu unserer Arbeit nötig: Unermüdliche Ausdauer und die Bereitschaft, etwas, in das man viel Zeit und Arbeit gesteckt hat, wieder wegzuwerfen."

Durch bloßes logisches Denken vermögen wir keinerlei Wissen über die Erfahrungswelt zu erlangen; alles Wissen über die Wirklichkeit geht von der Erfahrung aus und mündet in ihr."

„Der Mensch erfand die Atombombe, doch keine Maus der Welt würde eine Mausefalle konstruieren."

Quelle: https://gutezitate.com/autor/albert-einstein