

## Prof. Dr. Christian Schönenberger

Research group website: <https://nanoelectronics.unibas.ch/>

### Employment

Since 1995 Professor for Experimental Physics, University of Basel  
1993 – 1995 Research Staff Member, Philips Research, Eindhoven, The Netherlands  
1990 – 1993 Postdoctoral Fellow, Philips Research Eindhoven, The Netherlands  
1986 – 1990 Graduate Researcher, IBM Research Laboratory, Rüschlikon, Switzerland  
1979 – 1980 Research Assistant (as an electrical engineer) at the Molecular Spectroscopy group of Prof. K. Dressler at Physical Chemistry, ETH-Zürich, Switzerland

### Education

1990 Ph.D. in Physics, ETH-Zürich, Switzerland  
Thesis: *Understanding Magnetic Force Microscopy*. Supervisors:  
H.C. Siegmann (ETHZ) and S. Alvarado (IBM)  
1986 Diploma in Physics, ETH-Zürich, Switzerland  
1979 Electrical Engineer of Applied Sciences, Technikum Winterthur (today ZHAW)

### Institutional responsibilities (selection)

- Director and Co-Founder of the *Swiss Nanoscience Institute (SNI)*, University of Basel (2006-2022)
- Member of the Advisory Council of the *CSEM-Muttenz* (2011-2022)
- Member of the Advisory Council in Nanotechnology of the *HTZ-Brugg* (2014-2022)
- President of the *Swiss Network in Micro- and Nanotechnology MNT* (2017-2019)
- Vice-president of the *Swiss Network in Micro- and Nanotechnology MNT* (2015-2017)
- Director of the *NCCR on Nanoscale Science and Technology* (2005-2013)
- Vice director of the *NCCR on Nanoscale Science and Technology* (2000-2005)
- Chair of the Department of Physics, University of Basel (Sept. 1996 - Aug. 1997 & Sept. 2000 - Aug. 2001)

### Research interests and expertise

Nano- and quantum electronics, nanowire and quantum-dot physics, charge- and spin-transport in low-dimensional systems such as semiconducting nanowires, carbon nanotubes, graphene and other 2D van der Waals materials, topologically protected (helical) edge states, superconducting hybrid-devices, circuit-QED and microwave measurement techniques, reflectometry, and noise measurements.

### Publication record and 5 key publications

ORCID: <http://orcid.org/0000-0002-5652-460X>

Google scholar: <https://scholar.google.ch/citations?user=zAQ3kRAAAAJ&hl=de>

- A. Bordoloi, V. Zannier, L. Sorba, C. Schönenberger, and A. Baumgartner, *Spin cross-correlation experiments in an electron entangler*, **Nature**, 612, 454 (2022). <https://doi.org/10.1038/s41586-022-05436-z>
- P. Rickhaus, P. Makk, Ming-Hao Liu, E. Tóvári, M. Weiss, R. Maurand, K. Richter, and C. Schönenberger, *Snake trajectories in ultraclean graphene p–n junctions*, **Nature Communications** 6, 6470 (2015). <https://doi.org/10.1038/ncomms7470>
- S. De Franceschi, L. Kouwenhoven, C. Schönenberger, and W. Wernsdorfer, *Hybrid superconductor quantum dot devices*, **Nature Nanotechnology** 5, 703 (2010). <https://doi.org/10.1038/nnano.2010.173>
- L. Hofstetter, S. Csonka, J. Nygard, and C. Schönenberger, *Cooper pair splitter realized in a two-quantum-dot Y-junction*, **Nature** 461, 960 (2009). <https://doi.org/10.1038/nature08432>
- M. Henny, S. Oberholzer, C. Strunk, T. Heinzel, K. Ensslin, M. Holland, and C. Schönenberger, *The Fermionic Hanbury-Brown and Twiss Experiment*, **Science** 284, 296 (1999). <https://www.science.org/doi/abs/10.1126/science.284.5412.296>

### Third-party funded research projects (most recent ones)

2020 – 2024 Swiss National Science Foundation, *Quantum-Transport Phenomena in Hybrid Devices based on Nanowires* (follow-up of a series of SNSF projects along the line of quantum transport in hybrid devices made from semiconducting nanowires and carbon nanotubes)  
2020 – 2024 Swiss National Science Foundation, NCCR Spin Qubits in Silicon (SPIN)

- 2018 – 2023 ERC Advanced Research Grant *Engineered Topological Superconductivity in van der Waals Heterostructures (TopSupra)* (2<sup>nd</sup> ERC Advanced Research Grant)
- 2019 – 2023 H2020-FET-open project *Andreev qubits for scalable quantum computation (AndQC)*
- 2020 – 2023 H2020-FET-open project *Topologically Protected and Scalable Quantum Bits (TOPSQUAD)*
- 2010 – 2022 Swiss National Science Foundation, NCCR *Quantum Science and Technology (QSIT)*

### Supervision of junior researchers at graduate and postgraduate level

- Leader of a research group of currently 19 members (12 PhD students, 5 post-docs, 2 senior scientists)
- Supervision of around 70 PhD students to completion

### Teaching activities

- Established together with colleagues a full bachelor/master program on nanoscience in 2001, thereby establishing an exceptional interdisciplinary study program, the only one of this kind in Switzerland. It was highlighted in Nature under the heading "A success story", see Nature Nano 11, p908 (2016).
- Design and delivery of undergraduate lectures *Physics I: Mechanics and Thermodynamics*, *Physics II: Electrodynamics and Optics* and *Physics III: Introduction to Quantum und Atomphysics*
- Design and delivery of *Condensed Matter Physics*, lectured during several years.
- Lecturer at various PhD schools on nanoelectronics, quantum transport and quantum technologies.
- Lectures over many years at High Schools under the umbrella TecDay organized by the SATW (Swiss Academy of Technical Sciences).

### Membership in panels, boards, societies, and scientific reviewing activities

- Reviewer for scientific journals: Science, Nature, Nat. Phys., Nat. Nanotechnol., Nat. Commun., Phys. Rev. Lett., Phys. Rev. A, Phys. Rev. X, Phys. Rev. B, Phys. Rev. Appl., Appl. Phys. Lett, Nano Lett., ACS Nano, Adv. Mat., Nanotechnology, Nanoscale, Small, New J. of Phys.
- Reviewer for funding agencies: Swiss Nat. Sci. Foundation, ERC, Nat. Sci. Foundation (USA), Israel Sci. Foundation, Deutsche Forschungsgemeinschaft, Helmholtz Gesellschaft, Netherlands Organization for Sci. Research, Nat. Research Foundation of Korea, Leibnitz Science Foundation Ireland and more.
- Member of the Swiss, German, and the American Physical Society.
- Member of the ERC panel PE3 for Adv. Research Grants (2018 & 2020).
- Mitglied der Forschungskommission FAG Basel (Freiwillige Akademische Gesellschaft Basel) since 2001.

### Conference presentations

- The Schönenberger group received ~75 invitations to conferences, workshops, schools, colloquia and seminars (10 year record)

### Organization of conferences

- (Co-) organizer of 14 schools, 7 int. and 8 national conferences. Member of many program committees.

### Collaborations

Collaborations with in-house PI's (alphabetic order): A. Baumgartner, C. Bruder, A. Hofmann, J. Klinovaja, D. Loss, P. Maletinsky, E. Meyer, M. Poggio, R. Warburton, I. Zardo, D. Zumbühl

Prof. Szabolcs Csonka, BME, Budapest

Prof. Peter Makk, BME, Budapest

Prof. Lucia Sorba, NEST & SNS, Pisa

Prof. Jesper Nygard, Niels Bohr, Copenhagen

Prof. Eric P. A. M. Bakkers, TUE, Eindhoven

Prof. David Mandrus, Univ. of Tennessee

Prof. Takashi Taniguchi, NIMS, Tsukuba

Dr. Minkyung Jung, DGIST, Daegu, Korea

Prof. Claes Thelander & K. A. Dick, Lund Univ.

Dr. Felix Bussi re, idquantique, Geneva

Prof. Attila Geresdi, Chalmers Univ., Gothenburg

Prof. Pasquale Scarlino, EPF-Lausanne

Prof. Mitali Banerjee, EPF-Lausanne

Prof. Klaus Ensslin, ETH Z rich

Prof. Andreas Wallraff, ETH Z rich

Prof. Georgios Katsaros, IST, Vienna

Prof. Floris Zwanenburg, TU-Twente, Enschede

Prof. Alexander Brinkman, TU-Twente, Enschede

Dr. Joost Ridderbos, TU-Twente, Enschede

Prof. Anton Akhmerov, TU-Delft, Delft

Prof. Alfredo Levy Yeyati, UAM, Madrid

Dr. Marcelo Goffman, Dr. Hugues Pothier, Dr.

Christian Urbina, CEA-Saclay, Paris

Prof. Takis Kontos, ENS, Paris

### Honours and awards (selection)

2012 Fellow of the American Physical Society

2010 Life-time member of the Swiss Academy of Technical Sciences (SATW)

2012, 2018 ERC Advanced Research Grants

## Research Profile

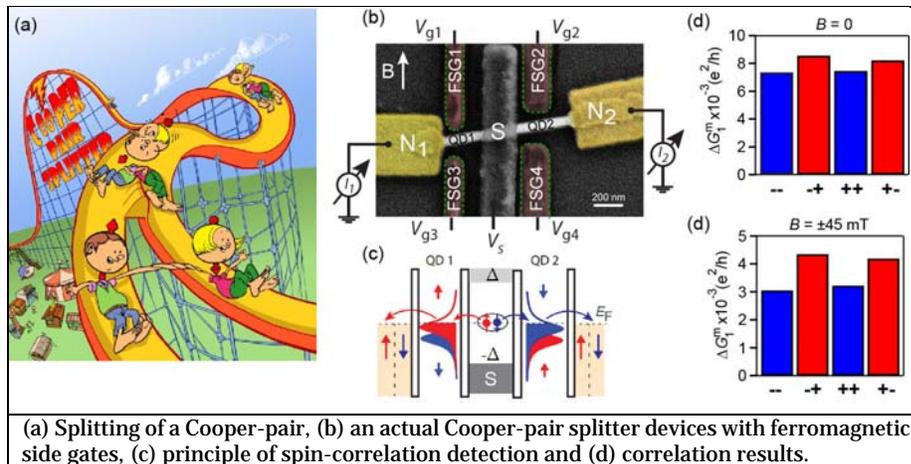
### Mission

The nanoelectronics group explores fundamental electrical properties of engineered nanoscale devices operating in the quantum regime. We probe these devices by electrical transport measurements both at low (close to DC) and high frequency (GHz range) and at cryogenic temperatures (Kelvin to milli Kelvin). Our devices are based on novel materials with reduced dimensions, such as quasi one-dimensional semiconducting nanowires (NWs) or two-dimensional graphene and van der Waals heterostructures which are defined by state-of-art e-beam lithography and complemented with gate and contact electrodes. The group is internationally recognized as a leader in so-called *hybrid quantum devices* that embody in addition to normal metal also superconducting and ferromagnetic electrodes. The latter introduce exchange fields and pairing interactions, which in combination with intrinsic properties and surface effects can give rise to novel correlated many-body states. Examples are topological states such as helical edge states in topological insulators, Andreev and Yu-Shiba-Rusinov bound states. We are using modern microwave techniques, such as GHz reflectometry and circuit-QED employing high-impedance superconducting resonators. The most recent highlights are the discovery of strong edge currents in a Weyl semimetal, strong coupling of a singlet-triplet qubit in an InAs double quantum dot to the photons of a NbTiN microwave resonator and the first demonstration of (negative) spin-spin correlations in a Cooper-pair entangler (Cooper-pair splitter).

### Key Results

#### **Cooper-Pair Splitter: Source of Entanglement in the Solid-State**

An elegant way for the creation of entangled electrons in a solid-state device is to split Cooper pairs by coupling a superconductor (SC) to two parallel quantum dots (QDs) in a Y-junction geometry. We have realized the first Cooper pair splitting (CPS) device using InAs nanowires (NWs) and could eventually demonstrate a record splitting efficiency of  $> 90\%$  making CPS a viable method for an efficient EPR source of entangled electron pairs. In further studies, we have clarified the requirements on the detector to probe entanglement and studied



(a) Splitting of a Cooper-pair, (b) an actual Cooper-pair splitter devices with ferromagnetic side gates, (c) principle of spin-correlation detection and (d) correlation results.

CPS in new regimes where additional correlations appear, for example, due to the superconducting proximity effect leading to extended Andreev-bound states (ABSS) and interesting non-local correlations. In the most recent work we reported on the first spin-spin correlation experiment in a Cooper-pair splitter device using ferromagnetic side gates: *Nature* 612, 454–458(2022).

#### **The Superconducting Proximity Effect to NWs and QD devices: Andreev and Yu-Shiba Rusinov Bound State in Quantum Devices**

We were the first to study QDs that are coupled to SCs. Our devices were realized with carbon nanotubes (CNTs) and semiconducting NWs (SNWs). In our early work we studied the interplay between Kondo physics and the superconducting proximity effect. We could demonstrate that if the Kondo temperature is larger than the superconducting pairing energy, the Kondo resonance would survive leading to an enhanced electrical conductance, signaling the transition to the Josephson effect. In the opposite limit, the gap of the SC would greatly suppress Kondo screening. These early studies have received great attention in recent years since it is now possible to study hybrid QD devices with different coupling strengths and beyond two-terminals. We have demonstrated coherent two particle resonant and inelastic Andreev tunneling in a CNT QD coupled to a superconducting and normal metal contact. N-QD-S devices with weak coupling to the normal contact N allowed us to perform spectroscopy on the Andreev-bound states (ABSS) that form between the QD and the superconducting contact. The proximity effect to a SNW with large spin-orbit interaction is currently a hot topic due the reports on Majorana physics in similar systems. Most recently, we have been concentrating on QDs that are defined by heteroepitaxy during growth in SNW.

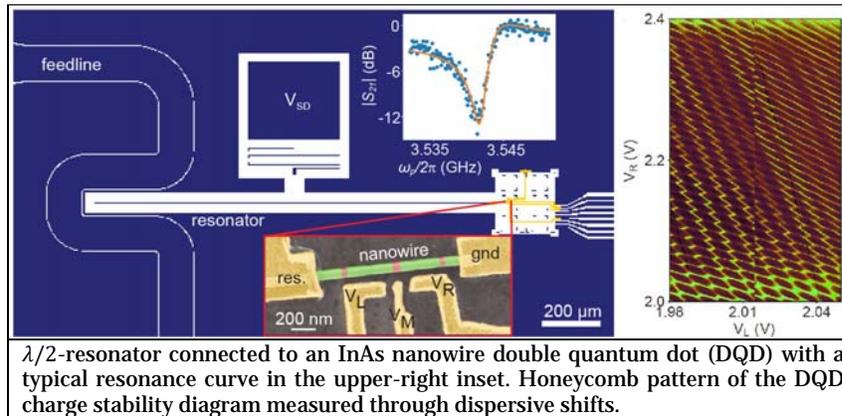
#### **Charge Correlations in Transport probed by Shot Noise Measurements**

Our group has done pioneering shot-noise measurements in nanodevices in various geometries and regimes from single-electron tunneling to quantum ballistic multiterminal devices demonstrating, for example, the antibunching of fermions. These studies were all done at modest detection frequencies in the 10–100kHz range.

In recent years, we have developed a wide bandwidth noise measurement scheme that works at GHz frequencies where we can benefit from low-noise cryogenic HEMT amplifiers. Due to the  $50\Omega$  transmission lines, we had to develop impedance matching circuits to efficiently interface to high impedance quantum devices, such as QDs. Recently, we have found that a great number of “blocking states” can appear in QDs leading to strongly enhanced shot-noise above the Schottky limit.

### Circuit-QED Approach to Quantum-Devices

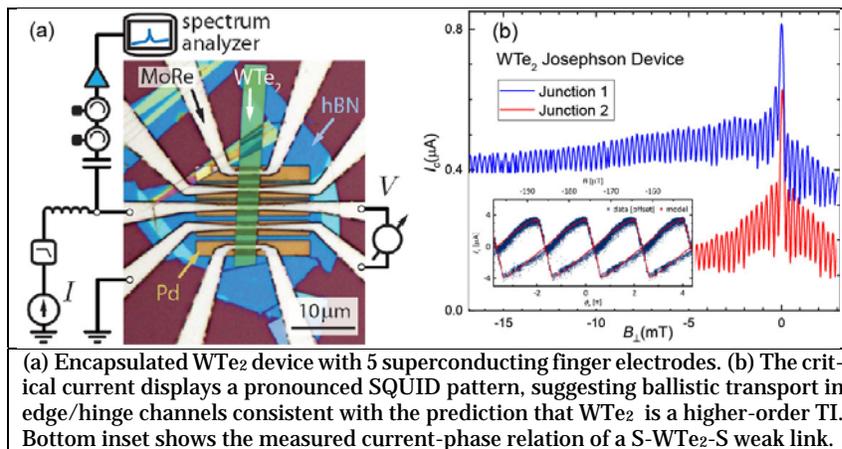
Our new noise setup is very powerful as it also enables us to measure the ac admittance of devices at GHz frequencies. First, due to the high frequency a large bandwidth is available, enabling fast measurements. On top of this, measurements are also sensitive to the capacitive/inductive parts of a device, which can conveniently be measured by monitoring frequency shifts. We have embarked on this and have studied simple QDs, double QDs and recently also graphene pn junctions. In addition, we have demonstrated charge pumping in a SNW QD device at GHz frequency. Most recently, we have realized InAs-NW based Josephson junctions and characterized the AC Josephson effect through emission studies and Shapiro steps. We currently also study circuit-QED approaches of InAs devices coupled to superconducting microwave resonators. In collaboration with M. Jung we have



demonstrated a nano-electromechanical graphene resonator oscillating at GHz frequency. In recent works we have studied spin-qubits in DQD of GeSi core-shell nanowires and superconducting Andreev (spin-) qubits coupled to high-impedance magnetic-field resilient microwave resonators. The activity on c-QED will continue and run in the future as part of the NCCR Spin.

### From Suspended Graphene to Stacks of van der Waals Materials with Topological Properties

Ballistic graphene (Gr) offers a promising platform for electron optical devices with both positive and negative refraction. We have developed a versatile technology that allows to suspend Gr and complement it with arbitrary bottom and top-gate structures. Using current annealing we demonstrated exceptional high mobilities. These suspended devices are ballistic over micrometer length scales and display intriguing interference patterns. We have used pn junctions to define an electron waveguide, explore guiding by snake-states, realize mirrors, momentum filters, beam splitters, and Fabry-Pérot-like cavities. We have also done an extensive study of pn-junctions in encapsulated Gr, where we find conductance oscillations due to Fabry-Pérot resonances, valley-isospin modulation along edges, interplay of classical snake-states with the Aharonov-Bohm effect of.



approach to engineer topological states in Gr is to induce a large spin-orbit (SOI) term by proximity. We have used  $WSe_2$  and found a large anisotropic spin-relaxation due to a dominant valley-Zeeman SOI. An intrinsic property of coupled and aligned (small twist angle) 2D van der Waals materials is the formation of a Moiré superlattice with a large unit cell. This leads to secondary Dirac points in the band structure. We have studied superlattice effects in encapsulated pn junctions both in the normal state and with superconducting contacts. An intriguing feature is our discovery of coherent edge currents over long distances in Josephson junctions realized in the Weyl semimetal  $WTe_2$ . Additionally, we have embarked in a search for the fractional Josephson effect, missing Shapiro steps and the diode effect in superconducting devices the embody materials with potentially helical edge states, such as (higher order) topological insulators. This later activity is the key focus of my currently active 2<sup>nd</sup> ERC Advanced Research grant Top-Supra.