Quantum-entangled Photon-pairs On-chip based on Layered Integrated Semiconductors (q-POLIS)

What are entangled photons? The importance of quantum technologies and their impact on scientific research and society are growing at an impressive pace. As the 20th century technology has been shaped by electronic and photonic devices (the first quantum revolution), a completely new class of applications based on our ability to detect and manipulate single quantum objects (the second quantum revolution) will characterize the 21st century. Many applications of quantum technologies, including quantum information, computing, cryptography, spectroscopy and sensing, require the use of **entangled photon pairs**. One of the most efficient approaches for entangled photon pair generation is via the parametric second-order **nonlinear process** known as **spontaneous parametric down-conversion (SPDC)**, in which a high energy pump photon annihilates into the sum of signal and idler photons in a nonlinear crystal. The quantum superposition of signal and idler states generates entangled states of light, which constitute the basic building block of a quantum processor.

Entangled photon sources currently have macroscopic size. The maximum efficiency of a nonlinear process is achieved by minimizing the wave vector mismatch, achieving the so-called **phase matching** condition. **Typical phase-matched nonlinear crystals**, *e.g.*, β-barium borate and periodically poled lithium niobate, have **moderate second-order nonlinearities** ($\chi^{(2)}$=1-30pm/V) but can reach **high nonlinear efficiencies** due to their **large thickness** (millimeter/centimeter). However, such macroscopic thickness required to reach useful efficiencies **limits further technology development and on-chip integration.**

What role can two-dimensional materials play in the miniaturization paradigm? The miniaturization and on-chip integration paradigm, which has dominated the world of electronics, is now shifting to the field of photonics. The discovery of graphene, a one-atom-thick sheet of carbon atoms, opened research on other two-dimensional materials, like semiconducting **transition metal dichalcogenides (TMDs)**, *e.g.*, MoS_2. TMDs are van der Waals layered materials which are having a **transformative impact on nonlinear optics**, because of their **huge optical nonlinearity ($\chi^{(2)}$~100-1000 pm/V)**. From the first report of second harmonic generation from monolayer TMDs, many other parametric nonlinear processes have been observed, *e.g.*, sum-frequency, optical parametric amplification, third and higher order harmonics, four wave mixing and, very recently, also the generation of entangled photon pairs via SPDC.

Despite the giant nonlinearity, **the nonlinear efficiency** ($\propto[\chi^{(2)}]^2 z^2$) **of monolayer TMDs is still limited by their sub-nanometer thickness** z. Such efficiency can be boosted by increasing the propagation length through the medium, *i.e.*, by increasing the TMD thickness z. However, the most studied 2H polytype is centrosymmetric in crystals with an even number of layers, resulting in a vanishing second-order nonlinearity. Recently **this limitation has been circumvented using a different crystalline phase, the non-centrosymmetric 3R polytype**. Using 3R-MoS_2 flakes, nonlinear efficiencies have been increased by ~10^4-10^5x compared to monolayers.

Pushing towards even higher conversion efficiencies, however, **requires phase-matching** the nonlinear interactions. Very recently the realization of **periodically poled 3R-stacked TMDs (PPTMDs)** has enabled quasi-phase-matched second harmonic generation and SPDC. Thanks to their superior nonlinearity, PPTMDs finally provide (i) **similar conversion efficiencies as standard bulk crystals** but **within micron thicknesses** and (ii) **SPDC coincidence-to-accidental-ratio (CAR)>350**, outperforming any SPDC source based on bare van der Waals flakes reported to date.

On-chip entangled photon sources. Despite efficient, ultracompact, broadband and programmable entangled photon sources based on layered semiconductors are now finally available, **integrating them on chip** is essential for new photonic quantum technologies required to address rising demands for fast and energy-efficient quantum processing, and it still **remains an open *challenge***.

q-POLIS wants to solve this *challenge*, **implementing entangled photon pair sources based on nano-engineered 3R-TMDs directly onto universal silicon photonics circuitry**. Producing photon pairs directly on chip will be an enabling technology for next-generation quantum photonic devices, bypassing the loss associated with coupling each photon onto the chip, which scales exponentially with the number of photons produced. Thus, integrating **TMD-based entangled photon sources** could address a major bottleneck in photonic quantum computing, impacting the **future of secure quantum operations**, creating entirely **new digital protocols and technologies**, and **enabling significant advances in computing speed, with drastically lower energy dissipation**.