



**Project Number:** 16433  
**Project Acronym:** SINPHONIA  
**Project Title:** Single-photon nanostructured detectors for advanced optical applications

**Instrument:** Specific Targeted Research Project

**Thematic Priority:** Sixth Framework Programme Priority 3-NMP  
**Priority 2** - Information Society Technologies (IST)  
**Priority 3** - Nanotechnologies and nanosciences, knowledge-based multifunctional materials, and new production processes and devices (NMP)

**Project start date:** 01/01/2006

**Publishable final activity report**

**Nature<sup>1</sup>:** R

**Dissemination level:<sup>2</sup>** PU

**Due date:** Month 39

**Date of delivery:** 2009-05-15

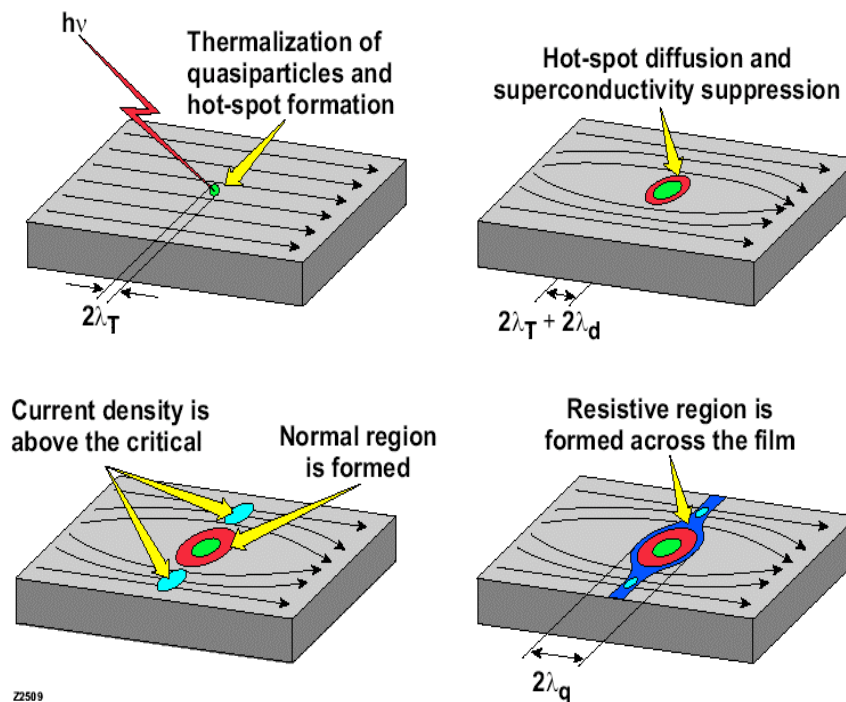
**Authors:** TUE

<sup>1</sup> R = Report, P = Prototype, D = Demonstrator, O = Other

<sup>2</sup> PU = Public, PP = Restricted to other programme participants (including the Commission Services), RE = Restricted to a group specified by the consortium (including the Commission Services), CO = Confidential, only for members of the consortium (including the Commission Services)

## I. Objectives

The goal of SINPHONIA is to develop and investigate a specific type of single-photon detector based on superconductor nanostructures, and demonstrate its use in a number of applications requiring ultimate sensitivity in the near-infrared (IR) and high speed of operation. These superconducting single-photon detectors (SSPDs), demonstrated for the first time by one of SINPHONIA's partners, rely on the formation of a resistive "hot spot" in a superconducting nanostripe (see figure below) upon absorption of a single photon, and on the consequent generation of a voltage pulse. Dark count rates as small as 1 counts/s can be achieved, several orders of magnitudes lower than semiconductor detectors with comparable efficiency in the near-IR. Unlike other approaches to single-photon detection using superconductors, the localised nature of the hot spot allows an ultrafast ( $\approx 20\text{-}30$  ps) thermalisation of the excitation and therefore a response time several orders of magnitudes faster than e.g. avalanche photodiodes.



**Fig. 1** Mechanism of single-photon detection in SSPDs: The absorption of a photon creates a locally resistive region ("hot-spot") in the superconducting stripe. The supercurrent avoids the hot spot and accumulates in the stripe periphery. As the critical current density is reached, the entire stripe becomes resistive and a voltage pulse is generated. Partner MSPU pioneered this technology [Gol'tsman et al., *Appl. Phys. Lett.* 79, 705 (2001)].

By a combination of material optimisation, nanofabrication development, physical characterisation and modelling we pursue the following objectives:

- Achieve a performance by far surpassing any competing approach in the near-IR, by improving material control and nanofabrication techniques, including new fabrication approaches and new functionalities (photon-number-resolution, arrays, preamplifiers).
- Develop a thorough understanding and modelling of the physical processes underlying the detector operation, and demonstrate SSPD operation using alternative materials allowing higher operating temperature and improved performance.
- Demonstrate the use of superconducting detectors in practical applications, including quantum cryptography and optical communications.

## II. Project structure

The project is divided into five workpackages (WPs).

**WP1 - Material optimisation, device fabrication** deals with the deposition of thin films of NbN and other superconductors, including high- $T_c$  oxides, and the nanofabrication of SSPD devices, including closely-packed meanders, linear arrays, advanced optical structures (microcavities, waveguides), integrated superconducting circuits for preamplification and photon-number discrimination.

**WP2 – Characterisation and modelling** addresses the investigation and modelling of thin films and SSPD devices, including the physical investigation and modelling of the detection process, the high-frequency characterisation of SSPDs, and the characterization and modelling of advanced optical structures.

**WP3 – Applications** is aimed at the implementation of SSPDs in several applications, including high-speed quantum cryptography, commercial quantum cryptography testbeds, and long-distance unamplified optical communications.

**WP4 – Use and dissemination** addresses the promotion of SSPD technology through dissemination activities, including scientific publications and the organisation of a workshop, and the preparation of plans for using the knowledge generated within the project.

**WP5 – Management** deals with the coordination and management.

### List of partners (as of May 15, 2009) and activities

No.	Participant name and activities in the project	Short name	Country
1	<a href="#">Technische Universiteit Eindhoven (starting Oct 1 2007)</a> Project coordination, optical characterisation, modelling	TUe	Netherlands
2	<a href="#">Commissariat à l'Energie Atomique</a> Film growth, nanopatterning, optical characterisation, modelling	CEA	France
3	<a href="#">Consiglio Nazionale delle Ricerche</a> Film growth, nanopatterning, optical characterisation	CNR	Italy
4	<a href="#">Moscow State Pedagogical University</a> Film growth, nanopatterning, optical characterisation	MSPU	Russia
5	<a href="#">University of Geneva</a> Film growth, physical investigation and modelling, quantum cryptography	GEN	Switzerland
6	<a href="#">VeriCold Technologies GmbH</a> Cooling systems	VER	Germany
7	<a href="#">id Quantique SA</a> Quantum cryptography testbeds	idQ	Switzerland
8	<a href="#">Pirelli Labs</a> Optical communication testbeds	PIR	Italy
9	<a href="#">Thales TRT</a> Quantum cryptography	THA	France
10	<a href="#">SCIPROM Sarl</a> Project Manager	SciProM	Switzerland
11	<a href="#">Ecole Polytechnique Fédérale de Lausanne (ended Sep 30 2007)</a> Film growth, optical characterisation, modelling	EPFL	Switzerland

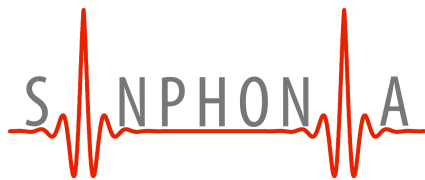
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## Project website

<http://www.sinphonia.org>

## Project logo



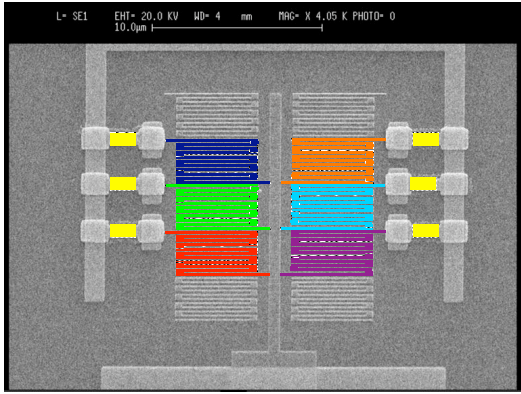
## III. Project technical results

### WP1: Materials and devices

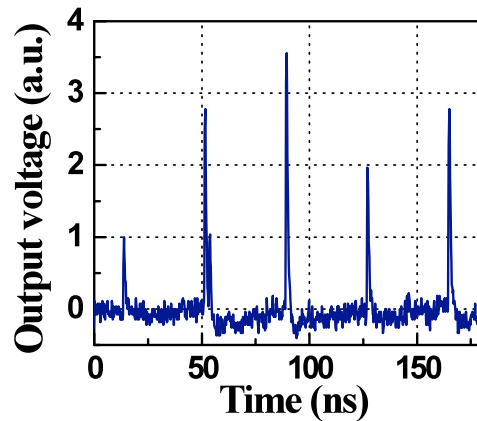
SINPHONIA has pushed the technology of ultrathin superconducting films much beyond the state-of-the-art. On the traditional NbN material platform, major advances have been the control of ultrathin films ( $\approx 4$  nm) with critical temperature  $T_c$  up to 13 K on sapphire wafers up to 4'', the development of passivating capping layers, and the optimisation of film deposition on other substrates (Si, GaAs). Alternative materials were also investigated, and very thin (10 nm) films of YBCO with high superconductive properties ( $T_c > 70$  K) have been achieved. High-performance SSPDs were fabricated by several partners on these optimised films, with quantum efficiencies (QEs) up to 30% at 1.3  $\mu$ m wavelength. The combination of high QE, low dark count rate ( $< 0.1$  Hz) and high repetition rate ( $> 80$  MHz) make these detectors the most sensitive and fastest single-photon detectors ever reported at telecom wavelengths. Advanced detector structures, including monolithic optical microcavities, and linear arrays of up to 16 detectors were fabricated and tested. Entirely novel functionalities were also demonstrated: Photon-number-resolving detectors capable of counting between 1 and 6 photons with record sensitivity and speed were developed, based on the novel concept of parallel nanowires<sup>3</sup> (see fig. 2). Integrated preamplifiers of the detector output signal were also demonstrated for the first time, based on carefully designed nanowire circuits.

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<sup>3</sup> Divochiy et al., Nature Photonics 2, 302 (2008)



**Fig. 2a:** SEM image of a parallel-nanowire photon-number-resolving detectors.



**Fig. 2b:** Photoresponse of a parallel-nanowire photon-number-resolving detector under laser illumination, showing discrete output levels.

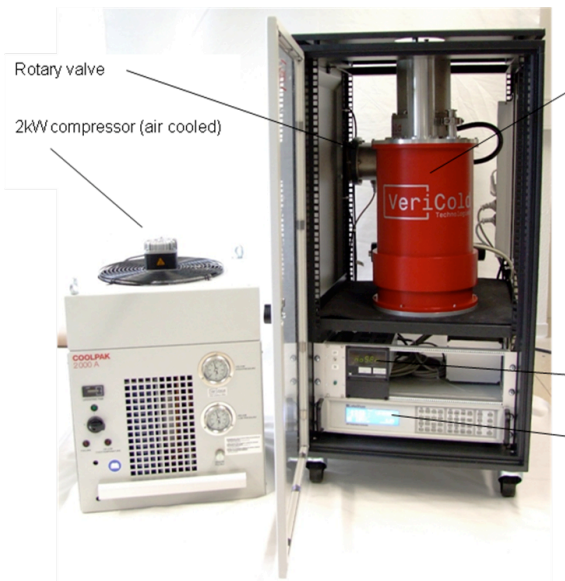
## WP2: Characterisation and modelling

Through an intense exchange of characterisation methods, films and devices, a common set of procedures and data has been established within the consortium. A spatially-resolved mapping of the detector response has given insight on the possible origin of wire inhomogeneities. Extensive high-frequency characterisation of SSPDs has allowed us to test the speed limits (dead time, afterpulsing) of different device structures. A novel SSPD geometry has been proposed and demonstrated to overcome the kinetic inductance limit and increase the maximum photon counting rate to a record value  $>1$  GHz. Electrical and electro-thermal modelling of standard and advanced SSPDs has been performed, showing the role of the coupled electrical and thermal dynamics on the device recovery and latching process.

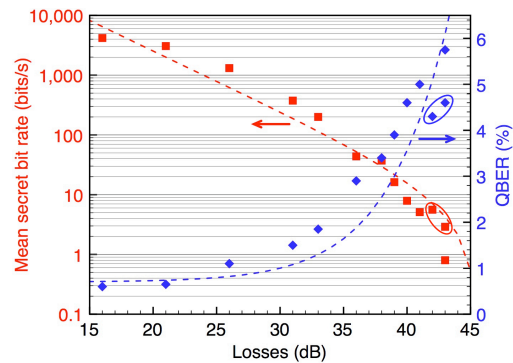
## WP3: Applications

SSPDs have been integrated into fiber-coupled, user-friendly systems including liquid-He or cryogen-free cooling, bias and amplification electronics. In particular, two generations of pulse-tube coolers, specifically designed for SSPDs, have been developed (fig. 3a), showing a base temperature of 3.3K and 1.1K, respectively, and extremely high thermal stability  $< 1$  mK. Several generations of packages for mounting of SSPDs into these systems have been realized and tested. Record QE values of 4% and 9.6% (at  $\lambda=1.55$   $\mu\text{m}$  and 10 Hz dark count rate) were measured from fiber input in the cryogen-free system and liquid-He system, respectively. These systems have been extensively used in quantum cryptography (QC) applications, enabling the demonstration of several record-breaking experiments. Entanglement swapping using continuous-wave sources<sup>4</sup>, quantum key distribution over 150 km of installed fiber (between Geneva and Neuchatel, see Fig. 3b) and over 250 km of fiber-on-a-spool, were demonstrated with SSPDs, setting the state-of-the-art for long-distance quantum communications. Additionally, SSPDs were successfully integrated in a time-coding QC set-up and a commercial plug&play QC appliance, showing the maturity and flexibility of the technology. Optical data transmission at 2.5 Gb/s was also demonstrated using fast SSPDs operated in linear mode, as a first step towards application in ultralong-distance optical communications.

<sup>4</sup> Halder et al., Nature Physics 3, 692 (2007)



**Fig. 3a:** Photograph of the 3K cryogen-free cooler used for QKD experiments.



**Fig. 3b:** Secret bit rates and quantum bit error rate in the Geneva-Neuchatel QKD experiment as a function of fibre loss

### Comparison to state-of-the-art

Overall, the SINPHONIA consortium is currently defining the state-of-the-art for the device performance in terms of sensitivity (QE/dark count rate) and speed, for the device functionality (photon-number-resolution, preamplification) and for applications (best available fiber-coupled SSPD system, record distances in QKD). The consortium's activity has been very visible in conference and journal publications, including papers in top journals (Nature Physics and Nature Photonics). Few other groups worldwide (MIT and Jet Propulsion Laboratory in the USA, NICT in Japan and TU Delft in Europe) have demonstrated an independent fabrication process of high-efficiency SSPDs. In terms of efficiency, the world record (57% at 1550 nm) has been reported at MIT using integrated top mirrors<sup>5</sup>, but the dark count rate was not reported. In terms of applications, the use of SSPDs fabricated at MSPU has been demonstrated by other groups (NIST, Stanford) in quantum optics and quantum communication experiments, most notably for long-distance QKD (200 km in the laboratory<sup>6</sup>). The development of SINPHONIA cryogen-free system has recently provided the consortium with a more sensitive fiber-coupled detector, allowing us to establish a new record of 250 km, and to demonstrate a field-trial over 150 km of installed fiber.

### Comparison to objectives

SINPHONIA has reached the large majority of its objectives. Among the 23 technical milestones over the entire project duration, 19 were achieved, one (M2.3) was partially achieved, and only three were not achieved (due to technical problems). In many cases (photon-number-resolution, preamplification, high speed) the milestones have been achieved through innovative technical solutions totally unexpected at the beginning of the project, showing the innovative and dynamic character of SINPHONIA work. Most importantly, SINPHONIA has fully achieved its main objectives (Section 1 of the DoW)

- Fabricate single-photon optical detectors with unprecedented performance at telecom wavelengths
- Demonstrate their implementation in several IST applications by industrial partners

and by doing that has developed and promoted the SSPD technology to the point where it has become a key technology for single-photon applications.

<sup>5</sup> Rosfjord et al., Opt. Express 14, 527 (2006)

<sup>6</sup> H. Takesue et al., Nature Photonics, 1 343 (2007)

## **IV. Use and dissemination**

### **Project's activity**

SINPHONIA has been extremely active in disseminating the scientific results of the project's activity, as well as promoting the use of the SSPD technology. 29 papers have been submitted/published in peer-reviewed journals, and 55 papers have been presented at international conferences, including many invited papers. A special symposium on SSPDs has been organized in the framework of the Single-Photon Workshop SPW2007<sup>7</sup>, with a strong representation of both SINPHONIA partners and external laboratories. SINPHONIA papers have been presented in all major events on superconductive devices and single-photon detectors. Additionally, the SSPD technology has been promoted by invited seminars in external laboratories and on-site lab demonstrations. Extended information on the project is available on the public part of the project's website: [www.sinphonia.org](http://www.sinphonia.org). On the exploitation side, five project-related patents have been filed by SINPHONIA partners during the project's lifetime, and patent searches and market analyses have been periodically carried out. Use and dissemination plans have been produced both at the mid-term and at project end.

### **Summary of exploitation plans**

During the project lifetime, and in large part due to the partners' efforts, SSPDs have evolved from a technological curiosity to an established technology, widely recognised as the key approach to ultrasensitive single-photon measurements. The SINPHONIA consortium has identified different areas of applications where SSPDs can find use. On one hand, the optical instrumentation market represents already today an interesting, small-volume market for SSPDs. On the other hand, quantum key distribution, remote sensing, picosecond integrated circuit analysis and optical communication can open up larger markets in the medium term.

A first commercial solution is already available from a spin-off of a SINPHONIA partner<sup>8</sup>, and has found initial acceptance in the instrumentation market. Future plans include the development of SINPHONIA's technical breakthroughs as commercial products, and extending the market share by the development of more advanced system solutions including cryogen-free cooling. The vigorous research activities deployed during the project will continue in SINPHONIA and other laboratories, and will contribute to the further development of this exciting research and application field.

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<sup>7</sup> <http://www.inrim.it/~degio/SPW2007-base.html>

<sup>8</sup> Scontel, [www.scontel.ru](http://www.scontel.ru)