FBKs key technological platforms for realization of quantum-devices

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QT platforms in FBK

- Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers
- Quantum imaging with SPAD detectors
- Development of a platform for on-chip quantum experiments
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

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- Motivation
- Technology
- Test device fabrication
- Electrical characterization
- Superconducting circuits
- Parametric amplifiers
- Outlook
Basic building blocks are superconducting qubits coupled to superconducting waveguide resonators. In this context Josephson junctions are used as the key nonlinear element of these devices. A Josephson junction is essentially a thin insulating barrier between two superconductors that gives rise to coherent quantum tunnelling of Cooper pairs.

Key technologies:
- Josephson junction’s: double angle evaporation using aluminium as superconductor and aluminium oxide as dielectric layer.
- Resonators: coplanar waveguides based on aluminium.

Initial goal: demonstrate the feasibility of this technology with minimal effort.
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

Josephson Effect

With two superconductors adjacent to each other separated only by a thin insulating layer or more in general a barrier, the phase difference ($\phi_1 - \phi_2$) between the two superconductors will generate a current of superconducting Cooper pairs flowing between the superconductors.

The effect can be seen with any type of restriction or barrier:
- SIS Insulating barrier
- SNS Normal metal barrier
- Geometrical restrictions
- Grain boundaries
- ............

$I = I_0 \sin \delta \quad \delta = \phi_1 - \phi_2$

$\frac{d\delta}{dt} = 2eV/h = 2\pi V/\Phi_0$

$I_0$ Critical Current (maximum supercurrent)
$\phi$ phase of the macroscopic wave-function that describes the Cooper pair condensate
$\Phi_0$ Magnetic flux quantum

Theory: Josephson (1962)
Experiment: Anderson and Rowell (1963)
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

• Precision metrology
  • A series of Josephson junctions provides a definition of the voltage standard through a frequency standard. Josephson voltage standard
• SQUID’s are used as very sensitive magnetometers and are widely used in science and engineering, e.g. magnetoencephalography
• Superconducting digital computing
  • Digital processors with clock frequencies up to 20 GHz have been developed
• Superconducting quantum computing
  • Flux and charge qubit’s and transmons are based on Josephson junctions
  • Large quantum computing processors (see Sycamore di Google)
• SQUID-based Parametric Amplifiers for ultrasensitive detection at the quantum & subquantum limit
  • microwave/qubit photon detectors
  • cavity-based axion detectors
  • SQUID multiplexing for large scale arrays of TES (Transition Edge Sensors) or Magnetic Calorimeters for CMB and X-ray astronomy.
• Basic Research with circuit-QED
  • Dynamical Casimir Effect (DCE): photons out of quantum vacuum
  • Generation/detection of squeezed microwave radiation and quantum optics experiments with microwaves
  • Etc.
Two Josephson junctions are connected in parallel on a superconducting loop. With no magnetic field applied the current splits equally in two branches.

With a small external magnetic field is applied to the superconducting loop, a screening current begins to circulate the loop that generates the magnetic field cancelling the applied external flux, and creates an additional Josephson phase which is proportional to this external magnetic flux.

In one branch the screening current adds to the current, in the other subtracts to the current. As soon as the current in either branch exceeds the critical current of the Josephson junction, a voltage appears across the junction.

Each junction has a self-capacitance $C$ and an added resistive shunt $R$

Provided that (I condition) $\beta_\phi = 2\pi I_0 R^2 C/\Phi_0 \leq 1$.

the I-V characteristic is non-hysteretic

II condition: $2\pi k_B T/I_0 \Phi_0 \ll 1$

*Experiment: Jaklevic, Lambe, Mercereau, and Silver (1964)*
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

- In most cases Josephson junction’s are of the **SIS type** based on aluminium oxide either with aluminium as superconductor material (Al/Al₂O₃/Al) or in combination with niobium (Nb/Al/Al₂O₃/Nb)
  - The isolator thickness is in the range of 1 nm!
- The junctions can be fabricated with standard microfabrication techniques
- Often special fabrication techniques are employed
- One is the **double angle evaporation** technique or **Dolan bridge** technique, another one is the **Manhattan** technique.
  - The Dolan bridge techniques achieves the overlapping of the two superconductors by tilting the sample between evaporations, while in the Manhattan type technique the overlapping of the evaporations is obtained by deep photoresist trenches that cross each other at 90° and the rotation of the sample.
- Passive elements of the circuits are resonators based on coplanar waveguides, interdigitated capacitors etc.

Small area Josephson Junctions, as requested by quantum applications, require normally **e-beam lithography** or can be made with **submicron optical lithography**.
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

Technology I

- Fabrication process with the Dolan bridge technique
  - Oxidation
  - Base metal deposition
  - Josephson junction formation by lift-off
    - 1° angled aluminium deposition + oxidation
    - 2° Angled aluminium deposition

- Lithography for the Dolan bridge technique
  - Lithography: a suspended bridge structure is formed in a bilayer resist with submicron lithography, either optical or e-beam.
    - First tests by using the stepper
      - Base resist: LOR, 0.470 μm thick
      - Top resist: OIR 674-9, 0.75μm thick
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

Technology II

- Practical implementation of the double angle evaporation
  - Deposition by PVD with e-gun.
  - Double angle evaporation with a tilting mechanism based on a stepper motor.
  - Oxidation by admission of pure oxygen and controlling the partial oxygen pressure and the exposure time.

$$w = 2 \left( h - \frac{g}{2 \tan \alpha} \right) \tan \alpha$$
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

Test device fabrication

- A first test layout has been designed for the stepper following the lines of P. Krantz, Investigation of transmon qubit designs - a study of plasma frequency predictability. Master thesis at Chalmers University of Technology, 2010
  - 2 x 4 arrays of single Josephson junctions and SQUIDs
    - Junction lengths range from 0.4 to 0.7 μm
    - Junction widths range from 1.0 to 2.5 μm
    - Rectangular and reduced junctions are included
  - Passive elements like capacitors and inductors
  - Actual minimum feature size for Josephson junctions: 0.40 μm
  - Actual minimum feature size for inductors and capacitors: 0.6 μm
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

.....the cross-section of the junction. High resolution TEM pictures show a ~1.5 nm thick oxide layer
RT electrical characterisation

- Room temperature characterization
  - Device resistance is obtained from I/V measurement
  - Comparison of the resistance of devices with different bridge widths allows to calculate the overlap and the junction area
  - The resistance values of the first functional devices scale with the junction area
    - $\rho$ single junctions: $542 \pm 10 \, \Omega \mu m^2$
    - $\rho$ SQUIDs: $272 \pm 4 \, \Omega \mu m^2$

\[ R_N = \frac{\rho}{A} \]
\[ O_t = \frac{\Delta w}{1 - \frac{R_w}{R_{w+\Delta w}}} \]
Fabrication technology for Josephson junctions, SQUIDs and parametric amplifiers

Low T functional testing

Functional testing and characterization at low temperature

I/V characteristics: Device cQED2 w2 D2015 SQUID Die B

\[ \Phi = \Phi_{\text{ext}} + mL_0 = (n+1/2)\Phi_0 \]

- \( 2I_L = 0.26 \text{ mA} \)
- \( V_{\text{2V}} = 720 \text{ \mu V} \)
- \( R_0/2 = 430\Omega \) (\( R_0/2_{\text{amb}} = 426.1 \Omega \))

Measured
- 156 \mu A to have 1\Phi_0
- \( V_{\text{2V}} = 360 \mu V \)
- \( I_{\text{th}} = 110 \mu V \)

Expected (T=0)
- 160 \mu A to have 1\Phi_0
- \( V_{\text{2V}} = 3.528kT/e = 380 \mu V \)
- \( I_{\text{th}} = (\pi/4) V_{\text{2V}} \tanh[3.528T/(4T)] = 300 \mu V \)
Outlook:
With the same technology in this simple form it is possible to realize Cooper box type and transmon type qubits for quantum applications SQUID based parametric amplifiers for ultrasensitive detector readout at the quantum & subquantum limit.
Quantum Photonic Technologies

Centre for Sensors and Devices

Development of integrated (quantum) photonic circuits, plasma processes for thin films growth and the synthesis, study of innovative functional materials

*Unit Head: Georg Pucker*  
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Development of advanced solid-state sensors, either using dedicated technology processes or state-of-the-art CMOS technologies, with special and fully customizable features

*Unit Head: Matteo Perenzoni*  
*perenzoni@fbk.eu*
Quantum imaging with SPAD detectors
Know-how and Expertise

Custom Detectors
• Detector TCAD simulation
  • Single-Photon Avalanche Diodes (SPAD), Silicon PhotoMultipliers (SiPM), Silicon Drift Detectors (SDD), Custom Silicon Detectors
• In-house Clean Room
  • Technology development and transfer to volume foundry
• Test and characterization
  • Electro-optical characterization of SiPM, SDD, etc.

Full Custom FBK Technology

Modeling & design

Custom production

Testing
IRIS Research Unit
Research activities

• Quantum technologies → single photon detectors
• Space applications → rad-hard SiPMs, Lidar, star-tracking sensors
• Medical Imaging → d-SiPM for particle therapy
• Surveillance → Vision sensors and embedded processing
• Science → specific detector development
• Multispectral Imaging → terahertz detectors
The enabling technology: SPAD
Enabling technology: SPAD and SiPM

• Single photon detection in silicon
  • SiPM in custom FBK technology $\rightarrow$ optimized process
  • SPAD in CMOS technology $\rightarrow$ electronics integration

Photons $\rightarrow$ digital pulses, Noise $\rightarrow$ dark count rate (DCR)
The enabling technology: SPAD

**SPAD and SiPM in custom FBK technology**

- **Position Sensitive**
  - **NUV-HD-LF**: Optimized for cryogenic applications
  - **VUV-HD**: ARC optimization for detection in VUV (~175nm)
  - **RGB-UHD**: Ultra-high density (very small cells)
  - **NIR-HD**: Thick epi-layer for improved 800-1000nm PDE

- **Electric field engineering** for green and UV response
- **High density cells with deep trench isolation**

**Timeline**
- 2012
- 2013
- 2014
- 2015

**Today**
**The enabling technology: SPAD**

**Single-photon avalanche diodes in CMOS**

- *Simulation, design, electrical and optical characterization of SPADs in standard CMOS processes*
- Tech nodes: 350nm, 180nm, 150nm, 130nm, 110nm, 65nm

Photon detection probability

<100ps single photon timing resolution

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QT-platforms@ FBK Center for S and D - 2021
The enabling technology: SPAD
Requirements for quantum sensing

High Efficiency (PDE)
- Improve fill-factor $\rightarrow$ decrease dead areas
- Improve PDP $\rightarrow$ excess bias, multiplication region

Low Noise (DCR)
- Fine tune the electric field
- Temperature: $\sim \times 10$ DCR / 20K
  - Tunneling limits performance
Cryogenic optimization of SiPMs

- Std field devices → limited by B2BT
- Low field devices → 3 orders of magnitude improvement

The enabling technology: SPAD

- c.c. cryostat at LNGS
- c.c. cryostat at FBK
Quantum imaging with SPADs
Quantum sensing experiments

- Typical experiment
  - Entangled photon source
  - Different light paths
  - Correlate clicks

- Examples
  - Superresolution imaging
  - Ghost imaging

- Example of source
  - PPKTP: phase matching in type-0 SPDC
    - Energy conservation: 1 ph @405 nm → 2 ph @~810 nm
    - Momentum conservation

- Ideal detector
  - *Time-resolved, fast, sensitive, high temporal aperture, imaging*
Quantum imaging with SPADs
224x272-pixel multifunctional SPAD imager

- **Pixel**
  - Photon counting (7bit/pixel)
  - Coarse (10ns) or fine (180ps) timestamping
  - Fast binary imaging (10ns/frame, 7 frames)

- **High sensitivity**
  - Low noise (150 cps median)
  - 12.9% fill-factor

- **High temporal aperture**
  - Up to 3 kfps (row skip)
Quantum imaging with SPADs
Experiments with time-resolved SPAD arrays

Detecting entangled photons via time coincidence

405 nm pump Non-Linear Crystal Photon pair

Integrated Intensity
Integrated anticorrelations

\[ \int G(2)(\Delta + k, \Delta - k) \, dk \]

405 nm pump
Photon pair

Imaging at the Heisenberg limit with optical centroid measurement

Rayleigh limit \( R \propto \frac{\lambda}{NA} \)
Heisenberg limit \( R \propto \frac{\lambda}{2 \, NA} \)

\( \lambda = 405 \, \text{nm} \)
\( \lambda = 810 \, \text{nm} \)
\( \lambda = 810 \, \text{nm} – \text{OCM} \)
Quantum imaging with SPADs
EU FET FastGhost – Ghost Imaging

Imaging array
CMOS
Single-photon VIS camera

Bucket detector
Superconducting Single-photon MIR detector
Quantum imaging with SPADs
Event-based SPAD array for ghost imaging

• Challenges:
  • *Correlate with bucket trigger and keep only “good” photons*
  • *Be always ready, bucket triggers asynchronously*
  • *Readout quickly, to improve time aperture*

• Concept:
  • *“back-in-time” image sensor*
Quantum imaging with SPADs

Event-based SPAD array for ghost imaging

- Event-based architecture
- Periphery time-tagging
- Fast readout: M+N for a MxN array

Simulation of a ghost imaging acquisition with 5ns correlation window

Original image  Ideal detector  Real detector  Noisy pixels off
QRNG with SPADs
EU FET Qrange: Full CMOS integration

- Generate in silicon
- Detect in silicon
- Use statistics of photons to generate random numbers
- Use multiple structures to increase the throughput
Single photon detectors @ FBK-IRIS

Conclusions & Outlook

• SPAD is an enabling technology for quantum imaging
  • Single-photon sensitivity
  • Precise timing resolution

  For each pixel in tens/hundreds of kpixels!

• Applications addressed: superresolution, ghost imaging, qrng
  • But also sub-shot noise imaging, quantum distillation, etc…

• Outlook:
  • Improving performance: PDP↑, DCR↓, smart processing
  • Smaller pixels → higher resolution while addressing speed limitations
  • New applications: e.g. quantum lidar
Development of a platform for on-chip quantum experiments
Platform for on-chip quantum experiments

- Silicon-on-Insulator SOI (thickness 250-500nm, λ > 1μm, $\chi^{(3)}$ optical nonlinearities)
- Silicon Nitride (λ > 0.3μm, from VIS to MIR, $\chi^{(3)}$ optical nonlinearities)
- Silicon Oxynitride (λ > 0.45μm, from VIS to NIR, $\chi^{(3)}$ optical nonlinearities)
- Silicon Nitride and Oxynitride circuits with integrated detector in silicon
- E-beam, Stepper and FIB for definition from micron to sub 50nm
- Ti/TiN heater technology for thermal modulation
- DRIE facet etching for IN- and OUT-coupling with fibers
- Inverse taper technology
Integrated Quantum Photonics promises to steer photonics in a direction quite orthogonal to electronic technologies. In essence, the advantage of integrated (quantum) photonics could be simply in fields still not covered by electronics (physical phenomena relaying on wave nature of particles and extremely long coherence times of uncharged particles).
Platform for on-chip quantum experiments

The project H2020 EPIQUS

Schematic view of a QS chip

Quantum chemistry  New materials  Many-body interactions

\[ \hat{H} = \sum_{n=1}^{N} \hat{T}_n + \hat{V} \]

www.epiquus.eu
Platform for on-chip quantum experiments

Nonlinear silicon oxynitride waveguides for generation of entangled photons

- Optical loss

<table>
<thead>
<tr>
<th>@ $\lambda = 850nm$</th>
<th>SiON</th>
<th>SiNx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation loss</td>
<td>$(1.6 \pm 0.1)$ dB/cm</td>
<td>$(2.2 \pm 0.2)$ dB/cm</td>
</tr>
<tr>
<td>Insertion loss</td>
<td>$(2.5 \pm 0.8)$ dB</td>
<td>$(12.0 \pm 0.7)$ dB</td>
</tr>
<tr>
<td>Bend loss</td>
<td>$(0.11 \pm 0.03)$ dB/90°</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Platform for on-chip quantum experiments

Nonlinear silicon oxynitride waveguides for generation of entangled photons

- Self-Phase-Modulation
  - Spectral analysis

- Self-Phase-Modulation
  - Nonlinear Kerr parameter

### Broadening of laser puls for different pump power, data courtesy of UniTN

**Experimental data**

<table>
<thead>
<tr>
<th>$w_g$</th>
<th>$w_gL$</th>
<th>$n_2(780nm)$</th>
<th>$n_2(840nm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 μm</td>
<td>27 mm</td>
<td>13.1 ± 0.5</td>
<td>5.7 ± 0.4</td>
</tr>
<tr>
<td>1.1 μm</td>
<td>37 mm</td>
<td>13.5 ± 0.5</td>
<td>5.0 ± 0.4</td>
</tr>
<tr>
<td>1.3 μm</td>
<td>27 mm</td>
<td>12.3 ± 0.7</td>
<td>5.8 ± 0.5</td>
</tr>
<tr>
<td>1.3 μm</td>
<td>37 mm</td>
<td>13.5 ± 0.7</td>
<td>5.6 ± 0.5</td>
</tr>
</tbody>
</table>

\[ n_2 = 10^{-20} \text{ m}^2/\text{W} \]

**References**

Platform for on-chip quantum experiments

Integration of PIN diode in optical platform

Fig. 1. (a) Sketch of the coupling method and numerical simulations.

We have estimated 4.84 dB of insertion and 1.54 dB/cm of propagation losses at a wavelength of 850 nm. External quantum efficiency of 12.7% (target 20-24%).

IV-curves at different input optical powers. (inset) PD current as a function of the optical power. The optical image shows the trace of the waveguide and the PD region under operation. Note the weaker scattering from the tapered waveguide, when approaching the PD.

Integrated SPAD brand new measurements
Thank you