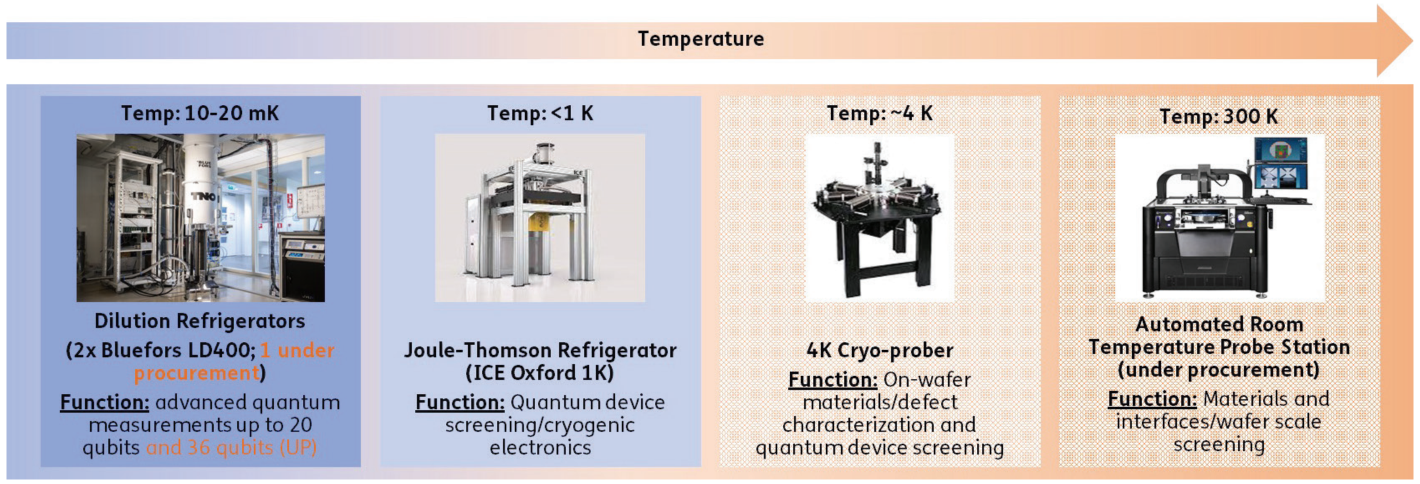
Facilities

State-of-the-art cleanrooms
TNO's Van Leeuwenhoek Laboratory (VLL) in Delft is a 3000m² cleanroom (ISO-class 5) for more customised device fabrication with state-of-the-art equipment feeding into many quantum technology roadmaps (spin qubit, superconducting qubit, topological qubit, diamond-based devices, etc.). The Else Kooi Laboratory (EKL) cleanroom is more geared towards batch processing of 100 mm wafers for MEMS and active CMOS devices.

Quantum Information Technology Testing (QITT) facility
The QITT facility enables qubit characterisation, high-throughput device and electrical component screening, material and defect characterisation that influences qubit performance, as well as material and defect characterisation at room temperature. This array of systems allows us to integrate or test devices, subsystems and full systems.


Van Leeuwenhoek Laboratory (VLL)


Else Kooi Lab (EKL)



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Quantum technology in development | TNO

QITT: Independent Quantum Technology Testing | TNO

TNO innovation for life

Your partner for quantum device development

TNO innovation for life

A name you can trust

Since 1932, TNO has been the independent link between academic investigation and real-world application. Our work focuses exclusively on developing the technologies, systems and applications that demonstrate a direct benefit to partner competitiveness and to society as a whole.

Our unique position as a Research and Technology Organisation (RTO) enables us to work at the cutting edge of the most revolutionary technologies, while remaining focused on their practical application and direct impact on Dutch and European society and economies.

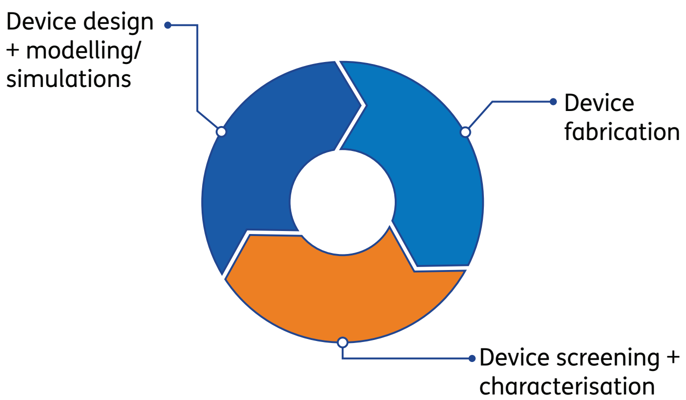
Quality materials, state-of-the-art chip design and precision fabrication are some of the key performance indicators for quantum device performance and associated useful deployment of quantum technologies. Quantum states are fragile and may lose their state due to decoherence caused by a noisy environment. Therefore, in addition to the growth of low-defect and low-disorder materials and reliable device fabrication, in-depth material and device characterisation is imperative.

TNO takes a multi-faceted approach to developing quantum devices. We not only focus on further improving our state-of-the-art quantum device fabrication protocols, but also perform in-depth device characterisation and metrology. This enables TNO to better understand device fabrication yield, reproducibility, and other device parameters so that the information from device characterisation can be fed into device fabrication and designing protocols.

Our cleanrooms house state-of-the-art equipment for material etching and deposition, lithography and material growth, as well as for material characterisation and metrology. In particular, we specialise in the nanofabrication of Si/Ge quantum dot devices, superconducting/semiconducting hybrid devices, superconducting quantum devices, as well as devices based on color centers in diamond for applications related to quantum computing, quantum internet, and quantum sensing.

Market offerings and propositions

- Modelling/simulation of quantum device and chip design (spin qubit devices and superconducting quantum devices)
- On-demand fabrication of Si/Ge quantum dot devices, quantum devices in diamond, hybrid Al/III-V devices, and superconducting quantum devices (TWPA, SQUIDs, Josephson junctions and fluxonium qubits)
- Material inspection using optical microscopy, AFM, SEM, EDX spectroscopy, Raman and PL spectroscopy, ellipsometry, XPS
- Characterisation of semiconducting spin qubit, superconducting devices and diamond devices at cryogenic temperatures
- In-depth material characterisation including AlOx/Si interface, defect characterisation, dielectric properties, metal resistivity at both RT and 4K temperatures
- Consulting services for on-demand development of specific quantum device prototypes and advanced fabrication and device and/or material characterisation



Tno capabilities

In-depth device modelling

Modelling and simulation play a critical role in understanding quantum devices and optimising their performance. At TNO, we investigate the relationship between design and intrinsic device parameters by conducting high-frequency simulations. Our experience includes modelling superconducting resonators for sensing and readout, parametric amplifiers (e.g., JPAs, TWPAs), superconducting near-field antennas, SQUIDs, transmon qubits, spin qubit systems, and micromagnetic simulation. These simulations, combined with experimental device characterisation in our facilities, help us make conscious design refinements and boost their performance.

Simulation software proficiency:

- Finite Element Method (FEM) simulations:
  - Ansys HFSS (stand-alone and with Qiskit Metal)
  - PathWave ADS
  - CST Studio Suite

- Josephson junction-focused simulation software:
  - Inductex (Circuit Parameter Extraction)
  - JoSim (Analogue Circuit Simulator)

On-demand device fabrication

Quantum devices are at the heart of performant quantum systems. TNO develops prototypes of quantum devices by closing the feedback loop between device design, device fabrication, and device characterisation. To supplement that, we perform in-depth material investigation to evaluate the 'physical' quality of quantum devices.

- Material characterisation (AFM, SEM, EDX spectroscopy, Raman and PL spectroscopy, ellipsometry, XPS and XRD)
- Material etching (dry and wet) and deposition (PVD, CVD, PECVD, ALD)
- Lithography (optical and electron beam)

Extensive quantum chip characterisation

Semiconducting spin qubits

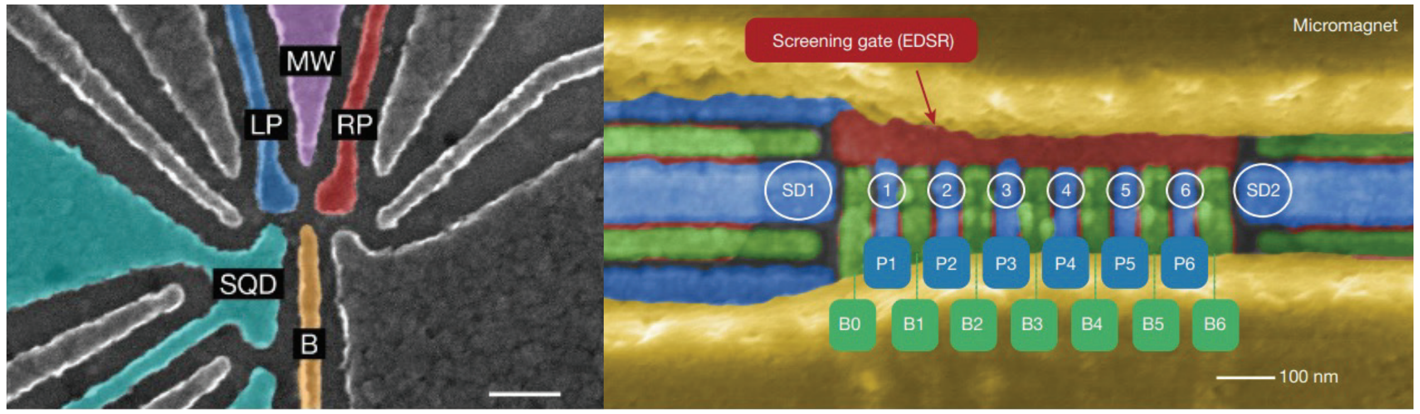
- 72 DC lines for gate voltage applications
- 10-400 MHz reflectometry for SET charge sensing et al.
- leakage measurements, DC transport
- 1-axis 3T magnet
- SET charge sensing, measurement of charge noise
- simultaneous baseband pulses on 22 gates, 2 MW line, 1 reflectometry
- multiplexing with cryogenic and room-temperature microwave switches
- manual dot tuning

Superconducting resonators

- device diagnosis through S-parameters: resonance frequency, quality factors, measurement of resonator properties versus magnetic field and temperature
- consulting services for device modelling/simulation

Superconducting qubits (transmons)

- device diagnosis through S-parameters
- characterisation of up to 20 individually-driven transmons current biasing of all 20 qubits simultaneously possible
- qubit parameter characterisation (frequency, T1, T2*, T2echo)
- qubit-qubit coupling, directly via fixed or tunable coupler
- flux-controlled CZ gate for nearest-neighbour pairs (planned expansion)
- measurements with a parametric amplifier (possible future expansion)
- consulting services for device modelling/simulation



Spin qubit quantum dot devices fabricated and validated at TNO.

Superconducting low-noise amplifiers (TWPAs)

- full S-matrix parameter characterisation (cryogenic SOLT calibration)
- amplification factor and bandwidth characterisation
- noise temperature measured using a reference noise source
- quantum efficiency measurements
- consulting services for device modelling/simulations

Color center in diamonds (primarily NV-based)

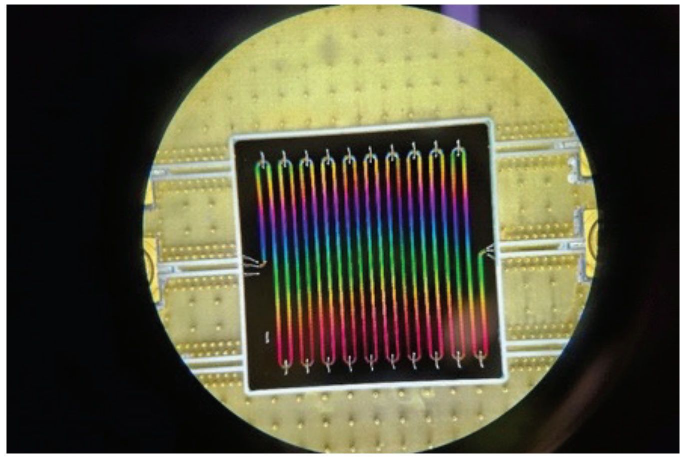
- Confocal NV characterisation - localising, screening, and characterising NVs in diamond
- Accurate 3D locating of NVs, density approximation, NV orientation in crystal lattice, photon count-rate under excitation saturation
- ESR, T1, T2*, G2 characterisation with external microwave application

- High degree of automation → short measurement-round times
- Characterisation of single color centers: single-shot readout (SSRO) characterisation including Rabi measurements

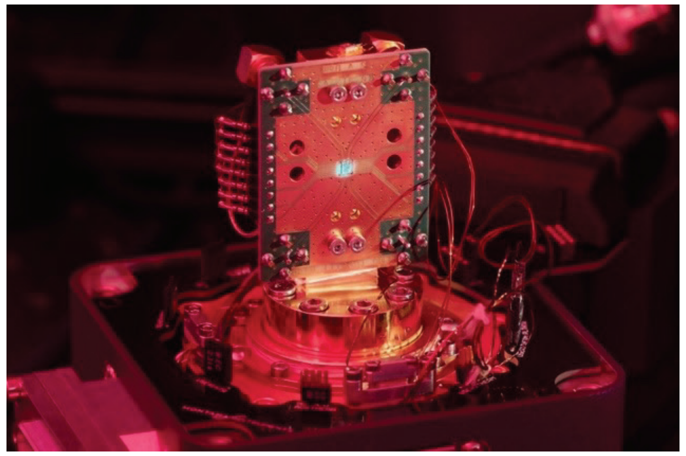
Testing of microwave components

Verification of operation at temperatures outside of the temperature range guaranteed by manufacturer

- Characterisation of microwave components in 0.1-18 GHz range using prototype SOLR calibration standards



Superconducting TWPA designed, fabricated and chartcterised by TNO.



NV center SIL devices designed, fabricated and validated at TNO, employed in optical systems in collaboration with Fraunhofer ILT.

Materials and interfaces

Material research and in-depth understanding of material defects (e.g., quality of a gate oxide and gate oxide/ semiconductor interface or homogeneity of dangling bonds on crystalline surfaces) is crucial for improved chip design. Furthermore, spin qubit devices may be improved by addressing material challenges, such as the influence of:

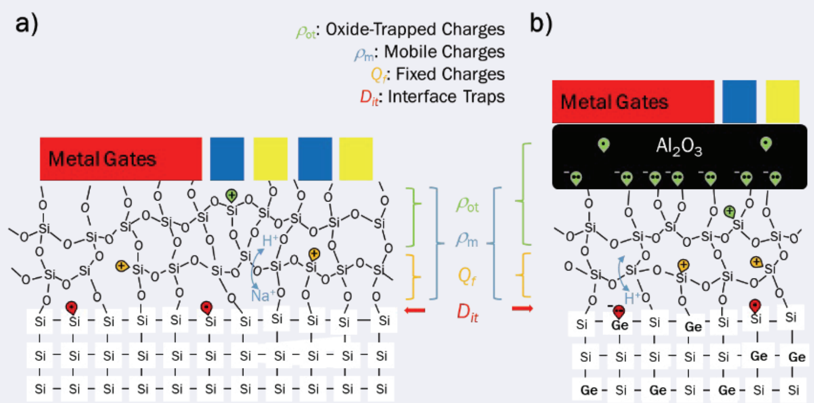
- interconnect fanout on qubit heating
- defects in dielectrics and gate oxides on device drift, jumps, and charge noise
- fabrication processing on materials properties

TNO conducts in-depth metrology of material properties that may influence electronic device performance. This includes metal resistivity characterisation, bulk dielectric property analysis, and gate oxide defect characterisation (CV, GV, IV, and semiconductor physics modelling).

We also provide consultancy on the proper test structure design to obtain material properties of interest with minimal artefacts from stray capacitances and resistances.

We have extensive experience in designing and fabricating test structures for materials analysis, proper measurement techniques to avoid stray artefacts and reduce noise, and fitting of experimental data to various materials-based models.

- CRX-4K cryogenic probe station with:
  - Integrated M81 containing 6 separate voltage or current source or measure modules
  - Permanent magnet set with 4 magnets delivering vertical magnetic fields up to 190 mT
  - 6 probe arms for DC/AC with CVT tips for continuous electrical contact over a temperature range of 150 K
  - GSG RF probes with 100 µm pitch for delivering frequencies up to 40 GHz
  - 4 arms supporting multi-contact wedges (tips containing up to 14 probe needles would need to be specified and built)
- Measurement equipment:
  - B1500A: 4 MPSMUs and a MFCMU module for CV measurements
  - E4980A: LCR



Various material charge defects at dielectric/ semiconductor interface that electrically influence qubit performance.