The physics of nanowire superconducting single-photon detectors

Renema, J.J.

Citation

Renema, J. J. (2015, March 5). *The physics of nanowire superconducting single-photon detectors*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/32149

Author: Renema, Jelmer Jan
Title: The physics of nanowire superconducting single-photon detectors
Issue Date: 2015-03-05

Acknowledgements

Science is at heart a collective endeavour, so a sincere thanks to all who made this work possible is in order. First, I thank those who were involved in the supervision of my PhD project: Martin van Exter, Andrea Fiore and Dirk Bouwmeester. I thank my colleagues on the SSPD work: Michiel de Dood and Qiang Wang. Michiel has had a huge if informal guiding role during the last four years. I thank Qiang for the FDTD simulations which are a vital element in Chapter 5 of this thesis, and for many scientific discussions. I thank my students - Shawn Levie, Chris Lemmens, Marc van Kralingen, Bob Rengelink and Irina Komen, who all contributed to the content of this thesis. Marc, Bob and Irina worked on the challenging magnetic field experiments presented in Chapter 6.

When I started this project, I knew next to nothing about superconductivity. I thank Peter Kes, Jan Aarts, Andreas Engel, Denis Vodolazov and Eduard Driessen for filling that gap. I would in particular like to thank Andreas for scientific discussions on his numerical model and SSPD physics in general. I thank Richard Gill for scientific discussions about the statistical methods used in this thesis. I thank Michael Furtado for proofreading the manuscript of this thesis.

I thank the people from the PSN group in Eindhoven. In particular, I am indebted to Rosalinda Gaudio for producing the majority of samples on which the work in this thesis was done, and to Giulia Frucci for teaching me how to work with SSPDs. Furthermore, I thank Saeedeh Jahanmirinejad, Zili Zhou and Döndü Sahin for sample fabrication and many useful discussions. I thank Alessandro Gaggero, Francesco Mattioli and Roberto Leoni from CNR-IFN Rome for sample fabrication and scientific discussions.

The excellent support at LION is one of the things that makes it such a good place for science. I thank Henriette van Leeuwen, Marcel Hesselberth, Arno van Amersfoort, Rene Overgauw, Raymond Koehler, Emiel Wiegers, Fred Schenkel and Jeroen Mesman. I thank Daan Boltje in particular, whose last-minute wirebonding saved valuable measurement time on more than one occasion. I thank Doreen Wernicke from Entropy GmbH.

Finally, I would like to thank Vera, for being a constant support. Without her, this thesis would not have been possible.

Curriculum Vitae

Jelmer Renema was born on the 4th of July 1986 in Hoogeveen. He graduated from Groene Hart Lyceum secondary school in 2003 with a specialization in science and technology and went on to study physics at Leiden University. Jelmer obtained a BSc from that university; the final project was *Surface plasmon spectroscopy.* He then went on to do an MSc at Leiden University, with two projects: *Two-photon interference on Young's double slit* and *Magnetometry and entanglement with room-temperature caesium atoms.* After a year at the Niels Bohr Institute working on cold atomic ensembles he returned to Leiden to work on superconducting single-photon detectors in the group of Dirk Bouwmeester.

List of Publications

1. W.H. Peeters, J.J. Renema, M.P. van Exter *Engineering of two-photon spatial quantum correlations behind a double slit* Phys. Rev. A **79** (4), 043817 (2009)

2. W. Wasilewski, K. Jensen, H. Krauter, J.J. Renema, M.V. Balabas, E.S. Polzik *Quantum noise limited and entanglement-assisted magnetometry* Phys. Rev. Lett. **104** (13), 133601 (2010)

3. A. Louchet-Chauvet, J. Appel, J.J. Renema, D. Oblak, N. Kjaergaard, E.S. Polzik *Entanglement-assisted atomic clock beyond the projection noise limit* New J. Phys. **12** (6), 065032 (2010)

4. J.J. Renema, G. Frucci, Z. Zhou, F. Mattioli, A. Gaggero, R. Leoni, M.J.A. de Dood, A. Fiore, M.P. van Exter *Modified detector tomography technique applied to a superconducting multiphoton nanodetector* Opt. Exp. **20** (3), 2806-2813 (2012) (Chapter 2 of this thesis)

5. A.J.H. van der Torren, S.C. Yorulmaz, J.J. Renema, M.P. van Exter, M.J.A. de Dood *Spatially entangled four-photon states from a periodically poled potassium-titanyl-phosphate crystal* Phys. Rev. A **85** (4), 043837 (2012)

6. J.J. Renema, G. Frucci, M.J.A. de Dood, R. Gill, A. Fiore, M.P. van Exter *Tomography and state reconstruction with superconducting single-photon detectors* Phys. Rev. A **86** (6), 062113 (2013)

7. J.J. Renema, G. Frucci, Z. Zhou, F. Mattioli, A. Gaggero, R. Leoni, M.J.A. de Dood, A. Fiore, M.P. van Exter *Universal response curve for nanowire superconducting single-photon detectors* Phys. Rev. B **87** (17), 174526 (2013) (Chapter 3 of this thesis)

8. J.J. Renema, R. Gaudio, Q. Wang, Z. Zhou, A. Gaggero, F. Mattioli, R. Leoni, D. Sahin, M.J.A. de Dood, A. Fiore, M.P. van Exter *Experimental Test of Theories of the Detection Mechanism in a Nanowire Superconducting Single-Photon Detector* Phys. Rev. Lett. **112** (11), 117604 (2014) (Chapter 4 of this thesis)

9. J.J. Renema, R.J. Rengelink, I. Komen, Q. Wang, R. Gaudio, K.P.M. op 't Hoog, Z. Zhou, D. Sahin, A. Fiore, P. Kes, J. Aarts, M.P. van Exter, M.J.A. de Dood, and E.F.C. Driessen, *The Magnetic Field Response of Nanowire Superconducting Single-Photon Detectors* Submitted to Applied Physics Letters (Chapter 6 of this thesis)

List of Symbols and Material Parameters

Symbol	Name	Value/expression	Reference
A(x)	Local absorption probability	-	-
B	Magnetic field	-	-
B_0	Field scale	350 mT	-
B_Γ	Usadel field scale	$\sqrt{6}\hbar/ew\xi = 2.7$ T	[a]
χ^2	Goodness of fit	$\chi^2 = \sum_i \frac{(y_{i,exp}-y_{i,fit})^2}{\sigma_i^2}$	-
c	Speed of light	$3.00 * 10^8$m/s	-
C	Photon count rate	-	-
C_e	Hot electron density	-	-
C_{qp}	Quasiparticle density	-	-
c_i	Expansion coefficient	$c_i = e^{-N}\frac{N^i}{i!}$	[b]
d	Thickness	4.9 nm	-
D	Diffusion constant	0.4 cm^2/s	-
Δ	Superconducting gap	1.9 meV @ 1.5 K	-
ε_0	Vortex entry energy	$\Phi^2/2\pi\mu_0\Lambda_\perp = 67.6$ meV	[25]
ϵ	Dielectric constant	-	-
E	Excitation energy	-	-
Φ_0	Elementary flux quantum	$h/2e = 2.067$ fWb	-
γ	Energy-current interchange	2.9μA/eV	[a]
$\gamma'(x)$	Local value of γ	-	-
Γ	Intrinsic pair breaker	≈ 100 μeV	-
η	Linear optical efficiency	-	-
h	Planck's constant	4.14 feV s	-

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[a] For a 150 nm wide detector

[b] For coherent states

Symbol	Name	Value/expression	Reference
I_b	Bias current	-	-
I_c	Critical current	28 μA	[a]
I_0	Reference current	$I_0 \approx 0.8 I_c$	[b]
I_{th}	Threshold current	$I_{th} = I_c - \gamma E$	-
I_Γ	Usadel current scale	$\sqrt{2}\Delta/eR(\xi) = 180\ \mu$A	[a]
j	Current density	-	-
j_c	Critical current density	40 GA/m^2	-
$j^\star$	Rolloff current density	0.9 GA/m^2	-
k_b	Boltzman constant	$8.6 * 10^{-5}$eV/K	-
λ	Penetration length	430 nm, 500 nm	[28, 21]
λ	Optical wavelength	-	-
λ_c	Cutoff wavelength	-	-
$\Lambda_\perp$	Effective penetration length	50 μm	-
L	Wire length	-	-
l_{taper}	Taper effective length	74 nm	-
μ_0	Magnetic permeability of vacuum	$4\pi * 10^{-7}$N/A^2	-
n_{max}	Model selection cutoff	-	-
n_{se}	Density of supercond. electrons	-	-
N_0	Density of states	51 nm^3/eV	[28]
N	Mean photon number	-	-
ν_h	Reduced vortex entry energy	3-8, 40-110	[25, 26][c]
ν	Vortex entry energy	$\varepsilon_0/k_b T = 250$	[25]
ν	Photon energy	-	-
p_n	Internal detection probability	-	-
$P(x)$	Local detection probability	-	-
ς	QP conversion efficiency	0.25	[28]
R	Detection probability per pulse	-	-
$R_\square$	Sheet resistance	600 Ω	-
s	Hotspot size	22 nm	-
t	Reduced temperature	T/T_c	-
T	Temperature	-	-
T$_c$	Critical temperature	9.5 K	-
τ	Timescale for QP multiplication	1.6 ps	[28]
v_s	Supercond. velocity	-	-
v_c	Critical velocity	-	-
V	Visibility	-	-
w	Wire width	-	-
ξ	Coherence length	3.9 nm	-

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[a] For a 150 nm wide detector

[b] For low threshold values

[c] For photon counts and dark counts, respectively

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