The physics of nanowire superconducting single-photon detectors

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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	-

[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	-	-
$R_\Box$	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	-

[a] For a 150 nm wide detector
[b] For low threshold values
[c] For photon counts and dark counts, respectively

Bibliography

[1] G. N. Goltsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, "Picosecond superconducting single-photon optical detector," *Appl. Phys. Lett.*, vol. 79, no. 6, p. 705, 2001.

[2] M. Eisaman, J. Fan, A. Migdall, and S. Polyakov, "Single-photon sources and detectors," *Rev. Sci. Instrum.*, vol. 82, p. 071101, 2011.

[3] C. Natarajan, M. Tanner, and R. Hadfield, "Superconducting nanowire single-photon detectors: physics and applications," *Supercond. Sci. Technol*, vol. 25, no. 6, p. 063001, 2012.

[4] F. Marsili, F. Najafi, E. Dauler, F. Bellei, X. Hu, M. Csete, R. Molnar, and K. Berggren, "Single-photon detectors based on ultranarrow superconducting nanowires," *Nano Lett.*, vol. 11, p. 2048, 2011.

[5] R. Collins, R. Hadfield, V. Fernandez, S. Nam, and G. Buller, "Low timing jitter detector for gigahertz quantum key distribution," *Electron. Lett.*, vol. 43, no. 3, p. 180, 2007.

[6] D. M. Boroson, J. J. Scozzafava, D. V. Murphy, and B. S. Robinson, "The Lunar Laser Communications Demonstration (LLCD)," *2009 Third IEEE International Conference on Space Mission Challenges for Information Technology*, no. Llcd, pp. 23–28, 2009.

[7] K. M. Rosfjord, J. K. W. Yang, E. A. Dauler, A. J. Kerman, V. Anant, B. M. Voronov, G. N. Goltsman, and K. K. Berggren, "Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating." *Opt. Express*, vol. 14, no. 2, pp. 527–34, 2006.

[8] M. Hofherr, D. Rall, K. Il'in, M. Siegel, A. Semenov, H.-W. Hübers, and N. A. Gippius, "Intrinsic detection efficiency of superconducting nanowire single-photon detectors with different thicknesses," *J. Appl. Phys.*, vol. 108, no. 1, p. 014507, 2010.

[9] A. J. Kerman, E. A. Dauler, W. E. Keicher, J. K. W. Yang, K. K. Berggren, G. Goltsman, and B. Voronov, "Kinetic-inductance-limited

reset time of superconducting nanowire photon counters," *Appl. Phys. Lett.*, vol. 88, no. 11, p. 111116, 2006.

[10] V. Anant, A. J. Kerman, E. A. Dauler, K. W. Joel, K. M. Rosfjord, and K. K. Berggren, "Optical properties of superconducting nanowire single-photon detectors," *Opt. Express*, vol. 16, no. 14, pp. 46–52, 2008.

[11] E. F. C. Driessen, F. Braakman, E. Reiger, S. Dorenbos, V. Zwiller, and M. J. A. de Dood, "Impedance model for the polarization-dependent optical absorption of superconducting single-photon detectors," *Eur. Phys. J. Appl. Phys.*, vol. 47, p. 10701, 2009.

[12] E. Driessen and M. de Dood, "The perfect absorber," *Appl. Phys. Lett.*, vol. 94, p. 171109, 2009.

[13] V. Verma, F. Marsili, S. Harrington, A. Lita, R. Mirin, and S. Nam, "A three-dimensional, polarization-insensitive superconducting nanowire avalanche photodetector," *Appl. Phys. Lett.*, vol. 101, p. 251114, 2012.

[14] J. Kitaygorsky, "Photon and dark counts in NbN superconducting single-photon detectors and nanostripes," Ph.D. dissertation, University of Rochester, 2008.

[15] A. Semenov, G. Goltsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica C*, vol. 351, pp. 349–356, 2001.

[16] R. Lusche, A. Semenov, K. Il'in, M. Siegel, Y. Korneeva, A. Trifonov, A. Korneev, G. Goltsman, D. Vodolazov, and H.-W. Hübers, "Effect of the wire width on the intrinsic detection efficiency of superconducting-nanowire single-photon detectors," *J. Appl. Phys.*, vol. 116, no. 4, 2014.

[17] J. J. Renema, R. Gaudio, Q. Wang, Z. Zhou, A. Gaggero, F. Mattioli, R. Leoni, D. Sahin, M. J. A. de Dood, A. Fiore, and M. P. van Exter, "Experimental test of theories of the detection mechanism in a nanowire superconducting single photon detector," *Phys. Rev. Lett.*, vol. 112, p. 117604, 2014.

[18] A. Semenov, A. Engel, H.-W. Hübers, K. Il'in, and M. Siegel, "Spectral cut-off in the efficiency of the resistive state formation caused by absorption of a single-photon in current-carrying superconducting nano-strips," *Euro. Phys. J. B*, vol. 47, no. 4, pp. 495–501, 2005.

[19] A. Abrikosov, "Size effect on the critical field of superconductors of the second group," *Dokl. Akad. Nauk. SSSR*, vol. 86, p. 489, 1952.

[20] A. Engel, A. Aeschbacher, K. Inderbitzin, A. Schilling, K. Il'in, M. Hofherr, M. Siegel, A. Semenov, and H.-W. Hübers, "Tantalum nitride superconducting single-photon detectors with low cut-off energy," *Appl. Phys. Lett.*, vol. 100, no. 6, p. 062601, 2012.

[21] A. Kamlapure, M. Mondal, M. Chand, A. Mishra, J. Jesudasan, V. Bagwe, L. Benfatto, V. Tripathi, and P. Raychaudhuri, "Measurement of magnetic penetration depth and superconducting energy gap in very thin epitaxial NbN films," *Appl. Phys. Lett.*, vol. 96, no. 7, p. 072509, 2010.

[22] C. P. Bean and J. D. Livingston, "Surface barrier in type-II superconductors," *Phys. Rev. Lett.*, vol. 12, pp. 14–16, 1964.

[23] A. D. Semenov, P. Haas, H.-W. Hübers, K. Il'in, M. Siegel, A. Kirste, T. Schurig, and A. Engel, "Vortex-based single-photon response in nanostructured superconducting detectors," *Physica C*, vol. 468, no. 7-10, pp. 627–630, 2008.

[24] L. Bulaevskii, M. Graf, C. Batista, and V. Kogan, "Vortex-induced dissipation in narrow current-biased thin-film superconducting strips," *Phys. Rev. B*, vol. 83, no. 14, p. 144526, 2011.

[25] L. Bulaevksii, M. Graf, and V. Kogan, "Vortex-assisted photon counts and their magnetic field dependence in single-photon superconducting detectors," *Phys. Rev. B*, vol. 85, p. 014505, 2012.

[26] R. Lusche, A. Semenov, Y. Korneeva, A. Trifonof, A. Korneev, G. Goltsman, and H. Hübers, "Effect of magnetic field on the photon detection in thin superconducting meander structures," *Phys. Rev. B*, vol. 89, p. 104513, 2014.

[27] R. Lusche, A. Semenov, H. W. Huebers, K. Ilin, M. Siegel, Y. Korneeva, A. Trifonov, A. Korneev, G. Goltsman, and D. Vodolazov, "Effect of the wire width on the intrinsic detection efficiency of superconducting-nanowire single-photon detectors," *arXiv:1303.4546*, 2013.

[28] A. Engel and A. Schilling, "Numerical analysis of detection-mechanism models of superconducting nanowire single-photon detector," *J. Appl. Phys.*, vol. 114, no. 21, 2013.

[29] J. R. Clem and K. K. Berggren, "Geometry-dependent critical currents in superconducting nanocircuits," *Phys. Rev. B*, vol. 84, p. 174510, 2011.

[30] D. Henrich, P. Reichensperger, M. Hofherr, J. Meckbach, K. Il'in, M. Siegel, A. Semenov, A. Zotova, and D. Y. Vodolazov, "Geometry-induced reduction of the critical current in superconducting nanowires," *Phys. Rev. B*, vol. 86, p. 144505, 2012.

[31] H. L. Hortensius, E. F. C. Driessen, T. Klapwijk, K. Berggren, and J. Clem, "Critical-current reduction in thin superconducting wires due to current crowding," *Appl. Phys. Lett.*, vol. 100, p. 182602, 2012.

[32] A. Engel, J. Lonsky, X. Zhang, and A. Schilling, "Detection mechanism in SNSPD: Numerical results of a conceptually simple, yet powerful detection model," *arXiv:1408.4907*, 2014.

[33] A. N. Zotova and D. Y. Vodolazov, "Photon detection by current-carrying superconducting film: A time-dependent Ginzburg-Landau approach," *Phys. Rev. B*, vol. 85, p. 024509, 2012.

[34] A. Zotova and D. Vodolazov, "Intrinsic detection efficiency of superconducting single photon detector in the modified hot spot model," *Supercond. Sci. Technol.*, vol. 27, p. 125001, 2014.

[35] D. Y. Vodolazov, "Current dependence of the red boundary of superconducting single-photon detectors in the modified hot-spot model," *Phys. Rev. B*, vol. 90, p. 054515, 2014.

[36] J. S. Lundeen, A. Feito, H. Coldenstrodt-Ronge, K. L. Pregnell, C. Silberhorn, T. C. Ralph, J. Eisert, M. B. Plenio, and I. A. Walmsley, "Tomography of quantum detectors," *Nat. Phys.*, vol. 5, no. 1, pp. 27–30, 2008.

[37] A. Feito, J. S. Lundeen, H. Coldenstrodt-Ronge, J. Eisert, M. B. Plenio, and I. A. Walmsley, "Measuring measurement: theory and practice," *New J. Phys.*, vol. 11, no. 9, p. 093038, 2009.

[38] L. Artiles and R. Gill, "An invitation to quantum tomography," *J. R. Stat. Soc. B*, vol. 67, no. 1, pp. 109–134, 2005.

[39] D. Bitauld, F. Marsili, A. Gaggero, F. Mattioli, R. Leoni, S. Jahanmirinejad, F. Lévy, and A. Fiore, "Nanoscale optical detector with single-photon and multiphoton sensitivity." *Nano Lett.*, vol. 10, no. 8, pp. 2977–81, 2010.

[40] Z. Zhou, G. Frucci, F. Mattioli, A. Gaggero, S. Jahanmirinejad, T. B. Hoang, and A. Fiore, *Phys. Rev. Lett.*, vol. 110, p. 133605, 2013.

[41] A. J. Kerman, E. A. Dauler, J. K. W. Yang, K. M. Rosfjord, V. Anant, K. K. Berggren, G. N. Goltsman, and B. M. Voronov, "Constriction-limited detection efficiency of superconducting nanowire single-photon detectors," *Appl. Phys. Lett.*, vol. 90, no. 10, p. 101110, 2007.

[42] A. Zotova and D. Vodolazov, "Differences in the effects of turns and constrictions on the resistive response in current-biased superconducting wire after single photon absorption," *Supercond. Sci. Technol.*, vol. 26, p. 075008, 2013.

[43] M. K. Akhlaghi, A. H. Majedi, and J. S. Lundeen, "Nonlinearity in Single Photon Detection : Modeling and Quantum Tomography," *Opt. Express*, vol. 19, pp. 21 305–21 312, 2011.

[44] M. K. Akhlaghi and A. H. Majedi, “Semiempirical Modeling of Dark Count Rate and Quantum Efficiency of Superconducting Nanowire Single-Photon Detectors,” *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 361–366, 2009.

[45] E. Knill, R. Laflamme, and G. J. Milburn, “A scheme for efficient quantum computation with linear optics.” *Nature*, vol. 409, no. 6816, pp. 46–52, 2001.

[46] I. Afek, O. Ambar, and Y. Silberberg, “High-NOON states by mixing quantum and classical light.” *Science*, vol. 328, no. 5980, pp. 879–81, 2010.

[47] A. Gaggero, S. Jahanmirinejad, F. Marsili, F. Mattioli, R. Leoni, D. Bitauld, D. Sahin, G. J. Hamhuis, R. Nötzel, R. Sanjines, and A. Fiore, “Nanowire superconducting single-photon detectors on GaAs for integrated quantum photonic applications,” *Appl. Phys. Lett.*, vol. 97, no. 15, p. 151108, 2010.

[48] J. S. Lundeen, K. L. Pregnell, A. Feito, B. J. Smith, W. Mauerer, C. Silberhorn, J. Eisert, M. B. Plenio, and I. A. Walmsley, “A proposed testbed for detector tomography,” *J. Mod. Optic.*, vol. 56, no. 2-3, 2009.

[49] G. Brida, L. Ciavarella, I. P. Degiovanni, M. Genovese, L. Lolli, G. Mingolla, F. Piacentini, M. Rajteri, E. Taralli, and M. G. A. Paris, “Full quantum characterization of superconducting photon counters,” *New J. Phys.*, vol. 14, p. 085001, 2012.

[50] T. Amri, “Quantum Behavior of Measurement Apparatus,” *arXiv:1001.3032*, 2010.

[51] A. Divochiy, F. Marsili, D. Bitauld, A. Gaggero, R. Leoni, F. Mattioli, A. Korneev, V. Seleznev, N. Kaurova, O. Minaeva, G. Goltsman, K. G. Lagoudakis, M. Benkhaoul, F. Lévy, and A. Fiore, “Superconducting nanowire photon-number-resolving detector at telecommunication wavelengths,” *Nature Photon.*, vol. 2, no. 5, pp. 302–306, 2008.

[52] O. Haderka, M. Hamar, and J. Perina, “Experimental multi-photon-resolving detector using a single avalanche photodiode,” *Eur. Phys. J. D*, vol. 28, no. 1, p. 11, 2003.

[53] P. P. Rohde, J. G. Webb, E. H. Huntington, and T. C. Ralph, “Photon number projection using non-number-resolving detectors,” *New J. Phys.*, vol. 9, no. 7, pp. 233–233, 2007.

[54] E. A. Dauler, A. J. Kerman, B. S. Robinson, J. K. W. Yang, B. Voronov, G. Goltsman, S. A. Hamilton, and K. K. Berggren, "Photon-number-resolution with sub-30-ps timing using multi-element superconducting nanowire single photon detectors," *J. Mod. Optic.*, vol. 56, no. 2, p. 13, 2008.

[55] F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, and B. Baek, "Detecting Single Infrared Photons with 93% System Efficiency," *Nature Photon.*, vol. 7, pp. 210–214, 2013.

[56] A. Verevkin, J. Zhang, R. Sobolewski, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, K. Smirnov, G. N. Goltsman, and A. Semenov, "Detection efficiency of large-active-area NbN single-photon superconducting detectors in the ultraviolet to near-infrared range," *Appl. Phys. Lett.*, vol. 80, no. 25, p. 4687, 2002.

[57] M. J. Stevens, B. Baek, E. A. Dauler, A. J. Kerman, R. J. Molnar, S. A. Hamilton, K. K. Berggren, R. P. Mirin, and S. W. Nam, "High-order temporal coherences of chaotic and laser light." *Opt. Express*, vol. 18, no. 2, pp. 1430–7, 2010.

[58] C. Zinoni, B. Alloing, L. H. Li, F. Marsili, A. Fiore, L. Lunghi, A. Gerardino, Y. B. Vakhtomin, K. V. Smirnov, and G. N. Goltsman, "Single-photon experiments at telecommunication wavelengths using nanowire superconducting detectors," *Appl. Phys. Lett.*, vol. 91, no. 3, p. 031106, 2007.

[59] M. Halder, A. Beveratos, M. Gisin, V. Scarani, C. Simon, and H. Zbinden, "Entangling independent photons by time measurement," *Nat. Phys.*, vol. 3, pp. 692–695, 2007.

[60] J. J. Renema, G. Frucci, M. J. A. de Dood, R. Gill, A. Fiore, and M. P. van Exter, "Tomography and state reconstruction with superconducting single-photon detectors," *Phys. Rev. A*, vol. 86, p. 062113, 2012.

[61] R. H. Hadfield, J. L. Habif, J. Schlafer, R. E. Schwall, and S. W. Nam, "Quantum key distribution at 1550 nm with twin superconducting single-photon detectors," *Appl. Phys. Lett.*, vol. 89, no. 24, p. 241129, 2006.

[62] N. Mohan, O. Minaeva, G. N. Goltsman, M. B. Nasr, B. E. Saleh, A. V. Sergienko, and M. C. Teich, "Photon-counting optical coherence-domain reflectometry using superconducting single-photon detectors." *Opt. Express*, vol. 16, no. 22, pp. 18 118–30, 2008.

[63] S. N. Dorenbos, E. M. Reiger, U. Perinetti, V. Zwiller, T. Zijlstra, and T. M. Klapwijk, "Low noise superconducting single photon detectors on silicon," *Appl. Phys. Lett.*, vol. 93, no. 13, p. 131101, 2008.

[64] A. Annunziata, D. Santavicca, J. Chudow, L. Frunzio, M. Rooks, A. Frydman, and D. Prober, "Niobium Superconducting Nanowire Single-Photon Detectors," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 327–331, 2009.

[65] F. Mattioli, M. Ejrnaes, A. Gaggero, A. Casaburi, R. Cristiano, S. Pagano, and R. Leoni, "Large area single photon detectors based on parallel configuration NbN nanowires," *J. Vac. Sci. Technol.*, vol. 30, no. 031204, 2012.

[66] J. Zhang, W. Slysz, A. Pearlman, A. Verevkin, R. Sobolewski, O. Okunev, G. Chulkova, and G. Goltsman, "Time delay of resistive-state formation in superconducting stripes excited by single optical photons," *Phys. Rev. B*, vol. 67, no. 13, p. 132508, 2003.

[67] J. J. Renema, G. Frucci, Z. Zhou, F. Mattioli, A. Gaggero, R. Leoni, M. J. A. d. Dood, A. Fiore, and M. P. van Exter, "Modified detector tomography technique applied to a superconducting multiphoton nanodetector," *Opt. Express*, vol. 20, no. 3, pp. 2806–2813, 2012.

[68] K. Il'in, M. Lindgren, M. Currie, A. Semenov, G. Goltsman, R. Sobolevski, S. Cherednichenko, and E. Gershenzon, "Picosecond hot-electron energy relaxation in NbN superconducting photodetectors," *Appl. Phys. Lett.*, vol. 76, p. 2752, 2000.

[69] D. Rall, P. Probst, M. Hofherr, S. Wünsch, K. Il'in, U. Lemmer, and M. Siegel, "Energy relaxation time in NbN and YBCO thin films under optical irradiation," *J. Phys.: Conference Series*, vol. 234, no. 4, p. 042029, 2010.

[70] A. Gurevich and V. Vinokur, "Comment on: Vortex-assisted photon counts and their magnetic field dependence in single-photon superconducting detectors," *Phys. Rev. B*, vol. 86, no. 2, p. 026501, 2012.

[71] A. Gurevich and V. Vinokur., "Size Effects in the Nonlinear Resistance and Flux Creep in a Virtual Berezinskii-Kosterlitz-Thouless State of Superconducting Films," *Phys. Rev. Lett.*, vol. 100, no. 22, p. 227007, 2008.

[72] J. J. Renema, G. Frucci, Z. Zhou, F. Mattioli, A. Gaggero, R. Leoni, M. J. A. de Dood, A. Fiore, and M. P. van Exter, "Universal response curve for nanowire superconducting single-photon detectors," *Phys. Rev. B*, vol. 87, p. 174526, 2013.

[73] A. Engel, K. Inderbitzin, A. Schilling, R. Lusche, A. Semenov, D. Henrich, M. Hofherr, K. Il'in, and M. Siegel, "Temperature-dependence of detection efficiency in NbN and TaN SNSPD," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, p. 2300505, 2013.

[74] D. Y. Vodolazov, "Saddle point states in two-dimensional superconducting films biased near the depairing current," *Phys. Rev. B.*, vol. 85, p. 174507, 2012.

[75] K. Suzuki, S. Shiki, M. Ukibe, M. Koike, S. Miki, Z. Wang, and M. Ohkubo, "Hot-Spot Detection Model in Superconducting Nano-Stripline Detector for keV Ions," *Appl. Phys. Expr.*, vol. 4, no. 8, p. 083101, 2011.

[76] A. Verevkin, A. Pearlman, W. Slysz, J. Zhang, M. Currie, A. Korneev, G. Chulkova, O. Okunev, P. Kouminov, K. Smirnov, B. Voronov, G. Goltsman, and R. Sobolewski, "Ultrafast superconducting single-photon detectors for near-infrared-wavelength quantum communications," *J. Mod. Optic.*, vol. 51, no. 9-10, pp. 1447–1458, 2004.

[77] T. Yamashita, S. Miki, W. Qiu, M. Fujiwara, M. Sasaki, and Z. Wang, "Temperature Dependent Performances of Superconducting Nanowire Single-Photon Detectors in an Ultralow-Temperature Region," *Appl. Phys. Expr.*, vol. 3, no. 10, p. 102502, 2010.

[78] H. Bartolf, A. Engel, A. Schilling, K. Il'in, M. Siegel, H.-W. Hübers, and A. Semenov, "Current-assisted thermally activated flux liberation in ultrathin nanopatterned NbN superconducting meander structures," *Phys. Rev. B*, vol. 81, p. 024502, 2010.

[79] A. Korneev, P. Kouminov, V. Matvienko, G. Chulkova, K. Smirnov, B. Voronov, G. N. Goltsman, M. Currie, W. Lo, K. Wilsher, J. Zhang, W. Slysz, A. Pearlman, A. Verevkin, and R. Sobolewski, "Sensitivity and gigahertz counting performance of NbN superconducting single-photon detectors," *Appl. Phys. Lett.*, vol. 84, no. 26, p. 5338, 2004.

[80] A. Korneev, V. Matvienko, O. Minaeva, I. Milnostnaya, I. Rubtsova, G. Chulkova, K. Smirnov, V. Voronov, G. Goltsman, W. Slysz, A. Pearlman, A. Verevkin, and R. Sobolewski, "Quantum efficiency and noise equivalent power of nanostructured, NbN, single-photon detectors in the wavelength range from visible to infrared," *IEEE Trans. Appl. Supercond.*, vol. 101, pp. 49–54, 2005.

[81] R. Lusche, A. Semenov, K. Il'in, Y. Korneeva, A. Trifonov, A. Korneev, H.-W. Hübers, M. Siegel, and G. Goltsman, "Effect of the wire width and magnetic field on the intrinsic detection efficiency of superconducting nanowire single-photon detectors," *IEEE Trans. Appl. Supercond*, vol. 23, 2013.

[82] A. Kadin, M. Leung, and A. Smith, "Photon-assisted vortex depairing in two-dimensional superconductors," *Phys. Rev. Lett.*, vol. 65, p. 3193, 1990.

[83] H. B. Coldenstrodt-Ronge, J. S. Lundeen, K. L. Pregnell, A. Feito, B. J. Smith, W. Mauerer, C. Silberhorn, J. Eisert, M. B. Plenio, and I. A. Walmsley, "A proposed testbed for detector tomography," *J. Mod. Optic.*, vol. 56, no. 2-3, pp. 432–441, 2009.

[84] K. Il'in, D. Rall, M. Siegel, A. Engel, A. Schilling, A. Semenov, and H. Huebers, "Influence of thickness, width and temperature on critical current density of Nb thin film structures," *Physica C*, vol. 470, p. 953, 2010.

[85] K. Inderbitzin, A. Engel, and A. Schilling, "Soft x-ray single-photon detection with superconducting tantalum nitride and niobium nanowires," *IEEE Trans. Appl. Supercond.*, vol. 23, p. 2200505, 2013.

[86] K. Burnham and D. Anderson, *Model selection and multimodel inference*. Springer, 1998.

[87] A. Kerman, D. Rosenberg, R. Molnar, and E. Dauler, "Readout of Superconducting nanowire single-photon detectors at high count rates," *J. Appl. Phys*, vol. 113, p. 144511, 2013.

[88] E. Reiger, S. Dorenbos, V. Zwiller, A. Korneev, G. Chulkova, I. Milostnaya, O. Minaeva, G. Gol'tsman, J. Kitaygorsky, D. Pan *et al.*, "Spectroscopy with nanostructured superconducting single photon detectors," *IEEE J. Sel. Top. Quantum Electron.*, vol. 13, no. 4, pp. 934–943, 2007.

[89] C. M. Natarajan, A. Peruzzo, S. Miki, M. Sasaki, Z. Wang, B. Baek, S. Nam, R. H. Hadfield, and J. L. O'Brien, "Operating quantum waveguide circuits with superconducting single-photon detectors," *Appl. Phys. Lett.*, vol. 96, no. 21, p. 211101, 2010.

[90] H. Takesue, S. Nam, Q. Zhang, R. Hadfield, T. Honjo, K. Tamaki, and Y. Yamamoto, "Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors," *Nature Photon.*, vol. 1, p. 343, 2007.

[91] N. Gemmell, A. McCarthy, B. Liu, M. Tanner, S. Dorenbos, V. Zwiller, M. Patterson, G. Buller, B. Wilson, and H. R.H., "Singlet oxygen luminescence detection with a fiber-coupled superconducting nanowire single-photon detector," *Opt. Express*, vol. 21, p. 5005, 2013.

[92] T. Yamashita, S. Miki, H. Terai, and Z. Wang, "Low-filling-factor superconducting single photon detector with high system detection efficiency," *Opt. Express*, vol. 22, p. 27122, 2013.

[93] L. Maingault, P. Cavalier, R. Lamaestre, L. Frey, and J. Villegier, "Quantum efficiency and polarization effects in nbn superconducting single photon detectors," *Proc. ASC 2008 in IEEE Trans. Appl. Supercond.*, 2008.

[94] D. Sahin, A. Gaggero, Z. Zhou, S. Jahanmirinejad, F. Mattioli, R. Leoni, J. Beetz, M. Lermer, M. Kamp, S. Höfling, and A. Fiore, "Waveguide photon-number-resolving detectors for quantum photonic integrated circuits," *Applied Physics Letters*, vol. 103, no. 11, p. 111116, 2013.

[95] C. Natarajan, L. Zhang, H. Coldenstrodt-Ronge, G. Donati, S. Dorenbos, V. Zwiller, I. Walmsley, and R. Hadfield, "Quantum detector tomography of a time-multiplexed superconducting nanowire single-photon detector at telecom wavelengths," *Opt. Express*, vol. 21, pp. 893–902, 2013.

[96] D. Sahin, "Waveguide single-photon and photon-number resolving detectors," Ph.D. dissertation, University of Eindhoven, 2014.

[97] M. Tinkham, *Introduction to superconductivity.* McGraw-Hill, 1996.

[98] A. N. Tikhonov, "On the stability of inverse problems," *Dokl. Akad. Nauk SSSR*, vol. 39, no. 5, pp. 195–198, 1943.

[99] V. B. Verma, A. E. Lita, M. R. Vissers, F. Marsili, D. Pappas, R. Mirin, and S. W. Nam, "Superconducting nanowire single photon detectors fabricated from an amorphous $Mo_{0.75}Ge_{0.25}$ thin film," *arXiv:1402.4526.*

[100] Y. P. Korneeva, M. Y. Mikhailov, Y. P. Pershin, N. N. Manova, A. V. Divochiy, Y. B. Vakhtomin, A. A. Korneev, K. V. Smirnov, A. G. Sivakov, A. Y. Devizenko, and G. N. Goltsman, "Superconducting single-photon detector made of MoSi film," *Superconductor Science and Technology*, vol. 27, no. 9, p. 095012, 2014.

[101] H. Shibata, "Fabrication of a MgB_2 nanowire single-photon detector using Br_2–N_2 dry etching," *Appl. Phys. Expr.*, vol. 7, no. 10, p. 103101, 2014.

[102] A. Eftekharian, H. Atikian, M. Akhlagi, A. Jafari Salim, and A. Hamed Majedi, "Quantum ground state effect on fluctuation rates in nano-patterned superconducting structures," *Appl. Phys. Lett*, vol. 103, p. 242601, 2013.

[103] A. Engel, A. Schilling, K. Il'in, and M. Siegel, "Dependence of count rate on magnetic field in superconducting thin-film TaN single-photon detectors," *Phys. Rev. B*, vol. 86, p. 140506, 2012.

[104] A. Anthore, H. Pothier, and D. Esteve, "Density of states in a superconductor carrying a supercurrent," *Phys. Rev. Lett.*, vol. 90, p. 127001, 2003.

[105] K. D. Usadel, "Generalized diffusion equation for superconducting alloys," *Phys. Rev. Lett.*, vol. 25, pp. 507–509, 1970.

[106] "Quantum design application note 1070-207: Using PPMS superconducting magnets at low fields."

[107] E. F. C. Driessen, P. C. J. J. Coumou, R. R. Tromp, P. J. de Visser, and T. M. Klapwijk, "Strongly disordered TiN and NbTiN s-wave superconductors probed by microwave electrodynamics," *Phys. Rev. Lett.*, vol. 109, p. 107003, 2012.

[108] P. C. J. J. Coumou, E. F. C. Driessen, J. Bueno, C. Chapelier, and T. M. Klapwijk, "Electrodynamic response and local tunneling spectroscopy of strongly disordered superconducting tin films," *Phys. Rev. B*, vol. 88, p. 180505, 2013.

[109] B. Plourde, D. van Harlingen, D. Y. Vodolazov, R. Besselink, M. Hesselberth, and P. H. Kes, "Influence of edge barriers on vortex dynamics in thin weak-pinning superconducting strips," *Phys. Rev. B*, vol. 64, p. 014503, 2011.

[110] K. Il'in and M. Siegel, "Magnetic field stimulated enhancement of the barrier for vortex penetration in bended bridges of thin TaN films," *Physica C*, vol. 503, pp. 58–61, 2014.

[111] G. Stan, S. B. Field, and J. M. Martinis, "Critical field for complete vortex expulsion from narrow superconducting strips," *Phys. Rev. Lett.*, vol. 92, p. 097003, 2004.

[112] K. Il'in, D. Heinrich, Y. Luck, Y. Liang, and M. Siegel, "Critical current of Nb, NbN and TaN thin-film bridges with and witout geometrical nonuniformities in a magnetic field," *Phys. Rev. B*, vol. 89, p. 184511, 2014.

[113] B. Sacépé, C. Chapelier, T. I. Baturina, V. M. Vinokur, M. R. Baklanov, and M. Sanquer, "Disorder-induced inhomogeneities of the superconducting state close to the superconductor-insulator transition," *Phys. Rev. Lett.*, vol. 101, p. 157006, 2008.

[114] Y. Noat, V. Cherkez, C. Brun, T. Cren, C. Carbillet, F. Debontridder, K. Il'in, M. Siegel, A. Semenov, H.-W. Hübers, and D. Roditchev, "Unconventional superconductivity in ultrathin superconducting NbN films studied by scanning tunneling spectroscopy," *Phys. Rev. B*, vol. 88, p. 014503, 2013.

[115] J. Bueno, P. C. J. J. Coumou, G. Zheng, P. J. de Visser, T. M. Klapwijk, E. F. C. Driessen, S. Doyle, and J. J. A. Baselmans, "Anomalous response of superconducting titanium nitride resonators to terahertz radiation," *Applied Physics Letters*, vol. 105, no. 19, pp. –, 2014.

[116] G. Berdiyorov, M. Milosevic, and F. Peeters, "Spatially dependent sensitivity of superconducting meanders as single-photon detectors," *Appl. Phys. Lett.*, vol. 100, p. 262603, 2012.

[117] D. Henrich, L. Rehm, S. Dorner, M. Hofherr, K. Il'in, A. Semenov, and M. Siegel, "Detection efficiency of a spiral-nanowire superconducting single-photon detector," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 2 200 405–2 200 405, 2013.

[118] Q. Wang and M. J. de Dood, "An absorption-based superconducting nano-detector as a near-field optical probe," *Opt. Express*, vol. 21, p. 3682, 2013.

[119] A. Jukna, J. Kitaygorsky, D. Pan, A. Cross, A. Perlman, I. Komissarov, O. Okunev, K. Smirnov, A. Korneev, G. Chulkova *et al.*, "Dynamics of hotspot formation in nanostructured superconducting stripes excited with single photons," *Acta. Phys. Pol. A*, vol. 113, no. 3, pp. 955–958, 2008.

[120] A. Semenov, A. Engel, K. Il'in, G. Gol'tsman, M. Siegel, and H.-W. Hübers, "Ultimate performance of a superconducting quantum detector," *Eur. Phys. J. Appl. Phys.*, vol. 21, no. 03, pp. 171–178, 2003.

[121] R. Gaudio, K. op 't Hoog, Z. Zhou, D. Sahin, and A. Fiore, "Inhomogeneous critical current in nanowire superconducting single-photon detectors," *Submitted to Appl. Phys. Lett.*, 2014.

[122] S. P. Chockalingam, M. Chand, J. Jesudasan, V. Tripathi, and P. Raychaudhuri, "Superconducting properties and hall effect of epitaxial NbN thin films," *Phys. Rev. B*, vol. 77, p. 214503, 2008.

[123] F. Marsili, M. J. Stevens, A. Kozorezov, V. B. Verma, C. Lambert, J. A. Stern, R. Horansky, S. D. Dyer, M. D. Shaw, R. P. Mirin *et al.*, "Hotspot dynamics in current carrying wsi superconducting nanowires," in *CLEO: QELS_Fundamental Science*. Optical Society of America, 2014, pp. FM4B–7.

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