Hotspot Relaxation Dynamics in a Current Carrying Superconductor

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Dynamics of hotspot relaxation in current carrying superconducting nanowires

• Time-resolved two-photon detection experiments in WSi SNSPD.
• Theory of hotspot relaxation.
• Fano-fluctuations in SNSPDs.
• Role of diffusion

Single-photon detection regime

Two-photon detection regime

Gol’tsman et al., APL 79, 705 (2001)
$P_{\text{click}}$ vs Time Delay vs Bias Current

Never Observed Before
Experiment

Wavelength dependence

Temperature dependence

- $\lambda = 1200 \text{ nm}$
- $\lambda = 1650 \text{ nm}$
- $T_B = 250 \text{ mK}$
- $T_B = 2 \text{ K}$
- $T_B = 250 \text{ mK}$
- $\lambda = 1550 \text{ nm}$
Theoretical model

- Dirty superconductor model
- WSi alloy close to metal-insulator transition
- Strong e-e scattering, fast local equilibration:
  - One temperature model
  - Two-temperature model
- Usadel eqns
- Kinetic eqns
Dynamics of hotspot relaxation in superconducting nanowires

\[ E_{HS}(T, I_b) = 2N(0)V_{HS} \int_0^\infty d\varepsilon \rho(\varepsilon, T, I_b) \frac{\varepsilon}{\exp(\varepsilon/T) + 1} \]

Initial temperature:
\[ E_{HS}(T_i, I_b) = E_{HS}(T_b, I_b) + \eta E_\lambda \]
\[ T_i = T_i(I_b, T_b, E_\lambda) \]

Relaxation edge (cut-off temperature)
\[ E_{HS}(T_s, I_b) = E_{HS}(T_{co}, I_b) + \eta E_\lambda \]
\[ T_{co} = T_{co}(I_b, E_\lambda) \]

Switching current
\[ E_{HS}(T_s, I_s) = E_{HS}(T_b, I_s) + \eta E_\lambda \]
\[ I_s = I_s(T_b, \lambda) \]
Comparison with experiment

Solution of kinetic equation.
Relaxing HS with changing spectrum.
Strongly non-linear self-recombination.
Summary of simulations vs normalised bias current. Comparison with experiment.
Fano fluctuations in superconducting nanowire single photon detectors

• \( E = \eta E_\lambda, \quad \eta < 1 \)
• \( \eta \) is subject to Fano fluctuations due to
  a) De-coupling from the condensate
  b) Loss of athermal phonons

\[
PCR = \frac{1}{2} \text{erfc} \left( \frac{E(I_b, T_s, B) - E(I_b, T_b, B) - \bar{E}}{\sqrt{2}\sigma} \right)
\]
\[
\sigma^2 = \sigma_1^2 + \sigma_2^2
\]
Effect of Fano fluctuations on PCR
Comparison of theory and experiment

Experiment

Theory
PCR vs magnetic field

FIG. 5: a) - Count rate, for NbN sample illuminated with 826 nm light at $T = 1.8$ K, for different magnetic fields ranging from 0 mT to 300 mT, in steps of 30 mT. b) - Critical current as a function of magnetic field.

Renema et al (2015)

FIG. 6: Simulated PCR as a function of magnetic field for NbN SNSPD.
Fano fluctuations effect on two-photon PCR vs time delay

Experiment

Theory
Summary

• We observed for the first time that the hotspot relaxation time of a superconducting nanowire can be increased by increasing the bias current.
• We developed a model that explains and quantitatively reproduces all the experimental data.
• Fano fluctuations play a fundamental role in determining the SNSPD response.
Non-linearity of response

- Linear extrapolation to $E_\lambda \to 0$ is not consistent with predictions of the kinetic theory.
- Reference current, $I_0 < I_C$ (obtained as linear intercept of bias current axis) and its $T$-dependence has no physical meaning within kinetic scenario.
- Linear bias current - photon energy dependence appears to be an approximation, which is justified for a limited photon energy range and bias currents outside the range $1 - \frac{I_B}{I_C} \ll 1$.
- Discrimination between mechanisms of single photon detection (Renema et al (2014)) requires more experimental and theoretical efforts.

FIG. 12: Cut-off current as a function of photon energy. Solid line - theory, solid boxes - experiment, dashed line - linear extrapolation.
Experimental Apparatus


$P_{\text{click}}$ doubles for “short” $t_D$
Modeling Hot Electron Dynamics

![Diagram showing the dynamics of electron temperature over time, with markers for the first and second photons, and regions for normal and superconducting states.]
Modeling Hot Electron Dynamics
Summary of simulations vs normalised bias current

FIG. 10: Single photon system detection efficiency (a) and PCR (b) as a function of temperature and wavelength respectively.