Materials for superconducting nanowires for quantum phase-slip devices

J C Fenton[1,2], C H Webster[2] and P A Warburton[1]

[1] London Centre for Nanotechnology, UCL, 17–19 Gordon Street, London WC1H 0AH, UK
[2] National Physical Laboratory, Hampton Road, Teddington TW11 0LH, UK

E-mail: `j.fenton@ucl.ac.uk`

Abstract. Quantum phase-slip processes in superconducting nanowires of suitably small cross-section have been proposed as the basis for a new current standard, based on physics dual to that for the Josephson voltage standard. The practical realisation of such devices presents several challenges. We consider the requirements which need to be met in constructing a nanowire quantum-phase-slip device and in particular the need to maximise R_ξ, the normal-state resistance of a length of nanowire equal to the superconducting coherence length. Titanium and niobium–silicon are promising materials for the nanowires.

1. Introduction

In 2006 Mooij and Nazarov demonstrated that circuits containing quantum phase slip (QPS) junctions are exactly dual to circuits containing Josephson junctions [1]. For example, a voltage-biased circuit containing a QPS element, an inductance and a resistance in series is dual to a current-biased circuit containing a Josephson element in parallel with a capacitance and a resistance; this example has particular technological relevance since it raises the possibility of a quantum current standard based on the dual of the Shapiro effect in Josephson junctions on which the international voltage standard is now based.

There have been experimental efforts by a number of groups to realise nanowires in which QPS can be observed, on a number of different materials. Several groups have reported a larger resistance for $T < T_c$ than would be expected in a homogeneous material from thermally activated phase slips. Similar observations might, however, also arise due to sample inhomogeneities. Observation of a critical voltage below which no current flows would be a less ambiguous demonstration of QPS but to date, there has been only one isolated such report [3]. It is important, therefore, to carefully consider the experimental criteria needed to observe QPS. Here we focus particularly on choice of nanowire material.

2. Candidate materials

A narrow wire along whose length occurs a sufficiently high rate Γ_S of quantum phase slips is suitable as a QPS element. T_c should be high enough that measurements are possible at temperatures significantly less than T_c. Phase slips occur over a lengthscale ξ and nanowires for devices should therefore have transverse dimensions less than ξ. QPSs are expected to be only weakly interacting [2] and therefore observable when $Z_c > R_q \equiv h/4e^2 = 6.45\ \mathrm{k\Omega}$, where $Z_c = \sqrt{L'/C'}$ is the characteristic impedance of the nanowire, L' is the kinetic inductance of the nanowire per unit length and C' is its capacitance per unit length. For a QPS device in which Shapiro steps might be observed, the series inductance L should be much larger than $R_q/2\Gamma_S$ to make the charge a well-defined variable and the series resistance R large enough that the damping parameter $\beta_L \equiv 2\pi^2(2L\Gamma_S/R_q)(R_q/R)^2$ is $\lesssim 1$. It has been suggested [1] that $\Gamma_S \sim 10^{11}$ s^{-1} with achievable values of R and L would be suitable for a QPS device.

Experimental studies on Al (BCS coherence length $\xi_0 = 1600$ nm, $T_c = 1.19$ K), Ti ($\xi_0 = 6200$ nm, $T_c = 0.4$ K) and Nb–Si (typical $\xi_0 = 175$ nm, $T_c = 1.5$ K) are among those previously reported [2, 3] — see the review by Arutyunov [2] for a detailed survey.

Theoretical analysis of the problem has generated a number of formulas for the QPS rate, depending on the details of the situation and the underlying assumptions. One example [4] is

$$\Gamma_S = b\frac{\Delta_0}{\hbar}\frac{l}{\xi}\frac{R_q}{R_\xi}\exp\left(-a\frac{R_q}{R_\xi}\right), \quad (1)$$

where Δ_0 is the superconducting energy gap, l is the length of the wire, $a \sim 1$, $b \sim 1$ and R_ξ, the normal-state resistance of a length ξ of the superconducting nanowire. Note that, for a BCS superconductor with $T_c = 1K$, $\Delta_0/\hbar = 2.3.10^{11}$ s^{-1}. A common feature of these formulas for the QPS rate is the exponential factor dependent on R_ξ. Therefore, for making a QPS nanowire, it is a crucial requirement that $R_\xi/R_q \gtrsim 1$ otherwise the QPS rate will be exponentially suppressed.

3. Maximising R_ξ

To maximise $R_\xi \equiv \rho\xi/A$, we should clearly maximise the resistivity ρ and minimise the cross-sectional area A. For a given material, ρ increases as the mean free path λ decreases, i.e. as the material becomes more dirty. For a free electron metal, $\rho\lambda$ is set by band-structure properties of the material. Noting that the Ginzburg–Landau coherence length ξ_{GL} in the dirty-limit is $\sim \sqrt{\xi_0\lambda}$, it follows that $R_\xi(\lambda) \sim 1/\sqrt{\lambda}$ in the dirty limit.[1] Samples with small λ are therefore the most suitable for QPS nanowires.

We can estimate the maximum obtainable resistivity of some candidate materials for QPS nanowires. We use experimentally reported values for ξ and $\rho\lambda$ [2, 3, 5, 6], assuming that this product would remain constant even for short λ and we assume that the shortest achievable mean free path is 0.2 nm, of the order of the interatomic spacing. Assuming a cross-sectional area $A = 100$ nm^2, the maximum value of R_ξ/R_q at low temperature is ~ 0.1 in Al, ~ 1 in Ti and ~ 1 in NbSi. This suggests that, unless A can be further reduced, even the most resistive Al nanowires will have R_ξ too small for the QPS rate to be significant. Ti and NbSi nanowires with very short λ are more promising. Since T_c may be below its value for a pure, bulk material in such dirty materials, the doping and composition need to be carefully controlled to obtain the highest ρ while maintaining an acceptable T_c and good sample homogeneity.

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References

[1] Mooij J E and Y V Nazarov 2006 *Nat. Phys.* **2** 169
[2] Arutyunov K Y 2008 *Phys. Rep.* **474** 1
[3] Van der Sar T 2007 *Master's thesis* (Delft)
[4] Golubev D S and Zaikin A D 2001 *Phys. Rev. B* **64** 014504
[5] Mayadas A F 1968 *J. Appl. Phys.* **39** 4241
[6] Caballero J (1984) *Thin Solid Films* **117** 1

[1] Additional scattering from the boundaries has been shown to cause increases in the resistivity of thin-film samples when the thickness of the sample is $\sim \lambda$. This effect should be small for samples in which the mean free path is similar to the atomic spacing. Other changes away from the bulk 3–D properties due to the small sample dimensions are possible, but are neglected here.