Physica B 165&166 (1990) 81–82
North-Holland

COMPARISON OF SHUNTED DC-SQUIDs WITH LARGE β

E.P.HOUWMAN, D.VELDHUIS, J.FLOKSTRA, and H.ROGALLA

University of Twente, Faculty of Applied Physics, Low Temperature Group,
P.O.Box 217, 7500 AE Enschede, The Netherlands.

The performance of DC-SQUIDs with inductively and resistively shunted inductances is studied theoretically and experimentally and compared to the performance of a standard (unshunted) SQUID. By shunting the inductance the voltage modulation depth remains unaffected for large β. The consequences for the flux-voltage transfer and the noise performance are discussed.

1. INTRODUCTION

Since the description of the standard DC-SQUID by Tesche and Clarke several modifications on the SQUID design were proposed to overcome the fairly strict constraint for the screening parameter $\beta = 2LI_0/\Phi_0 \approx 1$. L is the SQUID inductance, I_0 the critical current of a junction and Φ_0 the flux quantum. Thermal noise restricts I_0 to values larger than about 4 μA, for practical devices operated at LHe temperature. This limits L to about 250 pH at the most.

We are developing a fabrication process for DC-SQUIDs for the application to neuromagnetometry (1). In that case the SQUID is coupled to an inductance of about 1 μH. In the Ketchen-Jaycox washer design this can be achieved by a planar, tightly coupled coil with many (n_i = 30-60) turns. Apart from fabrication problems, the capacitive coupling between SQUID and input circuit may cause resonances in the system, that can give rise to excess noise.

The SQUID inductance can be increased, thus n_i decreased, by the introduction of a shunt across L, on the expense of some loss of sensitivity, that may be acceptable for many neuromagnetic experiments. On the other hand excess noise due to resonances may be avoided.

We are studying the properties of the standard, the resistively and the inductively shunted SQUID experimentally.

2. THEORETICAL CHARACTERISATION

The voltage modulation depth of a standard SQUID in the optimum bias point depends on β as $\Delta V_m \approx I_0R/(1+\beta)$ (2), where R is the shunt resistance of the junction. A simple estimate of the noise leads to an energy sensitivity $\varepsilon/(2k_BT\Phi_0/I_0R) \approx (\beta+1)^2/\pi^2\beta + \beta/4$. This expression underestimates the noise, but describes the functional behaviour fairly well.

For the resistively shunted SQUID it was shown that $\Delta V_m \approx I_0R/2$ is nearly independent of β, if $\gamma = R/R_{sh}$ is about 1 or larger, where R_{sh} is the shunt resistance over L (3). The energy resolution is analytically obtained as $\varepsilon/(2k_BT\Phi_0/I_0R) \approx 4/\pi^2\beta + \beta(1+2\gamma)/4$. For low β the estimate is too low, but it becomes rather good for larger β and $\gamma > 0.5$. For large β optimum performance is obtained for $\gamma \approx 1$.

For the inductively shunted SQUID the flux quantisation condition can be written as (4) $\delta_1-\delta_2 = \pi[\beta_{sh}-\beta_{sh}^2/(\beta_p+\beta_{sh})]j + 2\pi[\Phi_p\beta_{sh}/(\beta_p+\beta_{sh})]$ where δ_i is the phase difference over junction i, j the circulating current through the junctions and Φ_p the flux in the large pick-up loop, formed by the loop inductance L_p and the shunt inductance L_{sh}. It is assumed that no flux is applied to the small loop, made up of L_{sh} and the junctions. For $\beta_p \gg \beta_{sh}$ and $\beta_{sh} \gg 1$ this condition is that of a standard SQUID, to which an effective flux $\Phi_{eff} \approx \Phi_p/(\beta_p+1)$ is applied, but with effective screening parameter $\beta_{sh} \approx 1$. Thus $\Delta V_m \approx I_0R/2$, but the transfer becomes $\partial V/\partial\Phi_p \approx (\partial V/\partial\Phi_{eff})/(\beta_p+1) \approx (\pi I_0R/\Phi_0)/(\beta_p+1)$. The energy resolution is obtained, neglecting the mixing due to the junctions and assuming that the noise current is shunted by L_{sh}, as $\varepsilon/(2k_BT\Phi_0/I_0R) \approx 0.35(\beta_p+1)^2/\beta_p$

Figure 1 shows the voltage modulation depth as function of β, respectively β_p, for the standard and the shunted SQUIDs, calculated from an analytical model based on the work of Enpuku *et al*. Theoretically the effect of the shunting is very pronounced in the used approximations.

Figure 2 shows the energy resolution according to the above approximate formulas. In all three cases ε shows a clear minimum for $\beta \approx 1$ and a linear increase with β for larger β. The price for larger β is some increase of ε, that is comparable for the three designs.

3 FABRICATION AND EXPERIMENTAL RESULTS

10 SQUIDs of the three designs, are fabricated in a single run. The SQUID washer is formed by a Nb/Al,AlO$_x$/Nb tri-layer process, using DC magnetron sputtering and thermal oxidation. The junction areas (5x5 μm^2) are defined by a standard SNAP process, by which also an insulation layer is formed on the washer. The employed

0921-4526/90/$03.50 © 1990 – Elsevier Science Publishers B.V. (North-Holland)

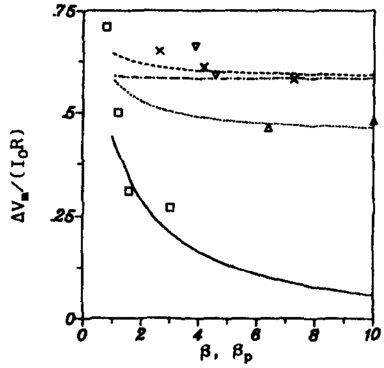

Fig. 1 : Voltage modulation depth as function of β for noiseless SQUIDs with $\beta_c=0$, at $I_B=2.1\ I_0$. Lines : theory, symbols : experimental data. ——,□ standard SQUID; -·-··-,x resist.shunted SQUID ($\gamma=1$); ·········,Δ induct.shunted SQUID ($\beta_{sh}=1$), ----,∇ ($\beta_{sh}=0.5$).

junctions are fabricated with a double oxide barrier. The junctions are of high quality with V_m up to 80 mV at 4.2 K and 600-1100 mV at 1.6 K. The fabrication and characterisation of the junctions is described elsewhere (5). A second insulation and planarisation layer of RF sputtered SiO_2 is deposited. The final Nb layer is patterned to form the contacts to the counter electrode of the junctions and the modulation and signal coils.

The resistively shunted SQUIDs have inductances 240, 470, 1200 and 2400 pH. We chose $\gamma \approx 1$ and R, such that $\beta_c = 2\pi I_0R^2C/\Phi_0 \leq 0.3$, throughout.

The two standard SQUIDs have inductances 110 and 240 pH. The junctions are placed at the inside of the washer to avoid the parasitic slit inductance.

The inductively shunted SQUIDs consist of a small washer with a hole inductance of 110 pH, on which the modulation coil is placed. This washer is attached to a large washer, with an inductance of 940 or 2400 pH, on which the input coil is placed.

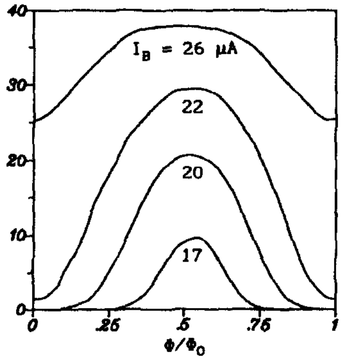

Fig. 3 : Experimental flux-voltage transfer of inductively shunted SQUID.

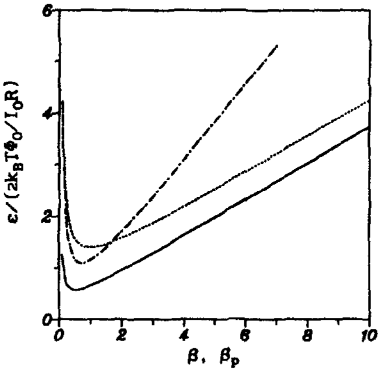

Fig. 2 : Energy sensitivity as function of β. —— standard SQUID; -·-··- resist.shunted SQUID ($\gamma=1$); ········· induct.shunted SQUID ($\beta_{sh}=1$).

In figure 1 some first results on the experimental ΔV_m (at $I_B \approx 2.1\ I_0$), obtained for the three SQUID designs, are shown. The strong dependence of ΔV_m on β for the standard SQUID is clearly seen, in contrast with the relative independence of ΔV_m on β for the shunted SQUIDs.

Figure 3 shows the flux-voltage transfer of a typical inductively shunted SQUID, with $\beta_p \approx 10$, $\beta_{sh} \approx 1.2$, $I_0 \approx 11\ \mu A$ and $R \approx 4.3\ \Omega$. The large voltage swing and the high symmetry of this curve, make this SQUID very suitable for application in flux-locked loop systems.

The sensitivity is still to be determined and will be reported elsewhere.

4. CONCLUSIONS

The dependence of ΔV_m and ε of the standard, resistively and inductively shunted SQUIDs on β is calculated. For the shunted SQUIDs ΔV_m is nearly independent of β, in contrast with the strong dependence for the standard SQUID. The dependence of ε on β is comparable for the three designs.

A fabrication process for high-quality Nb/Al,AlO_x/Nb tunnel junctions (V_m up to 80 mV at 4.2 K and over 600 mV at 1.6 K) was developed and applied to standard and shunted DC-SQUIDs.

The ΔV_m of the SQUIDs was determined as function of β and is found to be in accordance with the theoretical expectations.

REFERENCES

(1) H.J.M.ter Brake *et al.*, Design and Construction of a 19-Channel DC-SQUID Neuromagnetometer, this Volume.
(2) R.L.Peterson and C.A.Hamilton, J.Appl. Phys.**50**, (1979) 8135.
(3) K.Enpuku *et al.*, J.Appl.Phys.57,(1985) 1691.
(4) H.Koch, ICEC **10**, (1984) 834.
(5) E.P.Houwman *et al.*, accepted for publ. in J.Appl.Phys. (1990).
D.J.Adelerhof *et al.*, Conductance Studies on Different Types of Nb/Al,AlO_x(/Al)/Nb Josephson Tunnel Junctions, this Volume.