SQUID readout and flux feedback based on a SiGe bipolar transistor at 4.2K*

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ABSTRACT

I have experimented with a SiGe heterojunction transistor at 4.2 K acting as a readout amplifier for dc SQUIDs. Flux noise level of $0.35\ \mu\Phi_0/\sqrt{\mathrm{Hz}}$ was reached with one SQUID type. Slew rate exceeding $5\times10^7\ \Phi_0/\mathrm{s}$ was observed with another SQUID type in a flux feedback arrangement. The SiGe transistor dissipated 9 mW at 4.2 K, but dissipation levels in the 0.1 mW range appear feasible.

INTRODUCTION

Multiplexed arrays of transition-edge sensors (TESes), such as the EURECA X-ray calorimeter array [1, 2], require readout amplifiers functioning in the close proximity to the sensors and subsequently at sub-kelvin temperatures. The readout amplifiers should have a large linear dynamic range, low power dissipation, low noise temperature and high bandwidth. Superconducting Quantum Interference Devices (SQUIDs) have the required properties, except for the linearity. The SQUID response can be linearized and the dynamic range extended by negative feedback over an additional post-SQUID amplifier stage. An additional stage is necessary because the signal at the output of a SQUID has typically challenging low level, and negative feedback over the SQUID alone would further reduce the signal level. So far room-temperature semiconductor amplifiers have been attempted as the post-SQUID amplifiers (Fig. 1a), but the delay in the cable between cryogenic and room-temperature stages limit the achievable bandwidth and loop gain.

A cryogenic post-SQUID amplifier (Fig. 1b) would allow a short feedback path which makes large loop gains at high frequencies achievable. A suitable cryogenic amplifier should have a reasonably low power dissipation, sufficient dynamic range, and a sufficient noise match to the SQUID. In principle, a GaAs MESFET or HEMT could act as such an amplifier [e.g. 3], but to my knowledge has so far only been applied either at microwave frequencies or in conjunction with rf SQUIDs [e.g. 4]. We have proposed a direct unmodulated readout of dc SQUIDs by using a silicon-germanium (SiGe) heterojunction bipolar transistor [5, 6]. This paper reports our first quick experiment of the concept.

Dissipation, dynamic range and inductance screening

So far our approach [9, 10] has been an attempt to increase the natural non-fedback dynamic range of the SQUID by simultaneously reducing the flux noise and reducing the input sensitivity (the input coil mutual inductance) of the SQUID. The input-referred current noise is thus kept at a constant level approximately equal to the TES noise. This approach is based on the assumption that it is difficult to obtain large loop gains for negative feedback at high frequencies which are necessary in the frequency-domain multiplexing (FDM) approach [2, 8]. Such an approach, however, unavoidably increases the power dissipation of the SQUID[1] located at the sub-kelvin stage where cooling power is at premium. The emergence of novel linearization schemes (Figs. 1 b-d) makes larger loop gains / linearization factors possible, so that it becomes attractive to trade the power dissipation at the sub-kelvin stage (due to the SQUID) against some more dissipation at the 4.2K (due to the SiGe amplifier) or at a higher temperature (more complicated electronics at the 300K compartment of the satellite). Note that when comparing power dissipation levels at different temperatures, one should scale them by the refrigerator efficiency which is often significantly less than the theoretical limit of the Carnot efficiency.

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[1] The same limit applies both to single SQUIDs and SQUID arrays.

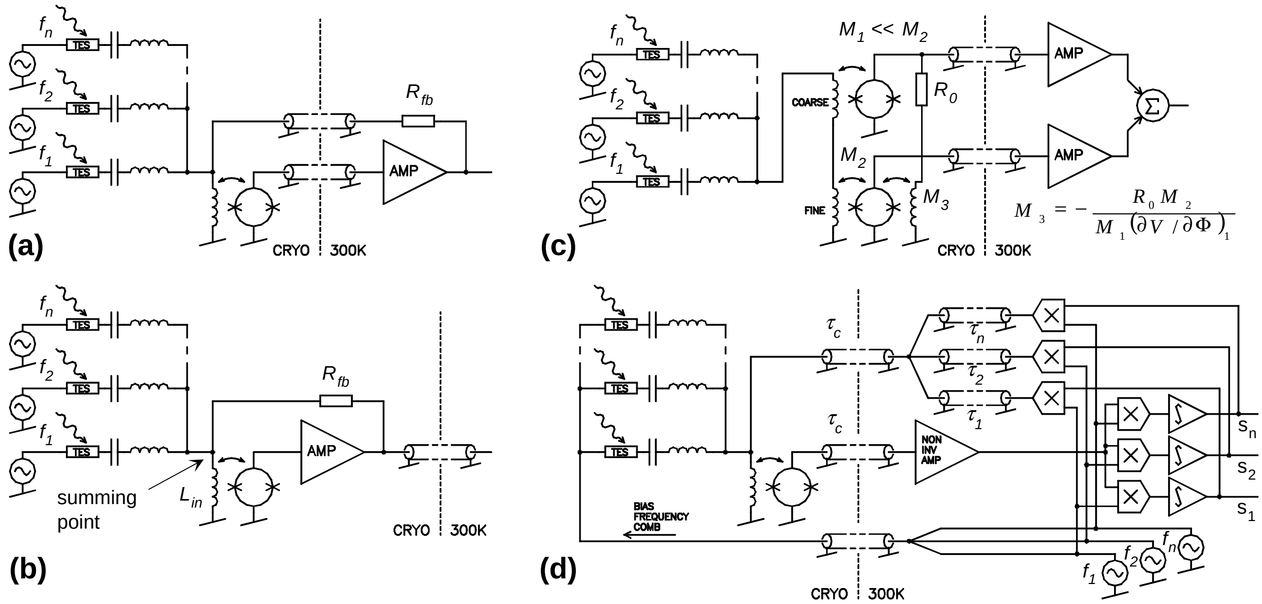

Figure 1: Some linearization schemes considered for EURECA. (a) Traditional negative feedback. (b) Cryogenic negative feedback. (c) Coarse-fine feedforward [7]; the simplest parameter choice nulls the signal in the *fine* SQUID and prevents its nonlinearities from appearing. (d) Baseband feedback [8] where the delays τ_k (k = 1..n) are chosen such that the phase shift due to the delay $2\tau_c+\tau_k$ is exactly 180^o at the corresponding modulation frequency f_k .

An additional advantage of having a large loop gain is the screening of the SQUID input inductance[2] due to the negative feedback. The screening effect is also present in the feedforward approach (Fig. 1c). The common inductance, formed by the parasitic inductance of the interconnections and the SQUID input inductance L_{in}, limits the total bandwidth available to the multiplexed frequency bands and should thus be minimized [2, 8]. EURECA requirements limit the common inductance to sub-nH level, which would require (i) integration of the readout SQUID to the TES chip; (ii) increasing the impedance level of the TES signals by an on-chip transformer before feeding them to the interconnection parasitics; or (iii) arranging the feedback summing point (Fig. 1b) to reside on the TES chip so that feedback screens away both SQUID input inductance and the interconnection parasitics.

EXPERIMENTAL SETUP

The experimental setup consists of a cold amplifier card and a room-temperature electronics card (Fig. 2), inserted in a 4.2 K dipstick (Fig. 3). The cabling consisted of phosphor-bronze twisted pairs with ~7 Ω return path resistance. In the cold amplifier card there is a Infineon BFP650 SiGe heterojunction transistor in a common emitter configuration. Its bias resistors are located at room temperature, allowing easy experimenting with various bias combinations. Typically, I used 6 mA collector current and 1.5 V collector-to-emitter voltage, at which condition the cold amplifier stage provides 270 V/V voltage gain. A current-biased dc SQUID of the washer type, described in [10], was used. The cold amplifier was ac-coupled using ceramic NP0 and Panasonic ECPU-type plastic film capacitors which function nicely at 4.2 K. There was a room-temperature amplifier stage, designed to terminate resistively the 60 Ω dipstick wires. The active termination, however, showed instability when connected to the SiGe transistor which I could not cure before submitting this presentation. As a result, there is a ~ 5 MHz cutoff, due to capacitance of the unterminated dipstick cables.

The signal at the collector of the transistor is fed back to the SQUID input coil through the R_{fb} = 301 Ω (nominal) feedback resistor. The achievable loop gain is

$$G_L = M \; dV/d\Phi \; G_T \; R_{fb}^{-1} \;, \tag{1}$$

where M is the mutual inductance of the SQUID input, $dV/d\Phi$ is the flux-to-voltage transfer coefficient, and G_T is voltage gain of the transistor stage. Rather low R_{fb} value is required to obtain G_L larger than unity with typical SQUID

[2] Note that the coupled energy resolution of the SQUID $\varepsilon = ½ \, L_{in} \, I_n^2$, expressed in terms of the input inductance and the current noise, appears to be no longer a fundamental figure-of-merit, as L_{in} can be adjusted by feedback.

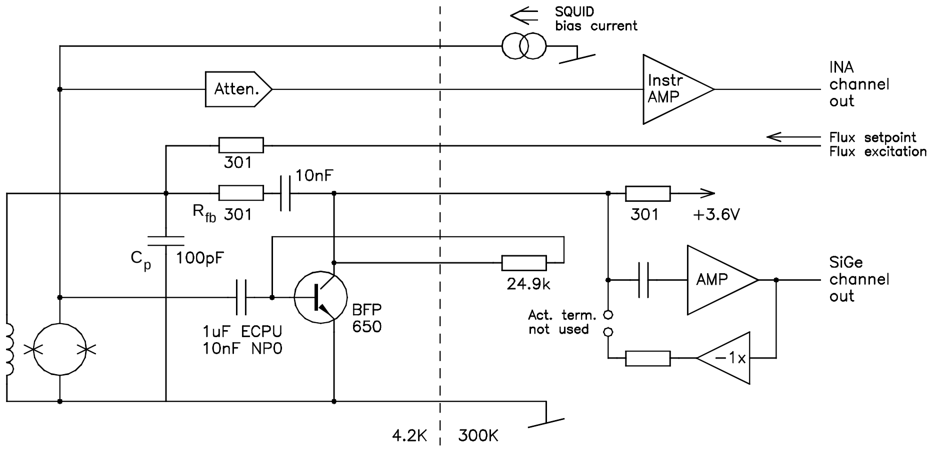

Figure 2: Simplified schematic of the experimental setup.

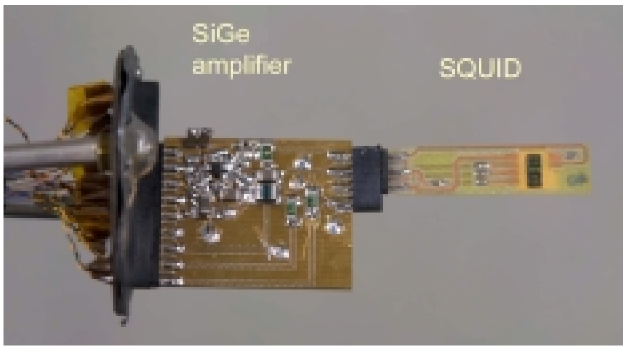

Figure 3: Photograph of the cold part of the experimental setup inserted in the dipstick.

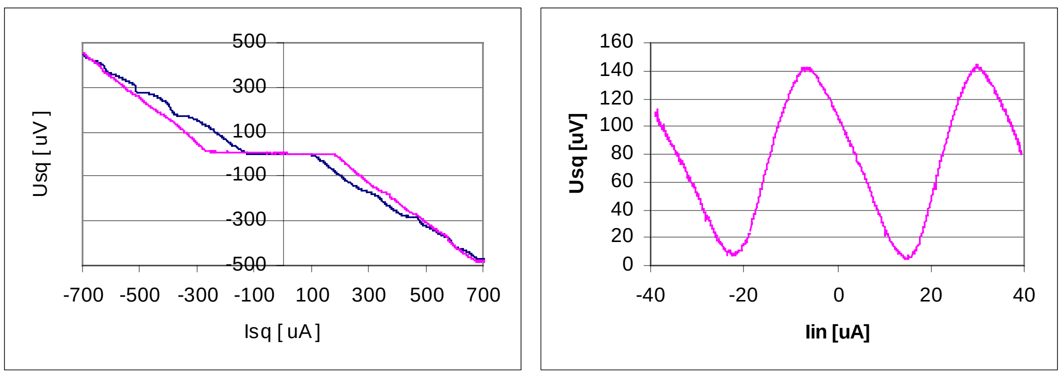

Figure 4: Current-to-voltage and flux-to-voltage characteristics of the washer SQUID.

parameters. In our case loading due to the R_{fb} reduces the transistor gain to G_T = 130 V/V. The loading effect prevents the R_{fb} value from being reduced further.

The 100 pF capacitor provides a controlled pole in the feedback loop at 5 MHz. For stability it is necessary that the loop gain rolls of to below unity before the second (parasitic) pole is introduced. Because the second pole in our system is probably at hundreds of MHz, the choice of 5 MHz is very conservative.

RESULTS

Washer SQUID

The first SQUID tested was a washer SQUID, described in [10]. This SQUID type has a low input inductance, has exhibited 0.12 $\mu\Phi_0/\sqrt{\text{Hz}}$ noise level [10] and it is intended for readout of TESes at sub-kelvin tempertures. Characteristics of the individual SQUID tested are shown in Fig. 4. The SQUID had slightly different critical currents in its two junctions, and as a result its flux-to-voltage characterisics are tilted. The chosen setpoint at the steeper slope yields the flux-to-voltage transfer ratio of $dV/d\Phi$ = 420 μV / Φ_0.

The device shows 0.35 $\mu\Phi_0/\sqrt{\text{Hz}}$ white noise level, when read out by the SiGe transistor without flux feedback, i.e. with the resistor R_{fb} removed. This number can be intepreted as the 0.15 nV//$\sqrt{\text{Hz}}$ voltage noise of the SiGe transistor scaled through the measured $dV/d\Phi$, i.e. the noise is not limited by the SQUID but by the SiGe transistor. The noise spectrum as well as the measured small-signal frequency response are shown in the Fig. 5.

The mutual inductance of the device M^{-1} = 37 μA/Φ_0 leads at the setpoint to the loop gain (1) of $G_L \approx 5\times$ only. When excited with a sinusoidal flux signal at 500kHz, with the feedback present, symptoms of unlocking began to emerge at the peak-to-peak signal amplitude of 1.5 Φ_0. The noise level was not affected by the feedback. The loop gain could in principle be increased (i) by boosting the $dV/d\Phi$ in the 1:5 transformer present on the SQUID chip; or (ii) by increasing G_T by using a two-stage transistor amplifier.

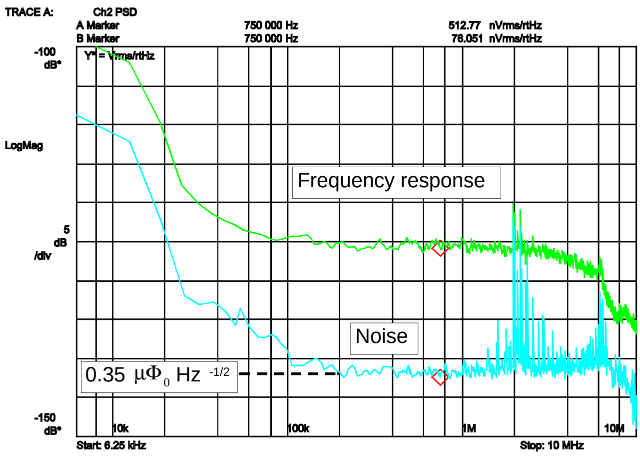

Figure 5: Noise spectrum of the washer SQUID as read out by the SiGe transistor, up to 10 MHz, with 5 dB/div vertical scale. The frequency response was also measured by feeding white pseudorandom noise to the flux input of the SQUID.

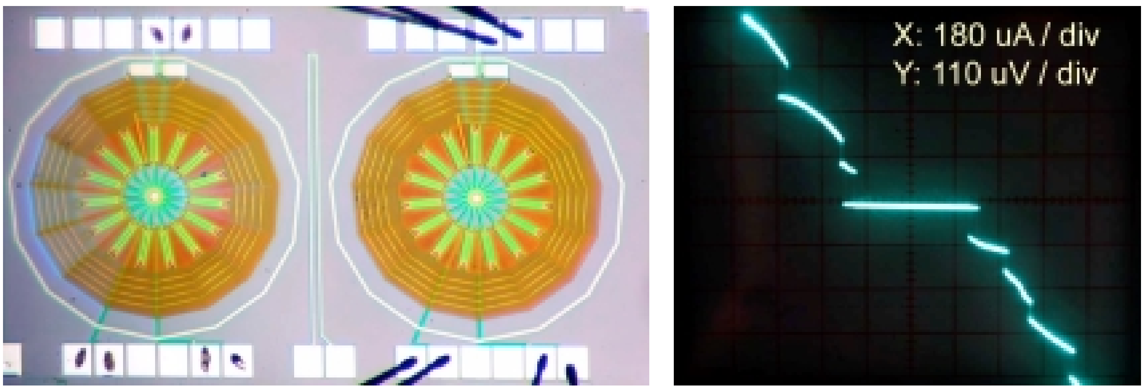

Figure 6: Microphotograph of a multiloop SQUID and its current-to-voltage characteristics.

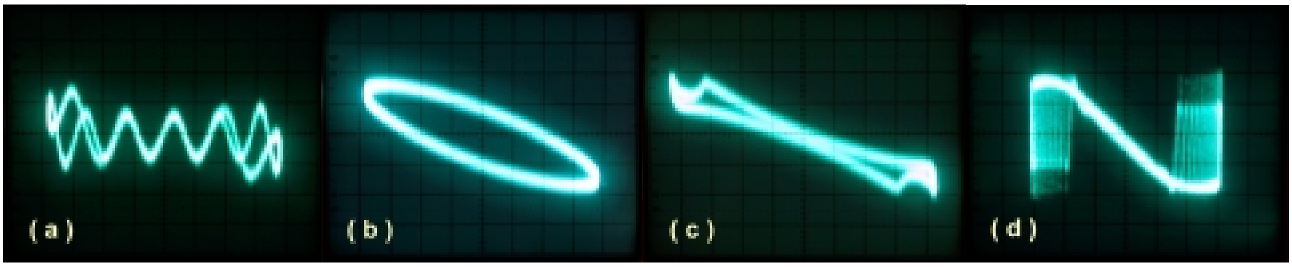

Figure 7: (a) Response through the INA channel for 100 kHz flux excitation over approximately 5.5 Φ_0 when the SiGe transistor remains unbiased and no feedback takes place. (b) Response through the INA channel at 500 kHz flux excitation with the SiGe transistor biased and the feedback subsequently activated. The phase shift is due to the vicinity of the frequency cutoff of the instrumentation amplifier. (c) Increasing the flux excitation amplitude into 6 Φ_0 shows the symptoms of unlocking as the loop approaches instability. (d) Slow 50 Hz flux excitation with 0.5 Φ_0 amplitude when the SiGe transistor is biased shows the emergence of high-frequency instability as the turning point of the slope is approached.

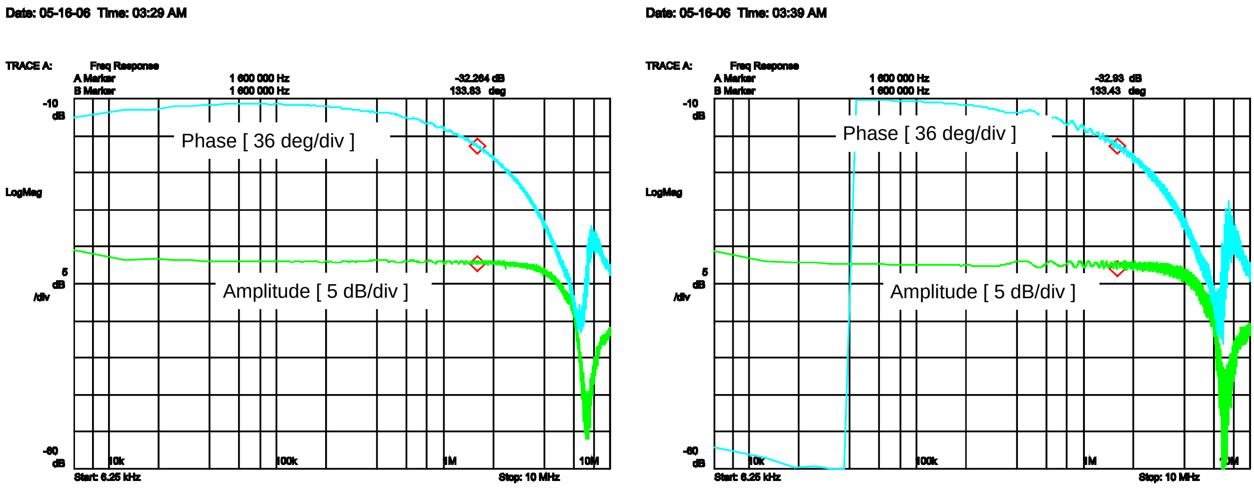

Figure 8: Amplitude and phase responses (up to 10 MHz)of the multiloop SQUID as read through the SiGe transistor with the feedback activated. Excitation is a frequency chirp with an amplitude of 2 $\Phi_{0\ p\text{-}p}$ (left) and 4 $\Phi_{0\ p\text{-}p}$ (right).

Multiloop SQUID

In order to obtain a larger loop gain we tested the SQUID device shown in Fig. 6. It is a multiloop SQUID, fabricated on the same processing round [10] as the washer SQUID. Its 150µm-radius main loop is divided into 15 parallel sub-loops to obtain a 7 pH loop inductance. The main loop is surrounded by a 75-turn input coil. There is a superconducting ring outside the input coil to screen away the homogenous ambient magnetic field, in effect configuring the main loop into a *radial gradiometer*. The shunt resistors for the Josephson junctions are located at the ends of the transmission-line spokes, with the line impedance chosen such that the resistors act simultaneously as microwave terminations. Due to a design flaw, the realized mutual inductance of the device is only $M^{-1} \approx 3$ µA/Φ_0 instead of the design goal $M^{-1} = 0.8$ µA/Φ_0. Still, a calculated loop gain of $G_L = 23\times$ is obtained at a setpoint with $dV/d\Phi = 160$ µV / Φ_0.

When read out with the SiGe transistor, with the feedback active, the system tolerated sinusoidal flux excitation at 500 kHz with up to 5.5 Φ_0 peak-to-peak amplitude (Fig. 7). The frequency response was measured at 2 $\Phi_{0\ p\text{-}p}$ and 4 $\Phi_{0\ p\text{-}p}$ excitation amplitudes (Fig. 8). Thickening of the traces in the 4 $\Phi_{0\ p\text{-}p}$ case is due to appearance of non-linearities, which begin to fold the frequency content of the excitation chirp to other frequencies. At 1 MHz sinusoidal excitation the measured 2nd and 3rd harmonics were 31dB and 36dB below the fundamental when the amplitude was 2 $\Phi_{0\ p\text{-}p}$ and 26dB and 34dB felow fundamental when the amplitude was 4 $\Phi_{0\ p\text{-}p}$. The 4.5 MHz cutoff is due to capacitance in the dipstick cabling. Because of the cable cutoff, the design bandwidth of the feedback loop was intentionally limited to 5 MHz even though much larger banwidths appear feasible. The observed 4.5 MHz cutoff frequency at 4 $\Phi_{0\ p\text{-}p}$ excitation corresponds to 5.5×10^7 Φ_0/s slew rate.

SiGe amplifier at low power dissipation

The 9mW dissipation of the SiGe transistor is tolerable in ground-based applications, but refrigerators in space-based applications, such as the XEUS mission [11], tend to have a low cooling capacity so that lower power dissipation is desirable. I measured voltage noise spectra for a number of bias conditions (Fig. 9). It appears conceivable to operate the transistor at $V_{ce} \approx 0.5$ V close to the knee of the saturated region and at low collector currents so that the power dissipation would be in the 100 µW range. An additional observation was that the 1/f corner in the voltage noise goes down as the collector current is reduced. Low frequency noise with a slope steeper than 1/f can be explained by the shot noise of the base current acting on the reactance of the 1 µF input capacitor. The dipstick cable capacitance (unterminated cables) create a high-frequency cutoff which moves to lower frequencies when the dynamic resistance of the transistor output goes up as a function of decreasing bias power.

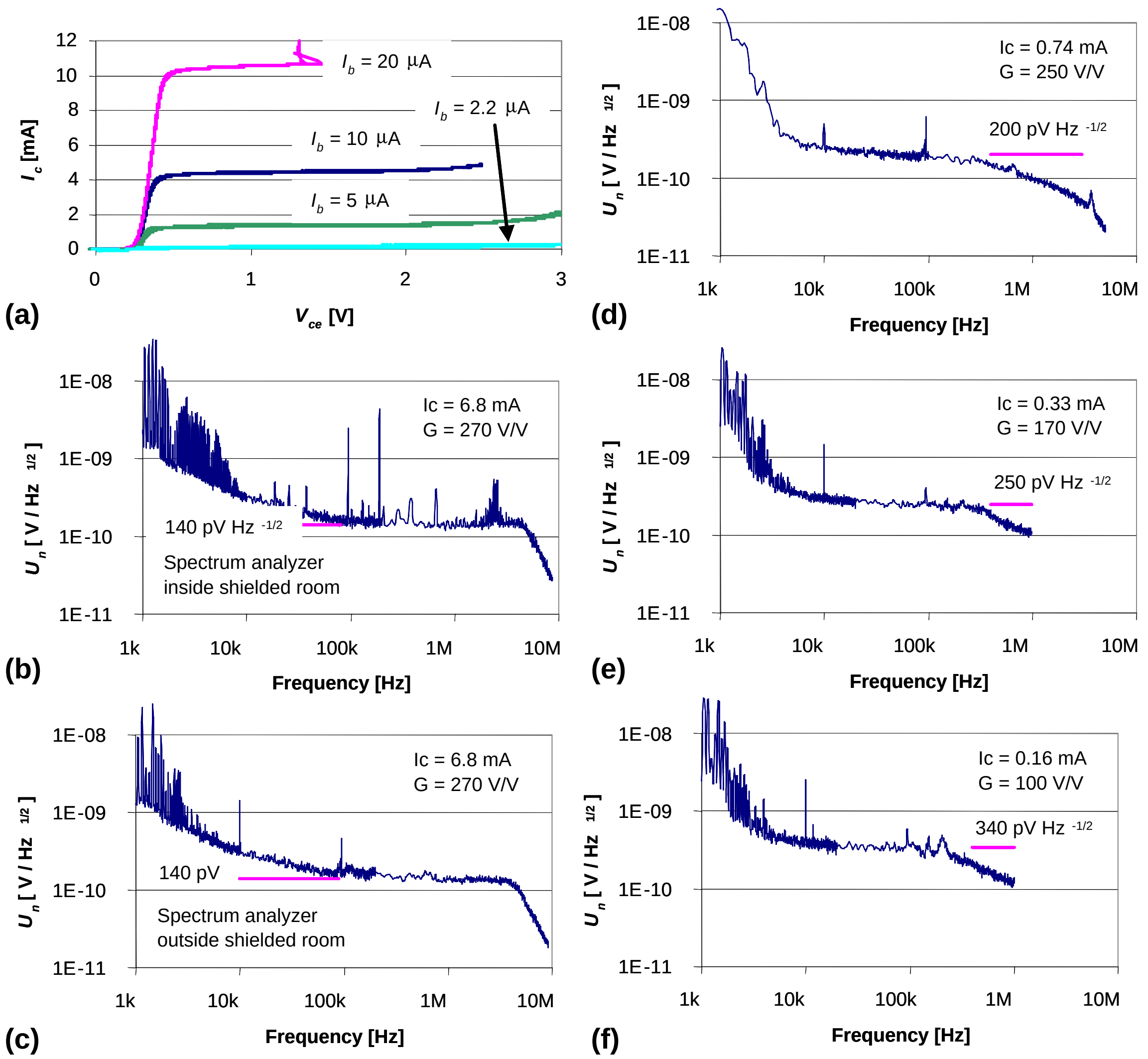

Figure 9: (a) Collector voltage to collector current characteristics of the BFP650 transistor measured at 4.2 K for various base currents. (b-f) Measured voltage noise spectra at 4.2 K for various collector currents and V_{ce} = 1.5 V when input of the amplifier stage is terminated at a 3.3 Ω resistor.

The calculated noise temperatures (assuming that the current noise is only due to the shot noise of the base current) for the bias conditions in Fig. 8 are T_n = 12.0 K, 8.0 K, 8.6 K and 10.6 K from the highest to the lowest bias power, and the corresponding noise matching resistances are R_{opt} = 60 Ω, 180 Ω, 260 Ω and 400 Ω. The effect of the bias power to the transistor bandwidth is not known. The usable bandwidth of the transistor at reasonable bias powers is probably in the several GHz range, which would make possible SQUID feedback configurations with extremely high bandwidths. It is even conceivable to observe the Josephson oscillation of the SQUID directly, and measure the J-frequency instead of the SQUID voltage for readout.

CONCLUSION

I have observed that the Infineon BFP650 SiGe transistor at 4.2 K has a voltage noise of 0.14 nV / √Hz and 1/f corner of about 100 kHz when operated at 9 mW bias power. Lower bias power levels down to 0.1 mW range appear usable, with an associated advantage of reduced 1/f corner frequency. Furthermore, I have used the SiGe transistor to read out a washer-type dc SQUID at a 0.35 $\mu\Phi_0$ /√Hz flux noise level. When operated with short negative feedback, a multiloop type SQUID reached a 5.5 Φ_0 dynamic range at 500 kHz excitation before visible evidence of unlocking occurred. The flux-locked frequency response suggests larger than 5×10^7 Φ_0/s slew rate. Even such a slew rate is modest compared with the potential of the SiGe device, realization of which would require more experimenting.

ACKNOWLEDGEMENTS

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SUPPLEMENT

Improved bias circuitry constructed after the WOLTE workshop facilitated 75 pV/rtHz voltage noise level. Contrary to the workshop presentation the 1/f noise *does not* improve at low bias powers and the base shot noise acting on the input capacitance *does not* explain the low-frequency 1/f^2 noise.