DESIGN AND FABRICATION OF A HTC QUASI-ONE JUNCTION SQUID BASED COMPARATOR FOR A 4-BIT SUPERCONDUCTIVE FLASH A/D CONVERTER

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Abstract--A design of a comparator for an all HTC superconductive 4-bit flash A/D converter is proposed and discussed. The design has been simulated and optimized using the PSCAN computer package [1,2]. The required junction and circuit parameters are thus calculated and compared with the experimental junction parameters. The operating temperature is intended to be as high as 40 K. Due to the current noise-level at these temperatures the I_c of the junctions should be higher than 100 μ A. The output voltages should be of the order of 500 μ V and higher. The junctions in the quasi-one junction SQUID are structured on 2 ramp-edges. The operating frequencies will be below 1 MHz in this first design. Optimization to the GHz range seems very well possible. A first realization uses the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) superconductor and $\text{PrBa}_2\text{Cu}_3\text{O}_{7-x}$ (PBCO) as junction barrier and electrode inter layer material. On a $10 \times 10 \text{ mm}^2$ SrTiO_3 (001) substrate, 9 comparators and 4 separate ramp-edge junctions are realized. This relative large number of elements on a wafer should allow us to extract statistical information on the scattering of properties due to the fabrication processes.

I. INTRODUCTION

The basic element in the flash A/D converter is the comparator, which is a one-junction SQUID, as proposed by Ko [3,4]. This device converts the analog input current to a periodic junction current I_j [5]. In order to sample the junction current, the basic one-junction SQUID is extended with an additional junction, the so-called sample junction J_s . This circuit, a quasi-one junction SQUID (QOS), is drawn in fig. 1.

The basic equation for this QOS circuit, using a DC approximation, is:

$$\varphi_a - \varphi_0 = \beta_L \sin \varphi_0 + \arcsin \left[\frac{I_b + I_0 \sin \varphi_0}{I_s} \right] \quad (1)$$

which can be approximated for low bias currents by:

$$\varphi'_a - \varphi_0 = \beta'_L \sin \varphi_0 \quad (2)$$

Fig. 1 Equivalent circuit of the quasi-one-junction SQUID. The junctions J_0 and J_s have critical currents of respectively I_0 and I_s , where $I_0 < I_s$.

in which

$$\varphi'_a = \varphi_a - \arcsin \left(\frac{I_b}{I_s} \right), \quad \beta'_L = \beta_L + \frac{\left(\frac{I_b}{I_s} \right)}{\sqrt{1 - \left(\frac{I_b}{I_s} \right)^2}} \quad (3)$$

In these equations $\varphi_0 = \sin^{-1}(I_0/I_0)$ is the phase of the junction J_0 with critical current I_0 , I_s the critical current of junction J_s , $\varphi_a = 2\pi L I_a / \Phi_0$ and $\beta_L = 2\pi L I_0 / \Phi_0$, where Φ_0 is the flux quantum. The current through J_s is sampled by periodically applying a current pulse to the bias input I_b . In a well trimmed circuit the pulse applied to the QOS will let J_s switch periodically with the input current to the voltage state. The current period is Φ_0/L , as can be concluded from the equations above. As proposed by Ko [4], trimming can be performed by adjusting the DC-bias current such that at $I_a = 0$ the junction J_s switches, due to thermal activation, to a voltage state for 50 % of the applied pulses.

This parallel-like A/D conversion scheme requires 4 comparators for 4-bit A/D conversion. To obtain a Gray-coded output signal, the input of the N^{th} comparator, responsible for bit N (where $N=1$ and 4 for respectively the least and most significant bit) has to be connected to 2^N times the current to be sampled. In the next sections, an all HTC QOS design will be presented, which is similar to the designs based on the classical superconductor Nb [3,4,6,7,8,9]. The design of the input signal dividers, as well as all other elements needed in a complete A/D converter, are beyond the work presented here.

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II. DESIGN

The design of a QOS operating at relatively high temperatures is facing the problem of thermally induced switching of the junction current when using a low critical current junction. The noise sensitivity is determined by the barrier energy with respect to the thermal energy $E_J/E_{th} = \Phi_0 I_0 / 2\pi k_B T$. For proper operation this factor should have a high value. Assuming a value of $E_J/E_{th} = 100$, the critical current I_0 should be higher than 17.6, 168 and 322 μA , respectively for temperatures of 4.2, 40 and 77 K. Because the QOS threshold curve should be single valued, β_L should be smaller than 1, for high frequency operation in the GHz range preferably less than 0.5 [3,4]. From this the maximal allowed value of the loop inductance can be estimated at 1.65 pH for $I_0 = 100 \mu A$. This small inductance can not be implemented by using holes or washers, because the structure containing the Josephson junctions should be of (sub)micrometer dimension. In this design an inductance implemented as a stripline above a ground plane is proposed to realise the inductance of the order of 1 picoHenry in the QOS. The thus obtained inductances can be estimated using the approach of Chang [10]. In the calculations of the stripline inductances, a penetration depth of $\lambda = 145$ nm was used for the superconductor at 40 K. The typical inductance is estimated at 0.13 pH/ μm for a stripline of width $w = 5 \mu m$, superconducting electrode thicknesses of 100 nm and an interspacing of also 100 nm. The junctions are ramp type YBCO/PBCO/YBCO junctions [11] and in this QOS design located on two different ramps, as can be seen in fig. 2. In this figure the inductance, as lumped circuit element between the two junctions, is clearly visible. For frequencies higher than 1 MHz another design using a separate ground plane will be necessary.

According to Gao [12], the junction capacitance is estimated at 10^{-14} F, using the RSJ model and the hysteresis of the IV curve at 4.2 K. The capacitance parallel to the junctions, due to the two superconductive thin films separated by a thin inter layer, is much higher. This parasitic parallel capacitance is of the order 1 pF for typical overlap areas of $10^3 \mu m^2$ and a 100 nm thick inter layer (using 10^{-7} Fcm $^{-2}$ and a dielectric constant 3 to $4\epsilon_0$). The McCumber hysteresis parameter β_C has a high value due to a relative high R_N and C value. Assuming $R_N = 10$ -100 Ohm, according to Gao [12] for this kind of junctions, $\beta_C = 30$ to 3000 ($I_0 = 100 \mu A$, $C = 1$ pF). This β_C value can be reduced in a future design by carefully minimizing the overlap of the electrodes.

III. FABRICATION

The fabrication of the quasi-one junction SQUIDS is similar to the process of single ramp type junction fabrication. An additional ex-situ process step is involved to produce the second ramp for the sample junctions J_s . For

Fig. 2 Lay-out of the all HTC QOS design, based on 2 ramp type YBCO/PBCO/YBCO junctions and a stripline inductance.

Table 1. Sputter parameters

Sputter pressure (Pa)	7
Gas mass flow Ar:O ₂	15:4
Heater temperature (°C)	740 (YBCO) 640-740 (PBCO)
Sputter power (J/s)	90
Distances to target centre	
radial (cm)	8
axial (cm)	4
Deposition rate (nm/hr)	12-15
Presputter time (hr)	¼
Cool down	in 20 kPa O ₂ atmosphere to 400 °C during ½ hr., to room temperature during ½ hr.

clarity, the fabrication contains the following process steps. (1) Sputter deposition of an YBCO/PBCO double layer. The settings for the YBCO/PBCO sputter deposition are presented in Tab.1. (2) Definition of the first ramp edge by photo lithography (PL) and ion-beam milling. The ion-beam milling is performed with a Kaufman source, operated in pulsed mode (on 8 sec., off 10 sec.), a beam voltage of 500 V and a beam current of 10 mA. The incident angle of the beam on the sample is 45°, resulting in an etch rate of 5 nm/pulse. (3) Definition of the second ramp edge, as in step (2). (4) Ion-beam cleaning (in situ) of the ramp edges, immediately followed by sputter deposition of the PBCO junction barrier and the YBCO counter electrode. Cleaning consists of a sequence of 4 and 2 ion-beam pulses at respectively a beam voltage of 500 and 200 volt. In order to avoid contamination on the ramp edges, and thus in the junction barrier, the cleaning is performed at low angle of incidence to the substrate (about 15°) and parallel to the edges. (5) Sputter deposition of Ti/Au electrical contacts and definition by lift-off. (6) PL and ion-plasma etching through the YBCO top electrode. This last etching step is performed in a parallel plate reactor at a rf sputter power of 80 Watt (on 5 sec., off 10 sec.), a self-bias of 610 V and an argon pressure of 2.5 Pa. The resulting etch rate is about 8 nm/min. In this

final step the junctions, including voltage and current paths as well as the stripline inductance located in between the two junctions on top of the PBCO inter layer, are structured.

IV. RESULTS

A. Simulations

The simulations of the quasi one-junction SQUID have been performed using the PSCAN package [1,2]. The units of current and voltage in the simulations were respectively 0.1 mA and 0.1 mV, resulting in units of resistivity, inductance, capacity, frequency and time which are respectively 1 Ohm, 3.295 pH, 3.295 pF, 0.304 THz and 3.25 ps. The transient response of the current through junction J_0 on a sinusoidal input current I_a of 100 MHz is shown in Fig. 3. For this circuit, using the realistic parameters ($\beta_L = 0.5$, $\beta_{C0} = 30$, $\beta_{Cs} = 3$, $I_0/I_s = 10$ and $I_c R_N = 1\text{mV}$) as determined in the second paragraph, a smooth and nice response is visible on the sinusoidal input current with amplitude 5 mA (corresponding to exact $4\Phi_0$). With the same parameters but at a frequency of 1 GHz, some oscillations of the junction current I_{J0} occur after this current has changed sign and especially at moments when the input current rapidly changes value. This is also visible in Fig. 4, in which the dynamic response is presented for a sinusoidal input current I_a of 1 GHz and an equivalent amplitude $\Phi_a = LI_{a,\text{max}} = 4\Phi_0$. From this figure it can be observed that, although the static response curve (dashed line) shows no hysteresis, because $\beta_L = 0.5 < 1$, the dynamic curve at 1 GHz (but also at a several 10 MHz) does. This inherent dynamic behaviour of the circuit is probably within acceptable limits up to 1 GHz, as reported by others [4,9].

An example of QOS response on a sinusoidal input current I_a and a pulsed current applied to the bias input is presented in Fig. 5. The junction parameters are the same as in Fig. 3 and 4. The frequency is 10 MHz however, and the amplitude of the sinusoidal input current is equivalent to $1\Phi_0$. The sample pulses, applied on the bias input, have a frequency of 500 MHz (50 pulses/period, pulse width 200 ps) and an amplitude equal to the critical current of junction J_s . As can be seen in Fig. 5, the QOS responds with voltage pulses that are periodic with the input current I_a . Switching of J_s to the voltage state, as response on an applied pulse, is observed in the dynamic simulations in particular at input currents I_a for which the flux in the QOS is about $(2m \pm 1)\Phi_0/2$. This dynamic response on short pulses is slightly different from the expected behaviour within a static model, which also neglects the parallel current path through J_0 and L . In that case switching of J_s to the voltage state can be expected when the current through J_s is positive, which occurs when the applied flux is $0 < \Phi < \Phi_0/2$ ($\pm m\Phi_0$). As mentioned before, fine tuning to obtain a real periodic pulsation of the QOS can be achieved by changing the pulse amplitude and the DC bias level.

Fig. 3 Transient QOS response of the current through J_0 (solid) on a 100 MHz input current of amplitude $4\Phi_0/L$ (dashed). For parameters see text.

Fig. 4 Dynamic response (solid), I_{J0}/I_0 versus Φ_a/Φ_0 for an input current of 1 GHz and amplitude $4\Phi_0/L$. The static response is dashed. For parameters see text.

Fig. 5 QOS response on input current (dashed) of 10 MHz and pulses on the bias input, showing output voltage pulses (upper solid). The junction current I_{J0} is given by the lower solid curve.

B. Experimental

In a first attempt to realise a QOS it was found that it is very important to deposit particle free films of YBCO and PBCO. Films containing crystallites are not suited for use in a comparator of the proposed design, because of the induced shorts in the electrode overlap area and the non-reproducible and uncontrollable junction properties. As an example, the top view of a structured QOS is shown in Fig. 6. As can be seen in this figure, the YBCO/PBCO/YBCO films have many granular out-growths. This problem can be solved by optimizing the deposition conditions as has been shown in the past [11,12].

Fig. 6 Top-view on structured QOS. The junctions J_0 and J_1 are located on resp. the left and right edge. The stripline inductance is in between the junctions.

V. SUMMARY AND CONCLUSIONS

A design of an all HTC QOS, intended for use in an A/D converter, is presented. Ramp type junctions of YBCO/PBCO/YBCO are used. The inductance can be realised by a stripline between the junctions. Simulations by the PSCAN package show correct behaviour of the QOS up to frequencies of approximately 1 GHz. The output voltage pulses are periodic with the input current, as expected. In the dynamic simulations, output voltage pulses are observed at an applied flux of around $(2m-1)\Phi_0/2$. This value is slightly shifted compared with the value expected from a static QOS model, which predicts an applied flux value for pulse-induced switching between 0 and $\Phi_0/2$ ($\pm m\Phi_0$). A first realisation shows the importance of a smooth YBCO/PBCO multi layer structure. Granular films with out-growths are not applicable due to the many resulting shorts in the relative large electrode overlap area and the uncontrollable junction parameters.

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