Superconducting Electronics

Horst Rogalla

University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands

During the last decades superconducting electronics has been the most prominent area of research for small scale applications of superconductivity. It has experienced quite a stormy development, from individual low frequency devices to devices with high integration density and pico second switching time. Nowadays it offers small losses, high speed and the potential for large scale integration and is superior to semiconducting devices in many ways - apart from the need for cooling by liquid helium for devices based on classical superconductors like niobium, or cooling by liquid nitrogen or cryocoolers (40K to 77K) for high- T_c superconductors like $\text{YBa}_2\text{Cu}_3\text{O}_7$. This article gives a short overview over the current state of the art on typical devices out of the main application areas of superconducting electronics.

INTRODUCTION

Superconducting electronics devices are around since quite a long time. In their early days such devices made use of heat or a magnetic field to switch between the normal and superconducting state [1,2]. Both methods are quite slow and/or the resulting resistance change is small (superconducting to vortex flow state). With the prediction of the Josephson effect in 1968 [3] and its experimental verification shortly afterwards [4], a fast 2-terminal switching device with a number of very interesting and unique properties became available. A new area in superconducting electronics began, the Josephson electronics [5]. Josephson junctions were primarily made from lead or later niobium, the classical materials for superconducting electronics. Based on such junctions, many different devices were developed. The most important areas of interest were: sensors (e.g., x-ray detectors and SQUIDs), digital devices (e.g., gates and flip-flops) and high frequency devices (e.g., detectors, mixers, and oscillators up to about 500 GHz).

With the invention of the copper oxide superconductors [6] by Bednorz and Müller in 1986, a further important step towards a broader application of superconducting electronic devices was done. The workhorse of current high- T_c superconducting electronics, the $\text{YBa}_2\text{Cu}_3\text{O}_7$ with its T_c of 92K, opened the possibility to operate superconducting devices in liquid nitrogen at 77K. Apart from a higher operating temperature also a larger energy gap should be available at low temperatures. Such an energy gap could cut the switching time by at least a factor of ten and extend the maximum frequency of high frequency devices by a factor of ten up into the TeraHertz range. These possibilities are currently verified, step by step, as the understanding and the preparation methods of these new materials become better.

Although a lot remains to be done on the fundamental research of superconductivity, many results of the applied laboratories have lead to first demonstrators or first commercial applications. To put this development on a sound base, superconducting electronics engineering as a part of cryogenic engineering has to develop the tools for the design of standard circuits and their layout, packaging and cooling, to provide the tools for simulation and the standards for the quality control. This is especially necessary for the high- T_c superconductors. It would be another very important step to the industrial commercialization of superconducting electronics. With a few examples, where engineering needs played a major role in the applied research, this article will give a short overview over the status of superconducting electronics.

MATERIALS

After many years of small enhancements in T_c up to 23K (the A15 superconductor Nb_3Ge [7]), the materials' development in terms of T_c took an incredible jump forward in the few years since the finding of high- T_c superconductivity by Bednorz and Müller. In Fig. 1, T_c is plotted against the year of the finding of the superconductor. The highest T_c reported and verified so far is that of $HgBa_2Ca_2Cu_3O_{8+\delta}$ with 133K [8]. Nevertheless, the workhorse of high- T_c superconductivity is still the $YBa_2Cu_3O_7$ with a T_c of 92K, found in 1987 by Chu [9]. Most of the current high- T_c superconducting electronic devices are based on this material. Nevertheless, most superconducting electronic devices are still based on Nb.

This is similar to the situation for large current applications, where most devices still use the classical superconductor NbTi, although Nb_3Sn is long known and highly developed.

With its mechanical and electrical stability, Nb is resistant against thermal cycling, very much in contrast to lead, the material of choice in the 1970ties and the material used in the failed computer project of IBM [10]. With its T_c of 9.2K Nb is very well suited to operate in liquid helium at 4.2K at a reduced operating temperature $t=T/T_c$ of 0.6. At such a reduced temperature the electrical properties are only weakly dependent on the temperature, so that small temperature fluctuations do not influence the operation of a device. This is very much in contrast to the operation of $YBa_2Cu_3O_7$ in liquid nitrogen. A temperature of 77K corresponds to a typical reduced temperature of 0.91 for multilayer thin film devices with a T_c of about 85K. Then all properties are strongly dependent on the temperature and small temperature variations can already affect the operation of devices, e.g., increase the low frequency noise of superconducting sensors. The consequence of this argumentation for $YBa_2Cu_3O_7$ devices of some complexity: (1) Reduce the operating temperature to about 50K that is easily reachable by cryocoolers or (2) switch to the Bi- or Hg-compounds and thus work at a reasonable reduced temperature. The first consequence is easy to

Figure 1 : Critical temperature T_c as function of the year of the finding of the superconductor. Note the logarithmic scale in T_c .

Figure 2 : Critical current as function of an external field for a specially shaped Josephson junction. In the insert the dependence for a square junction is shown.

achieve from the material's side, but requires some work on the cryocoolers in terms of mechanical and magnetic noise. The second consequence implies nearly no research on cooling, but much research on the material's side for these highly layered compounds. It is a long term goal but then really fulfills the promise of operation of complex superconducting circuits in liquid nitrogen.

SENSORS

Superconducting sensors belong to the most sensitive devices available. In general, they make use of tunneling (e.g., x-ray detectors) or its combination with phase coherence effects (e.g., Superconducting Quantum Interference Devices or short, SQUIDs [11]). In both device areas huge progress has been made in the last years. SQUIDs are already commercially available in a number of applications, from rock magnetometers and current comparators to complex multisensor biomagnetic systems for the analysis of the magnetic activities of the human heart and brain. X-ray detectors are on the way to reach their design resolution and efficiency and are likely to be applied in x-ray space telescopes in a number of years. Here two examples will be given, one for x-ray detectors and one for SQUIDs, how the cooperation between physics and engineering can help to reach the design goals.

The absorption of an x-ray photon in one of the electrodes of a Josephson tunnel junction generates there a great number of quasiparticles by pair breaking. X-ray detectors detect these quasiparticles by the enhanced subgap tunneling current through a current biased Josephson tunnel junction. The Josephson supercurrent through the junction is highly unwanted. One can suppress it by a magnetic field since the dependence of the maximum supercurrent through a junction with square footprint is Fraunhofer like:

$$I_c = I_{c0} \sin \frac{\pi \Phi}{\Phi_0} / \frac{\pi \Phi}{\Phi_0}$$

The zero locations are very sharp and a good suppression of the supercurrent is only reliably possible at sufficiently high fields, when the current maxima are already quite low. In a laboratory environment difficulties with frozen flux and Fiske resonances are unwanted, but in a space environment they could hamper the operation completely. Changing the shape of the junction to a "quartic" shape, can nearly fully suppress the current of the first order maximum (see Fig. 2) [12,13]. The supercurrent can be suppressed with a much smaller field and the mentioned side-effects are weaker. In terms of reliability this shape engineering is an essential step for a remote operation of an x-ray detector.

Figure 3 : Schematic view of a classical dc SQUID with pick-up coil, its voltage response to an external field, and the corresponding IV-curves for shunted and unshunted Josephson tunnel junctions.

Figure 4 : Schematic view of a 1 channel DROS system with voltage readout for biomagnetic applications.

In the second example the engineering need is not only increased reliability, but also a reduction in system complexity and cost and extension of the operating time due to reduced heat input. The current tendency in magnetic imaging of the brain and heart goes towards biomagnetic SQUID systems with more and more channels. Already 256 channel systems are under development. Mostly dc-SQUIDs are currently used with flux and bias current modulation and resonant transformer or low impedance low noise input amplifier. In Fig. 3 a schematic drawing of a typical 1-channel system is depicted. It should be mentioned that the voltage leads from the SQUID have to be low-ohmic and thus introduce heat into the cryostat. Imagine the complexity of, e.g., a 256 channel system, the heat input and all the electronics needed. One very interesting possibility for a drastical improvement is the change of the sensor readout, making use of relaxation oscillations [14]. A current biased hysteretic dc-SQUID shunted with a series connection of a resistor R and an inductor L (relaxation oscillator SQUID or ROS) oscillates at a frequency f_r [15] :

$$f_r = \frac{1}{t_o + t_v} \quad \text{with} \quad t_o = \frac{L}{R} \ln \frac{I_b}{I_b - I_c(\Phi)} \quad \text{and} \quad t_v = \frac{L}{R} \ln \left(\frac{RI_c(\Phi)}{V_g - I_b R} + 1 \right)$$

Here $I_c(\Phi)$ is the flux dependent critical current of the SQUID and V_g the sum gap voltage. Flux coupled into the ROS changes the effective critical current and thus also its oscillation frequency and its mean dc voltage. Frequencies of 1 GHz are easily obtainable. A series connection with a second SQUID (double relaxation oscillator SQUID or DROS) keeps all the attractive properties but adds an improved transfer coefficient : a steepness of $50 \text{ mV}/\Phi_0$ can be reached. This results theoretically in an energy resolution of about $10h$ for the 1GHz version, h being Plank's quantum. This value has experimentally been verified [16]. Fig. 4 shows the schematic of a typical 1 channel system. For the readout only a standard low-noise operational amplifier for the amplification of the input signal and another one for the feedback integrator are needed. Due to the high signal voltages and low currents all input leads into the cryostat can be realized with, e.g., manganin wire, thus drastically reducing the overall heat input in a multichannel system. The changed read-out system thus easily fulfills the engineering requirements for a multichannel system by keeping the high sensitivity of the system: field sensitivities of about $3 \text{ fT}/\sqrt{\text{Hz}}$ have been realized.

DIGITAL CIRCUITS

Besides their outstanding properties as sensors, superconductors also offer the possibility of very fast switching

devices and the transmission of signals with low dispersion up to very high frequencies. For classical superconducting devices based on Nb Josephson junctions switching times of few picoseconds have been realized. For high- T_c superconductors with their in principle larger gap, switching times could be shorter by a factor of more than 10. This has not yet been realized since currently available high- T_c Josephson junctions mostly show gap values comparable to those of classical junctions.

In general, two classes of digital circuits have been developed, latching and non-latching ones. Latching circuits have been realized in many ways, e.g., as magnetically coupled SQUID gates or as directly coupled current-injection gates. The latter ones were used in the Japanese project for a superconducting microprocessor [17]. The measured performance of a 4-bit processor was: maximum clock rate 770MHz at a dissipation of 5mW. A comparable microprocessor in GaAs-technique allowed a maximum clock rate of 72Mhz at 2.2W power dissipation. Further development is still going on, for instance at the ETL in Japan.

For non-hysteretic Josephson junctions, like high- T_c junctions in general, only non-latching circuits can be applied. In this class the rapid single flux quantum (RSFQ) logic [18] is the most prominent one. It makes use of flux quantization in conjunction with Josephson junctions. If the number of flux quanta changes in a superconducting ring containing a Josephson junction, a short voltage spike appears, which can be transmitted to other gates and can be used for logical combinations with other voltage spikes from other sources. The pulses are very short which gives a speed advantage, but which is also the source for a major difficulty in more complex circuits. The pulses have to be at the gate within a short time window. Pulse shaping and stretching and careful design in terms of transmission time helps to realize very fast specialized computer circuits, e.g. for high speed data switches. Larger parts of more general (super)computers are unlikely to be realized with RSFQ due to the mentioned difficulties.

A further very interesting application lies at the interface between analog and digital signals: the analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). Rapid conversion times would open the possibility of digital signal processing in the frequency range of up to 100GHz. Fast switching times are inherent in the RSFQ-like logic and in the near future a number of ADCs can be expected which open this frequency range. In Fig. 5 the scheme of a 'quasi one junction' digitizer is shown together with a realization using high- T_c ramp type Josephson junctions [19]. These digitizers can be used in parallel with Gray code weight to increase the digital resolution without sacrificing speed. Such devices have been successfully tested and are further developed and evaluated together with the electronic industry.

Figure 5 : Schematic of a quasi-one-junction digitizer (top) and realization with high- T_c ramp type Josephson junctions.

CONCLUSION

Superconducting electronics is a highly developed area of superconductivity research, both, in the material science aspects (e.g., epitaxy of multiple layers of perovskites) and solid state physics and solid state electronics aspects (e.g., transport properties and switching behavior). In future, a broader engineering base without too much scientific overhead has to be developed to make these techniques available to commercial production.

Devices which do not simply copy semiconductor circuits but use inherent superconductor features such as phase coherence are especially promising candidates for a broader industrial application. SQUIDs have quite a potential in non-destructive testing and biomagnetism. Fast digital circuits based on RSFQ or current-injection gates are likely to be used in specialized applications like fast data switches and ADCs/DACs. Also an application of high- T_c digital circuits in central processing units could be reality some day if semiconductors have to be cooled to liquid nitrogen temperature to reach the necessary speed. Recently, some progress has been made with high- T_c three terminal devices like superconducting field effect and current-

injection transistor. Reasonable power gain is likely to be obtained in these devices in future.

Urgently needed are cryocoolers for the operation of classical ($T_c \approx 5K$) and high- T_c superconductors ($T_c \approx 40K$). Two major design areas can be identified: small and cheap cryocoolers for 'throw away' applications like mine detection or oil field exploration and reliable cryocoolers which allow service access for general use (e.g., laboratories and hospitals). Independent of the price these cryocoolers have to be magnetically and acoustically low noise devices in order not to interfere with the sensitive superconducting electronics devices.

ACKNOWLEDGEMENTS

This work was supported by the dutch National Research Program on High- T_c Superconductors. My special thanks are due to Dr. D.H.A. Blank for his help with the illustrations.

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