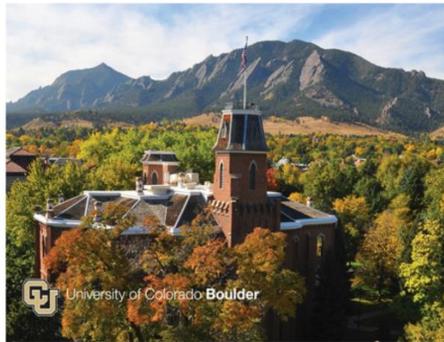


Superconductive Electronics with High- T_c Superconductors



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University of Colorado

(ECEE Department)

and

NIST

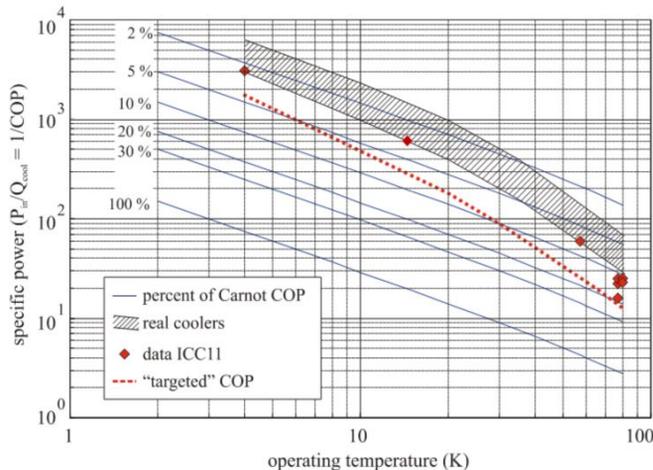
(Superconductive Electronics)

Boulder, USA



For inquires and comments, please send email to hrogalla@boulder.nist.gov .

Specific cooler input power



The need to cool Low- T_c superconducting devices to liquid helium temperature (4.2 K) or below strongly limits its usability – liquid helium containers are not easy to transport and pose a safety risk in closed environments. The use of cryo-coolers can help, but their use is limited to more or less stationary applications in laboratory environments as long as the operation temperature is 4.2K or below. If one could operate the devices at higher temperature, the cooling requirements would become less stringent and the superconductive electronics systems could find much broader applications.

The diagram¹ demonstrates the big advantage of higher operating temperatures: it shows the cooler input power for 1 W of cooling as function of the operating temperature. The specific cooling power at 4.2 K is about 3 kW; the compressors for these cryo-coolers are quite bulky and can be noisy.

If one increases the operating temperature to 15 K, the specific cooling power is reduced to 600 W – already a significant increase in usability: rack mounting of the whole system is possible. If one further increases the operating temperature, e.g. to 77 K, the electrical input power drops to less than 30 W and makes desktop and even battery operated applications possible.

Starting in the 60's, when new superconducting materials with higher T_c were found, work started in order to adapt these materials to superconductive electronics applications. One of the first applications was a SQUID made from Nb_3Sn by Wu and Falco² at Argonne National Laboratory in 1977.

¹ Slide made available by ter Brake, University of Twente, The Netherlands

² C.T. Wu and C.M. Falco, Appl. Phys. Lett. **30**, 609 (1977)

Early 'HTS' attempts

The old High- T_c materials

In the years before 1986 the materials with the highest T_c were the A15 compounds Nb_3Sn and Nb_3Ge . Both were investigated for applications in SE:
 Nb_3Sn in Stanford by the group of Mac Beasley and
 Nb_3Ge by my group in Giessen, Germany.

Both materials are high- κ materials:

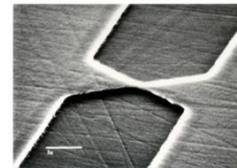
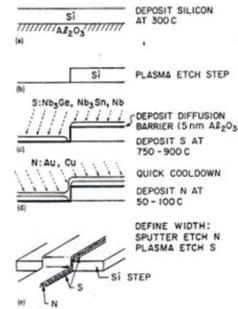
$$Nb_3Sn \quad \lambda = 50\text{nm} \quad \xi = 5\text{nm}$$

$$Nb_3Ge \quad \lambda = 90\text{nm} \quad \xi = 3\text{nm}$$

=> Tunnel junctions are extremely difficult to realize !!



=> SNS-junctions or nano-bridges



In the 1980's the effort to enhance the operation temperature of superconductive electronic devices increased: the group of Beasley at Stanford and my group in Giessen/Germany worked on the fabrication of Josephson junctions and SQUIDs from the A15 materials Nb_3Sn (T_c of 18.3 K) and Nb_3Ge (T_c of 23.2 K), respectively. Tunnel junctions from these materials are extremely difficult to fabricate – the high deposition temperatures for A15 materials starts chemical reactions at the interface with the barrier material and the diffusion is not negligible.

The Stanford group choose the route for Josephson junction fabrication via SNS-junctions¹: they etched a step in the substrate and used shadow technique to deposit Nb_3Sn on the planes, but not on the step. Then they deposited a Au- or Cu-layer across the step and thus created a Nb_3Sn -Au- Nb_3Sn SNS Josephson junction.

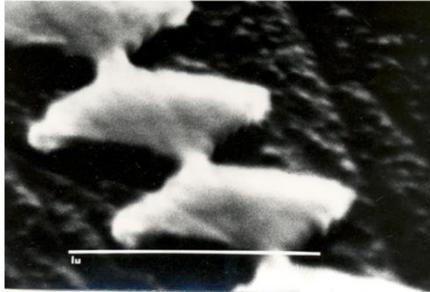
In Giessen we choose a different route to reach the highest operating temperature possible at that time: Nb_3Ge has a T_c of 23.2 K, and as thin film a T_c of about 21 K can be reached. Using coherent vortex motion in nano-bridges allows Josephson junctions that can be operated nearly to the T_c of the superconducting films. I converted an old SEM with beam blaker to an electron beam writer, that allowed us to make structures down to 40 nm; better than the 100 nm we needed for coherent vortex motion in a hyperbolic Nb_3Ge nano-bridge.

Together with Bernd David², we made first Nb_3Ge nano-bridge SQUIDs that we operated in liquid hydrogen at 20.2 K.

¹ A. De Lozanne, M. Dilorio and M.R. Beasley, Physica B+C, 108, 1027 (1981)

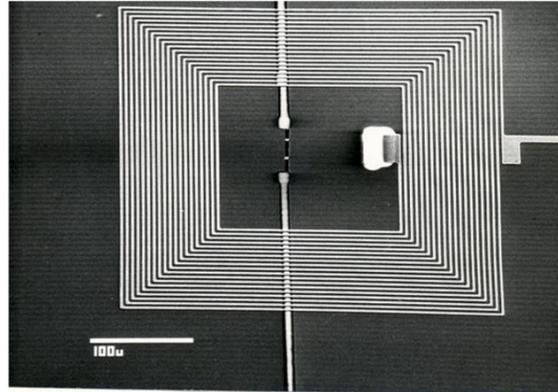
² H. Rogalla and B. David, J. Appl. Phys. 55, 3441 (1984)

First 'HTS' (Nb₃Ge) Applications



Serial array of Nb₃Ge nanobridges

H. Rogalla, B. David, M. Mueck (1985)



Integrated Nb₃Ge nano-bridge dc-SQUID operated in liquid hydrogen up to 20K



University of Colorado
Boulder



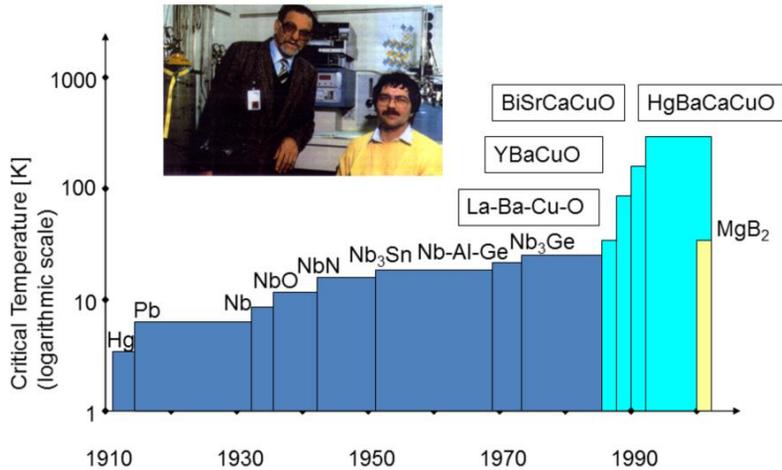
The Nb₃Ge nano-bridge technique turned out to be very powerful and we were able to create many junctions in series with a T_c close to 20 K.

An important step towards an integrated superconductive electronics is the availability of a multilayer technique. We found that a sputtered amorphous interlayer resisted recrystallization and chemical reaction with Nb₃Ge long enough to deposit a 2nd layer of Nb₃Ge onto it and that etching openings in the interlayer resulted in vias between the layers with high critical current density.

Applying the Nb₃Ge multilayer technique, we fabricated a first fully integrated Nb₃Ge SQUID of the Ketchen-type which operated at temperatures up to 20 K.

¹ H. Rogalla, B. David and M. Mück, in "SQUID '85 Superconducting Quantum Interference Devices and their Applications", ed. H.-D. Hahlbohm and H. Lübbig, Walter de Gruyter, 671 (1985)

Critical Temperature as Function of Time



The in 1986 the superconductive world changed dramatically, when Bednorz and Müller¹ published their article showing superconductivity in LaBaCuO near 30 K. And it changed even more dramatically when Chu et al.² showed superconductivity at 92 K in YBaCuO. Till then, T_c increased with time in a typical effort driven manner, linear in a semi-logarithmic plot of T_c as function of time. Within a few years T_c rose to 138 K (HgBaCaCuO) without pressure and up to 203 K (H₂S) with extreme pressure.

¹ J.G. Bednorz and K.A. Müller, Zeitschrift für Physik B64, 189–193 (1986)

² M.K. Wu, J.R. Ashburn, C.J. Torng, P.H. Hor, R.L. Meng, L. Gao, Z.J. Huang, Y.Q. Wang, C.W. Chu, Phys. Rev. Lett. 58, 908 (1987)

The Begin: How to fabricate a bulk YBCO sample

The following recipe holds for 0.1 mol $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$:

Dissolve BaCO_3 (5 mol l^{-1} , 39.47 g) in 60 ml nitric acid (65%) with 80 ml Q2-water and heat it.

Y_2O_3 (4 mol l^{-1} , 11.29 g) and CuO (5 mol l^{-1} , 23.86 g) are dissolved in 40 ml nitric acid (65%) each.

Fill the three liquids into one container, stir and add 126g of citric acid (stir) and neutralize with NH_4OH (25%) until the liquid is dark blue.

Heat the liquid in a Pyrex breaker until the pyrolysis starts.

(Step back not to burn your eye-brows and watch the pyrolysis reaction with your students: its fun to watch!)



Calcinate the powder for 10 hours at 920C, press it and sinter at 850C.



University of Colorado
Boulder

D. Blank et al.: Journal Physics D 21, 226 (1988)

NIST

National Institute of Standards and Technology

Just to make YBaCuO was simple – no need for ultra-high vacuum and complicated deposition techniques: just some chemicals could be wet-processed in a ‘cake-recipe manner’ and baked at high temperatures. This technical advantage had a bad science-policy consequence: since practically all laboratories could make it, a run on projects started and competence was not an important criterion anymore, but proposals with shiny promises in a time frame of months had a better chance than realistic ones with a time frame of many years. The downfall of High-Tc superconductive electronics was pre-programmed: many projects failed badly and funding became sparse. Only very few groups survived with funding that made long-term goals nearly impossible.

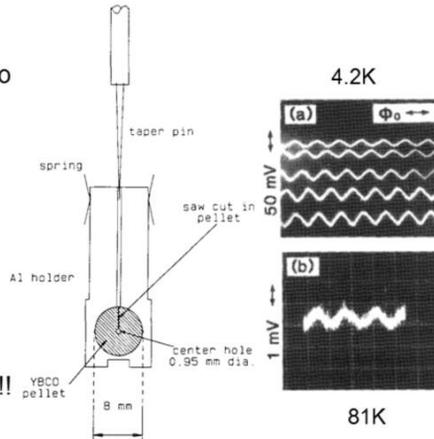
The Begin: How to fabricate an HTS-SQUID

Press and sinter powder into the form of a bulk cylinder,

drill a hole and cut partially with a thin saw.

Break the link and press it together again with an adjustable screw or taper.

Voilà – the SQUID is ready !!



Polycrystalline junctions



J. E. Zimmerman, J. A. Beall, M. W. Cromar, and R. H. Ono: Appl.Phys.Lett. 51, 617 (1987)

R.Koch, IBM; Twente (1987)

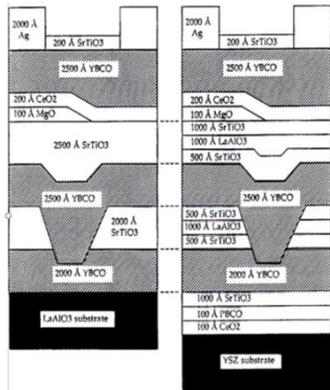


Once one had made a piece of YBCO one could show superconductivity with a levitating magnet - an excellent demonstration of superconductivity still widely used today. Jim Zimmerman in his very practical approach to science had the idea to make an rf-SQUID from such a piece of bulk polycrystalline YBCO: breaking the polycrystalline material and press it together in a controlled fashion created an adjustable 'break junction' showing Josephson behavior. Such a SQUID was shown to work even at 81K and could be used for the first rf-SQUID experiments in liquid nitrogen.

In 1987 thin films were deposited onto different single-crystal substrates in a 2-step process resulting in polycrystalline thin films. The grain boundaries worked as Josephson junctions and Roger Koch of IBM Yorktown Height and my group in Twente/Netherlands demonstrated dc-SQUID behavior in SQUID structures etched into such polycrystalline films.

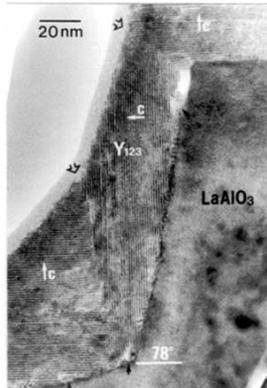
The Begin: Thin Film Josephson Junctions

Template Junctions

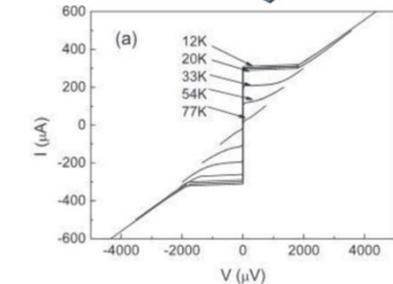
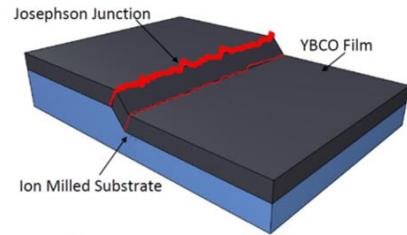


L.P. Lee, K. Char, et al. (Conductus Inc.)

Step-edge junctions



Jia et al. Physica C 175, 545 (1991)



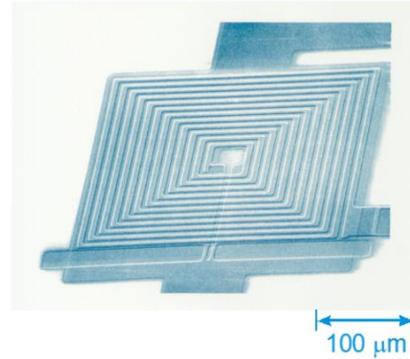
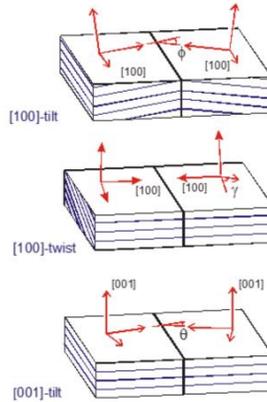
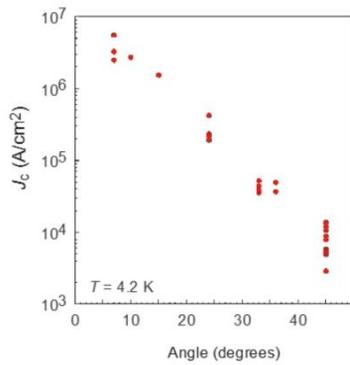
J. Du et al. Supercond. Sci, Technol. 21, 125025 2008.



Grain boundaries were and are still widely used as High- T_c Josephson junctions. Different techniques were developed over time to produce reproducible Josephson junctions this way: people at Conductus Inc. developed 'template junctions' using the change in orientation with which YBaCuO-films grew on single crystal CeO-films and other single crystal films like MgO. They also developed an advanced single crystal multilayer technology for the fabrication of superconductive electronics. 'Mr. SQUID', a simple dc-SQUID system for demonstration and educational purposes, has been developed in that time and is still available today.

An alternative technique leads to the the step-edge junctions. An YBaCuO-layer deposited onto a step, etched into a substrate (often MgO) with a sharp edge at the top and rounded at the bottom, results into two grain boundaries: a small one with a low critical-current density at the top and one with a high critical-current density at the bottom. Such junctions have excellent characteristics and a high T_c . Since the growth of the grain boundaries is still a quite random process, there is still quite some spread in the critical currents density of such junctions. The sketch of a step-edge junction by Shane Cybart demonstrates the randomness along the upper junction edge. Nevertheless, they are excellent for applications where such a spread is less important and where a high $I_c R_n$ -product and a high T_c is needed.

Bi-crystal Grain Boundary Junctions



Hilgenkamp & Mannhart, *Appl. Phys. Lett.* **73**, 265 ('98)

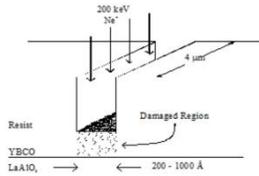
Dimos D., Chaudhari P., Mannhart J., Le Goues F.K.: *Phys. Rev. Lett.* **61**, 219 (1988)

H. Hilgenkamp et al.,
Appl. Phys. Lett. **64**, 3497 ('94).

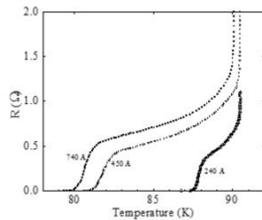
The currently most widely used grain–boundary Josephson junctions are the bi-crystal junctions, invented by Chaudhari, Mannhart et al. at IBM in 1988. The grain-boundary forms at the interface of two single crystal substrates, welded together under a well defined angle. Extensive investigation by Hilgenkamp and Mannhart showed that the critical current density through such junctions decreases linearly in a semi-logarithmic plot with the angle between the main axes of the bi-crystal. Thus the critical current density can already be determined to some degree by choosing the angle of the bi-crystal. A disadvantage for more complex applications is the linear geometry of the grain boundary.

In 1994, Hans Hilgenkamp prepared already a fully functional integrated dc SQUID in my group in Twente, using a bi-crystal substrate.

E-beam Patterned Ion-damaged Junctions



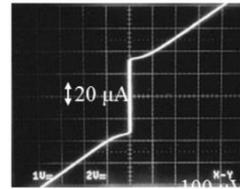
E-beam lithography and reactive ion etching used to unmask a small region to be damaged



The superconducting weak link critical temperature for three different lengths irradiated identically

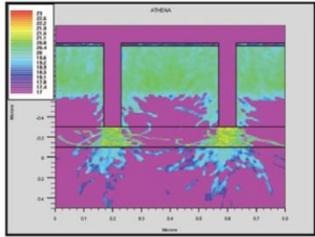
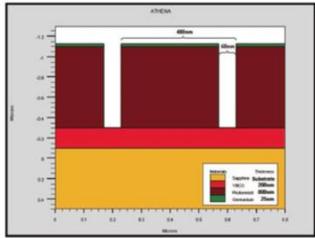


SEM Photo of the mask structure used for implanting a 100-junction array

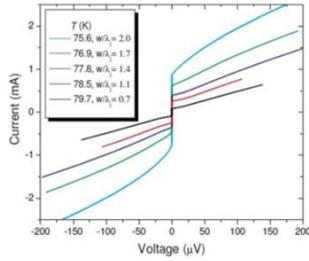


RSJ like I-V Characteristic for a single weak link.

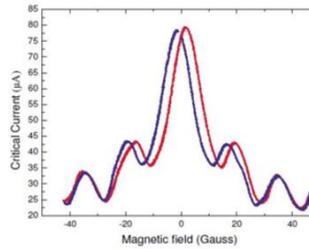
From early on some groups tried to create High- T_c Josephson junctions by controlled damaging a YBaCuO thin film with electron or ion beams. Especially the ion-beam work of Shane Cybart and Bob Dynes showed some promising results: they used e-beam lithography to create a very narrow slit in an electron beam resist and then used the slit as mask for a subsequent ion-bombardment step. The resulting junctions showed quite good IV-characteristics for higher dosages, but then also suppressed T_c .



Implantation Simulation
Thesis Cybart, UC San Diego 2005



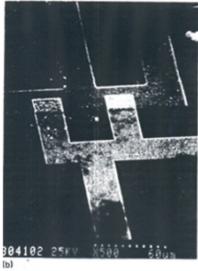
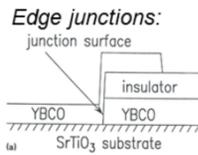
IV-characteristics
200 nm $\text{YBa}_2\text{Cu}_3\text{O}_7$ on LSAT,
implanted with $1 \cdot 10^{13}$
 Ne^+/cm^2 at 200 keV



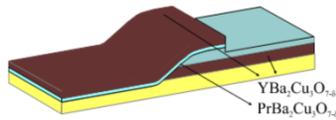
Fraunhofer pattern

The irradiation of the thin films was simulated by Shane Cybart. These simulations show the widening of the damaged area at the bottom of the film. At low dosages and/or low temperatures, the IV-characteristics don't look RSJ-like, but are flux-flow dominated.

Ramp-Type Josephson Junctions



Ramp-type junctions:



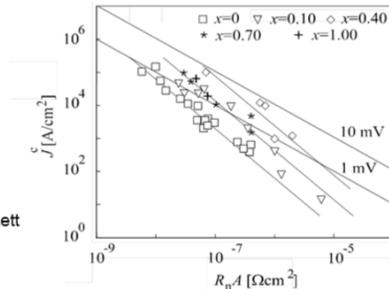
J. Gao, Y.M. Boguslavskij, B.B.G. Klopman, D. Terpstra, G.J. Gerritsma, H. Rogalla, Appl. Phys. Lett. 59, 2754 (1991)

Interface engineered junctions:

Properties of interface-engineered high T_c Josephson junctions

B. H. Moeckly¹⁾ and K. Char
 Conductus, Inc., 949 W. Main Avenue, Sunnyvale, California 94086
 (Received 25 June 1997; accepted for publication 26 August 1997)

Appl. Phys. Lett. 71, 27 (1997)



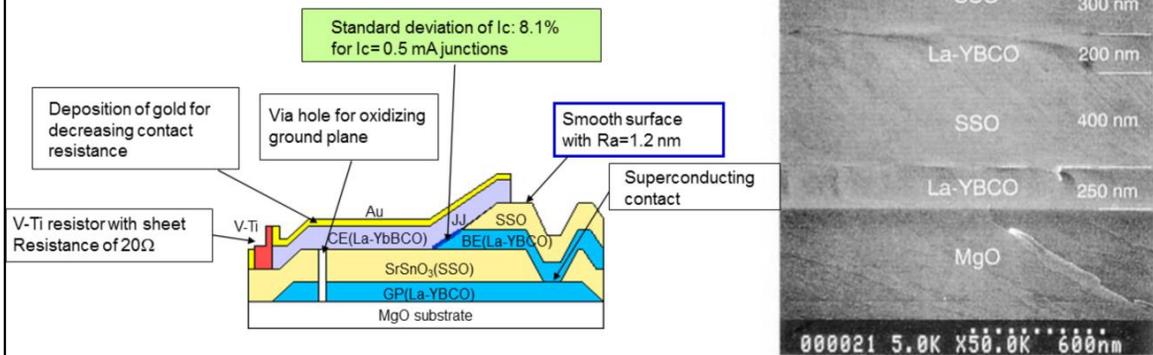
R.B. Laibowitz, R.H. Koch, A. Gupta, G. Koren, W.J. Gallagher, V. Foliatti, B. Oh, et al. Appl. Phys. Lett. 56, 686 (1990)



It was quite clear from the beginning, that the growth and the properties of grain boundaries could not be well controlled. Attempts to fabricate planar junctions had failed because of the layered structure of the high- T_c superconductors. It was clear that one had to use a quasi-planar epitaxial technique and that one had to get access to the CuO-planes for junctions with high $I_c R_n$ -product and some reproducibility. During a coffee break with my group in Twente, I had the idea to make a step-edge junction without step, but replace it by a flat ramp, so that layers could grow epitaxially on the ramp – and the ramp would give access to the CuO-planes. The idea was tried in my group and resulted in the first fully epitaxial High- T_c Josephson junction, which we called ‘ramp-type junction’. This junction type allowed to use different barrier materials for strong SNS-type coupling to nearly SIS-coupling. Especially interesting was the use of PrBaCuO as barrier material because it allowed to adjust the critical current density independent of the resistance of the barrier: the former was adjusted by the thickness of the barrier, the latter by the amount of doping of the PrBaCuO by Ga. This allowed to adjust the $I_c R_n$ product over a wide range.

These junctions were very successful and used in many laboratories, in the original configuration or in a slightly different configuration as ‘interface engineered junctions’. Till now they are the only successful planar junctions. Their preparation is non-trivial and the reproducibility limited to circuits with up to 100 junctions.

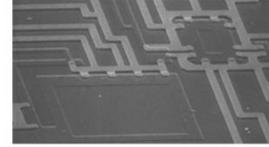
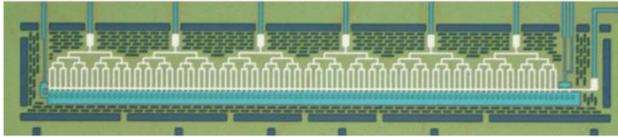
Multi-Layer HTS Integration with Ramp-Type Junctions (ISTEC)



Hasuo, ISTEC, Summerschool on Superconducting Electronics (2005)

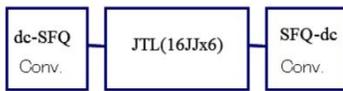
In Japan the ramp-type junctions were very successfully used in conjunction with their SrSnO₂-based multilayer technique. Three superconducting layers were realized. In Twente we also developed a multilayer technique with up to three superconducting layers above a ground-plane. Even though it worked very well, the limited support made it very difficult to keep the complicated multilayer technique available in Twente. It was discontinued in the early 2000s. Till a short while ago it was still available at ISTEC in Japan.

HTS 100 JJ circuit (ISTEC)

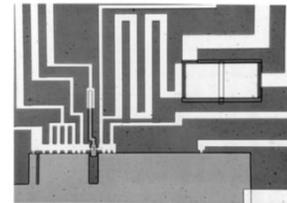
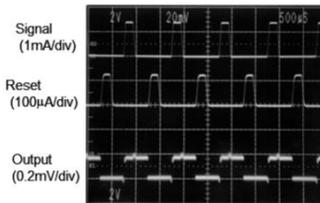


Ring Oscillator (21 JJ, Toshiba) 57 GHz @20K

Circuit including 101 JJs



Circuit



Ref: H.Wakana et al (ISTEC), ISS2004

Operation at 29 K Σ - Δ AD modulator (13 JJ, Hitachi) 100 GHz @20K



The Japanese High- T_c electronics program was especially successful at ISTEC. The multilayer technique together with ramp-type junctions allowed for circuits with up to 100 Josephson junctions. Among other circuits the demonstrated the operation of a DC-to-SFQ converter connected to a 96 junction JTL and an SFQ-to-DC converter. In the Japanese industry a ring-oscillator (Toshiba) and also a $\Sigma\Delta$ -modulator (Hitachi) was demonstrated with a clock frequency of 100 GHz. In Twente a similar modulator was operated at above 150 GHz.

HTS Electronics Applications



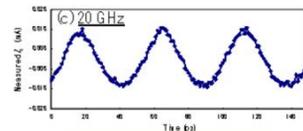
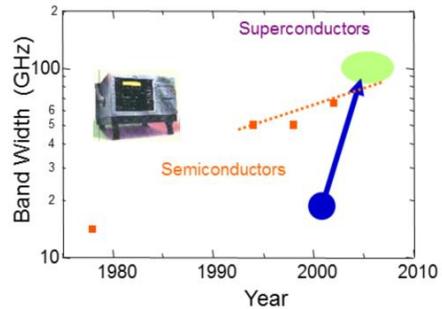
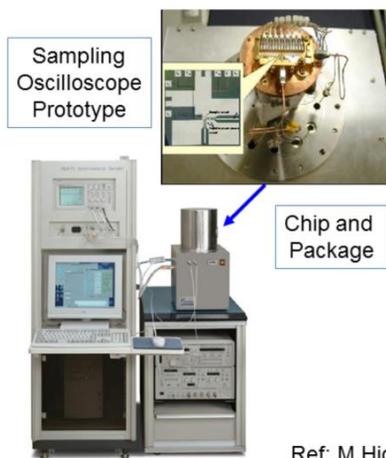
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Superconducting sampling oscilloscope



Ref. M.Hidaka (NEC) et al., ASC2000

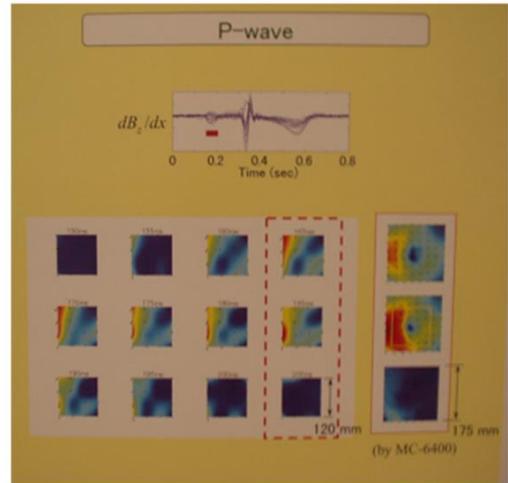
Waveform of 20GHz

There is only room for very few applications to be shown here. One of the early and very successful demonstrators is the 100 GHz sampling scope of Hidaka, at that time with NEC in Japan. It is one of the first demonstrations of a complete system around an High- T_c electronics circuit, mounted on a cryo-cooler and showing a performance that was not met by semiconductor circuits at that time. They showed operation, e.g., by sampling a 20 GHz signal with the 100 GHz sampler.

MCG (Hitachi)

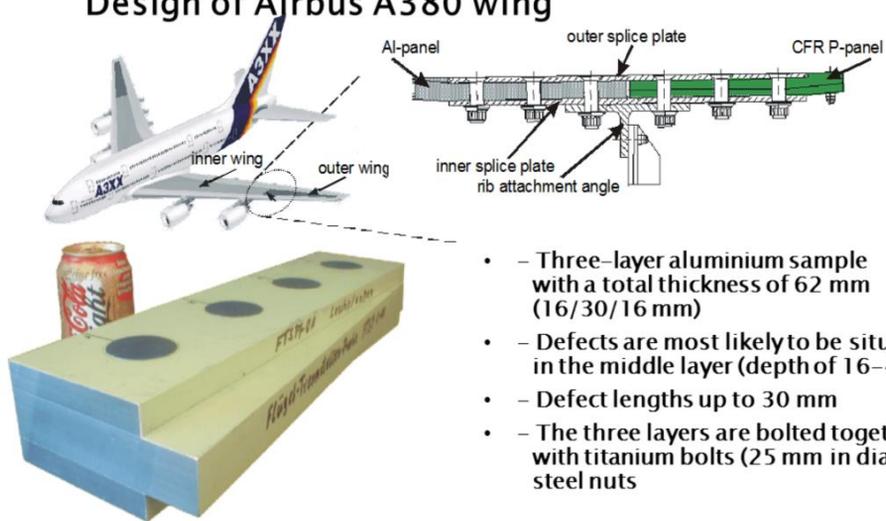


HTS 16ch MCG



This Hitachi system uses a 4x4 array of HTS SQUIDs with planar gradiometers. A 36-sensor version and an LTS version is also available that uses 64 sensors. However, these Hitachi systems are all required to be housed in an enclosure made of μ metal. As a result, these Hitachi system are very expensive. The Hitachi system allows the time resolved recording of the current distribution in the heart.

Design of Airbus A380 wing



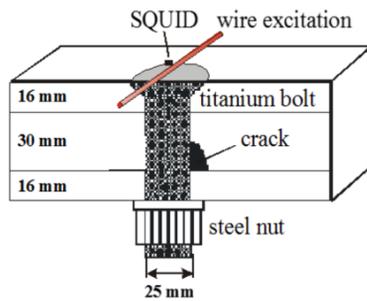
- Three-layer aluminium sample with a total thickness of 62 mm (16/30/16 mm)
- Defects are most likely to be situated in the middle layer (depth of 16–46 mm)
- Defect lengths up to 30 mm
- The three layers are bolted together with titanium bolts (25 mm in dia.) and steel nuts

University of Colorado Boulder

NIST National Institute of Standards and Technology

During the development of the Airbus A380, it was important to test the wing structure for cracks, especially around bolts trough compound plates. In a cooperation between Rohmann, Airbus, Lufthansa, ILK Dresden, University of Giessen and later also the Research Center Jülich, an High- T_c test system was developed and used in the wing testing.

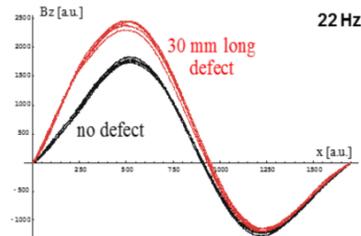
Deep lying defects in Airbus A380 wing splice



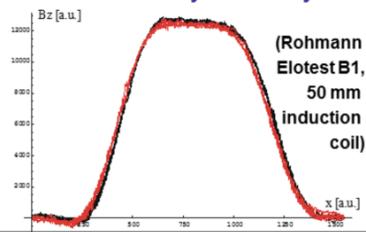
The crack is seen with the SQUID, but not detectable with conventional eddy current

Cooperation with Rohmann, Airbus,
Lufthansa, ILK Dresden, Uni Gießen

HTS rf-SQUID magnetometer



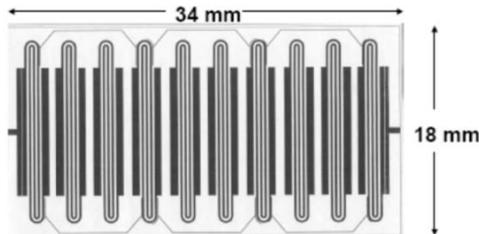
Conventional eddy-current system



The conventional eddy-current system by Rohmann-company was not able to detect certain cracks, whereas the HTS rf-SQUID system was able to clearly detect the cracks.

Filter

High-Performance HTS Bandpass Filter



- Compact
- 10 resonator / 6 transmission zeros
- AMPS B Band Pass Filter



 SUPERCONDUCTOR
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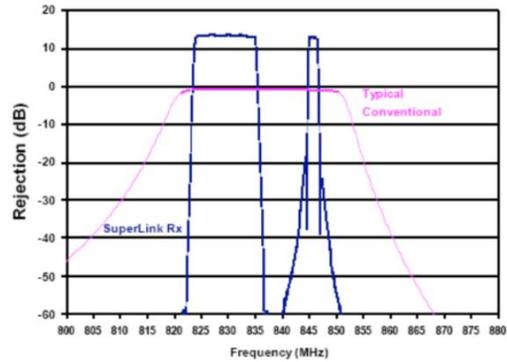
University of Colorado
Boulder

 NIST
National Institute of Standards and Technology

Because of their low losses, High- T_c superconducting filters were especially adapted to applications where steep filter characteristics were needed. In the commercial field, channel separation and an extended range because of reduced losses were an important argument to apply superconducting filters in base stations for cellular telephony. Superconducting Technologies among other companies fabricated such filters, that were very compact and could be realized in a one-layer technique.

RF-performance - 850MHz Cellular Band

- *In Band Performance*
 - NF : 0.42dB
 - VSWR : 1.5:1
 - OIP3 : +30dBm
- *Rejection*
 - SMR: 75 dB
 - Tx Band: 85dB
 - B Band: 40dB



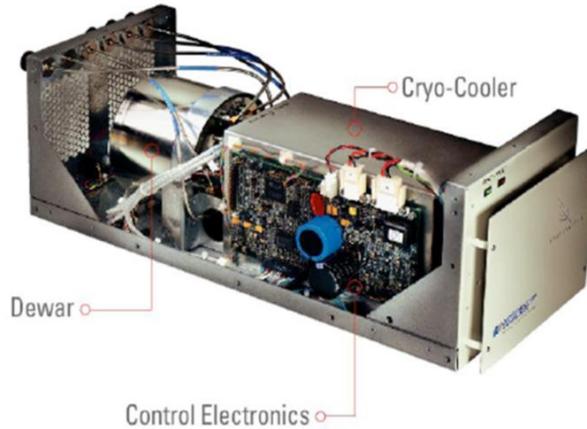
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These filters showed excellent channel separation, much better than typical conventional filters.

HTS Filter System



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Because of the low electrical input power needed to cool these filters, they could be housed in a small cryostat directly connected to a cryo-cooler. Together with some small control electronics it could be housed in a 14" sub-unit for rack mounting.

Status in 2016 on HTS Josephson Junctions

For practical applications:

There are **NO** practical planar HTS Josephson junctions !

(The only working ones were the ramp-type junctions).

The best we have after about 30 years of High- T_c :

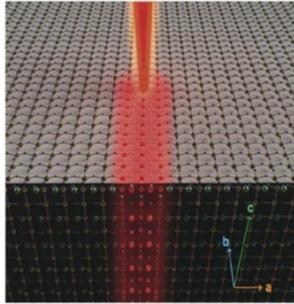
- Bi-crystal and step-edge grain boundary junctions
- Ion-damaged junctions

Realistically one can say that over the last 50 years not many High- T_c superconductive electronics applications have survived and create a notable amount of income for the medical or electronics industry. There are interesting niche applications, but overall the standing of this technology is somewhat disappointing. The prime reason is the lag in having a Josephson junction technology available which can create 10,000s of Josephson junction with high T_c , high $I_c R_n$ -product and high reproducibility with narrow critical-current density margins. The best we currently have are bi-crystal and grain boundary junctions and to a lesser extend ion-damage junctions.

But there is some light at the horizon: there is recent progress in ion-damage junctions and also in step-edge junction.

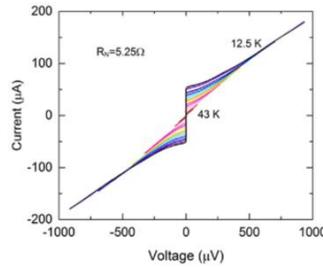
He ion-damage junctions

Maskless direct-write ion implantation

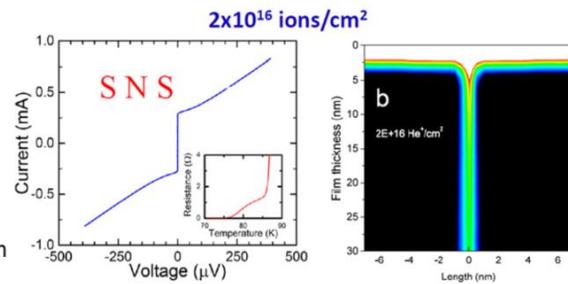


Implantation of a YBCO crystal

Carl Zeiss Orion Nanofab: He-ion 35 keV 0.5 nm



S. A. Cybart et al.,
Nature Nanotechnology 10,
p 598, 2015

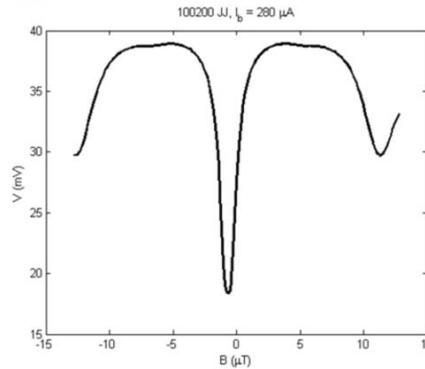
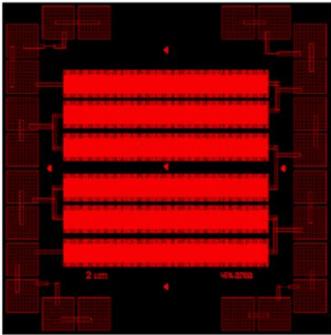


Recently, Shane Cybart and his group showed that direct writing of ion-damage junctions with a Zeiss 0.5 nm He-ion source results in junctions that show good RSJ-like IV-characteristics at high dosages, which constant resistance as function of temperature and very localized damage. Also the stability of these junctions seems to be good. Still, the $I_c R_n$ -product is low and the T_c could be improved. Nevertheless, by changing preparation parameters like beam energy and film thickness, one could expect further improvements in the junction characteristics. This technique has the advantage that the junctions can be written anywhere and would also be compatible to a multilayer process, since they could be written in the top-layer of a layer stack.

Largest SQIF array with SEJs, $N=100,200$ Best sensitivity to date: $V_B = 23,000$ V/T



Array Fabrication:
J Du, J Y Lazar, S K H Lam,
E Mitchell and C P Foley
SUST 27 (2014) 095005



- 100200 junctions
- 45% spread area
- $\beta_L \sim 0.42$ when $I_c = 20 \mu\text{A}$
- $R_N \sim 50 \Omega$
- $I_b = 280 \mu\text{A}$
- Voltage modulation ~ 20.5 mV
- Sensitivity $\sim 23,000$ V/T

The group of Cathy Foley of CSIRO has recently demonstrated an impressive result by fabricating SQIFFs with more than 100,000 step-edge junctions. Even though step-edge junctions are very likely bound to a 1-layer technique, the good reproducibility of these junctions opens new areas for High- T_c SQUID arrays and SQIFFs with excellent characteristics. Still, the spread in critical-current density and the likely limit to one superconducting layer makes this junction type not (yet) applicable to digital superconductive electronics applications.

¹ Data on this slide made available by Cathy Foley, CSIRO.

In view of these new results in High- T_c Josephson junction technology, it is time to revisit some of the applications which had been giving up in the past because of a lack of a well-developed Josephson junction technology. Together with the advantages in cryo-cooler techniques, some applications might have a good chance to make it into the commercial/military market.