Journal of Superconductivity and Novel Magnetism (2021) 34:1695–1697
https://doi.org/10.1007/s10948-020-05612-0

REVIEW

How the Josephson Effect Started to Dominate My Life in Physics

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Received: 8 July 2020 / Accepted: 17 July 2020 / Published online: 31 July 2020

Abstract

Dear Brian Josephson, my heartiest congratulations to your 80th birthday!
We actually never met in person, but I can tell you that your great discovery truly dominates my life in physics, perhaps 90% of my publications are related to Josephson junctions. Maybe it is a good occasion to briefly tell you my story.

Keywords Josephson effect

Your famous paper [1] appeared on July 1, 1962. Back then, I was just 6 weeks old and did not know anything about superconductivity or physics in general. Much later, in the mid-1980s, being a student of physics at the Technical University of Munich, I got attracted to superconductivity through a series of lectures that were based on the German textbook by Werner Buckel, a book which later on I had the honor to continue as an author. In 1986, in the last class before my oral exams, the professor told us that a new superconductor, LaSrCuO, had been found, with a T_c of about 30 K. This superconductor is well understood and presumably is on the limit of what can be done in terms of T_c. This, of course, was fascinating and I decided, if possible, to make my Diploma thesis on a topic in superconductivity. When preparing for my exams the situation became even more exciting with the discovery of $YBa_2Cu_3O_7$ (YBCO); it also became clear, that these new superconductors were perhaps not so well understood. Even more exciting!

So after the Orals I asked Klaus Andres, director at the Walther Meißner Institute (WMI), for a topic for a Diploma thesis. He offered that I might try to fabricate a YBCO SQUID that operates at 77 K. Back then, the WMI had no real thin film deposition technologies for YBCO, but Klaus Andres told me that there is a new method, plasma spraying, that may allow me to deposit YBCO on some thin cylinder which I then might scratch properly to create Josephson junctions and thus a 3D SQUID. In fact, we—my direct supervisor Paul Müller and myself—never tried out this technique, and even today I don't know if it would have worked. Instead, I fabricated pellets of sintered YBCO and started to make point junctions and break junctions from them, and I also drilled holes into the pellets using a needle and diced them with a piece of a diamond blade to form constrictions.

Figure 1 shows one of these "SQUIDs." Of course, the dimensions of the constrictions were by far too large to work as Josephson junctions. Still, in experiment some of the structures showed a (more or less!) periodic magnetic-field response of the voltage across the weak links. Only, the period of oscillations was by far too large to originate from the SQUID hole, and later on I found that the device still had such a response when one of the weak links was broken. Around this time it became clear from the IBM work [3] that grain boundaries in the sintered material act as Josephson junctions and what I had seen here was just the accidental response of some of the loops of this 3D Josephson network. Still, it was ok for my Diploma thesis [2]!

I finished the thesis in the end of 1988 and had the chance to immediately continue with my PhD thesis. Back then, we grew YBCO and also $Bi_2Sr_2CaCu_2O_8$ (BSCCO) single crystals at the WMI, and the original plan was to create YBCO point junctions in various directions and probe the anisotropy of the material. This project never really started, because Paul and I stumbled across a theoretical paper entitled "BCS versus Josephson pair hopping between the CuO_2 layers in high-T_c superconductors" [5]. Since we had the feeling that the Josephson effect is really everywhere in the cuprates, the new plan was to take (BSCCO) single crystals and perform out-of-plane transport experiments on them, testing the hypothesis that such crystals act as stacks

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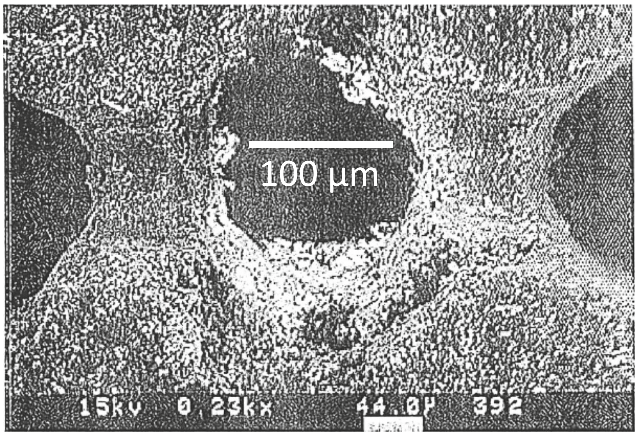


Fig. 1 SEM image of a dc SQUID fabricated from a sintered YBCO pellet during my Diploma thesis. Image from Ref.[2]

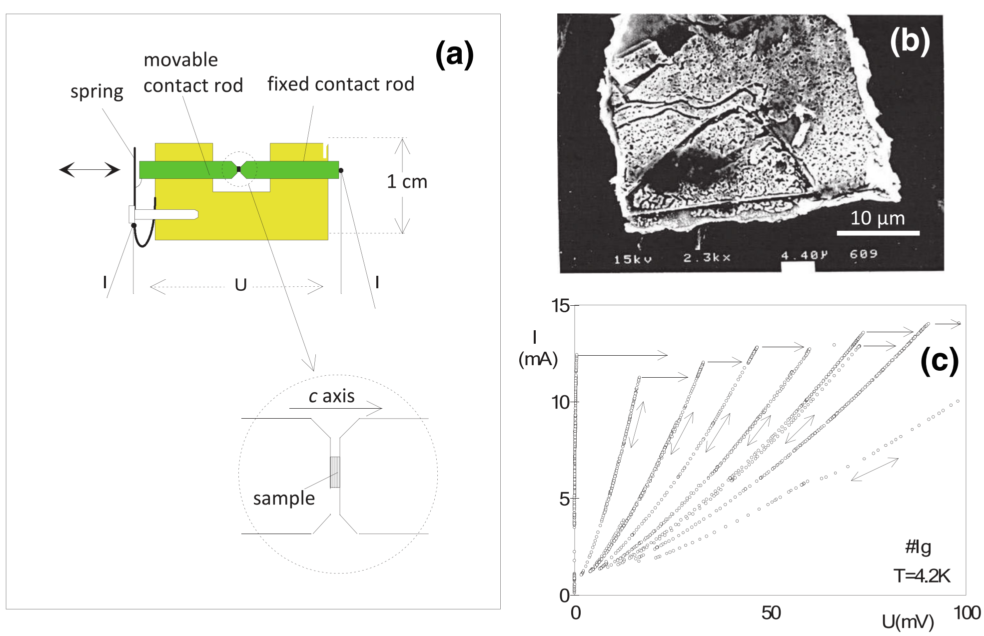
of "intrinsic" Josephson junctions (IJJs). Experimentally, the big question was how large the crystals should be. As we know today, the theoretical description of stacks of IJJs is quite sophisticated, involving many different length scales. Back in 1990 this was unclear, thus I just (incorrectly, seen from 2020!) used the expression for the Josephson penetration length λ_J for a single junction. This gave me a number of about 30 μm for the lateral size of the crystal. I wanted short junctions with a length not much larger than λ_J and, lacking proper lithography techniques, after a while I decided to just take a millimeter-sized flake of a crystal, evaporate gold on both surfaces, and cut out small pieces from the flake and finally clamp it between two contact rods to perform transport experiments. This approach worked right away!

Figure 2a sketches the sample holder, which I fabricated with the help of Florian Steinmeyer, back then also a PhD student at WMI (now being a senior person at Bruker). Figure 2b shows a SEM image of one of the crystals and Fig. 2c shows part of a current-voltage characteristics of one of the crystals. The crystal was about 1 μm thick and consisted of a stack of almost 700 IJJs. The junctions are underdamped, each IJJ has a strongly hysteretic current-voltage characteristic and for the whole stack one can find as many branches in the resistive state as we have junctions in the stack. Since then, there is worldwide research on intrinsic Josephson junctions, most recently with a focus on Terahertz generation [6].

To shorten the story a bit—in 1994 and 1995, now increasingly equipped with the high-tech part of fabrication, I had the chance to be a post doc in John Clarke's lab in Berkeley, working on high-T_c SQUIDs [7] plus, in collaboration with Bob Dynes' group in San Diego, on hybrid c-axis Josephson junctions between Pb and YBCO, made to study the symmetry of the YBCO superconducting order parameter[8]. Back in Germany I extended this to c axis Pb/BSCCO junctions[9] in Paul Müller's group in Erlangen. After finishing the habilitation in Erlangen I continued as a professor in Tübingen, where I share a group with Dieter Koelle, who is also highly influenced by the Josephson effect.

Of course, your discovery dominates our research also in Tübingen, and we have activities on nano-sized SQUIDs to measure magnetic nanoparticles[10], on the intrinsic Josephson effect, and also on some more fancy types of Josephson junctions, like π junctions [11] or 0-π junctions [12, 13]. In the latter case, the ground state phase jumps

Fig. 2 Intrinsic Josephson effect in BSCCO single crystals. **a** Sketch of sample holder. **b** SEM image of a BSCCO crystal. **c** Part of a current-voltage characteristic, measured at 4.2 K. Modified from Ref. [4]



from 0 to π inside the junction, and a Josephson vortex carrying a half flux quantum can form[14, 15]. We can even realize 0-κ junctions, where the ground state phase jumps by an arbitrary value of κ, allowing the creation of vortices that carry only a fraction of the magnetic flux quantum[16].

So, dear Brian Josephson, you see that you are a truly important person in my scientific life. Perhaps not only in my scientific life—even my parents (not at all in physics; 89 (mother) and 92 (father) years old, at the time of writing these lines) know your name.

I wish you a very happy 80th birthday!

Acknowledgments The author thanks B. D. Josephson for the discovery of his wonderful effect.

Funding Open Access funding enabled and organized by Projekt DEAL.

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