Applications of superconductivity – So near and yet so far?

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Here I deal with the developments towards applications of superconductivity relevant to the Indian context. Where necessary, I shall mention the global developments for comparison. As of now, in the world scene, established applications have come from only the conventional superconductors (LTSC). Although, there have been impressive developments with regard to the high temperature superconductors (HTSC), it is generally recognized that the applications based on them are some years away. Accordingly I will focus on the LTSC situation and the HTSC developments will be mentioned towards the end.

Development of enabling technologies for applications

There are two major directions in the utilization of superconductors. The first is the energy saving applications mainly making use of the property that the resistivity in the superconducting state is nearly zero. Superconducting magnets for a variety of applications—e.g. motors, generators, field gradient ore separators, magnetic resonance imaging for clinical diagnostics—fall under this class. The primary requirement for this class of applications is the development of stable and high current carrying conductors. The second major direction is the realization of sensitive devices like SQUIDs, high frequency radiation detectors and high speed electronics, all based on Josephson effect. The primary requirement for this class of applications is the development of SIS (Superconductor–Insulator–Superconductor) tunnel junctions. As a result of sustained developments carried out mostly under the laboratories of the Department of Atomic Energy, both these primary requirements, viz. the conductor and the tunnel junction—what one may call the enabling technologies, have been realized.

Nb–Ti multifilamentary conductor

With good mechanical and metallurgical properties, niobium–titanium alloy has been the work-horse for high current applications up to about 8 T. In a collaborative programme initiated at IGCAR and largely executed and sustained at BARC, a process route for the fabrication of Nb–Ti wire in a multifilamentary form in copper matrix has been standardized, compatible with a high critical current density (J_c) and stability in service. A typical wire with 84 filaments, having an overall diameter of 0.7 mm has been produced in maximum single lengths of 8 km with a measured short sample J_c exceeding 2200 A cm^{-2} at 4.2 K and 5 T. This value compares well with the international commercial products. This development also represents the competence to fabricate conductors in most other configurations. Figure 1 shows a cross-section of the composite conductor at an intermediate stage of fabrication.

Nb–Al_2O_3–Nb tunnel junctions

In the case of superconducting devices, Nb–Al_2O_3–Nb trilayer tunnel junctions have proved to be the most reliable in terms of mechanical stability, ruggedness and thermal cycling among all possible materials and configurations. IGCAR has standardized a process for their microfabrication by the whole wafer sandwich technique which involves the deposition of the trilayer *in situ* in a UHV chamber and subsequent sculpturing out the junction in the required geometries down to a resolution of 2 μm by a selective niobium etching process. The tunnel junctions developed have low sub-gap leakage and are characterized by the quality parameter V_m of 60 mV which is among the best obtained internationally. The fabrication of such technological grade junctions and other structures are accomplished in a specially established superconducting device laboratory conforming to class 1000 cleanliness.

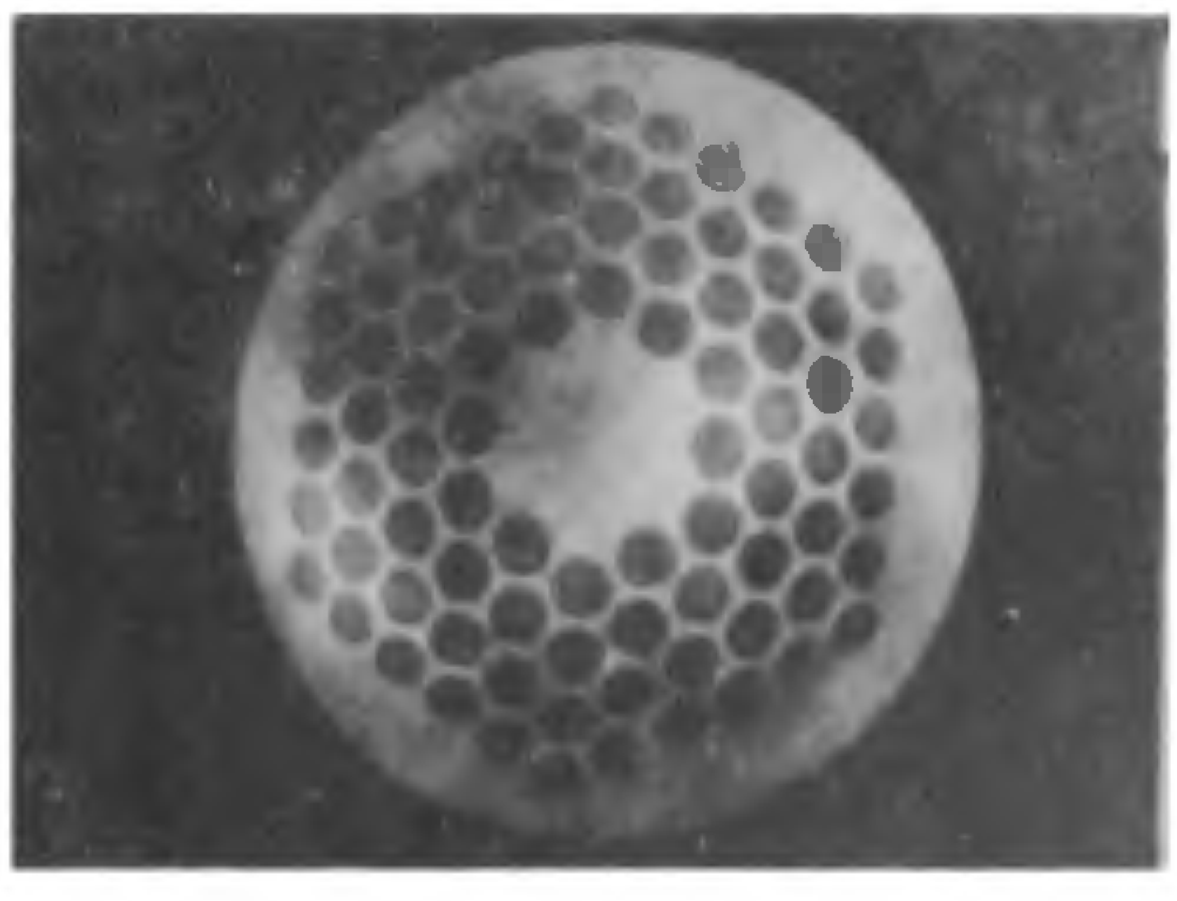

Figure 1. Cross-section of a Nb-Ti/Cu composite multifilamentary conductor at an intermediate stage of fabrication (Courtesy M. K. Malik, BARC)

Applications of high current conductors

Table 1 lists the superconducting magnets and systems built or under execution in the Indian research laboratories and other institutions.

It is to be noted that many of the magnets fabricated, particularly those in the DAE institutions have used the indigenous Nb–Ti wire. The first commercial application of superconductivity will be realized when the S-HGMS being established for processing up to 5 tons/h of slurry for upgradation of clay, is commissioned in an estimated period of a year.

Two major national projects that are being set up, both under the DAE, when completed should have significant technological fallouts in the areas of superconductivity and cryogenics. Work on a 500 MeV superconducting cyclotron project has just commenced at the VEC Centre at Calcutta, a crucial component of which is the superconducting magnet. It will have a central field of about 5.5 T, a stored energy of 22 MJ and will use about 40 km of a cryostatically stabilized Nb–Ti/Cu composite conductor of a specified configuration with a design current of 1030 A. A short section of the conductor fabricated at BARC is undergoing tests. The other project is INDUS 2, the X-ray synchrotron being established at CAT, Indore. A few superconducting magnets may be used as wigglers, each at least a metre in length and with a peak field of over 6 T. It is expected that the conductors and the magnets for both the projects will be indigenously developed. The successful accomplishments of these projects will pave way for large scale applications of superconductivity in India.

Applications of Josephson junctions–SQUIDs and other devices

An early activity in the direction of low current devices has been the establishment of a voltage standard at 1 mV level by NPL using Nb–Nb point contact junction. Recently, following the successful development of Nb–Al_2O_3–Nb type tunnel junctions, IGCAR has completed the development of DC SQUID structures in Nb slit washer geometry incorporating two Josephson junctions through several layers of lithography with one micron overall alignment. A thin film input coil has been integrated with the SQUID for effective coupling of magnetic flux for detection. Figure 2 shows a completed SQUID structure with a loop inductance of 78 pH, a junction capacitance of 0.8 pF, junction areas of $4\,\mu m \times 4\,\mu m$, and an input coil inductance of 125 nH. This SQUID is expected to have a field sensitivity of $2 fT/\sqrt{Hz}$ in the white noise region which has to be experimentally ascertained.

SQUID or the Superconducting Quantum Interference Device, as is well known can be configured as the most sensitive detector of magnetic flux. They are employed not only in laboratory experiments demanding utmost sensitivity but also in a large number of application areas such as biomagnetism, geophysics, etc. A single SQUID can be configured as a magnetic anomaly detector that can be used for civilian (NDT) or military applications. A susceptometer employing a superconducting magnet and a SQUID can be used for basic research, magnetopneumography for the detection of lung contamination and also for the study of rock magnetism. A triple axes SQUID magnetometer can be employed in magnetotelluric (MT) studies in geophysics and can be of value in mineral and oil prospecting. It may be noted that NGRI routinely employs MT using conventional induction coils which have far lower sensitivity than SQUIDs. Multi SQUID arrays are under development internationally for magnetoencephalography (MEG) for clinical diagnostics and for studies of neuromagnetism. Many such significant applications of varying

Table 1. Superconducting magnets and systems

Description	Major specification	Institution
Simple solenoids	up to 8 T	IGCAR, BARC, NPL
High homogeneity notched coils (100 ppm)	up to 6 T	IGCAR, BARC
Symmetric and asymmetric split coils	up to 4 T	BARC
NbTi/Nb_3Sn hybrid coil	11 T	NPL
Superconducting high gradient magnetic separator (S-HGMS)	Warm bore 5 T	BHEL, NPL, BARC
Commercial S-HGMS*	3.5 T	BHEL, M/s English Indian Clay
Superconducting generator	220 kVA	BHEL
Superconducting generator*	5 MVA	BHEL

*under execution.

Table 2. Major developments using HTSC

Development	International	National	Institutions
Bulk materials, shapes, targets	Commercially available	Confined to laboratories	Several; IIT (B)
Melt-texture-YBCO bearing	$J_c > 10^4$ A cm^{-2} (20 T, 77 K) 520,000 RPM on 10 g rotor tested	MTG process established	DMRL, IGCAR
Thin films microwave devices	High J_c; field tests	High J_c resonators; 1 μm patterning	Several; TIFR IIT (Kh)
SQUIDs	Thin film device with input coil resolution: 40 fT/√Hz at 1 Hz	Thick film RF SQUID 2 pT/√Hz at 1 Hz	NPL
BSCCO wire short length	$J_c = 10^4$ A cm^{-2} (1 T, 77 K)	10^4 A cm^{-2} (0 T, 77 K)	RRL (T), BHEL

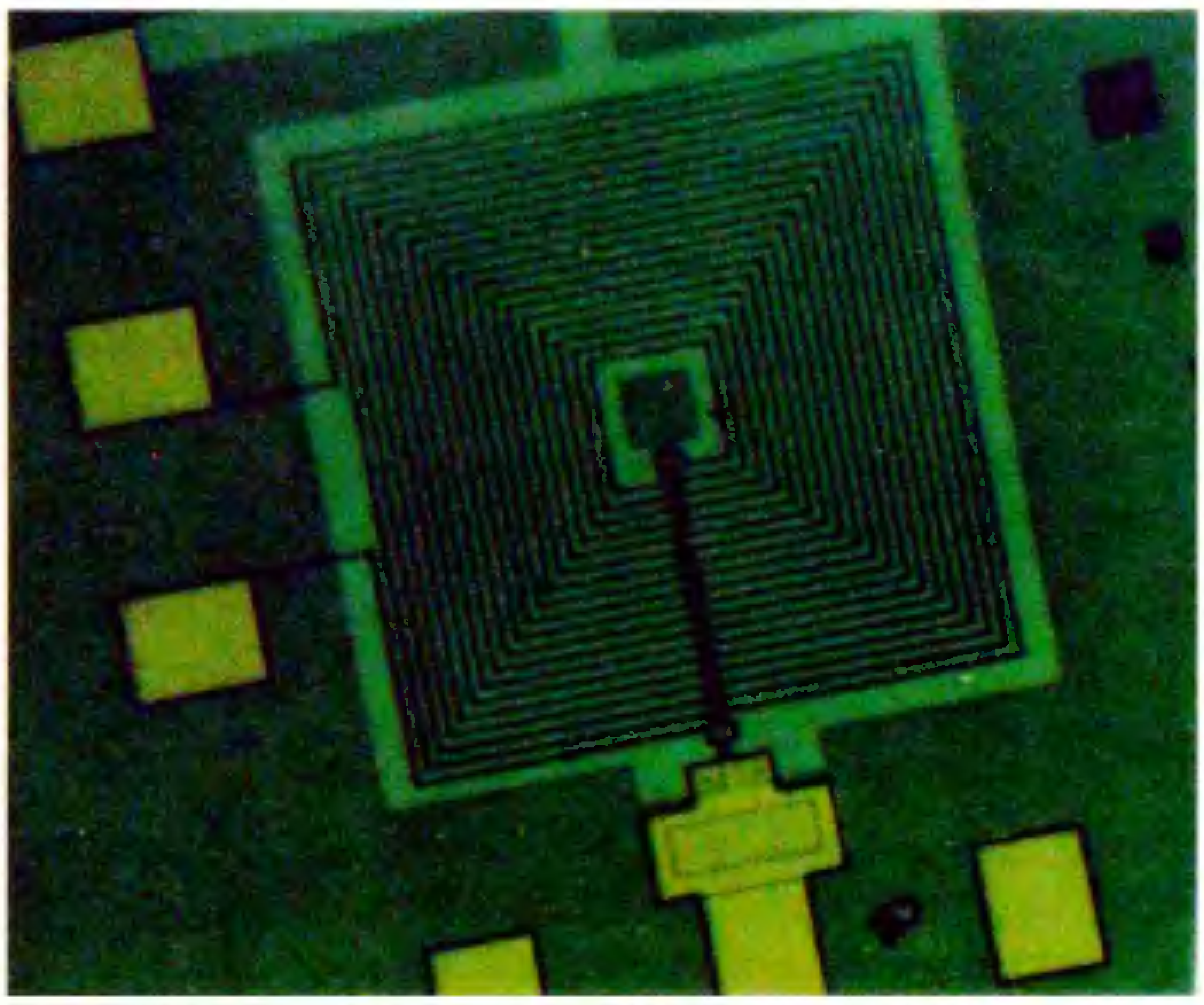

Figure 2. Optical micrograph of a DC SQUID structure with integrated input coil (× 60).

complexities can be realized in the Indian context using the developments already completed without requiring any additional major technological breakthrough. It is however to be emphasized that the use of SQUIDs for diverse applications needs the development of application specific gradiometers for rejection of background noise of electric and magnetic nature.

High temperature superconductors

Table 2 lists the major developments towards applications using the high temperature superconductors both in the international and national contexts. In the latter case, the institutions involved in the developments are also mentioned.

It can be seen from Table 2 that SQUIDs are the most promising of the developments and are the closest to finding applications in the international context. Thin film HTSC SQUIDs are yet to be developed in India. In the case of the conductor, a distinct goal is their development in long lengths for use at 77 K and in modest fields. This is yet to be realised.

Summary and outlook for the future

On a technological plane it is clear that in the Indian context many useful applications using LTSC can be realized based on the developments already completed. In the international context, applied superconductivity centres and commercial groups are engaged in the application-oriented developments. In contrast, in India, such work is carried out only at a few select laboratories and that too with subcritical support. It is to be recognized that the developments accomplished need consolidation. Creation of specific R & D centres for superconductivity will go a long way in establishing a strong expertise base for interaction with appropriate user agencies to realize identified and focused application objectives. As for HTSC, it has been recognized internationally that success in applications can only be accomplished by sustained efforts over a long period of time. This would apply even more in the Indian context.