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PROSPECTS AND PROGRESS
OF HIGH T_c SUPERCONDUCTIVITY FOR SPACE APPLICATIONSRobert R. Romanofsky and Marty M. Sokoloski
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It had been recognized from the onset that high temperature superconductivity held great promise for major advances across a broad range of NASA interests. The current effort is organized around four key areas: communications and data, sensors and cryogenics, propulsion and power, and space materials technology. Recently, laser ablated YBa₂Cu₃O_{7-x} films on LaAlO₃ produced far superior RF characteristics when compared to metallic films on the same substrate. This achievement has enabled a number of unique microwave device applications, such as low insertion loss phase shifters and high-Q filters. Melt texturing and melt-quenched techniques are being used to produce bulk material with optimized magnetic properties. These yttrium-enriched materials possess enhanced flux pinning characteristics and could lead to prototype cryocooler bearings. Significant progress has also occurred in bolometer and current lead technology. Studies are being conducted to evaluate the effect of high temperature superconducting materials on the performance and life of high power magneto-plasma-dynamic thrusters. Extended studies have also been performed to evaluate the benefit of superconducting magnetic energy storage for LEO space station, lunar and Mars mission applications.

Introduction

NASA has sustained a significant effort in low temperature superconductivity research and development because of the unique applications to spaceborne science instrumentation. A current example is Gravity Probe B, an experiment being developed to confirm or refute certain tenets of Einstein's general theory of relativity. The experiment is designed to precisely measure an almost imperceptible gyroscope tilt which should result from the influence of a moving mass (the Earth) on space-time. SQUID magnetometers will be used to detect the London moment created by rotating niobium-coated quartz spheres. Additionally, superconducting lead sleeves will be used to attenuate the Earth's magnetic field and prevent interference with the sensitive instrumentation. Research efforts are also underway to develop superconducting/insulator/superconducting (SIS) tunnel junctions for submillimeter mixers to be used in heterodyne remote sensing systems. A 0.3 square micron NbN/MgO/NbN junction has been demonstrated at 205 GHz. Emphasis on applications of low temperature superconducting technology to sensor systems will continue.

The promise of revolutionary advancements in satellite and deep-space communications, astrophysics and Earth observation technology, and space-based magnetic energy storage and propulsion

inspired an intensive research effort. Preliminary activities concentrated on identifying applications which were peculiar to the NASA mission or of high priority interest. The ensuing application specific materials development has met with considerable success. Prototype thin film electronic devices promise to emerge first, although bulk materials technology for certain applications such as cryocooler current leads and magnetic bearings is evolving rapidly. Specific research and development efforts are described in subsequent sections.

Thin Film Applications

Thin film analog signal processing electronics was envisioned as the first practical application for high temperature superconductors. Development was not precluded by high current density or high critical magnetic field requirements. The major prerequisite for microwave communication devices and circuits was comparatively low RF surface resistance. Enthusiasm waned as tests on the new materials at microwave frequencies revealed fundamental limitations. Poor RF characteristics were attributed to grain boundaries and anisotropy. Recently; however, films deposited by laser ablation have produced excellent RF properties as high as 35 GHz [1]. Thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films were deposited on LaAlO_3 , which was heated to 700 degrees Celsius in a 100 mtorr atmosphere. Samples were slowly cooled to room temperature at an oxygen pressure of one atmosphere. The best films had critical temperatures of approximately 90 K. Based on microstrip resonator techniques, the unloaded quality factor (Q) of the superconductor equalled that of a metallic (gold) film at approximately 60 K and exceeded the Q of the metallic film by 150 % at 25 K. Figure 1 shows typical measured resonator return loss data.

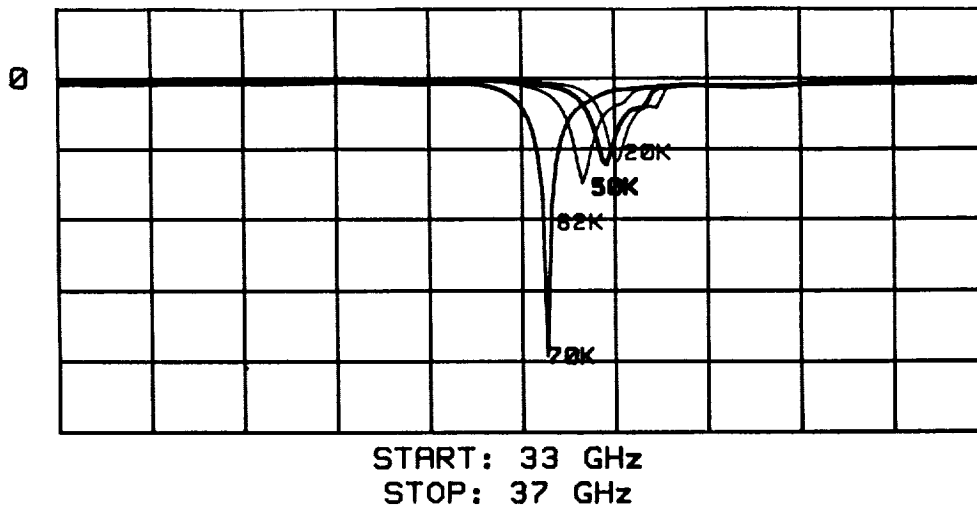


Figure 1. Resonator reflected power (10 dB/div)

Processing advantages of laser ablation such as exposure to relatively low temperatures are attractive for device applications. Such progress suggests the eventual possibility of hybrid superconducting/semiconducting circuits. Experiments based on transmission through $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films have also been performed

to assess additional microwave properties [2]. Table I summarizes important parameters derived from the data assuming Bardeen-Cooper-Schrieffer (BCS) behavior.

A number of devices are being developed including: filters, phase shifters, and antennas. A novel phase shifter has been designed which has theoretically symmetric insertion loss and is immune to bias line interactions [3]. High-Q bandpass microstrip filters, offering tremendous weight reduction compared to conventional waveguide implementations, are being fabricated. The new superconductors also enable practical electrically small antennas, normally shunned due to extremely poor efficiencies resulting from high ohmic loss (compared to radiation resistance). High gain, high directivity arrays are being investigated.

Table I
Thin film microwave properties including T=0 bandgap and magnetic penetration depth (conductivity units are S/m)

PARAMETER	SE	MgO	LA	LaAlO ₃	ZrO ₂
σ_1 (70K, 35 GHz)	3.72×10^4	3.30×10^8	2.48×10^5	4.28×10^5	
σ_2 (70K, 35 GHz)	3.47×10^4	8.51×10^6	4.75×10^6	9.23×10^5	
σ_1 (40 K, 35 GHz)	4.46×10^3	3.52×10^5	2.64×10^4	4.57×10^4	
σ_2 (40 K, 35 GHz)	1.22×10^5	3.32×10^7	6.44×10^6	1.10×10^7	
$\frac{2 \Delta}{K T_c}$	4.19	4.35	4.32	4.31	
λ (um)	3.33	0.40	0.69	1.23	

NASA has unparalleled requirements in science sensor technology because of unique and extensive astrophysics and Earth observation missions. The sensors thrust is focused on two major areas: detectors and cryogenic systems. NASA has a keen interest in applying the new materials to spectroscopy in the submillimeter to far-infrared spectrum, and in developing high sensitivity, high spectral resolution instruments. Assuming that existing theories are valid for the new class of superconductors, detection down to approximately 100 microns should be possible. Of equal importance is the need to develop reliable (long-life) cryogenic systems. Such systems could be enabling for prefatory interplanetary exploration leading to lunar and mars outposts. Existing options are limited to inefficient cryocoolers or stored cryogenes. A number of potential benefits to these critical systems using high temperature superconductors have been identified. NASA has undertaken several major projects in these areas: bolometer detectors, superconducting tunnel junctions, cryocooler current leads, and passive magnetic bearings for cryocoolers.

Planetary missions rely on liquid helium cooled detectors or relatively poor performance >65K detectors. HgCdTe focal plane arrays are useful to approximately 20 microns; however, far infrared spectroscopy necessitates thermal sensors. The new oxide

superconductors enable an intermediate performance thermal detector capable of operating at 65 to 95 K. This is a temperature range potentially achievable through radiative cooling in space. The first approach was to use a transition-edge meander line bolometer [4]. Figure 2 shows a schematic of the composite bolometer assembly. In the bolometric mode, the film is held near its transition temperature, where the temperature derivative of resistance is maximum. Radiation is absorbed by a thin film of bismuth deposited on a silicon substrate in contact with the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}/\text{SrTiO}_3$ circuit. The DC responsivity was measured as 1900 V/W. Goals for this type of detector are a near DC detectivity of greater than $10^{10} \text{ cm}(\text{Hz})^{0.5}/\text{W}$ and a time constant of less than 300 ms. A near DC D^* of 1.1×10^8 and a time constant of 32 seconds was measured. Techniques to reduce the time constant, attributed primarily to the heat capacity of the SrTiO_3 , include thinning the substrate or using a diamond substrate. A second approach is to build a kinetic inductance bolometer. A superconducting meander line is configured as a wheatstone bridge and monitored by a SQUID galvanometer. Since the magnetic field penetration depth is temperature sensitive, the inductance will depend on temperature. This approach eliminates Johnson noise and is potentially more sensitive (higher D^*) than the transition-edge device.

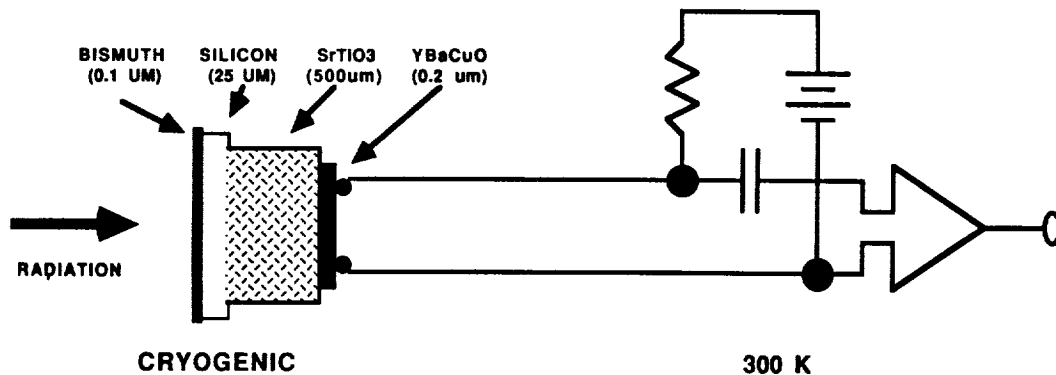


Figure 2. Composite transition-edge bolometer

The production of tunnel junctions and other microdevices requires high quality thin films with superconducting surfaces. To date; however, operation of high T_c junctions has been degraded by poor surface morphology and stoichiometry, and is further complicated by the extremely short coherence length of the new superconductors. Interaction at metal and substrate interfaces has also been detrimental. The elimination or prevention of non-superconducting surface layers is critical to eventual device fabrication. Significant improvements in the electrical properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films have been demonstrated using a 1% Br by volume in ethanol etch [5]. Evidence suggests that the etch is effective in removing surface contamination layers without adversely affecting the stoichiometry. Table II lists properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}/\text{Au}/\text{Nb}$ contacts. $I_c R_n$, which is proportional to the bandgap at the surface, increased by a factor of 10 to 20 for typical samples. Contact resistance decreased by approximately a factor of 10. Practical devices will also require surfaces which are insensitive to environmental effects. A promising passivation

technique using a post-anneal chemical treatment has been developed. Treatment with a nonaqueous HF solution has been shown to reduce the reactivity of the superconductor to air [6]. These, or similar, processing techniques are prerequisite to microdevice fabrication. The investigation of surface modification techniques is continuing. Short-term objectives include the fabrication of planar geometry tunnel junctions and the demonstration of high frequency local oscillators operating at 77 K using SNS microbridges.

Table II
Characteristics of $10 \times 10 \text{ um}^2$ SNS contacts

	UNTREATED SAMPLE	30 SEC. Br ETCH
Jc (A/cm^2)	5	180
Rn (Ω)	10.5	2.8
IcRn	53 μV	0.5 mV
RnA (Ωcm^2)	1.05×10^{-5}	2.8×10^{-6}

Bulk Applications

Stored cryogens and closed cycle refrigerators play a vital role in numerous science and exploration missions. Astrophysics and Earth observation technology, in particular, demand cryogenically cooled high resolution sensor systems. Long duration science missions, prefatory to human exploration for example, require correspondingly long lifetime coolant systems. At the present time, both mechanical refrigerators and stored cryogen systems have significant drawbacks. Stored cryogen coolers have limited lifetimes because of parasitic heat loads, resulting in accelerated cryogen boil-off. Mechanical coolers require large power budgets, and have limited cooling capacity. High temperature superconductors have the potential to alleviate some of the major shortcomings. Specifically, High Tc current leads could reduce the parasitic heat load on stored cryogen coolers by as much as 50 %. Furthermore, High Tc passive magnetic bearings could reduce friction and heat leaks in mechanical coolers, improve stability, and significantly improve efficiency.

In typical stored cryogen cooler sensor systems, detectors at 4 K must interface with amplifiers at approximately 80 K. This interconnection is performed with copper or manganin wires, which represent substantial heat leaks. A unique characteristic of the ceramic superconductors is their ability to be excellent electrical conductors and poor thermal conductors simultaneously. Near liquid nitrogen temperatures, the thermal conductivities of copper and YBaCuO are approximately 400-500 W/mK and 5-10 W/mK respectively. Although key issues remain to be resolved, in this application the technology appears precocious. Current densities of 10^3 to 10^4 A/cm^2 in ambient fields of several hundred Gauss are obtainable. All High Tc materials are brittle ceramics and tend to

be unstable. TlCaBaCuO and BiCaSrCuO appear to offer better characteristics in terms of stability against oxygen diffusion. Silver/YBaCuO composites have greater flexibility but at the expense of thermal conductivity. Furthermore, clarification is required with regard to thermal cycling effects and radiation damage susceptibility. Despite these uncertainties, progress has been steady and indications suggest this could be one of the first practical bulk material applications. The potential to extend mission life by perhaps a factor of two simply using near optimal current leads is highly motivating. Prototype encapsulated current leads have already been developed. Rigid tape-cast leads, which are conformable in the green state, have undergone preliminary thermal and mechanical shock testing. Various techniques to produce continuous filaments and ribbons are being pursued.

Mechanical closed-loop refrigeration systems are being developed for long term missions. Such coolers have the potential to overcome the weight and lifetime penalties of stored cryogen systems. Conventional bearings for these coolers have several drawbacks, including: low reliability, excessive weight, large heat leaks, and active feedback control requirements. Passive High Tc magnetic bearings are inherently stable due to the Meissner effect. Potential benefits include considerable reductions in cryocooler input power, weight savings, and long-life, high reliability operation. Synthesis of suitable bulk High Tc materials, in terms of mechanical and magnetic properties, is the first priority. Synthesis of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ by crystallization from a melt has yielded encouraging results [7]. In general, microstructural defects act as flux pinning centers in type II superconductors and determine the character of the material. A balance between too few and too many defects produces material which exhibits optimum magnetic properties. Crystal orientation and the presence of voids also impacts the magnetic behavior. The partial melting technique fortuitously yields a 211 phase impurity which acts as a dopant. Evidence also suggests an optimal excess yttrium concentration to provide maximum magnetization. Experiments seeking to tailor the structure to produce maximum stiffness and levitation force for eventual use in passive magnetic bearings are underway. Critical current densities approaching 10^5 A/cm^2 at one Tesla have been deduced from magnetization data. A process to simultaneously exploit the advantages of melt quenched growth and controlled stoichiometry is undergoing further optimization. Melt quenched and partial melting techniques have produced favorable magnetic characteristics and have proven to be far superior to sintered material. Prototype cryocooler bearings with suitable force and stiffness characteristics are being developed for demonstration.

Alternate cooler embodiments, promising to benefit from High Tc superconductor technology, are also being explored. A flux compression magnetic refrigerator utilizing high Tc superconductors is being considered. Initial work has focused on conventional superconductor flux pump cooling. Calculations indicate that a 0.5 W refrigerator operating between 20 K and 2 K will require a six Tesla field. A superconducting cylinder approximately 15 cm in diameter and 10 cm long is necessary.

Research is motivated by the potential for this type of refrigerator to approach ideal Carnot performance.

Longer range applications include active (supercurrent) bearings for rocket engines. Liquid hydrogen turbopumps provide a natural environment for high Tc bearing insertion, and it is easy to speculate on tremendous improvements in terms of longevity and reliability. Although this application is still immature, progress leading to high current solenoids has been steady and encouraging.

Detailed system studies have been performed to evaluate potential benefits of High Tc superconductors to various space applications. Several candidate systems selected for emphasis include: magneto-plasma-dynamic (MPD) thrusters, superconducting magnetic energy storage (SMES), and power transmission.

An MPD system is a low thrust, high fuel efficiency alternative to conventional chemical propulsion promising pragmatic interplanetary travel. Unfortunately, state-of-the-art performance is inadequate due to limited thruster efficiency and electrode lifetime. A lunar based Mars cargo vehicle, for example, would require total impulse and electrode lifetime improvements approximately two orders of magnitude beyond demonstrated systems [8]. Figure 3 illustrates the thruster concept. The magnetic field forms a virtual nozzle which contains the applied arc currents generated between the cathode and anode. Acceleration is produced by the $J \times B$ forces on the plasma as well as the propellant pressure. High Tc superconducting magnets may have the potential to provide the necessary improvements in cathode lifetime and thruster efficiency. Mass and reliability enhancements are expected as well.

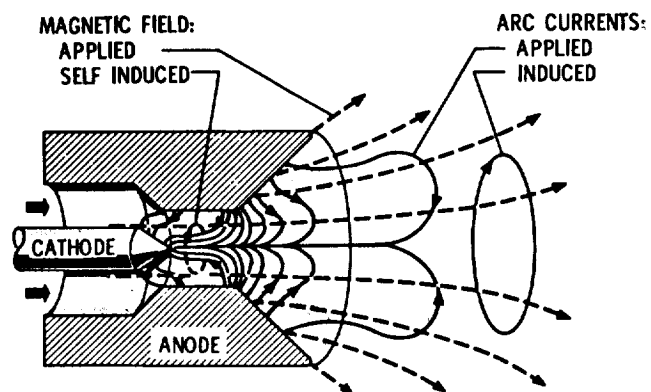


Figure 3. MPD thruster concept illustrating currents and fields

Energy storage is a crucial integral part of spacecraft operation, tending to be the most massive onboard system. Proven technologies, such as nickel-hydrogen cells, nickel-cadmium batteries, and regenerative fuel cells, often require careful trade-offs between cycling flexibility, weight, and lifetime. Principal advantages of SMES include high efficiency and insensitivity to demanding charge/discharge rates. SMES has the potential to equal the specific power of conventional systems and

should prove competitive in terms of the major relevant criteria.

The resurgence of interest in microwave-beam power transmission presents another opportunity for high Tc superconductors to provide enhancing, if not enabling, system contributions. A Mars satellite-to-rover power transmission scenario, for example, could alleviate numerous complications involved with surface power generation and transmission. High power submillimeter-wave transmission from synchronous orbit (17,000 Km) is feasible. High Tc superconductors could be utilized in at least two areas: high field solenoids for gyrotrons and SIS rectenna elements. In lieu of free-space power transmission, High Tc superconducting transmission lines could be used to distribute power from distant nuclear plants with high efficiency. In addition, with currently demonstrated current densities of 1000 A/cm², a one kilometer high Tc superconducting transmission line would be 500 % lighter than a high purity aluminum line [9].

Significant activities are also underway to develop innovative approaches for synthesizing bulk and thick film materials as well as to study the effects of processing on microstructure. For example, investigations to: explore the role of anisotropy, characterize susceptibility to radiation damage, and determine durability in an atomic oxygen environment have been initiated. A glass-ceramic approach based on bismuth compounds, which promises high density, pore-free fibers, is also being developed. Finally, composite materials, consisting of appropriate metallic or polymer matrices, are being explored and may eventually produce the necessary structural and environmental properties for space power and propulsion systems.

Figure 4 projects stages of development for various high Tc superconductor applications being pursued by NASA. The milestones represent ambitious but not overly optimistic goals. The chart reflects only a few examples from a myriad of applications under investigation by NASA, other government agencies, industry, and academia.

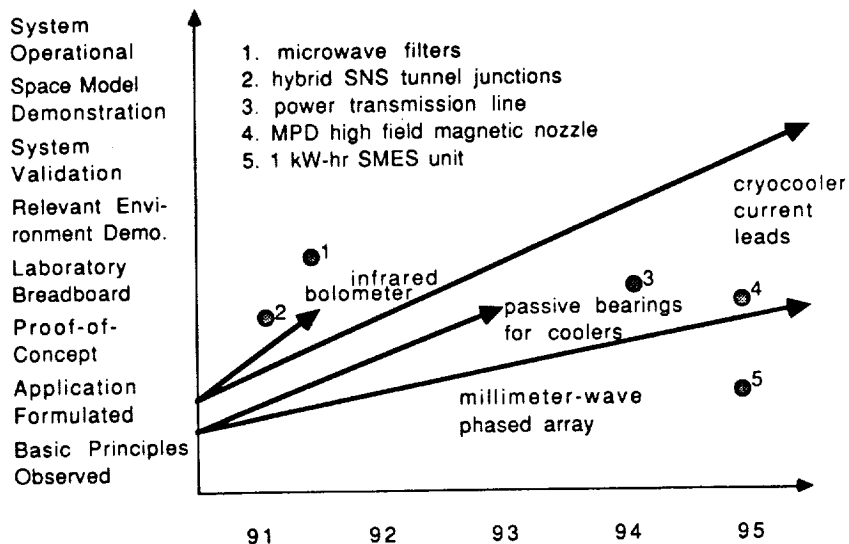


Figure 4. Projected maturity of several NASA high Tc superconductor applications

Conclusions

Many breakthroughs in processing technology have already occurred, and practical, near term applications have emerged for both thin film and bulk material. Amidst intermittent skepticism, tenacious researchers have continued to produce better and better materials. Current densities, critical fields (H_{c2}), and film morphology have improved enough to satisfy requirements for many bulk and thin film devices, although implementation is still challenged by mechanical and structural limitations. Considering the brief history of high T_c technology; however, its evolutionary progress has been dramatic. The successful implementation of this burgeoning technology will require a concerted agency-wide and National effort to promote farsighted research and development.

Numerous near-term practical insertion opportunities as well as more speculative applications have been presented. Prototype cryocooler bearings, cryocooler current leads, superconductor-normal-superconductor microbridge oscillators, microwave filters and phase shifters, and infrared bolometers will likely evolve in very reasonable time frames. Capitalizing on recent developments for space and other applications will require unwavering commitment to make the pivotal transition from materials research to prototype device development.

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