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Development of Energy-Efficient Cryogenic Leads with High Temperature Superconducting Films on Ceramic Substrates

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Abstract

High temperature superconductor (HTS) material can be used for the implementation of high-speed low-heat conduction data links to transport digital data from 4 K superconductor integrated circuits to higher-temperature parts of computing systems. In this work, we present a conceptual design of energy efficient interface and results in fabricating such HTS leads. Initial calculations have shown that the microstrip line cable geometry for typical materials employed in production of HTS thin films can be a two-layered film for which the two layers of about 10 cm long are separated by an insulation layer with as low permittivity as possible. With this architecture in mind, the pulsed laser deposition process has been designed in a 45 cm diameter vacuum chamber to incorporate an oscillating sample holder with homogeneous substrate heating up to 900°C, while the laser plume is fixed. This design has allowed us to produce 200 nm to 500nm thick, 7 cm to 10 cm long YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7} thin films with the homogeneous critical temperature (T\textsubscript{c}) of about 90 K. The critical current density (J\textsubscript{c}) of the short samples obtained from the long sample is of (2\pm 1) \times 10\textsuperscript{10} A/m\textsuperscript{2}. Lines of 3-100 \mu m wide have been successfully patterned along the length of the samples in order to directly measure the T\textsubscript{c} and J\textsubscript{c} values over the entire length of the samples, as well as to attempt the structuring of multichannel data lead prototype.

Keywords: YBCO films, data cables, pulsed-laser deposition (PLD)

1. Introduction

Energy efficiency has become the dominant parameter for the design and implementation of the next generation of computing and communication systems. The next generation of supercomputers, the Exascale supercomputers, will not be feasible unless the energy-efficiency of the core digital and memory technologies and overall computing system are radically increased [1]. Cryogenic superconductor single flux quantum technology (SFQ) is viewed as a technology capable to achieve drastically higher energy efficiencies.
than other technologies [2]. For any cryogenic electronics, an energy-efficiency of the integrated system is critical. Power savings obtained by using energy-efficient electronic technologies will be wasted, if the system design is not optimized for low power. Achieving high overall systems efficiency involves optimizing power delivery to cryogenic electronics modules, input/output data interconnect, efficient cryopackage and cryocooler designs. The optimum placement of various system elements and technologies at different temperature stages following the hybrid temperatures, hybrid technologies (HTHT) integration principle [3] can be used to achieve the lowest overall heat load and overall power consumption for the cryocooler [2].

One of the significant heat loads for the cryocooler is related to the heat generation and conduction from higher-temperature to the lower-temperature stages via the network of cables required to deliver power to run cryogenic electronics. For normal metal cables, the minimum heat load $Q_{b\text{min}}$ for a particular value of the bias current $I_b$ delivered between two different temperatures can be obtained by following the WiedemannFranz (WF) law connecting Joule heating and thermal conduction by electrons [4]. For a typical two-stage cryocooler, the WF-optimised specific heat load for delivery of bias current from the 50 K stage to the 4 K stage will be $Q_{b\text{min}}/I_b = 7.8$ mW/A [5, 6]. This is too high to be acceptable for the energy-efficient optimised cryogenic systems.

Fortunately, the WF is not applicable to superconductors. High temperature superconductors (HTS) can significantly lower the overall heat loads at the 4 K stage that houses Nb-based superconductor integrated circuits due to their low thermal conductivity and resistance-free DC current transport. A multi-line flexible HTS cable made using a commercial YBCO coated tape on Hastelloy substrate was successfully demonstrated [5]. For this cable, the heat leak measured per YBCO line was 1/10th of that for optimised leads made from normal metals for the typical values of bias currents used for the RSFQ integrated circuits. In order to achieve this low heat conduction, a silver coating was removed from the commercial tape, so the heat was conducted through the unpatterned Hastelloy substrate. Recently, a different method was used in order to reduce heat transport via the substrate. The Hastelloy substrate was cut into strips by dicing [6]. However, this heat load reduction was due to geometrical factors and insufficient for energy-efficient applications.

For further reduction of parasitic heat flow to the 4 K thermal stage, it is necessary to use a less heat conductive substrate. The natural choice for such substrates is flexible yttria-stabilized zirconia (YSZ). A YSZ substrate has the additional advantage that it can be used for high frequency RF applications unlike the prohibitively lossy conducting Hastelloy used in previous DC lead work [5]. Such substrate was successfully used to fabricate flexible multi-line cable using medium-temperature superconductor material MgB$_2$ [7]. However, its lower operation temperature ($< 35$ K) limits the applicability of such leads to practical 4 K electronics systems with desirable two cooling stages from room temperature to liquid nitrogen (conventional copper leads employed) and from liquid nitrogen to 4 K (YBCO leads employed).

In this paper, we will describe design, fabrication process, and measurements of YBCO lead prototypes made on low heat conductive and slightly flexible YSZ substrates. These cables capable of operating at temperatures up to 80 K can match the needs of energy-efficient superconductive system integration.

2. Experimental details

In general, we are able to grow high quality YBCO films and REBCO multilayers (RE being the rare earth elements) by pulsed-laser deposition with the help of KrF Excimer Laser (248 nm) on (100) SrTiO$_3$ (STO) or similar substrates in oxygen atmosphere of 300 mTorr in a 45 cm diameter vacuum chamber equipped with a three dimensional sample heater manipulator [8]. The distance between REBCO targets and substrates was about 6 cm, although depending on substrate employed and the distance the electromagnetic and structural properties of the films can substantially be changed [9]. The optimal deposition temperature (at which the highest critical current density $J_c(T = 77$ K) at zero applied field, the highest critical temperature ($T_c$) and the sharpest superconducting transitions are obtained) for the YBCO films was found to be 780°C. The critical temperature $T_c = 90 \pm 1$ K is typical for so-deposited YBCO films and REBCO multilayers. The typical $J_c$ values at $T = 77$ K are of about $2.5 \times 10^{10}$ A/m$^2$. These values form our standard. The optimal thickness (with the same criterion as for deposition temperature) was found to vary from 0.1 to 0.4 μm. However, the criteria for the optimal thickness is quite different for microwave applications and determined by the penetration depth ($\lambda$).
Fig. 1. Pulsed laser deposition technique modified to produce films of up to 10 cm long.

Fig. 2. A long sample obtained in the modified PLD chamber with patterned stripe features of 100 μm wide. The gold padding on the left hand side of the sample is clearly seen.

To characterise films obtained in this work, we employ Quantum Design Magnetic Property Measurement System (MPMS) 5XL which has allowed us to measure magnetization (\(M\)) curves as a function of temperature (\(T\)) and applied magnetic field (\(B_a\)). In addition, the transport current measurement insert has been developed which allows us to directly measure critical current and \(T_c\) by means of the standard four terminal technique. The limitation of this method is the current which can be applied to the current leads. It should not be higher than \(\sim 0.1\) A. As a consequence, it is impossible to measure critical currents at temperatures much lower than about 80 K, even after patterning the films by optical lithography into the narrow bridges of 50 to 200 μm wide. A standard criterion of \(10^{-6}\) V/cm has been used for determining the transport critical current, the criterion can now be modelled to correspond results obtained by different techniques (for example, magnetisation measurements and transport measurements) [10]. The surface resistance measurements have been described elsewhere [11].

3. Development of long sample deposition and measurement techniques

The existing PLD chamber has allowed us to deposit only rather small thin films of about \(1 \times 1\) cm\(^2\) without a strong change in superconducting properties and thickness towards the edges of the films. Hence, in order to obtain a long (7 cm to 10 cm) YBCO films a considerable modification of the deposition process has been undertaken. Fig. 1 shows the schematics of the modified PLD chamber which shows the long substrate attached to the special gearing mechanism driven by a stepping motor, which is controlled through
a computer interface with variable speed and motion patterns. An optimisation process has determined that the sample drive speed of 5 mm/min provides films with the properties similar to our standard films obtained with the fixed heater stage [8]. An ion gun has been mounted in the chamber as well to create the possibility of the deposition of YBCO films by Ion Beam Assisted Deposition (IBAD) on polycrystalline substrates, in a similar way as was done in Ref. [12]. However, in this work we report the results obtained for the films deposited directly on 8 cm to 10 cm long YSZ single crystal substrates of 10 mm wide and 0.5 mm thick. The most challenging part of the design was the sample heater which would allow us to control the deposition temperature with high accuracy and reproducibility. A few designs has been trialled which included single and multiple halogen lamp radiation heaters, as well as resistive heaters with different number of heating elements. The resistive heater with two and three heating elements turned out to be the most successful, accurate, homogeneous, and reproducible. The problem of the homogeneous heating arose due to the fact that with the resistive heating elements the contact between the substrate to the heater surface determines the actual deposition temperature. Hence, substrates have to be well attached to the heater surface. However, this leads to a possibility of breaking the long sample upon removal them from the heater. The special clamping mechanism on the H-shape heater design with the heating elements on the sides of the substrates has satisfied all the requirements to the setup. A typical deposition run for about 45 min to 60 min with the pulsed laser frequency from 5 Hz to 10 Hz with a growth rate of about 40 nm/min results in a 200 to 400 nm thick YBCO films.

The patterning of 3 to 100 μm wide stripes for multichannel signal transmission has been created by optical lithography (Fig. 2). Both wet (chemical) etching and dry (ion) etching of the YBCO films have been attempted. Wet etching is rather simple procedure, so it is tempting to employ it in the first instance. However, as can be seen in the images taken with the help of an optical microscope shown in Fig. 3, the quality of the film edges in the wet etching procedure is considerably rougher than those obtained by dry etching. In fact, the roughness of the wet etched edges is of the same magnitude (∼ 2 – 4 μm) as the line width (3 μm) obtained by the dry etching process. Using wet etching, it is difficult to obtain a reasonable quality pattern features with dimensions < 20 μm. Gold pads on the stripes for connectorizing the signal leads have also been deposited by PLD in vacuum of about 10^{-6} Torr at temperatures slightly higher than room temperature, and the interconnects removed by employing lift-off lithography procedure. A typical thickness of the gold pads is of 100 nm to 200 nm thick.

In order to measure the properties of the films obtained over the entire deposited length, a special insert into a continuous flow cryostat has been designed which enables critical temperature and critical current measurements of long samples by means of the four terminal transport technique at a certain temperature.
4. Results and discussion

As long substrates (including YSZ) are rather expensive to use for optimization procedures, we have used small YSZ substrates of $3 \times 3$ mm$^2$ or $5 \times 5$ mm$^2$ during the optimization process. Fig. 4(a) shows the results of the final optimization stage with the small samples, which were mounted with silver paste on the long heater at three different positions (in the middle, at the upper end, and the lower end) and deposited simultaneously with the oscillating heater at 780° driven by the stepping motor. All three samples show very similar onset of the critical temperature $T_c = 90.0 \pm 0.6$ K, while the width of the superconducting transition is broader for the samples situated at the ends. Because of the similarity of the broadening, we attribute it to the changes in temperature homogeneity of the long heater due to the edge effects. Heat transfer is likely to be different in the centre of the heater and its ends.

However, the uncertainty with this optimization procedure based on the deposition of individual small samples is the mounting procedure. The small substrates were attached to the heater surface by the silver paste providing strong heat exchange, while the long substrate has to be mounted by the end clamping, so that the contact heat exchange is considerably reduced. This leads to the temperature difference between the heater surface and the substrate surface of up to 100°C to 200°C. Hence, a further corresponding optimization was necessary. The result of the resistivity measurement of the superconducting transition in a 8 cm long sample over its nearly entire length is shown in Fig. 4(b).

A typical small piece of the long sample taken from about ±3.5 cm from the middle point shows the critical current density ($J_c$) dependence on the applied magnetic field ($B_a$) which is similar to the best available YBCO films with $J_c(77\,\text{K}, 0) \approx 2.4 \times 10^{10}$ A/m$^2$ [Fig. 5(a)]. This value entirely satisfies the application demand of the heat switch link for DC signals and digital electronics.

Moreover, the surface resistance of our YBCO films have been measured to ensure their characteristics for data transfer at Gigahertz frequencies. A $2 \times 2$ cm$^2$ films of 420 nm thick exhibited the surface resistance $R_s = 4.3 \mu\text{Ohm}$ at 1 GHz and 77 K. The temperature dependence of the surface resistance for a smaller film of $1 \times 1$ mm$^2$ and 500 nm thick measured at the resonance frequency of 25 GHz is shown in Fig. 5(b). However, this film might be exposed to some degree of degradation during measurement handling, which may be seen in a steep rise of the surface resistance at relatively low temperatures. Nevertheless, these films exhibit results similar to the best available in the literature [13] and suitable for the high speed data transfer for digital electronics.
5. Conclusion

The HTS YBCO long film multichannel cables with 100 μm wide superconducting stripes have been deposited by PLD technique after modification of a standard PLD chamber. A long oscillating contact resistive heater has been identified to be the most accurate and robust design, providing the most homogeneous 8 cm to 10 cm long films during PLD process. The magnetic and resistance measurements exhibit high quality rather homogeneous films with properties comparable with best small samples obtained in our standard PLD setup and those available in the world for various applications. The critical current density in self field and at 77 K is of $2.4 \times 10^{10}$ A/m$^2$, the critical temperature onset $T_c \approx 90$ K over the entire length of the long sample, and the surface resistance $R_s \approx 4 \mu$Ohm at 1 GHz (equivalent to $\sim 2$ mOhm at 25 GHz) and 77 K. These properties are sufficient for applications in electronics, providing effective reduction in transferred and generated heat.

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