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Novel Applications of Tl-Ca-Ba-Cu-O Thin Films to Active and Passive High Frequency Devices

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ABSTRACT

We will present our recent work on the applications of high temperature superconducting thin films to the development of new passive and active circuitry operating up to 40 GHz. We will discuss thin film deposition (including new results on the effect of low temperature anneals) and patterning Tl-based films to linewidths of 3 μm, and contacting. A number of HTS device will be discussed including passive resonators and filters and an active device, the superconducting flux flow transistor (SFFT), that can be used in applications such as amplifiers and phase shifters.

KEY WORDS: Tl superconductor, superconducting devices, microwave applications

INTRODUCTION

In order to develop high frequency applications for HTS materials, three main issues must be addressed. The film process must be stabilized and the resulting films must have low surface resistance at frequencies up into the millimeter wave regime and good surface morphology. Existing device processing technologies must be modified for the Tl-Ca-Ba-Cu-O and other HTS films. This technology must include lithography with resolution of better than a few μm, high quality contacts, and stable non-reactive deposition of dielectrics and normal metal layers compatible with the HTS films. Finally, passive and active device concepts must be found that address applications requirements while fitting the characteristics of these unique materials.

Tl-Ca-Ba-Cu-O FILMS

Due to the volatility of Tl, development of films in the Tl-Ca-Ba-Cu-O system has necessitated ex-situ processing. This processing consists of three main steps: deposition, sintering and annealing. Work to date indicates that the first step is not critical as long as an approximately correct stoichiometry is obtained and the formation of intermetallic phases is prevented. The second step, however, is critical; phase and morphology are established during sintering in air. The third step, a controlled oxygen anneal, optimizes the superconducting properties of the films.

Metallic films are deposited by sequential electron beam evaporation of the pure metals onto the substrate of choice, $LaAlO_3$ for experiments described below, under a slight oxygen overpressure ($1\text{-}3 \times 10^{-5}$ mbar) to prevent intermetallic phase formation. The evaporations are done in layers starting with Cu and ending with Cu to encapsulate the structure. The as-deposited partially oxidized structures are metallic as expected and show no evidence of superconductivity. Such precursor films are sensitive to oxygen and moisture and consequently are stored in an argon atmosphere dry box while waiting to be sintered and annealed.

Precursor films are oxidized and the Tl-Ca-Ba-Cu-O superconducting phases synthesized during the sintering process. The morphology of the oxidized film is also established at this time. Liquid Tl phases appear to be crucial to the formation of clean, sharp grain boundaries. Films are sintered with the substrate sitting film side up on bulk $Tl_2Ca_2Ba_2Cu_3O_y$ ceramic while a second bulk $Tl_2Ca_2Ba_2Cu_3O_y$ ceramic is located above, but not in contact with, the film. The "sandwich" structure is placed in a 3" Pt crucible with a tight fitting lid. The lid has an approximately 5 mm hole allowing Tl leakage and producing quasi-equalibrium conditions of Tl and oxygen partial pressure. Films are sintered for 16 minutes at 850 °C.

The exact composition of the bulk ceramics used for the Tl source is critical. A narrow window of compositions from $Tl_{2.04}$ to $Tl_{1.96}$ produces the best results. Bulk ceramics that are too Tl rich do not produce uniform growth of superconducting phases on the wafer. Bulk ceramics that are Tl deficient produce good $Tl_2Ca_2Ba_2Cu_3O_y$ phase growth but with random orientation and weak links. The metal ratios in the films as deposited are very close (±5%) to the desired $Tl_2Ca_2Ba_2Cu_3$ composition. Typical anneals are 10 min. (0.3 μm films) at 750 °C followed by a furnace cool. In the best films the effect of this anneal is small with increases in T_c of 2-5 K and increases in J_c of ~10%. Recent work has shown that anneals below 600 °C and as low as 300 °C can substantially improve the superconducting properties of TlCaBaCuO thin films and single crystals. Optimum results are typically obtained at

400 °C in oxygen in a range where DTA and TGA show no significant thermal events. Marginal films (J_c= 10^3-10^5 A/cm^2) can typically be substantially improved while higher quality films (J_c> 10^5 A/cm^2) show less improvement. Best results have shown 10-15K increases in T_c and order-of-magnitude increases in J_c (2 x 10^4 to 2 x 10^5 A/cm^2). Better films show 10-15% increases in T_c and J_c. Work to date indicates that these improvements arise from changes in doping levels due to changes in cationic disorder and oxygen vacancy density. Low temperature annealing potentially provides a mechanism for the precise tailoring of film properties.

The morphology and structure of the films were determined by scanning electron microscopy (SEM) with energy dispersive x-ray analysis (EDS) and by x-ray diffraction. The 0.3 μm films are smooth on a scale ~ 0.05 μm and are highly dense (> 90%). The grain size varies from 10 to >100 μm, indicative in some cases of an approach to true epitaxial growth. Cleaved films were examined by SEM normal to the substrate surface. In all cases the individual grain thickness is equal to the film thickness and no layering is observed. The lateral and vertical uniformity strongly supports the bulk superconducting nature of the films. Most of the films show complete c-axis orientation perpendicular to the substrate but only partial a-axis orientation in the plane.

PROCESSING DEVICES

All of the circuits to be described are made with standard optical lithography (using a solvent based negative photoresist) and wet etching. A solution of 2 % Br in isopropanol [1] is used for mesa etching with an etch rate of approximately 30 nm/sec. With this process, stable 3 mm linewidths are obtainable. In some applications described below, controlled film thinning is required. For example, a narrow region (e.g. 10 μm by 20 μm) must have its thickness reduced from 300-700 nm to less than 100 nm. This is done with a carefully timed etch of 0.5-0.8% Br in isopropanol.

Dielectric and normal metal levels are also required in some applications. A hard-baked layer of negative photoresist works as an adequate dielectric for many applications (stable and low loss, tan $\delta \sim 10^{-4}$). Other dielectrics are under investigation. Most normal metals are usable for other layers. If the metal is in contact with a Tl-Ca-Ba-Cu-O level, it must not easily oxidize or oxygen may diffuse from the superconductor causing contact problems. The metals used are Au, Ti, Al, W-Si and Ag. The W-Si is used frequently as an oxygen diffusion barrier for Ti and Al resistors. For ohmic contacts, we use annealed silver contacts deposited through a shadow mask. Contact resistances of less than 0.1 Ω have been achieved and do not appear to degrade with time.

PASSIVE DEVICES

A number of different passive microwave components have been developed both for applications (in conjunction with the active devices discussed below) and for use in materials characterization. The first components, the ring resonators, have been built and are used for materials characterization [2]. An all-gold structure is first used to calibrate the system for the surface resistance of gold. To evaluate the HTS material, ring resonators were constructed using a TlCaBaCuO top conductor and a gold ground plane. With the gold surface resistance data and the data from this resonator, it is possible to compute the HTS surface resistance. The method is valid for arbitrary film thicknesses and the structure is easy to measure using a contactless probe (see Fig. 1). For our Tl films, we have measured a surface resistance of about .6 mΩ at 8 GHz and 77K. This can be compared to the theoretical value for gold of about 9 mΩ at 8 GHz and 77K. Modified versions of the Tl ring resonator have been used as frequency-determining networks in oscillators [3].

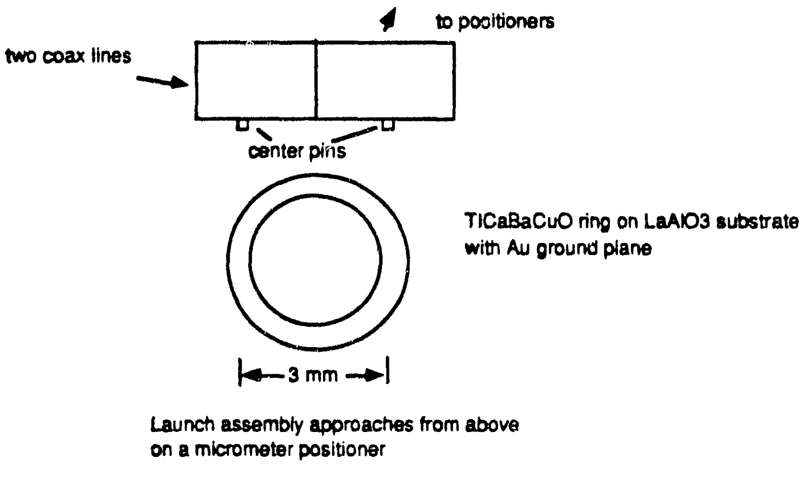

Fig. 1. The ring resonator and probe assembly to measure surface resistance (8.2 GHz).

Confocal resonators have also been used for materials characterization. The structure uses a normal metal mirror focussing a Gaussian beam (mode TEM_{00n}) [4] onto a planar sample as shown in Fig. 2. Because the magnetic fields are strongest at the sample in this configuration, losses in the normal metal are not as important to the total Q as in a cylindrical cavity system. Since this system is quasi-optical, it can be easily extended to much higher frequencies (100 GHz). The surface resistance of TlCaBaCuO films at 77K and 36 GHz has been measured to be ~.8 mΩ.

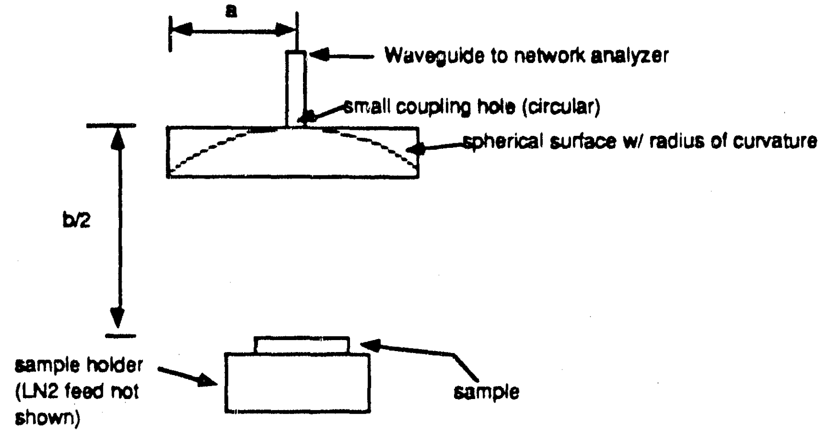

Fig. 2. Experimental arrangement for surface resistance measurements using a confocal resonator. The spherical mirror has a radius of curvature b.

Coplanar waveguide filters in Tl films have been developed. This structure was chosen over the more common microstrip filters[5] because of the planar nature of the active devices used and the desire to avoid requiring double sided films. On a 700 nm Tl film ($LaAlO_3$ substrate) the filter (9.5 GHz cut-off designed) showed a passband loss of .5 dB and matched simulation results to within 1 dB over the range 7 GHz to 11 GHz. The substrate was apparently of sufficient quality that twinning did not disrupt the microwave performance.

ACTIVE DEVICES

The device of most interest to us so far is called the Superconducting Flux Flow Transistor (SFFT) [6]-[9]. It consists of a parallel array of weak superconducting links (separating two unweakened banks of superconductor) and a control line to provide a local magnetic field. An example of this structure is shown in Fig. 3. When the device is biased below the critical current (typically on the order of 1 mA), no flux is admitted into the link system (perfect Meissner state). Above the critical current, flux is admitted in discrete quanta known as vortices[10]. These vortices can move since the bias current generates a Lorentz-type force on the vortices. The vortices are also subject to forces from external magnetic fields (from the control line), viscous damping, pinning forces (which are undesirable in that the average vortex speed is reduced) and surface barriers at the edges of the links which hamper flux entry and exit. The balance of these forces determines the flux motion and hence the terminal voltage. In terms of active device performance, the key principle is the use of an external magnetic field (via the control line) to modulate the flux density in the link system [11],[12] and the resulting flux motion.

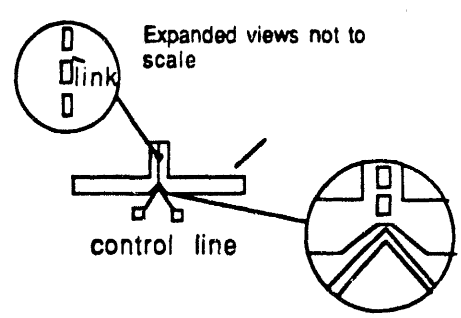

Fig. 3. A layout of the Superconducting flux flow transistor (SFFT). The links are 3-5 μm by 10 μm and are 50-100 nm thick (the banks are 300-700 nm thick). The control line provides a magnetic field that modulates the flux density in the link system.

A typical set of I-V curves is shown in Fig.4 The transition between the zero-voltage section and the flux flow section is apparent. By modulating the flux density in the link system, the control field causes a horizontal translation of the flux flow branches (with an accompanying change in critical current).

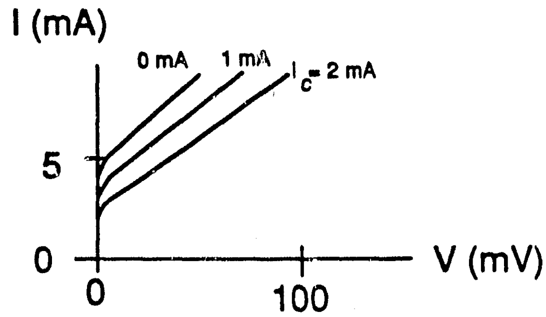

Fig. 4. I-V curves for the device of Fig. 3. Note the flux flow branches and the effects of control current I_c.

The device behavior is closely correlated to the quality of the film remaining in the link region. While increased pinning results in higher critical currents, it also reduces sensitivity to external magnetic fields (and hence gain) and reduces the flux speed and frequency response of the SFFT. A material with a low H_{c1} is desirable in that it is easier to admit flux to the system and increase sensitivity to the control fields. The penetration depth is also important since it strongly influences the surface barriers and hence control-field sensitivity [13]. In addition, the effective penetration depth changes with link thickness, greatly increasing the effect of the film thinning process. Maximum gain occurs for links thinner than a penetration depth but not so thin that the superconductivity is destroyed or the defect density rises enough to induce excessive pinning centers. For a stable film production process, the effect of link thickness must be very reproducible (typical thickness of the active region is about 80 nm). Films with higher J_c tend to have narrower windows of acceptable link thickness but may still be used with good results.

The next step in the development of microwave applications is the creation of an equivalent circuit; one is shown in Fig. 5 [13]. The input impedance is low (a resistance of less than .5 Ω from contacts and surface resistance and an inductance of around 200-300 pH). For applications in a 50 Ω system, impedance matching is necessary. The output is dominated by the transresistance mechanism (a dual of the transconductance mechanism in a FET), an output resistance on the order of 3-5 Ω, and an output inductance that is non-linear for sufficiently large current swings. A typical value of transresistance ($r_m = \Delta V_{out}/\Delta I_{ctl}$) for a TlCaBaCuO device at 77K is 15-20 Ω.

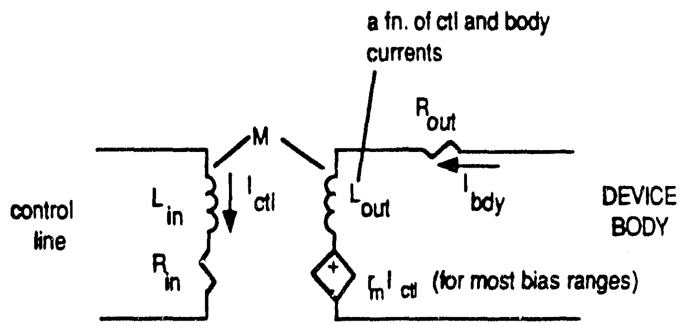

Fig. 5. An equivalent circuit for the device of Fig. 3. For large signal analysis, the output resistance is modeled as part of a non-linear voltage source. The output inductor can also be non-linear.

Two factors affecting device speed are the input and output L/R time constants as can be seen from Fig. 5. By reducing device dimensions, these inductances can be reduced, in turn reducing the time constants below 50 ps in most circuits. Besides the circuit time constants, there is a fundamental device time constant as well. The vortices take a finite amount of time to cross the link system. This delay is the transit time constant. With vortex speeds on the order of 5×10^5 m/s (at 77K) [13] and typical link dimensions (3-5 links, each 3 μm in the direction of flux motion) this time constant is about 10-30 ps. As lithographic capabilities improve, this time constant can be reduced further. Device operation has been demonstrated at 35.8 GHz (a smaller device than that described above, used as a mixer) when the net time constant predicts a cut-off of 36.7 GHz [13].

The SFFT can produce net gain in a 50 Ω system [3]. With some impedance matching, one group of devices have the gain shown in Fig. 6. Because of the very low input impedance, very high gain can be achieved with perfect impedance matching. Preliminary noise measurements show a minimum noise figure of about 0.8 dB at 4 GHz [14]. Work continues on broader band amplifiers and on the evaluation of noise and non-linearities.

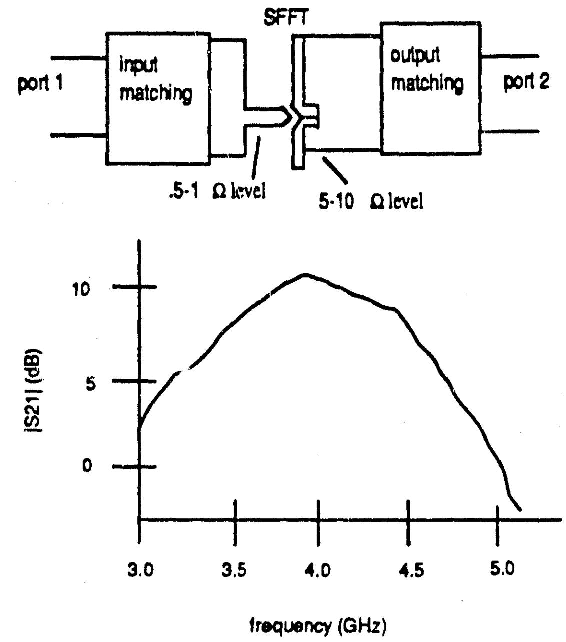

Fig. 6. The upper image is the SFFT embedded in its matching networks (composed of superconducting transmission lines and inductors); the circuit was designed to operate at 4 GHz. The lower image shows amplifier gain in a 50 Ω system. The 3 dB bandwidth was about 1.1 GHz.

The variable output inductance has been used to create a phase shifter. To allow large amounts of linear phase shift (> 2 π radians desired), several devices are used embedded in an artificial transmission line. The individual SFFTs form the inductors of the transmission line and gap capacitors are used to adjust the impedance level to a nominal 50 Ω. At a 4 GHz test frequency, 2π of phase shift was generated by a control current of 3.5 mA as shown in Fig. 7. The corresponding insertion loss was less than 4 dB and the useful bandwidth exceeded 2 GHz.

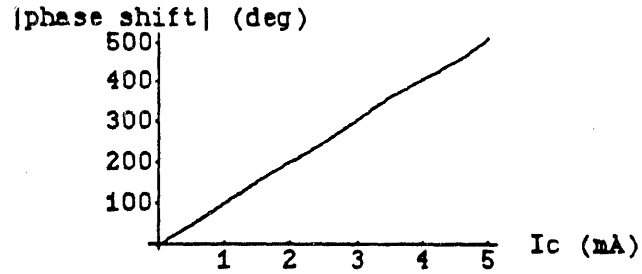

Fig. 7. Phase shifter performance at 4 GHz as a function of control current. Note the linearity and the large amount of phase shift available.

CONCLUSIONS

We have produced TlCaBaCuO films using e-beam evaporation with subsequent sintering and annealing that have critical current densities of at least several hundred kA/cm^2, critical temperatures over 100K and surface resistance lower than that of gold at 77K and 8 GHz. Processing techniques have been developed for making passive microwave elements and a four terminal active device called the superconducting flux flow transistor (SFFT) for microwave applications. The techniques include contacting, dielectric and normal metal layer deposition, and controlled HTS film etching. The SFFT shows promise as a microwave amplifier and as a phase shifter. It has also been used as an active impedance convertor between LTS Josephson junctions and GaAs MESFETs and in prototype digital circuits. The advantages of the device include high speed, potentially low noise and, for some applications, useful impedance levels. Passive resonators also show promise as demonstrated by us and many others.

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