MICROWAVE DETECTORS BASED ON GRANULAR HIGH-Tc THIN FILMS

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ABSTRACT

Detecting and mixing properties of microstrip superconducting YBCO and BCSCO granular thin film structures have been investigated. The microstrips were deposited on various substrates by two different techniques. Device performance has been tested in 25, 55 and 110 GHz bands and temperature range from 50 to 80K. Detectors response was bias and temperature dependent. The mixing experiments were performed in 25 GHz frequency band. The i.f. frequency was varied from 50 MHz to 5 GHz without any decrease in the mixer output up to 3 GHz. YBCO and BCSCO thin film devices are operational in temperature range from $T=T_c-10K$ to about 50K. The lower limit is imposed by quantum effects which render erratic the output signal. Although the mechanism responsible for the detecting and mixing properties have not been positively identified, the auxiliary emission measurements performed at 12 GHz and down to 4.2K revealed that low temperature performance limit is associated with Josephson radiation from weak-link clusters composed of multi-loop quantum interferometers.

INTRODUCTION

Current state-of-the-art in thin film technology of high T_c superconductors strongly suggests that near term most successful applications of these materials will be in high-speed electronics. It has been demonstrated (1) that transmission lines patterned from non granular high-Tc film can sustain distortion-free propagation of electrical transients having a bandwidth of more than 100 GHz. However, only granular high-T_c superconductors have been so far implemented in active superconductive devices operational at liquid nitrogen temperatures. In fact, granular films have been successfully tested as sensitive microwave and far infrared detectors and mixers (2,3).

In this presentation we report on our studies of *granular* Y-Ba-Cu-O (YBCO) and Bi-Ca-Sr-Cu-O (BCSCO) detectors operational over the frequency range between 24 and 110 GHz at liquid nitrogen temperatures. We report also on mixing of two microwave signals in YBCO film. The latter effect is characterized by short relaxation time of the order of 40 ps.

FABRICATION OF YBCO AND BCSCO THIN FILMS

In order to optimize the performance of the detectors we tried to fabricate the active material of appropriate granularity using either magnetron sputtering or spray-on deposition techniques (4,5). We found that the properties of high-T_c ceramics depend strongly on the substrate material on which the deposition is performed. Eight different substrates were tried: Al_2O_3, $LaAlO_3$, $LaGaO_3$, MgO, $SrTiO_3$, $HFO_2+Y_2O_3$,$ZrO_2+Y_2O_3$ and $ZrO_2+Gd_2O_3$. Although the first four of the above listed materials show excellent dielectric properties at microwave frequencies and we succeeded to grow superconducting films on all of them, the best detectors were as yet produced using ZrO_2, MgO and sapphire substrates. The films deposited on MgO substrates showed generally lower T_c, probably due to the diffusion of magnesium to the superconducting ceramic. Special post-deposition heat treatment was always necessary in order to obtain granularity and critical current appropriate for attaining good detection characteristics. The heat treatment is to some extent more critical than the type of the deposition technique used. Both magnetron sputtered films and spray-on deposited films from nitrate precursors were found useful when prescribed annealing procedure was correctly applied. Magnetron deposited films were more resistant to aging and showed better reproducibility. The advantage of spray-on films is that they can be easily patterned directly in the deposition process by the application of metallic stencil masks; the disadvantage is film porosity and coarse pattern resolution. For more complicated and finer patterning photolitographical followed by chemical etching technique has been successfully applied to both types of films.

We found that sharpness of the transition to the superconducting state is not of primary importance for the described application.

EXPERIMENTAL ARRANGEMENT

There are some well known difficulties in obtaining impedance match between a superconducting film and waveguide. Matching can be improved by the proper choice of the superconducting strip width and possibly by using waveguide of reduced height. The thickness of the

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dielectric substrate is important and its optimal value is frequency dependent. Matching is also bias dependent and temperature sensitive, though these effects have much smaller influence. It was found that strips 80 to 300 μm wide with active length of 2 to 3 mm could be matched with the VSWR less than 3.

Samples for our experiments were prepared in the form of superconducting microstrip lines. The superconducting stripe was illuminated directly by carrier signal propagating in R 220 waveguide and the microstrip line, composed of the stripe, its substrate and a ground plane, served as *if* and/or *video* output line. After deposition onto the substrate of the superconducting stripe the entire back surface of the substrate was silver coated in vacuum to form the microstrip ground plane. Both ends of the superconducting strip were next vacuum covered by silver contact pads. One of the contacts was extended over the substrate edge to make a short circuit with the ground plane. The second silver contact was patterned into a filter structure for the carrier frequency. The detector chip prepared in such a way was incorporated into a window cut in a wafer made of microwave cooper-clad reinforced-teflon laminate on which second filter section was elaborated. The whol structure was then sandwiched in between a copper heat sink and a special flange of the waveguide. Mylar washer was used to insulate the microstrip *video/if* output line and to set an appropriate capacitance of the filter. The assembled detector was placed inside a small glass-cryostat equipped with temperature regulating system from 4.2 to 100 K. The *video/if* output was connected to the signal processing electronics via a semi-rigid coaxial line.

DETECTING PROPERTIES OF YBCO AND BCSCO FILMS

We tested the detecting properties of granular high-T_c thin films using several YBCO and BCSCO samples. The measurements were performed at three millimeter wave bands: 25, 55 and 110 GHz, in the temperature range from 50 to 80 K. Additionally, the noise properties of the films were tested down to 4.2 K. In each band we used a standard experimental set-up composed of a klystron source (OKI 24V11, 55V11 or 100V11), ferrite isolator, ferrite modulator, cascaded calibrated rotary vane attenuators and a circulator or directional coupler. At 25 GHz a slotted line was used for VSWR measurements.

In Figs.1 and 2 we show the response of YBCO and BCSCO detectors, respectively to 1 kHz amplitude modulated 25 GHz signal. In some experiments 20 kHz modulation frequency was used without any effect on the detector response. For comparison purposes the samples shown in Figs.1 and 2 while composed of different materials have similar critical currents at 77 K. The transition temperature of YBCO was 92 K. In the BCSCO film beside the 88 K phase some admixture of 110 K phase was present. Remarkable sensitivity increase accompanied the temperature decrease below 77 K. BCSCO detector exhibited more than 20 dB increase of sensitivity when cooled down to 50 K. Similar, though smaller sensitivity increase was noted for YBCO detector. In this case however, the decrease of the temperature below 65 K rendered the detecting properties sensitive to bias current in a complicated manner.

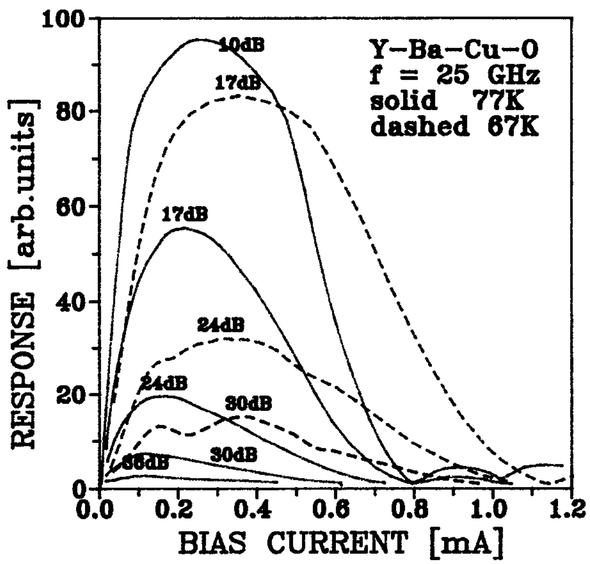

Fig.1 Video response of the 25 GHz YBCO on ZrO_2 detector at 77 K and 65 K. Relative power levels are indicated on curves.

Such features are shown in Fig.3 for the same sample as in Fig.1 but at 50 K. We have found also that at 50K and some bias currents the response of this detector was very sensitive to the externally applied magnetic field.

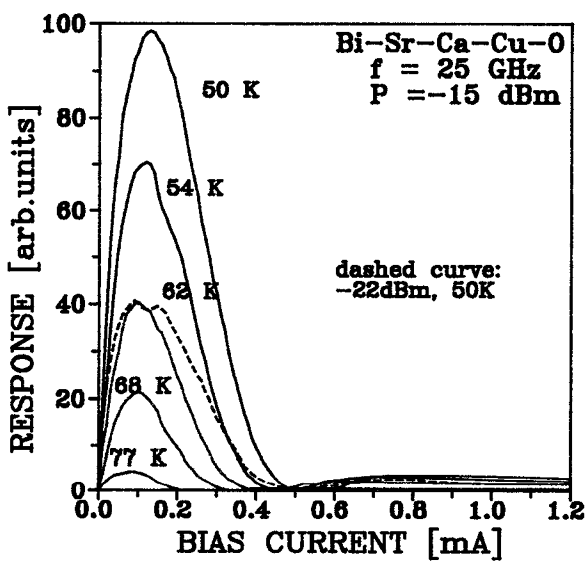

Fig.2. Sensitivity of video response of the 25 GHz BCSCO-on-MgO detector versus bias current for a sequence of working temperatures.

At 55 and 110 GHz we observed no new features. At 110 GHz the best results (Fig.4) were obtained for YBCO deposited on sapphire. Note that the proportionality of the detected voltage to the incident 110 GHz power can be deduced from Fig.4. The sensitivity increase upon cooling down from 77 K to about 55 K for this particular detector was about 13 dB. Comparing this sensitivity to the sensitivity of 1N53 crystal detector we have found that 1N53 was barely 6 dB better.

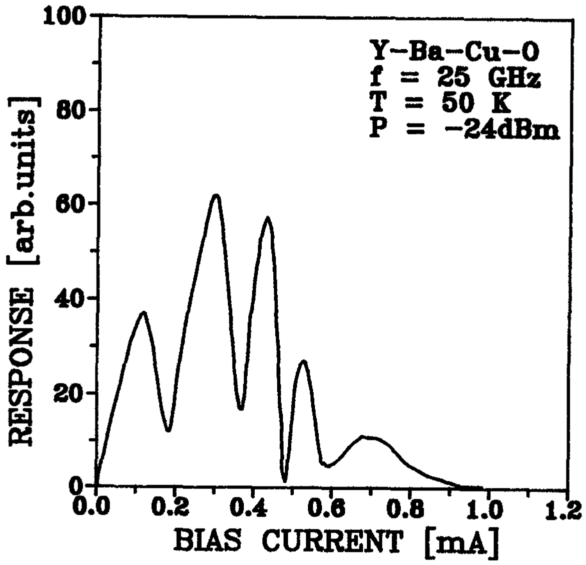

Fig.3. YBCO-on-ZrO2 detector response at 50 K. (the same sample as shown in Fig.1.)

Mixing experiments were performed in 25 GHz frequency range. We used 2 klystron microwave sources and spectrum analyzer as *if* receiver. The results obtained on YBCO and BCSCO were quite similar to those earlier reported (3). Mixer response was linear at signal levels from -10 to -50 dBm. The local oscillator level was not very

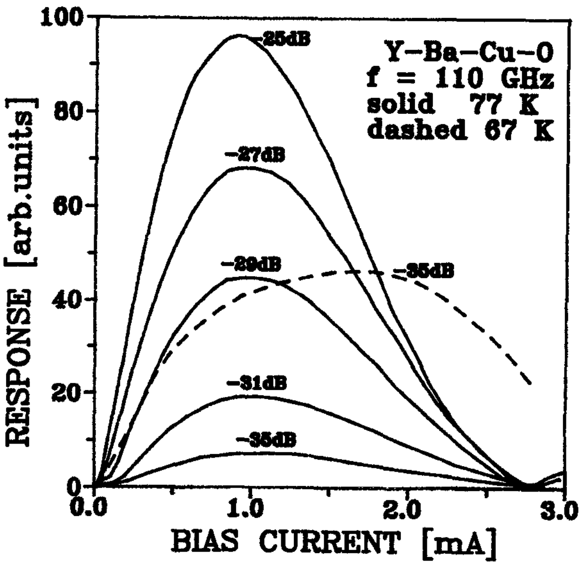

Fig.4. Video response of 110 GHz YBCO on Sapphire detector at 77 K and at 67 K. Relative power levels are indicated on curves.

critical. We found a flat optimum of the order of few mW. The mixing action disappeared at about 80K for YBCO and 70 K for BCSCO. By tuning both microwave sources, we were able to obtain *if* frequencies from 50 MHz to 5 GHz. The *if* level was almost constant for *if* frequencies up to 3 GHz. Further frequency increase deteriorated the output. This deterioration, however, was not exponential and could not have been caused by any relaxation processes in the superconducting material. We ascribe it rather to the limited bandwidth of our *if* output line.

DISCUSSION

The physical processes responsible for the observed detection and mixing effects are not very clear. Most probably the involved processes are a complicated mixture of known - and perhaps some unknown - mechanisms, appropriately enough for the complicated nature of the investigated system which is a mixture of superconducting grains, intra- and inter-grain weak links, and normal phase. In general, the behavior of our detectors is quite similar to that found by Bertin and Rose (6) in Sn granular thin films (their *enhanced mode* detection).

The observed short relaxation time seems to rule out classical bolometric effects, though proportionality of the detected voltage to the incident microwave power is typical for that process. On the other hand, we have proved (7) the existence of Josephson weak links in our granular films by direct evidence of microwave radiation emanating from these films. A typical example of radiation from YBCO film, as recorded by 12 GHz receiver of 250 MHz bandwidth, is shown in Fig.5.

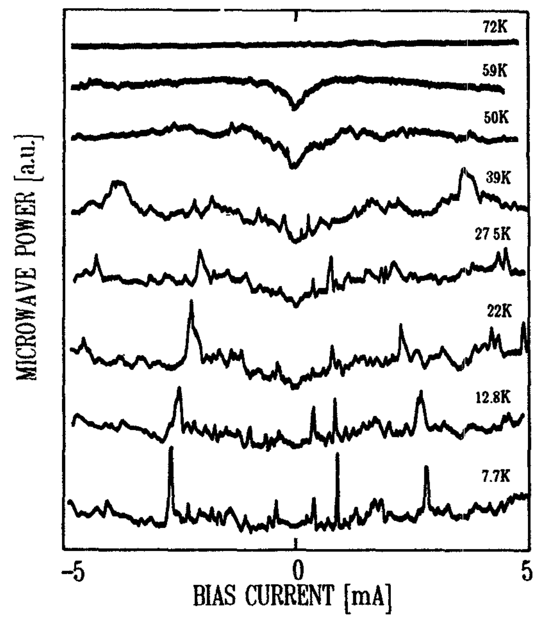

Fig.5. Wide-band microwave emission (f=12 GHz, B=250 MHz) from current biased YBCO film at different temperatures. Successive curves are shifted for clarity.

Such noise, clearly visible at liquid helium temperatures, decreases with temperature increase and vanishes around liquid nitrogen temperature. This is consistent with Josephson coupling energy becoming smaller than the energy of thermal fluctuations and seems to eliminate Josephson mechanism as responsible for mixing observed at high temperatures, otherwise an obvious candidate.

However, let us observe that the measured dc I-V characteristics of our films were highly nonlinear. Optimum bias, required to maximize the sensitivity of video detection (cf. Figs.1 and 2) corresponded always to regions of highest nonlinearity. The incidence of microwave power directly influenced the I-V characteristics in a manner resembling the effects of microwave power on imperfect Josephson junctions (8).

Surprisingly, the efficiency of mixing exhibited a flat maximum at zero bias and was vanishingly small at the bias currents optimal for video detection. Apparently the mechanisms involved in mixing and in video detection are different.

One should mention that the existence of normal phase distributed between superconducting grains in our films can lead in the presence of microwaves to the creation of a dense network of hot spots of very small total volume and can disturb the dynamical equilibrium of the system. The relaxation times involved in such processes can be of the order of 1ps at 4 K (9) and at 77 K could be much shorter.

CONCLUSIONS

In conclusion, high-Tc granular thin films offer interesting possibilities both as coherent and video detectors of millimeter waves. The lack of understanding of relevant physical mechanisms makes the device optimization difficult, but not impossible. The best performance is obtained so far at temperatures in the vicinity of 60 K but the use of a higher Tc superconductor (e.g. Tl-Ba-Ca-Cu-O) will probably allow to obtain efficient detection at 77 K.

We must emphasize that while detection sensitivity increases with decreasing temperature, there is a limit to the lowest usable temperature. It is imposed by quantum effects which manifest themselves below about 50K. These effects are caused by Josephson junction clusters arranged in multi-loop interferometers (10). As a result, the detector response is strongly bias dependent (cf. Fig4.) and extremely sensitive to magnetic field. The excess noise generated in this manner was measured to be about $4*10^{-16}W(Hz)^{-1/2}$ at 4.2 K (7,10).

Finally, one must consider the high frequency limit of the proposed devices. Theoretically it should be determined by the superconducting energy gap and fall in the terahertz range. However, our recent experiments (11) indicate that video response falls off by one order of magnitude for carrier in the frequency range between 100 GHZ and 300 GHz.

ACKNOWLEDGMENTS

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REFERENCES

(1) D.Dykar,R.Sobolewski, J.Chwałek, J.Whitaker T.Y.Hsiang, G.A.Mourou, D.Lathrop, S.E.Russek and R.Buhrman, "High frequency characterisation of thin film Y-Ba-Cu-O oxide superconducting transmission lines", APPL.PHYS.LETT. 53, Apr. 1988, pp.1444-1446

(2) U.Strom, E.S.Snow, R.L.Henry, P.R.Broussard, J.H.Classen and S.A.Wolf, "Photoconductive response of grsnular superconducting films", PROC. ASC Conf '88, San Francisco, IEEE TRANS. MAG-25, 1989, to be published.

(3) J.Konopka, R.Sobolewski,A.Konopka, S.J.Lewandowski and W.Kula, "Detection of millimertre wave radiation by Y-Ba-Cu-O thin films at liquid nitrogen temperatures", PROC.18-th EUROPEAN MICROWAVE CONF., Microwave Exhib. and Publ., Tunbridge Wells, 1988, pp.189-194

(4) P.Gierłowski, W.Kula, G.Jung, A.Konopka, J.Konopka, R.Sobolewski and J.Staskiewicz,"DC Magnetron Sputtering of YBa Cu O Thin Films", PHYSICA SCRIPTA (in print)

(5) W.Kula, R.Sobolewski, P.Gierłowski, J.Konopka S.J.Lewandowski, and A.Graczyk, "Simple Patterning of Spray Deposited Y-Ba-Cu-O Films", SUPERCONDUCTOR SCI.& TECH.,1, 1988, pp. 145-147.

(6) C.L.Bertin, K.Rose, "Enhanced-Mode Radiation Detectors", J.APPL.PHYS. 42, 1971,pp 631-642.

(7) J.Konopka and G.Jung,"Microwave Radiation from current biased Y-Ba-Cu-O Thin Films", EUROPHYS.LETT., in print.

(8) cf. D.Morisseau, J.Lewiner, S.J.Lewandowski and G.Jung, "Capacitor shunted Josephson junction for improved coupling with microwave fields",APPL.PHYS.LETT. 29,(1976), pp. 59-60.

(9) D.Karecki, G.L.Carr, S.Perkowitz, D.U.Gubser and S.A.Wolf, "Far infrared conductivity and anomalous below gap absorption in superconducting granular NbN", PHYS.REV. B28, 5460, (1982).

(10) G.Jung and J.Konopka, "Quantum coherence effects in microwave emission from Y-Ba-Cu-O films" submitted to EUROPHYSICS LETTERS.

(11) V.B.Anzin, P.Gierłowski, Yu.G.Goncharov, B.P.Gorschunov G.Jung, J.Konopka, G.V.Kozlov, W.Kula, S.J.Lewandowski, O.I.Sirotynskyi and R.Sobolewski, "Detection of submillimeter radiation by granular Y-Ba-Cu-O films", to be published.