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A 12 GHz oscillator based on a GaAs HEMT integrated to a HTS resonator

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Abstract: A hybrid oscillator operating at 12 GHz and 77 K was designed and characterised. The design incorporated on a single substrate a passive superconductive circuit and a III-V active device. YBaCuO films (300nm), grown on MgO, had a surface resistance at 77 K of 0.3 m Ω scaled to 12 GHz. The DC and RF characteristics of the pseudomorphic HEMT showed minor differences before and after hybridation. The characterisation of a preliminary prototype oscillator including a superconducting resonator patterned on a MgO substrate, a gold matching network fabricated on Al₂O₃ and a transistor wire bonded gave a phase noise as low as - 75 dBc/Hz at 10 KHz.

1. INTRODUCTION

Microwave circuits for radar or communications are likely to be the first area of practical applications of high temperature superconductors (HTS). As a matter of fact HTS thin films such as YBaCuO or TlBaCaCuO have a microwave surface resistance that is orders of magnitude lower than that of metals at liquid nitrogen temperature [1]. That is why a variety of passive devices like resonators, filters, delay lines or antennae have been successfully developed. For example, the HTSSE [2] space experiment is aimed at demonstrating the feasibility of incorporating HTS technology into space environment.

In order to impact subsystem or system level applications, it is necessary to have active devices which produce gain with low noise characteristics. To date, current active HTS devices exhibit too high noise to be used in high performance microwave circuits. On the contrary, III-V solid state devices provide these characteristics and have enhanced performance at cryogenic temperatures. Several authors already reported on hybrid devices assembling HTS passive components and III-V active devices [3],[4],[5]. However the schemes with commercial active devices and conventional integration technique show unsatisfactory parasitic noise.

The purpose of this paper is to report on the development of a hybrid oscillator operating at 12 GHz and combining a pseudomorphic HEMT and a microstrip YBaCuO ring resonator. Both chips are integrated on a single substrate with the so called Flip-Chip or ELO techniques, described hereafter, which take advantage of the low parasitic inductance and capacitance. In a first part the typical parameters of superconductor deposition and resonator patterning are emphasized. The second part details the oscillator design and the characteristics of a first prototype. The third part describes the hybridation processes and their characteristics. Finally the capabilities of the circuit are discussed.

2. SUPERCONDUCTOR

2.1 Superconducting film deposition

High quality epitaxial YBCO films with low surface resistance are required for microwave applications. Many research groups fabricate such YBCO films using MOCVD [6], Inverted Cathode Magnetron Sputtering [7] and Pulsed Laser Deposition (PLD) techniques [8], on MgO, LaAlO₃ and Al₂O₃. In this study, films were deposited on (100) MgO by PLD using a pulsed excimer laser in a procedure which has been described elsewhere [9]. MgO substrates were chosen as a good compromise between substrate brittleness, substrate microwave properties and YBCO film quality. The substrate surfaces were characterised prior to deposition by X-Ray Topography and Atomic Force Microscopy (AFM). Their RMS roughness was in the 0.1-0.3 nm range. The substrates, after rinsing in toluene, acetone and iso-propanol, were glued onto the heating block with silver paste. The furnace temperature was monitored by a thermocouple clamped inside the heating block. The substrate temperature measured by a pyrometer in frontal view in the wavelength band 8-14 μm , was controlled before and after deposition. It was found to be higher than the temperature indicated by the thermocouple by ca. 10°C.

Films, 300 nm thick, with a pure $c_{\perp 0}$ texture (c_{\perp} texture without in-plane misoriented grains) were routinely grown in the 750-775 °C temperature range (see figure 1).

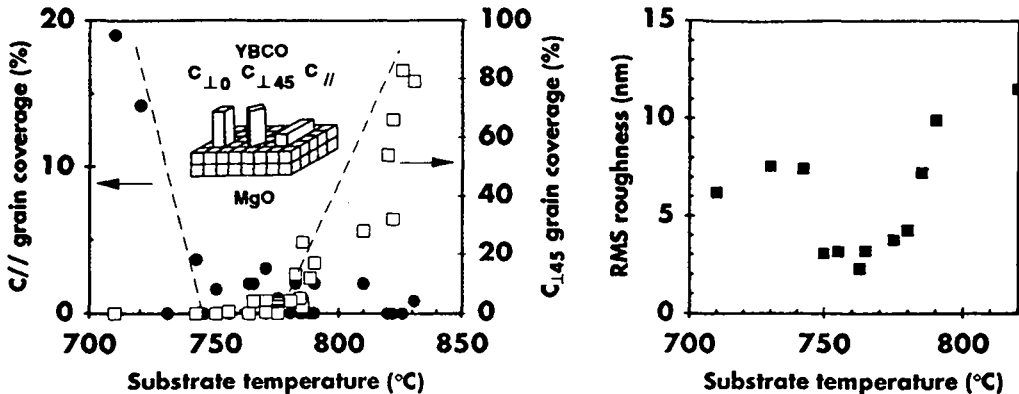


Figure 1: Influence of the growth temperature on the crystalline texture (left) and on the RMS roughness (right) of YBCO films 300nm in thickness. Broken lines are guides to the eye.

Their RMS roughness, as observed by AFM, was around 2 nm in this temperature range. After deposition, an annealing procedure was necessary to fully oxidise the films. Typical T_c and $J_c(77\text{ K})$ values of films thus made were in the range 88-92 K and $5 \cdot 10^5$ - $2 \cdot 10^6$ A/cm² respectively. The best surface resistance value measured in transmission at 22 GHz and 77 K on these films was as low as 1 m Ω [10].

2.2 Film patterning and metallisation

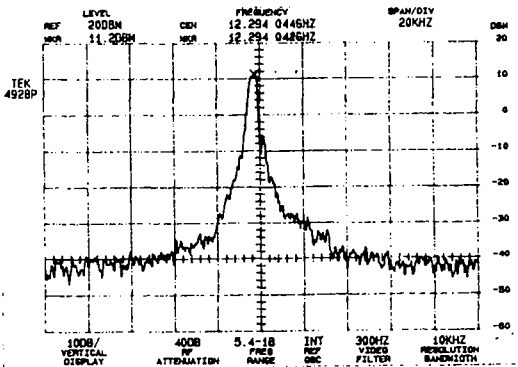
The films were patterned by wet chemical etching using EDTA as the reactant. The procedure uses a standard positive photoresist process. An undercutting of 1 to 2 μm was measured and the patterned edge roughness was about 100 nm. Investigation on the patterning induced damages was conducted both by means of micro-Raman spectroscopy with a spatial resolution of less than 1 μm and X Ray Diffraction (XRD) analysis. Negligible damage was observed in XRD spectra. The micro-Raman signal close to the patterned edge was unchanged up to a distance from the edge equal to the spatial resolution. The presence of residual strains, poor oxygen stoichiometry and impurity phases result in significant changes in the Raman spectrum of YBaCuO, mainly frequency shifts and additional peaks [11]. Metallisation steps were necessary for electrical contact and ground plane deposition. Gold contacts were made by sputtering in a lift-off process prior to the etching. Ti and Au precursor films were sputtered on the back side of the substrates for

and the gold matching network on a 250 μm thick Al_2O_3 substrate. An in house transistor was epoxied and connected with bonding wires which were taken into account in the simulations. The layout of this circuit is shown in the figure 3.

3.2 Oscillator characterization

The oscillator shown in the figure 3, mounted inside a nitrogen cryostat was characterised at 77K using a Wiltron Spectrum Analyser. The phase noise, the output power, P_{out} and the oscillation frequency, f_0 were directly deduced from the curve of the figure 4 :

$f_0 = 12,3\text{GHz}$, $P_{out} = 11 \text{ dBm}$, Phase noise = - 75 dBc/Hz at 10 KHz from the carrier. The bias of the transistor was maintained at $V_{ds} = 2 \text{ V}$ and $I_{ds} = 30 \text{ mA}$, leading to an efficiency of 22 %.



These experimental output power and phase noise are much better than those measured on a similar gold circuit operating at 300 K and 12 GHz. They are comparable to those measured on a fully integrated oscillator operating at 77 K and 6.5 GHz [4]. The best phase noise already reported (-125 dBc/hz) had been measured on a hybrid but not integrated oscillator [5]. The HTS resonator exhibited very high Q factor.

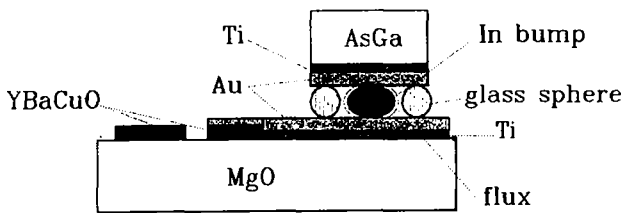
Figure 4: Oscillation spectrum.

4. HYBRIDATION

4.1 Flip-chip bonding technique

4.1.1 bonding materials

In the flip-chip bonding technique [12], a chip is connected onto a substrate via solder bumps as shown in the figure 5.



Numerous alloys, having melting temperatures between 100°C and 300°C have been properly used in the Flip-chip technology [13]. The hybrid oscillator above mentioned, included YBaCuO patterns and operated in liquid nitrogen.

Figure 5: flip-chip bonding technology.

In order to preserve the oxygen content of the superconducting thin film and thus its properties, bonding process below 150-200°C was preferred. In addition good mechanical properties are required for the solder since it is subjected to large stresses during the thermal cycles due to thermal expansion coefficient mismatch between chip and substrate. Both constraints led us to select In solder bumps. This material exhibits the best fatigue life compared to In alloys [14] and a rather low melting point (157°C). Then, the

metallic contact pads should have good wettability with In, like Au or Cu, and low dissolution with solders like, Pd, Ni, Pt, Ti... For all these reasons, a Ti-Au stacking was chosen in the oscillator fabrication.

4.1.2. bonding process

In the hybrid oscillator design, the connection bumps were located at the extremities of 50 Ω microstrip lines. The typical widths of these lines were 200-250 μm depending upon the substrate microwave characteristics. In order to match the characteristic impedance as close as possible, In slices 300 μm in diameter and 200 μm in thickness were fabricated. They were then deposited on the top of the Au patterns. Dielectric spacers were added to maintain the shape of the solder bumps. They consisted of glass spheres glued with an U.V polymerisation glue.

The bonding set up comprised a thermoelectric cooler with inverse biasing able to provide a quick heating and holding the substrate. The upper chip was maintained on a vacuum chuck forced down along the z-axis to perform final alignment through a binocular. In addition a small pressure could be applied to the two aligned samples before or during heating .

4.1.3 sample performance

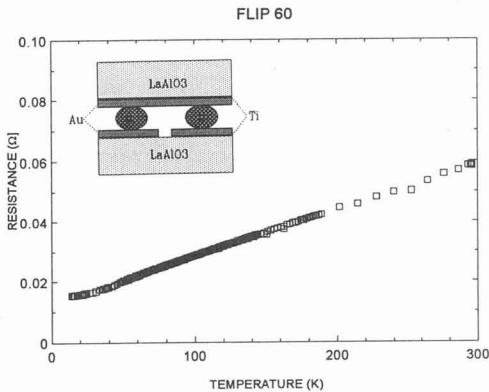


Figure 6: resistance variation of a flip-chip test sample

4.2 Epitaxial lift-off technique

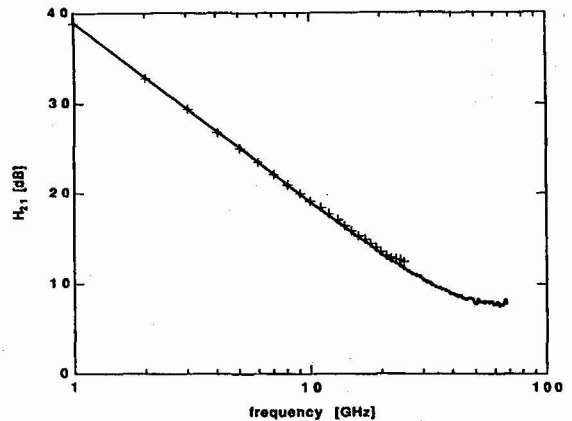
The selective etching (with respect to GaAs) of a high quality thin AlAs layer in HF solution has triggered the development of the Epitaxial lift-off technique (ELO) [15]. A high quality epitaxial layer is grown lattice matched with incorporation of an AlAs release layer. After selective etching of the AlAs layer, the wax-covered epitaxial structure is removed from its original substrate and transferred to its new host substrate.

Figure 7: Measured H21 characteristics before (+ to 25 GHz) and after (- to 67 GHz) Epitaxial Lift-Off.

The mechanical properties of the flip-chip structures were investigated during temperature cycles.

The resistance variation of test samples, shown in the figure 6, were monitored between 77 K and 300 K. The linear behavior of the resistance value versus temperature meant that the structure remain unchanged during thermal cycles. If not, the resistance would suddenly increased.

The characteristic impedance of a microstrip line having two parts connected in a flip-chip manner as described before is investigated with Time Domain Response. The 50 Ω characteristic impedance of the microstrip gold line patterned on MgO substrate was locally decreased to 48 Ω .



The ELO technique has clearly demonstrated its power in the fabrication of a wide variety of high quality devices on dissimilar substrates and has now entered the stage of technological development^[16]. GaAs pseudomorphic HEMT with a gate length of 0.25 μm were lift-off from the GaAs substrate and attached to MgO or LaAlO₃ substrates. Only minor differences were observed in the DC and RF characteristics before and after ELO (see figure 7).

A high extrinsic transition frequency (95 GHz) and a high microwave gain (MAG = 16 dB at 12 GHz) was measured. Typical phase noise characteristics were measured (NF_{min} = 1dB at 12 GHz) indicating that the high frequency noise was not affected by the ELO.

5. CONCLUSION

A hybrid oscillator integrating a pseudomorphic HEMT and a YBaCuO ring resonator on a single substrate was designed using the S parameters of the transistor measured at 77 K. The computed frequency of the device was 12 GHz while an experimental frequency of 12.3 GHz was measured. The as grown superconductor film had a surface resistance of 0.3 m Ω scaled to 12 GHz at 77 K. The patterning operation was well characterised so that no degradation of the superconductor was observed. The DC and RF characterisation of the hybridized transistor showed minor differences before and after hybridization. The characterisation of a preliminary prototype oscillator including a superconducting resonator patterned on a MgO substrate, a gold matching network fabricated on LaAlO₃ and a transistor wire bonded gave a phase noise as low as -75 dBc/Hz at 10 KHz. This value allows one to expect even improved performance for the hybrid oscillator integrated on a single substrate.

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References:

- [1] H. Piel and G. Muller, *IEEE Trans magn*, MAG 27 (1991), 854.
- [2] J. C. Ritter, M. Nisenoff, G. Price and S.A. Wolf, *IEEE Trans magn*, MAG 27 (1991), 2553.
- [3] R. Kleiber, R. Ramish, A. Valenzuela, R. Weigel, P. Russer, *IEEE Microwave and Guided Wave Letters*, vol. 2 (1992) 22-24.
- [4] N. J. Roher, G.J. Valco, K.B. Bhasin, *IEEE Trans Microwave Theory Tech.*, MTT41 (1993), 1865.
- [5] Z. Y. Shen, P. Pang, C. Wilker, D. B. Laubacher, W. L. Holstein, C. F. Carter, *IEEE Transaction on Applied Superconductivity*, vol 3 (1993) 2832-2835.
- [6] J. Luine, K. Daly, R. Hu, A. Kain, A. Lee, H. Manasevit, C. Pettiette-Hall, R. Simon. *IEEE Trans. Magn.*, MAG 27, (1991), 1528.
- [7] L. Antognazza, K. Char, T.H. Geballe, L.L.H. King. *Appl. Phys. Lett.* 63 (7) (1993), 1005.
- [8] J.C. Villegier, H. Moriceau, H. Boucher, R. Chicault, L. Di Cioccio, A. Jager, M. Swerdtfeger, M. Vabre, C. Villard, *IEEE Trans magn*, MAG 27, (1991), 1552.
- [9] D. Chambonnet, C. Belouet, C. Fages, M. Puech. in Laser ablation of electronic materials. editors : E. Fogarassy & S. Lazare (North-Holland, Amsterdam, 1992), p.317.
- [10] F. Mehri, P. Lepercq, J.C. Carru, E. Playez, C. Thivet, A. Perrin, D. Chambonnet. Third SEE Workshop "Supraconducteurs à haute température critique", Caen, 16-17 november 1993.
- [11] S. F. Karmenko et al. *Supercond. Sci. Technol.* 6, (1993), 23.
- [12] M. Wale, M. Goodwin, *Circuits and Devices* (1992) pp 25-31.
- [13] K. Pickering, P. Southworth, C. Wort, A. Parsons, and D. J. Pedder, *J. Vac. Sci. Technol. A* 8, (1990), 1503.
- [14] K Hashimoto, T Nakanishi, M. Ochiai, *Fujitsu Sci. Tech. J.* 28 (1992), pp 301-309.
- [15] E. Yablonoitch, T. Gmitter, J. P. Harbison, R. Bhat, *Appl. Phys. Lett.* 51 (1987) 2222.
- [16] G. Borghs, J. De Boeck, I. Pollentier, P. Demeester, C. Brys, W. Dobbelaere, Proc. 20th Int. Symp. on GaAs and related compounds, Freiburg 1993.