INTEGRATION OF SEMICONDUCTOR AND CERAMIC SUPERCONDUCTOR DEVICES FOR MICROWAVE APPLICATIONS

B.B.G. Klopman, H.W. Weijers, J. Gao,
G.J. Gerritsma, and H. Rogalla
University of Twente, Faculty of
Applied Physics, P.O.Box 217,
7500 AE Enschede, The Netherlands

Abstract

Due to the very low-loss properties of ceramic superconductors high-performance microwave resonators and filters can be realized. The fact that these devices may be operated at liquid nitrogen temperature, facilitates the integration with semiconductor devices. Examples are bandpass amplifiers, microwave-operated SQUIDs combined with GaAs preamplifiers, detectors, and MOSFET low-frequency amplifiers. We will discuss the design of such circuits on a single one inch alumina substrate using surface mount techniques. Furthermore data on circuits that have been realized in our laboratory will be presented.

Introduction

Passive microwave applications of superconducting materials are based on the low surface impedance of superconductors. At non-zero frequencies the surface impedance of superconductors is not zero, but it can be several orders of magnitude smaller than the surface impedance of a normal conductor. As a result, the power losses in superconductors are considerably smaller, indicated by a much higher quality factor Q. This makes superconductors suitable for applications which are impossible (or of much poorer performance), if normal conductors are used.

Passive superconducting microwave devices include high-Q resonators, high-Q filters and compact delay lines. High-Q resonators are suitable for stable oscillators, which can be considered as a secondary frequency standard [1]. High-Q filters offer the possibility of low loss, sharp bandpass filters [2], which are extensively used in the communications technique. Delay lines are valuable components for microwave analog signal processing, such as pulse compression and real-time spectral analysis of wideband signals [3]. The need for reasonable delays in a small volume, without impractical transmission loss, precludes the use of normal conductors.

Active microwave applications rely on the Josephson effect. Making use of the strong non-linearities in the IV-characteristics of tunnel junctions, very sensitive broadband detection of microwave radiation is possible. These devices are less apt for power amplification of microwave signals. Such amplification is more easily implemented with microwave semiconductor devices, like GaAs high electron mobility transistors.

Circuits of high performance can be obtained, when these devices are integrated with superconducting passive microwave components. The advent of high temperature ceramic superconductors facilitates the integration of superconductor and semiconductor devices, because both can be operated at liquid nitrogen temperature.

In our laboratory, work is in progress to combine a low noise microwave FET with a high temperature superconducting bandpass filter. In the present paper we report on the low loss properties of high temperature superconducting passive microwave devices, specifically on the surface resistance of $YBa_2Cu_3O_{7-x}$ thin films on MgO substrates.

Surface resistance of superconductors

Besides easier cooling, high temperature superconductors offer several advantages over classical superconductors. Using the theory of Mattis and Bardeen [4], numerical computations of the surface resistance of superconductors were performed by Turneaure [5] and Halbritter [6]. For $T \leq 0.5\ T_c$ those results may be approximated by the following analytical formula:

$$R_s = \frac{A}{T} f^{\alpha} \exp(-\Delta/kT) + R_{res} \qquad (1)$$

where A is a material dependent constant, f is the frequency, Δ is the superconducting gap, α ranges from 1.5 to 2.0 and R_{res} is a residual resistance that follows from experiment. If the two fluid model is applicable for high temperature superconductors, the material constant A is approximately ten times lower than that of niobium.

So far experimental results are several orders of magnitude worse than predicted by equation (1) without taking R_{res} into account [7]. To our knowledge the best results so far are obtained by an in situ laser ablation deposition technique, but this may soon be equaled by in situ off-axis sputtering. Using a copper host cavity Klein et al. [8] measured the surface resistance of two $YBa_2Cu_3O_{7-x}$ films deposited on <100> $SrTiO_3$ at 86.7 GHz. At a temperature of 77 K the best sample has a surface resistance of less than 8 mΩ. As far as applications are concerned $SrTiO_3$ is not a good substrate because of its high dielectric constant that changes rapidly with temperature and because of its high losses. Coplanar waveguide (CPW) resonators of $YBa_2Cu_3O_{7-x}$ deposited on <100> MgO have an unloaded quality factor of 1300 at 77 K and 9 GHz [9] and on <100> $LaAlO_3$ [10] of 3850 at 77 K and 6.5 GHz. From the latter result, using the value for the dielectric loss tangent of $LaAlO_3$ at 77 K and 10 GHz [11], a surface resistance of 0.14 mΩ was inferred, which is still two orders of magnitude higher than predicted by equation (1).

A possible explanation is given by Halbritter [12] where a large residual resistance is assumed due to the granularity of the high temperature superconductors. Most results so far reported in literature are based on films that have not been prepared in situ, resulting in the formation of grains, whereas (almost) epitaxial thin films are grown with in situ deposition techniques.

Thin film preparation

In our laboratory we use both in situ sputtering as well as laser deposition techniques. Here we report on the results of $YBa_2Cu_3O_{7-x}$ films that have been sputtered on <100> MgO substrates by a modified off-axis rf magnetron sputtering technique [13]. A ground plate is mounted, facing the target at a 45° angle, which considerably

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reduces backsputtering effects. Stoichiometric sintered $YBa_2Cu_3O_{7-x}$ targets with a diameter of 50 mm are used. The sputtering gas is a mixture of 50 % oxygen and 50 % argon, with a pressure between $5\cdot10^{-2}$ and $3\cdot10^{-1}$ mbar. During deposition the substrates are heated to temperatures between 640 and 700 °C. The rf sputter power density at the target varies between 2.5 and 5 W/cm^2.

Measurement of the surface resistance

For the investigation of $YBa_2Cu_3O_{7-x}$ thin films we used a coplanar waveguide (CPW) geometry. This transmission line type has its metallization on one side of the substrate and still supports a dominant quasi-TEM mode. The single-sided metallization has technological advantages; both the preparation of thin films and the mounting of devices are easier. It is also possible to mount a smaller substrate ("chip") with passive and/or active microwave components on the motherboard (Fig. 1).

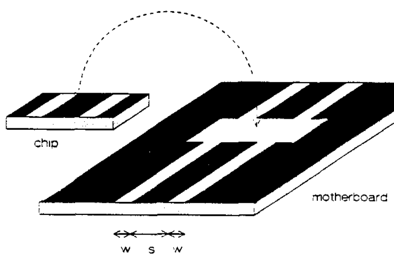

Figure 1. Schematic presentation of the surface mounting of the chip with a superconducting film onto the motherboard (not on scale). In the illustration the chip contains a CPW transmission line. With two gaps in the centre conductor an end-coupled resonator is created.

The motherboard can contain the body of the circuitry. The more demanding parts are located on the smaller chip. In this way the effort for the preparation of homogeneous high-quality films is restricted to a much smaller area. The chip can also easily be replaced by another, which is especially attractive in a laboratory environment. Disadvantages of this arrangement are the reflections resulting from the transitions at the edges of the chip and a more complicated structure to analyse.

A 50 Ω CPW with geometrical parameters s = 0.5 mm and w = 0.2 mm is fabricated on a MRC alumina substrate of 1 square inch, with dielectric constant ε_r = 9.9 and thickness h = 0.635 mm. The return loss, resulting from coax-to-CPW transitions at both sides of the substrate, is better than 15 dB from 6 to 18 GHz. Placing a MgO substrate on top of the CPW decreases this value to 11 dB, which is still reasonable for analysing loosely coupled high-Q resonators. When better return losses are desired, a matching network is required.

$YBa_2Cu_3O_{7-x}$ thin films with a nominal thickness of 250 nm on MgO substrates are patterned to λ/2 CPW resonators by etching in a solution of phosphoric acid in water (1:100). The resonator has a length of 5.4 mm and is coupled by a gap of 600 μm. The resonator is placed on top of the motherboard as shown in Fig. 1. The complete structure is mounted in a test-fixture.

A SWR-bridge is connected to the test-fixture inside the cryostat via an air-line. The output voltage of the SWR-bridge, which is a measure of the reflection ratio |Γ|, is measured by a digital multimeter. Microwave signals are generated by a synthesizer. Both the multimeter and the synthesizer are controlled by computer.

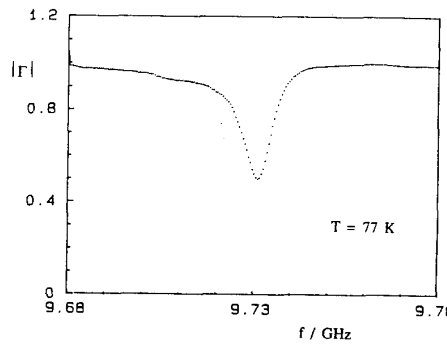

Figure 2. Reflection ratio near the resonance frequency f_0 = 9.7308 GHz of the superconducting resonator at T = 77 K.

In Fig. 2 our best result for the resonance peak of a $YBa_2Cu_3O_{7-x}$ resonator at T = 77 K is presented (microwave input power -20 dBm). In the case of a transmission resonator the quantity $2\cdot(1+|\Gamma|^2)/(1-|\Gamma|^2)$ depends linearly on $(f-f_0)^2$ in the vicinity of the resonance frequency (Fig. 3).

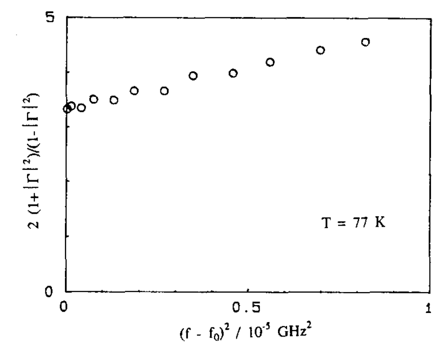

Figure 3. Fit of the quantity $2\cdot(1+|\Gamma|^2)/(1-|\Gamma|^2)$ on $(f-f_0)^2$ as obtained from the measurement of Fig. 2.

By taking the slope S and the y-axis cutoff a, an accurate determination of the unloaded quality factor Q_0 is obtained:

$$Q_0 = \left(\frac{S}{a-2}\right)^{1/2} \frac{f_0}{2} \qquad (2)$$

From Fig. 3 a quality factor of Q_0 = 1650 is deduced for T = 77 K. At T = 4.2 K a Q_0 factor of 8200 is obtained.

A reasonable estimate for the surface resistance can be obtained by a quasi-static approach, applied to CPW. To account for the geometry of the chip on top of the motherboard, the value for the effective dielectric constant ε_{re} is calculated from the resonance condition (neglecting open-end effects) $l = 1/2\ c/(f_0\ \varepsilon_{re})$. Here l denotes the length of the resonator and c the velocity of light in vacuum. In this way the surface resistance R_s is evaluated as, for the present geometry:

$$R_s = 0.85/Q \quad [\Omega] \qquad (3)$$

The main inaccuracies arise from the neglect of radiation and dielectric losses and from the fact that the thickness of the film (250 nm) is not large compared to the penetration depth (≈ 150 nm). With respect to dielectric losses it should be mentioned that a low estimate of the loss tangent tan δ of 10^{-4} leads to a quality factor of 10^4 for the dielectric, in the case of a homogeneous filling. It therefore seems reasonable to presume that at T = 4.2 K the measured Q_0 = 8200 is mainly limited by dielectric losses.

With the neglect of these dielectric losses the surface resistance obtained from (3) is evaluated as R_s = 0.5 mΩ at T = 77 K and R_s = 0.1 mΩ at T =4.2 K. This is compared to the textbook value for the surface resistance at the same frequency of OFHC Copper in Fig. 4.

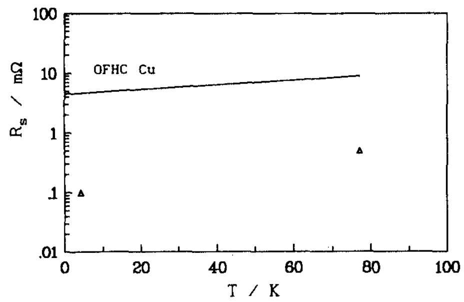

Figure 4. Surface resistance of $YBa_2Cu_3O_{7-x}$ at T = 4.2 K and T = 77 K (Δ), compared to OFHC copper.

Also at T = 77 K the surface resistance of the $YBa_2Cu_3O_{7-x}$ thin film is substantially lower (about a factor of 18) than OFHC copper. These results can be extrapolated to other frequencies, assuming a quadratic frequency dependence of the surface resistance. This yields R_s = 0.2 mΩ for T = 77 K at 6.5 GHz, which is approximately the same value as the result of Valenzuela et al. [10] at the same temperature and frequency (R_s = 0.14 mΩ). It is remarkable that our films, prepared by in situ sputtering, are apparently comparable to laser ablated films with respect to microwave properties.

Low input powers can result in large currents in the resonator, because the currents are concentrated in a small area. The dependence of the surface resistance on the input power at T = 4.2 K is given in Fig. 5.

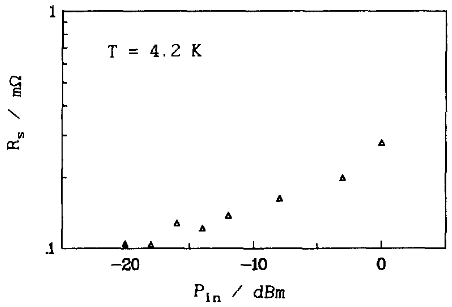

Figure 5. Dependence of the surface resistance of $YBa_2Cu_3O_{7-x}$ on the microwave input power P_{in} at T = 4.2 K.

The losses increase at powers as low as -16 dBm, although the total increase over two decades in power is only a factor of 3. One reason for the increase of the losses at relativey low powers is the fact that the resonator is not very loosely coupled for these high quality factors, resulting in higher currents at the same power level than in the loosely coupled case.

Conclusions

To measure the surface resistance of $YBa_2Cu_3O_{7-x}$ rf magnetron sputtered thin films on MgO substrates as a function of temperature and microwave power, we have developed coplanar waveguide resonators. At T = 77 K and 9.7 GHz the losses in the films are about 18 times lower than in OFHC copper. Therefore these films are very well suitable for the use in passive low-loss microwave devices. The measured results on these off-axis sputtered films are comparable to the best results obtained so far for laser ablated films of $YBa_2Cu_3O_{7-x}$ on MgO.

References

1. D.L.H. Blomfield and A.J. Pointon, "Short-term frequency stability of an L band oscillator with a superconducting cavity", *Electron. Lett.*, 9, 461-462, 1973.

2. J.L. Stone and W.H. Hartwig, "Performance of superconducting oscillators and filters", *J. Appl. Phys.*, 39, 2665-2671, 1968.

3. R.S. Withers, A.C. Anderson, J.B. Green and S.A. Reible, "Superconductive delay-line technology and applications", *IEEE Trans. Magn.*, MAG-21, 186-192, 1985.

4. D.C. Mattis and J. Bardeen, "Theory of the anomalous skin effect in normal and superconducting metals", *Phys. Rev.*, 111, 412-417, 1958.

5. J.P. Turneaure, Thesis, HEPL-report-507, Stanford University (1967)

6. J. Halbritter, "On surface resistance of superconductors", *Z. Physik*, 266, 209-217, 1974.

7. D.E. Oates and A.C. Anderson, "Stripline measurements of surface resistance: relation to HTSC film properties and deposition methods", SPIE manuscript code no. 1187-42.

8. N. Klein, G. Müller, H. Piel, B. Roas, L. Schultz, U. Klein and M. Peiniger, "Millimeter surface resistance of epitaxially grown $YBa_2Cu_3O_{7-x}$ thin films", *Appl. Phys. Lett.*, 54, 757-759, 1989.

9. A.A. Valenzuela and P. Russer, "High Q coplanar transmission line resonator of $YBa_2Cu_3O_{7-x}$ on MgO", *Appl. Phys. Lett.*, 55, 1029-1031, 1989.

10. A.A. Valenzuela, B. Daalmans and R. Roas, "High-Q coplanar transmission line resonator of $YBa_2Cu_3O_{7-x}$ on $LaAlO_3$", *Electron. Lett.*, 25, 1435-1436, 1989.

11. R.W. Simon, C.E. Platt, A.E. Lee, G.S. Lee, K.P. Daly, M.S. Wire, J.A. Luine and M. Urbanik, "Low-loss substrate for epitaxial growth of high-temperature superconductor thin films", *Appl. Phys. Lett.*, 53, 2677-2679, 1988.

12. J. Halbritter, "RF residual losses, surface impedance and granularity in superconducting cuprates", submitted to *J. Appl. Phys.*

13. J. Gao, B. Häuser and H. Rogalla, "High critical current density ultrathin $YBa_2Cu_3O_{7-x}$ films made by a modified rf-magnetron sputtering technique", *J. Appl. Phys.*, 67, 2512-2515, 1990.