FABRICATION AND MODELING OF PASSIVE COMPONENTS FOR InP-BASED MMICs

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SUMMARY

Passive components for use in planar Monolithic Microwave Integrated Circuits (MMICs) based on High Electron Mobility Transistors (HEMTs) on indium phosphide substrates are presented. Design, fabrication, and modeling issues of capacitors, resistors, inductors, transmission lines, via holes, and air bridges have been addressed. Sputtered thin films have been utilized to make metal-insulator-metal (MIM) capacitors and thin film resistors (TFRs). Silicon dioxide and silicon nitride MIM capacitors exhibited capacitances from 100 to 300 pF/mm^2 and tantalum nitride TFRs sheet resistivities of 80-85 ohms per square. Our microstrip transmission line fabrication technology has been utilized to make multi-turn, air bridged spiral inductors spanning from 0.5 nH to 4 nH. Air bridges and ground via holes have been used for connection and testing purposes. Scattering (S-) parameters, from 5 to 48 GHz, of all fabricated components have been measured and scalable models for CAD purposes investigated.

INTRODUCTION

MMIC technology requires passive components such as capacitors, resistors, inductors and transmission lines, air bridges, and via holes. Passives can be implemented in lumped form or in distributed transmission line form. Regardless of method, a substantial area of the chip will be occupied by passives. The choice of technique is generally dependent on the intended operating frequency. Lumped elements are usually employed when their physical size is small enough to neglect transmission line effects. However, with careful modeling the frequency range of usage for lumped components can be extended.
In this study, fabrication as well as modeling issues of passive components for MMICs are addressed. The models were compared with S-parameter measurements from 5 to 48 GHz.

MIM CAPACITORS

The metal-insulator-metal capacitors were fabricated using reactively sputtered silicon nitride (Si_3N_4, thicknesses 2100 Å and 3900 Å) and silicon dioxide (SiO_2, thicknesses 1100 Å and 2200 Å) at deposition rates of 2-3 Å/s. Figure 1 shows a photograph of the capacitor layout and a SEM micrograph of the connecting air bridge. The DC current conduction properties of the dielectric for low electric fields were investigated to give a first indication of the dielectric quality. This simple test has proven to be very important since breakdown characteristics, and ultimately reliability of the capacitor, depend directly on the current conduction [1]. Current-voltage characteristics were measured using a semiconductor parameter analyzer. For electric fields below 1 MV/m, the capacitors show a resistivity of about 10^{13} Ωcm for both the deposited silicon nitride and silicon dioxide films, which is adequate for MMIC capacitors.

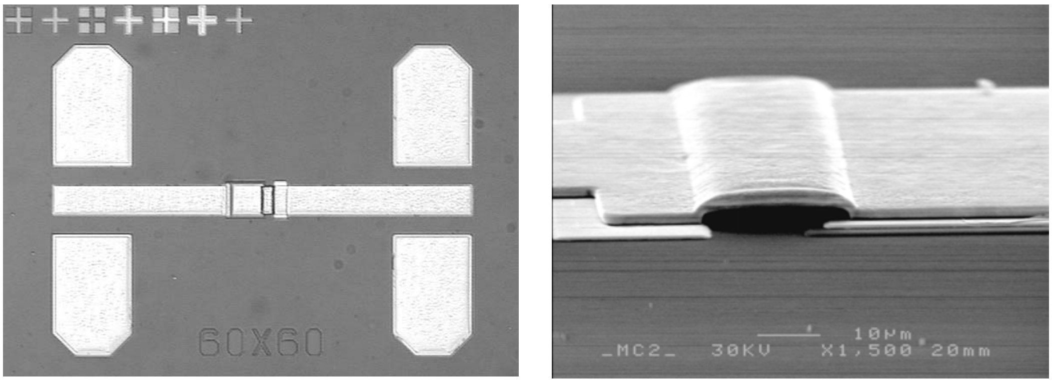


Figure 1
Photograph of a 60x60 μm^2 capacitor (left) and a SEM micrograph showing the air bridge. The dielectric material is 2100 Å silicon nitride.

To check the validity of the scalable models, 8 different capacitor geometries were studied: 25x25, 50x25, 50x50, 50x100, 100x50, 100x100, 150x100, and 200x100 μm^2, where the first figure refers to the width and the second to the length. Several approaches for high frequency modeling of a MIM capacitor have been suggested, see for instance [2-6]. For convenient scalability, we have used the distributed model shown in Figure 2. The key elements are two coupled transmission lines with end effects. The air bridge and the capacitor plate to transmission line transitions are also accounted for by transmission line models. Figure 3 shows this modeling approach.

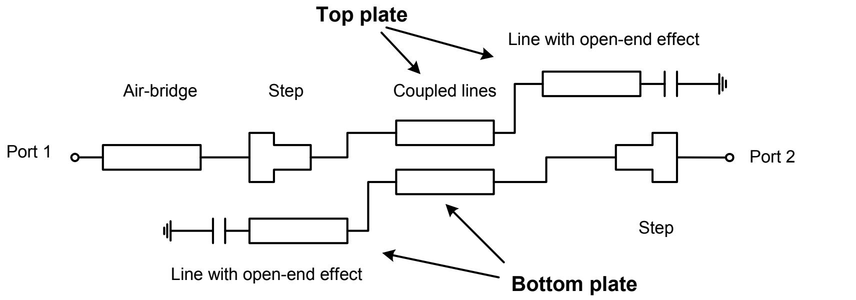
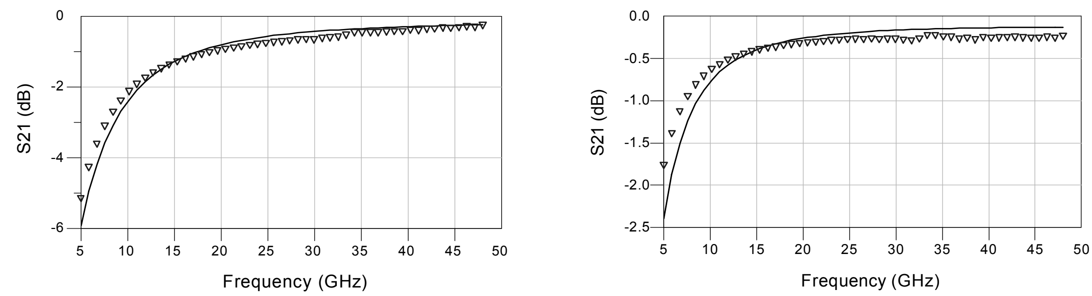


Figure 2
Fully distributed model of a capacitor. The end effects are represented by open stubs and the air bridge by a transmission line. The steps in width of the transmission lines are also taken into account.



a) b)

Figure 3
Measured (triangles) and modeled (solid) capacitors (2100 Å silicon nitride). a) 25x25 μm^2, b) 50x25 μm^2.

THIN FILM RESISTORS

We have fabricated thin film resistors (TFRs) with tantalum nitride (TaN) as the resistive material. TaN has been shown to display many of the qualities desired in a TFR material for microwave devices. The requirements are a high resistivity, a low temperature coefficient of resistivity (TCR), simplicity of fabrication and chemical and temperature stability [7, 8]. TaN, along with NiCr, are the two most common materials used today for these applications since they best satisfy the above requirements [9]. TaN was reactively sputtered at a rate of approximately 3Å/s using an N_2/Ar ratio of 0.2. The sputtering time was adjusted to achieve a film thickness of 550 to 700 Å with reproducible resistances of 80-85 Ω/sq, which represent convenient values for circuit design. The TFRs were modeled by a lossy microstrip line [10] and verified by EM simulations, see Figure 4.

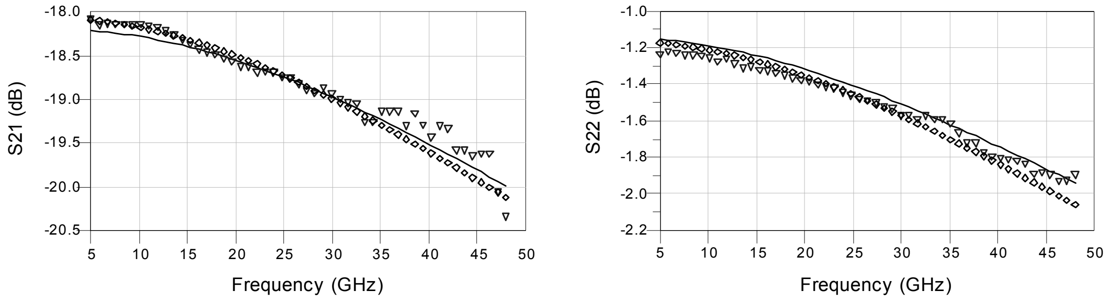


Figure 4
Measured (triangles), modeled (solid), and EM simulated (diamonds) S-parameters for a 25x200 μm^2 TRF.

INDUCTORS, TRANSMISSION LINES, AIR BRIDGES, AND VIA HOLES

Electroplating of gold was utilized to form transmission lines and spiral inductors (Figure 5). The lines were deposited on a silicon nitride dielectric layer to reduce losses. Air bridges were employed to connect the center of the spiral inductors. The inductors were modeled using the ADS model MRIND based on the results of [11-15]. As seen in Figure 6, EM simulations verified the results.

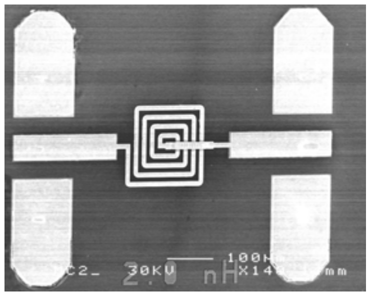


Figure 5
SEM micrograph of a 4-turn spiral inductor.

To provide grounding in a microstrip design, through-substrate via holes must be employed. The InP wafer was thinned down to 75 µm and openings for the via holes were formed by optical lithography. The holes were etched in a solution composed of hydrogen bromide acid, acetic acid, and potassiumdi-chromate. Backside metallization was accomplished by electroplating of gold. The via holes were modeled by a cylindrical conductor with inductance derived from Maxwell's equations [16, 17].

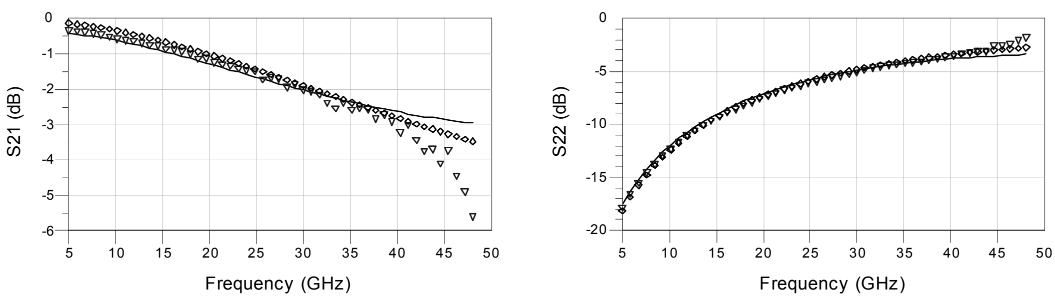


Figure 6
Measured (triangles), modeled (solid), and EM simulated (diamonds) S-parameters for a 2-turn spiral inductor.

CONCLUSION

A complete set of passive components for InP-based MMIC technology have been fabricated, characterized, and modeled. Because fabricated MMICs cannot be tuned to meet specifications, special effort has been put into the investigation of scalable models for CAD purposes. The developed components will constitute the baseline for the InP MMIC process at the Microwave Electronics Laboratory at Chalmers.

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REFERENCES

[1] J. Scarpulla, E. D. Ahlers, D. C. Eng, D. L. Leung, S. R. Olson, and C.-S. Wu, "Dielectric breakdown, defects and reliability in SiN MIMCAPs," *GaAs Reliability Workshop*, pp. 92-105, 1998.

[2] G. Bartolucci, F. Giannini, E. Limiti, and S. P. Marsh, "MIM capacitor modeling: a planar approach," *IEEE Transactions on Microwave Theory and Techniques*, vol. 43, pp. 901-903, 1995.

[3] M. Engels and R. H. Jansen, "Rigorous 3D EM simulation and an efficient approximate model of MMIC overlay capacitors with multiple feedpoints," *IEEE MTT-S International Microwave Symposium Digest*, pp. 757-760 vol.2, 1993.

[4] W. S. Lam, A.K. Nakano, K. Ip, K. Yang, C. Liu, L. Yen, H.C., "Experimental modeling for millimeter-wave monolithic integrated circuit components," *IEEE MTT-S International*, vol. 1, pp. 477-480, 1988.

[5] J. P. Mondal, "An experimental verification of a simple distributed model of MIM capacitors for MMIC applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-35, pp. 403-408, 1987.

[6] E. Pettenpaul, H. Kapusta, A. Weisgerber, H. Mampe, J. Luginsland, and I. Wolff, "CAD models of lumped elements on GaAs up to 18 GHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, pp. 294-304, 1988.

[7] L. Gmelin, "Gmelins Handbuch der anorganischen Chemie System-Nr 49 Niob T.B. L. 1," 8., vollig neu bearb. Aufl. / begonnen im Auftrage der Deutschen chemischen Gesellschaft von R. J. Meyer ... ed: Springer-Vlg,, 1970, pp. 49.

[8] R. Williams, *Modern GaAs processing methods*, 2nd. ed. Norwood, MA: Artech House, Inc., 1990.

[9] R. F. Kopf, R. Melendes, D. C. Jacobson, A. Tate, M. A. Melendes, R. R. Reyes, R. A. Hamm, Y. Yang, J. Franckoviak, N. G. Weimann, H. L. Maynard, and C. T. Liu, "Thin-film resistor fabrication for InP technology applications," *Journal of Vacuum Science Technology B*, vol. 20, pp. 871-5, 2002.

[10] E. J. Hammerstad, O., "Accurate models for microstrip computer-aided design," *MTT Symposium*, pp. 407-409, 1980.

[11] C. L. Hoer, C., "Exact inductance equations for rectangular conductors with applications to more complicated geometrics," *Journal of Research of NBS*, vol. 69C, pp. 127-137, 1965.

[12] N. Marcuvitz, "Waveguide Handbook," in *Waveguide Handbook*. New York: McGraw-Hill, 1951, pp. sections 5.11 and 5.28.

[13] U. S. Ghoshal and L. N. Smith, "Skin effects in narrow copper microstrip in 77 K," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, pp. 1788-1795, 1988.

[14] K. Gupta, R. Garg, and I. Bahl, *Microstrip lines and slotlines*. Dedham, MA: Artech House, 1979.

[15] H. Wheeler, "Formulas for the Skin Effect," *Proc. IRE*, vol. 30, pp. 412-424, 1941.

[16] M. E. Goldfarb and R. A. Pucel, "Modeling via hole grounds in microstrip," *IEEE Microwave and Guided Wave Letters*, vol. 1, pp. 135-137, 1991.

[17] M. E. Goldfarb and V. K. Tripathi, "The effect of air bridge height on the propagation characteristics of microstrip," *IEEE Microwave and Guided Wave Letters*, vol. 1, pp. 273-274, 1991.