GaAs Integrated Passive Technology at Freescale Semiconductor, Inc.

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Abstract

Radio transmit modules continue to shrink in die size and cost, requiring novel approaches for integration of the numerous passive elements of the radio front-end. An Integrated Passive Device (IPD) technology has been established based on low cost mechanical grade LEC GaAs substrates, for application including impedance matching, filtering and switching. Low pass harmonic filters integrated with coupler for AMPS/GSM 824-915 MHz and PCS/DCS 1710-1910 MHz bands were designed and fabricated showing excellent performance.

INTRODUCTION

Radio transmit modules for cellular phones use several passive elements in various circuit functions in the front-end, such as harmonic filters, decoupling circuits, impedance matching and switching such as shown in Figure 1. As modules continue to shrink in die size and cost, novel approaches for integration of the numerous passive elements are required. Surface mount discretes and embedded passives have been used to a great extent in modules in the past based on High Density Integrated (HDI) and Low Temperature Co-fired Ceramic (LTCC) substrates. Passives based on semiconductor processes are finding applications in modules [1]. Semiconductor processes offer the advantage of precise process control of the module elements through the fine line lithography and thin film deposition and etch processes. We describe an IPD process based on low cost, mechanical grade GaAs LEC substrates and the design and fabrication of high performance harmonic filters and integrated couplers for application to the radio front-end.

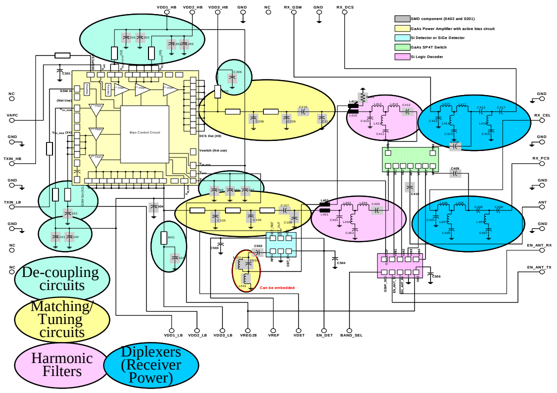

Fig. 1. Radio Module with several blocks of passive elements that can be integrated.

INTEGRATED PASSIVE PROCESS

The GaAs IPD cross-section is shown in Figure 2. The process was derived from Freescale Semiconductor backend HBT technology [2], and modified for enhanced passive Q factors, using 6-inch mechanical GaAs substrates.

The process features three levels of plated gold interconnect metal with thicknesses of 1.1um for MET1, 2.5 um MET2 and 10 um MET3. All plated metals use TiW/Au seed prior to plating. The process starts with deposition of 2000 Å of TiWN metallization used for low value resistors (1 to 200 ohms). The resistivity of the refractory metal is 9.5 ohms/sq and is reactively sputtered. One sigma variation of the resistor values is 3%. The variation depends on the width and length of the resistors and wider and longer resistors exhibit smaller variations. After patterning the resistors with reactive ion etch, 1000 Å of PECVD SiN is deposited and VIA0 defined. Metals 1 and 2 are formed with intervening capacitor dielectric and VIA1 as in the HBT technology. Capacitors formed with MET1 bottom plate and MET2 top plate and a SiN dielectric result in density of 650 pF/mm^2 and breakdown voltage 80 V. Capacitor tolerance for this density is 3%, 1 sigma. After a 1000 Å SiN deposition, an airbridge photo process is performed prior to 10 um gold MET3 definition and plating. Inductors consist of the 10 um gold metal rings and underpass of a stack of MET1 and MET2 with intervening VIA1. The inductor rings cross-over the underpass via airbridge. Transmission lines are based on the 10 um gold, and capacitors are connected by MET3 over an airbridge, and through VIA2. All components are passivated with a final SiN dielectric.

A library of inductors based on MET3 widths ranging from 20 um to 60 um, space 13.5 um and inductor number of turns from 1.5 to to 4.5, were generated. The internal diameters ranged from 75 um to 350 um. Inductor values ranged from 1.5 nH to 15 nH, For application to harmonic filters, appropriate inductors were selected with Q-values in excess of 30 over the frequency range 1- 2 GHz.

INDUCTOR CHARACTERIZATION

High performance circuits require inductors with high Q, therefore a passive component characterization mask set was first built with various inductor widths, IDs and turns to study inductor value and Q. The effect of GaAs substrate thickness was also examined.

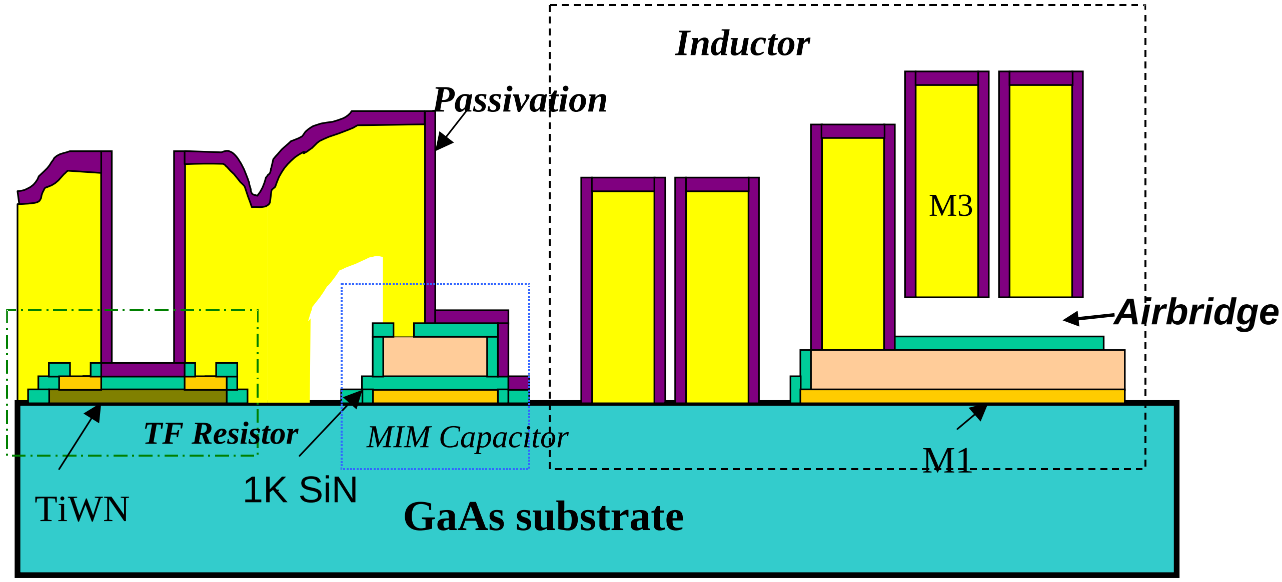

Fig.2 Process Cross-section of IPD Technology

Test structures were characterized using transmission line (TRL) structures with RF calibration standards of SHORT, THRU, OPEN and 50 OHM LOAD. Figures 3 and 4 show inductance and Q as function of frequency of some inductors. Table 1 shows general trends of the effects on the peak value of Q which was defined as Q= {Reactance}/{Real [Impedance]-50}. Peak Q as high as 45 was achieved on some inductors.

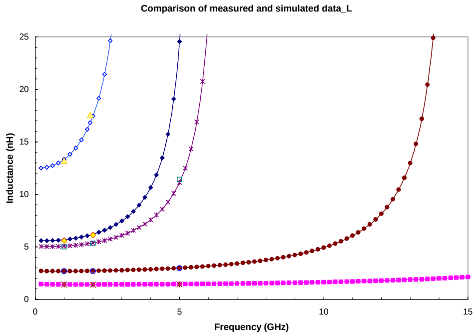

Fig. 3. Inductance of various inductors as function of frequency.

HARMONIC FILTER DESIGN

The basic harmonic filter topology is shown in Figure 5, and consists of a series of two tank circuits controlling the second and third harmonics. The circuits were designed for application to AMPS/GSM band (824-915 MHz) and

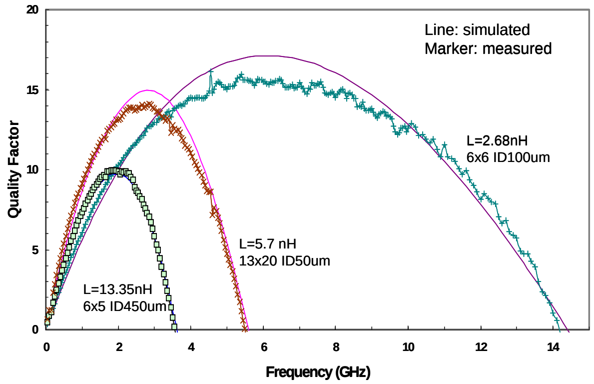

Fig 4. Q-values of various inductors versus frequency. The inductance and Q-values were confirmed by electromagnetic simulation using IE3D software tool.

Table 1. General trends on inductance and Q values of inductors based on effects of inductor width , turn, shape and GaAs substrate thickness. Up sign indicates increase. Down sign is decrease and horizontal sign is insignificant difference.

EFFECT	INDUCTANCE L(nH)	Q
ID INCREASE	⇧	⇧
WIDTH INCREASE	⇩	⇧
# TURN INCREASE	⇧	⇩
OCTAGONAL VS SQ.	⇔	⇧
10 MIL VS 3MIL SUBSTRATE	⇧	⇧

DCS/PCS bands (1710-1910 MHz) requiring separate designs for low band and high band. The fourth harmonic was controlled by a center shunt capacitor and wirebond to the pad. Both designs had input and output impedance of 50 ohms using shunt capacitors and wirebonds to the input and output pads, respectively. To meet performance and cost targets a general design methodology (Figure 6) was followed. This consists of the following steps: 1) Assemble circuit from Library components, and perform design with ADS (Agilent software); 2) Physical layout to fit available space; 3) Perform EM simulation to optimize for component interactions; 4) Repeat as required to meet performance and cost targets. The low and high band designs used 6nH and 3nH inductors, respectively, and appropriate capacitors were selected through optimization with Agilent ADS software for the harmonic rejections. The capacitor values were tuned using EM simulation of the entire layout with electromagnetic simulator such as Ansoft HFSS or IE3D. EM simulation was essential, particularly as die size was reduced by compacting components to meet cost targets, since coupling effects of compact components are not captured by the ADS software alone.

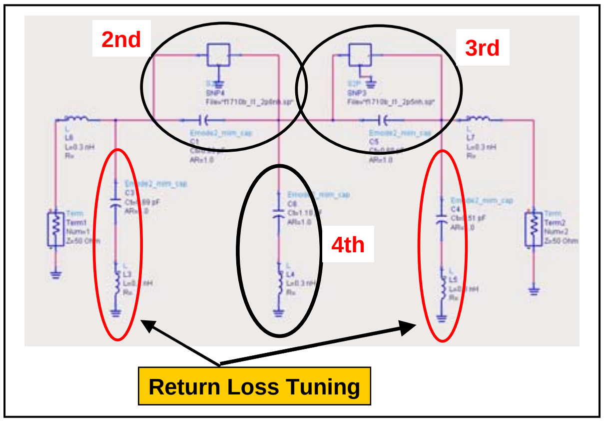

Fig 5. Topology of Harmonic Filters using 2 inductor design.

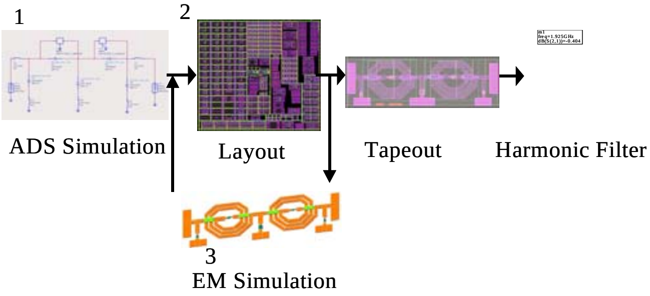

Fig. 6. Design methodology of integrated passives.

HARMONIC FILTER RESULTS

Figure 7 shows a high band harmonic filter die with 4 wirebonds to input (LEFT) pad and output (RIGHT) pad. The three ground pads are connected with 2, 3 and 2 pads. S-parameters S21 and S11 were measured with and without globbing the die. Figure 8 shows the output characteristics of the filter unglobbed. Application of glob shifts the insertion loss to –0.43 dB and the harmonic rejections slightly.

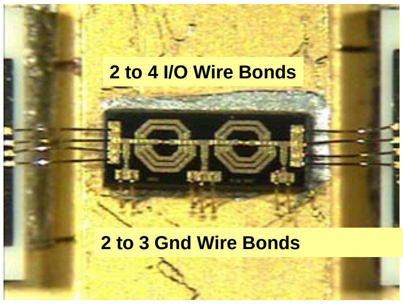

Fig 7. High Band harmonic Filter die mounted for RF test.

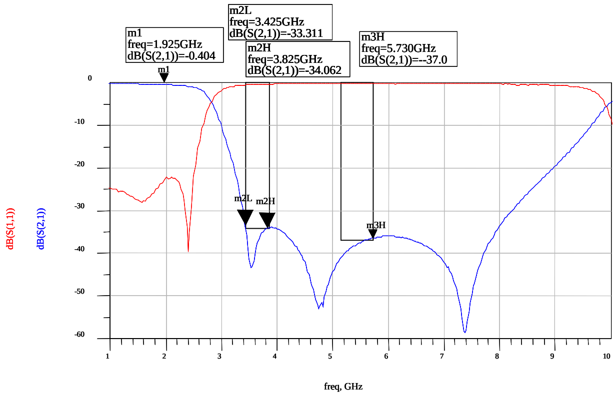

Fig. 8. Output characteristics of high band harmonic filter. Insertion loss is -0.404 dB and rejections in the band are H2=-33 dB and H3=--33.7 dB and H4=-37.1 dB. Application of glob shifted insertion loss to - 0.43 dB.

The characteristics of a globbed low band harmonic filter is shown in Figure 9. The insertion loss is –0.45 dB, H2=-30.5 dB, H3 is –28.3 dB and H4=-24.2 dB. Depending on the specifications of the module these characteristics may be adjusted by the values of the capacitors and inductors. Center ground wire bonds largely determined the fourth-harmonic frequency, whereas the tank circuits determined the H2 and H3.

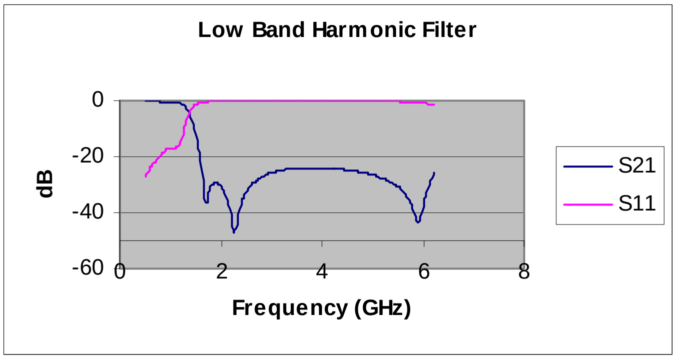

Fig. 9. Output characteristics of low band harmonic filter

COUPLER

While a harmonic filter is used for signal selectivity over radio bands, a coupler is used for signal level sensing and control. A coupler is used to couple the RF signal in a transmit path to a detector for signal power level control. Normally a coupler is a separate component from a filter and both have sizes on the order of $1mm^2$. A coupler was successfully integrated with the harmonic filters reducing overall module size and cost. Integration was successful in overall footprint of about $1\ mm^2$ using one of the interconnect metals in proximity with an inductor, and a terminating resistor fabricated with TiWN or an impedance network of a resistor in parallel with a capacitor. Figures 10 and 11 show representative characteristics. The effectiveness of a coupler is measured by the coupling factor, the directivity and isolation where coupling is measured as S-parameter S_{31} in a 4-port RF network. The directivity is difference of S_{23} and S_{21}, and isolation is absolute sum of coupling and directivity in dB. Typical coupling was -15 to -26 dB with directivity of about 14 to 20 dB in both the high band and low bands. The directivity was strongly dependent on the terminating resistor impedance.

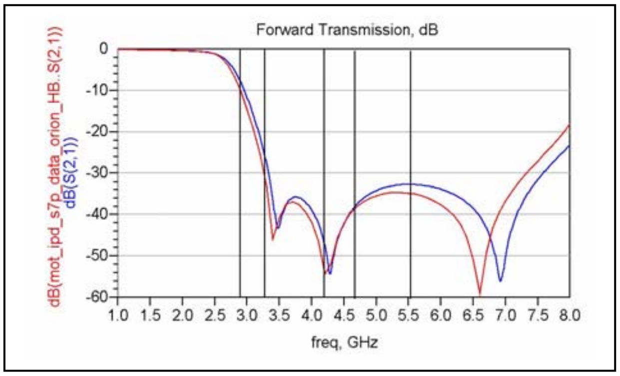

Fig. 10 Measurement and simulation response of harmonic filter integrated with coupler

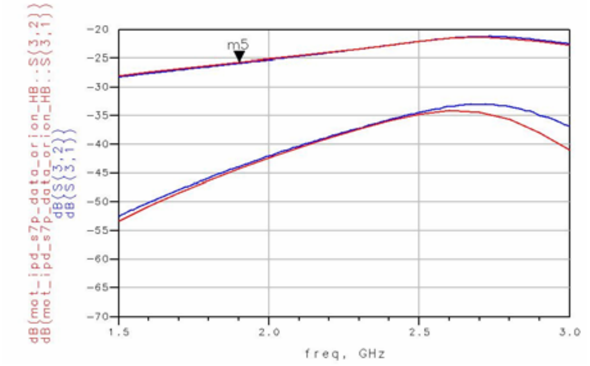

Fig. 11 Measurement and simulation response showing coupling of -26 dB and directivity of 14 dB.

CONCLUSIONS

Integrated passives based on semiconductor processes offer the advantage of excellent parameter control, and allows simplified and compact module design. A GaAs Integrated Passive Device (IPD) process was established based on low cost mechanical grade GaAs LEC substrates and used to fabricate high performance harmonic filters and couplers for application to front-end modules for AMPS/GSM 824-915 MHz and PCS/DCS 1710-1910 MHz bands.

ACKNOWLEDGMENTS

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