System in a Package Solution for RF Receiver with SAW Filter Integration

Jong-Soo Lee, Young-Min Lee, Choong-Mo Nam, In-Ho Jeong, Dong-Wook Kim, Young-Se Kwon*
Telephus Inc.
25-11 Jang-dong, Yuseong-gu, Taejon, 305-343, Korea
Tel : +82-42-866-1361 jslee@telephus.com
*Dept. EE, KAIST
373-1 Kusong-dong, Yuseong-gu, Taejon, 305-701, Korea

Abstract

RF receiver module including SAW filter in a package has been developed for providing system in a package (SIP) solution. The most significant feature for receiver module is that RF SAW (surface acoustic wave) filter is integrated within a package. Typical silicon substate with thick oxide on top (~25um) made it possible to implement the different technology such as GaAs MMIC and SAW filter on a single substate. MCM-D technology using silicon substrate in this paper shows the proper solution for system in a package (SiP). RF performance and basic circuit compoents such as inductor, capacitor, resistor and transmission line are developed. To verify the application of silicon substrate to a system, RF receiver module having dual band/tri-mode functions (CDMA, AMPS, and PCS) is implemented on silicon substrate. Low noise amplifier, RF SAW filter and mixer are integrated on a specialized silicon substrate and shows 2.4 ~ 3dB NF and 27 ~ 28dB gain for PCS (1840 ~ 1870MHz) and CDMA (869 ~ 894MHz), respectively.

Introduction

As the system requirements for multi-functions, low cost, small size and low volume are essential and applicable to portable systems such as mobile phone systems, many sub-blocks are integrated into a single package. For this purpose, especially at RF range, single chip solution is the best way but cost and yield can be barriers for final goal. Instead of single chip solution, there are a lot of efforts to realize system in a package technology with low cost and volume production.

For small size and low cost SiP (system in a package) or SOP (system on a package), two main technologies are being evaluated in many companies and academies. Low temperature co-fired ceramic (LTCC) technology are now thought as the best candidates for SiP solution [1], while MCM-D technology based on glass or low loss substrate are conflicting with LTCC technology for better appraoch [2]. These two technologies have their own advantages over the other technology and in some area, LTCC or MCM-D are more applicable.

SiP technology based on LTCC has the advantages of multi-layer (more than 20 layer), 3D implementation of passive component, no need for extra package substrate, high power capability and easy to make SiP. The minimum feature, however, can not be reduced below 1 mil and size reduction or shrinkage problem during firing process makes it difficult to implement reliable components, which results in yield problems [1].

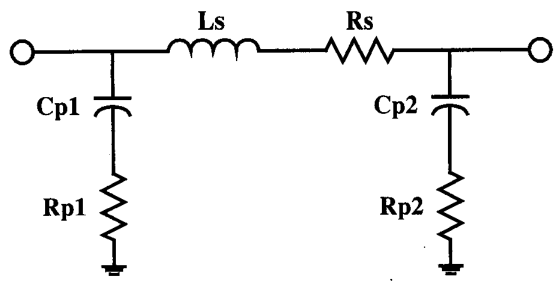
On the other hands, MCM-D tehcnology is based on photo-lithography process which can obtain minimum pattern size of 1μm. Also, due to the nature of semiconductor process, it is very reliable, that is, the component variations is very small and no shrinkage problem. But, RF signal loss of substrate is extremely important for this technology and it's very hard to find out the proper substrate considering cost and yield. In [2], borosilicated glass carrier substrate (tangent loss is about 9.1x10-4) is adapted as MCM-D substrate. However, glass substrate can be easily broken and it is more suitable for high frequency range (more than 10GHz) because of cost issue.

Silicon substrate, which is called as Smart Substrate from Telephus has thick oxide layer (~25μm) on top of p+ type silicon and shows low RF signal loss up to 10GHz. Silicon substrate is known as low cost semiconductor with stable process. Therefore, Smart substrate is very suitable for low loss and low cost SiP solution up to 10GHz. In this paper, basic technology using Smart substrate for MCM-D SiP solution is developed and its application to dual band/tri mode RF receiver with SAW filter integration is evaluated to verify the capability of Smart substrate for SiP.

Basic Technology for SiP using Smart Substrate

Even though Silicon has a lot of excellent properties, it is very difficult to be used at RF frequency range. One main factor for preventing the use of silicon in RF is the quality factor of inductor [3]. With special nonstandard process, Q factor of sprical inductor on silicon does not exceed 30. Because of this property, it is very hard to get high performance RF chips in spite of high integration [4]. The most important feature for low loss and high-Q performance comes from the substrate quality. As in [2], glass or SiO2 shows superior low loss performance to other substrate. Smart substrate [5], which has thick oxide (~25μm thickness) on top shows very good RF performance compared to GaAs, glass or even LTCC.

In standard process for Smart Substrate in Telephus, 3 metal layers and 2 dielectric layers are incorporated to make MCM-D technology for SiP solution. Ti/Au or Ti/Cu metal 1 is used for interconnection and bottom metal for MIM (metal-insulator-metal) capacitor and Ti/Cu metal 2 is used for top metal of MIM capacitor and interconnection. Metal 3 of thick Cu plated metal is used for pad and interconnection. SiN layer is deposited for dielectric layer of MIM capacitor and BCB (benzo-cycobutene) dielectric layer is coated for inter-layer between metal layer. Because of thick plated Cu (~10μm), the signall loss of spiral inductor and transmission line can be reduced. The process is similar to [2] but Smart Substrate is more suitable for low cost and low frequency (up to 10GHz) applications.



(a)

Ls (nH)	Rs (Ω)	Cp1 (fF)	Rp1 (Ω)	Cp2 (fF)	Rp2 (Ω)
4.7	1.6	32	29	103	151

(b)

Fig. 1. Equivalent circuit model for circular inductor on Smart Substrate and model parameters. The inner diameter is 125μm and number of turn is 4.5. Line width and spacing is 10μm with 10μm Cu plating.

To utilize the basic performance of circuit components in Smart Substrate, the library for passive devices such as inductor, capacitor and resistor are set up using conventional CAD software. Equivalent model for ADS simulator from Agilent is provided to user and it is very easy to use the model in CAD program. Fig. 1 shows the CPW type circular inductor with equivalent model parameters for 4.7nH inductor. Inner diameter is 125μm and number of turn is 4.5. Line width and spacing is 10μm with 10μm Cu plating. With S-parameter measurements and modeling, maximum Q-factor is 54 at 3.95GHz and more than 30 at 2GHz.

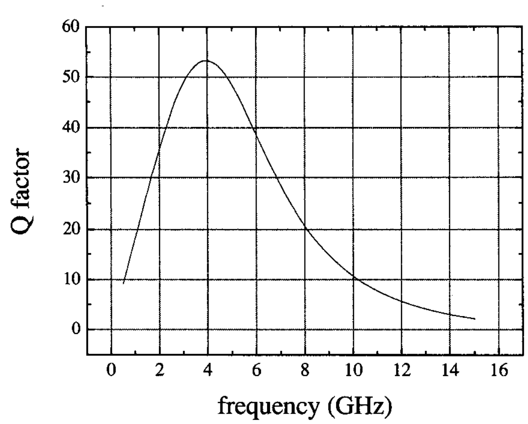


Fig. 2. Quality factor of CPW spiral inductor on Smart Substrate. Maximum Q-factor is 54 at 3.9GHz with 36 at 2GHz (4.7nH).

Q-factor of circular spiral inductor on Smart Substrate can be more than 100 at small value of inductor (around 1.5nH) near 8GHz. This performance is comparable to that on the glass [2] or LTCC substrate. Maximum Q factor of 5.4nH on LTCC subsrtrate can be 60 at 1.8GHz [1], while 1.5nH inductor on glass shows Q factor of 110 at 13GHz [2]. Smart substrate technology, however, can give more stable and reliable passive device library compared to LTCC substrate or can give much cheaper solution rather than glass below 10GHz range.

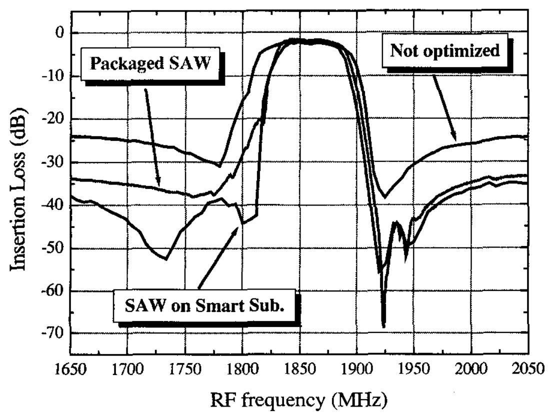
Similar device libarary for capacitor and resistors are set up in Telephus, where SiN and NiCr (or TaN) are used as dielectric material and resistor metal, respectively. 0.47nF/mm2 of capacitance density is obtained and accurately predicted by the area scaling rule for capacitor. Sheet resistance for NiCr is controlled by 20Ω/sq. Transmission line characteristics, which is one of the most important parameters in RF frequency range shows 0.03dB/mm at 2GHz and 0.05dB/mm at 5GHz of signal loss. All these data are suitable for designing and producing integrated passive devices (IPD) for implementing system in a package solution. LPF, BPF, Balun and power combiner are designed and made based on the passive library from Telephus [5], [6].

SAW Filter Integration

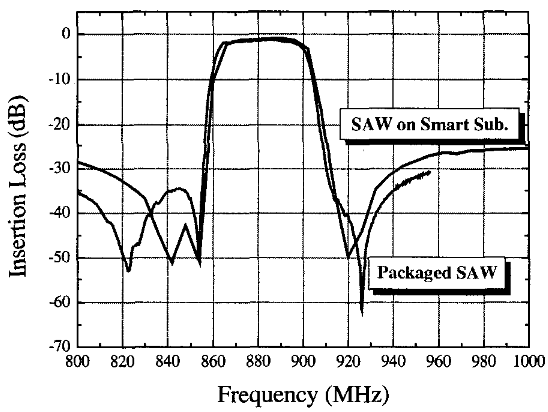
Recently, many RF chips are extending their functional capabilities to meet the system requirements such as low power operation and multi-band operation. In receiver system, RF blocks are similar to each standard system. After receiving signal is fed from antenna, low noise amplifier (LNA) enlarges the weak RF signal for mixer and subsequent blocks to handle the signal with noise. For channel or band selection, band pass filters such as SAW (surface acoustic wave) filters are required between LNA and mixer. The inherent material difference, however, of SAW filter and conventional semiconductor makes it difficult for system engineer to integrate SAW filter into their MMIC chips. The best way for SiP in RF receiver system (LNA + SAW + Mixer) is, therefore, multi-chip module technology. As mentioned above section, the proper selection for MCM substrate is important and affects the total performance of system.

Smart substrate is used for MCM substrate to incoperate the GaAs MMIC chip (LNA + Mixer) with SAW filter. To reduce the final package size, bare die SAW filter is used instead of ceramic packaged SAW filter. Nowadays, CSP (chip scale package) type SAW filter with small size are commercially available from several vendors but it is still larger than bare die SAW filter (~1.0x1.0mm). And also, there should be assembly margin on PCB between SAW filter and MMIC.

It is very important to see the ground effect or wire bonding effect when attaches SAW filter on substrate or package because the insertion loss and more seriously, attenution at out-of-band are strongly affected by the inductance from wire bond. To optimize the bonding effect on attenuation level, several ground pattern with bonding pads are formed on Smart substrate and measured the S-parameters under several condition. Fig. 3 shows the measurement results of bare die SAW filter on Smart Substrate and comparison of packaged SAW filter for Korea PCS band (1840 ~ 1870MHz) and CDMA/AMPS Rx band (869 ~ 894MHz). In Fig. 3(a), the effect of ground pattern underneath of SAW filter and wire bonding can be clearly seen; attenuation is reduced from –25dB to –35dB. There are some difference between measured bare die SAW filter and packaged SAW filter at out-of-band. This is mainly caused by the ground wire (which is perfectly optimized in package) and radiation loss of bare die SAW filter because the measurement was done at on-wafer test. With these results, it is possible to integrate the RF receiver SAW filter with GaAs MMIC (LNA and Mixer), which forms the full receiver system in RF.



(a)



(b)

Fig. 3. Measurements of bare die SAW filter on Smart substrate for (a) Korea PCS Rx band (1840 ~ 1870MHz) and (b) CDMA/AMPS Rx band (869 ~ 894MHz). They also show the comparison with packaged SAW filter.

Dual Band Receiver Module on Smart Substrate

Based on the previous results using SAW filter, it is possible to integrate the GaAs MMIC with SAW filter, which has different substrate material from GaAs or other semiconductor. As said before, the GaAs MMIC chips for CDMA and PCS band were used as die form with related SAW filter on Smart substrate. Table 1 and Table 2 show the RF specifications of LNA and Mixer for PCS and CDMA band by the GaAs MMIC with 3dB atteuation pad instead of SAW filter. The most important parameters from the view point of receiver system are noise figure and IIP3. To satisfy the system SNR and BER, it is very tight to control the noise figure of LNA, SAW and Mixer.

Table 1. Performance of MMIC (LNA, Mixer) : PCS band

Parameter	Test Condition	Units	Meas.
Conversion Gain	Vcont = 1 ~ 3V	dB	19~25
Noise Figure	Vcont = 3V	dB	2.5
IIP3	RF=-30dBm, Vcont=3V	dBm	-8
IDD		mA	20~26

Table 2. Performance of MMIC (LNA, Mixer) : CDMA band

Parameter	Test Condition	Units	Meas.
High gain mode (CDMA)			
Conversion Gain	RF=0.88GHz	dB	28
Noise Figure	LO=1.01GHz	dB	3.0
IIP3	LO=-6dBm	dBm	-12
IDD	IF=130MHz	mA	21
Low Gain Mode (CDMA)			
Conversion Gain	RF=0.88GHz	dB	13
Noise Figure	LO=1.01GHz	dB	11.5
IIP3	LO=-6dBm	dBm	+3
IDD	IF=130MHz	mA	16
AMPS Mode			
Conversion Gain	RF=0.88GHz	dB	20
Noise Figure	LO=1.01GHz	dB	2.5
IIP3	LO=-6dBm	dBm	-1
IDD	IF=130MHz	mA	17

Simple process procedures for Smart substrate are given below.

- Thick oxide formation on Si substrate – Smart Substrate
- First Metallization for interconnection and bottom metal for capacitor (Ti/Cu or Ti/Au)
- SiN deposition for MIM capacitor
- SiN etching for interconnection
- Thick metal plating (Au or Cu)
- Passivation using BCB or SiN (optional)

Fig. 4 shows the whole 6" Smart substrate with thick oxide layer (~25μm) on top to reduce the RF signal loss of silicon wafer. The measured signal loss of transmission line on Smart substrate is 0.03dB/mm at 2GHz and 0.05dB/mm at 5GHz [5].

The size of each chip is; 1) PCS MMIC 1x1.3mm2, 2) PCS SAW filter 1x1.1mm2, 3) CDMA MMIC 1.4x1.6mm2, 4) CDMA SAW filter 1.1x1.6mm2. And Fig. 5 shows the photograph of dual band receiver module mounted on Smart Substrate with bonding pads, interconnection and capacitors for bypassing and blocking. The actual size of Smart substrate is 4x3.6mm2. There should be marginal (unwanted) space between attaced chips and bonding pads on Smart substrate because epoxy material can bleed out to bonding pad.

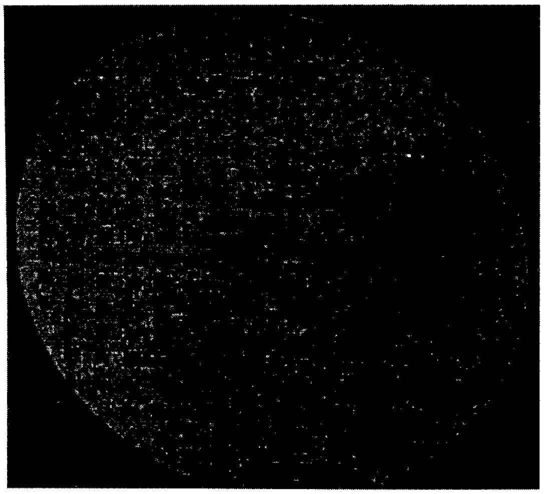


Fig. 4. Photograph of 6" Smart substrate for RF SiP. Available area from Smart substrate is approximately 15,000mm2. Thick oxide layer (~25μm) is formed on top of Si substrate to reduce the signal loss at RF. Signal loss of transimission line is about 0.03dB/mm at 2GHz and 0.05dB/mm at 5GHz.

After assembling the chips and wire bonding, the Smart substrate is mounted on ceramic package to make final package. Ceramic package was selected because the SAW filter requires hermetic sealing for reliability and it has 24pins for I/O and bias. Fig. 6 shows the photograph of evaluaion board with dual band receiver chips to test the whole RF performance with matching and bias network. The size of receiver chip is 7x7x1.5mm. There are a lot of discrete inductors and capacitors on evaluation board, but most of them are used for bias network and IF matching network from Mixer. Few components (6 SMD)are used to match the LNA inputs for both CDMA and PCS band.

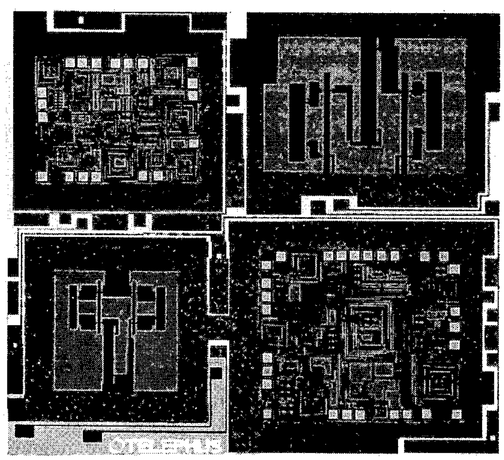


Fig. 5. Photograph of dual band receiver module on Smart substrate using GaAs MMIC (LNA and Mixer) and bare die SAW filter. The size is 4x3.6mm2 including bonding pads and every capacitors.

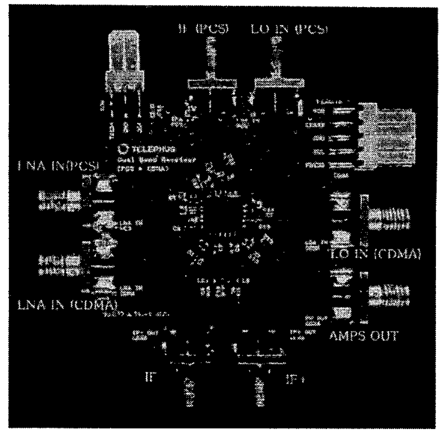


Fig. 6. Photograph of integrated evaluation board to test the dual band receiver module. The receiver module in ceramic package is 7x7x1.5mm with 24 out pins.

RF performance of dual band receiver module were measured using vector network analyzer, spectrum analyzer and noise figure meter. The gain, noise figure and IIP3 characteristics should meet the electrcial specification when discrete chips are integrated.

From Fig. 7 to Fig. 10, they show the measured RF performance of dual band/tri mode (including AMPS) receiver module. Fig. 7 and Fig. 8 shows the gain and noise figure measurements for CDMA band. To prevent the interference from the air, all measurements were done in shield room. Gain control can change the cascade gain from 27dB to 11dB according to the control voltage (2.7V for high gain mode and 0V for low gain mode). Pass band gain for AMPS mode is about 23dB, which has similar noise figure with CDMA high gain mode. In Fig. 8, noise figure of high gain and low gain mode is shown. Actual noise figure from LNA to Mixer including SAW filter (insertion loss is about 2.5dB) is 3dB for high gain mode. Other important figure of merit, IIP3 was measured under two –3dBm input power signal with 1MHz deviation. Fig. 9 shows the photograph of response of spectrum analyzer when –30dBm two tone input were applied to CDMA receiver input. Nonlinear behavior of receiver shows IIP3 of –14 ~ -15dBm (sample variation).

For dual band operation, Fig. 10 shows the other band, PCS band RF performance. 28dB of cascade gain and 2.4dB of NF were obtained from single chip dual band receiver module. All measured data were similar to Table I and Table 2 except IIP3 specification, which is critically affected by the gain of cascaded chain and matching point.

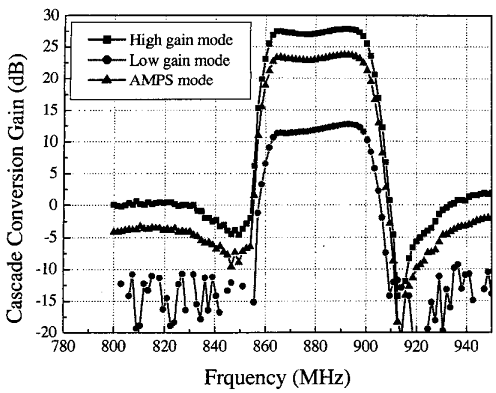


Fig. 7. Measurements of cascade conversion gain for LNA, SAW filter and Mixer in CDMA band and AMPS mode. Gain control from 27dB to 11dB can be obtained by variation of control voltage from 2.7V to 0V. Also, gain for AMPS mode is as high as 23dB.

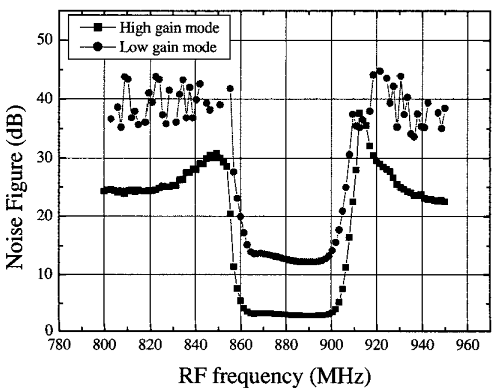


Fig. 8. Noise figure of CDMA band for high gain mode and low gain mode. NF for high gain mode is about 3dB. In case of AMPS mode, noise figure is the same with high gain mode. All measurements were done in shield room to prevent the interference from the air.

Recently, small size of SAW filters adapting chip scale package are available from several vendors and it is more useful to use CSP type SAW filter to reduce the total cost further. The ceramic package used in SAW filter is usually expensive material and cost portion of package among total cost is relatively high. Therefore, with CSP type SAW filter, cheap package solution can be applied to this dual band receiver modue to reduce the final cost.

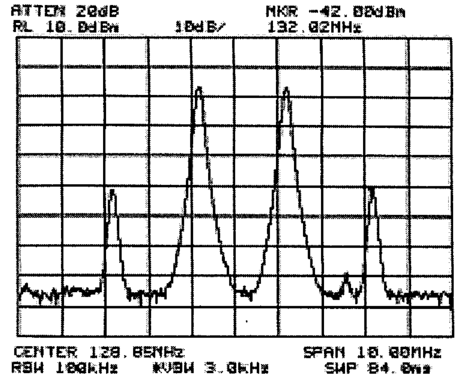


Fig. 9. Measurements of nonlinear behavior of CDMA receiver with –30dBm RF input power. From these reults, IIP3 of receiver is about –14 ~ -15dBm.

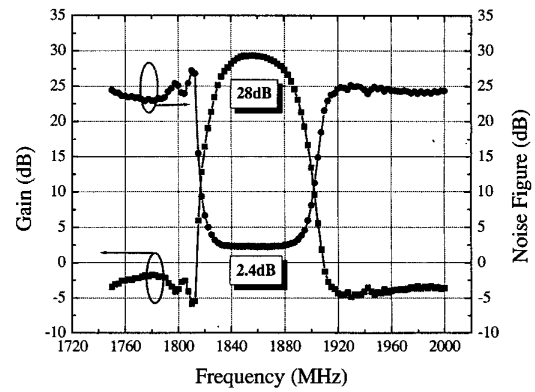


Fig. 10. Measurement result for PCS band receiver performance.

Conclusion

In this paper, another way to implement SiP technolgy based on MCM appraoch was illustrated and developed by the Smart substrate on silicon. Due to thick oxide on Silicon substrate, it is possible to obtain good RF performance. Dual band/tri mode receiver including PCS, CDMA and AMPS mode were developed to verify the capability of Smart substrate from Telephus. This paper will guide the way for system to go.

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