Multichip Module on Silicon for SAW Filter Embedded RF Receiver

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ABSTRACT
Dual band/tri mode (PCS, CDMA and AMPS) receiver module where RF SAW (surface acoustic wave) filters between LNA (low noise amplifier) and Mixer are included has been developed on Si Smart Substrate. Si Smart Substrate has very thick oxide (~35μm) on top using specific technology and shows good RF performance. Signal loss of transmission line (co-planar waveguide type) is 0.03dB/mm and 0.05dB/mm at 2GHz and 5GHz, respectively. The key technology, Si Smart Substrate is for extending the pure Si technology to RF region based on thick oxide layer. Basic RF and microwave passive component such as inductor, capacitor, resistor and transmission line are characterized on Si Smart Substrate and library for customer design has been set up. With these technology, multichip module for system-in-package (SiP) on Si substrate has been developed. To prove this technology, dual band/tri mode receiver with 2.4 ~ 3dB NF (LNA + SAW filter + Mixer) and 27 ~ 28dB gain for Korea PCS (1840 ~ 1870MHz) and CDMA (869 ~ 894MHz) band has been demonstrated.

Key word: receiver module, Si Smart Substrate, SAW filter, NF, gain, System-in-package

INTRODUCTION
Nowadays, RF system which has small volume or size, low cost and multi-functional integration is one of the hottest topics and many companies and academy are trying to integrate several chips or component in a package [1], [2]. This system-in-package technology makes system smaller and easier to handle for assembly engineer. So, there is no doubt for technical trend of one package solution.

Several problems, however, exists on the way to final goal. High performance substrate with reliable process and low cost is very difficult to be found. There are a lot of efforts to search proper substrate for RF application. Some companies use high resistive silicon substrate and organic material such as BCB (Benzocyclobutene) or polyimide for high isolation [3], [4], [5] while other engineers are looking for another alternatives.

LTCC (low temperature co-fired ceramic) substrates are now very popular and commercial products using LTCC are released from several companies. Bluetooth and wireless LAN system select the LTCC technology for small size module or system-in-package [7]. The critical issues for these material still exit. High resistive silicon substrate is expensive compared to other substrate material and processing issues are occurred. Even though LTCC technology has a lot of advantage for system engineer, (still) higher cost for multi-layer LTCC and shrinkage problem when fired make it difficult to found stable passive component library.

Si material is the most stable in the world and physics and process are well established during last half century. The signal loss, however, especially at RF range causes several problems for the use of Si. Intrinsic semi-insulating property of GaAs makes itself more popular than Si at high frequency range. The weak point of Si is the inherent conductive substrate of Si.

To overcome this conductivity, organic materials such as BCB or polyimide were coated on Si and passive components were formed on organic material. But, there are still limitations of this approach. In this paper, another solution for high performance and reliable substrate with low cost using Si is shown to prove the RF characteristics and dual band/tri mode receiver module including LNA, SAW filter and mixer in a package was illustrated.

BASIC TECHNOLOGY AND PERFORMANCE
Si Smart Substrate uses standard 6” p+ silicon substrate (5 ~ 10Ω-cm), which is easily available from several vendors with low price. With special and unique oxidation technology, 35μm thick oxide can be grown within an hour [6]. This thick oxide layer eliminates the inherent conductivity of Si substrate and makes it possible to use the Si at high frequency range. The surface is very flat (surface roughness is less than 15Å) which is the advantage over organic material coating approach. Standard lithography using g- and i-line stepper reduces the minimum pattern size to 1μm on Si Smart Substrate with excellent uniformity in entire 6” wafer. There is no firing process like LTCC and it is always possible to

obtain same pattern with high repeatability.

Transmission line for 50Ω characteristic impedance was established using 50µm width and 15 µm spacing on Smart Substrate. The measured signal loss is 0.03dB/mm at 2GHz and 0.05dB/mm at 5GHz. Thick Cu metal of 10µm height was used to reduce the metal loss. This number is enough to use Smart Substrate in RF range.

Library for passive components such as resistor, inductor and capacitor was set up for custom design [8]. All components are modeled in ADS simulator from Agilent and provide sufficient RF simulation capability. Quality factor of inductor that is one of the most important factors in passive library ranges from 20 to 120 according to inductance. Up to 40nH inductor with 10µm line width and spacing is possible to be used. Self resonant frequency for high value inductor is higher than 2GHz. Fig. 1 shows the modeled S-parameter of 1.4nH spiral inductor on Smart Substrate.

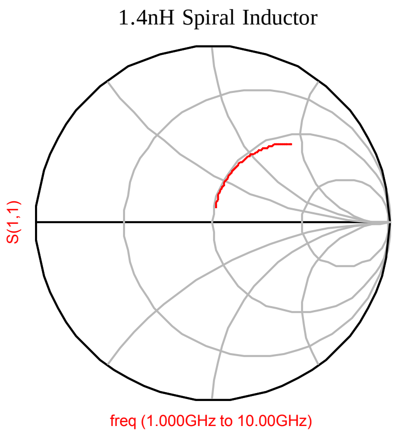
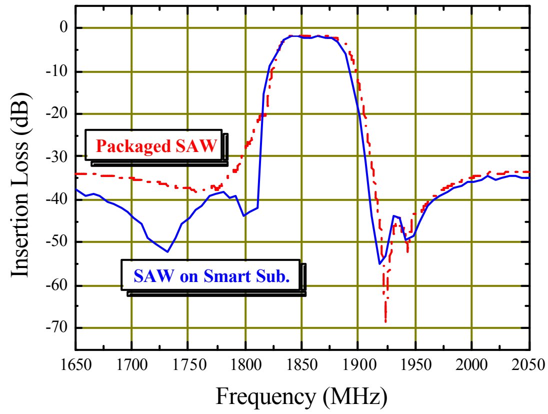


Fig. 1. S-parameter of 1.4nH spiral inductor on Smart Substrate. Q factor of this inductor is about 40 at 2GHz and 70 at 7.7GHz with higher than 15GHz of self-resonant frequency.

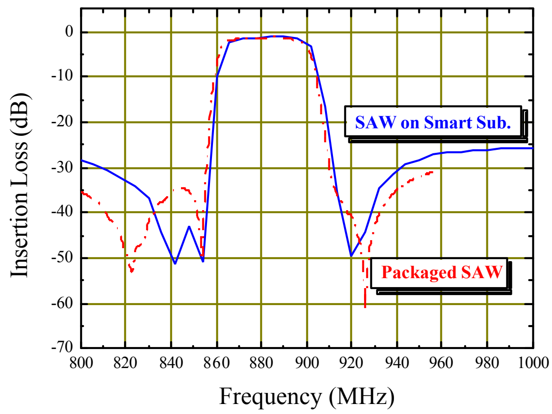
NiCr metal with 20Ω/ is used to form resistors in library and MIM (metal-insulator-metal) capacitor with 1000Å SiN layer forms total passive library using Smart Substrate. All components are measured and equivalent electrical models are established in ADS simulator. Therefore, every passive functional system such as filters, balun, combiner, matching network and so on can be implemented based on the passive library on Smart Substrate.

SAW FILTER INTEGRATION ON SMART SUBSTRATE

Recently, as the requirements for system become more complex and high level integration, many RFIC chips include several functions like multi-band operation, gain control, IP3 control and so on combining low noise amplifier and mixer for receiver path. SAW (surface acoustic wave) filter, however, is difficult to be integrated with other RFIC because the substrate material is different from GaAs, Si or SiGe. Piezoelectric substrate (lithium-niobate or lithium tantalate) is essential in SAW filter and also there should be air cavity above the chip to maintain surface wave on piezoelectric substrate. Due to these reasons, SAW filters in RF transmitter and receiver path are always off-chipped. From the viewpoint of system engineer or assembly company, off-chip SAW filter adds additional pick-and-place procedure and also it occupies more area of system board. All these result in cost increase and possibility of reliability problem from solder joint. Especially, these situations become frustrated for multi-band application because number of off-chipped SAW filter is the same with that of bands used. So, it is right way to put the RF SAW filter into receiver chips, as



(a)



(b)

Fig. 2. Measurement results of bare SAW filter on Si Smart Substrate for a) Korea PCS (1840 ~ 1870MHz, above) and b) CDMA (869 ~ 894MHz, below) compared to commercial packaged SAW filter. All pass band and attenuation characteristics of bare SAW filter are similar to commercially available SAW filter.

to reduce the board area and assembly cost. Even though CSP (chip-scale package) type SAW filter or flip-chipped SAW filter are now available from several vendors, the size is still larger than bare SAW filter. Therefore, bare SAW filter was mounted on Smart Substrate that has thick oxide layer on top and characteristics were measured via S-parameter. Fig. 2 compares the measured transmission characteristics of bare SAW filter on Smart Substrate (solid line) with commercially available packaged SAW filter (dash-dot line). The ground pattern beneath the core SAW filter and bonding effects as well as package effect should be considered to assemble SAW filter. Attenuation level at out of band may increase with improper grounding around the filter. The above data were obtained after optimum design of ground pattern was developed. Pass band characteristics and out of band rejection of bare SAW filter is closely similar to the packaged SAW filter, which means that SAW filter integration as die form into a package with MMIC can be possible and reduce the final package and board area using this technology.

DUAL BAND/TRI MODE RX MODULE

Based on the above results, dual band/tri mode (Korea PCS, CDMA and AMPS; 1840 ~ 1870MHz, 869 ~ 894MHz) was developed. MMIC chips of low noise amplifier and mixer with bare SAW filter were mounted on Si Smart Substrate as shown in Fig. 3. Two MMIC chips (LNA+Mixer) with two bare SAW filters are attached using conductive epoxy. Because of the epoxy bleeding, marginal area from die edge to bonding area should be required. The size of each chip is; 1) PCS MMIC 1x1.3mm^2, 2) PCS SAW filter 1x1.1mm^2, 3) CDMA MMIC 1.4x1.6mm^2, 4) CDMA SAW filter 1.1x1.6mm^2. Die size of Smart Substrate is 4x3.6mm^2 including capacitors and bonding pads.

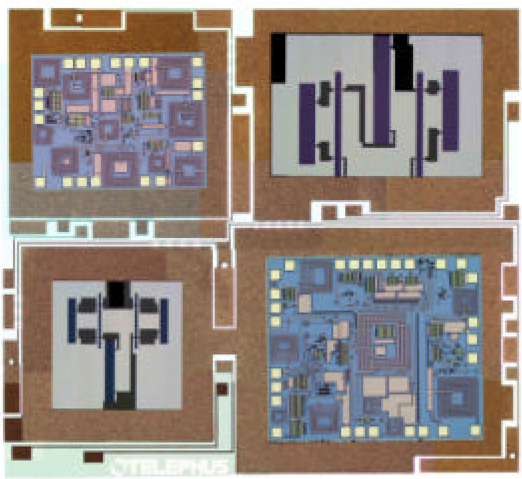


Fig. 3. Photograph of dual band/tri mode receiver module using MMIC (LNA+Mixer) and bare SAW filter on Smart Substrate. Interconnection line, capacitors for bypass and blocking, as well as bonding pads are formed on Smart Substrate. The size of substrate is 4x3.6mm^2.

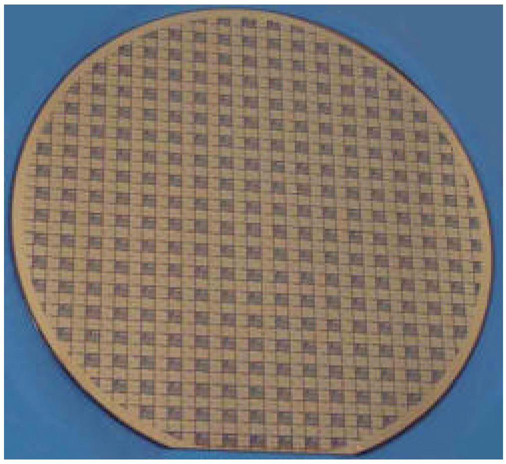


Fig. 4. Photograph of whole 6" Smart Substrate for receiver module. Thick oxide layer of 35µm are formed on top of substrate.

Normal process flow for Smart Substrate is summarized below.

1. Thick oxide formation on Si substrate – Smart Substrate
2. First Metallization for interconnection and bottom metal for capacitor
3. SiN deposition for MIM capacitor
4. SiN etching for interconnection
5. Thick metal plating (Au or Cu)
6. Passivation using BCB or SiN (optional)

For making resistor, NiCr metal should be deposited after step 1. Fig. 4 shows the whole 6' wafer where module substrate was fabricated.

Because of hermetic characteristics of SAW filter, the package type should have air cavity on top of SAW filter substrate instead of conventional EMC (epoxy molding compound) encapsulation. Conventional ceramic package with 3 layers and kovar lid on top was adapted for final package of dual band/tri mode receiver module. Fig. 5 shows the photograph of ceramic package of dual band/tri mode receiver module with embedded SAW filter, where

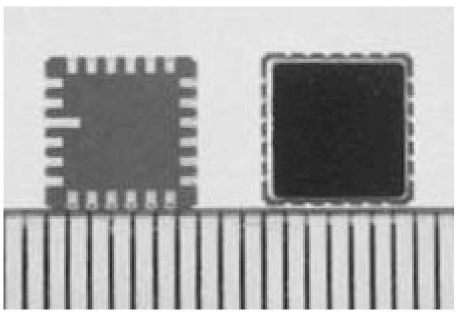


Fig. 5. Photograph of final package for dual band/tri mode receiver module with embedded SAW filter. The size is 7x7x1.5mm^3 with 24 pins.

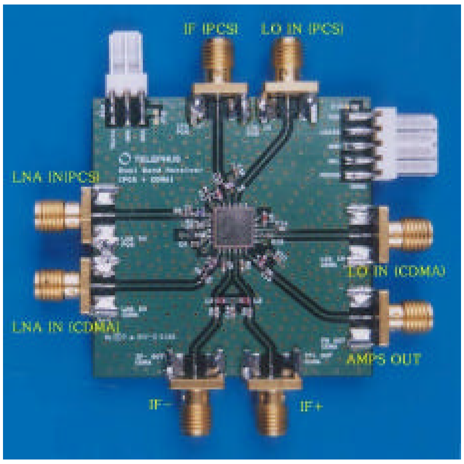


Fig. 6. Photograph of evaluation board for measurement of receiver module.

the outline size of package is 7x7x1.5mm^3. 24 output pins are formed with leadless type for bias, RF coupling at source of MESFET and also RF input/output port for LNA and Mixer.

To test the performance of this module, evaluation board should be prepared on BT or FR-4 material with bias capacitor, inductor and matching network for LNA input and IF output port. About 30 SMDs are used in evaluation board, but most of them are for bias network and IF matching network. Only 6 components are used for LNA input matching network of CDMA and PCS band. The components in bias circuits are essential but have very large value that cannot be supported by Smart Substrate. The situation in IF matching network is similar to bias circuit. All these depend on the design of MMIC chips. Recently, high value capacitor, inductor for bias and IF matching network in Mixer is off-chipped because of the size of MMIC chip. The photograph of evaluation board for measurement is shown in Fig. 6 with the size of 5x5cm.

RF characteristics of receiver module were measured using vector network analyzer, spectrum analyzer and signal generator. All the electrical specifications should be met with the original specification of MMIC chips (LNA + Mixer) except total conversion gain from LNA to Mixer because of SAW filter. Supply voltage for CDMA and PCS band is 2.7V and 3V, respectively.

Fig. 7 shows the measured gain characteristics of CDMA band including SAW filter. There are two-gain control, low gain mode and high gain mode. Ga in characteristics of AMPS are also displayed. Overall gain of receiver module for high gain state is 27dB in pass band (869 ~ 894MHz) with –5dB at out of band range. More than 30dBc attenuation can be obtained from pass band to rejection band, which is similar performance to SAW filter (Fig. 2). This means that the there is no difference between the use of packaged SAW filter and bare SAW

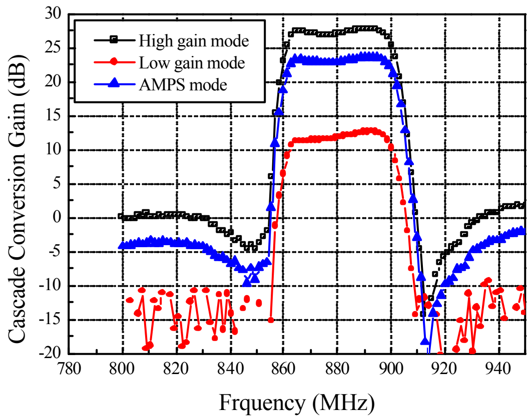


Fig. 7. Measured overall gain characteristics of CDMA and AMPS mode. Gain control of CDMA band can change the pass band gain from 27dB to 11dB (low gain mode). Attenuation at out of band is more than –5dB. More than 30dBc gain difference can be obtained due to embedded SAW filter.

filter on Smart Substrate. Noise figure (NF), another important parameter of receiver module, are shown in Fig. 8 for CDMA band. Measured NF was 3dB at pass band. Because of environmental RF signal that can affect receiver performance, measurements were done at shield condition. NF for each circuit is 1.5dB (LNA), 3dB (SAW filter) and 5dB (Mixer). The measured gain and NF characteristics are exactly the same with the recommended specification in datasheet of MMIC chip. Typical components in evaluation board are inductor in matching network at LNA input and large capacitor at source of FET in LNA. These components seriously affect the RF performance of receiver module.

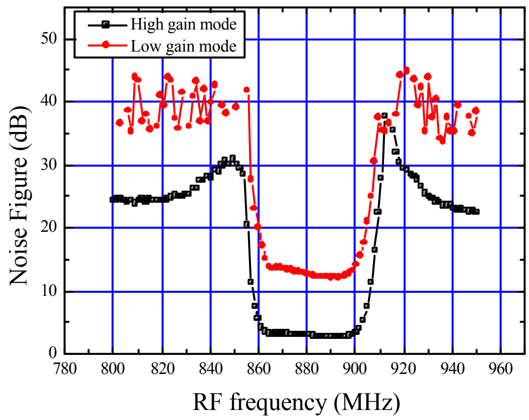


Fig. 8. Measured noise figure of overall receiver module for CDMA band. 3dB NF can be obtained at pass band. Measurement was done in shield room to prevent the environmental RF signal from affecting the system performance.

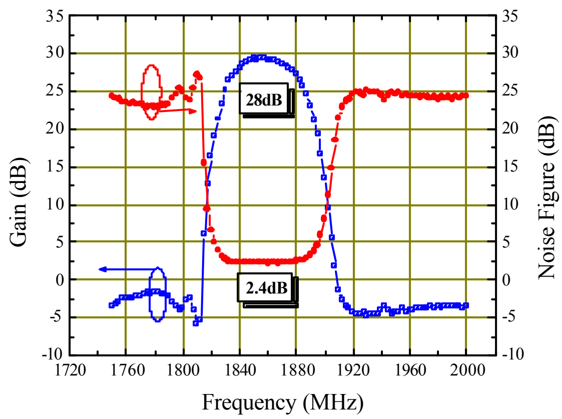


Fig. 9. Measured gain and NF of PCS band (Korea PCS, 1840 ~ 1870MHz) for receiver module. Gain at pass band is 28dB and 2.4dB of NF. The out of band attenuation is less than –5dB, which results in more than 30dBc between pass band and rejection band.

Overall gain and NF characteristics of Korean PCS band (1840 ~ 1870MHz) were displayed in Fig. 9. The frequency band of receiver module was determined by the SAW filter inside because the MMIC chip (LNA and Mixer) can cover from 1800 ~ 2000MHz. Receiver module for US-PCS band can be easily established by replacing the SAW filter. Measured gain and NF is 28dB and 2.4dB, respectively. If this module was used in dual band phone, system noise figure can be met through 2.4dB NF (PCS) and 3dB (CDMA) because total system NF for PCS and CDMA is 6.9dB and 10dB under the measured gain of receiver stage. Because the overall gain of receiver, noise figure of following stage has little effect on the system noise figure.

Two-tone tests for measurements of IIP3 (3^{rd} order input intercept point) were also performed for PCS and CDMA band with –30dBm of input power and –10dBm (PCS) and –6dBm (CDMA) of LO power. Signal spacing for RF input signals are 1MHz. Table 1 and Table 2 summarized the measured RF characteristics of receiver module with test condition. Every electrical specification is exactly the same with the data of MMIC only (in case of SAW filter excluded).

ADVANTAGE OF EMBEDDED SAW MODULE

Until now, we have demonstrated dual band/tri mode receiver module which has SAW filter in a package. There must be several advantages over discrete implementation of receiver part. Here are summary for bright side of one package receiver module.

1. Area saving. When the receiver section is implemented using discrete chip and packaged SAW filter, required board area increases compared to one package solution. This situation is very serious especially for multi-band system. For example, in dual band system, there should be 4 discrete chips in receiver part. There should be marginal space between chips, which results in large board area.

2. Assembly cost. Usually, the pick-and-place cost for SMD device is approximately 1 cent (US). Therefore, instead of four times chip attachment, there is only one time pick-and-place for one package solution reducing the assembly cost.

3. Impedance matching. SAW filter maker should think about the matching properties between LNA and SAW filter, and SAW filter and Mixer. It takes a lot of time and labor for SAW filter maker because slight difference of matching properties from system company to company. From the viewpoint of system maker, they should consider the matching network for LNA input, LNA output to SAW input, SAW output to Mixer input and Mixer output to IF part. Using the one package solution, matching consideration for only LNA input and IF part is required. This reduces the cost and labor for each SAW filter maker and system maker.

4. Size reduction of receiver part. This advantage is natural for module technology. The size of bare die is much smaller than that of packaged one.

Table 1. Measurement Results for PCS band (1840 ~ 1870MHz)

Parameter	Test Condition	Units	Meas.
Conversion Gain	Vcont = 1 ~ 3V	dB	19~28
Noise Figure	Vcont = 3V	dB	2.4
IIP3	RF=-30dBm, Vcont=3V	dBm	-11
I_{DD}		mA	21~27

Table 2. Measurement Results for CDMA and AMPS 869MHz ~ 849MHz)

Parameter	Test Condition	Units	Meas.
High gain mode (CDMA)			
Conversion Gain	RF=0.88GHz LO=1.01GHz LO=-6dBm IF=130MHz	dB	27
Noise Figure		dB	3.0
IIP3		dBm	-14
I_{DD}		mA	22
Low Gain Mode (CDMA)			
Conversion Gain	RF=0.88GHz LO=1.01GHz LO=-6dBm IF=130MHz	dB	11
Noise Figure		dB	13
IIP3		dBm	0
I_{DD}		mA	18
AMPS Mode			
Conversion Gain	RF=0.88GHz LO=1.01GHz LO=-6dBm IF=130MHz	dB	22
Noise Figure		dB	3
IIP3		dBm	-10
I_{DD}		mA	13

5. Reduction of SMD. Sometimes, the input matching network or bias network can be incorporated into a package (not in the case of this paper) because Smart Substrate can implement limited value of inductor, capacitor and resistor. As the Smart Substrate adapts conventional semiconductor process, possible passive components are limited. However, RF matching network and part of bias network can be embedded in Smart Substrate. This also reduces the labor from system maker and cut down the developing and assembly cost.

CONCLUSION

In this paper, another proper solution for high level integration of module technology is suggested using Smart Substrate. Smart Substrate can extend all advantages of Si to high frequency application. Because of thick oxide layer on 6' silicon substrate, signal loss may be reduced to 0.05dB/mm at 5GHz. Passive library for inductor, capacitor and resistor on Smart Substrate is well established for custom design of any passive circuitry in microwave range. All characteristics of passive circuitry are exactly predicted and obtained because of accurate library model.

Dual band/tri mode receiver module was implemented using Smart Substrate for explaining the advantage of Smart Substrate applicable to small size, multi-functional subsystem in a package. To maximize the advantage of module technology, RF SAW filters are embedded as bare form in a package. Optimum ground pattern are determined to reduce the out of band attenuation. Less than 3dB of noise figure and 25 ~ 28dB of gain can be obtained for each CDMA and PCS band. All frequency bands of interest are determined by the SAW filter. All measured performances of receiver module are well matched to the recommended receiver characteristics that are obtained using discrete chips and packaged SAW filter.

The application of Smart Substrate has no limitation to passive circuitry. From the basic circuits such as inductor array, capacitor array and resistor array to functional circuits like switch-diplexer system can be implemented with low cost, small size and multi-function. And also, it is very compatible with other technologies such as LTCC or conventional plastic package. Passive circuit on Smart Substrate and other active circuit on LTCC can be implemented by the standard process. So, Smart Substrate is believed to provide another good solution to system in a package technology.

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