# Monolithic Planar RF Inductor and Waveguide Structures on Silicon with Performance Comparable to those in GaAs MMIC

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**Abstract**

The monolithic inductors and transmission lines on Si substrate with very high Q factor, low insertion loss, and high resonant frequency, are achieved by using very thick polyimide (10μm) as dielectric material, and thick Al (4μm) metalization system. This structure is made on the finished conventional standard two layer metalization BiCMOS wafer. For 10 nH inductor, 6 GHz resonant frequency, maximum Q factor of 5.5 at 1.2 GHz, and 1.2dB insertion loss at 3 GHz are obtained, which are very comparable to those available in GaAs MMIC. These inductors can be used as RF choke as well as matching element. Transmission lines are also fabricated using this technology. The $S_{21}$ of coplanar waveguide with 1mm length is -0.2dB at 4 GHz, and that of microstrip line is -0.3 dB. It is expected that, using these passive elements, Si RF IC can be designed upto several GHz with performance comparable to GaAs MMIC.

## Introduction

Recently emerging need for RF IC for such markets as CATV, GPS, PCN, and mobile cellular phone, has pushed the Si technology to several giga-hertz applications. Lossy characteristic of Si-substrate, however, has prohibited the fabrication of high Q inductors and low loss transmission lines on this best established technology. So, till now, GaAs substrate is mainly used for monolithic RF & microwave circuits in virtue of its semi-insulating characteristic and high mobility. Modern Si IC process offers good active devices that have high enough $f_T$ and $f_{max}$ [1], but it does not provide passive elements like inductors and transmission lines with acceptable performance. This is due to the semiconducting nature of silicon substrate. There have been several efforts to fabricate these passive elements on the Si-substrate, but neither the obtained performance such as Q factor, resonant frequency and insertion loss are good enough, nor the process is compatible with standard IC's [2][3]. In this paper, we present the monolithic inductors and transmission lines on silicon substrate with very high Q factor, low insertion loss, and high resonant frequency. These are based on very thick polyimide (10μm) and Al (4μm) metalization system that is fabricated on the finished conventional standard two layer metalization BiCMOS wafer. The measured RF performances of the fabricated inductors are very comparable to those on the semi-insulating GaAs substrate, and the loss of transmission line of 1 mm length is less than 0.2 dB at 4 GHz. These results show us that the inductors and transmission lines using thick polyimide as an insulator and thick Al metalization on Si substrate are very promising components for low GHz applications.

## Fabrication

The starting wafer is B-doped p-type <100> Si wafer, whose resistivity is 20 Ω·cm. On top of the processed 2-metal standard BiCMOS wafer, 10 μm thick polyimide and 4 μm thick Al metal (M3) are deposited and patterned as shown in Fig. 1. We used polyimide because: (i) it has relatively low dielectric constant with low loss, and (ii) it is relatively easy to deposit thick film. 20 μm thick polyimide is spin-coated using Asahi chemical company's G-7613M photo-sensitive polyimide. After curing process at

350°C, the thickness is decreased to 10 μm. Polyimide via contact is patterned using chemical wet etching. 4 μm Al film is then sputter deposited, and patterned using isotropic wet etching process.

The schematic structure of the inductor is shown in Fig. 2. We fabricated also metal-2/metal-1 (M2) inductors for comparison with metal-3/metal-2 (M3) elements. In M2 inductors, W is 5 μm, S is 5 μm, and D is 100 μm. In M3 inductors, W is 7 μm, S is 13 μm, and D is 100 μm. Numbers of turns are 2,4,6,8, and 10, respectively. In Fig. 3, the microphotographs of M2 & M3 inductors with 4 turns are shown. Microstrip lines and coplanar waveguides are also fabricated, whose schematic cross section is shown in Fig. 4. The lengths of transmission lines are all 1 mm. The signal line widths are 12 μm, and the spaces between signal and ground in coplanar waveguide are 18 μm. The ground of the microstrip line is metal 2

## Results and Discussion

The frequency dependent S-parameters of inductors and transmission lines are measured by Wiltron 360B vector network analyzer and Cascade on-wafer probe upto 10 GHz. The parasitics are deembedded using dummy patterns. Fig. 5 shows the deembedded S-parameters of the 6-turn inductor. The equivalent circuit of the inductor is represented in Fig. 6 [2], whose extracted parameter values are shown in Table 1. The parameters are extracted and simulated by EEsof Libra .

The measured resonant frequency, insertion loss, and Q factor of inductors are compared in Fig. 7, Fig. 8, Fig 9, respectively. As shown in Fig. 7, the resonant frequency of 10 nH inductor is 6 GHz, and can be used upto 3-4 GHz. Note that in this frequency range, 10 nH is large enough to be used as RF choke. Insertion loss of a two-port element can be represented by S parameters as following,

$$I.L = \frac{|S_{21}|^2}{1-|S_{11}|^2} \quad (1)$$

In Fig. 8, the insertion losses of inductors at 3 GHz are presented which shows that the insertion losses of M3 inductors upto 10 nH are comparable to those on the semi-insulating GaAs substrate at 3 GHz. As shown in Fig. 9, the Q factors of our inductors are very similar to those on the semi-insulating GaAs substrate.

As shown in figures 7-9, the perfomances of our inductors are very comparable to those on the semi-insulating GaAs substrate. Figures 7-9 shows that we can use 10 nH inductor upto 3 GHz. Not only its inductance value is large enough for RF choke but also Q factor is high enough to be used for matching element. The insertion losses of our transmission lines are shown in Fig. 10. The measured insertion loss of the coplanar waveguide is 0.2 dB at 4 GHz, which is low enough for all practical MMIC application.

## Conclusion

In summary, planar monolithic inductors with high resonant frequency, high Q factor, and low insertion loss, and low loss transmission lines are fabricated by adding thick polyimide/Al metalization system on the conventional standard BiCMOS process. The high Q inductance as large as 10 nH is obtained, which is large enough for RF choke and matching element. The loss of transmission line with 1mm length is also very small as 0.2 dB at 4GHz. All of these results indicate that the proposed technology can push silicon MMIC technology at least upto 10 GHz.

## References


[1] Hee K. Park et al., "High-speed polysilicon, emitter-base bipolar transistor", *IEEE Electron Device Letter*, vol. EDL-7, no. 12, pp. 658-660, 1986.

[2] Nhat M. Nguyen and Robert G. Meyer, "Si IC-compatible inductors and LC passive filters", *IEEE J. Solid-State Circuits*, vol. 25, no. 4, pp 1028-1031, 1990.

[3] J. Y. -C. Chang, Asad A. Abidi, Michael Gaitan, "Large suspended inductors on silicon and their use in a 2-μm CMOS RF amplifier", *IEEE Electron Device Letter*, vol. 14, no. 5, pp 246-248, 1993.

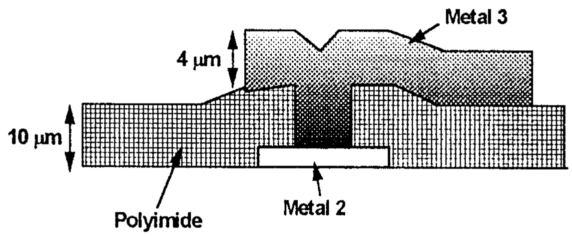



Fig. 1 Schematic cross section of the proposed metal 3 process

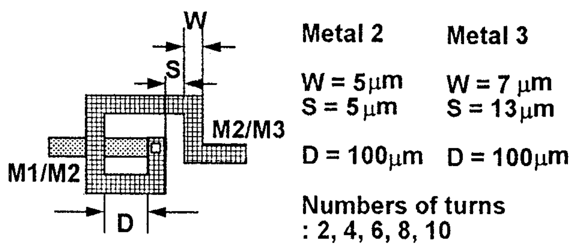
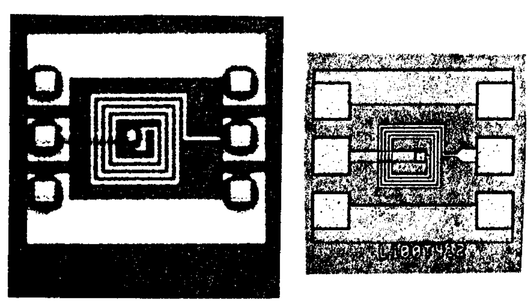



Fig. 2 The structure of the spiral inductors



(a) (b)

Fig. 3 Microphotograph of the fabricated inductors:

(a) metal 3 inductor (b) metal 2 inductor

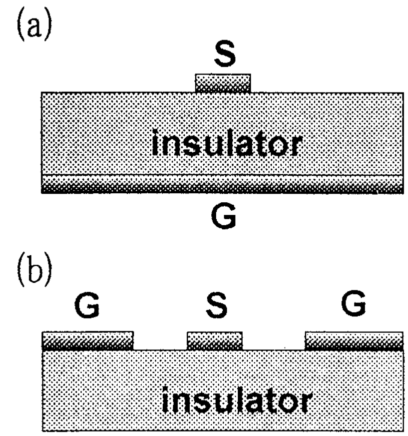



Fig. 4 The schematic cross section of transmission lines

(a) microstrip line and (b) coplanar waveguide

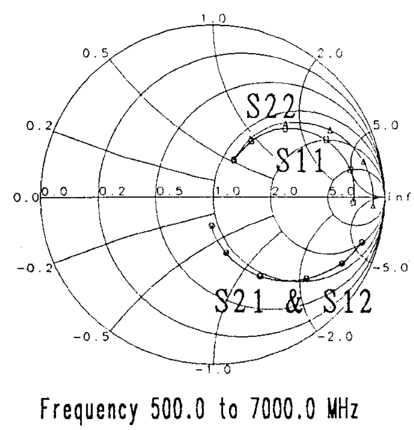



Fig. 5 Deembedded S-parameters of 6-turn inductor

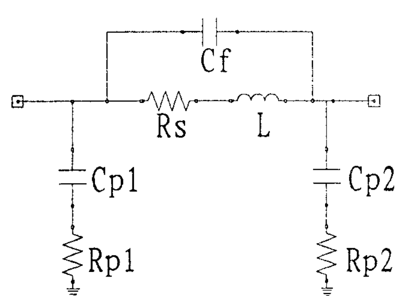



Fig. 6 Equivalent circuit of the monolithic inductor on Si-substrate

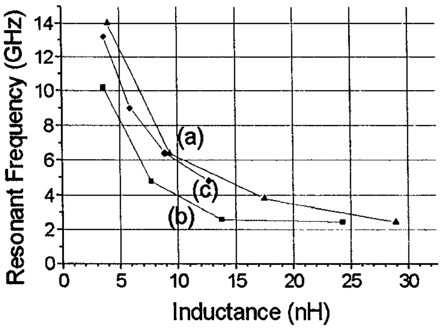



Fig. 7 Resonant frequency : (a) metal 3 inductor (b) metal 2 inductor (c) 3 μm thick Au inductor on semi-insulating GaAs substrate. The data for (c) is from GEC Marconi's GaAs MMIC data sheet.

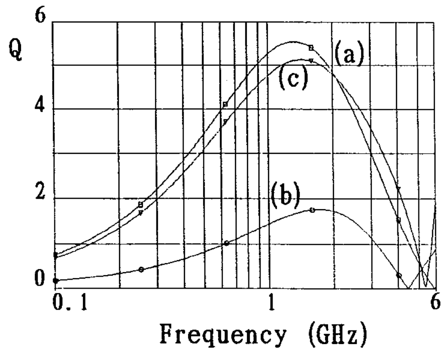



Fig. 9 Q factor of inductors. (a) 9.3 nH metal 3 inductor (b) 8.3 nH metal 2 inductor (c) 8.9 nH Au inductor on semi-insulating GaAs substrate. The data for (c) is from GEC Marconi's GaAs MMIC data sheet.

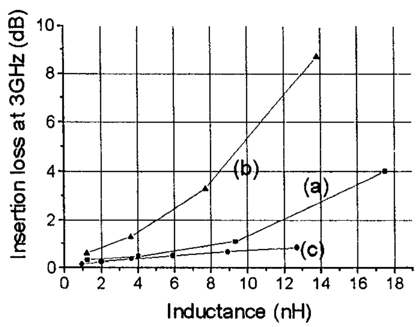



Fig. 8 Insertion loss at 3 GHz : (a) metal 3 inductor (b) metal 2 inductor (c) 3 μm thick Au inductor on semi- insulating GaAs substrate.The data for (c) is from GEC Marconi's GaAs MMIC data sheet.

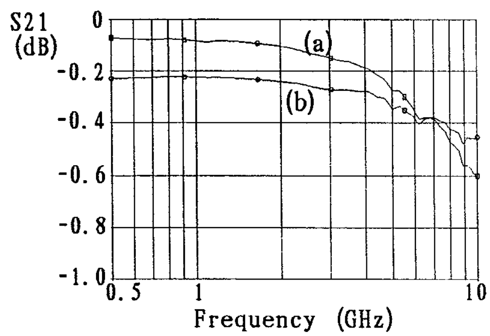



Fig. 10 S21 of transmission lines : (a) coplanar waveguide (b) microstrip line

Table 1. Equivalent circuit parameters of metal 3 inductor. The equivalent circuit is shown in Fig. 6.

| # of turns | L (nH) | Rs (Ω) | Cp1 (pF) | Cp2 (pF) | Cf (fF) | Rp1 (Ω) | Rp2 (Ω) |
|---|---|---|---|---|---|---|---|
| 2 | 1.23 | 3.66 | 0.039 | 0.013 | 0 | 187 | 13.5 |
| 4 | 4.03 | 4.54 | 0.057 | 0.029 | 9.2 | 247 | 156 |
| 6 | 9.33 | 7.34 | 0.084 | 0.067 | 12 | 172 | 74 |
| 8 | 17.50 | 13.0 | 0.14 | 0.11 | 16.2 | 165 | 92 |
| 10 | 28.85 | 21.0 | 0.22 | 0.15 | 13 | 173 | 77 |