國 立 交 通 大 學
電子工程學系電子研究所

碩 士 論 文

在 20 GHz 以上射頻 IC 應用上與 CMOS 製程相容的介電支撐物質製程開發與研究

A CMOS Compatible Patterned Dielectric Support Process for Beyond 20GHz Silicon RFIC Applications

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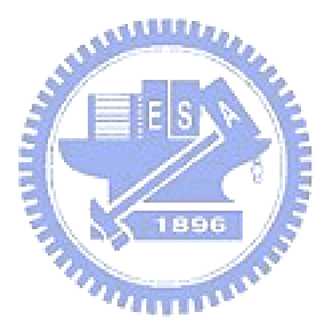
摘　　要

在現今的通訊晶片發展過程裡，SOP 技術已經有相當程度的發展；然而當我們把被動微波元件實現在低阻值的矽晶圓上時，矽基底所造成的能量損失已經讓此被動元件無法得到可應用的效果，也因此，各方都在找一個既便宜又有效果的解決辦法來改進此種現象帶來的缺失；而在徹底了解形成此基底效應的機制以及發展至今各方學界所發表的解決辦法之後，到目前為止，並沒有一個真正有個可以兼顧機械以及電性的方法來改善；因此，我們發展了一套利用一般常見的介電物質(二氧化矽、氮化矽)以及柵狀結構來有效的減少基底效應，而建築在此構造上的微波元件也都能達到我們想要的結果。此外，在本篇論文裡，我們更利用了介電物質的特性來達到可以減少一道製程，這也大大的減少此種製程的便利性；而表現出來的高頻特性（１～４０　GHｚ）更可以與一般印電路板相同的達到幾乎沒有能量的損失；在製程方面，利用了微機電製程中的感應耦合電漿蝕刻機（ＩＣＰ　ＤＲＩＥ）、高溫爐管以及低壓化學沉積系統ＬＰＣＶＤ來得到支撐

的介電柱狀結構，由以上可知，製程上更有與ＣＭＯＳ製程有相容性的優點，因此利用這個製程可以在 SOP 的應用上達到理想的效果。



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Abstract

A powerful reducing substrate loss method, trenched oxide-nitride islands, was demonstrated using CMOS-compatible fabrication process. The CPW on trenched oxide-nitride islands can achieve insertion loss as low as 0.045dB/150um at 40 GHz on low resistivity silicon substrate if we can solve the roughness problem. The simulated result of inductor comparison between on our design structure and conventional Si predict the improvement of inductor performance. Another advantage of trenched oxide-nitride islands is that can possess strong mechanical support and better reliability than the suspended structure

Index terms —RF MEMS, eddy current, coplanar waveguides, Bosch process, trenched dielectric islands

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首先，我想要感謝在交大電子所認識的每一個人；我的指導教授鄭裕庭老師，不管是您的思考路線或者是您帶學生方式，都帶給我無限的啓發以及成長；教授我ＡＩＣ的吳介崇教授，您讓我更深入的了解到電子電路神奇之處；實驗室的趙子元學長，這兩年來幾乎都靠你來解決我們研究上的問題；ＲＦＩＣ實驗室的傅昶綜學長，您在ＭＴＫ報告中對問題的看法讓我大開眼界；實驗室的阿拉拉建章學長，你對理論的熱忱就跟你的阿拉拉一樣滔滔不絕，讓我甘拜下風；畢業的光哥、瑋哥、川哥，沒有你們的努力我們沒有那麼多資源可以使用；躲桌子的達叔，福爾摩沙代言人的凱哥，謝謝您們在畢業後還如此關心我的研究；實驗室的榮譽博士生小筑，謝謝妳在必須周旋在眾男人的閒暇之餘，能夠聽我大吐苦水；同屆的特助chando，即使你在我最低潮的時候依然不改嘴賤的本事，但卻也讓我成長了許多；球速破百的火球男小Ｂ，你讓我漸漸懂得要如何觀賞設計的品味；龜縮的昱文，你那變化莫測的睡覺姿勢以及高腰褲可說是讓我大開眼界了；以及實驗室各個學弟妹們，你們對我的鼓勵我都很感激，實驗室接下來就靠你們了；陶藝社的宗凰、健誠等各位朋友，謝謝你們讓我在枯燥的研究生活中還能殘留一點大學生涯的元素；以及大學山服社的好朋友們，跟你們在一起的時光讓我可以隨時的補充能量，尤其是在這我人生最低潮的一年半中，能夠忍受我近乎白痴又無法控制的個人行爲並且陪著我一步步走出低潮；每一位在交大所認識的人，都讓我點滴在心頭，謝謝你們充實了我這兩年的生活。

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Chapter 1 Introduction

Inevitable substrate loss mechanism is one of major factors hinder silicon based RFIC technology for high frequency wireless communication applications. Poor passive components on Si-RFIC due to the substrate loss like low Q inductor, filter, and high loss TML (Transmission Line) could result in a circuit performance with smaller dynamic range, higher noise figure, and larger power consumption which would make the circuit hard to be applied for high speed data communication. Besides, the loss phenomenon will become more severe with the increase of operational frequency of the circuit. Therefore, a lot of research efforts have been put for eliminating the substrate loss mechanism. For examples, proton implanted silicon substrate can have higher resistivity than conventional Si substrate which makes the on-chip passives perform well and consistently up to 40 GHz [1], The silicon substrate with patterned ground shields can effectively enhance the Q performance of on-chip spiral inductor up to 10 GHz [2], and the others like silicon trenched islands, nitride blocks [4], pn junctions isolation [5], and suspended membrane support… etc., can all provide nice approaches for high performance passive fabrication. Nevertheless, while the frequency rises up to 40 GHz or even higher, only the membrane support with substrate removal and proton implanting methods are effective to eliminate the loss issue.

Among the above approaches, removing the substrate under the microwave

device directly is the most popular and well-developed technology using contemporary micromaching process. Since the substrate under the device is removed, as suspended structure or membrane structure, the resistivity of "substrate" (air) raises so high that it is very difficult to generate the eddy current due to the variation of magnetic flux. The less the eddy current, the less energy dissipated from substrate. On the other hand, the parasitic capacitor between the upper transmission line and substrate also decreases a lot. J. Y.-C. Chang etc. published the high Q large suspended inductor encased in oxide on a membrane over the substrate with the removal of underlying silicon in 1993[7], although it is for 2um CMOS RF amplifier. It has been proved that the quality factor and self-resonace can be improved when substrate removed. In 1998, Pieere Blondy published the high performance filter with removing the dielectric material up to a thin membrane that suspends the planar filters. [6]. he used the membrane made of ONO (oxide-nitride-oxide) structure, etching underlying silicon substrate, and two metalized cavities as upper and lower shielding. The combination of bulk micromaching by removal of the substrate and self packaging reduces the radiation loss both into air and substrate and also greatly reduces ohmic loss by allowing for very wide microstrip lines. The filters he designed consist of a 3.5%bandwidth two-pole Chebyshev filter with transmission zeros at 37 GHz, 2.7% and 4.3% bandwidth four- and five-pole Chebyshev filters at 60 GHz, and an 8% bandwidth elliptic filter at 60 GHz.

To date, many applications of suspended structure are post, tabled in table 1, for example, Hongrui Jiang etc. published the inductor suspended over the deep copper-lined cavities over 30-um deep.[8] They built a suspended inductor over a cavity whose bottom plane and sidewalls are metallized with copper. The deep cavity reduces the electromagnetic coupling and parasitic capacitance between the inductor and substrate that can increase quality factor and self-resonace. And the Cu-lined provide electromagnetic shielding. The quality factor of the inductor is over 30 and self-resonace frequency is 10 GHz. Moreover Jun-Bo Yoon etc. published a highly suspended spiral inductor in 2002[9]. The inductor was lifted 50um in height without any membrane and only suspended by two signal posts of 20 um in diameter without any additional mechanically supporting posts in order to minimize the substrate coupling. And the quality factor of the highly lift inductor is up to 70 at 6 GHz and it's self-resonace frequency is over 20 GHz.

Although the above suspended structures are so sensitive to the vibration of environment, it is not suitable for the portable communication technology due to lack of electrical and mechanical reliabilities. So, in 2005, Mina Raieszadeh published the trenched silicon island structure [3], which the inductor is supported by trenched silicon islands and the Q of the inductor is about 51 at 1 GHz It solved the vibration issue of suspended device. But the microwave device on this structure will suffer from the increasing substrate loss when the

frequency is higher frequency. It is because there is still silicon substrate contacted the device, that parasitic capacitor makes the operation frequency down.

In this paper, we will use the oxide-nitride islands patterned substrate and electroplate the Cu CPW on the patterned substrate. With oxide-nitride islands patterned substrate, we not only reduce the substrate loss due to it's isolation property but also electroplate the Cu CPW on the islands directly due to the small space of the gaps between neighbor islands. Better transmission line performance (1 GHz to 50 GHz) on oxide-nitride islands patterned substrate than those on silicon substrate are evidenced.

	Design	Author	Advantage	Weak-point
	Membrane with metallized shielding	Pierre Blondy	High performance up to 60 GHz	Weak to vibration and process complicated
	Photon implanted substrate	Albert Chin	High performance up to 40 GHz	cost
	Patterned ground shielding	C. Patrick Yue	High Q inductor at 1~10 GHz	Operation frequency lower
	SiRN/SiRN -Si block	M Elwensp-oek	Very thick dielectric layer	Operation frequency lower
	Pn junction isolation	Min Hao	Improve Qs of inductor 19%	Operation frequency lower
	Trenched silicon island	Farrokh Ayazi	High Q inductor at 1~10 GHz	Operation frequency lower
	Edge-suspended CPW	Lydia L. W. Leung	High performane CPW at 1~ 40G	Complicated applied for passive component

Table1- comparison of several methods for reducing substrate loss

Chapter 2 Concept Design

At microwave frequency, the variation speed of magnetic flux is so fast that induced eddy current in the silicon substrate with opposite direction to signal flow will convert magnetic energy into heat, so called substrate loss. Equation 1 and 2 show the element of induced current in substrate at the presence of electromagnetic fields [10]

$$\nabla \times H = j\omega\varepsilon' E + \omega\varepsilon'' E \tan\delta + \sigma E \quad [1]$$

$$\nabla \times E = -j\omega\mu H \, , J = \sigma E \quad [2]$$

Where σ and tanδ represent the substrate conductivity and loss tangent,ε'andε"are the real and imaginary part of the substrate permittivity, ω is the angular frequency, and μ is the permeability. For CMOS-grade silicon, the σE term which represent the electrically-induced current dominates over the terms ωε'Etanδ which represent the dipole loss.

Thus, we will effective reduce the substrate effective permittivity and conductivity by oxide-nitride island. Because slicing the substrate with deep high-aspect-ratio trenches, the path of induced current is disrupted that reduces the substrate effective permittivity and conductive which in turn reduces the electrically and magnetically-induced current as well as the dipoles. For higher frequency application, we further make the dielectric island to reduce the substrate loss.

At DC and low frequency, the current is uniformly distributed. When

frequency raises higher and higher, skin effect becomes significant, so that AC current is pushed towards the edges of signal line. Figure 1. shows the current distribution simulation of conventional CPW at 10 GHz with HFSS. Most of current is concentrated along the two edge of signal line. But if for other microwave device, for example inductor or filter, we could not replace dielectric material only for the substrate under the edge of signal line. Figure 2 shows the layout of trenched oxide-nitride islands design .With this structure, we can exactly reduce the substrate loss for any microwave device on the silicon.

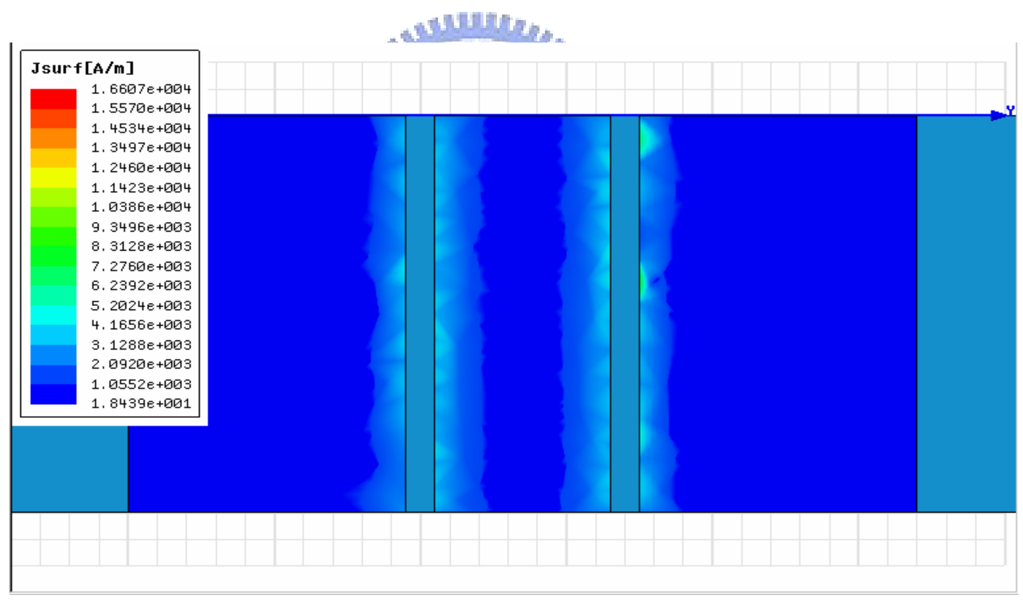

Figure1.simulated current distribution

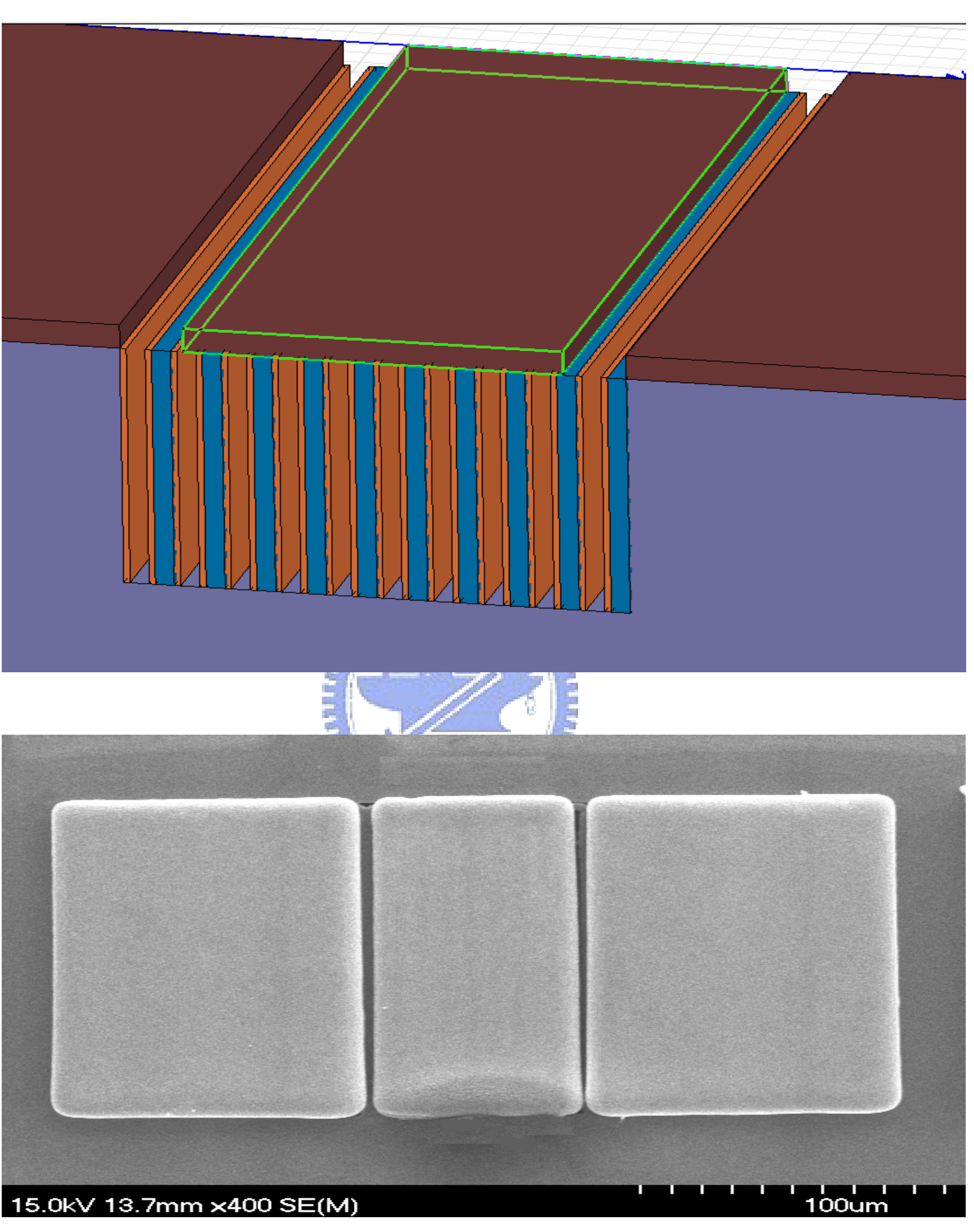

Figure 2 - (a) layout of trenched oxide-nitride islands (b) the SEM picture

Chapter 3 Fabrication

Figure3 shows the fabrication process flow for the CPW on the trenched oxide-nitride islands. First, deep high-aspect-ratio (10:1) trenches are etched by ICP DRIE,so called Bosch process. Then 1.3um thick thermal oxide is grown at 1100°C and using RIE to etch the upper horizontal oxide layer. At present, we can get the trenched silicon-oxide islands. After patterned the etching hole, we use ICP-DRIE to etch the resident silicon of silicon-oxide islands. Then deposit the silicon nitride by using LPCVD (Low pressure chemical vapor deposition). Because of the high covering property of LPCVD, we can get the oxide coated with nitride, oxide-nitride islands shown as figure 4. After using e-gun to deposit seed layer, we can electroplate CPW directly because nitride is hydrophobic shown as figure 5.

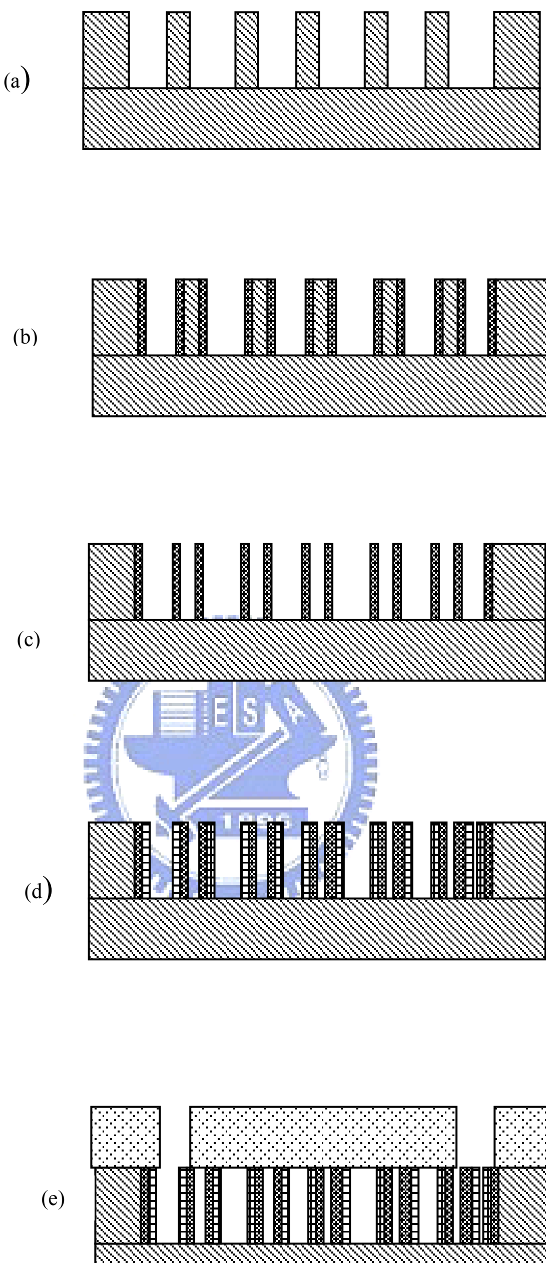

Figure 3. (a)Deep trench etching by Bosch process. (b)thermal oxide grown. (c)ICP etching resident silicon. (d) LPCVD deposit nitride. (e)electroplate CPW

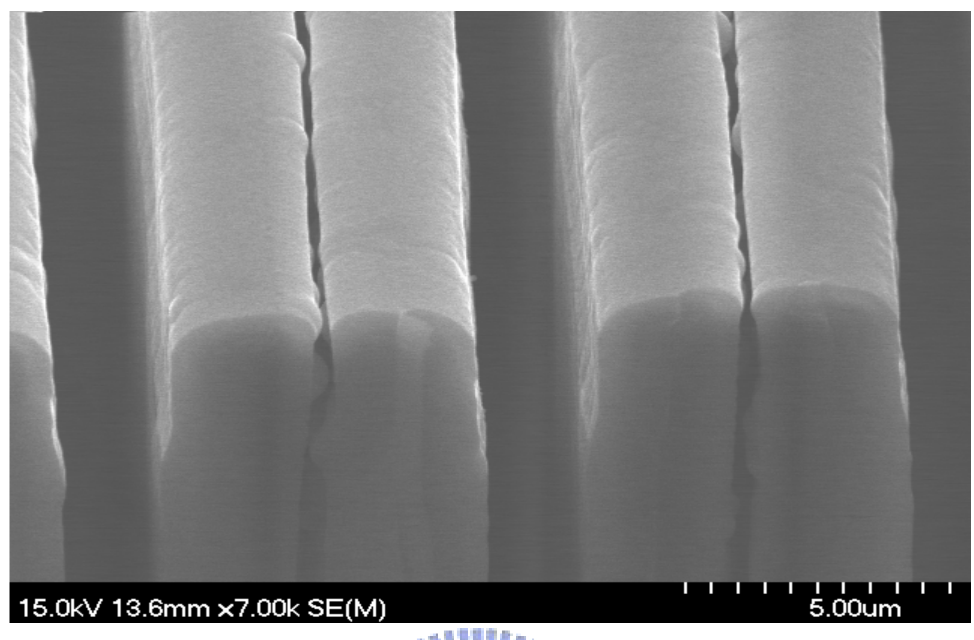

Figure.4 The SEM picture of oxide-nitride islands

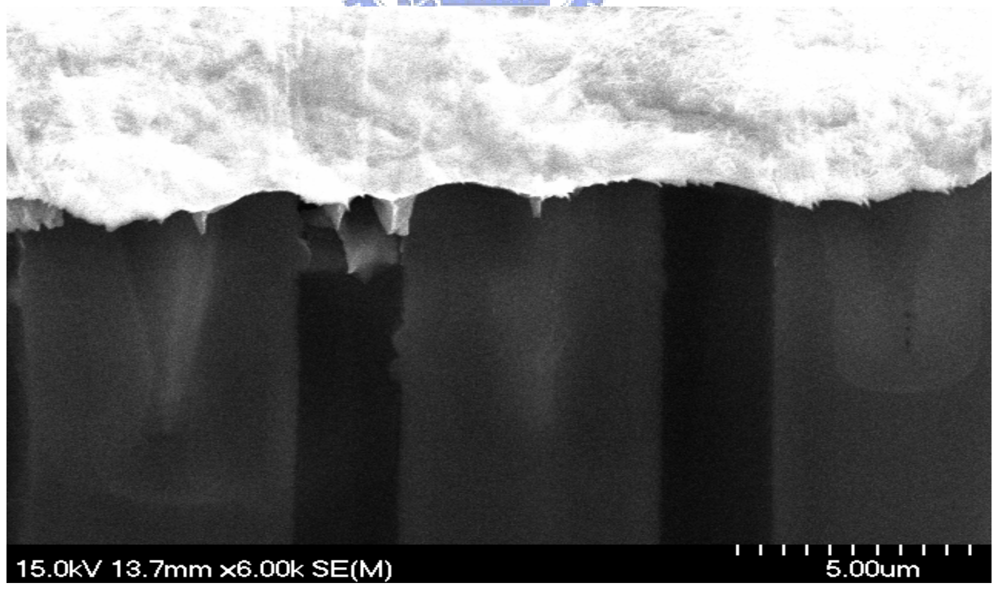

Figure.5 copper electroplated on islands directly

Chapter 4 Discussions

1. Electroplate copper without membrane

Because of the hydrophobic property of silicon nitride, we consider that by this property with designation we will make the electroplating solution separated from the trench due to the surface tension force.

In order to confirm that the tension force of water on nitride is enough to make water not flowing into trench, we measure the contact angles of DI water on the patterned silicon-nitride islands as shown table-2

		Contact angle	Height (mm)	Sessile volume (uL)
Silicon island	5-5	84.9	1.1899	4.9927
	5-4	84.5	1.2045	5.3562
	5-3	88.07	1.219	4.432
	5-2	91.65	1.277	5.014
	4-3	91.04	1.3205	5.2238
Nitride island	5-5	79.97	1.1319	5.1368
	5-4	81.49	1.1899	5.5119
	5-3	80.80	1.1319	4.947
	5-2	81.10	1.1754	5.1165
	4-3	80.13	1.2045	5.6933

Table-2 the contact angle of DI water on islands

2. **rooting phenomenon**

Although nitride is hydrophobic, the seed layer e-gun deposited before electroplating is hydrophilic. Thus, there is some copper electroplated on the sidewall of the trenched oxide-nitride islands. On the other hand, the copper is electroplated into the trenches, that makes the CPW like rooting. Figure 6.shows this rooting phenomenon clearly. Undoubtedly, this rooting part will influence the performance of main upon CPW. There are some un-anticipated parasitic effects between the rooting copper areas, and the uncontrolled characteristic impedance will make microwave devices designation difficult. Thus, we will solve this problem by controlling the lithography time. As figure 7 shows, the top of islands deposited seed layer does reflecting more UV, that makes the photoresist(AZ 4620) upon the islands effectively exposed twice as the photoresist upon the tenches only exposed once. So, we can control the exposed time to make the photoresist upon the islands hyper-exposed and that upon the trenches hypo-exposed, and can prevent the sidewall electroplated with copper. Figure 8 shows the improvement of rooting phenomenon. Obviously the rooting areas decrease, and the surface of CPW upon the structure is more smooth that make the performance of CPW better.

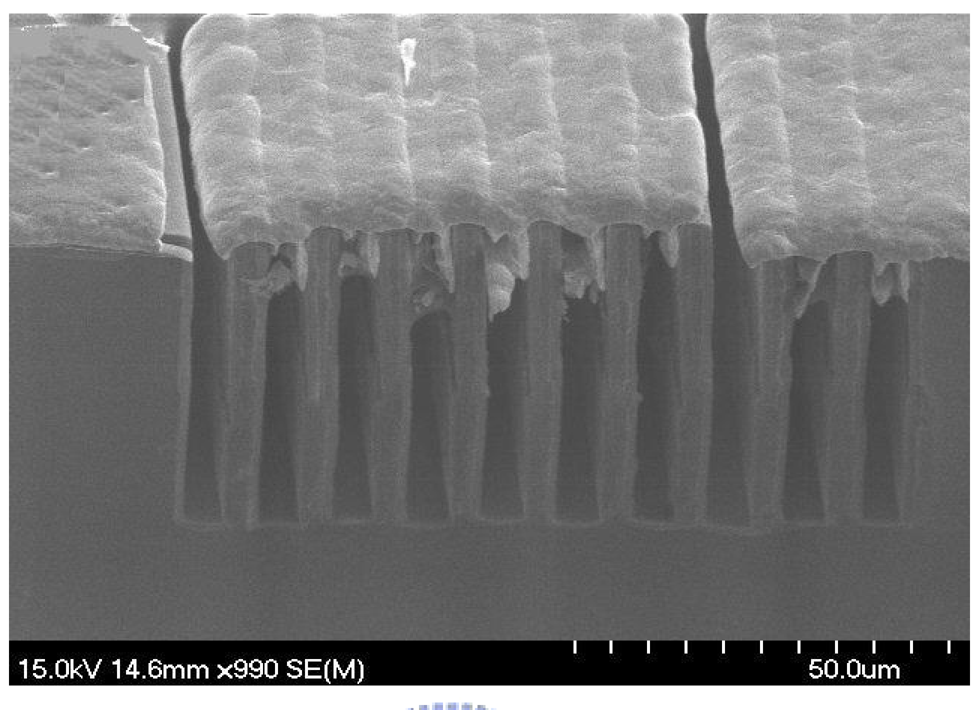

Figure.6 SEM picture of rooting phenomenon without controlling

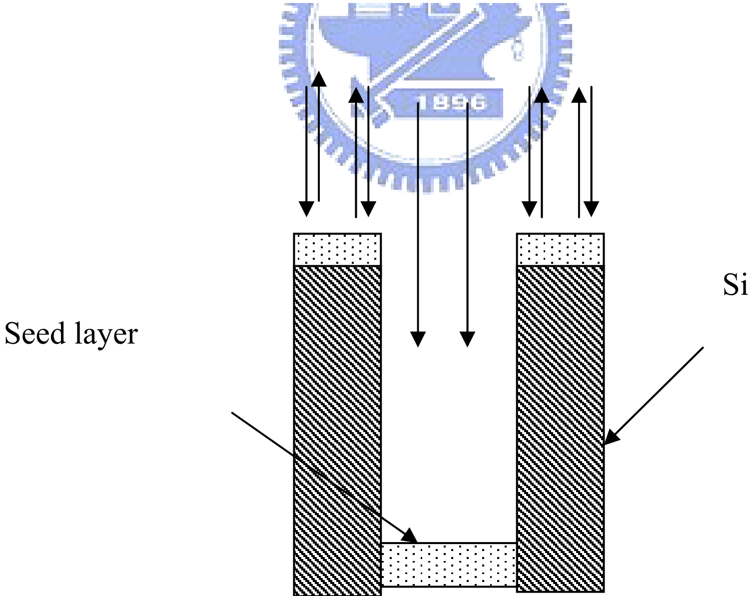

Figure 7. The lithography diagram of trenched island deposited seed layer

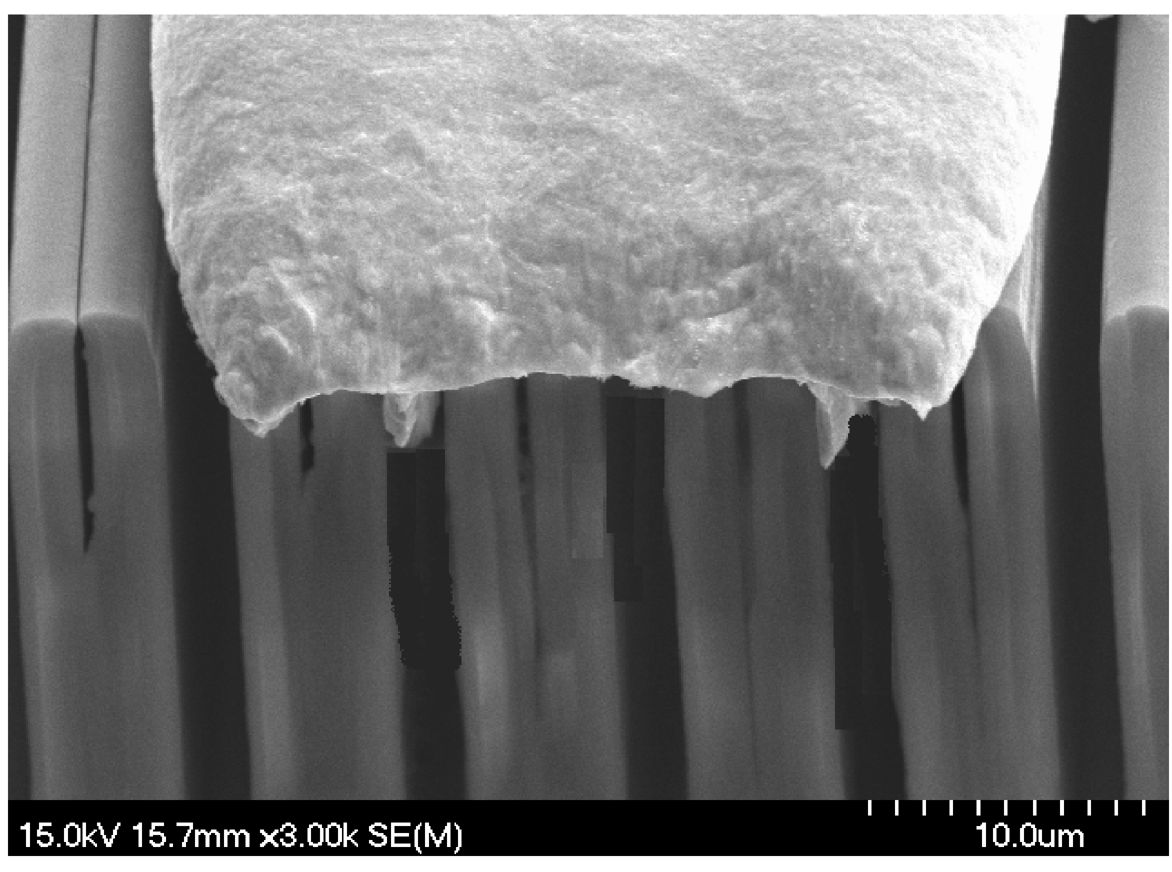

Figure 8. the SEM picture of rooting phenomenon with controlling exposed time

Chapter 5 Measurement and Simulation

Simulated and measurement results of 150um CPW are shown as figure9. As we predicted previously, at 40 GHz the insertion loss of CPW is so small (S21~0dB) and the return loss is also very tiny from 1 GHz to 40 GHz. Noted that, the measurement result differs from simulation result, S11 is higher and S21 is lower slightly. It's because the degree of roughness of CPW is not uniform and there are some inversion rooting areas under the CPW. The comparison of the loss of CPW on oxide-nitride islands and that on conventional Si substrate is shown as figure 10. We can see the huge improvement of S21, that is due to the substrate loss reduced effectively.

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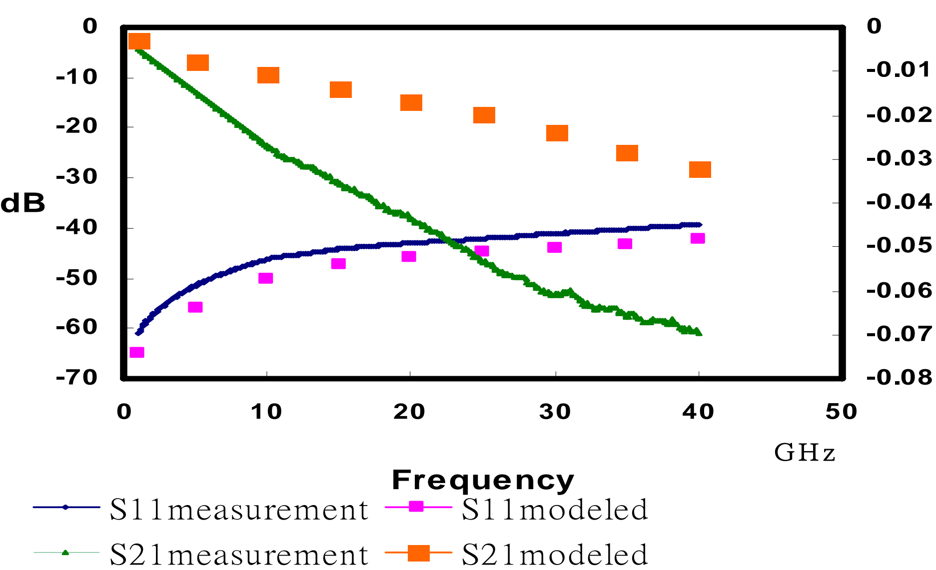

Figure 9 the measurement and simulation result of 150um CPW on the trenched oxide=nitride islands

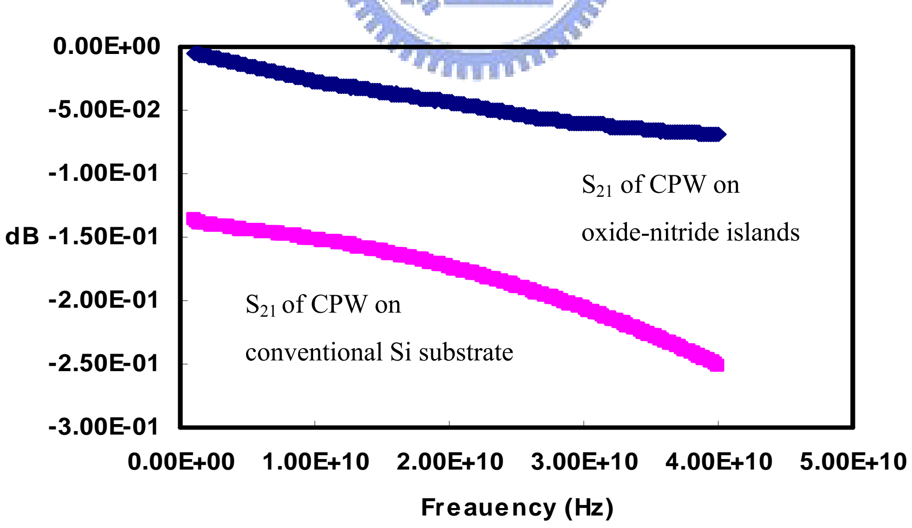

Figure 10 The S_{21}comparison between the CPWs on different substrates

In additional, we simulate a microwave device, inductor, on the trenched oxide- nitride islands to predict the effect of the inductor on trenched oxide-nitride islands. As figure11 shows, when the substrate replaced by trenched oxide-nitride islands the quality factor and self-resonance frequency of the inductor are improved. This is obviously because the parasitic conductance between the copper and substrate reduces with the reducing contact areas.

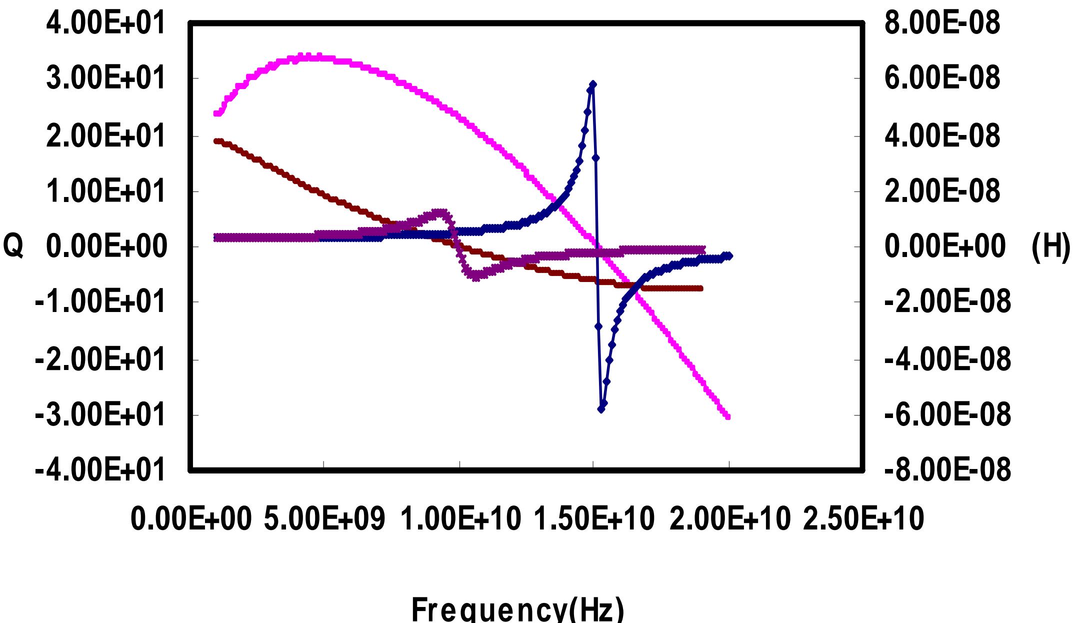

Figure11. the simulated comparison of the inductors between that on conventional Si substrate and on trenched oxide nitride islands

Chapter 6 Conclusion and Future Work

6.1 Conclusion

A powerful reducing substrate loss method, trenched oxide-nitride islands, was demonstrated using CMOS-compatible fabrication process. The CPW on trenched oxide-nitride islands can achieve insertion loss as low as 0.045dB/150um at 40 GHz on low resistivity silicon substrate if we can solve the roughness problem. With PECVD, we can deposit an oxide layer to solve the non-smooth problem. Thus the trenched oxide-nitride islands can provide even smaller insertion loss,0.045dB/150um.Another advantage of trenched oxide-nitride islands is that can possess strong mechanical support and better reliability than the suspended structure.

6.2 Future Work

Because the substrate under CPW is not simple as silicon , the filter design will be improve to make the performance of filter better and better as shown in figure 12.

We can utilize the design of trench pattern to make the Z0 of upper CPW designed , so that can use stepped-impedance method to design filter.

We can utilize this process to improve the Q of spiral inductor on Si .

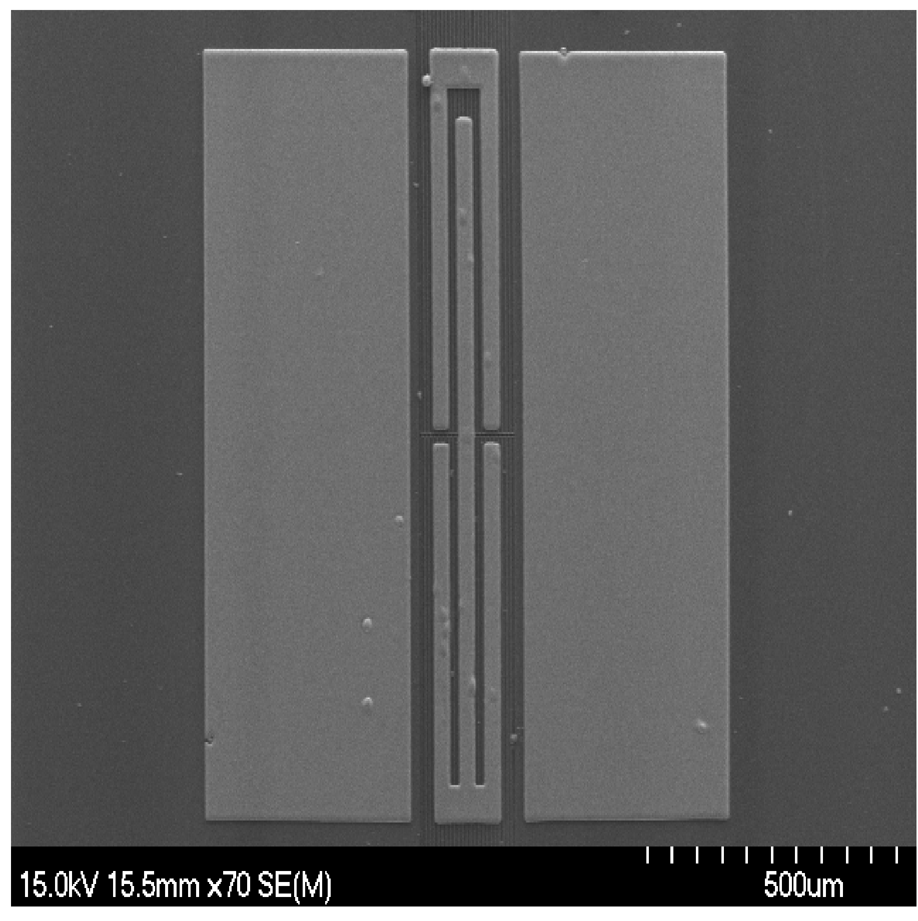

Figure 12. the filter on the oxide-nitride islands

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