Ultra-Thin Artificial Magnetic Conductor for Gain-Enhancement of Antenna-on-Chip

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Abstract—System-on-Chip (SoC) has become an attractive solution to achieve highly integrated wireless systems. However, the Antenna-on-Chip (AoC) suffers from poor radiation due to the lossy silicon substrate in standard CMOS processes. Artificial Magnetic Conductors (AMC) with the ground plane above the silicon can enhance the radiation, however, fitting the AMC completely in the thin stack-up ($\sim 10\text{-}15\ \mu\text{m}$) is extremely challenging, particularly for frequencies below 100 GHz. In this paper, Metallic Posts (MP) and Embedded Guiding Structures (EGS) have been investigated to reduce the AMC thickness by employing the available vias and metal layers in the stack-up. An in-house CMOS-compatible process has been used to realize the AoC, where typical low-conductivity adhesion layers have been avoided to reduce the undesired losses by using the surface roughness in a unique fashion. With MP and EGS approaches, AMC thickness can be reduced by 33% and 41% respectively. The AMC with EGS fits within an oxide of a thickness of $16\ \mu\text{m}$. A monopole antenna, backed by this AMC, demonstrates a gain of 5.85 dBi and radiation efficiency of 57% at 94 GHz, bettering the gain and radiation efficiency by 9.15 dB and 42% respectively as compared to the case without AMC.

Index Terms— Artificial magnetic conductor, embedded guiding structure, gain enhancement, metallic posts, on-chip antenna, system-on-chip.

I. INTRODUCTION

WIRELESS System-on-Chip (SoC), where all functional modules are integrated on a single chip, has attracted considerable research interest with the advantages of high-level integration, low power consumption, and low cost [1-4]. Typically, antenna is the largest part of a wireless system, and previously it was not feasible to integrate it on a chip. However, due to the push towards millimeter-wave spectrum, antenna sizes have dropped to the order of millimeters and thus become compatible with the typical chip dimensions [4-6]. On the other hand, silicon (Si) based semiconductor technologies, such as a Complementary Metal Oxide Semiconductor (CMOS) process, have come a long way and thus high-frequency circuits and antennas can be realized on a single chip in a compact fashion [7].

Though, the size of the mm-wave Antenna-on-Chip (AoC)

has become compatible with the typical CMOS chip dimensions, however, the CMOS stack-up is still not favorable for AoC implementation. This is mainly because of the very conductive Si substrate that also has a very high permittivity. Further, the embedded metal layers in a very thin silicon dioxide (SiO_2) ($\sim 10\text{-}15\ \mu\text{m}$), as shown in Fig. 1, are not very suitable for AoC implementation, particularly for lower GHz frequencies. Around six to nine metal layers are available in the SiO_2 with interconnected-vias in a typical CMOS stack-up. The high relative permittivity of Si ($\epsilon_r=11.9$) attracts most of the antenna fields towards the substrate instead of being radiated in the air [8, 9]. Further, the low resistivity ($\sim 10\ \Omega\text{-cm}$) of Si causes the loss of power in the Si substrate as heat. The poor radiation performance of the AoC is due to both, the high permittivity and conductivity. Besides, the Si substrate thickness ($300\text{-}700\ \mu\text{m}$) is also electrically large (particularly for mm-wave frequencies). Resultantly, surface wave modes get excited, which leads to the distortion of the radiation pattern [10, 11].

In order to improve the AoC radiation performance, two approaches have been reported extensively in the literature [8, 12-30]. First, it involves incorporating off-chip microwave lenses or superstrates. For instance, in [8], the gain of a 77 GHz on-chip dipole antenna has been boosted by 10 dB through the hemispherical lens. In [18], a high-contrast superstrate (PREFERM FLX 1100) has been placed above the AoC, which leads to a boresight gain improvement by 4.5 dB. In the second approach, either the lossy Si substrate is removed underneath the AoC or its properties are modified. For example, in [21], the Si beneath the AoC has been etched through micromachining and a gain of 4 dBi is achieved at 85 GHz. Similarly, in [28], the Si resistivity has been selectively enhanced by Helium-3 ion irradiation, resulting in an improvement in radiation efficiency by 43%. However, these methods are incompatible with CMOS processes and require complex post-fabrication steps, which not only increases the overall cost, but also adds alignment uncertainty and mechanical stability issues.

Alternatively, the Artificial Magnetic Conductors (AMC) can be employed to isolate the substrate and provide constructive reflection for the gain enhancement of AoC. Conventional implementation of AMC is to place the ground plane underneath the silicon substrate because of the thickness limitation of the SiO_2 , as shown in Fig. 2(a). Such a design was illustrated in [18], where the gain of the 71 GHz on-chip monopole was boosted by 4.1 dB. Nevertheless, in this situation, the AoC cannot be shielded completely from the

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Fig. 1. Typical CMOS stack-up.

silicon substrate, and the undesired crosstalk between circuits and antennas still exists [11]. A better solution is to fully isolate the lossy Si substrate by realizing the AMC ground plane above the Si, as shown in Fig. 2(b). However, this is dependent on the available SiO₂ thickness, which is typically limited to 10-15 μm and thus not suitable for the AMC realization as mentioned above. M. Nafe demonstrated an on-chip AMC with the ground plane above the silicon substrate, and the improvement of 8.4 dB in gain was achieved, however this was done at the expense of a thicker SiO₂ layer of 40 μm [31]. Nonetheless, contrary to other gain enhancement techniques, on-chip AMC can keep the system compact and provide an inexpensive solution due to its compatibility with the CMOS processes. The only bottleneck is that it is difficult to fit the AMC in the conventional thin SiO₂ layer.

Another issue that affects the efficiency of AoC is the presence of thin adhesion layers (10 nm titanium or chromium) that are employed to provide good adhesion to the main metal layers (copper or gold). The surface resistance of these adhesion layers is large because of the skin effect, and thus AoC suffers from undesired ohmic losses [32].

These two issues related to AoC, i.e., fitting the AMC in conventional SiO₂ thickness to isolate lossy Si substrate completely, and avoiding the ohmic loss due to the adhesion layers, are tackled in this paper. An attempt to introduce Metallic Posts (MP) by employing the vias in the stack-up, thereby reducing the AMC thickness, has been carried out in [33], while the sufficient insight into its working principle and comprehensive parametric analysis is presented in this paper. The MP behave as slow-wave structures, which affect the phase velocity and consequently helps in AMC thickness reduction. Furthermore, another novel thickness reduction structure (TRS), working the available metal layers into Embedded Guiding Structures (EGS), has been proposed in this paper. The EGS modifies the path of electric fields inside the AMC, making the AMC look electrically thicker. In contrast, the EGS provides more thickness miniaturization as compared to the MP. Finally, a 16 μm ultra-thin AMC is realized with a gain improvement of 9.15 dB as compared to a standalone antenna. In the fabrication, adhesion layers have been completely omitted so ohmic losses due to them have been avoided without losing the required adhesion for the main metal layers. As per author's best knowledge, this is the first demonstration of EGS for AMC realization in an on-chip environment to boost AoC gain and efficiency. The measured AoC gain is one of the highest in the literature that has been achieved without off-chip components or post-fabrication processes.

Fig. 2. Implementation approaches of AMC: the ground plane is (a) below Si substrate, and (b) above Si substrate.

II. ON-CHIP MONOPOLE ANTENNA WITH REFERENCE AMC

On-chip antennas are mostly designed to be horizontally placed on the top metal layer of the stack-up. This is because the top metal layer allows larger metal thickness which is beneficial for antenna's performance and also this arrangement enables the antenna to radiate directly into the air. According to the image theory, radiation performance of a horizontally placed antenna could be enhanced by a Perfect Magnetic Conductor (PMC) surface that can produce an image current in the same direction [34]. Since PMC surfaces do not exist in nature, AMC surfaces are developed to mimic the effect of PMC for a certain frequency range. Conventional AMC comprises three layers: a periodic metallic layer, a dielectric slab and a ground plane. The square patch based AMC is one of the most commonly used structures which demonstrates a low return loss and wide operating bandwidth [35]. So, in this article, a square patch based AMC is selected for further investigation. Throughout this work, the FEM-based 3-D full-wave electromagnetic (EM) solver, ANSYS High Frequency Structure Simulator (HFSS), has been used for simulations.

To isolate the silicon substrate completely from the antenna, the ground plane of the AMC is located on the top of the silicon substrate. The SiO₂ layer has a dielectric constant of 4.0 and houses the periodic square patch metallic layer. The metal layers are modelled by copper with a conductivity of 5.8×10^7 S/m. Besides, considering a chip with acceptable dimensions, the reference AMC model is simulated as a 4×4 finite surface, as shown in Fig. 3. Except the AMC thickness t_{AMC} , the other geometrical parameters are fixed for further investigation. According to the simulated result, shown in Fig. 3(b), the reflection phase of the AMC crosses zero degrees at 94 GHz when the AMC thickness becomes 27 μm .

In order to study the reflection and isolation performance of the reference AMC, a planar monopole antenna is placed on top of the AMC, as shown in Fig. 4. To test it with a probe, the antenna is fed by a coplanar waveguide (CPW); while in a practical system, the antenna can get signals fed through the vias in the standard CMOS stack-up. The AoC dimensions are given in Table I. According to the simulated results shown in

Fig. 3. 4×4 finite patch-based reference AMC: (a) Top view, $d = 590$, $l_u = 600$, (b) reflection phase, and (c) side view, $t = 0.5$, $t_{AMC} = 27$, $t_s = 500$ (all in μm).

Fig. 4. Reference AMC-backed monopole antenna: (a) HFSS model, (b) top view, and (c) side view.

Fig. 5, it is well-matched at 94 GHz with a return loss of 18.8 dB. It demonstrates boresight radiation with a gain of 4.5 dB

TABLE I
DIMENSIONS OF THE ANTENNA BACKED BY DIFFERENT AMC (ALL IN μm)

	l_a	l_f	w_a	w_f	w_{gnd}	h_a	g
Ref. AMC	213	200	20	50	200	2.5	15
AMC + MP [33]	200	181	20	50	200	1.5	15
AMC + EGS	380	100	10	15	160	1.5	25

Fig. 5. Simulated results of the monopole antenna backed by reference AMC: (a) S_{11} , (b) Normalized radiation pattern in E-plane (xz -plane) and H-plane (yz -plane).

and radiation efficiency of 45% at 94 GHz due to the in-phase reflection provided by the reference AMC.

III. AMC THICKNESS REDUCTION

For the AMC to work properly at 94 GHz, a SiO_2 layer thickness of 27 μm is required, as has been determined through EM simulations in the previous section. This thickness requirement is too high for the stack-up of current CMOS processes. Therefore, thickness miniaturization techniques need to be introduced in the AMC design to reach an acceptable oxide thickness. In this section, two kinds of thickness reduction structures (TRS) are introduced and investigated for a single AMC unit cell as well as the 4×4 finite AMC-backed AoC.

A. Metallic Posts (MP)

For a conventional patch based AMC, the equivalent model comprises a capacitance C_o with a shunt inductance L_o , where C_o is the capacitance between adjacent patches, while L_o refers to the inductor due to the backside ground plane [36]. Inspired by slow-wave structures, the vias available in the oxide layer can be utilized to form MP, as shown in Fig. 6(a), thus additional series inductors L_{MP} and shunt capacitors C_{MP} can be introduced, where L_{MP} is related to its height, and C_{MP} is the capacitance between the patch and the MP top surface. The phase velocity v_p of the waves propagating between the patch and the ground plane is inversely correlated with the additional reactance as given in (1) [37]

$$v_p \propto \frac{1}{\sqrt{2L_{MP} \times 2C_{MP}}} \quad (1)$$

Through this additional reactance, the phase velocity is reduced, and equivalently the electrical thickness of the AMC is increased. Considering the ohmic losses proportional to the metal volume in each unit cell, the loss resistance would be quite large if too many vias are introduced. Therefore, in the unit cell design, two vias originate from the ground plane but they are not connected with the patch, forming MP. It is noted that the monopole antenna in Fig.4 has the radiating arm in the

Fig. 6. Patch-based AMC with MP (a) equivalent circuit, (b) two MPs are introduced in one AMC unit cell.

x -direction, resulting in the electric fields excited in the AMC mainly vary along the x -direction. Therefore, the two MP are placed along the x -direction symmetrically, with a distance of g_p from the near side unit edge, as shown in Fig. 6(b).

A comprehensive study investigating the effect of the geometrical parameters of the metallic posts on the AMC resonance frequency f_{AMC} is conducted to achieve the best results. Typically, the via size l_p is often a fixed value but the degrees of freedom for design are its height, h_p , and location, g_p . To investigate the effect of these design parameters of MP on the AMC resonance frequency, l_p and t_{AMC} are fixed as 6.7 and 13 μm respectively. Firstly, in Fig. 7(a), g_p varies from 20 to 110 μm , while h_p is defined as 10.5 μm . It is found that f_{AMC} decreases gradually until g_p reaches 70 μm with a sharp depression at $g_p = 73 \mu\text{m}$, after which it starts to increase. As Fig. 8(a) and (b) show, the current on the patch is mainly distributed along the upper and lower side edge, which is opposite to the situation of the current in the ground plane. This can be explained as follows. When g_p increases, the additional inductance increases significantly, while the capacitance between the patch and the top surface of the posts decreases a little. Thus, the rising inductance dominates in (1), which leads to a decreasing f_{AMC} . However, when g_p becomes larger than 73 μm , the inductance increases slightly, but the capacitance decreases significantly, which means the decreasing capacitance is dominant in (1) and, thus, the resonance frequency rebounds.

Also, MP height, h_p , is varied from 1 to 10.5 μm while keeping the g_p as 73 μm . The result shown in Fig. 7(b) illustrates that f_{AMC} demonstrates a constant downward trend when h_p is increased. This is because when h_p increases, the current path is extended and the MP top surface becomes closer

Fig. 7. Tuning effect of MP on the AMC resonance frequency: Sweep of (a) g_p , and (b) h_p .

Fig. 8. Current distribution on (a) the square patch, and (b) the ground plane.

to the patch, thus the introduced inductance and capacitance both increase. According to (1), the phase velocity and the resonance frequency are both reduced.

From the results of the parametric sweep, it is clear that the MP can tune the AMC resonance frequency. By implanting two MP in each unit cell of the 4×4 finite patch-based AMC, as illustrated in Fig. 9, the AMC can resonate at 94 GHz with a thickness of 18 μm . Compared to the reference AMC, t_{AMC} is reduced by 33%. As reported in [33], the 94 GHz monopole antenna backed by this thin AMC with the dimensions given in Table I radiates in the boresight direction with a gain of 1.2 dBi and radiation efficiency of 23%.

B. Embedded Guiding Structures (EGS)

The stack-up of a standard CMOS process provides about six to nine metal layers inside the oxide. These metal layers are embedded in the dielectric part of the AMC, and can be smartly used to reduce its resonance frequency. As Fig. 11(a) shows, the electric fields around the EGS have to make a detour so that the electrical thickness of the oxide layer appears to be larger. Considering the influence of the resistance, only one metal layer is employed in the AMC unit cell study, as shown in Fig. 11(b). Similar to the MP, there are two symmetric guiding structures implemented into one AMC unit cell with planar dimensions of l_g and w_g . The gap between the structures and the edge of the unit cell is defined as g_g while h_g refers to the distance of the EGS to the ground plane. The equivalent circuit model of a conventional patch-based AMC is a parallel LC circuit [36]. Because of the EGS, new distributed capacitors and an inductor, as shown in Fig. 11(b), are introduced. The capacitance between the EGS and the patch is defined as C_{EGS} ; the capacitance between the EGS and the ground plane is C_{EGSG} ; the capacitance between the EGS of adjacent unit cells is modelled as C_{EGSO} . All introduced capacitances are in parallel with C_o in the equivalent circuit model [38]. The inductor on the EGS, L_{EGS} , appears on the branch of C_{EGSO} . The complete

Fig. 9. 4×4 finite patch-based AMC with MP: (a) proposed model, and (b) phase of the reflection coefficient.

Fig. 10. AMC with MP backed monopole antenna: (a) 3D exploded view, and simulated (b) S_{11} , (c) normalized radiation pattern [33].

equivalent circuit of the AMC with EGS is shown in Fig. 11(c). These additional capacitors and inductors provide further flexibility to tune the AMC resonance frequency.

To ascertain the effect of guiding structure parameters on the AMC's thickness reduction, a parametric sweep of each geometrical parameter of the embedded structures is considered. The AMC thickness t_{AMC} is 13 μm . Considering fabrication limitations of the in-house CMOS-compatible process, the gap between the structures and the unit edge g_g is varied from 5 to 45 μm , the height of the structures h_g is ranged from 1 to 10.5 μm , the length of the structures l_g is tuned from 200 to 390 μm and the width w_g is varied from 50 to 250 μm .

According to Fig. 12(a), the gap g_g is varied while the height, length and width of the EGS are fixed. It is noted that the resonance frequency is proportional to g_g . This is because the electric fields in the SiO_2 concentrate around the side edges, as Fig. 13 shows, thus the bending of the electric field path decreases with g_g increasing.

As Fig. 12(b) shows, when g_g , l_g and w_g are fixed, f_{AMC} goes down till the height h_g reaches 4 μm , and then it rebounds. According to the electric field distribution in the SiO_2 , the fields are stronger near the patch. When h_g increases, more electric fields detour due to the EGS, thus f_{AMC} decreases. However, when EGS is too close to the patch, the embedded structures provide reflection instead of guidance, which is similar to what the ground plane does. For instance, the vectors of the electric fields near the side edge of the EGS, when $h_g = 8 \mu\text{m}$, are shown

Fig. 11. Patch-based AMC unit cell with EGS: (a) Electric fields detour around EGS, (b) two EGSs are introduced in one AMC unit cell, (c) equivalent circuit model.

in Fig. 14(a). It can be noticed that when h_g reaches 8 μm , the electric fields near the embedded structures do not detour. Contrarily, the reflection characteristic of the EGS causes the decrease in the electrical thickness, resulting in the increasing trend of the resonance frequency when h_g is larger than 4 μm .

In Fig. 12(c) and (d), f_{AMC} shows a sharp decrease and then a rise with the increasing dimensions, l_g and w_g . When the length and width of the structure is less than 220 and 90 μm respectively, the propagation of more proportion of the electric fields meanders. However, when the dimensions of the embedded structures become too large, e.g. $l_g = 300 \mu\text{m}$ or $w_g = 180 \mu\text{m}$, the detour of the electric fields near the EGS disappears, as Fig. 14(b) and (c) illustrate, which causes the rebound of f_{AMC} .

The EGS is introduced in the 4×4 finite patch-based AMC, as shown in Fig. 15(a), where the structures on the chip edges have a gap of g_g away from the edge and dimensions of l_g and w_g , while the EGS between each adjacent unit cell along x direction is continuous with a length of l_g and width of $2 \times (g_g + w_g)$. According to Fig. 15(b), when $g_g = 5 \mu\text{m}$, $h_g = 9.5 \mu\text{m}$, $l_g = 310 \mu\text{m}$, $w_g = 100 \mu\text{m}$, the finite AMC with EGS has zero-phase of reflection at 94 GHz, while the oxide thickness of the AMC with proposed EGS is only 16 μm , which means a 41% reduction in thickness as compared to the reference AMC (without EGS).

Fig. 12. Tuning effect of EGS on the AMC resonance frequency: Sweep of (a) g_g , (b) h_g , (c) l_g , and (d) w_g .

Fig. 13. Side view of the electric field distribution around one of the EGS.

Fig. 14. Vectors of the electric field in the silicon dioxide: (a) $h_g = 8 \mu\text{m}$ (b) $l_g = 300 \mu\text{m}$, and (c) $w_g = 180 \mu\text{m}$.

Fig. 15. 4x4 finite patch-based AMC with EGS: (a) proposed model, and (b) phase of the reflection coefficient.

Fig. 16. AMC with EGS backed monopole antenna: (a) 3D exploded view, and simulated (b) S_{11} , (c) normalized radiation pattern.

Like the previous cases, a monopole antenna has been realized above the proposed AMC with EGS, as shown in Fig. 16 (a). The AoC has a good impedance matching at 94 GHz with a return loss better than 25 dB, while it provides a boresight gain of 5.08 dBi with a radiation efficiency of 50% (Fig. 16 (b) and (c)).

It is noted that another resonance appears at 96.5 GHz. This is caused by the EGS on the left and right edges, shown in circles in Fig. 17(a). This can be clearly seen in the current distribution on the EGS layer at 96.5 GHz. To further verify the origin of the second resonance, the lengths and widths of the circled EGS, marked as l_c and w_c , have been varied by 20 and 4 μm respectively, while the other EGS dimensions are not changed. The results of these simulations, shown in Fig. 17(b) and (c), confirm that the second resonance shifts by 1 and 0.8 GHz respectively, but there is no change in the main resonance at 94 GHz. The radiation pattern, shown in Fig. 16 (c), is for the 94 GHz band as that is the resonant frequency of the radiator.

C. Comparison of Thickness Reduction Techniques

Conventionally, the vias are used to connect multiple metal layers in the CMOS stack-up. However, in this work, the vias and metal layers have been utilized to reduce the thickness of the AMC. Two finite AMC surfaces implemented with different TRS have been proposed in the previous sections. In a standard CMOS process, the designer must carefully follow the foundry rules, typically called design rule check (DRC). For

Fig. 17. Resonance at 96.5 GHz in the case of AMC with EGS backed monopole antenna: (a) current distribution on EGS layer (b) resonance shifts with different lengths and, (c) widths of the circled EGS.

example, rules such as metal width, spacing between two conductors, etc. must be followed strictly in order to qualify for fabricating the design in a particular foundry. If we compare two TRS, it is obvious that MP approach is simpler in terms of design, DRC and fabrication aspects.

An identical monopole antenna is placed 2.5 μm above these AMC structures with MP and EGS respectively. Table II summarizes the AMC thicknesses and radiation performance.

It is clear that the implementation of EGS within the AMC leads to a greater reduction in thickness. The monopole antenna integrated with the EGS based AMC shows higher gain and radiation efficiency (5.08 dBi and 50%). The antenna backed by the MP based AMC has relatively low gain, due to the undesired high conductor loss. Using HFSS field calculator, power loss analysis of MP based AMC is performed for a fixed input power of 1 W, and conductor loss for each element is listed in Table III. It is evident that when AMC is integrated with MP, more proportion of energy is thermally lost in antenna, thus the radiation performance of this design is not that good.

Compared to the reference AMC, the AMC with EGS has the least thickness and offers the best gain. Therefore, it is selected for further investigation of the optimum AMC size. As Fig 18(a) shows, the peak gain of the on-chip monopole antenna positively correlates with the number of AMC unit cells. When there is no AMC, the gain of the standalone AoC is about -3.3 dBi and the radiation patterns are distorted (Fig 18(b)) Considering that, typically, the radiation pattern of a CPW-fed planar monopole antenna is symmetric in air, the lossy silicon substrate must be responsible for the slight distortion in the radiation pattern of the standalone antenna [39]. By implementing the AMC to isolate the antenna from the silicon substrate, the gain of AoC improves as the number of AMC unit cells increases, till it saturates when the number of unit cells reaches 16. Hence, the AMC size of 4×4 is selected as a

TABLE II
COMPARISON OF THREE KINDS OF FINITE ON-CHIP AMC SURFACES

	t_{AMC} (μm)	Thickness Reduction	Gain of AoC (dBi)	Radiation Efficiency
Ref. AMC	27		4.5	45%
AMC + MP	18	33%	1.2	23%
AMC + EGS	16	41%	5.08	50%

TABLE III
CONDUCTOR LOSS PROPORTION OF EACH PART OF AMC-BACKED AOC

	Antenna	Patch	TRS	Ground Plane
Ref. AMC	17.9%	27.3%		9.8%
AMC + MP	27.6%	36.7%		12.7%
AMC + EGS	5.1%	22%	4.7%	18.2%

Fig. 18. Investigation on the AMC with EGS surface: (a) Peak gain of the AOC versus the number of AMC unit cells, and (b) distorted radiation pattern of a standalone antenna.

Fig. 19. (a) Adhesion layers bind the oxide with copper. (b) Peak gain versus the chromium film thickness.

Fig. 20. Stack-up of the proposed structure.

compromise between the overall chip size and the gain of the antenna.

Fig. 21. Fabrication process without adhesion layers of the BEOL part.

IV. FABRICATION AND MEASUREMENT

A. Fabrication without Adhesion Layers

The on-chip monopole antenna backed by a 4×4 thin AMC with EGS is selected for fabrication as it exhibits the highest gain for the thinnest oxide layer. During the deposition of the patterned metal layer, specialized adhesion layers, composed of chromium or titanium, are always used in a typical fabrication process, as shown in Fig. 19. This is to improve the adhesion of the metals (copper or gold) to the oxide. The usage of the adhesion films helps the buildup of noble metal in device fabrication, but it reduces the average conductivity of metal layers and negatively affects the AMC and antenna radiation. It is noted that when extremely thin AMC thickness is required, the resistance corresponding to the conductor loss plays a significant role that could affect the zero-degree reflection phase property by causing PEC-like effect on the AMC [40]. It is observed that a 10 nm chromium film modelled at the lower surface of each copper layer as the adhesion layer, causes the antenna gain to reduce to -24.6 dBi and radiation efficiency to less than 0.1%. To study the effect of the adhesion layer thickness on the AoC radiation, the copper layer is fixed as 500 nm, while the thickness of the chromium adhesion film is varied from 10 to 250 nm. According to the simulated results, shown in Fig. 19(b), the peak gain shows a direct proportionality to the thickness of the chromium film. This is because the surface resistance is inversely proportional to the chromium film thickness when it is much thinner than the skin depth of chromium (595 nm at 94 GHz). Therefore, the conduction loss caused by the adhesion films decreases with the chromium thickness increasing. Nevertheless, the gain is still unideal even if the chromium thickness reaches 250 nm. Therefore, to realize a fabricated prototype that exhibits the enhanced gain and radiation performance as proposed in

Fig. 22. Fabricated sample: (a) Top view from a microscope. (b) Dimensional measurement with a Vernier caliper. (c) Cross-sectional view from the microscope.

simulations, the adhesion layers cannot be involved, but certain modifications to the fabrication process are required to help the copper layers still bond adequately to the oxide.

The stack-up of the proposed structure of the monopole antenna backed by ultra-thin AMC with EGS is depicted in Fig. 20, where the ground plane is supposed to fully cover the substrate, the EGS is designed at $9.5 \mu\text{m}$ above the ground plane, while the periodic patch layer of the finite AMC has a gap of $6.5 \mu\text{m}$ above the patch layer, and the planar monopole antenna is located $1.5 \mu\text{m}$ above the patch layer.

The back end of line (BEOL) process is visually shown in Fig. 21. To maintain the copper layer on SiO_2 without the

adhesion layer deposition, two things need to be taken care of. On the one hand, it is essential to improve the adhesion of the copper to the oxide, while on the other hand, during the lift-off step of the lithography, the solvent must contact the residual photoresist easily, thereby preventing the patterned copper from exfoliation that would be caused by conventional intensive ultrasonic lift-off. It can be noticed that prior to the lithography, in the step 4, the bombardment of argon atoms can make the surface of SiO₂ rough, thereby enhancing the friction force of the oxide to the copper and consequently improving the adhesion. After that, the wafer is coated with AZ 5214 image reversal photoresist whose ideal thickness is 1.6 μm, slightly larger than thrice of the thickness of the copper film. Then, the solidified photoresist is treated by dark-mask-covered exposure and the area except intended pattern is exposed. Next, the reversal baking with critical condition (120 °C for two minutes) and flood exposure makes the unexposed intended pattern area developable. After development, such a slanting wall can be found that the lift-off step turns out to be gentle due to the accessibility of the residual photoresist to the solvent.

Following the in-house CMOS-compatible process, the prototype is fabricated. It can be noticed that the pattern and alignment of each metal layer is in fair agreement with the proposed structure, and there is hardly any metal exfoliation as shown in Fig. 22(a). Measured by a Vernier caliper, the dimension of the chip is 2.8×2.8 mm². The chip side length is 0.4 mm longer than that in the simulation model. This extension is kept to ensure that the device is not damaged by the dicing blade when the fabricated chip is diced into smaller samples. The cross section is viewed by an optical microscope, and the realized total oxide thickness is found to be 18.18 μm within a slight error of 0.18 μm from the simulation model.

B. Measurement

The measurement of input impedance and radiation performance has been carried out in an Orbit μ-lab anechoic chamber integrated with an Agilent vector network analyzer (VNA) 5242A and relevant extender modules. The antenna under test (AUT) is fed by an Infinity probe II10-A-GSG-150. The setup of the impedance measurement is shown in Fig. 23. Once the system has been calibrated with a Cascade 104-783 W-band impedance standard substrate (ISS), the AUT is then placed on a foam chuck at the center of the chamber. The simulated and measured reflection coefficients of the AUT are in fair agreement for in-band response, as shown in Fig. 24. It is evident that the on-chip monopole antenna is well matched from 92 to 98 GHz with a return loss of 16 dB at 94 GHz.

The radiation performance has been characterized in the same chamber, where the probe-fed AUT is connected to port 1, and the scalar-feed-horn-10 (SFH-10) reference antenna is excited by port 2, as shown in Fig. 25. Here the reference antenna is set as the transmitter and the AUT works as the receiver. Fig. 26(a) and (b) give the measured radiation pattern. Due to the physical constraints of the chamber, the E-plane measurement of the AUT ranges from θ = -20° to 230° while φ = -90°, and H-plane is θ = 0° to 360° while φ is zero. Generally, the measured curves follow the same trends as the simulated

Fig. 23. Reflection coefficient measurement setup: (a) SNF anechoic chamber, (b) Probe landing.

Fig. 24. Simulated and measured reflection coefficient of the AUT.

curves, however, there are some discrepancies between them. The H-plane pattern is almost matched to simulated curve except a backside radiated lobe, while there are several additional side lobes measured in the E-plane. According to Fig. 26(c), the measured peak gain is also in fair agreement with the simulated results, showing an initial rise followed by a drop, in the impedance-matched frequency band (92 to 98 GHz). The highest value of the realized gain occurs at 94 GHz as 5.85 dBi, which is close to the gain value of 5.08 dBi in simulations. The 3 dB gain bandwidth is 5.4%. Furthermore, to characterize the directivity D and radiation efficiency η of the prototype, the spherical radiation pattern with the exception of the probe part ($\varphi = -30^\circ$ to $+30^\circ$, $\theta = 20^\circ$ to 130°) has been measured with an azimuth step of 5° and the inclination step of 2° . The measured data is substituted into the following equations:

$$D = \frac{\sum_{\varphi, \theta} \sin \theta}{\sum_{\varphi, \theta} F_n(\varphi, \theta) \sin \theta} \quad (2)$$

$$\eta = \frac{G}{D} \quad (3)$$

where $F_n(\varphi, \theta)$ is the normalized radiation pattern. Then the directivity is 8.22 dB and the radiation efficiency is 57%.

Fig. 25. Radiation measurement setup.

Fig. 26. Simulated and measured: (a) Normalized radiation patterns at 94 GHz in E-plane and (b) H-plane. (c) Peak gain versus frequency.

C. Discussion

It is anticipated that the discrepancy in impedance characterization, radiation pattern and gain is caused by the extra chip area and probe effect. Due to the risks associated with dicing, the side length of each sample is expanded to 2.8 mm instead of 2.4 mm, so the ground plane has also expanded with the increased chip size. Secondly, the huge conductor body and the uncovered tips of the feeding probe near the AUT bring unwanted coupling, self-radiation and reflection. Fig. 27(a) shows the post-measurement simulation model where the chip margin and probe body are both taken into consideration.

The post-simulation results show side lobes and back lobe in radiation pattern that are in decent agreement with the measured results. The matched reflection coefficient and the curve of gain versus frequency also verify that the main reasons for the discrepancy are the extra chip margin and the huge conductive feeding probe. It is envisioned that a customized absorber covering the probe and the de-embedding of the probe influence from regularly tested results would be helpful for a more accurate AoC measurement.

Table IV shows the gain-enhancement performance comparison between our work and similar works using AMC for AoC gain enhancement. According to author's best knowledge, this article presents the thinnest on-chip AMC design and the highest experimentally measured gain of an

Fig. 27. Post-measurement discussion: (a) AUT with the probe model, (b) Radiation pattern in E-plane and (c) H-plane, (d) S_{11} and gain versus frequency.

TABLE IV
COMPARISON WITH PREVIOUSLY PUBLISHED AMC-BACKED AOC

	Techniques	t_{AMC} (μm)	Measured Gain (dBi)	Incr. in Gain (dB)	η	Incr. in η
[41]	Ground plane underneath Si	300	0.12	NR	NR	NR
[38]	Two PRS layers + Ground plane underneath Si	250	0	3.3	21% (sim)	10% (sim)
[31]	Slotted patch + Ground plane above Si	20	-1.4	8	NR	NR
This work	EGS + Ground plane above Si + No adhesion layers	16	5.85	9.15	57%	42%

antenna by using on-chip AMC only.

V. CONCLUSION

Although SoC has become a promising solution to realize the modern wireless systems on a chip, the silicon substrate is unsuitable for hosting antennas on it. AMC implemented on a chip, whose ground plane is located on top of the substrate, cannot only isolate the lossy Si substrate, also provide in-phase reflection for the AoC, thereby alleviating the crosstalk between the antenna and on-chip circuits and enhancing the gain. However, the required AMC thickness is not compatible with typical CMOS processes. To reduce AMC thickness, two kinds of thickness miniaturization techniques, MP and EGS, have been demonstrated in this article. Smartly using the vias and metal layers available in the CMOS stack-up, an ultra-thin

94 GHz AMC is realized with a comparable thickness (16 μm) with the oxide layer of typical CMOS stack-up. Moreover, the conventional CMOS stack-up with low-conductivity adhesion layers brings some undesired losses. This article presents an in-house CMOS-compatible process. The adhesion of the metallic layer to the oxide has been improved without using adhesion layers. The measured input impedance and radiation performance of the AoC backed by the proposed ultra-thin AMC is fairly consistent with the simulations. It provides 5.85 dBi gain with a return loss of 16 dB at 94 GHz.

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