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# ANTENNA-ON-CHIP FOR WIRELESS APPLICATIONS: MODELLING AND SIMULATION ANALYSIS

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**Abstract:** This paper presents modeling and simulation characterization of radiating copper nanofilm based microstrip patch antenna for on-chip wireless systems around 20 GHz (K-Band). The proposed antenna uses high resistivity silicon wafer as substrate on which, the copper nanofilm forms radiating element. The antenna structure uses a scheme known as coplanar waveguide fed proximity coupled patch in order to avoid soldering high resistivity nanofilm and very low resistivity bulk feed. The nanofilm antenna design is modeled and simulated in IE3D software shows excellent performance in terms of impedance bandwidth, 57.66% higher over bulk patch antenna. The nanofilm antenna can be fabricated along with IC technology fabrication on the same silicon wafer substrate.

**Keywords:** Nanofilm, coplanar proximity coupled patch antenna, antenna-on-chip, inter and intra-chip communication

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## INTRODUCTION

On-chip antennas are tiny surface mount devices designed to provide inter and intra-chip wireless communication or for short range of air transmission. The typical on-chip antenna integrated with analog and digital circuitry on the same wafer finds applications in wireless LAN, GPS receiver, Bluetooth and cellular transceivers [1]. Earlier, antennas have to be interfaced with chip circuit using bond wires (off-chip). An on-chip antenna fabrication avoids the requirement of bond wires or off the chip components. Thus the on-chip antenna fabrication provides a robust solution in smaller form factors [2]. Furthermore monolithic fabrication of the antenna with RF electronics reduces power losses and parasitic effect compared to integration of discrete components. To achieve antenna integration within a single chip, different solutions have been suggested [3-4-5]. Silicon substrate allows the antenna coupling on a chip with RF electronics. Antenna integration with silicon has been demonstrated in [6-7]. However, most of them are either bulky or having narrow bandwidth. In this work copper nanofilm is modeled instead of bulk copper as antenna radiating element. There are two advantages by employing copper nanofilm, first, the density of antenna decreases, and second, improvement in impedance bandwidth due to high surface resistivity of nanofilm. The increase in high surface resistivity increases bandwidth. To our knowledge, for the first time we are modeling an on-chip nanofilm antenna using coplanar waveguide (CPW) proximity coupled antenna through simulation to decrease the density of antenna, enhancing the bandwidth and increasing return loss.

## ON-CHIP ANTENNA DESIGN

An important aspect in developing electronic applications using nano thickness materials is reliability of electrical contact. Generally, the antenna metallic parts consist of bulk patch, ground, and feeding line. In order to overcome the practical problem of reliable electrical contact between nanofilm radiating patch and bulk feedline, we have selected a feeding technique known as coplanar waveguide proximity coupling. It have many features such as low radiation loss, less dispersion, easy and simple configuration of integrated circuits with single metallic layer, and no via holes required [8]. The feeding approach is feasible and yield high coupling efficiency. The CPW proximity coupled antenna as shown in fig. 1 is continuation of the work presented in [9]. The antenna has substrate with conducting metal on both sides. On bottom side, a coplanar feedline extends to the edge of the substrate where Subminiature Version A (SMA) end launcher is connected to the signal line and ground on the same plane. The following modifications were made to the work presented in [9]: first, the radiating patch thickness is scaled down from 0.75 micron to 30 nm. Second, the silicon substrate has copper on both sides that is approximately 2 μm thick, instead of gold. Figure 2 illustrates side view of the CPW proximity coupled patch antenna. Third, for 30 nm thickness which is less than electron mean free path of copper, the surface resistivity is calculated using Fuchs-Sondheirmer equations [10]. The resonant frequency is controlled by varying the gap between feedline and ground, stub from centre of the substrate and patch dimensions.

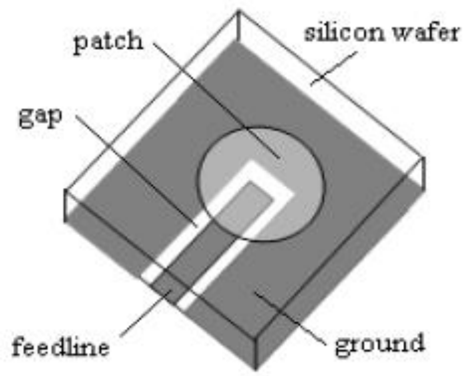



**Figure 1 Geometry of CPW proximity coupled patch antenna.**

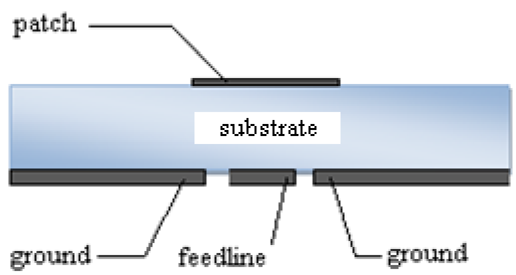
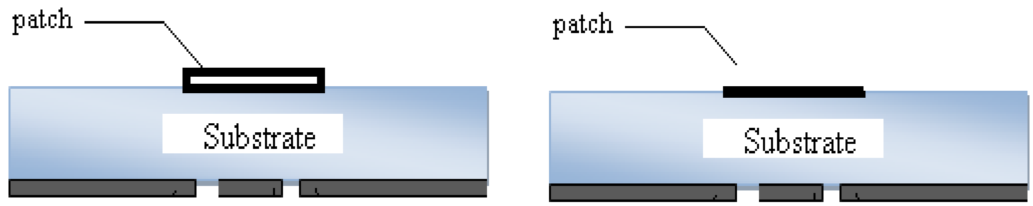



**Figure 2 Geometry of CPW proximity coupled patch antenna: side view**

**RADIATING PATCH THICKNESS MODELING**

The silicon wafer is modeled with copper on both sides approximately 2 μm thick. In IE3D simulator [11], the bulk patch is modeled using finite thickness strip model where skin depth $\delta_s$ (0.463 μm at 20 GHz) are included precisely, and nanofilm is modeled using zero-thickness strip model (30 nm less than $\delta_s$). In finite thickness strip model, the current is on 4 sides of the strip is as shown in fig. 3(a), while in infinitely thin strip model the current is assumed to be on the one single strip only, as illustrated in fig. 3(b). IE3D thick Strip model provides extremely accurate results on structures with thickness. The infinitely thin strip model is good when the strip width is much bigger than the strip thickness. In our proposed model the strip is in circular shape of width of 2.30 mm diameter and thickness of 30 nm.

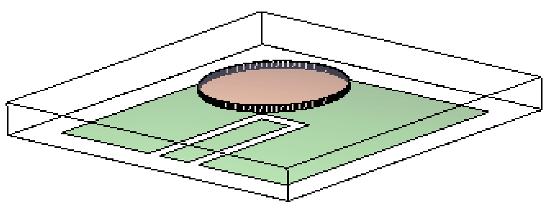



(a) (b)

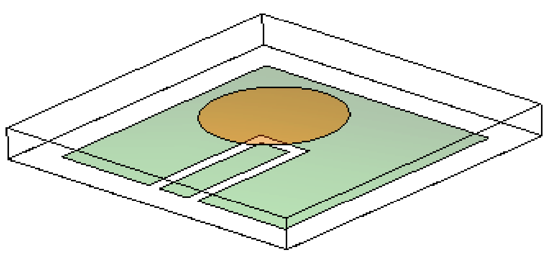
**Figure 3 Radiating patch (a) finite thickness model (b) infinite thin strip model**

**ANTENNA MODELING**

The complete CPW proximity coupled patch antenna is modeled for both bulk thickness patch and nanofilm thin thicknesses are illustrated in fig. 4. The simulation model of antenna has substrate and ground plane of 8 by 8 mm, and the high resistivity silicon wafer is 0.5 mm thick with a permittivity of 11.9, a material loss tangent of 0.015, and conductivity of 0.025 S/m. The metallic dimensions of antenna are: a 50Ω CPW feedline length and width of 4.65 by 1 mm, gap between coplanar ground and feedline is 0.38 mm, circular patch radius of 1.15 mm. The CPW proximity coupled antenna uses circular disk as radiating patch. The main advantage of circular patch over rectangular patch is that circular patch occupies less physical area. Thus in applications such as arrays, circular geometries are preferred.



(a)



(b)

**Figure 4 IE3D simulation model (a) Bulk patch antenna (b) nanofilm patch antenna**

The 2 μm bulk copper electrical specifications are: conductivity (σ) of 5.8*107 S/m, permeability (μr) of 1, permittivity ($\varepsilon_r$) of 1. If the metal film thickness is larger than electron mean-free-path p, the resistivity ρ is expected to be nearly the same as that of a bulk metal patch. When the metal film thickness is less than the order of the electron mean-freepath, then the role of electron scattering becomes significant. Very thin metallic films have a much higher resistivity than a bulk metal because of electron scattering from the metal film surface. For nanofilm of 30 nm, the conductivity f σ is computed using the following Eq. 1 [10],

$$\sigma_f = \frac{3t\sigma}{4p}\left[\ln\left(\frac{p}{t}\right) + 0.4228\right] \text{ S/m} \qquad \text{For } t << p \qquad (1)$$

Where $\sigma$ is bulk copper patch conductivity, t is patch thickness and p is electron mean-free-path in meters. Equation 1 holds good only if film thickness t is less than electron mean-free-path p. The surface resistance $R_s$ of nanofilm is independent of the dimensions of the square and equals, is given by:

$$R_s = \frac{1}{t.\sigma_f} \ \Omega/\text{square} \qquad (2)$$

According to the Fuch-Sondheimer theory, the surface resistance of a metallic film decreases as the thickness of the film increases. For our work we have selected thickness t of copper patch as 30 nm for antenna application which is less than electron mean-free-path p of copper (42 nm). The conductivity and surface resistivity of 30 nm copper patch is computed for thickness less than electron mean-free-path using Eq. 1 and 2. The computed values are listed as

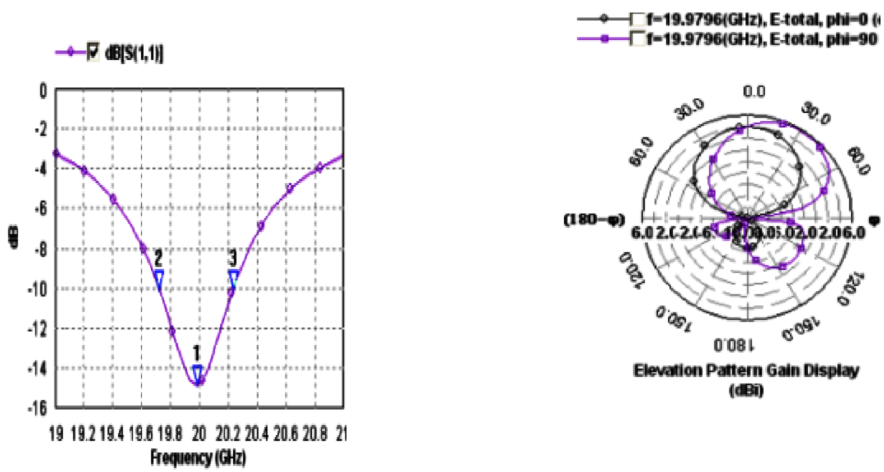
Conductivity of nanofilm: $\sigma_f = 2.43*10^7$ S/m (3)

Surface Resistance: $R_S = 1.371\ \Omega$/sq (4)

From the computation, it is observed that at patch thickness less than electron mean free path, there is decrease in the conductivity and increase in the surface resistance when compared to bulk thickness patch. For nanofilm modeling, numerical values in Eq. 3 and 4 are used in IE3D simulation.

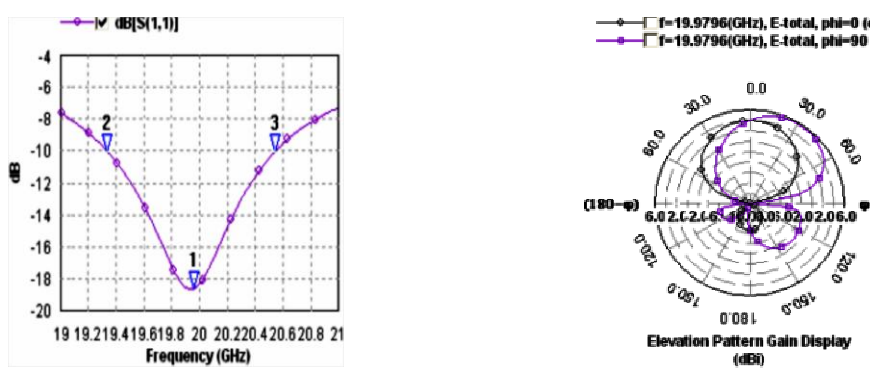
**ANTENNA SIMULATION**

IE3D version 14.65 electromagnetic simulators are used to model and simulate. IE3D simulator is a full wave, method of moments (MOM) based electromagnetic tool used for the design of general 3D and planar structures like patch antennas. It solves Maxwell's equation and its solutions include discontinuity effects, wave effects, coupling effects, and radiation effects. The modeled antennas are simulated with finite ground from 19 GHz to 21 GHz frequency ranges. The operating frequency ($f_r$), return loss *(RL)*, bandwidth *(BW)*, and gain were obtained from simulated reflection coefficient $S_{11}$ graph and 2D radiation pattern as shown in fig. 5 and 6 respectively.




**(a)** **(b)**

**Figure 5 Bulk Patch Antenna (a): Return loss vs. frequency, (b): 2D radiation pattern**




**(a)** **(b)**

**Figure 6 Nanofilm antenna (a): Return loss vs. frequency, (b): 2D radiation pattern**

The simulated results are listed in Table 1 for comparison between bulk patch and nanofilm antennas for analysis. The bandwidths of antennas were obtained from the following Eq. 5:

$$BW\ (\%) = 100\left[\frac{f_{max} - f_{min}}{f_r}\right] \quad (5)$$

Where $f_{max}$ and $f_{min}$ are maximum and minimum frequency, at -10 dB points, and $f_r$ is resonant frequency.

**TABLE 1 SIMULATED RESULT FOR BULK PATCH AND NANOFILM ANTENNA**

| Antenna Type | Antenna parameters after Simulation | | | | |
|---|---|---|---|---|---|
| | *$f_r$ (GHz)* | *RL (–dB)* | *BW (GHz)* | *Gain (dBi)* | *BW (%)* |
| Bulk patch | 19.97 | 14.78 | 0.509 | 5.63 | 2.54 |
| Nanofilm | 19.93 | 18.62 | 1.210 | 1.42 | 6.00 |

**RESULTS AND DISCUSSION**

From simulation results, it is found that nanofilm antenna exhibits outstanding performance in terms of bandwidth and return loss. As can be seen from $S_{11}$ graphs shown in fig. 5(a) and 6(a), nanofilm antenna presents a wide bandwidth of 1.21 GHz (6%) over bulk film antenna bandwidth of 0.509 GHz (2.54%), which is 57.66 % higher. Also, an increase in return loss of nanofilm antenna (-18.62 dB) over bulk patch antenna (-14.78 dB) confirms better antenna matching to the feedline. The increase in bandwidth may be attributed due to absence of eddy current loss in nanofilm, lesser antenna losses, and lesser scattering and diffraction effect on nanofilm. Surface irregularities and diffraction contributes more antenna losses. Also, because of high surface impedance of nanofilm metal compared to bulk patch thickness, the 'Q' of antenna decreases thereby increases in bandwidth. The radiation pattern shown in fig. 5(b) and 6(b) for nanofilm and bulk patch antenna demonstrates similar pattern with no deviation or changes, confirms patch thickness variation from bulk to nano thickness does not affect radiation pattern including resonance frequency. The radiation patterns are more directive with small rear lobes. The rear lobes appear due to finite ground modeling in IE3D. Similarly, the gain on patch thickness variation indicates that a patch thickness of 30 nm less than coppers electron mean-free-path of 42 nm, reduces gain from 5.63 dBi to 1.42 dBi. The reduction in gain affects antennas performance in terms operating range. Hence, antennas with nanofilm are useful in applications where short range chip-to-chip, intra-chip communication with higher data rates is required.

**CONCLUSION**

This paper has presented the effect of nanofilm radiating patch on antenna performance for wireless Microsystems applications. Copper nanofilm of 30 nm thickness less than electron mean-free-path of 42 nm is modeled over 0.5 mm high resistivity silicon wafer substrate for CPW proximity fed microstrip patch antenna. The CPW proximity fed antenna provides contactless electromagnetic coupling between nano thickness patch and bulk feedline, without having to be reliable contact. The antenna is simulated using IE3D method of moments based full wave simulator for radiation characterization. The simulation shows encouraging results in terms of enhanced wide bandwidth and higher return loss around 20 GHz. The large bandwidth is highly suitable for compact, high data rate System-on-Chip (SoC) applications and in intra-chip communication such as wireless global clock distribution system. With recent developments in nonmaterial's and nanotechnology systems/tools like PVD, CVD, sputtering etc, it is possible to fabricate nanofilm patch antenna on low loss high resistivity thin silicon wafer.

**ACKNOWLEDGEMENTS**

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