A Folded-Slot Antenna on Low Resistivity Si Substrate with a Polyimide Interface Layer For Wireless Circuits

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***Abstract*-- A novel mm-wave Finite Ground Coplanar (FGC) folded slot antenna on low-resistivity Si substrate (1 Ω-cm) with a polyimide interface layer is presented for the first time. The antenna resonates around 30 GHz with a return loss of 14.6 dB. Measured radiation patterns indicate the existence of a main lobe, but its radiation pattern is affected by a strong surface wave mode. This antenna can be part of various low cost wireless communication systems.**

Index Terms-- Folded slot antennas, low resistivity silicon, polyimide, finite ground coplanar lines.

I. Introduction

The possibility of low cost RF and microwave circuits integrated with digital and analog circuits on the same chip is creating a strong interest in silicon as a microwave substrate, especially with the development of SiGe Heterojunction Bipolar Transistors with a high frequency of oscillation [1]-[3]. The operation, however, of traditional microwave circuits, such as transmission lines and antennas, on low resistivity silicon wafers is problematic, due to the high loss that these circuits exhibit on CMOS wafers.

To overcome this problem researchers have used two different approaches. In the first approach, high resistivity Si wafers are used (ρ>2500 Ω-cm) [1]-[2] and traditional microwave components have a performance similar to those on dielectric substrates, such as GaAs. In the second approach, polyimide layers are used on top of the CMOS substrate to create an interface layer that can host low loss microwave components. Both microstrip and coplanar waveguide transmission lines fabricated in this way have exhibited low attenuation for an optimum polyimide thickness [4]-[5].

This paper focuses on the development of a Finite Ground Coplanar (FGC) folded slot antenna with a resonant frequency around 30 GHz, on a CMOS silicon substrate with a polyimide interface. Results from experimental measurements and 3-D Finite Element Method (FEM) analysis are presented. This antenna can be the radiating element of any low cost wireless communication system. One potential application is the development of a planar wireless communication system used to transmit data from one chip to another. This wireless scheme is studied as an alternative to traditional conductor-based interconnects for future systems. Another application is the development of mm-wave, low cost phased-arrays on silicon that are traditionally built on GaAs substrates.

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II. Antenna Design and Fabrication

The folded-slot antenna is a very popular planar antenna that has been used in a variety of applications. It consists of a folded-slot with a circumference approximately equal to one guided wavelength (λ_g) and can be fed with a CPW or FGC line from one end, allowing for easy integration of three-terminal devices or MMICs for microwave amplification and reception [6]. The basic property of this antenna is that the electric fields in the CPW line at the input port are 180° out-of-phase with the electric fields at the output port. It also has a broad bandwidth and pattern with maximum radiation at the broadside [6]. A schematic of a folded-slot antenna with various parameters is shown in Fig. 1.

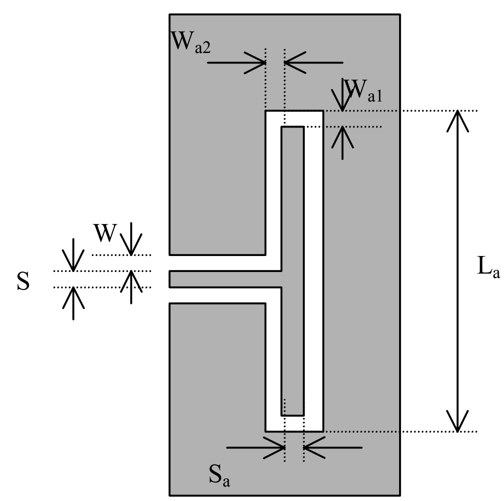

Fig. 1 Geometry of a folded slot antenna.

In order to operate such an antenna on a low resistivity (1-20 Ω-cm) Si wafer, the electric fields in the CPW or FGC lines must have minimum interaction with the lossy substrate. For this reason a thick layer (20 μm) of polyimide (DuPont WE 1111) is deposited and cured on top of the

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wafer. The transmission line feeding the antenna was also designed for minimum coupling with the substrate according to [7]. A schematic of the proposed FGC structure can be seen in Fig. 2. Original simulations with Ansoft's HFSS, that is based on the Finite Element Method (FEM), were performed in order to de-embed the antenna impedance at resonance. These simulations revealed a relatively high value of resistance at resonance (R~250 Ω) and, therefore, a quarter-wave transformer was designed for optimum matching between the feeding line (Zo=60 Ω) and the antenna. The transformer length was 1.075 mm while its impedance was approximately 124 Ω (s=10 μm, w=20 μm). The antenna resonance was fine-tuned further by inserting a 2.07 mm section of 60 Ω line between the transformer and the folded slot. Table I summarizes the various antenna parameters. For the fabrication of the folded slot antenna, standard lithographic techniques were used, and the conductors were Au electroplated to a thickness of 3 μm. A photo of the fabricated antenna can be seen in Fig. 3.

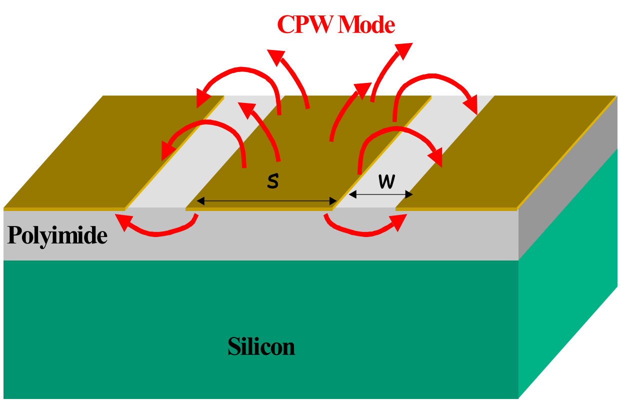

Fig. 2. FGC line on Si substrate with a polyimide interface layer.

Parameter	La	Wa_1	Wa_2	Sa	S	W
Size (μm)	2280	10	20	10	50	10

Tab le I. Design parameters for the folded-slot antenna

III. RESULTS

Simulated results with Ansoft's HFSS for the return loss of the matched antenna can be seen in Fig. 4, where a value of 16.5 dB is predicted at 30 GHz. The substrate was assumed to be 500 μm thick low resistivity silicon (σ=100 S/m, tanδ=0.0018) with a 20 μm polyimide overlay of ε_r= 2.8. The top and side-walls of the box surrounding the antenna were radiation boundaries. A perfect electric conductor was placed at the bottom of the Si substrate. Simulated radiation patterns at resonance are shown in Fig. 5, where a main lobe at broadside can be observed.

The antenna was characterized experimentally using an HP8510 Vector Network Analyzer and GGB Industries coplanar probes. The probe-to-FGC transition was de-embedded with a TRL calibration using *Multical* [8], that set the reference plane 500 μm away from the transition. The effective dielectric constant and attenuation of the 60 Ω line were measured first and results can be seen in Fig. 6. An attenuation of 5.7 dB/cm was measured at 30 GHz, while the effective dielectric constant was found to be ε_{eff} =2.23.

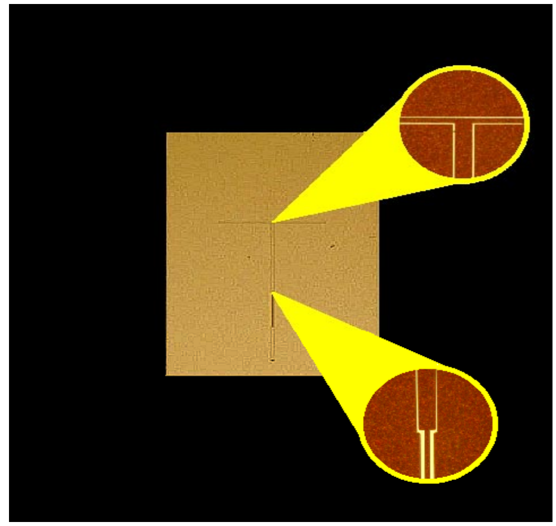

Fig. 3 Fabricated folded-slot antenna. Inserts show feedline-λ_g/4 and feedline-antenna junctions.

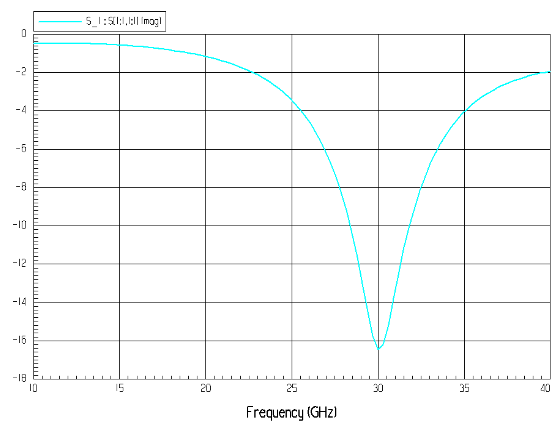

Fig. 4 Simulated return loss of the folded-slot antenna.

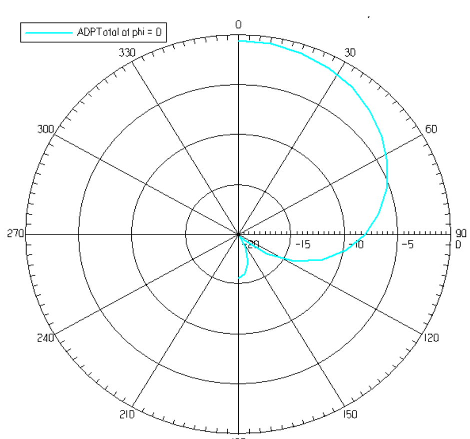

Fig. 5 Simulated radiation pattern.

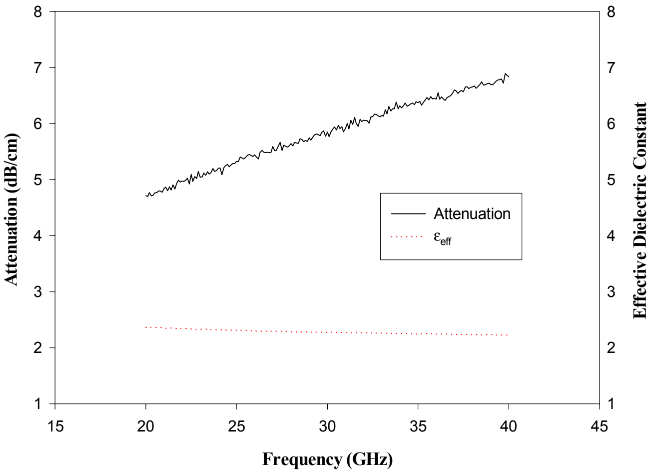

Fig. 6 Measured effective dielectric constant and attenuation for the antenna feeding FGC line.

The return loss can be seen in Fig. 7, where a value of 14.6 dB was measured at 30.5 GHz. These results agree very well with the HFSS simulations

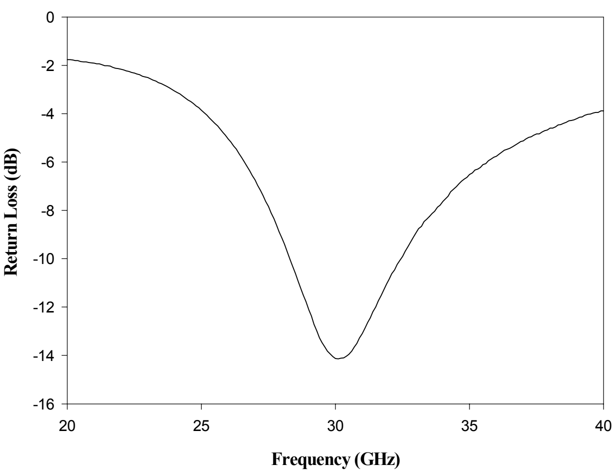

Fig.7 Measured return loss of the folded-slot antenna.

To characterize the radiation properties of the folded-slot antenna, the E- and H-plane patterns were measured at 30 GHz using a novel antenna pattern measurement system. Measurements are shown in Figs. 8 and 9 for the E- and H-planes, respectively The patterns are measured while the DUT antenna is excited by RF probes and the wafer is sitting on the metal wafer chuck of the RF probe station. The second antenna with the detector is swept in an arc around the DUT antenna. While this system permits quick radiation pattern measurements without dicing up the Si wafer, the RF probe does shield the E-plane pattern results, which accounts for the asymmetry in Fig. 8 and the low power levels for angles less than –20 degree. As can be observed in Fig. 8, the folded slot antenna has a main lobe around 0 degrees (broadside), but also radiates power in the form of surface waves as witnessed by the strong lobe around 83 degrees. It is believed that this strong excitation of the surface waves is partly due to the finite nature of the ground surrounding it (ground is only 2.1 mm wide), as well as the conducting nature of the silicon substrate. HFSS simulations did not reveal this behavior since radiation boundaries are placed on the side-walls and the ground width was infinite. Figure 9 shows that the H-plane is smooth with a maximum at 0 degrees, as is expected. Currently more experimental studies are under way to further and better understand the behavior of the folded-slot antenna on the polyimide-Si substrate.

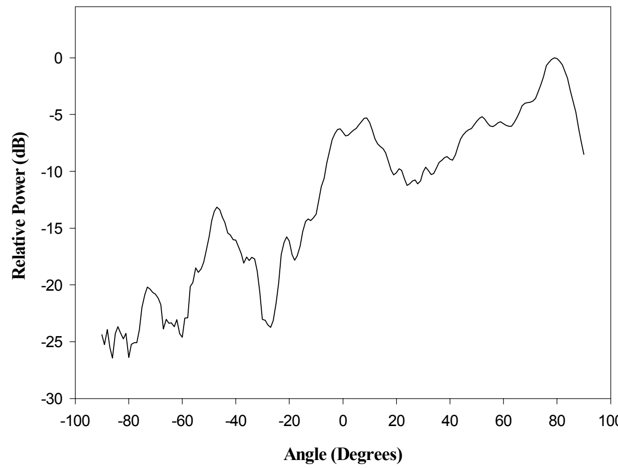

Fig. 8 Measured E-plane pattern at f=30 GHz.

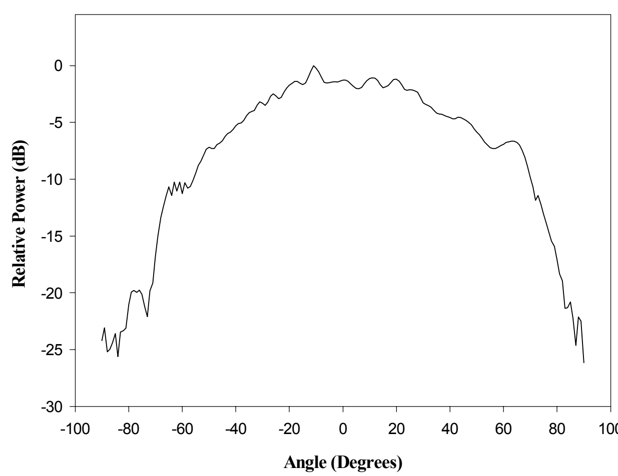

Fig. 9 Measured H-plane pattern at f=30 GHz.

IV. CONCLUSIONS

A finite ground coplanar folded slot antenna operating at 30 GHz has been developed for the first time on a low resistivity Si substrate with a polyimide interface layer.

Experimental results showed a 30.5 GHz resonance with a 14.6 dB return loss. Measurements of radiation patterns yielded an E-plane with a main lobe at broadside and strong surface waves around 83 degrees, as well as a smooth H-plane with a maximum at broadside. Measured results are in good agreement with HFSS simulations. Further studies are currently under way to better understand the behavior of this folded-slot antenna that can be implemented in low cost wireless communication systems.

V. ACKNOWLEDGEMENTS

This work was supported by the Semiconductor Research Corporation under Grant No. 99-NJ-736G.

VI. REFERENCES

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