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Electromagnetic Modeling of GaN Varactor Microwave Switches

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Electromagnetic Modeling of GaN Varactor Microwave Switches

by

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Submitted in Partial Fulfillment of the Requirements

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ABSTRACT

Microwave switches are important components which have been widely used in many microwave systems, such as electronic products, satellites communications, antennas, and radars etc. Traditionally, microwave switches are fabricated using pin diodes or MEMS, Si MOSFETs or GaAs HEMTs. These devices, due to the material limitations are suffering from a low breakdown voltage and are unable to handle high power. III-Nitride based varactor microwave switches provide opportunities for high power microwave devices, due to highly conducting 2D electron gas in the channel and high breakdown electric field.

Designing microwave switches typically involves modeling and simulation using tools such as MATLAB, ADS etc, to save the designing time and cost. However, these tools are not sufficient for precise simulation of low-loss microwave switches, where even minor scattering and loss in waveguides incorporating the device, may have significant effect on the overall switch performance.

In this thesis, HFSS electromagnetic simulation method is introduced to simulate microwave switches using GaN HFETs and varactors. First, the HFET and varactor models for HFSS has been developed and validated. Then various types of microwave switches with operating frequency above 10GHz have been simulated and optimized. Specific emphasis is made on a novel capacitively coupled contacts (C^3) varactor, not requiring ohmic contacts and gate electrodes. Using HFSS, this thesis demonstrated

several modified C^3 switch structures, achieving resonance in the operating frequency range thus greatly increasing the isolation, up to 42dB at 22GHz.

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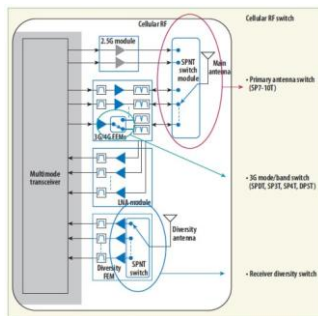
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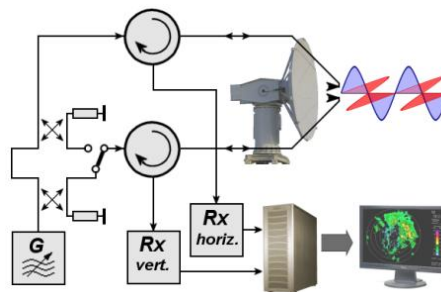
CHAPTER 1 INTRODUCTION

1.1 MICROWAVE SWITCHES AND APPLICATIONS

Microwave switches, with an electromagnetic spectrum of 300MHz to 30GHz, are components which have been widely used in many microwave systems, such as electronic products, satellites communications, antennas, radars and so on, as shown in the Figure 1.1[1]. These applications make microwave switches become one of the most important components in RF circuits and wireless communication systems.



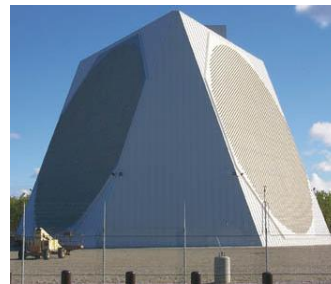
(a) 3G cellular multimode devices



(b) Radar



(c) Satellite



(d) Radar Antennas

Figure 1.1 Different applications of microwave switches

Microwave switches can be classified into two main categories: electromechanical switches and solid state switches. The operating principle of electromechanical switches is simply mechanically switching the cantilever or membrane up and down to the contact pad by the theory of electromagnetic induction. So during the switching process, the contact pad of switch changes its position physically. For applications require high power or lowest possible loss, electromechanical switches are usually used. Solid state switches, like PIN diode, MESFETs (Metal Semiconductor Field Effect Transistor), HEMTs (High Electron Mobility Transistor), HFETs (Heterostructure Field Effect Transistor), CMOS (Complementary Metal Oxide Semiconductor), etc., are semiconductor electronic switching devices made out of semiconductor materials by creating an electron flow path or so called channel. The channel can be turned on or off by applying positive or negative voltages. For applications required small size, switching speed or reliability, solid state switches are chosen [2].

In the past decade, a micro-electro-mechanical system (MEMS) switch designed to operate at RF and millimeter-wave frequencies (0.1 to 100 GHz). It combines the advantages of both electromechanical and semiconductor switches and provides the superior performances than PIN diode and FET switches. MEMS switches can provide low insertion loss (-0.1dB up to 40GHz), high isolation, very low power consumption (near zero), small size and weight. These high performances are due to the low capacitance and contact resistance. However, low switching speed (around 2-40us), bad power handling, high voltage driving and low reliability are still issues for MEMS switches and need to be further improved[3][4]. Both of electromechanical switches and solid state switches have their own advantages and disadvantages. An electromechanical

switch can have broader bandwidth (DC to 40 GHz or higher) with excellent signal linearity, very lower insertion loss, good isolation, and high power handling capabilities up to few hundred watts. However, an electromechanical switch also has disadvantages such as the limited operating life, slow switching time, and high cost due to more cables required in the system. On the other hand, solid state switch can switch 100 to 1,000 times faster than electromechanical switches and the size and weight can be reduced, so it is less expensive than electromechanical switches. Even so, there are still issues for solid state switch as well. It has limited operating power, limited linearity and can handle only narrow bandwidth. The insertion loss, DC power consumption and isolation of solid state switches are also worse than electromechanical switches [5]. Table 1.1 shows the comparison of different parameters in electromechanical and solid state switches.

Table 1.1: the comparison of different parameters in electromechanical and solid state switches[5]

	Electromechanical	Solid state
Frequency range	from DC	from kHz
Insertion loss	low	high
Return loss	good	good
Repeatability	good	excellent
Isolation	good	good
Switching speed	in ms	in ns
Settling time	< 15 ms	< 1 us
Power handling	high	low
Video leakage	none	low
Operating life	5 million cycles	infinite
ESD immunity	high	low
Sensitive to	vibration	RF power overstress, temperature

Today, there are various switch technologies in commercial market. PIN diode switches still play an important role in high power and high frequency applications. Because of the low resistance in the on state, they become a good choice for switching the RF power. Gallium Arsenide (GaAs) monolithic microwave integrated circuits (MMICs) can provide good performance for low power and high frequency applications. However, because of low cost and good integration, CMOS silicon on insulator (SOI) and silicon on sapphire (SOS) surpass the GaAs MMICs in low power applications. Due to low insertion loss, high isolation, high power handling and good reliability, GaN MMICs can replace PIN diode and become promise candidate for high power and high frequency applications [4].

Table 1.2: the comparison of different switch technologies [4]

Switch Technology/parameter	Monolithic PIN diode	GaAs MMICs	CMOS SOI/SOS	RF MEMS	GaN MMIC
Insertion Loss (dB)	0.3-1.5	0.3-2.5	0.3-2.5	0.1-5	0.1-1.5
Isolation (dB)	≥ 30	≥ 25	≥ 30	≥ 30	≥ 30
Power Handling (W)	≤ 50	≤ 10	≤ 50	≤ 10	≤ 100
Power Consumption	High	Low	Low	Low	Low
Switching Speed	ns to μ s	ns to μ s	μ s	μ s	ns
Ron*Coff (fs)	100-200	224	250 (.18 μ)	?	400
Cost	High	Low	SOS-Low SOI-very Low	Medium	High
ESD sensitivity	Medium	High	Low	High	Low

1.2 KEY PARAMETERS FOR MICROWAVE SWITCH

In order to meet the requirement of high performance and well signal control, a microwave switch has three requirements in general. The first requirement is how well the switch can transfer the power. A microwave switch should have low insertion loss (IL), which means when switch is in the on state, the attenuation between input port and output port should be low. The insertion loss is defined as:

$$IL = -20 \times \log|S_{21}(ON)| \quad (1.1)$$

The insertion loss can be effect by parasitic capacitance, resistance, inductance, and conductance present in the switch and it also dependent on the frequency. For the insertion loss, it usually needs to be less than 3dB. The second requirement is how well the switch can block the power. A microwave switch should have high isolation (IS) which means when switch is in the off state, the attenuation between input port and output port. Isolation is defined as:

$$IS = -20 \times \log|S_{21}(OFF)| \quad (1.2)$$

A good isolation, typically more than 25dB, can avoid signals from leaking into the desired signal path. The third requirement is the maximum power that the switch can transfer when switch is in the on state or the switch can block the power when switch is in the off state. A microwave switch should have power handling capability as high as possible. According to different material and design used in a switch, it can have different ability of power handling. In addition to these three important parameters discussed above, there are still some other parameters to be considered such as wide frequency range, high switching speed, low power consumption, reliable, good linearity, longer operating life and so on [6].

1.3 GAN HFET AND C³ VARACTOR

There are some different semiconductor materials or compound semiconductors including silicon (Si), germanium (Ge), gallium arsenide (GaAs), indium phosphide (InP), silicon germanium (SiGe), silicon carbide (SiC), and gallium nitride (GaN) that are widely used in microwave switches. Due to higher electron mobility, compound semiconductors usually work better than semiconductor materials for high-frequency applications. Table 1.3 compares some major parameters of different semiconductor materials. Due to the need of high power and high frequency properties, solid state switches require semiconductor materials with the properties of large breakdown voltage and high electron velocity, as well as the demand of high output power density, high operation voltage, and high input impedance of switch performances which can be achieved by using wide bandgap materials [7].

Table 1.3: the comparison of major electronic properties of GaN to other semiconductors [7]

	Si	GaAs	4H-SiC	GaN	Diamond
$E_g(eV)$	1.1	1.42	3.26	3.39	5.45
$n_i(cm^{-3})$	1.5×10^{10}	1.5×10^6	8.2×10^{-9}	1.9×10^{-10}	1.6×10^{-27}
ϵ_r	11.8	13.1	10	9.0	5.5
$\mu_n(cm^2/Vs)$	1350	8500	700	1200(Bulk) 2000(2DEG)	1900
$v_{sat}(cm/s)$	1.0×10^7	1.0×10^7	2.0×10^7	2.5×10^7	2.7×10^7
$E_{br}(MV/cm)$	0.3	0.4	3.0	3.3	5.6

Gallium Nitride (GaN), having material properties such as high mobility, high saturation velocity, high sheet carrier concentration and high breakdown field that can provide high power for switches, also high heat capacity and thermal conductivity that can provide good heat handling capability, and chemical inertness providing good reliability, becomes a novel semiconductor material which can provide superior performance for high-power and high-temperature microwave applications [8][9]. Thus GaN has been used in making high power microwave switches, such as AlGaIn/GaN heterostructure field-effect transistor (HFET), AlGaIn/AlGaIn metal-oxide-semiconductor heterostructure field-effect transistor (MOSHFETs), etc., which has demonstrated a good performance in maximum power density, bandwidth, widely operation temperature range, high switching power and high breakdown voltage[10]. Figure 1.2 shows the schematic of a HFET structure, which will be used as base components for microwave switch. HFET is a three terminals device, which is controlled by applying bias on the gate terminal to deplete the two dimensional electron gas (2DEG) channel. A more detailed working principle will be described in chapter3.

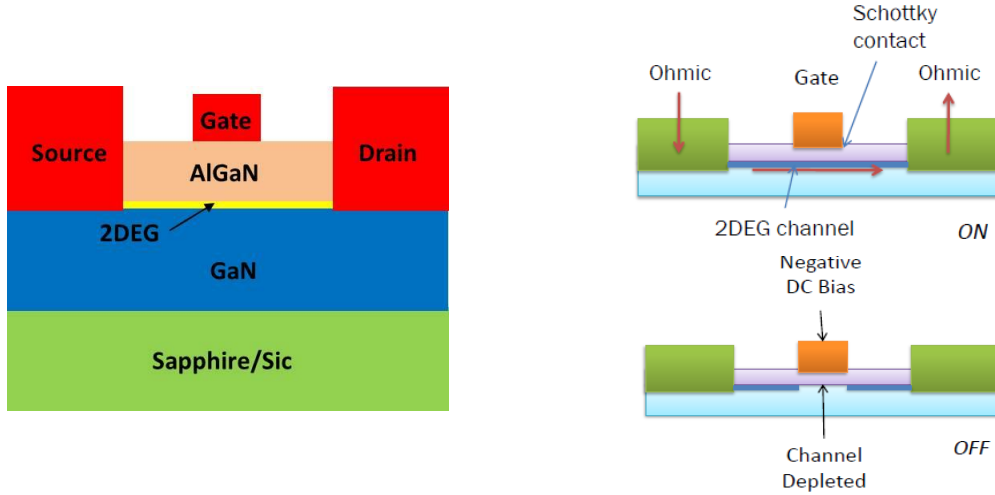


Figure 1.2 The schematic of a HFET structure

Traditional HFET devices were made with Ohmic source and drain contacts, which increase the difficulty of making devices. Forming Ohmic contacts on GaN material usually requires annealing temperature over 850°C [11] which will reduce the quality of the AlGaN/GaN heterostructure and form additional electron trapping center that can degrade the device high frequency performance and device reliability. Ohmic contacts also increase the complicity of the device process due to the face of difficulty in making good ohmic contact on high Al content AlGaN, which can resulting in the high contact resistance and the need of precise alignment. Another issue is related to the gate. In order to avoid the gate breakdown, the space of source-gate and gate-drain need to be high. However, this also increases the channel length and will cause the higher insertion loss which is due to the higher ON-resistance. For purpose of overcome these issues, a new device has been demonstrated.

A novel GaN varactor, namely GaN based voltage controlled capacitor, consisting the design of capacitively couple contacts (C^3), has been proposed and successfully

demonstrated an improved performance for a high power microwave switch [12]. The schematic of the GaN varactor is shown in the Figure 1.3. Instead of using the traditional ohmic contact, two electrodes with the design of C^3 forms the GaN varactor between the electrodes and the 2DEG channel. This type of design has many advantages such as the device can be fabricated by using alignment-free technology which decrease the complicity of device process and no need of annealing process preventing many devices issues and performance degradation. GaN varactors also show higher microwave power handling capability, and lower contact resistance as compare to Ohmic contact devices. Furthermore, GaN varactors can be controlled its ON/OFF states by either applying positive or negative voltage, instead of only negative voltage for traditional normally ON HFET devices [10][12][13][14]. The above mentioned merits suggest that GaN varactors are promising based device for the next generation microwave switch and related communication systems.

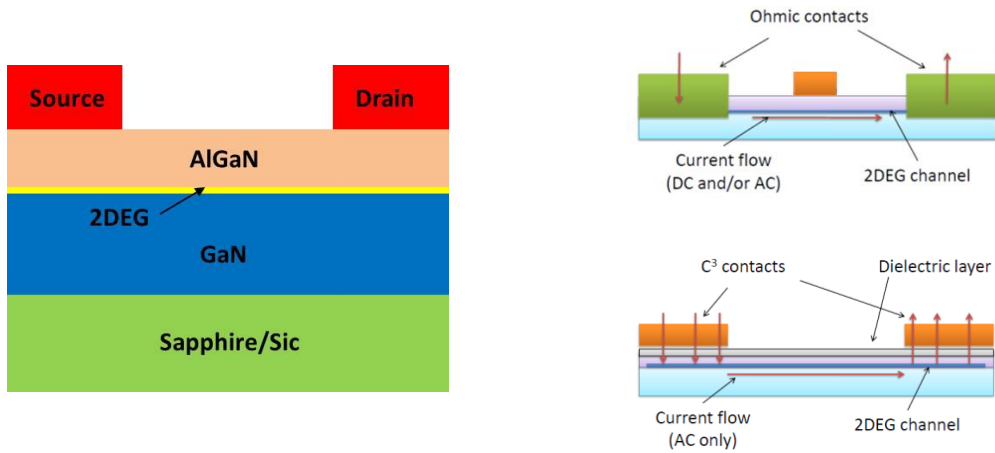


Figure 1.3 The schematic of a C^3 structure

1.4 ELECTROMAGNETIC SOFTWARE

Because of the increasing of the design for high frequency and high speed complex electronic systems, engineers use electromagnetic (EM) simulation software to pre-determine whether the system meet the design requirements. Microwave Electronic Design Automation (EDA) simulation software is related with the EM field of different numerical algorithms. Before we learn about microwave EDA software, we need to know all the numerical algorithms are based on the Maxwell's equations. Understanding the Maxwell's equations is the first step to learn the numerical algorithms in EM field.

There are some numerical algorithms used in the frequency domain, such as finite element method (FEM), method of moment (MoM), finite difference method (FDM), boundary element method (BEM), and transmission-line-matrix method (TLM). Some numerical algorithms used in the time domain, such as finite-difference time-domain (FDTD), and finite integration technology (FIT). Different EDA simulation software which can be classified into different groups according to the numerical analysis they are used [15][16]. Table 1.4 listed the most common EDA simulation software in the market. There is no an absolute advantage that which numerical algorithm has accuracy and efficiency. Different algorithms have different strengths, and suitable for different application.

Table 1.4: Common EDA simulation software in the market [15][16]

Numerical algorithms	software
MoM	Advanced Design System (ADS), Ansoft Designer, Sonnet, Microwave Office, Zeland IE3D, Ansoft Esemble, Super NEC and FEKO
FEM	Ansoft HFSS, and the version after ADS 2008
FDTD	EMPIRE and XFDTD
FITD	CST Microwave Studio

In this thesis, I am using Ansoft HFSS to do EM modeling for microwave switches. HFSS is one of the EM simulation software by using finite element method. FEM is a full 3D algorithm which can be used in arbitrary shape of structure. It has several advantages over MoM and can be applied to many applications such as the Bond-wire or Solder-balls in the package structure, Z-axis direction arbitrary structure, transition designs, and interconnect analysis. In addition, FEM can be calculated the question of finite size substrates, such as the structure of the cavity [17]. However, the simulation time of FEM is usually slower than MoM especially for multilayer planar applications. In the FEM, a large structure is divided into thousands of small area and use volumetric meshing in each sub-region with a local function. The geometric model is automatically divided into a large number of triangular pyramids, and the center point of the field quantities inside each triangular pyramid will be saved. Then, the Maxwell's equations can be transformed into a matrix problem and extract S-parameters of arbitrary shape that are solved by using mathematical operations. The way of FEM estimate the convergence is by comparing before and after operations results. If the error range is less

than a certain value, it is convergence. However, if the error is still too large, then the computer will be re-defined grid so that the grid density is increased in order to enhance the convergence. But, some regions in the 3D structure such as the surface of the structure, corner, and material interface, there will be the poor convergence. These situation will lead the FEM consumes a lot of memory and computing time. So, by supporting multi-core computing and improving the convergence of the structure are also very important issues in recent years. Figure 1.4 shows the geometric model which is divided into a large number of triangular pyramids (mesh).

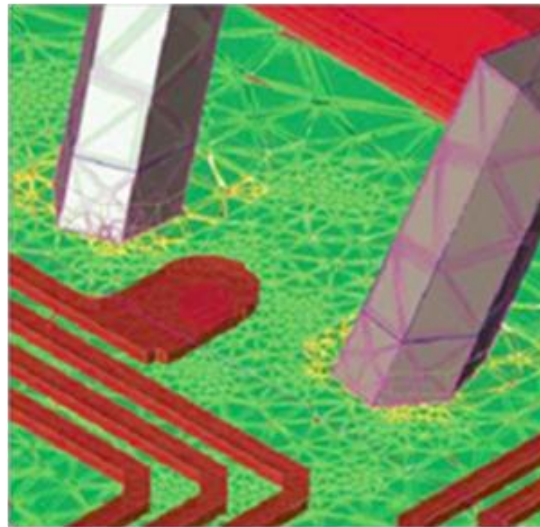


Figure 1.4 FEM three-dimensional mesh [18]

1.5 OUTLINE OF THIS THESIS

This thesis is mainly to establish models to simulate the effects of the device peripheral electromagnetic and coplanar waveguide to the microwave switches performance with switch operating frequency above 10GHz to 20GHz. First chapter

introduce the background of microwave switches, including its applications, types, market availability and base transistors used in this thesis. The comparison of the frequently used Microwave Electronic Design Automation (EDA) simulation software is also stressed in this chapter. In the second chapter, the problem in the MATLAB simulation methods is identified. Chapter3 introduces HFSS EM simulation software to simulate HFET based microwave switches. The newly proposed GaN capacitively coupled contact (C^3) varactor based microwave switches, simulated by establishing HFSS models, are performed in the chapter 4. Chapter 5 summarizes this thesis and point out future works.

CHAPTER 2 PROBLEM IDENTIFICATION

2.1 PROBLEM IDENTIFICATION

It is important to develop a reliable simulation model for devices before the final layout and fabrications, which can save time, cost and prevent experiment errors. In the past, researchers have designed microwave switches by using Advanced Design System (ADS), PSPICE and other tools employing circuit diagrams and equivalent circuits, including the input power, device width and length, frequency range, bias and other parameters that will affect the power go through the switches. Another way is using MATLAB simulation which is programming the related device formula to simulate low frequency large signal model to verify the design before final layout [16][17]. Our group has published several papers by using ADS and MATLAB to accurately simulate III-nitride microwave switches [18][19][20][21]. However, for higher frequency applications, typically more than 10 GHz, the effects of electromagnetic wave scattering and absorption become more significant than at lower frequencies. The simulation result inaccuracy increases while the operating frequency raise. Figure 2.1 shows the insertion loss comparative results of from the measurement of a real HFET SPST device and its MATLAB simulation data. The MATLAB simulation results are well matched with the device measurement data below 2GHz, however, the inaccuracy increases while the operating frequency increases. In our case, the insertion loss at 10GHz shows a difference of 0.5 dB, comparable to the loss itself.

In order to get more accurate device properties for microwave switches, a more accurate simulation tool which can precisely simulate higher frequency microwave switch, especially the effects of electromagnetic field to the device, is demanded.

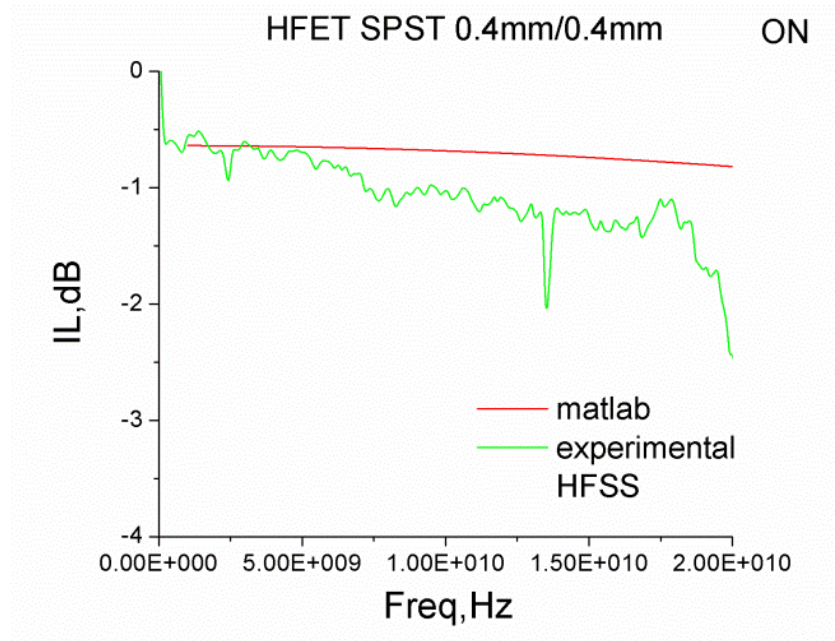


Figure 2.1 The comparison results of insertion loss

This thesis adopts HFSS (High Frequency Structure Simulator) 3D structure simulation to analyze the microwave switch performance. HFSS is the first commercial electromagnetic field simulation software using a 3D structure. It provides a simple and intuitive design interface, accurate and adaptive field solution, and electrical performance analysis capabilities. It can calculate the S-parameters of 3D passive structures of arbitrary shape and full-wave electromagnetic field. There are many results can be calculated by using HFSS. For example, basic numerical solution of electromagnetic fields and the open border issue, the problem of near-and far-field radiation, port

characteristic impedance and propagation constant, S-parameters and the corresponding port impedance normalized S-parameters, and resonant solution.

Although HFSS has many advantages, there are still some issues to be overcome. Compared with simulating a circuit diagram in ADS, HFSS cost more time which relate to the specification of computer and operator system. In general, it saves the time when you simulate a model which has a symmetrical structure.

CHAPTER 3 HFSS SIMULATION OF HFET MICROWAVE SWITCHES

3.1 INTRODUCTION

In this chapter, GaN HFET based switches with operating frequency at 10GHz, including through, series and single pole single throw (SPST), will be simulated by HFSS. These simulated results will be used to compare with MATLAB simulated results. MATLAB simulation principles are to find the on-resistance (R_{ON}) from its equivalent circuit, followed by applying the on-resistance to the insertion loss or isolation formula, which is briefly described here. Figure 3.1 shows an equivalent circuit of a series HFET microwave switch. During ON state, the on-resistance (R_{ON}) is given by:

$$R_{ON} = 2R_C + R_{GS} + R_G + R_{GD} \approx 2R_C + R_{CH} \quad (3.1)$$

Where R_C is the contact resistance, R_{GS} , R_G and R_{GD} can be expressed by ungated (R_{SH}) and gated (R_{SHG}) channel sheet resistance, i.e. $R_{GS} = R_{SH} \times L_{GS}/W$ and $R_{GD} = R_{SH} \times L_{GD}/W$, $R_G \approx R_{SHG} \times L_G/W$, where L_{GS} , L_{GD} and L_G are the gate-source space, gate-drain space and gate length, respectively, and W is the device width. When the device is fully turned on, $R_{CH} \approx R_{SH} \times L_{SD}/W$. For a typical AlGaIn/GaN HFET, the channel sheet resistance is around 300Ω/sq. From equation 3.1, R_{ON} can be easily calculated by giving the contact resistance, sheet resistance, source-drain space and the device width. To find the insertion loss of this HFET microwave switch, equation 3.2 is mostly used, where $Z_0 = 50\Omega$ and $R_{ON} \ll Z_0$.

$$IL(dB) = -20\text{Log} \frac{1}{1+R_{ON}/2Z_0} \approx 0.087R_{ON} \quad (3.2)$$

For finding the isolation, equation (3.3) is used, where $\omega = 2\pi f$ and f is the switch operating frequency [21].

$$IS(dB) = 20\text{Log}_{10} \left[\frac{1}{|1+1/(j\omega C_{OFF}2Z_0)|} \right] \quad (3.3)$$

As described in the problem identification chapter, the MATLAB simulation result shows larger error while the device operating at higher frequency.

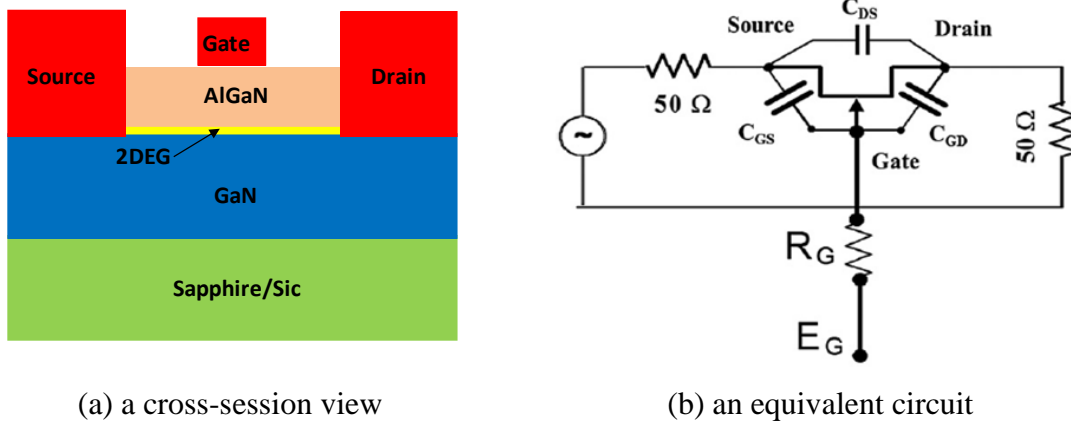


Figure 3.1 A HFET microwave switch

Instead of simply applying formula to the equivalent circuit which only concerns the internal circuit, HFSS is able to simulate 3D structure, including its peripheral electromagnetic field and parasitic effects by dividing the 3D structure to many blocks(meshes) as shown in Figure 3.2, and finding the relation and interactive effects between all the meshes.

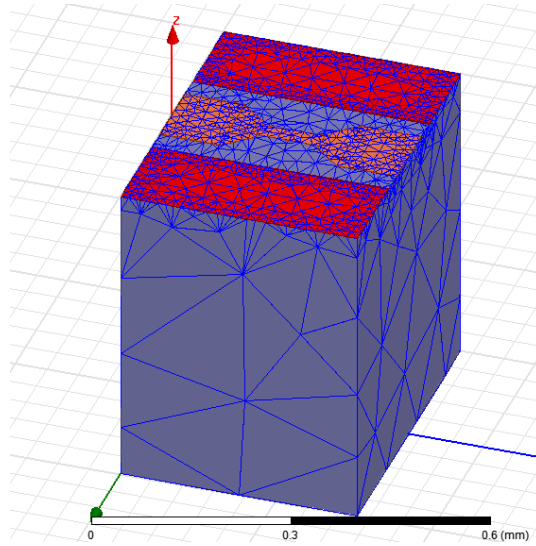


Figure 3.2 The mesh generation of a HFSS through model

3.2 THROUGH

HFSS is used to first simulate simplest circuit structure, which has no transistors or HFET devices embedded, namely through structure. Figure 3.3 shows HFSS layout diagram of the through structure, which only contains one input and one output, where the two ends are connected by a transmission line and the two red rectangles are grounds. This through structure is used to verify that this coplanar waveguide has very low signal loss, which can make sure this transmission line will not affect the overall performance after embed the HFET devices to form a switch.

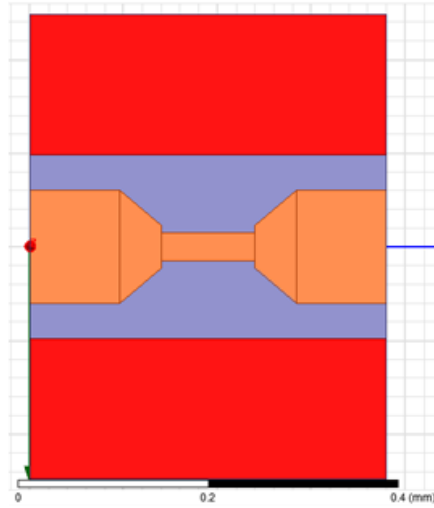


Figure 3.3 HFSS Diagram of through structure

Figure 3.4 expresses a very low insertion loss at frequency ranging from zero to 20GHz (approach 0dB). This indicating the structure is an ideal transmission line, since all the signals from the input pass through the transmission line to the output. It can be used as a base structure for the development of switch devices.

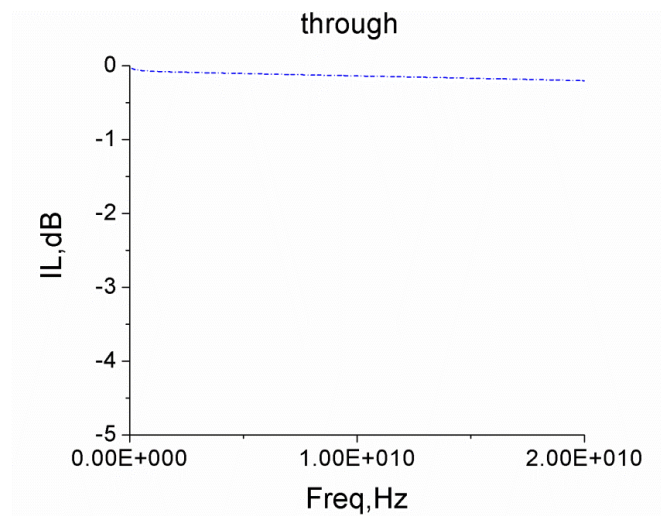


Figure 3.4 Through structure shows around 0dB insertion loss

3.3 SERIES STRUCTURE (100UM)

Series structure has one HFET device connecting the input and output, with total device width of 100um, as shown in Figure 3.5. The fingers area means a HFET device and the yellow portions between fingers represent 2DGE. Figure 3.6 (a) shows the HFET cross section view and its HFSS simulation model in ON state. The HFET gate was not drawn in the HFSS model, this is due to the resistance between the gate and 2DEG is very small, thus we can assume the two metals are connected to become one piece and the effect from the gate can be ignored. Figure 3.6(b) express the 2DEG disappeared, meaning the HFET is in OFF state. The gate was not shown in the HFSS model either, this is due to the depletion length and the 2DEG length was unknown under this state, and we are unable to draw a correct dimension for the gate, depletion region and 2DEG. Instead of putting the gate in the model, we compared the real device isolation to many HFSS models which have different finger gaps (1 to 5um), using the finger gap (1um) that shows the best matched result with real device as standard for the series structure simulation and later HFSS SPST model simulation. The parameters of this model in HFSS are set as in Table 3.1.

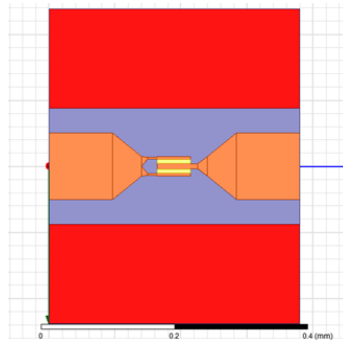


Figure 3.5 HFSS Series structure diagram

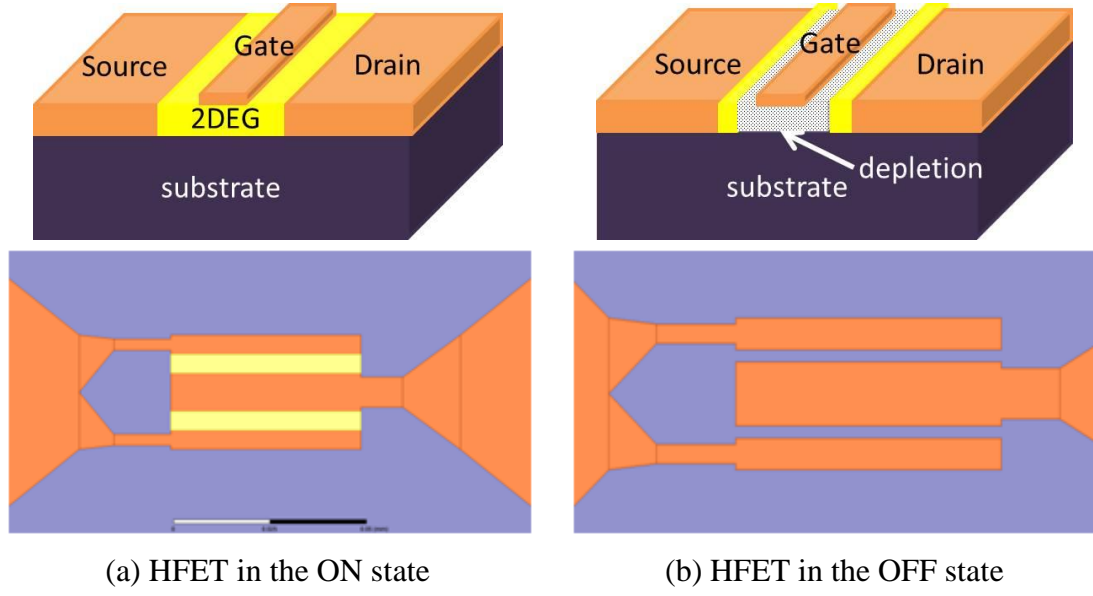


Figure 3.6 HFSS model design for HFET ON/OFF state

Table 3.1 Material parameter for HFET switch in HFSS

	Conductance	Permittivity	Thickness
2DEG	$300\Omega/\text{sq}$	9	0.2 μm
Finger	$4.1 \times 10^7 \text{ S/m}$	1	0.2 μm
Substrate	N/A	9	500 μm

Figure 3.7(a) shows that the insertion loss of the series structure characterized by HFSS simulation, MATLAB simulation and real device measurement. All the results are showing an insertion loss of about 2dB at 10GHz. The device isolation during OFF state is around -20dB for all the measured data at 10GHz as exhibited in the Figure 3.7(b). Both insertion loss and isolation characterized by HFSS model, MATLAB simulation and real device are well matched, indicating the HFSS model, MATLAB simulation can be used in simulation this type device structures.

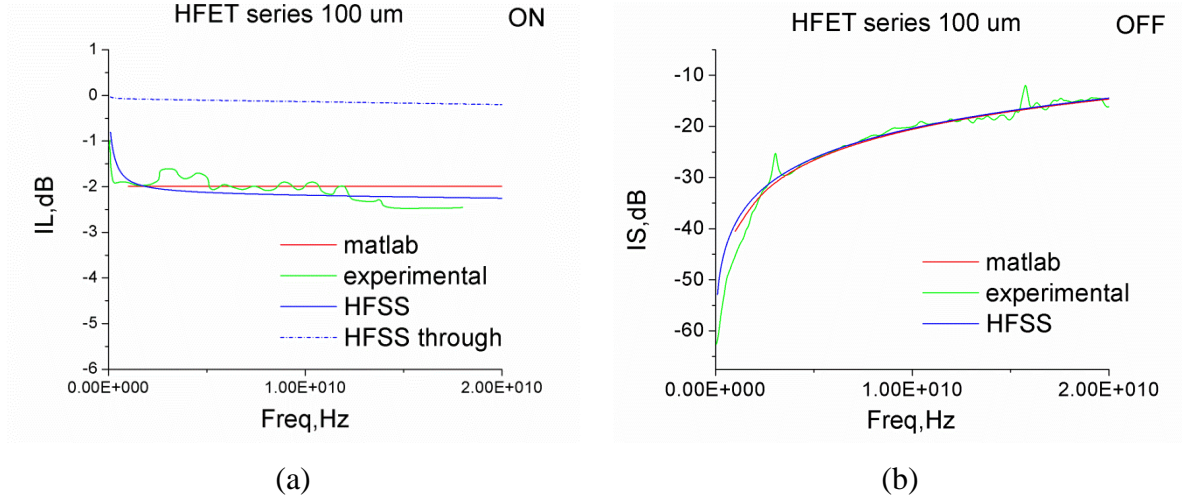


Figure 3.7 Insertion loss and Isolation of series structure

3.4 HFET SINGLE POLE SINGLE THROW(SPST) SWITCH

Single pole single throw (SPST) switch is one of the most common switches in the market. In this section, SPST switches containing different dimension sets of HFET will be used to verify the correctness of the HFSS simulation model. The data will be used to compare with the real device measurement and MATLAB simulation. Before switches were fabricated, different dimension optimization of a MATLAB simulation was used to find out the best combination of series and shunt device dimensions. Here SPST switch with series and shunt dimension sets of 1.05mm/ 0.75mm and 0.4mm/0.4mm which shown best insertion loss and isolation results from MATLAB simulation were chosen.

3.4.1 HFET SPST (1.05MM/0.75MM) DC-10 GHz SWITCH

Figure 3.8 exhibits a SPST switch, consisting series HFETs with overall device width of 1.05mm and shunt HFETs with total device width of 0.75mm (found using

MATLAB optimization). The insertion loss versus operating frequency curve of this SPST device is shown in Figure 3.9(a). It shows a clear trend that the insertion loss increases while the operating frequency increases. Usually the insertion loss is related to the overall impedance. In the ON state, the on-resistance from the series is almost frequency independent. Thus the increase of loss is resulted from shunt components, where the impedance of the off state capacitance is frequency dependent. Also, the HFSS model showing a well matched result to the real device at 10GHz operating frequency as compared to the MATLAB simulations. The isolation is shown in Figure 3.9(b), which also shows a better match for the HFSS model than the MATLAB simulation. The increase of the isolation is also due to the increase of the overall impedance, which can be easily explained by applying high frequency value to equation 3.3.

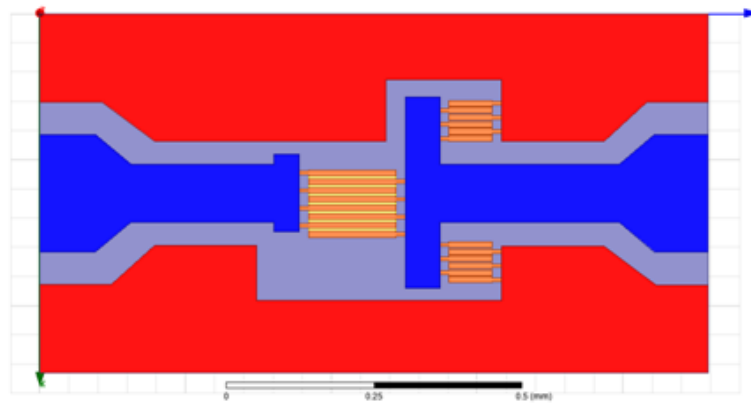


Figure 3.8 HFSS-SPST 1.05mm/0.75mm structure diagram

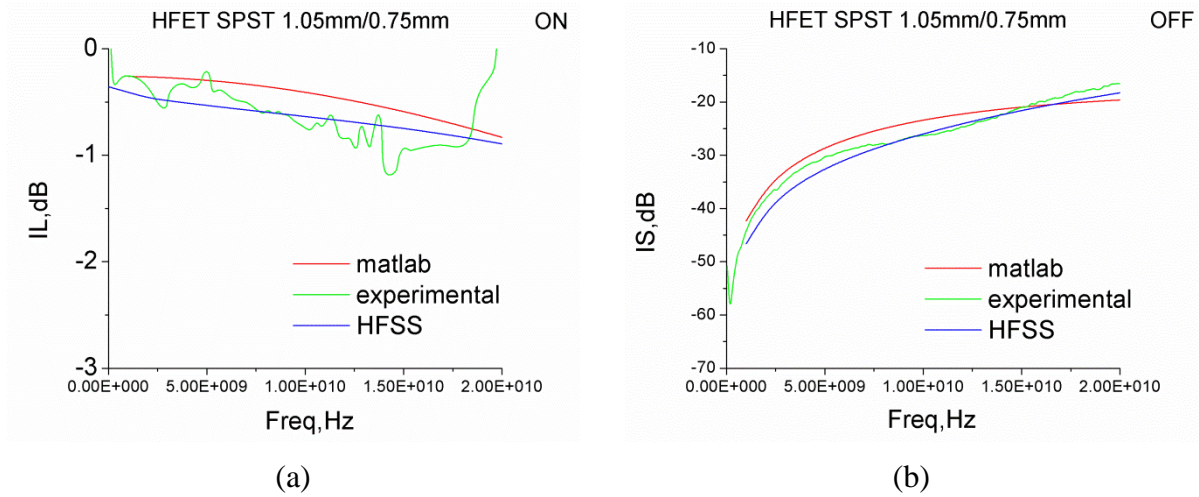


Figure 3.9 Insertion loss and Isolation of HFET-SPST 1.05mm/0.75mm switch

3.4.2 HFET SPST (0.4mm/0.4mm) DC- 20 GHz SWITCH

Another HFSS SPST switch model with HFET device width of 0.4mm at both series and shunt portions is shown in the Figure 3.10. In order to get a good switch performance at 20GHz, instead of 10GHz, we have used MATLAB simulation to find the best match of series-shunt configuration, and the series-shunt dimension set of 0.4mm/0.4mm was chosen. Both the insertion and isolation by the HFSS simulation are close to the real device performance at 20GHz. However, the insertion loss shows significant error in the MATLAB simulation. This difference is due to reflections and loss in the coplanar waveguide, not accounted for in MATLAB.

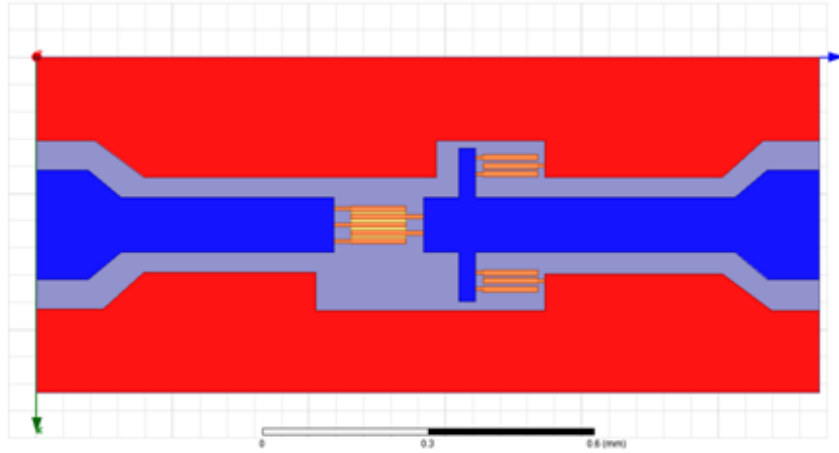


Figure 3.10 HFSS-SPST 0.4mm/0.4mm structure diagram

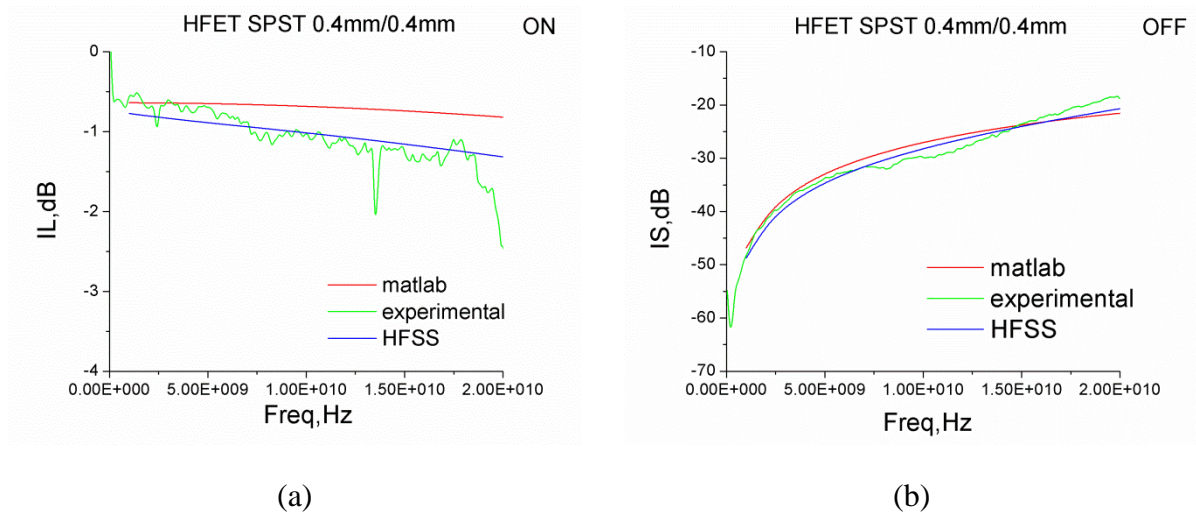


Figure 3.11 Insertion loss and Isolation of HFET-SPST 0.4mm/0.4mm switch

In this chapter, we have successfully showed that HFSS is able to accurately simulate the performance of simple through structure and HFET based series structure, and SPST microwave switches by establishing HFSS models with operating frequency ranging from 0 to 20GHz.

CHAPTER 4 HFSS SIMULATION OF GAN VARACTOR SWITCHES

4.1 INTRODUCTION

The concept of capacitively coupled contact (C^3) used in HFET has shown much higher microwave power handling capability and lower contact resistance as compared to regular devices with annealed Ohmic contacts [11][13]. Our group have further combined the concepts of voltage-controlled capacitor (varactor) in our GaN based HFET microwave switch, and published first GaN capacitively-coupled contact (C^3) varactors based microwave switch for MMICs [12][22], which gives higher flexibility to tune the source/drain spacing, since the gate has been removed and decrease the overall impedance. The symmetrical C^3 varactor also has advantages such as can be controlled either by applying positive bias or negative bias, and no need of post annealing process and gate alignment. The major difference between the traditional ohmic contact based transistors to the capacitively coupled contact based varactor switches is that the later does not require DC current flow through the device. Thus instead of flowing the current through the ohmic contacts, which physically connected to the device channel, the C^3 varactor pass the microwave signal through the 2DEG channel by generating strong capacitively coupling effect between the metal electrode and the 2DEG channel, as shown in the Figure 4.1.

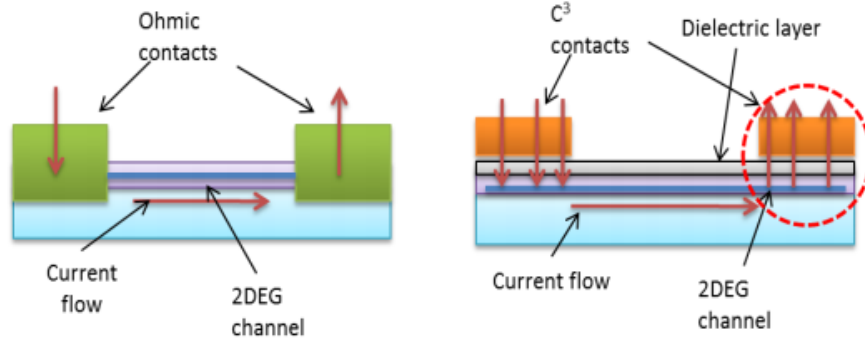


Figure 4.1 Comparison structure of ohmic and C^3 contact

As mentioned before that one of the advantages for using the C^3 varactor is this device can be controlled by applying either positive or negative bias. Figure 4.2(a) shows a layout of C^3 varactor device which can be turned off by applying voltage to either of the contacts with voltage exceeding the contacts pinch-off voltage, typically for Schottky contacts is around 3~4V as the case here, and around 6- 9V for metal-insulator-semiconductor (MIS) type contacts. To find the device performance such as insertion loss and isolation, it is prerequisite to find the device impedance, which can be extracted from the device equivalent circuit, as shown in the Figure 4.2(b). The impedance of C^3 varactor is defined by a series connection of capacitors, attributed to the two electrodes and channel, and resistors, attributed to the contact resistance and 2DEG resistance. Also, the existence of the C^3 metal contacts and the 2DEG channel, an RC transmission line is formed between them. And thus the total varactor impedance at zero bias can be found from equation 4.1 and 4.2:

$$Z_V = 2Z_{C3} + R_d \quad (4.1)$$

$$Z_{C3} = Z_0 \coth(\gamma L_c); \text{ where } \gamma = \sqrt{j2\pi f R_{sh} C_1} \text{ and } Z_0 = \frac{1}{w} \sqrt{\frac{R_{sh}}{j2\pi f C_1}} \quad (4.2)$$

Where Z_{C3} is the C^3 electrode impedance, γ is the propagation constant, Z_0 is the transmission line characteristic impedance, $R_d = R_{sh}d/W$, d is the electrode spacing, f is the operating frequency, R_{sh} is the channel sheet resistance, C_1 is the unit-area capacitance between the electrode and the channel, L_c and W are the electrode length and width. While at a low frequency, $|\gamma L_c| \ll 1$, and C^3 varactor impedance can be approximated as a series resistor with one-third of the total channel resistance and a series capacitor with the capacitance equals to a parallel capacitor of the same geometry, as expressed in the equation 4.3 [12]:

$$C_{C3} \approx C_1 W L_c \text{ and } R_{C3} \approx R_{sh} L_c / (3W) \quad (4.3)$$

The device insertion loss in ON state is related to channel resistance and the two contact resistances, which can be reduced by improving growth and device fabrication processes. Isolation in OFF state is related to the capacitance, which can be reduced by reformation the device layout.

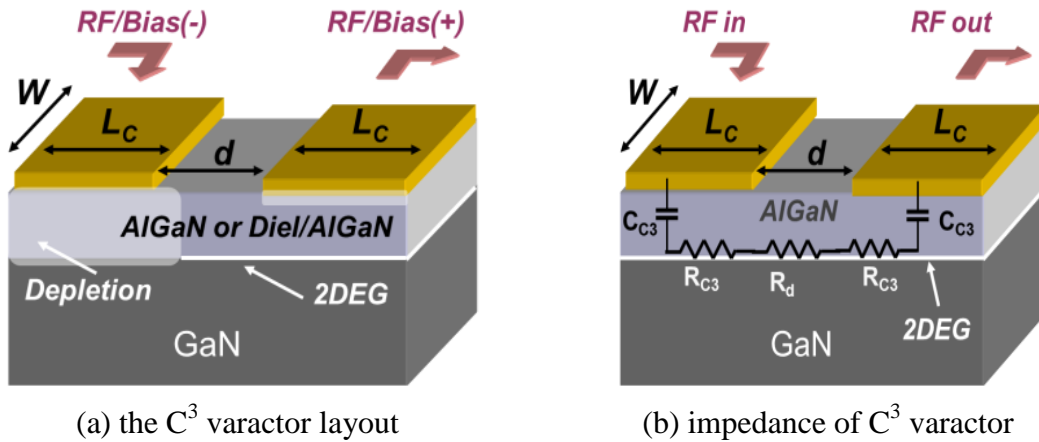


Figure 4.2 The schematic of C^3 varactor

In this chapter, we establish HFSS model to simulate the C^3 varactor based microwave switch at as high as 20GHz operating frequency. The MATLAB simulation results and real device measurement results will be also to compare and verify the correctness of the HFSS models.

4.2 C^3 VARACTOR TEST STRUCTURE DESIGN & SIMULATION

Before starting the establishment of the HFSS model, it is important to understand the principle behind switching the C^3 varactor between ON and OFF state. In the previous section, Figure 4.2 shows the layout of the C^3 varactor, and points out that the device is a normally ON device. To switch the device to OFF state, a voltage with a value exceeding any of the electrodes pinch-off voltage is required.

C^3 varactor is an active model, which is not able to simulation in HFSS. However, in either the ON or OFF state, C^3 varactor is composed of planar capacitors which are formed by electrodes on the top and 2DEG layer on the bottom. In this behavior, two HFSS models to simulating C^3 varactor device ON and OFF state are built as shown in Figure 4.3. During ON state, the 2DEG (yellow block) has the same length as the dielectric (purple block), indicating the 2DEG is able to couple the signal from the input to the output. During the OFF state, namely an exceeding pinch-off positive voltage has been applied to the right side finger, inducing more electrons to the right electrode and further resulting in a depletion region (black block) below the dielectric. Thus the 2DEG has shorter length resulting in the signal from the input cannot pass through the 2DEG reach output, since the 2DEG is not long enough to reach the portion under the output electrode.

Applying this ON and OFF simulation methods to microwave switch models which has multiple fingers, two HFSS simulation models representing the multiple fingers device ON and OFF states are exhibited in the Figure 4.3(b).

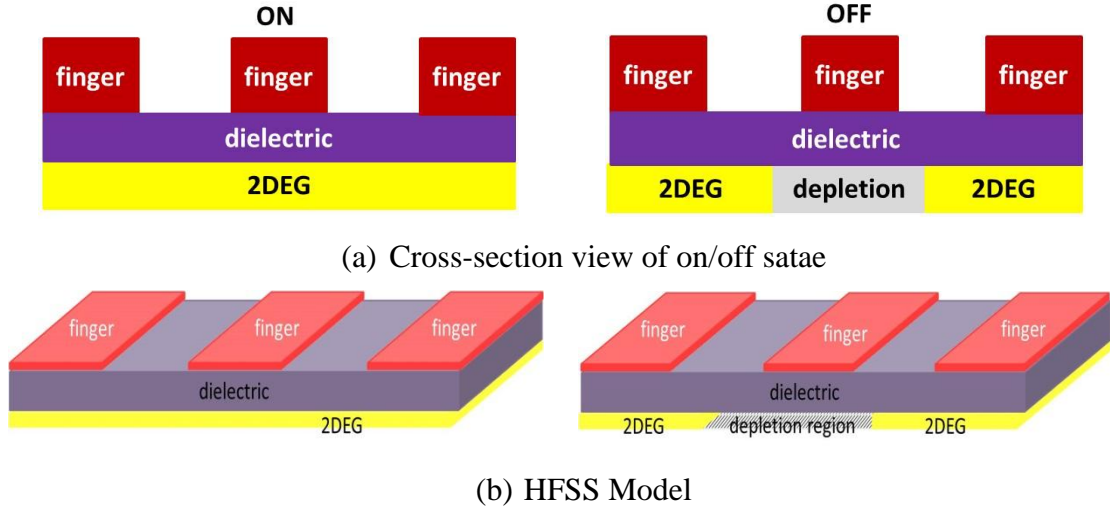


Figure 4.3 HFSS model design for C^3 device ON/OFF state

After we built this model in HFSS, we use it to simulate for three simply C^3 varactor series structures with three different device widths, which are 250um, 500um and 1000um. The schematic of a C^3 varactor series structure in HFSS is shown in Figure 4.4. For initial validation of this device concept, a multi-finger C^3 varactor test structure having the total width of 250, 500 and 1000 um with each electrode 2 um long and 50 um wide was designed. The gap between the two electrodes was kept 2 um and the 2DEG sheet resistance was 300 Ohm/Sq.

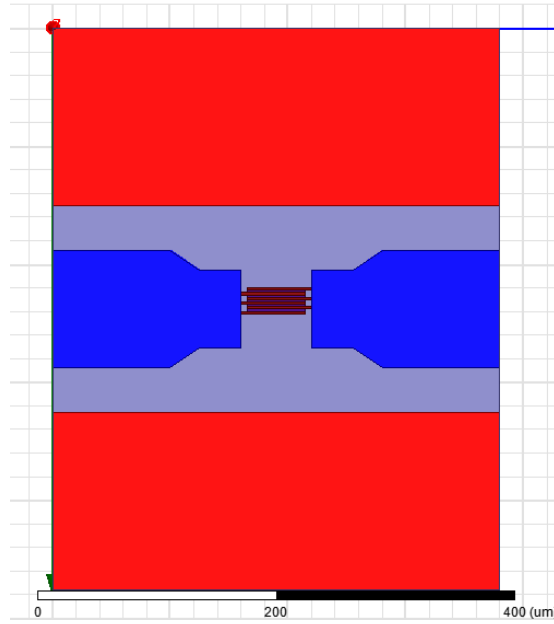


Figure 4.4 C³ series 250um structure diagram

The insertion loss results is showing in the Figure 4.5(a), where all the three dimensions of the HFSS models are showing good matched to the experimental results with an insertion loss of around -0.75dB~-0.25dB at 10GHz. Figure 4.5(b) also shows well matched results of three different devices isolation for HFSS simulation and the real device measurement. Both of the results have suggested that the establishment of the HFSS model to simulation this type of microwave switch is able to precisely predict the microwave switch performance.

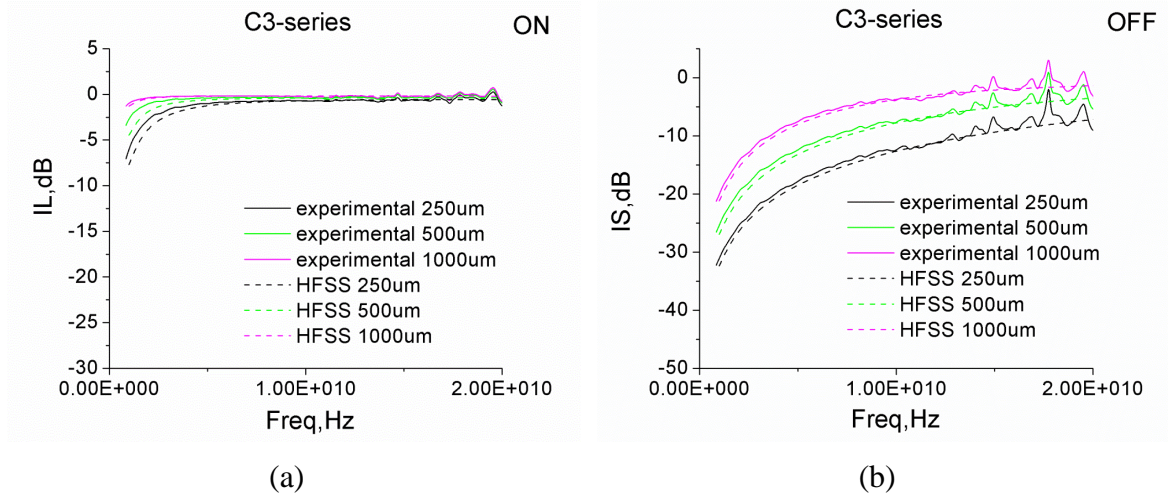


Figure 4.5 Insertion loss and Isolation of C³ Series structures

4.3 C³ SINGLE POLE SINGLE THROW(SPST) SWITCH (0.5MM/0.5MM)

In this section, C³ varactor based SPST microwave switch will be simulated. Like previously mentioned in the HFET section, MATLAB simulation with different sets of series and shunt device dimensions were used to find the best dimension combination before the device to be fabricated. Here C³ SPST switch with series and shunt dimension set of 0.5mm/ 0.5mm was chosen.

The microwave switch for this work was designed by our group using series-shunt layout that is shown in Figure 4.6. The series and shunt C³ varactors have multi-finger structure with 2 um electrode length, 2 um gap and single finger width $W_1=50$ um. The total width of the series and shunt varactors are both 0.5mm, i.e. $W_{SER}=W_{SHT}=10 \times W_1=0.5$ mm as optimized in MATLAB. For this design, we are able to get a very small off-state capacitance with $C_{OFF}=0.15$ pF/mm and to achieve minimal isolation of 25 dB at 18 GHz.

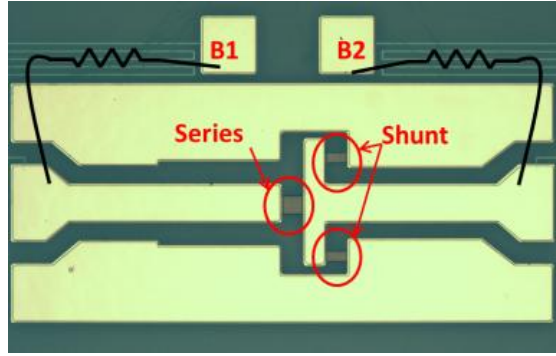


Figure 4.6 Series-shunt MMIC layout

Though from the above MATLAB design we were able to get an isolation of -25dB at 18GHz, it is needed to further improve of isolation to increase the efficiency. In order to decrease the simulated isolation, we have added inductances in series varactors with an inductance value of 0.3nH and in shunt varactors with inductance value of 0.1nH to compensate the capacitive component of the C^3 impedance as shown in the Figure 4.7. Figure 4.8 shows the insertion loss and isolation simulation results which clearly showing that after adding the compensating inductance to the simulation device, a resonant phenomenon occurs at 15GHz with an isolation as low as -28dB.

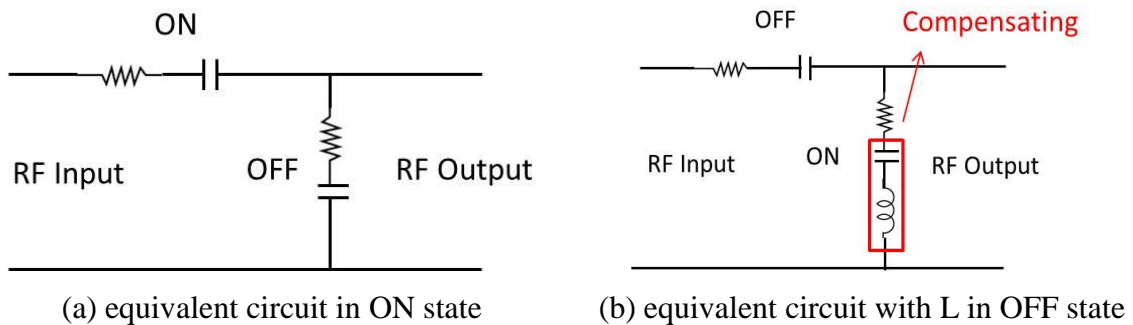


Figure 4.7 Equivalent circuit in ON and OFF states

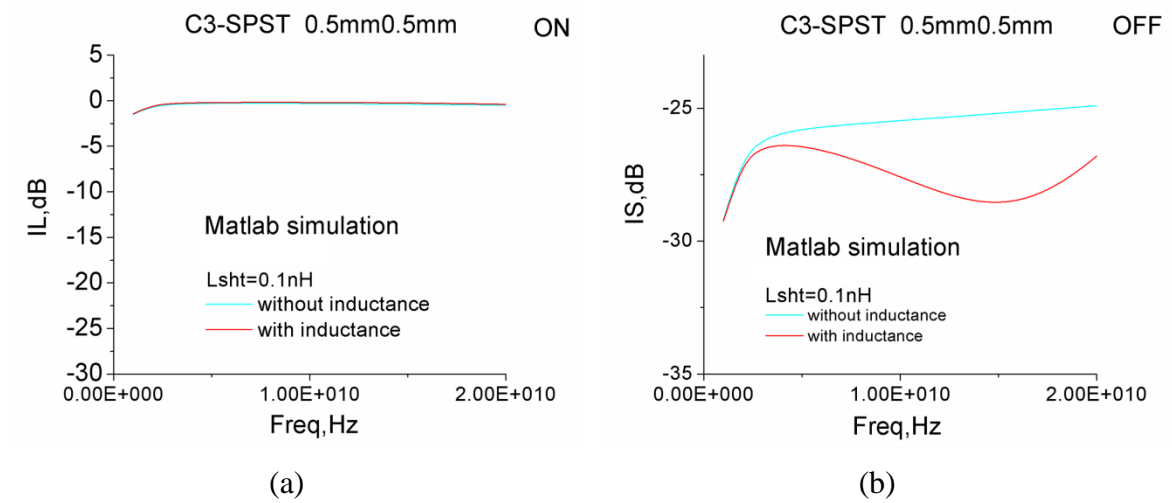


Figure 4.8 Simulated Insertion loss and Isolation over varying frequency with and without added inductance from MATLAB

In the following, we use above MATLAB designed device parameters, including the compensating inductances which were implemented by narrowing the signal lines and increasing the gap in the CPW pattern, to fabricate an C^3 SPST Switch with 0.5mm/0.5mm width. The real device testing results is showing in the Figure 4.9. Though the insertion loss for the real device and the MATLAB simulation results are close, the isolation results are having large errors. This maybe due to the MATLAB simulation was unable to precisely simulate the overall electromagnetic field effects around the coplannar waveguide.

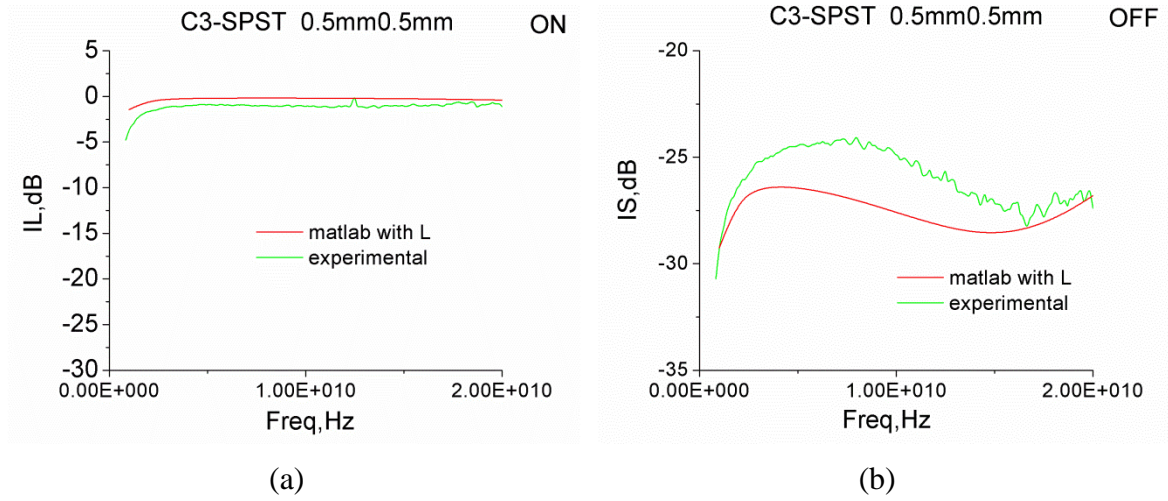


Figure 4.9 Insertion loss and Isolation of real C³ SPST switch

In order to provide a matched simulation results, we establish an HFSS model to simulation the above fabricated device. HFSS model of the C³ SPST microwave switch is shown in the Figure 4.10. The ON state insertion loss and OFF state isolation of MATLAB, HFSS simulation and real device measurement are exhibited in the Figure 4.11(a) and Figure 4.11(b) respectively. Both of the results show that HFSS model can be used to simulate the real device performance.

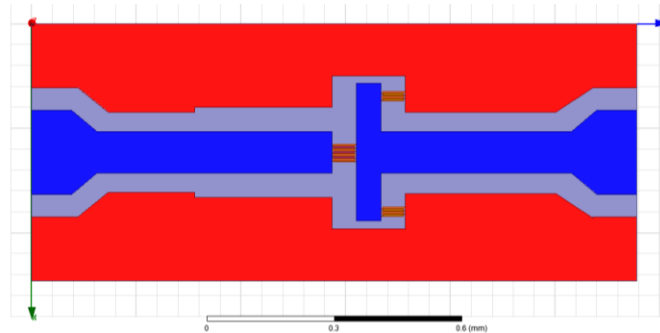


Figure 4.10 C³ SPST 0.5mm/0.5mm structure diagram

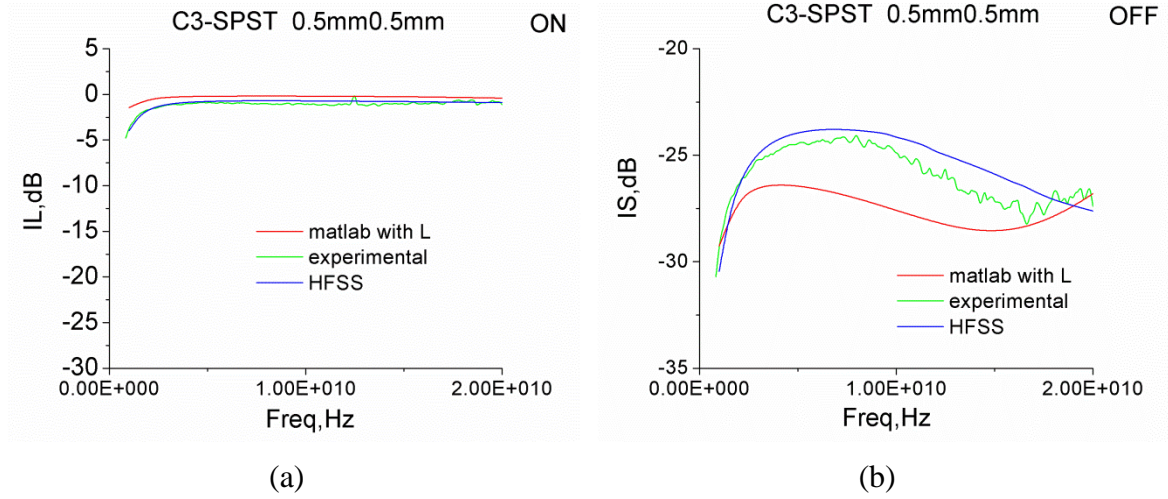


Figure 4.11 Insertion loss and Isolation of C³ SPST 0.5mm/0.5mm switch

In order to get closer layout design to a real MMIC SPST switch, we also established SPST model with smooth corner which is shown in Figure 4.12, where we modified all the corners from a sharp shape to a curve shape as shown in the inset image. In Figure 4.13, the simulation results of HFSS models with/ without smooth corner are showing similar insertion loss and isolation, indicating the design of smooth corner will not have major affects to the device performance. The establishment of HFSS model with smooth corner will take more time to draw than that without smooth corner. Since the smooth design did not show any differences from the sharp corner, we will keep using sharp corner design to establish HFSS model.

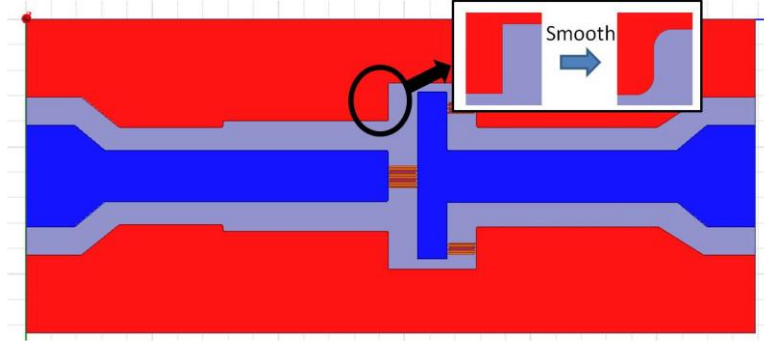


Figure 4.12 C^3 SPST 0.5mm/0.5mm structure diagram with smooth corner

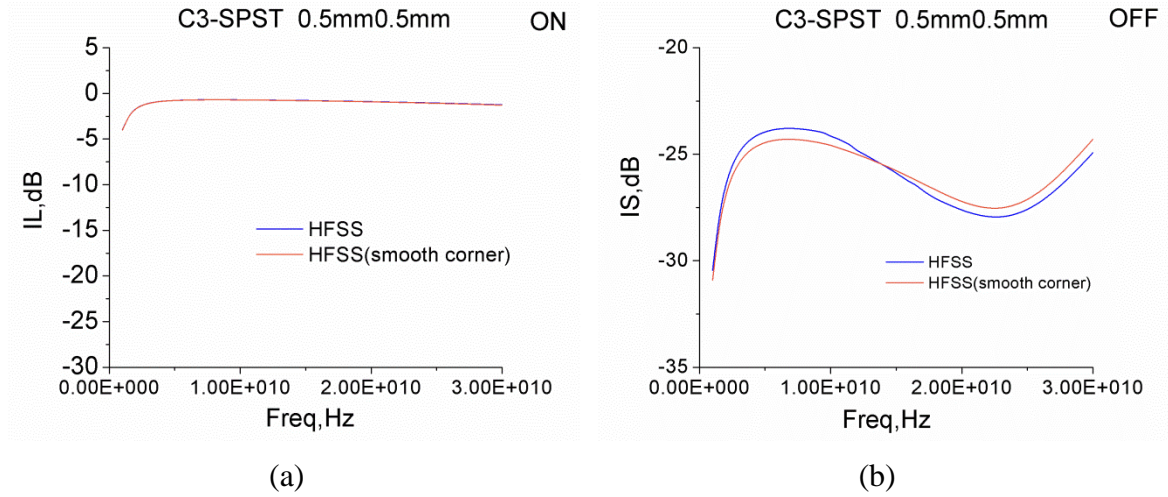


Figure 4.13 Comparison of insertion loss and isolation of C^3 SPST 0.5mm/0.5mm switch with/without smooth corner

After the successful demonstration of the real device performance by using HFSS simulation, we would like to use HFSS to further design the switch layout to get a resonance at different frequency. Since we have demonstrated from the MATLAB simulation and shown that an additional inductance may induce a compensating phenomenon, which can be implemented by narrowing the signal lines and increasing the gap in the CPW pattern. Thus in the Figure 4.14, we are showing a modified C^3 SPST

switch with an increased ground to signal line space to increase the compensating inductance.

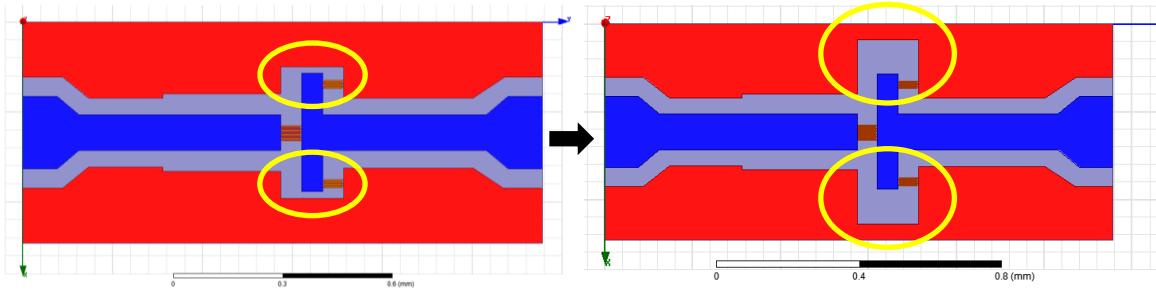


Figure 4.14 Modified C³ SPST 0.5mm/0.5mm structure diagram

The HFSS simulation results in the Figure 4.15 showing that the resonant frequency was shifted from 23GHz to 19GHz, which indicates that we are able to precisely simulate the resonant phenomenon, the space of the ground to signal line can increase the inductance and the increase of the inductance can shift the resonant frequency to a lower value. Thus we are able to use HFSS simulation to improve real device design by modifying the imperfect capacitance compensation effect.

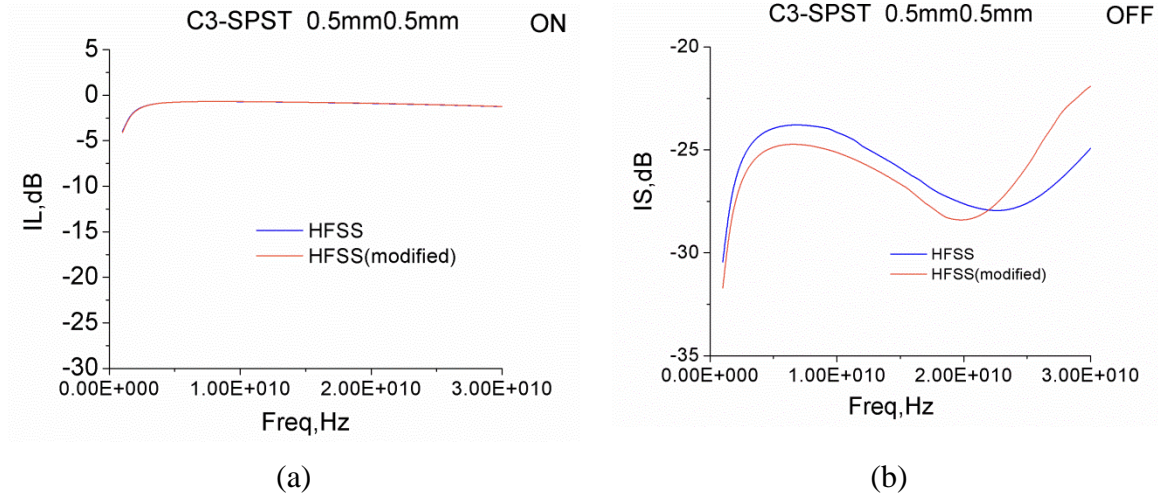


Figure 4.15 Insertion loss and Isolation of modified C³ SPST 0.5mm/0.5mm switch

The above simulation results suggest that the establishment of HFSS model is able to simulate simple structures such as through, series and SPST microwave switches. HFSS simulation is also able to provide a higher accuracy than the commonly used MATLAB simulation. Since HFSS simulation considers not only the transistors themselves, but also the peripheral electromagnetic field. It is automatically dividing the established HFSS model to many small blocks (meshes), and summarizing the effects between each mesh.

4.4 C³ SINGLE POLE DOUBLE THROW(SPDT) SWITCH

In this section, C³ varactor SPDT switch will be discussed. Unlike SPST, which has only one output, SPDT is a three ends switch, containing one input and two outputs, which increases switch functionality. A more complicated device is expected to have more coupling effects, which will increase the difficulty and inaccuracy of the simulation.

4.4.1 C^3 SPDT SWITCH (0.25MM/0.2MM)

Figure 4.16 express an SPDT HFSS model, where signals go from top input to either one of the side outputs. Here assume A end switch is ON and 2DEG appear at the two circles region. This switch has C^3 varactors with device width of 0.25mm at the series portion and 0.2mm at the shunt portion. As mentioned before, the series and shunt configuration plays a strong funtion to the switch performance. The increase of the shunt width will improve the isolation, however, that will also increase the insertion loss due to the increased off-capacitance caused from the larger width. Different sets of series- shunt dimensions were used to find the best match for switch performance. There exists a large gap between the signal and ground in the model, this is due to the need of placing the input and two outputs contact pads.

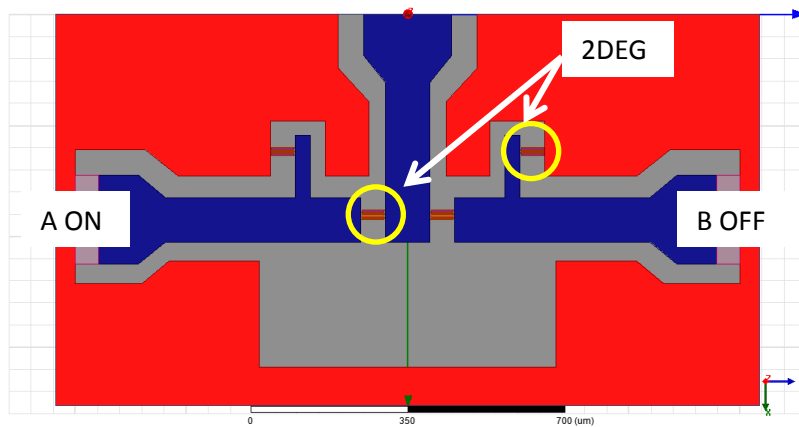


Figure 4.16 C^3 SPDT 0.25mm/0.2mm structure diagram

Insertion loss results are showing in the Figure 4.17(a), where HFSS result is showing around -2dB, experimental result is around -1.2dB and MATLAB is showing -0.5dB at 10GHz. Both HFSS and MATLAB shows errors as compare to the experimental

data. However, MATLAB shows a smaller insertion loss than the real device. This can be explained that due to MATLAB simulation did not consider the peripheral electromagnetic field and coupling effects from the coplanar waveguide. When the operating frequency increases, the difference becomes much smaller and the results match at around 20GHz. The isolation data is exhibited in the Figure 4.17(b). HFSS simulation also shows a better match to the experimental results while operating at the higher frequency, where both of the data shows the isolation ranging from -23dB to -25dB at operating frequency from around 3GHz to 20GHz. However for the MATLAB simulation data the isolation are ranging from -27dB to -32dB, which shows around 20% difference to the experimental results. Furthermore, the MATLAB simulation incorrectly predicts the isolation trend, where the data shows a resonant frequency at around 15GHz. But, there are no resonant phenomenon exists for the experimental curve.

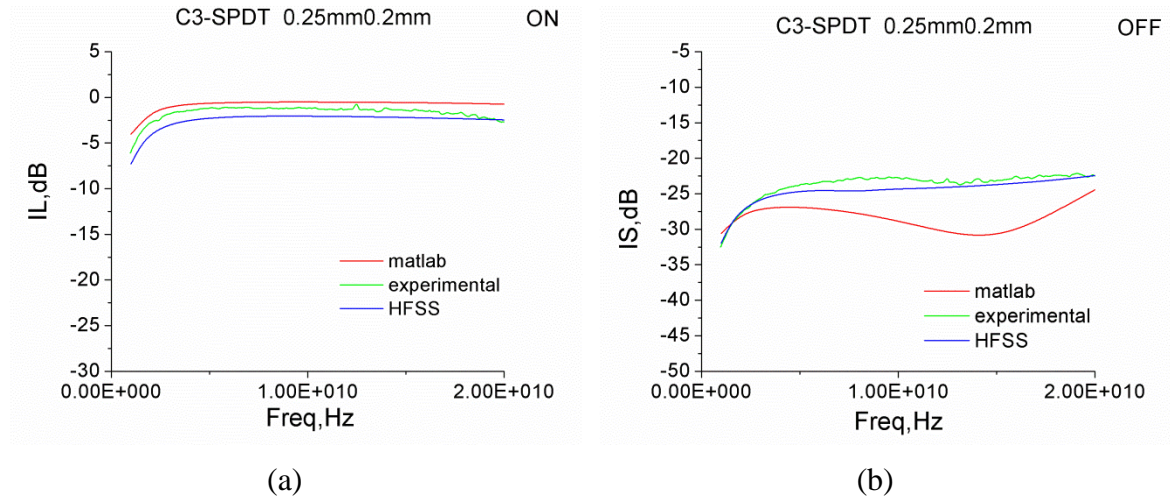


Figure 4.17 Insertion loss and Isolation of C³ SPDT 0.25mm/0.2mm switch

The establishment of HFSS model to simulate microwave switch at operating frequency at more than 10GHz is once again verified to be able to predict the loss performance of the switch in not only simple, but also complicated structure. The simulation accuracy increases while the operating frequency increases. In the following section, we will modified the existing C³ SPDT 0.25mm/0.2mm switch and try to design a new C³ varactor SPDT switch by establishing previously verified HFSS models.

4.4.2 C³ SPDT MODIFIED SWITCH (0.25MM/0.2MM)

An modified (from Figure 4.15 SPDT switch) SPDT HFSS model is shown in the Figure 4.18. We have found out from the previous section that the real device shown a worse performance as compare to its MATLAB simulation, and we assume the different is due to the real deivce has on purposely design a large gap for the insertion of contact pads. In this design, we would like to test the affects of filling up the bottom gray portion air gap with the ground metal, also we would like to form the contact pads outside the coplanar waveguide, since our previous HFET design shows that the contact pads formed outside the waveguide will not affect the switch performacne. We predict that this will help to eliminate the OFF state inductance impedance and may result in a decrease of isolation.

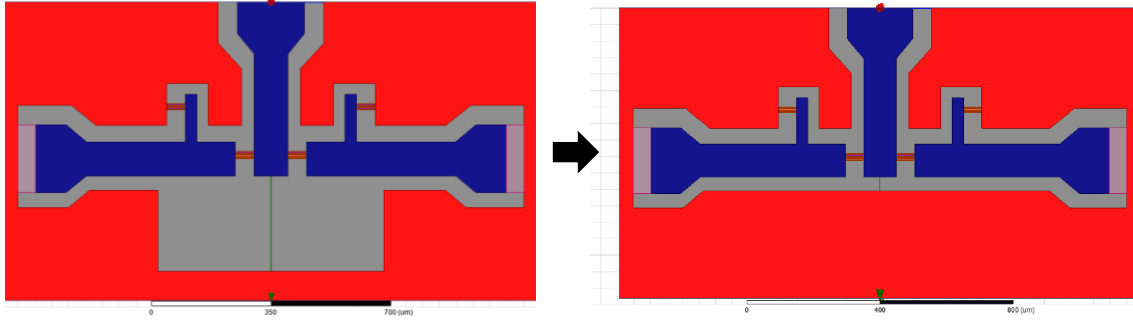


Figure 4.18 C^3 Modified SPDT 0.25mm/0.2mm structure diagram

Figure 4.19 exhibits the comparative results between the modified and unmodified switch. The insertion loss did not show much difference after we fill the additional ground to the device. However, the isolation for the modified structure showing a large improvement. Also a device resonant phenomenon appears at frequency of around 22GHz with an isolation of -42dB. We believe that this resonance is coming from increased capacitance, since the distance between the signal line and ground has been narrowed, causing a compensating effect and a resonance at the 22GHz operating frequency.

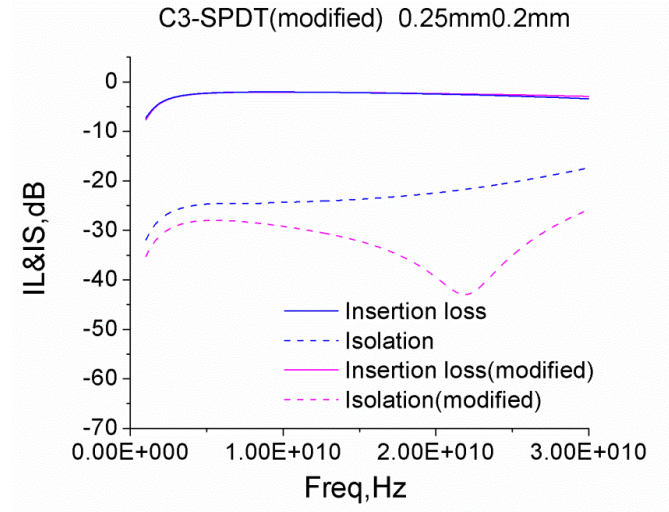


Figure 4.19 Insertion loss and Isolation of C^3 SPDT modified switch

4.4.3 NEW DESIGN OF C^3 SPDT SWITCH

In this section, we want to design a C^3 SPDT Switch (0.25mm/0.2mm) with a new coplanar waveguide layout. The structure diagram and design dimensions are showed in figure 4.20. In order to save the simulated time, approach the future fabricated real device performance and limit the errors which may caused by the complicated structure, we built a symmetrical layout. The model is simulated while A port is ON. B port is OFF and thus the 2DEG exist at the white circle region. The insertion loss results in the Figure 4.21 showing a value of -2.2dB at 10GHz, which is similar to the section 4.4.2 SPDT insertion loss result. The isolation is also showing a resonant phenonmenon with a low isolation of -41dB at the resonant frequency of 16GHz. We assume this resonant phenonmenon is due the existance of additional compensating inductance coming from the interaction between signal line A and siganl singnal line B. In the previous model, the two signal lines are too far to induce obvious inductance. Another reason for the improved performance, may due to the signal is parallelly transmit from the input to the output, instead of vertically

transmit.

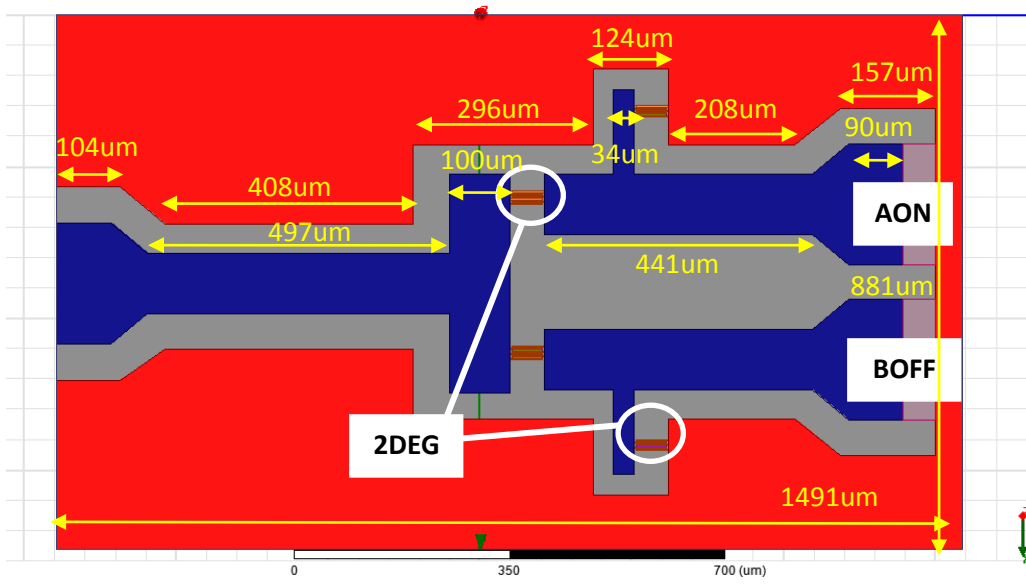


Figure 4.20 New C³ SPDT design structure diagram

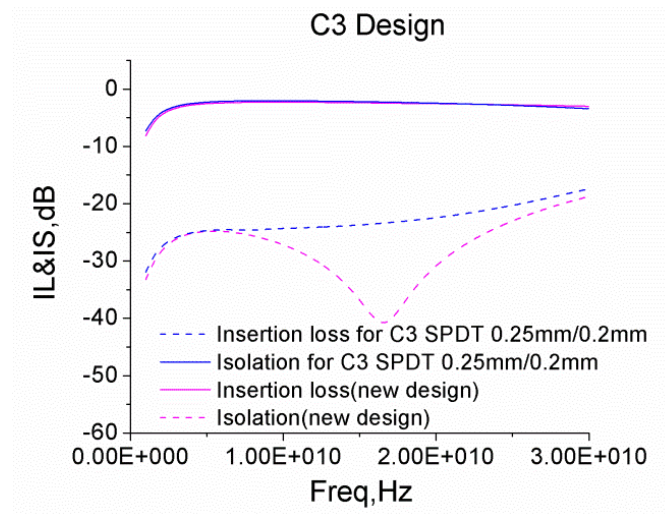


Figure 4.21 Insertion loss and Isolation of C³ SPDT design switch

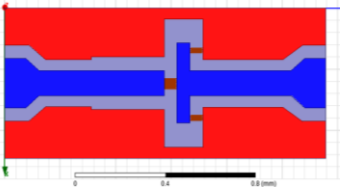
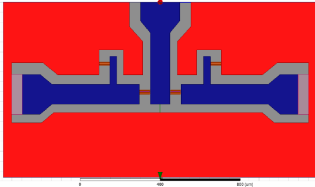
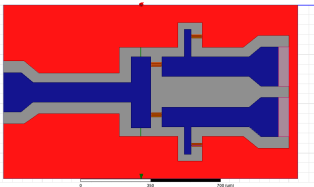
CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

This work presents the use of HFSS as a reliable electromagnetic simulation tool to simulate the effects of the peripheral electromagnetic field and coplanar waveguide coupling effects to the GaN HFET and GaN C^3 varactor based microwave switches. Unlike other devices such as power amplifier, which has power loss more than 3dB, GaN switch has outstanding performance with very low power loss less than 1dB. This low loss value makes any scattering and loss in waveguides incorporating the device becoming significant effect in the switch overall performance. Thus a simulation tool that can precisely simulate low-loss microwave switches is needed. The Device performance of structures like through, series, SPST and SPDT by using both HFET and GaN varactor based components were accurately simulated by establishing HFSS models. The structures were automatically divided by the software to many blocks or called meshes. The interactions and effects between these meshes were summarized, containing other parasitic effects from the peripheral metals. Although other simulation software, like MATLAB and ADS, has quick response time and lower computer specification required, they are not suitable to simulate high frequency microwave switch or devices, due to they are unable to consider the overall switch structure effects and thus unable to accurately simulate the real electromagnetic field effects.

In this research, we have shown that HFSS is able to simulate GaN HFET based structures such as series and SPST switches with two different dimension sets, 1.05mm/0.75mm and 0.4mm/0.4mm, and GaN C^3 varactor based structures. In addition to show the ability of simulating the existing devices, HFSS simulation can be also used to modify and design new microwave switches in either HFET or C^3 varactor based components. First, we presents a SPST model with smooth corner which can get closer layout design to a real MMIC SPST switch and it indicates the design of smooth corner will not have major affects to the device performance in HFSS. Second, we presents that HFSS is used to simulate C^3 varactor SPST switch and shows that by increasing the ground to signal line space, which is believed to increase the compensating inductance, and we are able to shift the resonant frequency. This can be used to tuning the RF switch with a desired resonant frequency. Another example is showing a C^3 varactor SPDT switch with the filling of the ground metal is able to induce compensating inductance and resulting in an occurrence of resonance with an isolation of -42dB at 22GHz. Thus we are able to use HFSS to improve the device insertion loss and isolation by modifying the model dimension or geometrical shape. Last, we also demonstrated the use of HFSS simulation to design a new model with a descent insertion loss and isolation as low as of -41dB at the resonant frequency of 16GHz. Table 5.1 shows the comparsion of three different works with improved switch performance in this thesis.

Table 5.1 Comparison of three different works with improved switch performance

Modified C³ SPST 0.5mm/0.5mm	Modified C³ SPDT 0.25mm/0.2mm	New designed C³ SPDT
increasing space between metal ground and signal line	filling the ground gap	parallel input and output design
Resonant frequency shift	Resonant phenomenon appear at 22GHz with isolation of 42dB	New coplanar waveguide design showing resonant phenomenon with low isolation of -41dB at 16GHz
		

5.2 FUTURE WORK

HFSS simulation will be used to modify existing structures to show a resonant phenomenon for the device without resonance, used in tuning the resonant frequency to the desired frequency and used to improve the isolation. HFSS will also be used to design microwave switch with higher than 20GHz operating frequency. Furthermore, since the compensating inductance is useful to coupling the capacitance and resulting in a resonant phenomenon, different geometrical shape design for getting a higher inductive efficiency will be studied. Last, instead of only used in HFET and C³ varactor, HFSS will be used to simulate other structures, devices and systems.

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