Chapter 6

Small Signal Equivalent Circuit Model Verification

6.1 Comparison of measured and simulation for 3T device

In this section, I would like to verify the small signal equivalent circuit of 3T device described in chapter 3. Why is doing verification of equivalent circuit so important? Even though the extraction equations derived for the proposed equivalent circuits are mathematically correct, the equations would be useless provided that the simulation done by the proposed equivalent circuit fails to fit the measured results with sufficient accuracy. Therefore, the development of an appropriate small signal equivalent circuit for specific bias condition is the major goal and the derivation of extraction equations is the approach to realize the goal. Eventually, the proposed small signal equivalent circuit will be verified through circuit simulation by comparison with the measured results under various bias conditions.

In the following, the verification results will be discussed for both 3T and 4T devices in various operation regions.

6.1.1 Linear regions for 3T device

Fig. 3-2 illustrates the equivalent circuit of 3T device after open de-embedding for bias condition at V_{gs}=V_{ds}=0V. In the circuit, R_{bulk} and C_{dnw} are the remaining unknown parameters, which are named as substrate network model parameters. The feasible way is to fine tune these two parameters through ADS simulation to fit 2-port measurement data. Im(Y_{22}) is the major parameter to reflect sensitively the substrate parameter effect. The tuning process indicates that R_{bulk} plays a major effect on Im(Y_{22})

at low frequency, C_{dnw} in medium frequency range, and inductors at high frequency. First as shown in Fig. 6-1, the comparison of simulation results with and without R_{bulk} and C_{dnw} was demonstrated. The other parameters in the equivalent circuit were extracted in section 3.2.1. It reveals that the equivalent circuit under V_{gs}=0 requires both R_{bulk} and C_{dnw} to fit the measured characteristics. The reason is that the signal coming from port-2 certainly has to pass through C_{jd} and experience the substrate network. In other words, the simulation and measurement cannot match each other without substrate network parameters. To improve the fitting results at high frequency, it is necessary to adjust the substrate network parameters for optimization. Fig. 6-2 shows the comparison of simulation and measurement after optimization. We have made extensive comparison on S and Y parameters to justify the accuracy and reliability of the proposed equivalent circuit and extraction method. The model parameters optimized for 3T device under V_{gs}=V_{ds}=0V are listed in Table 6-1.

Table 6-1 The optimized parameters of 3T device under V_{gs}=V_{ds}=0V (Open_de only)

(pH)	C_{gdo}	C_{gso}	C_{gb}	C_{jd}	C_{js}	L_G	L_D	L_S
N_F=18	28.52	30.12	7.21	45.70	50.78	73.10	56.83	20.20
N_F=36	56.88	61.62	13.78	91.08	96.14	58.15	56.07	21.04
N_F=72	114.60	118.80	26.37	183.62	188.72	53.77	52.98	21.06
(Ω) (fF)	R_G	R_D	R_S	R_{D_diff}	R_{S_diff}	R_{bulk}	C_{dnw}	
N_F=18	1.748	0.314	0.307	9.88	8.90	258.46	33.42	
N_F=36	1.268	0.314	0.308	4.64	4.39	140.10	75.53	
N_F=72	0.988	0.314	0.308	2.16	2.10	77.70	120.98	

The equivalent circuit of 3T device after open de-embedding for bias condition at V_{gs}=1.2V, V_{ds}=0V was previous shown in Fig. 3-6. The inversion channel is formed to connect source and drain terminals. Using the model parameters in Table 6-2 and optimized substrate parameters in Table 6-1, we can first compare the measurement and simulation with these initial parameter values. The results shown in Fig. 6-3 indicate good match in terms of S-parameters. However, for Y-parameters, we identify that there happened shift along the frequency. The deviation at high frequency is mainly affected by inductances at three terminals and optimization through tuning on the parasitic inductances and R_G can realize better match. Fig. 6-4 shows the results after optimization. The good match justifies the accuracy of equivalent circuit and extraction method. The optimized parameters are listed in Table 6-3.

Table 6-2　The initial parameters for 3T device at V_{gs}=1.2V, V_{ds}=0V (Open_de only)

	L_G (pH)	L_D (pH)	L_S (pH)	C_{gg} (fF)	C_{gd} (fF)	C_{gs} (fF)	C_{jd}=C_{js}
N_F=18	67.31	50.20	15.37	105.94	52.03	53.91	42.20
N_F=36	54.68	50.15	16.31	213.77	104.24	109.53	82.68
N_F=72	47.69	49.09	16.45	429.93	210.09	219.84	161.52

	R_G (Ω)	R_D (Ω)	R_S (Ω)	R_{D_diff} (Ω)	R_{S_diff} (Ω)	R_{ch} (Ω)
N_F=18	4.862	0.409	0.308	9.88	8.90	6.270
N_F=36	2.828	0.387	0.308	4.64	4.39	3.118
N_F=72	1.730	0.345	0.307	2.16	2.10	1.574

Table 6-3　The optimized parameters of 3T device at V_{gs}=1.2V, V_{ds}=0V

(pH)	C_{gd}	C_{gs}	C_{jd}	C_{js}	C_{dnw}	L_G	L_D	L_S
N_F=18	50.16	55.85	42.20	42.20	33.42	67.31	50.20	15.37
N_F=36	104.24	109.53	82.68	82.68	75.53	59.16	50.15	15.36
N_F=72	210.09	219.84	161.52	161.52	120.98	55.70	46.24	15.50
(Ω) (fF)	R_G	R_D	R_S	R_{ch}	R_{D_diff}	R_{S_diff}	R_{bulk}	
N_F=18	4.862	0.409	0.308	6.270	9.88	8.90	258.46	
N_F=36	2.969	0.387	0.308	3.118	4.64	4.39	140.10	
N_F=72	1.924	0.345	0.307	1.574	2.16	2.10	77.70	

There is something worthy of mention. An experiment was down by removing the substrate network from original equivalent circuit to check the results. As shown in Fig. 6-5, the substrate network was removed to re-do the simulation for this equivalent circuit. The simulation results shown in Fig. 6-6 indicate that there is almost no change through removing the substrate network elements. Even without substrate network in equivalent circuit, the simulation still can fit the measurement data very well. The results suggest that the substrate network does not make any effect under the bias condition at $V_{gs} >> V_T$. It is because the signal experiences much lower impedance going through channel inversion layer. In contrast, the substrate network cannot be neglected under $V_{gs}=V_{ds}=0V$ because substrate is the necessary path for signal to pass through under this bias condition, i.e. channel off state.

6.1.2 Saturation regions for 3T device

In the following, we continue to discuss the case of $V_{ds} \neq 0V$. I specifically focus on bias condition at $V_{gs}=V_{ds}=1.2V$. I tried to take the equivalent circuit [1] for the initial test. However, there exists large deviation in the simulated S_{22} from the measurement. Therefore, it is indispensable to modify the original equivalent circuit proposed in [1] to improve the fitting results by simulation. The equivalent circuit under this bias condition is the most complicated one because of current gain and asymmetry between source and drain along the channel. The new equivalent circuit was previously shown in Fig. 3-9. Firstly, we check the simulation results using initial parameters. The Initial model parameters adopted were referred to Table 6-4 as well as R_{bulk} and C_{dnw} optimized for $V_{gs}=V_{ds}=0$ in Table 6-1. The results shown in Fig. 6-7 reveal a large deviation between simulation and measurement especially for Y-parameters. However, the simulation using initial parameters roughly sketched the contours of measurement. The causes responsible for the deviation mainly come from C_{ds}, g_m and g_{ds}. The comment that C_{ds} may need significant optimization was previously addressed in section 3.2.2. The re-optimization required for g_m comes from the parasitic resistance effect on I_d and g_m. However, the toughest job is the extraction of g_{ds} and related resistances, R_{ch} and R_{ds}. The difficulty stems from the accuracy limitation of the measured I-V characteristics in terms of derivative terms such as g_{ds} and g_m. The deviation in g_{ds} will impact R_{ch} and R_{ds} derived from the reciprocal of g_{ds}. Therefore, carefully re-tuning and optimization on the mentioned parameters such as g_{ds}, R_{ch}, R_{ds}, and C_{ds}, is very tough but essential to enable good fit to measurement by simulation. The optimized parameters are listed in Table 6-5 and the simulation results after optimizing are shown in Fig. 6-8.

Table 6-4 The initial parameters for 3T device at V_{gs}=V_{ds}=1.2V (Open_de only)

	C_{gg} (fF)	C_{gs} (fF)	C_{gd} (fF)	C_{js} (fF)	C_{jd} (fF)	C_{ds} (fF)
N_F=18	94.0	64.9	29.1	42.20	29.12	99.71
N_F=36	190.0	131.5	58.5	82.68	58.36	224.47
N_F=72	382.2	264.1	118.1	161.52	114.87	483.20
	R_G (Ω)	R_D (Ω)	R_S (Ω)	R_{D_diff} (Ω)	R_{S_diff} (Ω)	R_{ch} (Ω)
N_F=18	4.862	0.409	0.308	9.88	8.90	123.83
N_F=36	2.828	0.387	0.308	4.64	4.39	61.58
N_F=72	1.730	0.345	0.307	2.16	2.10	30.90
	L_G (pH)	L_D (pH)	L_S (pH)	g_m(mA/V)	g_{ds}(mA/V)	R_{ds} (Ω)
N_F=18	67.31	50.20	15.37	56.8	2.5	276.17
N_F=36	54.68	50.15	16.31	104.4	5.0	138.42
N_F=72	47.69	49.09	16.45	197.0	10.0	69.10

Table 6-5 The optimized parameters for 3T device at V_{gs}=V_{ds}=1.2V

(fF)	C_{gg}	C_{gs}	C_{gd}	C_{js}	C_{jd}	C_{ds}	C_{dnw}
N_F=18	97.06	68.00	29.06	42.20	29.12	233.01	33.42
N_F=36	202.04	146.49	55.55	82.68	59.36	604.37	75.53
N_F=72	391.60	285.38	106.22	161.52	114.87	1207.28	120.98
(Ω)	R_G	R_D	R_S	R_{D_diff}	R_{S_diff}	R_{ch}	R_{buik}
N_F=18	5.653	0.409	0.308	9.88	8.90	138.80	258.46
N_F=36	3.238	0.387	0.308	4.64	4.39	65.61	140.10
N_F=72	1.978	0.345	0.307	2.16	2.10	32.34	77.70
(pH)	L_G	L_D	L_S	g_m(mA/V)	g_{ds}(mA/V)	R_{ds}(Ω)	
N_F=18	60.42	54.53	17.87	59.5	2.2	337.17	
N_F=36	57.44	55.24	17.16	115.4	4.31	161.13	
N_F=72	60.25	53.54	17.93	211.5	8.87	80.46	

Fig. 6-8 presents the good match between measurement and simulation by using optimized parameters. The obvious improvement over the initial parameters particularly in terms of Y-parameter fitting result justifies the optimization. The simulation results using optimized parameters may not be the best ones because the optimization was done manually. Through application of automatic extraction and optimization tool such as ICCAP in the future, the model parameter extraction and optimization will become more efficient.

6.2 Comparison of measurement and simulation for 4T devices

For 4T device, the proposed equivalent circuit operates under the same bias condition specified for 3T device. Figs 3-10 ~ 3-12 illustrate the equivalent circuits of

4T device corresponding to three specific bias conditions.

6.2.1 4T devices in Linear Region

Adopting the initial model parameters in Table 6-6 and optimized substrate parameters in Table 6-1, the simulation results and comparison with measurement were demonstrated in Fig. 6-9. For 4T device, the primary difference compared with 3T device is that there are two individual metal lines at source and bulk terminals. Therefore, we can identify that 3T and 4T devices reveal totally different characteristics in measurement even under the same bias condition. Through modification on 4T device as shown in Fig. 3-10, the simulation using initial model parameters provide not bad fitting results. Taking the optimized model parameters in Table 6-7, the simulated S-parameters and Y-parameters present much better fitting to the measurement as shown in Fig. 6-10. Regarding the larger deviation for N_F=72 , it may be caused by measurement error. Two other smaller devices with N_F=18 and 36 demonstrate very good match with measurement as shown in Fig. 6-11.

Table 6-6 The initial parameters for 4T device at V_{gs}=V_{ds}=0V (Open_de only)

	L_G(pH)	L_D(pH)	L_S(pH)	L_B(pH)	C_{gg}(fF)	C_{gdo}=C_{gso}	C_{gb}(fF)	C_{jd}=C_{js}
N_F=18	65.97	53.73	53.19	26.46	65.30	29.43	6.44	41.64
N_F=36	54.64	51.12	55.41	25.94	132.57	59.79	12.99	82.13
N_F=72	48.92	49.61	56.54	25.70	268.76	121.75	25.26	161.53
(Ω)	$R_{g,ext}$	$R_{g,int}$	R_D	R_S	R_B	R_{D_diff}	R_{S_diff}	
N_F=18	0.328	1.42	0.412	0.765	0.516	9.88	8.90	
N_F=36	0.328	0.94	0.375	0.835	0.488	4.64	4.39	
N_F=72	0.328	0.66	0.335	0.911	0.463	2.16	2.10	

Table 6-7 The optimized parameters for 4T device at $V_{gs}=V_{ds}=0V$

(fF)(pH)	C_{gdo}	C_{gso}	C_{gb}	C_{jd}	C_{js}	L_G	L_D	L_S	L_B
N_F=18	29.43	29.43	6.44	44.64	44.64	65.74	57.38	53.19	26.46
N_F=36	57.79	61.79	12.99	88.13	88.13	57.81	59.00	57.07	25.94
N_F=72	114.75	126.75	25.26	180.53	180.53	52.93	60.33	55.30	25.70
(Ω)	R_G	R_D	R_S	R_B	R_{D_diff}	R_{S_diff}	R_{bulk}	C_{dnw}	
N_F=18	1.748	0.412	0.765	0.516	9.88	8.90	258.46	33.42	
N_F=36	1.268	0.375	0.835	0.488	4.64	4.39	140.10	75.53	
N_F=72	1.444	0.335	0.911	0.463	2.16	2.10	77.70	120.98	

The equivalent circuit of 4T device under V_{gs}=1.2V, V_{ds}=0V was shown previously in Fig. 3-11. Similarly, the simulation results with initial model parameters in Table 6-8 and optimized substrate parameters in Table 6-1 are presented in Fig. 6-12. The dramatically large deviation revealed by the simulation w.r.t. the measurement suggests the failure of the initial model parameters. There must be some very important parameters with wrong values to cause the behavior of simulation like Fig. 6-12. During optimization, I find that the substrate parameters, R_{bulk} and C_{dnw}, have to be lowered many times than those optimized in section 6.1.1. That means that the values of substrate parameters aren't universal at different bias conditions for 4T device. But what I have done for 3T device is that I use universal substrate parameters to do simulation at three kinds of bias conditions. What values of substrate parameters for specific bias condition are true? The detailed discussion and explanation will be stated in the following section.

Returning back and focusing on this bias condition of 4T device, the optimized parameters are listed in Table 6-9 and simulation results are shown in Fig. 6-13. We can observe that I only slightly adjust the values of parameters except substrate parameters, R_{bulk} and C_{dnw}. Nevertheless, the substrate parameters go through a big optimization. According to optimization experience, I can't make simulation and measurement matched with original substrate parameters optimized in section 6.1.1 unless I lower the values of R_{bulk} and C_{dnw} with great change.

Table 6-8 The initial parameters for 4T device at V_{gs}=1.2V, V_{ds}=0V (Open_de only)

	L_G(pH)	L_D(pH)	L_S(pH)	L_B(pH)	C_{gg}(fF)	C_{gd}(fF)	C_{gs}(fF)	C_{jd}=C_{js}
N_F=18	65.97	53.73	53.19	26.46	105.45	49.61	55.84	41.64
N_F=36	54.64	51.12	55.41	25.94	213.82	99.83	113.99	82.13
N_F=72	48.92	49.61	56.54	25.70	435.09	208.41	226.68	161.53
(Ω)	R_G	R_D	R_S	R_B	R_{D_diff}	R_{S_diff}	R_{ch}	
N_F=18	4.862	0.412	0.765	0.516	9.88	8.90	6.270	
N_F=36	2.580	0.375	0.835	0.488	4.64	4.39	3.118	
N_F=72	1.703	0.335	0.911	0.463	2.16	2.10	1.574	

Table 6-9 The optimized parameters for 4T device at V_{gs}=1.2V, V_{ds}=0V

(pH)	C_{gd}	C_{gs}	C_{jd}	C_{js}	C_{dnw}	L_G	L_D	L_S	L_B
N_F=18	50.41	55.95	41.64	41.64	0.64	57.43	51.51	48.64	27.75
N_F=36	102.26	111.66	89.68	89.68	1.45	59.31	46.15	47.58	31.71
N_F=72	207.45	221.21	178.12	178.12	2.77	56.93	46.17	48.23	35.25
(Ω)	R_G	R_D	R_S	R_B	R_{ch}	R_{D_diff}	R_{S_diff}	R_{bulk}	
N_F=18	4.862	0.412	0.765	0.516	6.270	9.88	8.90	40.02	
N_F=36	2.828	0.375	0.835	0.488	3.118	4.64	4.39	22.69	
N_F=72	1.703	0.335	0.911	0.463	1.574	2.16	2.10	13.73	

6.2.2 4T Devices in Saturation Region

Finally, we focus on the last case of V_{gs}=V_{ds}=1.2V bias condition for 4T devices. The equivalent circuit is shown in Fig. 3-12. The simulation results with parameters of

Table 6-10 and substrate parameters optimized in section 6.1.1 are compared with measurement data and shown in Fig. 6-14. We can observe that the trend of initial simulations of S and Y parameters deviate from measurement data greatly. Trying to lower the value of substrate parameters like section 6.2.1 can improve the simulation results as shown in Fig. 6-15. The optimized parameter values are listed in Table 6-11. The optimized simulation in Fig. 6-15 is improved greatly than initial one but there are some deviations existing still. I think the cause of the deviations comes from measurement error because this case is measured last and the measurement system might lose the calibration standard. But the optimized simulation basically can still sketch the contours of measurement.

Table 6-10 The initial parameters for 4T device at V_{gs}=V_{ds}=1.2V (Open_de only)

	C_{gg} (fF)	C_{gs} (fF)	C_{gd} (fF)	C_{js} (fF)	C_{jd} (fF)	C_{ds} (fF)	
N_F=18	93.9	64.8	29.1	41.64	28.68	99.71	
N_F=36	189.8	131.4	58.4	82.13	58.04	224.47	
N_F=72	375.7	257.0	118.7	161.53	114.97	483.20	
(Ω)	R_G	R_D	R_S	R_B	R_{D_diff}	R_{S_diff}	R_{ch}
N_F=18	4.862	0.412	0.765	0.516	9.88	8.90	123.96
N_F=36	2.580	0.375	0.835	0.488	4.64	4.39	61.54
N_F=72	1.703	0.335	0.911	0.463	2.16	2.10	31.59
	L_G(pH)	L_D(pH)	L_S(pH)	L_B(pH)	g_m(mA/V)	g_{ds}(mA/V)	R_{ds}(Ω)
N_F=18	65.97	53.73	53.19	26.46	56.8	2.5	276.04
N_F=36	54.64	51.12	55.41	25.94	104.4	5.0	138.46
N_F=72	48.92	49.61	56.54	25.70	197.0	10.0	68.41

Table 6-11 The optimized parameters for 4T device at $V_{gs}=V_{ds}=1.2V$

(fF)	C_{gs}	C_{gd}	C_{js}	C_{jd}	C_{ds}	C_{dnw}	$R_{bulk}(\Omega)$
$N_F=18$	64.8	29.1	41.64	30.68	203.01	0.64	40.02
$N_F=36$	133.2	56.9	89.13	58.04	584.37	1.45	22.69
$N_F=72$	257.0	118.7	161.53	114.97	1207.28	2.77	13.73
(Ω)	R_G	R_D	R_S	R_B	R_{D_diff}	R_{S_diff}	R_{ch}
$N_F=18$	4.862	0.412	0.765	0.516	9.88	8.90	123.96
$N_F=36$	2.828	0.375	0.835	0.488	4.64	4.39	67.54
$N_F=72$	1.703	0.335	0.911	0.463	2.16	2.10	36.59
(pH)	L_G	L_D	L_S	L_B	g_m(mA/V)	g_{ds}(mA/V)	$R_{ds}(\Omega)$
$N_F=18$	68.97	53.73	53.19	26.46	59.5	2.5	276.04
$N_F=36$	52.64	55.62	50.41	25.94	115.4	4.3	156.46
$N_F=72$	51.77	51.45	47.56	23.70	210.0	8.57	80.41

6.3 The role of substrate parameters in equivalent circuit

Let me first state the problem I encountered. In section 6.1.1 of $V_{gs}=V_{ds}=0V$ bias condition, I optimized the values of substrate parameters for 3T device to make simulation matched with measurement. Then, I used these optimized values for following two bias conditions of 3T device. There is no abnormal phenomenon in the beginning. When I think that I could use these optimized values of substrate parameters for 4T device, I face the big problem during optimization. At $V_{gs}=V_{ds}=0V$ bias condition, 3T and 4T devices can have the same values of substrate parameters. But at the other two bias conditions, 4T device apparently has much lower values of substrate parameters than those of 3T device. 3T and 4T devices are all the same except common metal-3 layer between source and bulk terminals. Therefore, the environments of these two devices for small signal at specific bias condition should be exactly identical. And that is impossible existing two kinds of substrate parameters for making simulation matched with measurement. Finally, I want to focus on discussing what the real and true environment is for 3T and 4T devices at (1)V_{gs}=1.2V, V_{ds}=0V, (2)V_{gs}=V_{ds}=1.2V bias conditions.

Focusing on the equivalent circuit in Fig. 3-6 at V_{gs}=1.2V, V_{ds}=0V, I run the simulation again with varying the values of substrate parameters. In section 6.1.2, I have run the simulation with substrate parameters optimized in section 6.1.1. Now, I keep all parameters unchanged except R_{bulk} and C_{dnw} to observe how important the substrate network is in the equivalent circuit. The simulation results are shown in Fig. 6-16. We can observe that the simulation is almost unchanged. This represents the impedance of channel resistance is much lower than the substrate network for small signal to pass through. Therefore, no matter what values the substrate parameters are, the small signal will not experience any change of substrate network because it can pass through the R_{ch} to reach the bulk terminal by the common metal-3 layer of 3T device. In other words, we can get nothing about substrate parameters of 3T device at this bias condition. Oppositely, the necessity of using lower values of substrate parameters for 4T device gives us more correct view of environment for small signal. 4T device is sensitive to the substrate network because the small signal coming into from drain terminal has to pass through the substrate network to reach the bulk terminal because of absence of common metal-3 layer.

Similarly, I do the same procedure for 3T device at saturation condition. In Fig. 6-17, we can clearly observe again that the simulations are also almost unchanged with varying substrate parameters. The substrate network is also meaningless for 3T device at saturation condition.

According to the verification discussed in last two paragraphs, we can say that the variation of substrate network wouldn't affect simulation results of 3T device. This means that we can't obtain the true values of substrate parameters by optimizing them in equivalent circuit for 3T device. But 4T device can give us clues to the values of substrate parameters because it is very sensitive to the substrate network.

Only discussing on 3T device is not sufficient to realize the role of substrate network and how it affects the simulation. Based on the lack of common metal-3 layer in 4T device, we can explore the substrate network more clearly. I have no idea whether the values of substrate parameters of 4T device are definitely true. But I confirm at least that the substrate network is nearly useless for 3T device.

The lower values of substrate parameters obtained from 4T device in section 6.2.1 are left a question. The mechanism leading to lower values of substrate parameters has to be discussed further in the future.

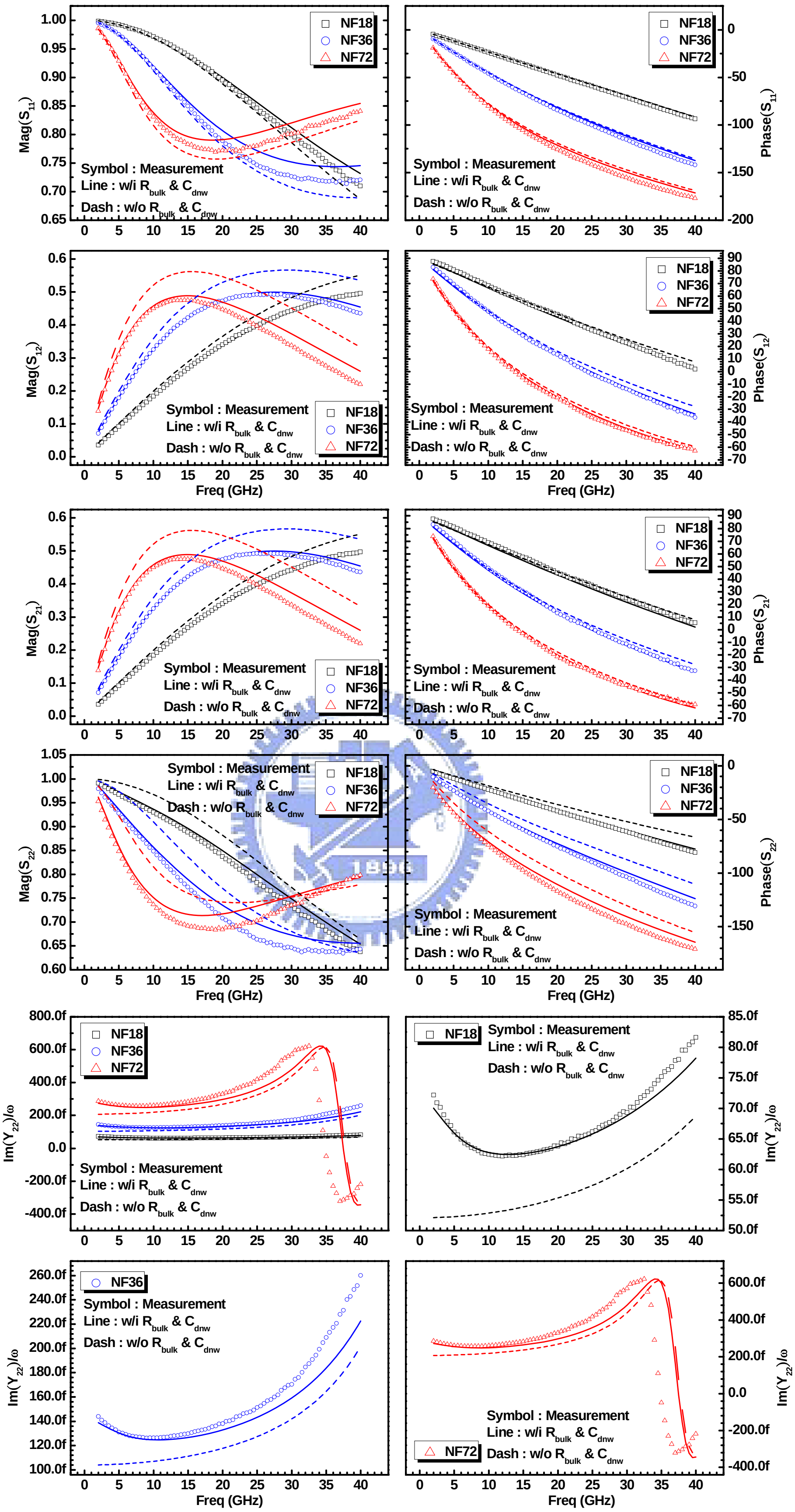
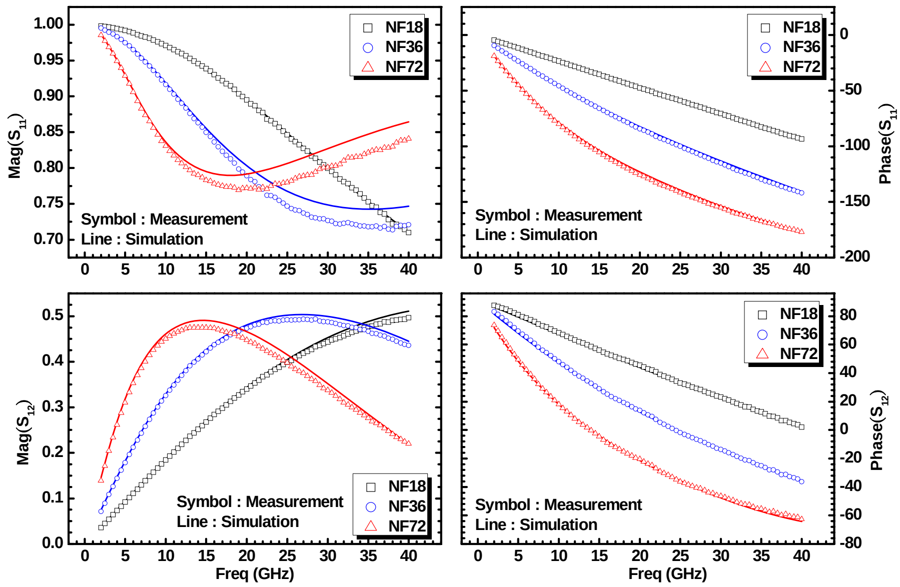
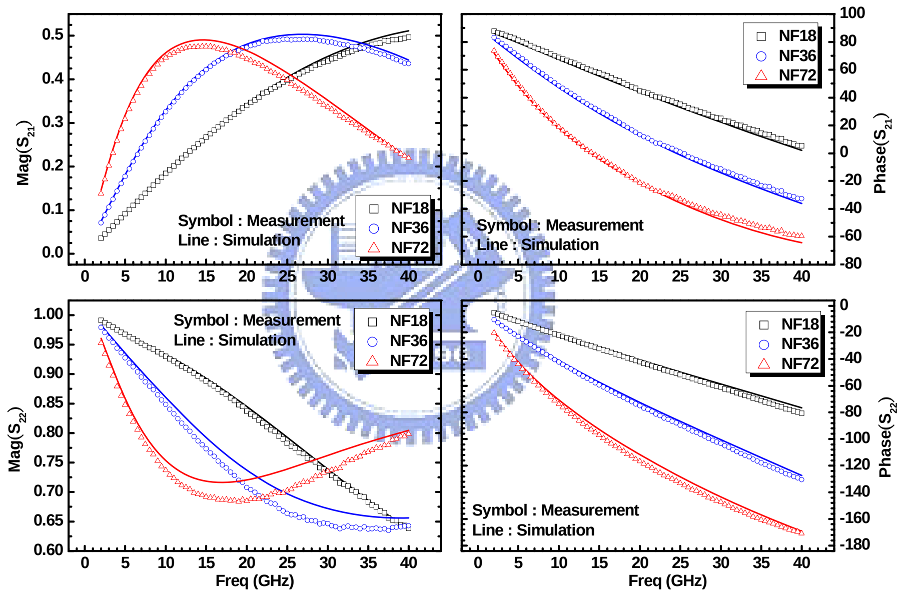
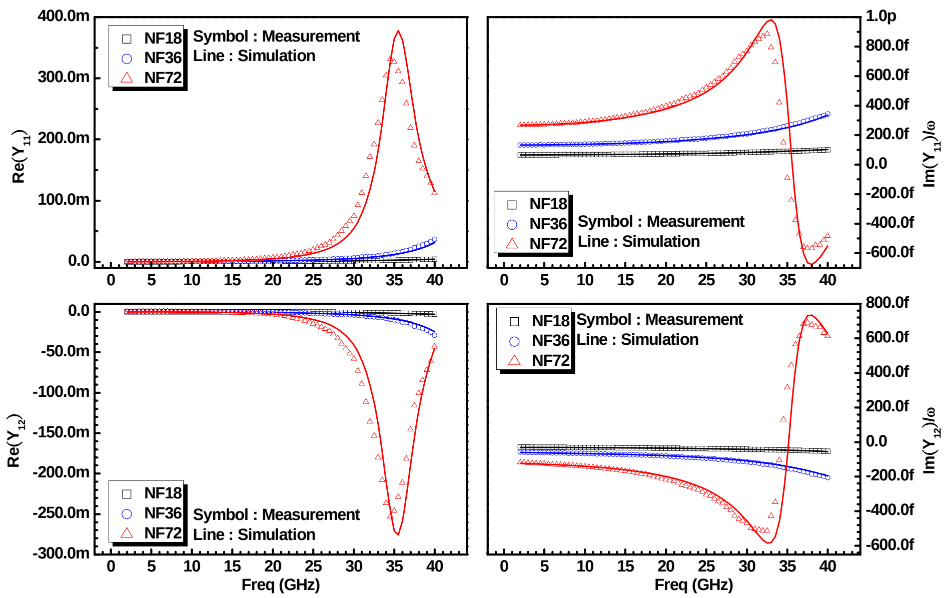


Fig. 6-1 The comparison results of 3T device at V_{gs}=V_{ds}=0V (w/i and w/o substrate parameters)


NF18
NF36
NF72
Symbol : Measurement
Line : Simulation
Mag(S11)
Phase(S11)
Mag(S12)
Phase(S12)
Freq (GHz)


NF18
NF36
NF72
Symbol : Measurement
Line : Simulation
Mag(S21)
Phase(S21)
Mag(S22)
Phase(S22)
Freq (GHz)


NF18
NF36
NF72
Symbol : Measurement
Line : Simulation
Re(Y11)
Im(Y11)/ω
Re(Y12)
Im(Y12)/ω
Freq (GHz)

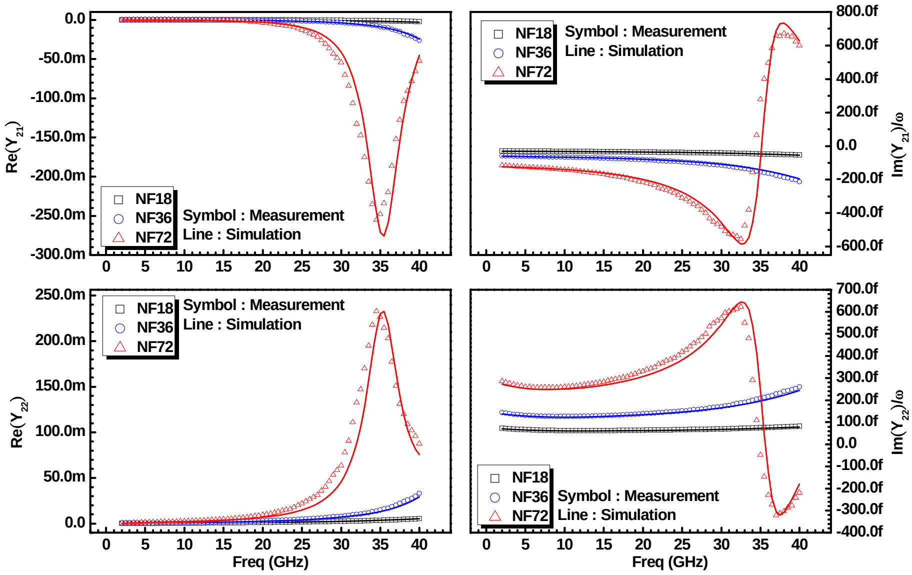
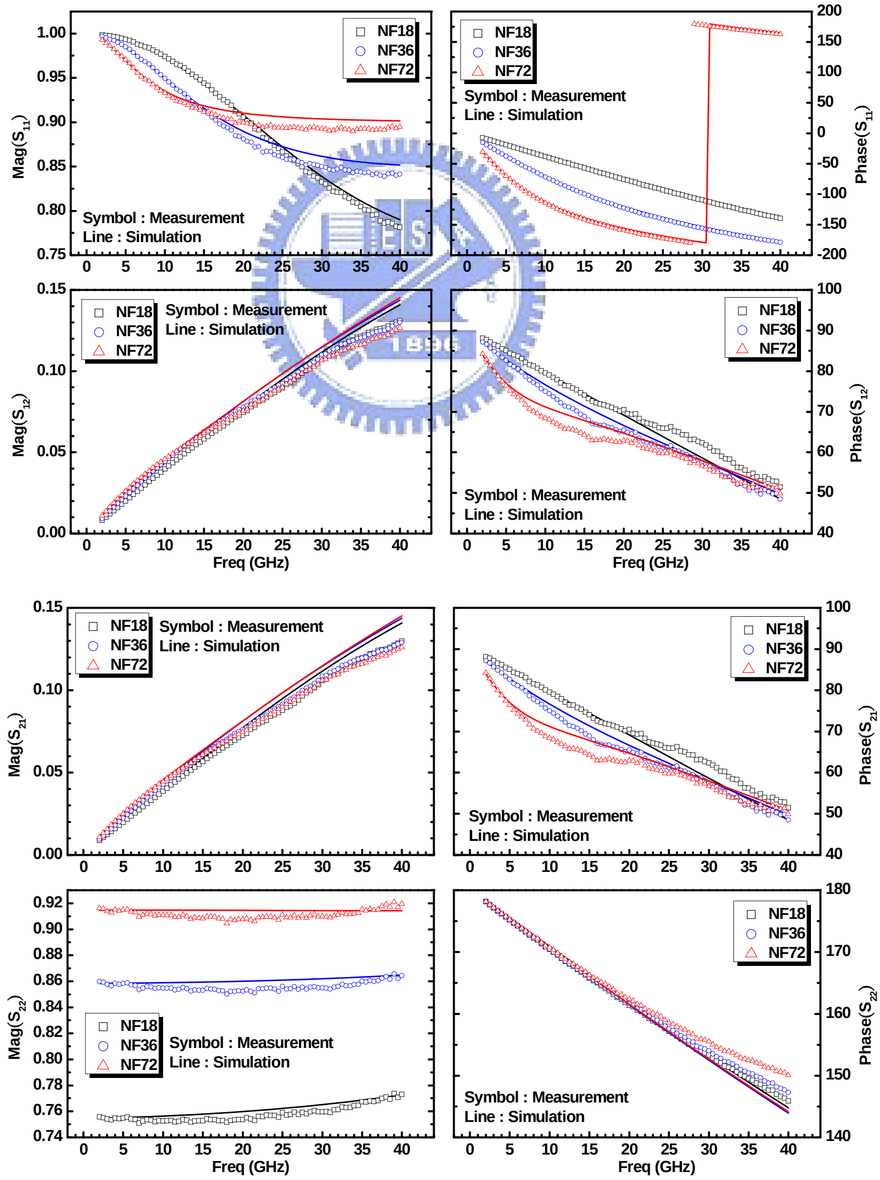


Fig. 6-2 The comparison results of 3T device at V_{gs}=V_{ds}=0V (Optimized)



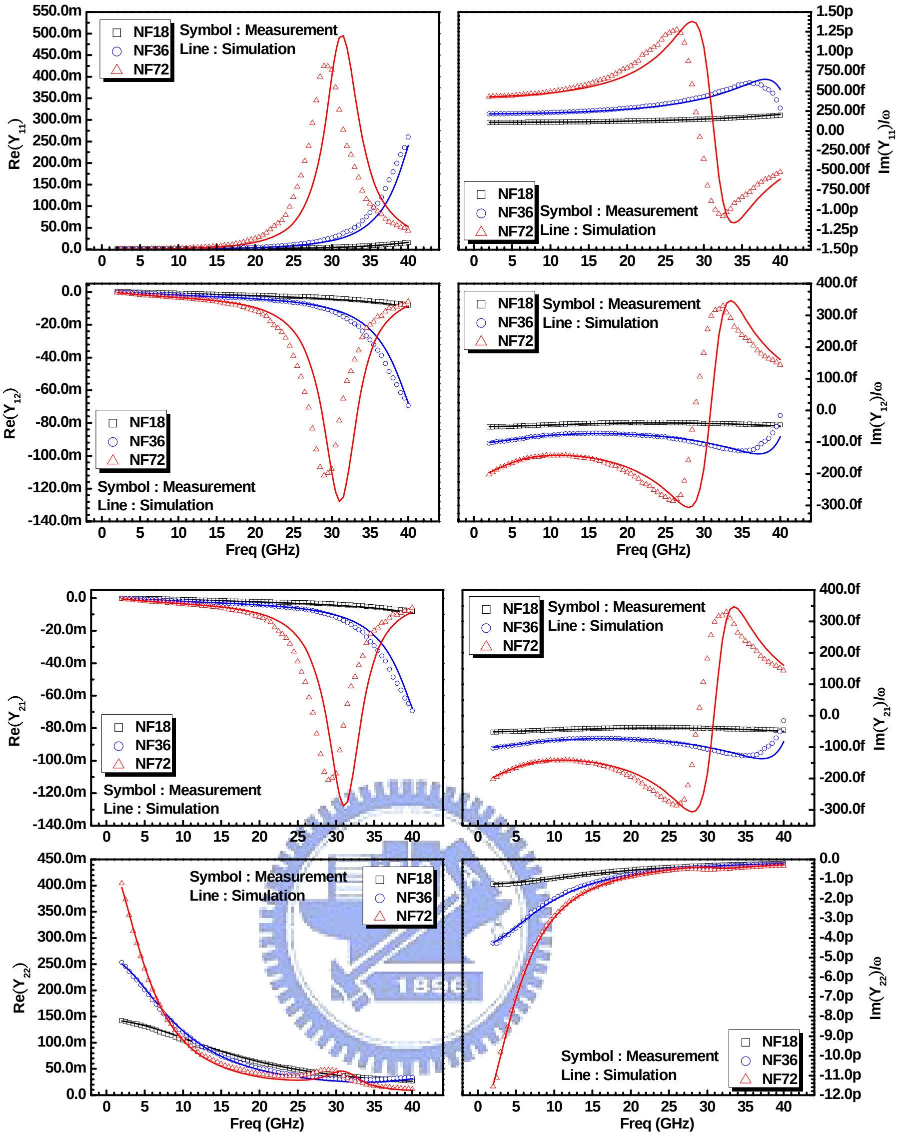
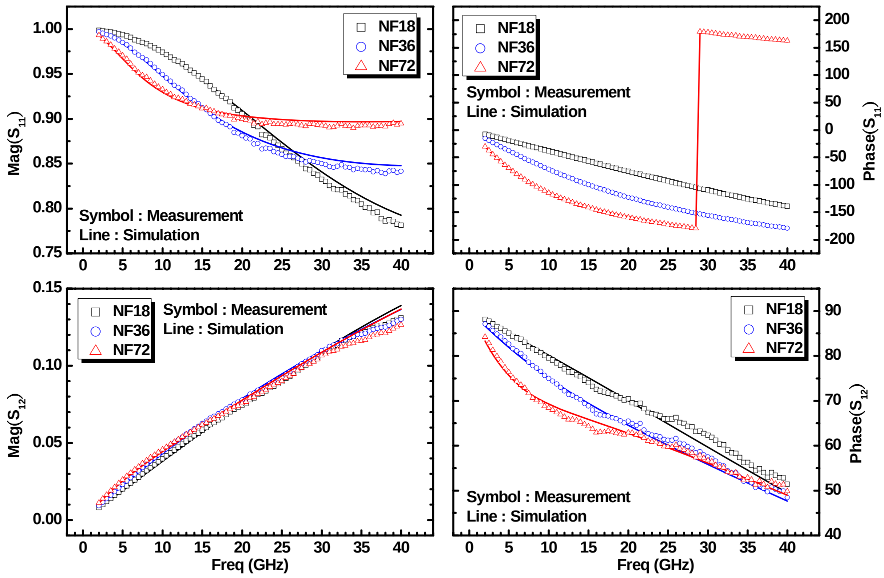


Fig. 6-3 The comparison results of 3T device at V_{gs}=1.2V, V_{ds}=0V (Initial)



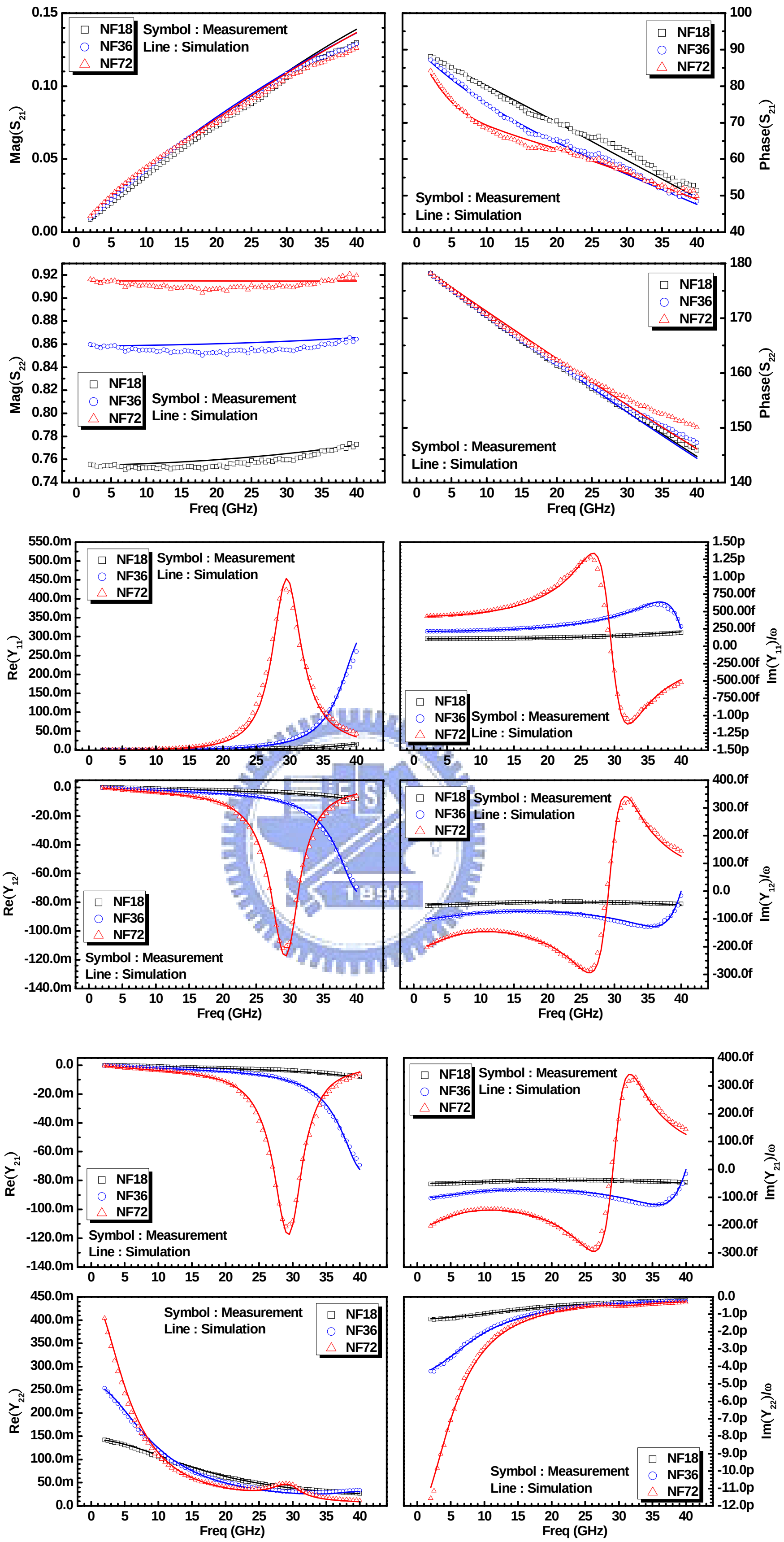


Fig. 6-4 The comparison results of 3T device at V_{gs}=1.2V, V_{ds}=0V (Optimized)

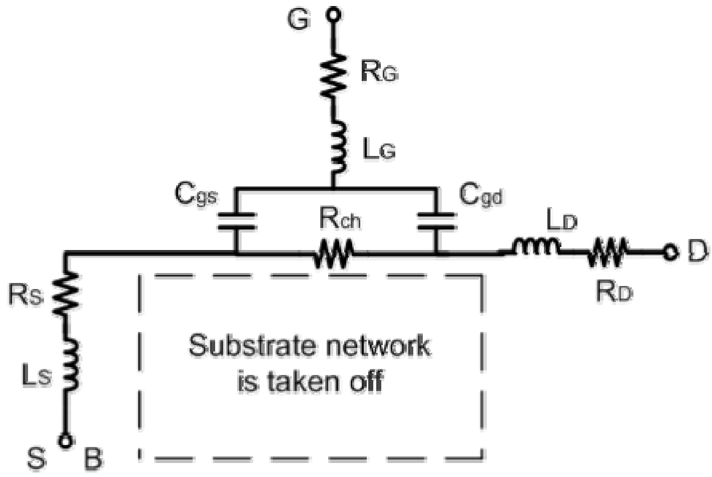
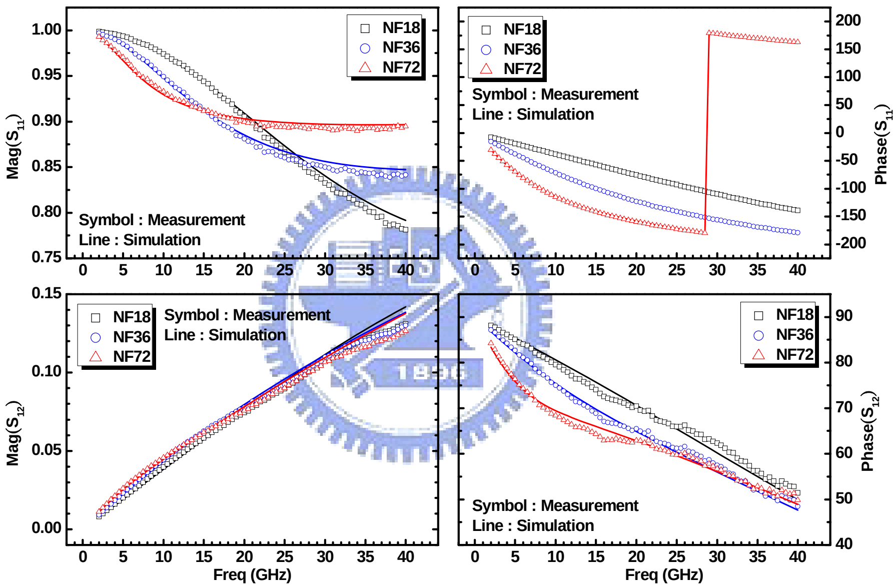
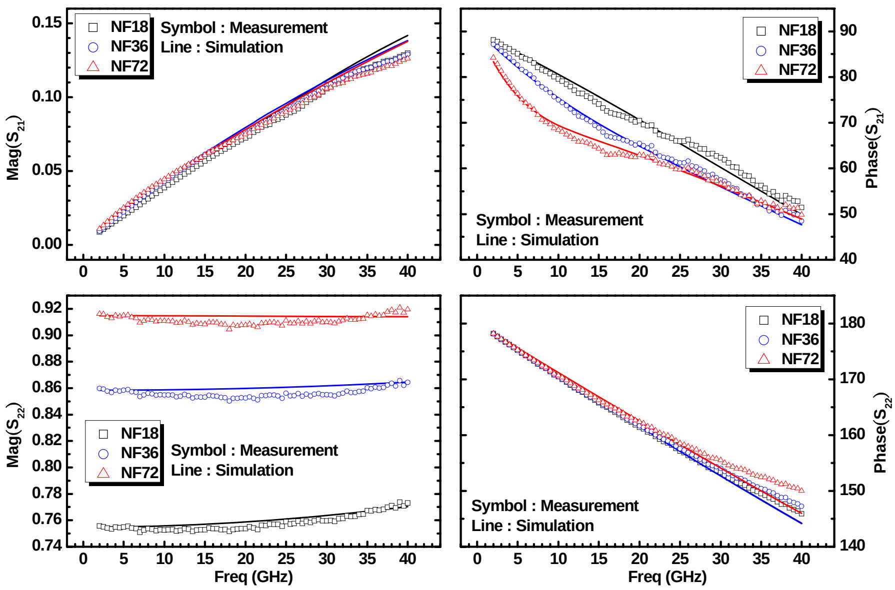


Fig. 6-5 The equivalent circuit taken off substrate network at V_{gs}=1.2V, V_{ds}=0V





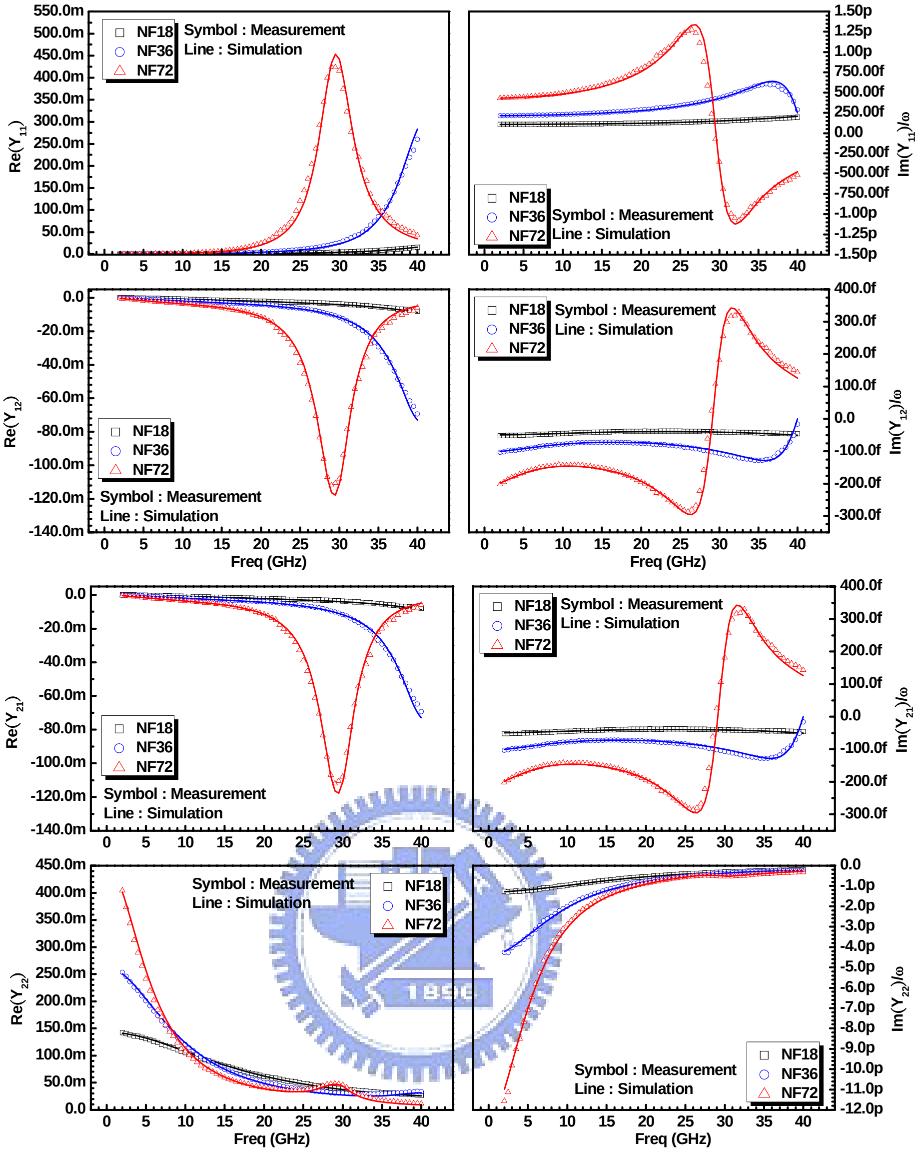
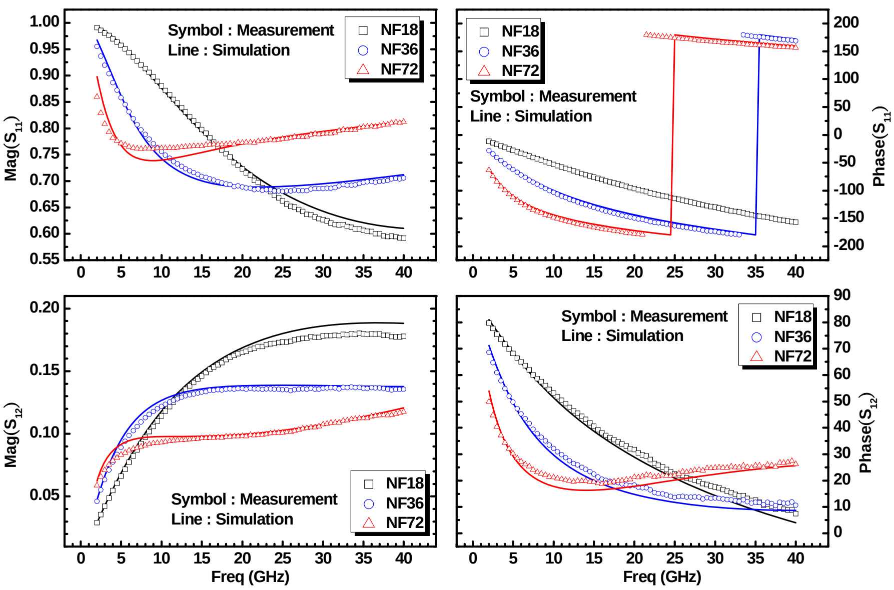


Fig. 6-6 The comparison results at V_{gs}=1.2V, V_{ds}=0V (w/o substrate network)



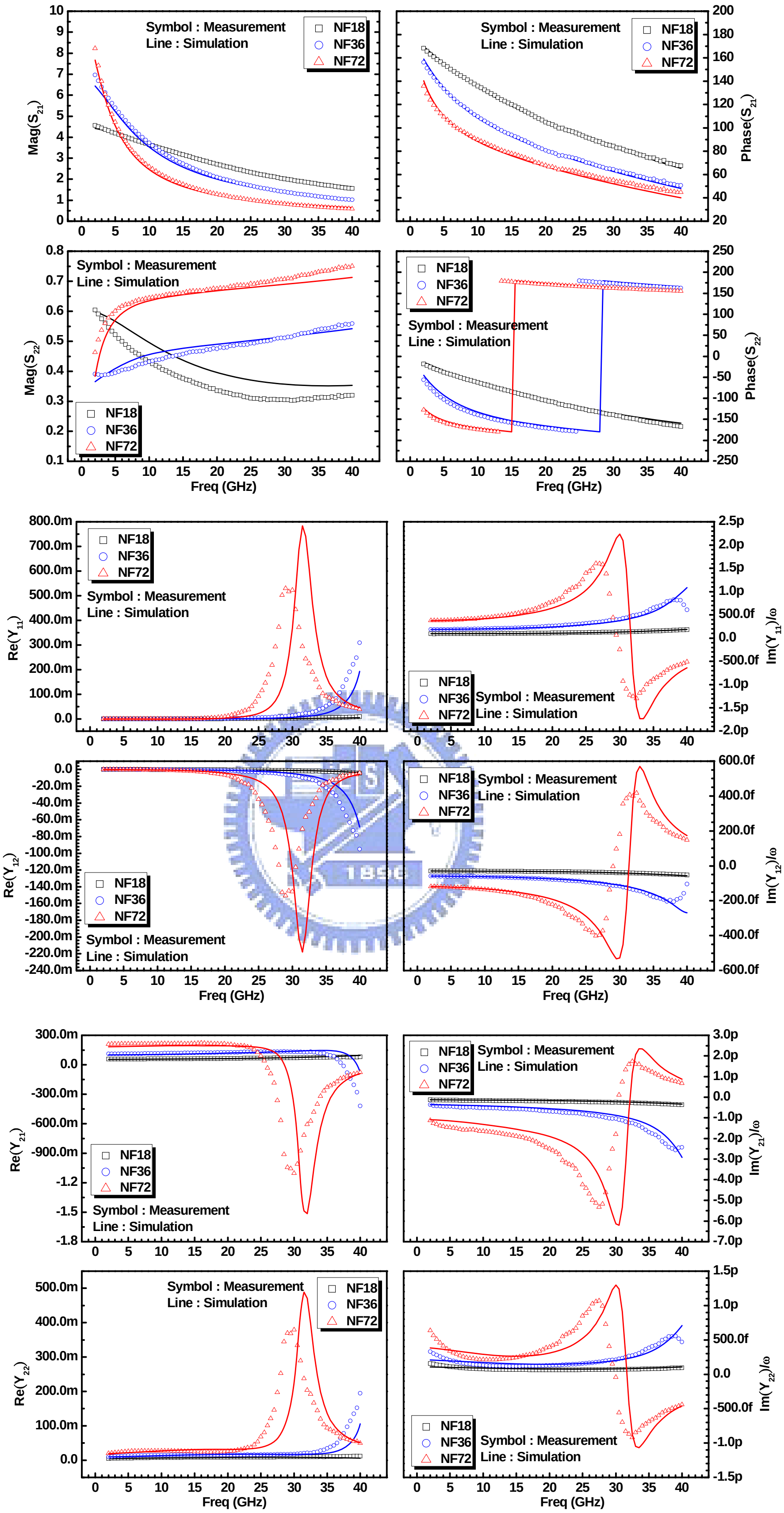
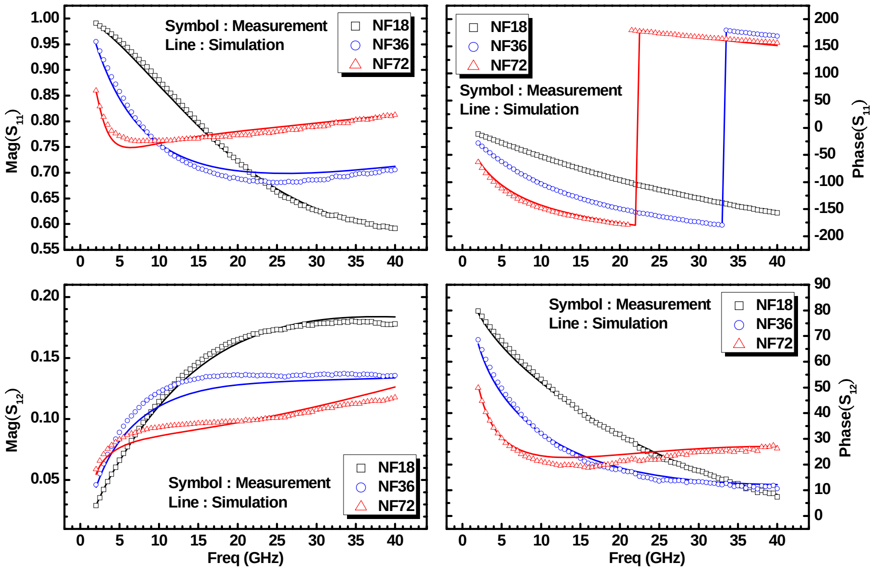
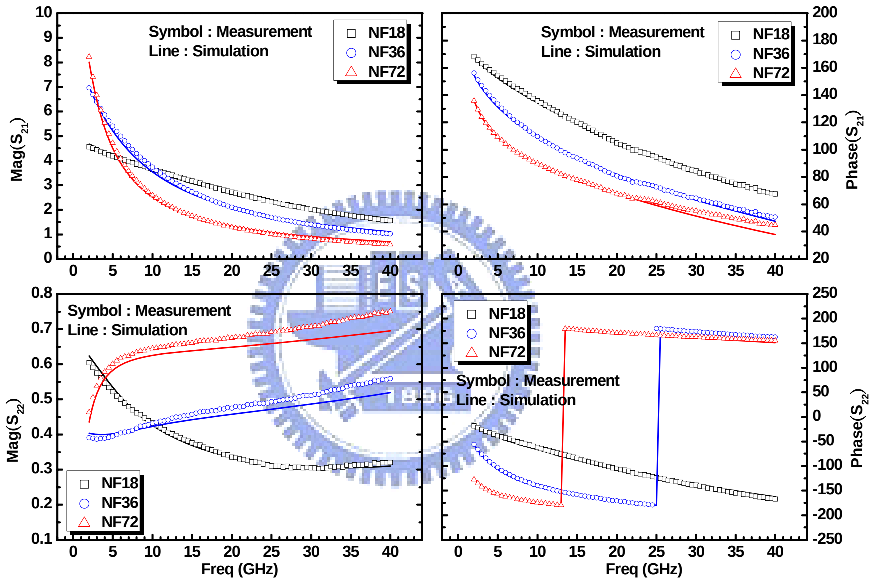


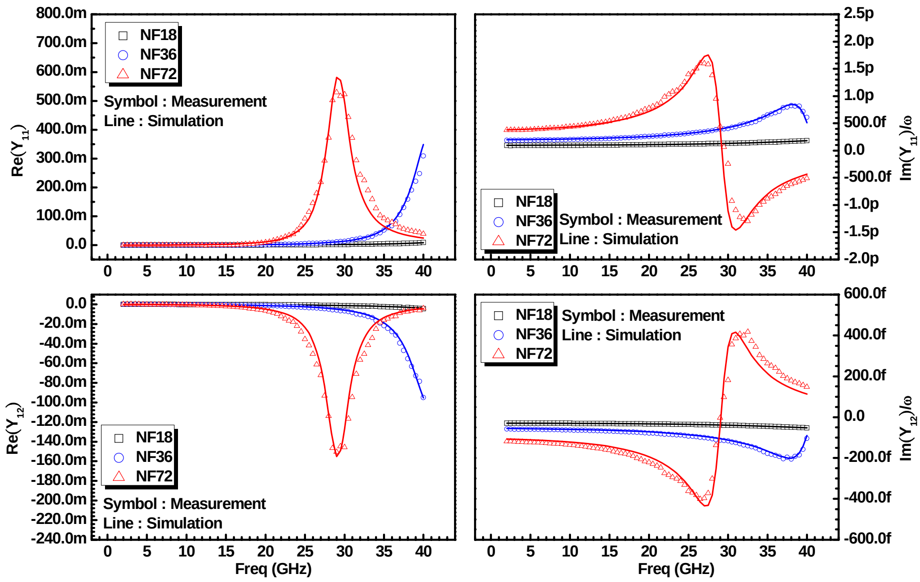
Fig. 6-7 The comparison results of 3T device at V_{gs}=V_{ds}=1.2V (Initial)



Symbol : Measurement
Line : Simulation
NF18
NF36
NF72
Mag(S11)
Phase(S11)
Mag(S12)
Phase(S12)
Freq (GHz)



Symbol : Measurement
Line : Simulation
NF18
NF36
NF72
Mag(S21)
Phase(S21)
Mag(S22)
Phase(S22)
Freq (GHz)



Symbol : Measurement
Line : Simulation
NF18
NF36
NF72
Re(Y11)
Im(Y11)/ω
Re(Y12)
Im(Y12)/ω
Freq (GHz)

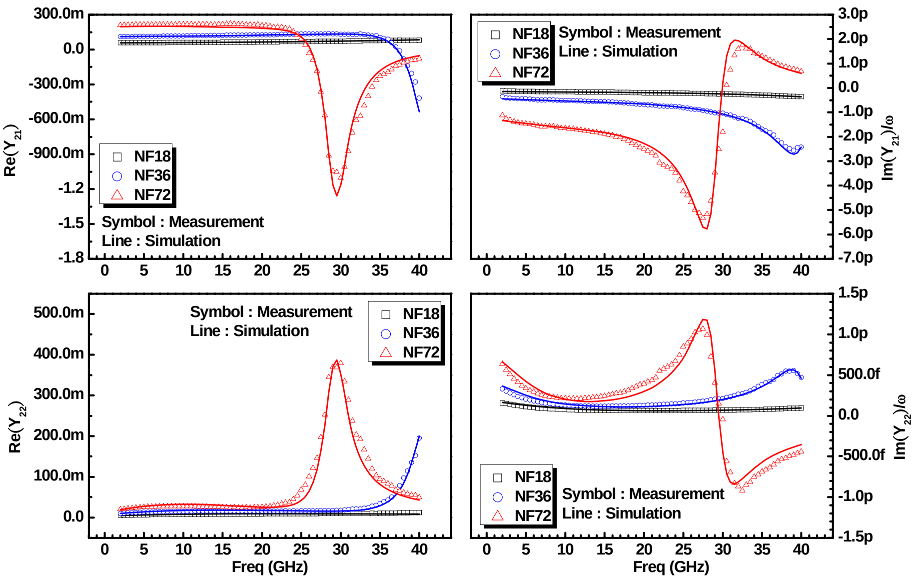
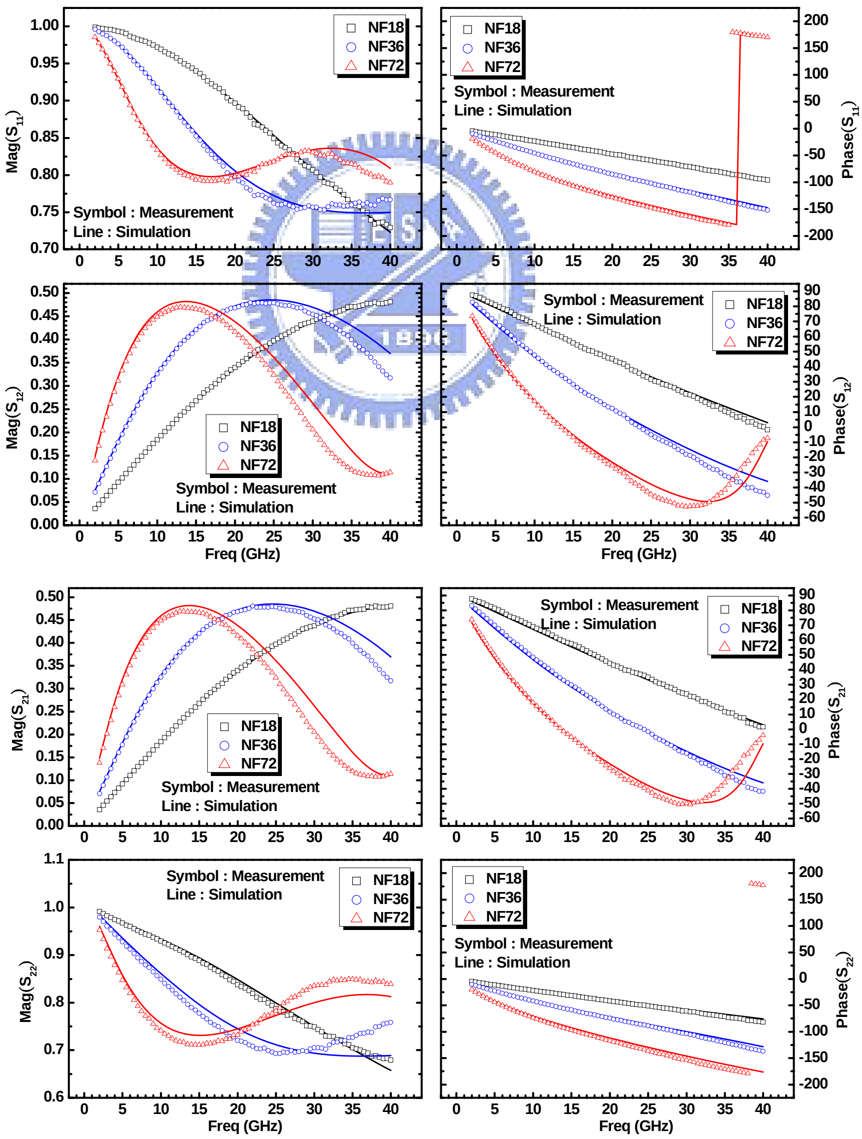


Fig. 6-8 The comparison results of 3T device at V_{gs}=V_{ds}=1.2V (Optimized)



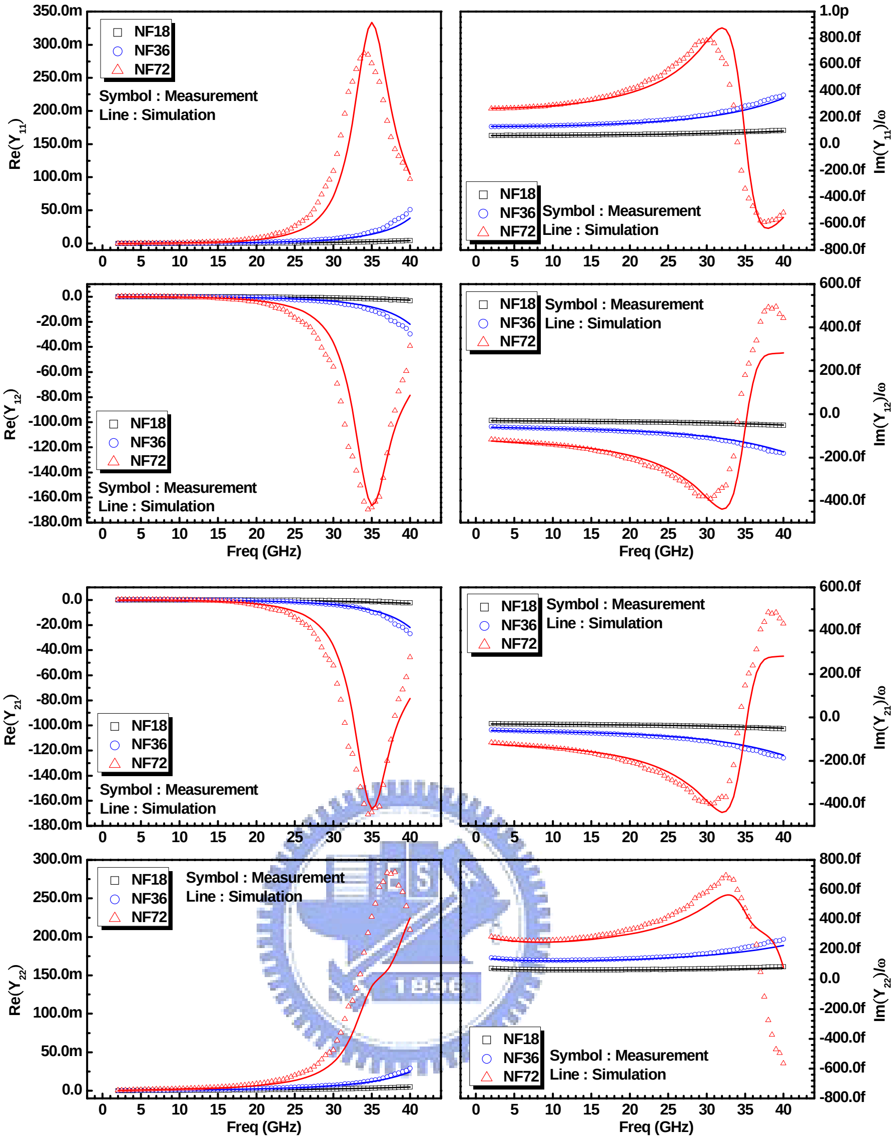
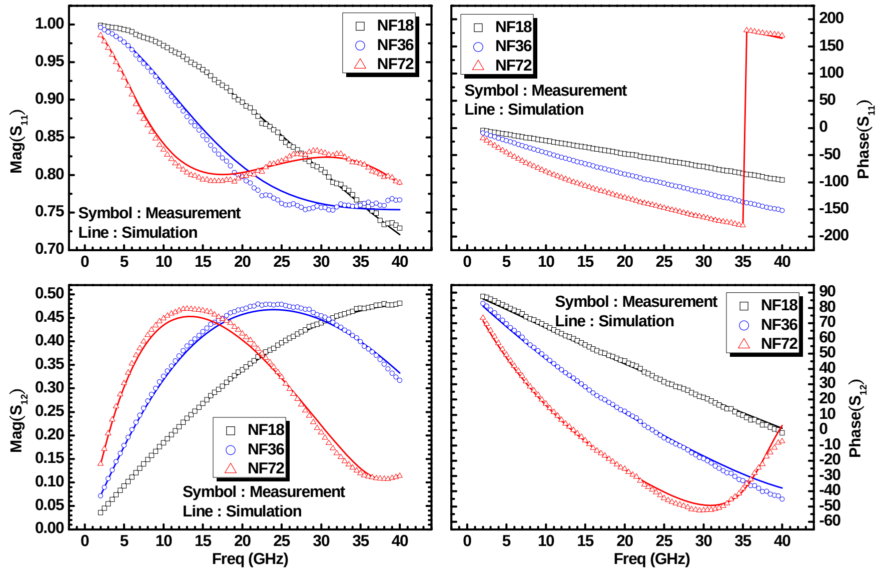


Fig. 6-9 The comparison results of 4T device at V_{gs}=V_{ds}=0V (Initial)



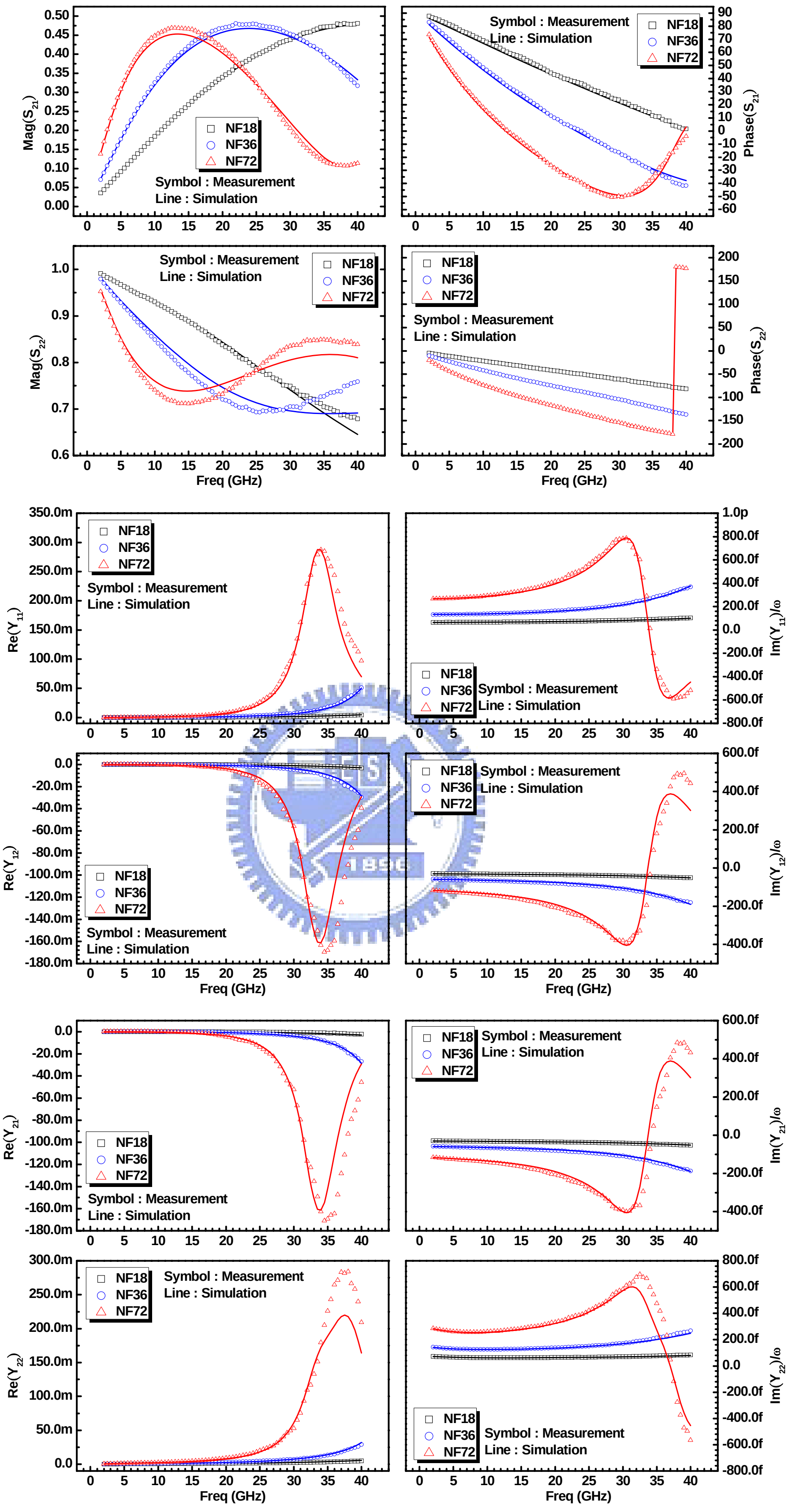
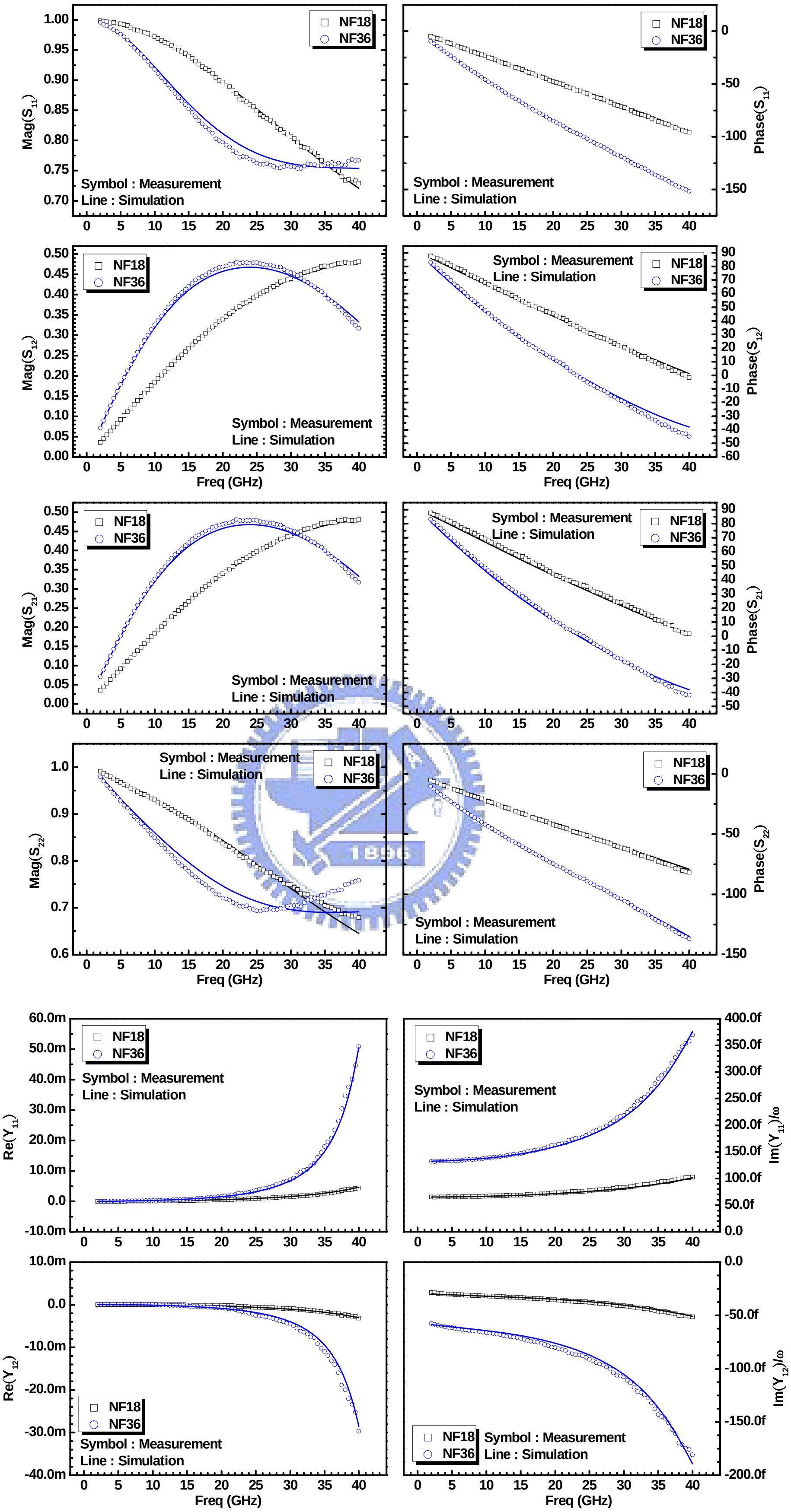


Fig. 6-10 The comparison results of 4T device at $V_{gs}=V_{ds}=0V$ (Optimized)



NF18
NF36
Symbol : Measurement
Line : Simulation
Mag(S11)
Phase(S11)
Mag(S12)
Phase(S12)
Mag(S21)
Phase(S21)
Mag(S22)
Phase(S22)
Re(Y11)
Im(Y11)/ω
Re(Y12)
Im(Y12)/ω
Freq (GHz)

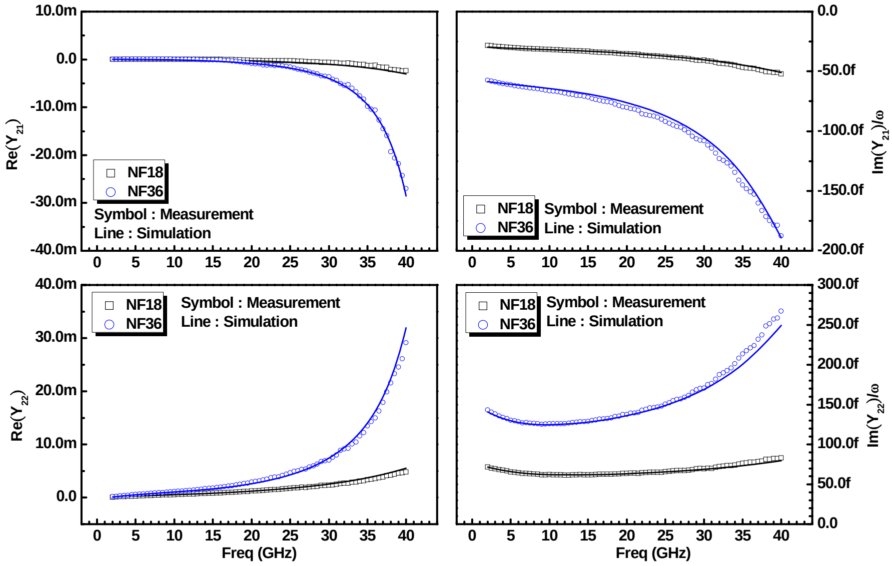
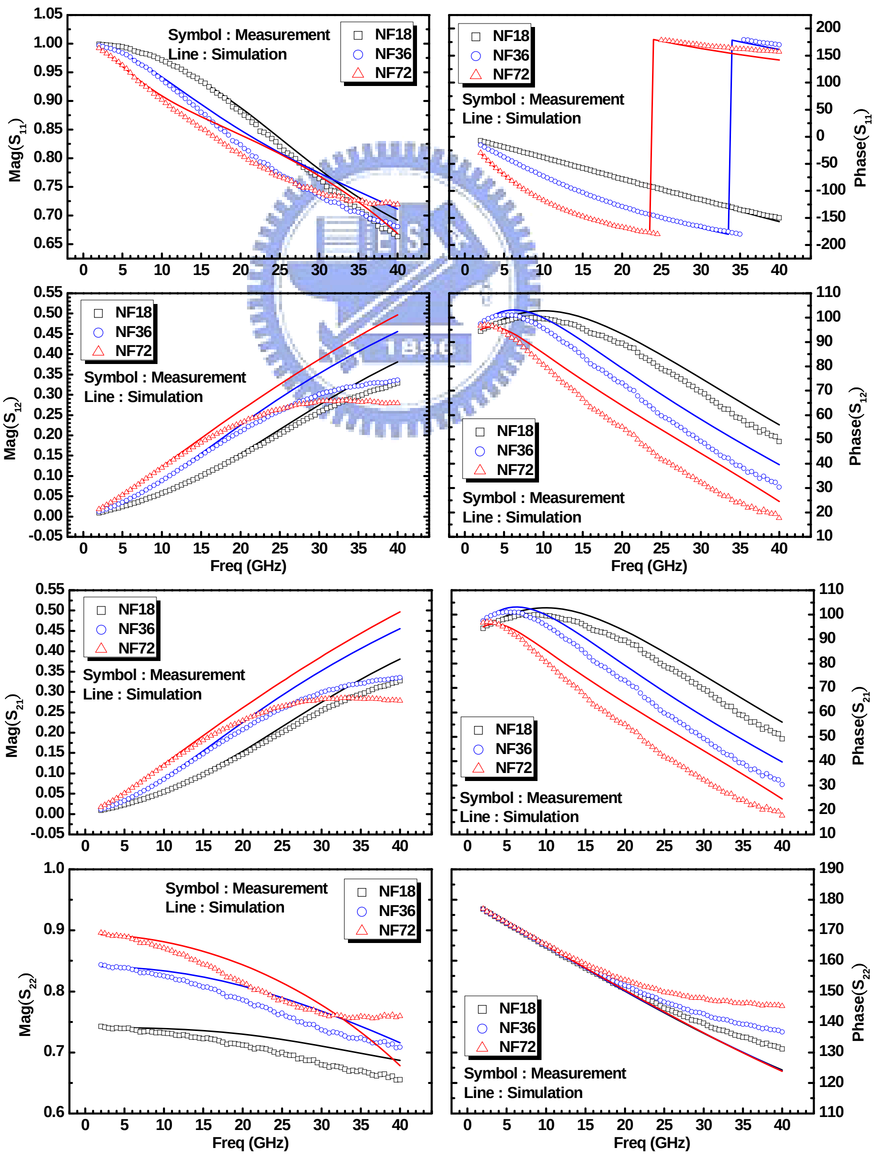


Fig. 6-11 The comparison results of 4T device at $V_{gs}=V_{ds}=0V$ (Neglecting $N_F=72$)



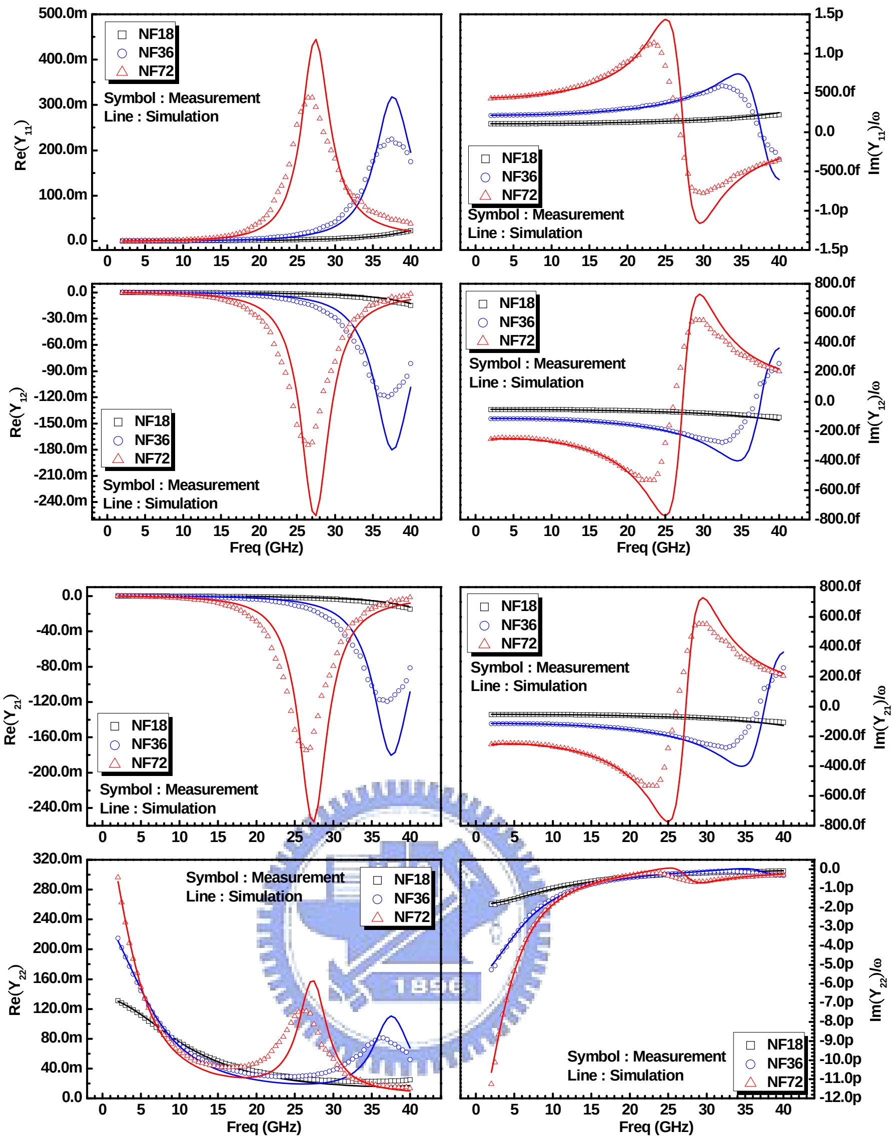
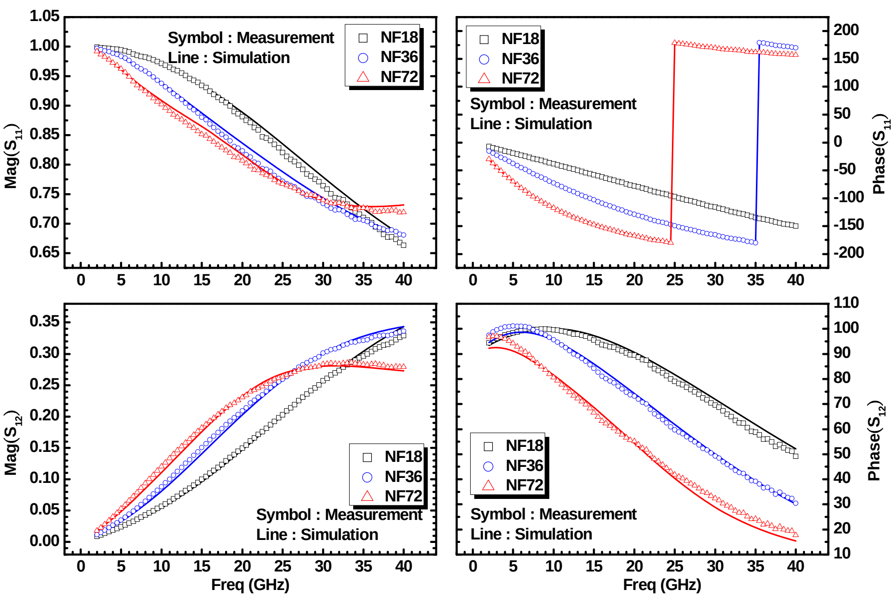


Fig. 6-12 The comparison results of 4T device at V_{gs}=1.2V, V_{ds}=0V (Initial)



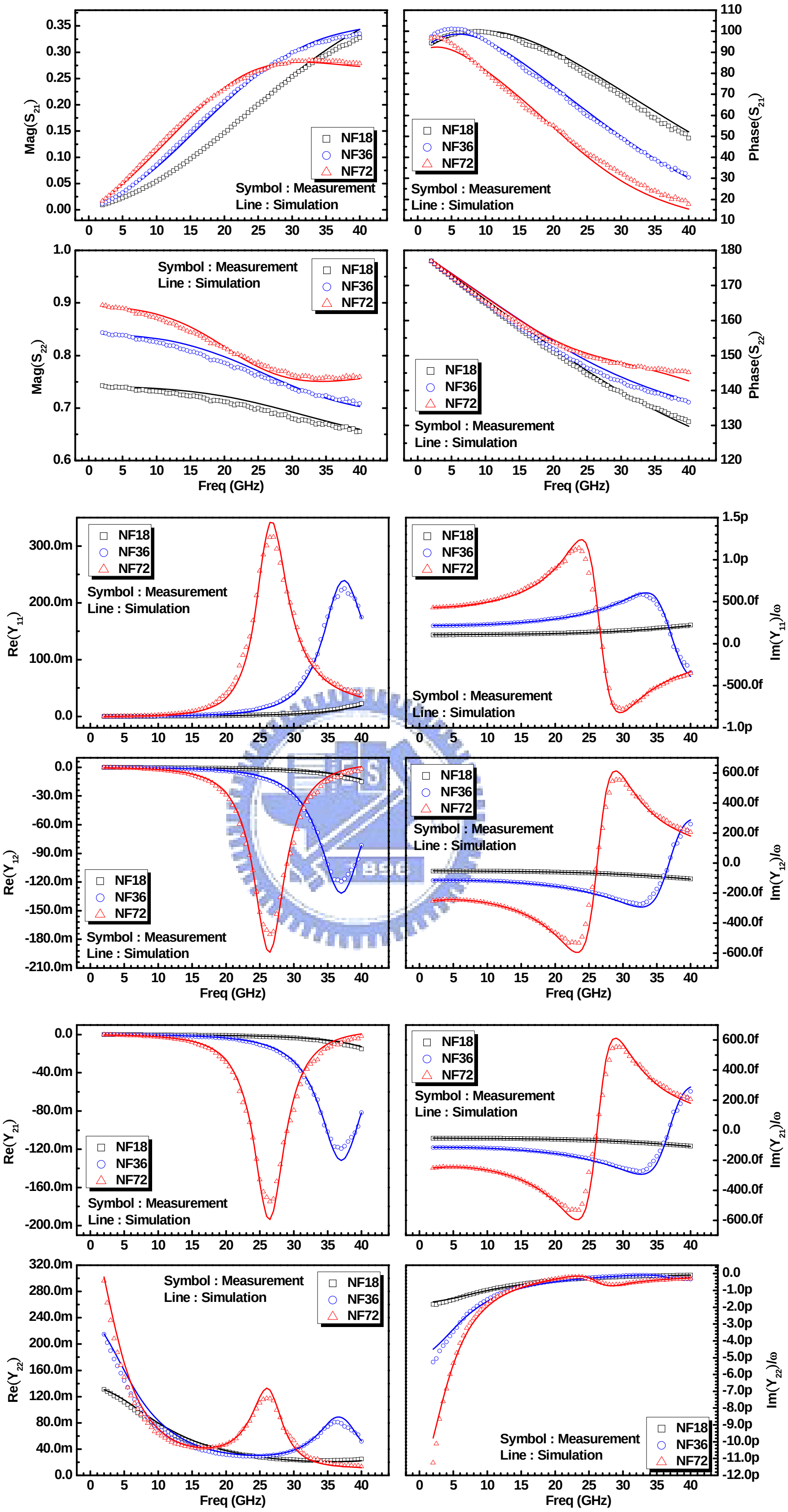
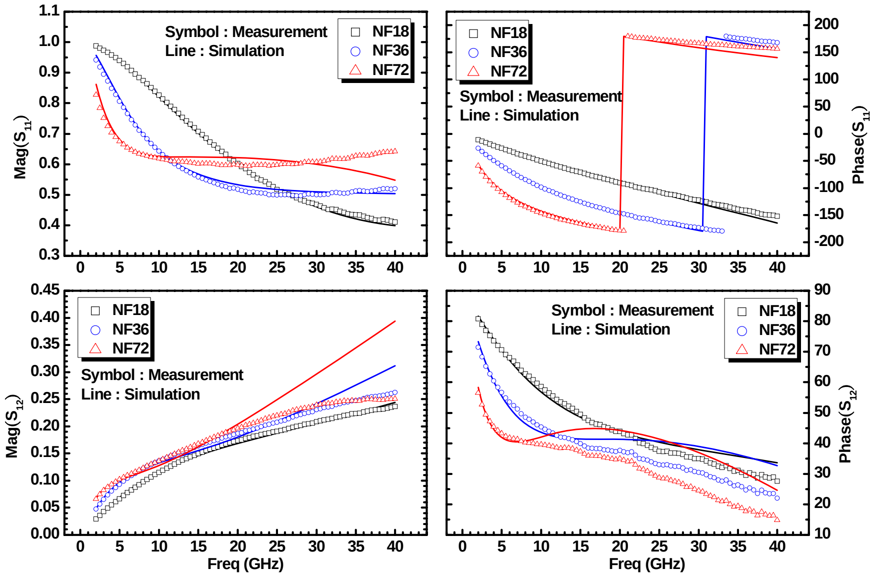
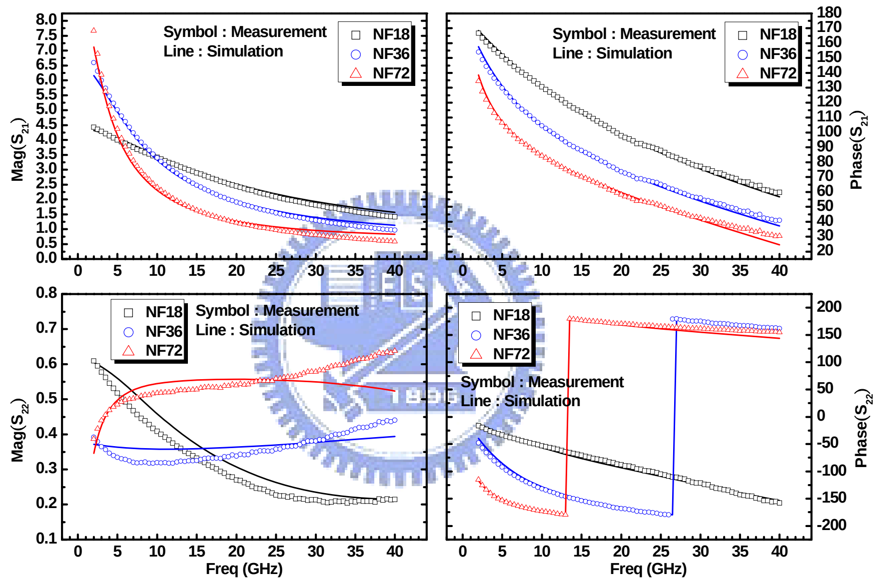
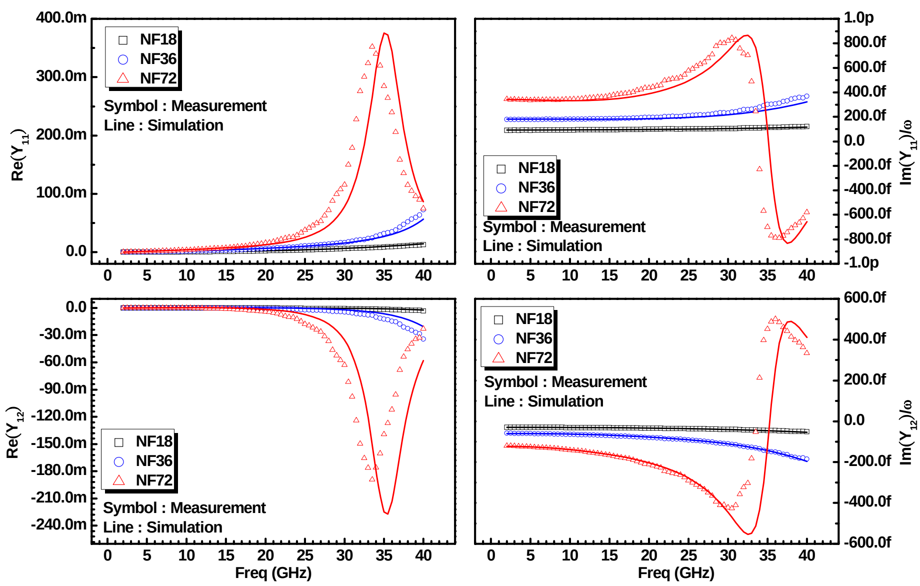


Fig. 6-13 The comparison results of 4T device at V_{gs}=1.2V, V_{ds}=0V (Optimized)


Symbol : Measurement
Line : Simulation
NF18
NF36
NF72
Mag(S11)
Phase(S11)
Mag(S12)
Phase(S12)
Freq (GHz)


Symbol : Measurement
Line : Simulation
NF18
NF36
NF72
Mag(S21)
Phase(S21)
Mag(S22)
Phase(S22)
Freq (GHz)


Symbol : Measurement
Line : Simulation
NF18
NF36
NF72
Re(Y11)
Im(Y11)/ω
Re(Y12)
Im(Y12)/ω
Freq (GHz)

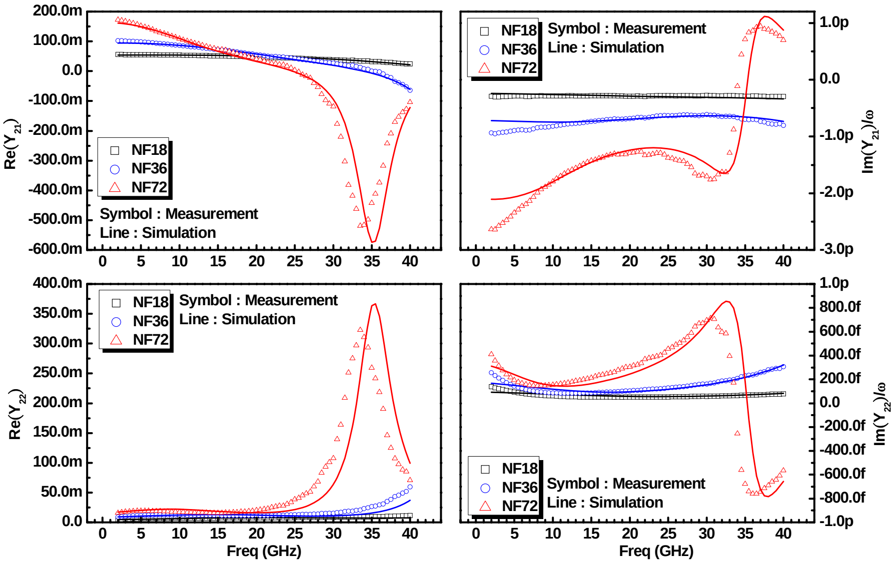
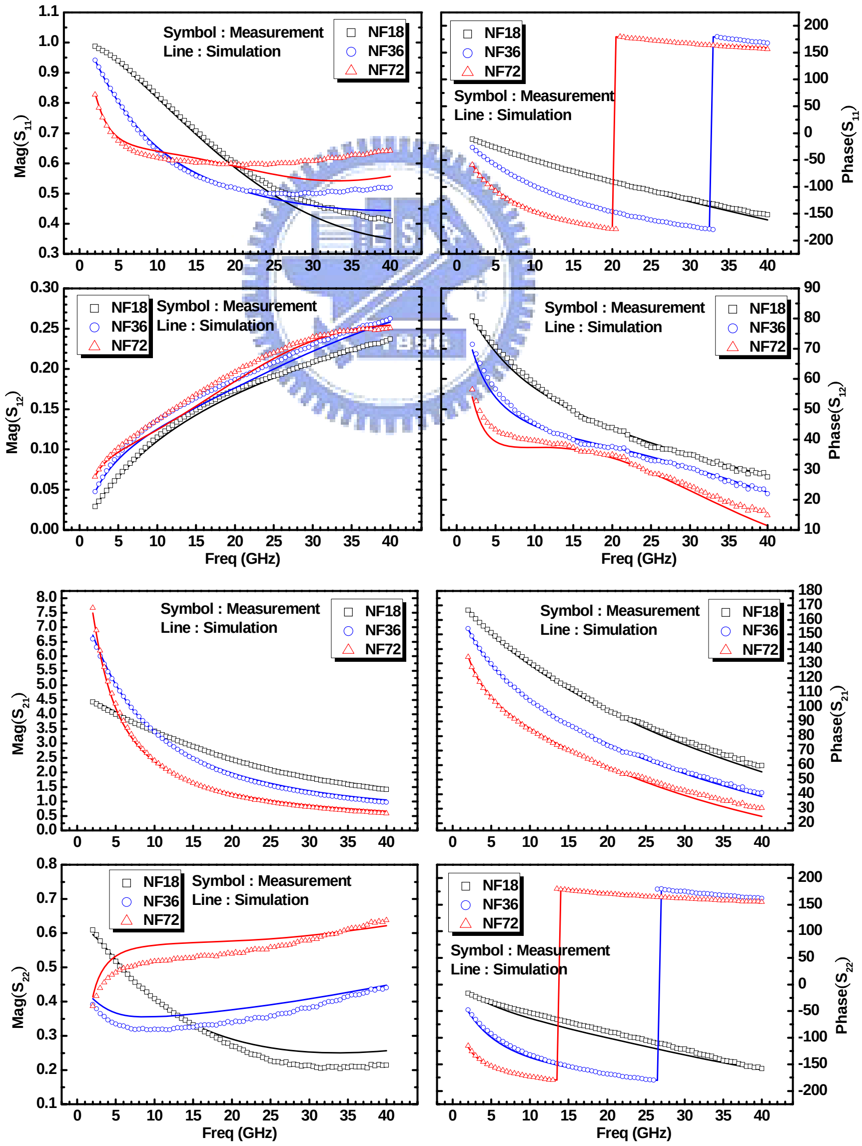


Fig. 6-14 The comparison results of 4T device at V_{gs}=V_{ds}=1.2V (Initial)



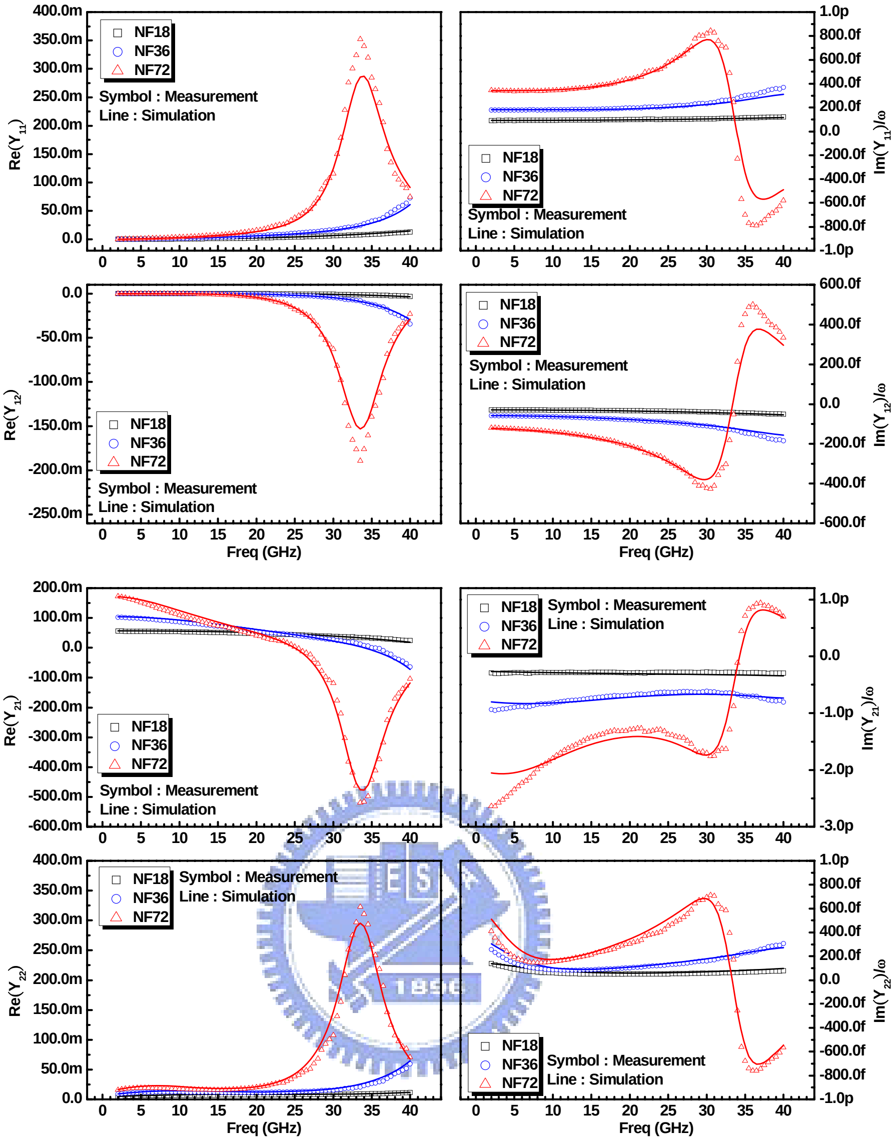
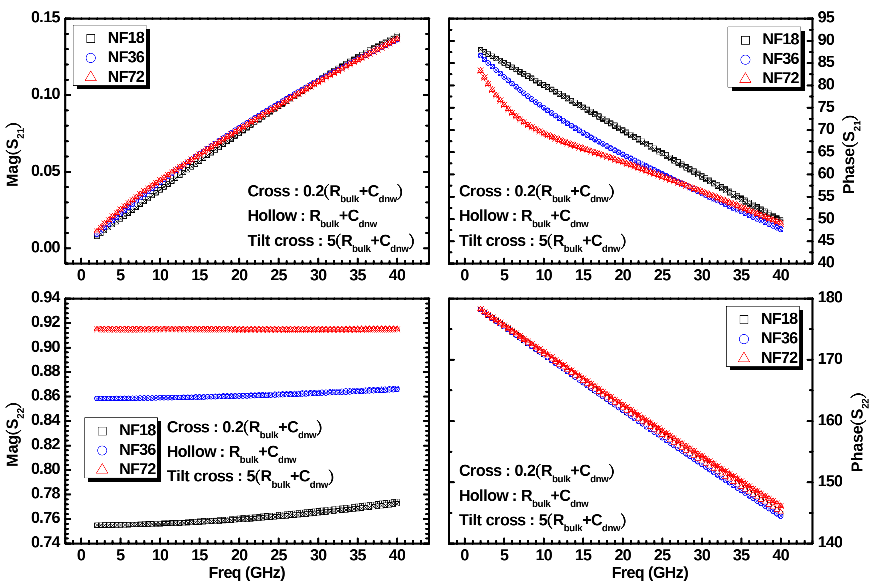


Fig. 6-15 The comparison results of 4T device at $V_{gs}=V_{ds}=1.2V$ (Optimized)



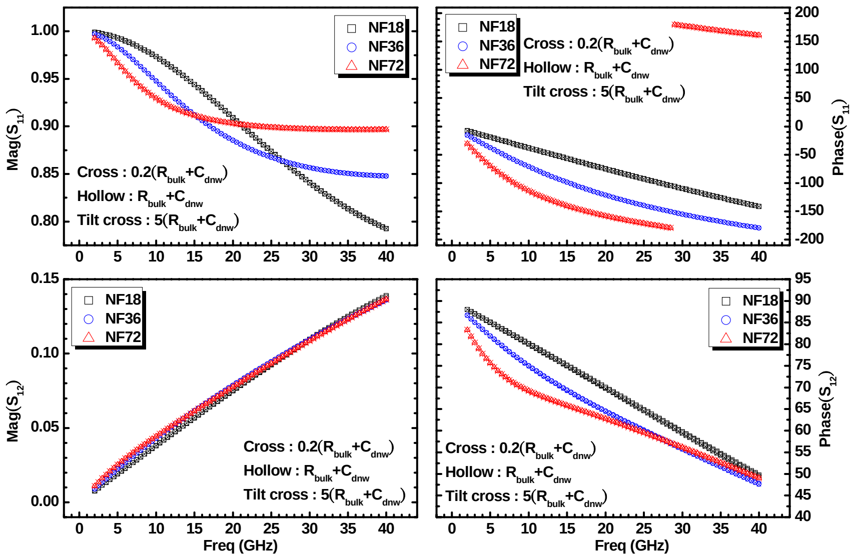


Fig. 6-16 The simulation of 3T device at V_{gs}=1.2V, V_{ds}=0V with varying R_{bulk} and C_{dnw}

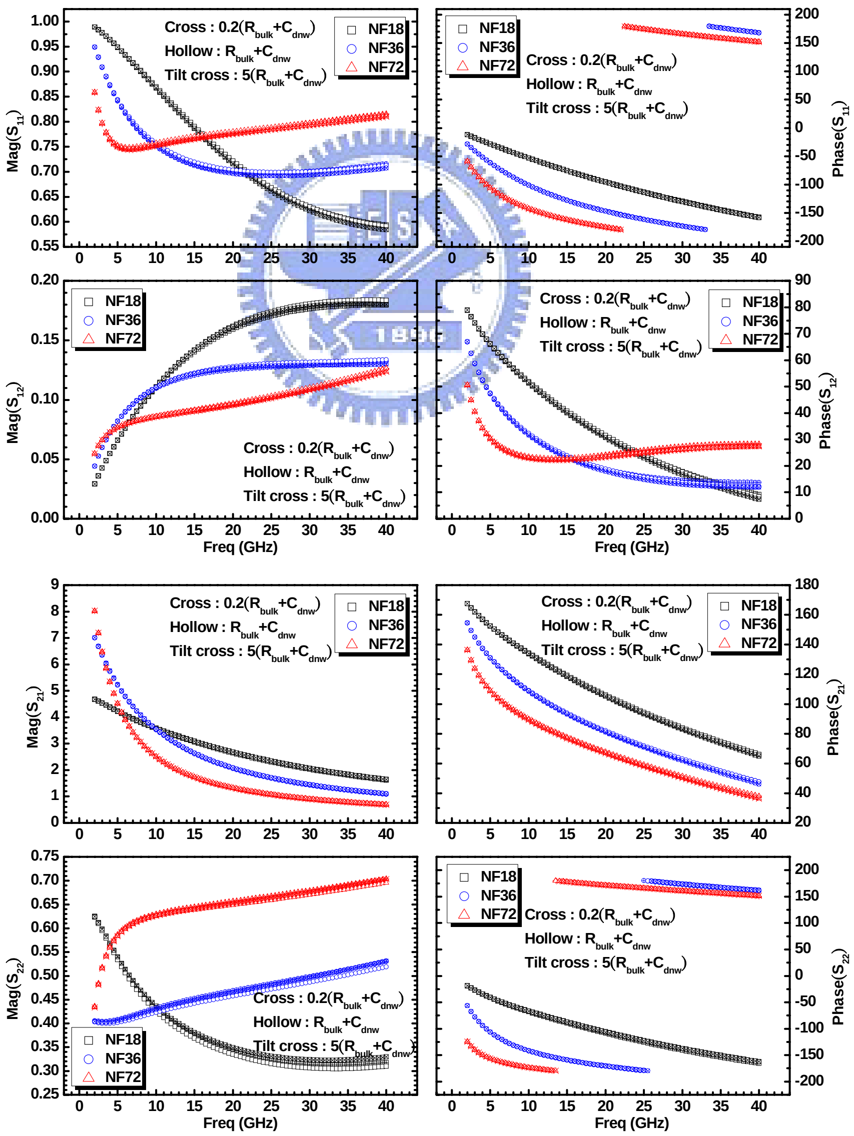


Fig. 6-17 The simulation of 3T device at V_{gs}=V_{ds}=1.2V with varying R_{bulk} and C_{dnw}