Achieving Traceable RFCMOS F_T and F_{MAX} Wafer Measurements

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***Abstract* — This paper investigates the impacts of RF probe aging, how RF probe contact resistances on test pads of calibration standards and devices affect the Ft and Fmax measurements of RFCMOS transistors. It is found that poor probe contact on calibration standards lead to large extracted load standard inductance when eLRRM calibration is used, degrading transistor Fmax. A RF wafer test strategy to help device and test engineers obtain accurate, repeatable and traceable Ft and Fmax measurements is proposed at the end of this paper.**

Index Terms — RFCMOS, Fmax, RF probe aging, contact resistance, de-embedding, RF calibration, wafer-level.

I. INTRODUCTION

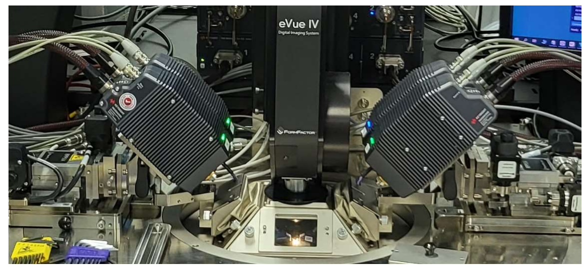
Higher operating radio frequencies (28, 38, 60 and 73 GHz) are needed to support wireless applications such as beyond 5G, wireless multimedia, IOT, big data and vehicular positioning systems at higher data rates and lower latencies [1]-[2]. To develop RFIC to support such applications, RF devices must be accurately characterized up to at least 110 GHz for wafer process development and SPICE model parameter extractions.

Ft and Fmax are important figure of merits for RFCMOS transistors and it has been a huge challenge in the industry to characterize and get reliable Fmax measurements. The ability for test engineers to make accurate, repeatable and traceable wafer-level Ft and Fmax measurements is critical for circuit designers before RFIC can be designed to support these emerging high data rate, low latency wireless applications. In this work, experiments are performed to study how the aging of RF probes, probe contact resistance on worn-out calibration standards and devices affect the Ft and Fmax measurement repeatability and traceability for RFCMOS transistors.

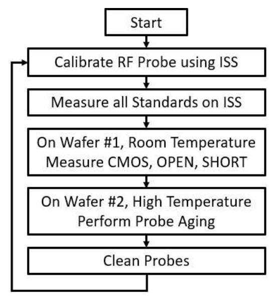
II. EXPERIMENTAL SETUP & TEST STRUCTURES

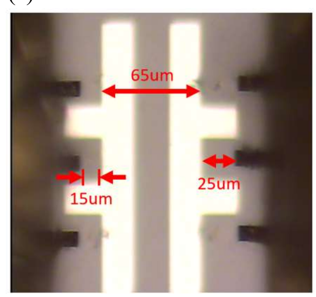
Test setup with 300mm FormFactor probe station, Keysight 110 GHz vector network analyzer (VNA) and B1500A device parameter analyzer, shown in Fig. 1(a), is used to investigate the impacts of RF probe aging and test pad degradations. 110 GHz RF probes and impedance standard substrates (ISS) are utilized for probe-tip calibrations and device measurements. 16-Finger and 100-Finger RF NMOS with nominal gate length are employed as test devices for this work.

Test flow of one typical aging cycle to investigate how aging of the RF probes, test pad degradations of ISS standards and device affect Ft and Fmax is outlined in Fig. 1(b). It starts by calibrating the pair of new RF probes using eLRRM [3], a probe-tip tolerant RF calibration method, with the short, open, load, thru' standards (portrayed in Fig. 2) and then measuring all the rest of the ISS standards to extract useful electrical characteristics. Next, on wafer #1, 16-Finger and 100-Finger



(a)





(b) (c)

Fig. 1. Test setup on a probe station with RF probes and 110 GHz vector network analyzer (a), experimental flow of one probe aging cycle to study its impact on RFCMOS's F_T and F_{MAX} (b) and RF probe scrub on the ISS 0.5 ps probe alignment structure (c).

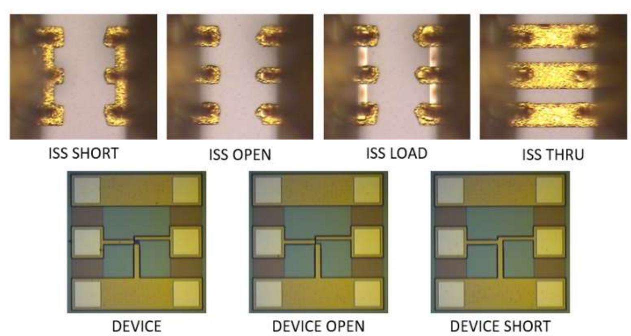


Fig. 2. Die photos showing calibration standards (SHORT, OPEN, LOAD and THRU') on the ISS and example of RF NMOS with OPEN and SHORT de-embedding test structures.

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RF NMOS devices and their corresponding short and open de-embedding test structures (shown in Fig. 2) are tested at 25°C with their Ft and Fmax extracted from the S-parameters measurements using methods outlined in [4].

To prevent degrading the RF NMOS device test pads at elevated temperatures, another wafer of the same mask layout, wafer #2, is used to age the RF probes. This wafer is subjected to high temperatures on the temperature-controllable chuck of the probe station. The gate RF probe, on a simple open test structure, is biased using Keysight B1500 and bias tees at 1V. The drain RF probe, on a simple short test structure, is separately biased with a stressing current. Both RF probes are aged by stepping across 100 to 200 dies with IV stressing of 10 minutes per die before they are cleaned with a probe cleaning pad to remove pad metal debris – this completes one aging cycle. By repeating two or more aging cycles, we are able to investigate how aging of the RF probe tips, degradation of ISS calibration standard and device test pads affect the Ft and Fmax of RF NMOS devices. Both FormFactor's Infinity and InfinityXT RF probes are used in this study, with their respective aging and test conditions outlined in Table 1.

TABLE 1. TEST CONDITIONS FOR EACH PROBE AGING CYCLE

RF Probe Type	Infinity	InfinityXT
Probe Aging Temperature (Wafer#2)	125 °C	150 °C
Number of Dies used for Aging	100	200
Max. Sweep Stress Aging Current	100 mA	100 mA
Duration of IV Stress on Each Die	10 mins	10 mins
Probe Scrub on ISS/Device Pads	15 µm	≥ 25 µm
RF Probe-Tip Calibration	eLRRM	
VNA Test Frequencies, Step Size	1 to 110 GHz, 1 GHz	
VNA Source Power, IF Bandwidth	-20 dBm, 30 Hz	

III. RESULTS AND DISCUSSIONS

In this section, we will present and establish correlations on how RF probe aging and test pad degradations impact ISS load standard inductance, ISS short standard resistance, device short de-embedding structure resistance, Ft and Fmax. As the aging IV stress conditions are designed to emulate how test engineers would characterize their RF NMOS devices, this work facilitates a tightly-controlled study of how Ft and Fmax are affected after each probe aging cycle.

A. Aging of RF Infinity Probes at 125°C

A fixed RF probe scrub of 15µm on the ISS and RF NMOS device pads is used for the infinity probes. This probe scrub is maintained throughout all the ISS/RF NMOS tests and probe aging cycles at 25 and 125°C respectively. Fig. 3 shows box plots of ISS load inductance, ISS short resistance, RF NMOS short resistance, Ft and Fmax at the start for a pair of new probes and how they change over three probe aging cycles with multiple measurements made for each of these test items.

From Fig. 3(b) and 3(c), it has been observed that both the 1 GHz resistances of ISS short standards and RF NMOS short de-embedding structures increase with probe aging cycles. The

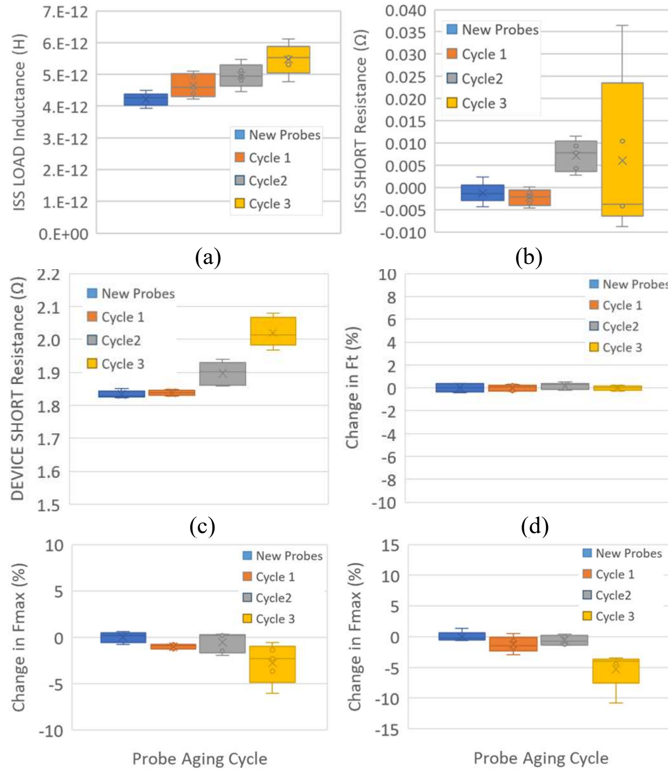

Fig. 3. Extracted ISS LOAD inductance (a), ISS SHORT resistance (b), Device SHORT resistance (c), 100-finger width RF NMOS's percentage change in Ft (d), Fmax (e) and 16-finger width RF NMOS's percentage change in Fmax (f) versus RF probe aging cycles at 125°C for Infinity RF Probes.

increase in resistances is due to probe tips wearing out over 1000 minutes of IV stressing at 125 °C per aging cycle as well as degradations of the ISS standards and RF NMOS devices test pads as a result of repeated probing. When the RF probe contact resistance increases, Fig. 3(a) documents gradual increase of ISS load standard inductances (eLRRM extracted) with each aging cycles from 4 to 6 pH, causing up to -5% and -10% drop in the extracted Fmax for 100-finger (Fig. 3(e)) and 16-finger (Fig. 3(f)) RF NMOS devices respectively. A significant drop in Fmax is observed because Fmax is inversely proportional to the gate impedance of the transistor, Zg as shown in (1), which explains why when the extracted load standard inductances and probe contact resistance increase, an overall degradation in Fmax is observed.

$$\text{Fmax} \approx \sqrt{\frac{\text{Ft}}{8\pi \cdot \text{Zg} \cdot \text{Cgd}}}\text{, where Ft} \approx \frac{\text{Gm}}{2\pi \cdot \text{Cgs}} \qquad (1)$$

Gm - transconductance of RF NMOS, Zg - gate impedance, Cgs - gate-source capacitance and Cgd - gate-drain capacitance.

Extracted Ft of the RF NMOS devices are very consistent, showing small variations of less than ±2% (Fig. 3(d)) throughout the three aging cycles because Ft, is directly proportional to Gm, the transconductance of the RF NMOS devices, which is less affected by the increase in the probe contact resistance as the channel resistance of the transistor is substantially larger than the probe contact resistances even when the NMOS are fully turned on.

B. Aging of High-Temperature RF InfinityXT Probes at 150°C

For the second part of this study, new InfinityXT probes are employed together with new ISS and new RF NMOS devices having fresh unprobed test pads. Probe scrubs of at least 25 µm on the ISS standard and RF NMOS device pads are used for these InfinityXT probes which are capable of operating at higher temperatures than Infinity probes. When resistances of the ISS short standard and device short de-embedding structure increase after each probe aging cycles, larger RF probe scrubs are adopted accordingly, beyond 25 µm, to ensure good probe contact for probe-tip calibration and RF NMOS measurements. Higher probe aging temperature of 150°C and up to 200 dies are utilized in each probe aging cycle for the InfinityXT probes.

Fig. 4 consolidates box plots of ISS load inductance, device short resistance at 1 GHz and Fmax of 2 probe aging cycles with a total IV stressing of 4000 minutes. The device short resistance in Fig. 4(b) is much lower with a flat and consistent trend, varying between 1.75 to 2 ohms compared to an increasing trend observed in Fig. 3(c), varying from 1.85 to 2.1 ohms for infinity probes, whereby fixed probe scrub of 15 µm over a total aging time of 3000 minutes were used. The low and consistent probe contact resistance allows for consistently low ISS load standard inductance of 1 to 3.4 pH to be obtained, enabling consistent and increasing Fmax of 5% to 12% to be obtained as depicted in Fig. 4(c) and (d).

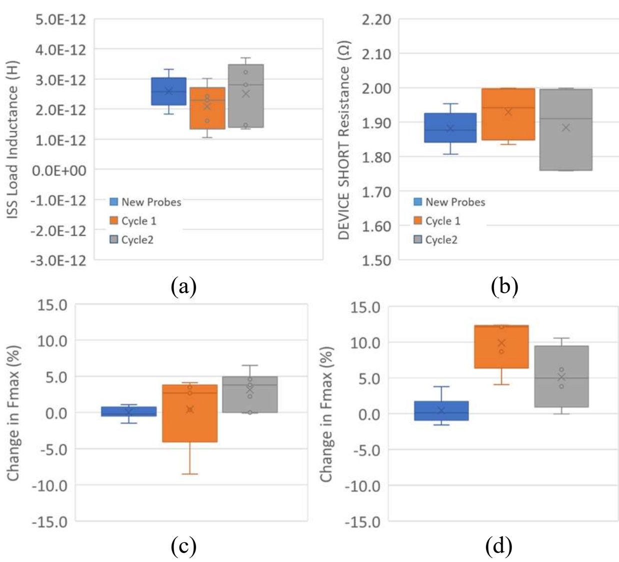

Fig. 4. Extracted ISS LOAD inductance (a), Device SHORT resistance (b), 100-finger width RF NMOS's percentage change in Fmax (c) and 16-finger width RF NMOS's percentage change in Fmax (d) versus RF probe aging cycles at 150°C for InfinityXT RF Probes.

IV. Strategy for Ft & Fmax Measurements

The RF probe aging results presented in the previous section highlight and emphasize the importance of having good probe contact resistance during calibration as well as making RF

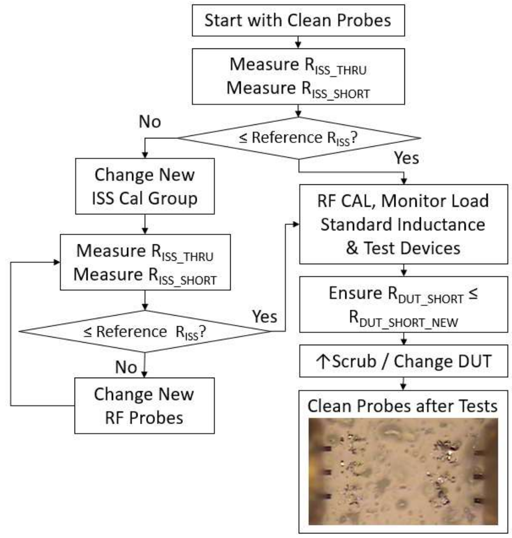

Fig. 5. Flowchart depicting a strategy to check ISS and device probe contact resistance for obtaining consistent Ft and Fmax measurements. Die photo with debris left on cleaning pad by RF InfinityXT probes.

NMOS measurements. On a daily basis, consistently low probe contact resistance can be achieved by comparing and monitoring DC resistances of in-use RF probes on ISS short/thru' standards and device short structures, against reference DC resistances measured when RF probes, ISS short/thru' standards and device short structures are all brand new, before commencing probe-tip calibration and device measurements, per the test strategy outlined in Fig. 5. Adopting these DC resistance checks will help test engineers determine the additional probe scrub needed or if there is a necessity to replace worn-out RF probes or calibration standards or devices with worn-out test pads, to ensure high accuracy, repeatability and traceability in Ft and Fmax wafer measurements for RFCMOS devices.

V. Conclusion

The impacts of RF probe aging, particularly, the degradation of RF probe tips and increase in contact resistances on test pads of calibration standards and RF NMOS devices have been investigated and presented in this work. Consistently small probe contact resistance on calibration standards and devices is instrumental in getting accurate, repeatable and traceable RFCMOS Ft and Fmax measurements.

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