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Importing experimental results via S2D model in ADS tool for Power Amplifier Design

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ABSTRACT

In this paper, behavioral modelling of a driver amplifier is implemented by using S2P and S2D model setup. By using the standard silicon-based driver amplifier for obtaining the measured results of Scattering (S-parameters and large signal parameters for temperatures 25 °C and 85 °C. These parameters are imported into the S2P and S2D models to perform the small signal and large signal analysis at 3 GHz frequency for temperatures 25 °C and 85 °C. Then, the simulated results are compared with the measured results to verify the efficient utilization of behavioral models. The novelty of this work deals with the simulation study of the characteristics of a silicon-based driver amplifier, which are obtained directly from the measurements. This proposed method is essential for performing hetero-integration of transceiver design, which can be further utilized to improve the efficiency of transceiver for high-frequency band. At last, the study of relative error performance analysis between measured and simulated results of different parameters is carried out and calculated value of NMSE (in %) for S11, S12, S21, S22, gain, pout, 1 dB compression point, ACP, 3rd harmonics, 4th harmonics, and 5th harmonics are 0.0083, 0.0055, 0.0086, 0.011, 0.0844, 0.814, 0.926, 0.71, 0.22, 0.012 and 0.070 respectively.

Keywords:

Power amplifier, Small signal analysis, Large signal analysis, Network analyzer, Radio-frequency.

1. INTRODUCTION

In modern times, Power amplifier (PA) has become the most demanding and promising circuit topology in the field of advanced wireless technology for efficient energy consumption and low transmitting expenses. With the utilization of circuit level, [1, 2] or behavioral models [3–5], a veracious modelling technique is required in the design of power amplifier. As compared to circuit-level models, behavioral mod-

els are much preferred because of the easy modelling method. The basic behavioral modelling of power amplifiers includes small signal analysis [6]. From this, small signal gain and basic linearity analysis can be carried out. However, a complete nonlinear analysis of the device under test (DUT) cannot be performed. Therefore, to study the accurate nonlinear behavior of power amplifiers, large signal analysis is required [7–9]. Furthermore, for the characterization of power amplifiers, behavioral models with some

mathematical formulation must be included. Most of the simulation and computer-aided engineering-based software, such as Keysight’s Advanced design system (ADS), is utilized to furnish the in-built behavioral models (such as S2D and P2D models) of PA with S-parameters [10, 11], 1 dB gain compression point and third order intercept point (IP3) for analyzing the large signal simulation.

In this work, importing of S2P and S2D models is being employed for the characterization and measurement of the driver amplifier. We have developed a pathway to incorporate the amplifier’s experimental results in an EDA tool (for this case, it is ADS) through S2D model file. This proposed approach is required when we are doing hetero-integration of the transceiver design, like some modules are on GaN/GaAs substrate and some modules are on Si or SiGe substrate. This kind of hetero-integration is utilized to increase the efficiency of the transceiver in the high-frequency range, like 6G. For getting an esteemed performance or formation project of any kind of hetero-integration platform, we require the proposed model that serves as a bridge between real-world measurements and simulation in ADS. When we know about the internal structure of the circuit, then we can easily simulate it on the ADS tool. But on the other hand, we don’t know about their internal circuit, like proprietary elements whose internal circuits are protected by industry IPs. Then, in order to forecast these performances in a transceiver system, we have only one pathway, which is measuring it and putting it in an ADS tool. Thus, this paper focuses on designing a model by which we can incorporate the experimental results of the device inside an ADS tool to forecast its behavior when used in a transceiver system. Thus, we require measurement data to represent the behavior of the driver amplifier inside the ADS tool. By using the behavioral model of PA, it is quite straightforward to perform the small signal and large signal simulation. Also, the impact of the temperature on measurement and simulation is analyzed for temperature (T) = 25°C and 85°C. The paper is organized as follows: Section II describes the basic structure of S2D modelling. Section III describes the measurement setup and the related procedures. Section IV presents the results and the discussion, and

finally, Section V concludes the paper.

2. PROPOSED MODEL AND CONFIGURATION

There are many behavioral model examples available in the electronic design automation (EDA) tool for the extraction of small signal and large signal parameters. In the ADS environment, the S2P model is available for small signal analysis of active and passive element-based circuits [12]. Here, All the S-parameters, i.e., input return loss (S11), small signal gain (S21), output return loss (S22), and insertion loss (S12), can be extracted by performing the S-parameter analysis for a particular range of frequency. For large signal analysis, the AMPS2D model setup is available in the ADS tool. Here, Radio-frequency (RF) parameters can be extracted by simulating the harmonic balance of the AMPS2D model setup containing the S2D file from the measured large signal parameters data. The basic flowchart of the S2P and S2D model-based simulation setup is given in Figure 1.

2.1 Steps for S2P model setup

1. First, start the ADS with the design environment window and open the S2P model setup in the schematic cell view.
2. Then, prepare the S2P file with the measured data in a predefined format and import it into the S2P model setup.
3. Start the S-parameter simulation to perform the small signal analysis.
4. Lastly, open the data display window to see the simulation result of the S-parameter.

2.2 Steps for S2D model setup

1. First, start the ADS and open the schematic window in the ADS design environment.
2. Then, prepare the S2D file in the predefined format according to the measured data type and import it into the S2D model setup.

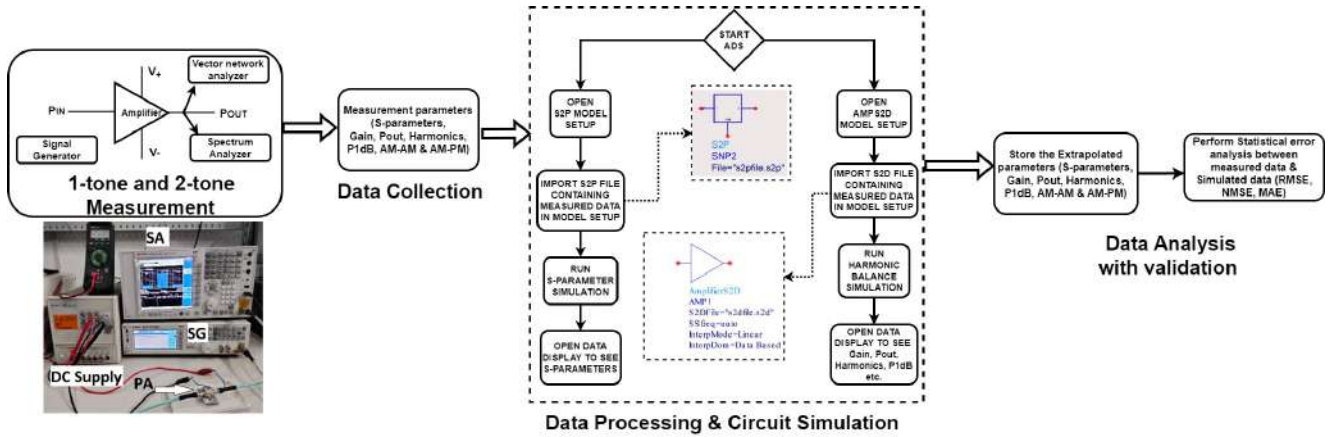


Figure 1: Design Workflow chart of S2P and S2D modelling.

3. Start the Harmonic Balance (HB) simulation to perform the large signal analysis (namely, one-tone and two-tone HB simulation).
4. Lastly, open the data display window to see the simulated results of 1-tone and 2-tone analysis in a separate window.

3. MEASUREMENT PROCEDURE

The measurement setup for small signal and large signal analysis can be performed for analyzing the non-linear characteristics of RF PA (ZX-60-63+) from Mini-circuits [13] biased at 5V,80 mA as shown in Figure 2. In order to observe the impact of temperature on small signal and large signal analysis, we have tested and verified the outcomes of RF PA at two temperatures, i.e., 25 °C and 85 °C.

3.1 Small signal analysis of PA

The small signal parameters (S-parameter) are measured by performing the small signal analysis of RF PA. The measurement setup for S-parameter analysis consists of a PNA network analyzer N5221A, RF testing cables, and RF PA. After completing the calibration of PNA for 2 ports [14], all the S-parameters are measured for the frequency ranging from 50 MHz

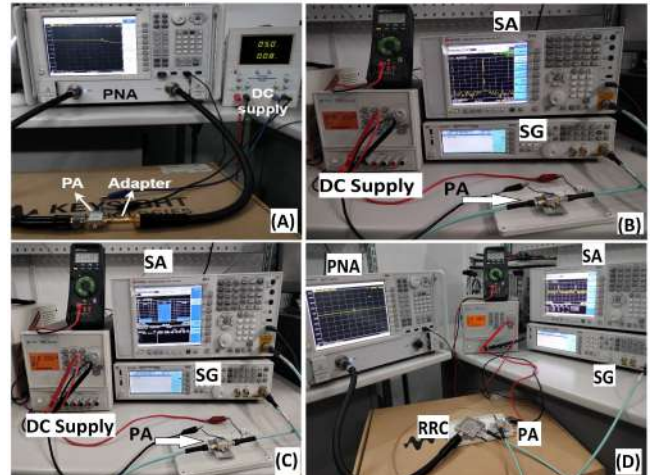


Figure 2: (A) Measurement setup configuration (B) Measurement setup of 1-tone analysis for output spectrum of PA (C) Measurement setup of 1-tone analysis for Adjacent channel power (ACP) (D) Measurement setup of 2-tone analysis of PA for third order intercept (TOI).

to 8 GHz with a step of 500 MHz. The measured S-parameters are saved in .csv file format. Then, the S2P file containing measured S-parameters of standard PA is imported into the S2P model of the ADS

software, and the small signal analysis within the same frequency range for 50-ohm termination. All the simulated S-parameters are available in the data display window of the simulated cell view.

3.2 Large signal analysis of PA

The measurement setup is the same as the small signal analysis. The only difference is that all the measurements are carried out with power sweep instead of frequency as in the case of small signal characterization. On PNA setup, Gain compression analysis (GCA) is performed. The gain of PA is calculated by using Eq.1. The measurement of large signal analysis can be performed in two ways, i.e., one tone and two tones. It is noted that after importing the measured data in the AmpS2D model, a simulation is performed for 1-tone and 2-tone analysis, and results are generated from the same AmpS2D model. The description of measurement setup and procedure of 1-tone and 2-tone analysis of PA is given in sections 3.2.1 and 3.2.2, respectively.

$$\text{Gain(dB)} = P_{\text{OUT}}[\text{dBm}] - P_{\text{IN}}[\text{dBm}] \quad (1)$$

3.2.1 1-tone analysis of PA

The 1-tone PA measurement setup consists of a DC supply with a multi-meter, MXA N9020A spectrum analyzer (SA), EXG N5172B signal generator (SG), and PA. The large signal parameters are measured by selecting the standard gain compression mode for the swept input power per frequency. For this type of measurement, input power from port 1 of PNA is swept from -30 dBm to 20 dBm with a step of 0.2. Port 2 of PNA is connected to the other terminal of PA to display the measurement results. Figure 2(B) shows the output spectrum of PA biased at 5V, 80 mA for 3 GHz frequency. Figure 2(C) shows the ACP analysis of PA biased at 5V, 80 mA for 3 GHz frequency.

The measured large signal parameters can be saved in .csv file format. The exported data contain the measured output power with respect to input power. Then, the measured data are saved in the S2D file format, which contains both the S-parameters (as explained in section 3.1) and large signal parameters

(Gain, output power, Harmonics, etc.) with respect to the swept input power for 3 GHz frequency. Then, this S2D file is imported into the behavioral model of PA given in the ADS tool, i.e., S2D model. Finally, the simulation setup of large signal analysis of PA having HB simulator with swept power and imported S2D file-based amplifier model is run to perform the simulation.

3.2.2 2-tone analysis of PA

The 2-tone PA measurement setup consists of a DC supply with a multimeter, spectrum analyzer (SA), signal generator (SG), Rat-race coupler (RRC) as power combiner [15], and PA biased at 5V, 80 mA. For 2-tone analysis, both the PNA and SG are set with the same amplitude of input power of 5 dBm. However, the operating frequency of PNA and SG is set at 3.01 GHz and 2.99 GHz, respectively. One signal is given to port 1 of RRC and the other one is given to port 3 of RRC. The RRC acts as a power combiner between the power signals of port 1 and port 3. The resultant output is a combined power signal, which is taken out from port 3 and given to the SA. It is noted that port 4 is kept isolated for the entire measurement procedure. The whole measurement procedure is carried out at a center frequency of 3 GHz with a frequency spacing of 20 MHz. The display of the measured two-tone spectrum is shown in Figure 2(D).

4. RESULT AND DISCUSSION

In this section, PA measurements and simulation results of S-parameters, as well as gain and output power versus input power for for $T = 25^\circ\text{C}$ and $T = 85^\circ\text{C}$, are represented as shown in Figure 3(A) and Figure 3(B). The value of output power is 15.94 dBm for 0 dBm input power, and the corresponding gain is 15.90 dB. It is observed that the output power of the PA is increasing up to 5 dBm input power. After a further increase in input power, the value of output power becomes saturated, which is said to be saturated power (P_{sat}). The 1 dB compression is normally defined as the corresponding output power

for which the gain drops by 1 dB. Here, the 1 dB compression point at 5 dBm input is 24.4 dBm. The value of measured and simulated gain of the PA is constant up to 0 dBm input power. After that, the value of gain starts decreasing linearly on increasing the swept input power. The trajectory of the slope of gain is opposite to the slope of the output power. This can be clearly explained by seeing the gain expression in Eq.1.

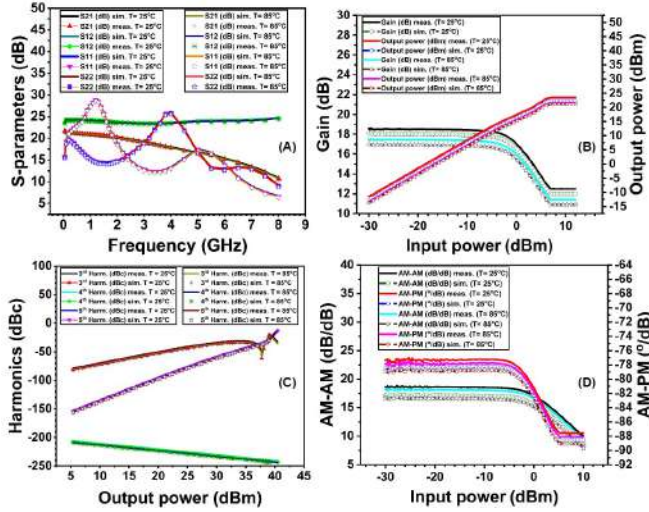


Figure 3: Measured and simulated result of (A) S-parameters, (B) Gain and Output power, (C) 3rd, 4th, and 5th order harmonics, and (D) AM-AM and AM-PM vs input power for one-tone measurement.

Also, after the completion of the measurement of ACP analysis at 3 GHz, 5 dBm input power signal, obtained ACP is -65.8 dBc. Figure 3(C) shows measured and simulated results of the 3rd harmonics, 4th harmonics, and 5th harmonics for different values of output power. It is observed that values of 3rd harmonics and 5th harmonics are more than -20 dBc which is required for better linearity of PA. Figure 3(D) shows the AM-AM and AM-PM plots for measured and simulated results of PA. The measured and simulated results of P1dB (dBm) are compared for T = 25°C and 85°C in Figure 4. To analyze the two-tone measurement of PA, Figure 5 shows the measured and simulated results of the output spectrum

for 25°C and 85°C. By observing the results, it is seen that the value of output power for two-tone frequencies (2.99 GHz and 3.01 GHz) is 22.91 dBm and 22.90 dBm for 25°C, respectively. Similarly, the output power value for 85°C is 22.87 dBm and 22.85 dBm.

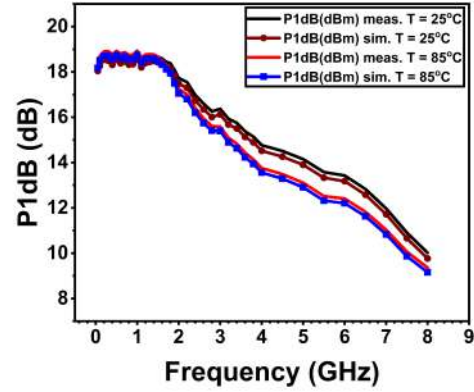


Figure 4: Measured and simulated results of P1dB (dBm) for one-tone measurement.

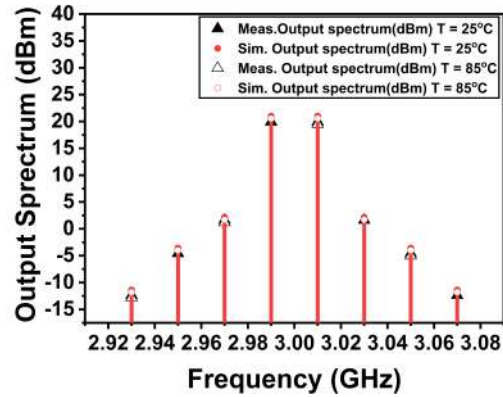


Figure 5: Measured and simulated results of Output spectrum for two-tone measurement.

$$NMSE = \frac{\sum_{i=1}^N (Y_{measured} - Y_{simulated})^2}{\sum_{i=1}^N (Y_{measured})^2} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (Y_{\text{measured}} - Y_{\text{simulated}})^2}{N}} \quad (3)$$

$$\text{MAE} = \frac{\sum_{i=1}^N (Y_{\text{measured}} - Y_{\text{simulated}})}{N} \quad (4)$$

It is observed that the simulated results of the S-parameter and large signal analysis of PA are similar to the measured results with some magnitude variations (in dB), which can be calculated as an error. This error shows the deviation of the simulated value from the measured value.

The simulated results are lower than the measurement, which can be attributed to several factors that may affect the accuracy of the simulation despite the direct import of measured data into ADS. These factors can include:

- **Model Fidelity:** The behavioral S2D model used may not perfectly capture all the intricacies of the real-world power amplifier. It simplifies the device's behavior and may not account for all the effects, leading to differences in simulation results.
- **Measurement Setup:** Even though the measured data is imported directly, the accuracy of measurements can be influenced by factors like test equipment calibration, environmental conditions, and setup variations. Small discrepancies in measurement accuracy can lead to differences in simulation results.
- **Frequency Dependency:** The behavior of amplifiers, especially at high frequencies like 3 GHz, can vary significantly with frequency. If the measurements and simulations are not carried out at exactly the same frequency, it can result in variations in the gain and power output.
- **Nonlinear Effects:** Power amplifiers can exhibit nonlinear behavior, and the simulation model's representation of these nonlinear effects may not be perfect. This can lead to discrepancies in large signal parameters like output power and gain.

- **Model Tuning:** Behavioral models may require fine-tuning and calibration to match measured results accurately. If this tuning is not done rigorously, it can result in differences between simulation and measurement.

- **Parameter Extraction Errors:** The process of extracting S-parameters and other parameters from measurements and importing them into the S2D model can introduce errors. These errors can propagate through the simulation, leading to variations in the results.

- **Load Mismatch:** Mismatches between the load conditions in the measurement setup and the simulation can affect the results. If the load conditions in the simulation are not well-matched to the measurement setup, it can lead to differences in gain and power.

- **Device Variability:** Power amplifiers can exhibit manufacturing variations. If the measured device and the simulated device have inherent differences in their characteristics, this can lead to variations in gain and power.

All the above factors can greatly affect the similarity between experimental and simulation results. The performance analysis of relative error between measured and simulated results of different parameters can be performed by calculating the error matrices such as Normalized mean square error (NMSE), Root mean square error (RMSE), and Mean absolute error (MAE). NMSE is defined as the ratio of summation of the square of the difference between the Y_{measured} (measured) and $Y_{\text{simulated}}$ (simulated) data and summation of the square of Y_{measured} (measured) data for N (number of residuals) as given in Eq.2. It is generally used to measure the normalized error between measured and simulated data. From Eq.3, RMSE is defined as the square root of the mean square error for N residuals. It is used to measure the standard deviation between the simulated and measured data. From Eq.4, MAE can be defined as the average of the

Table 1: Comparison of measured and simulated outcomes of PA for T= 25°C & T= 85°C

Parameters	for T= 25°C					for T= 85°C				
	Measured	Simulated	NMSE	RMSE	MAE	Measured	Simulated	NMSE	RMSE	MAE
S11 (dB)	-15.68	-15.86	8.31E-05	0.18	0.00415	-15.98	-16.11	4.16948E-4	0.13	0.00335
S12 (dB)	-23.56	-23.74	5.59E-05	0.16	0.00452	-23.86	-23.99	4.44063E-4	0.11	0.00372
S21 (dB)	21.9	21.72	8.60E-05	0.18	0.00462	21.6	21.47	4.13958E-4	0.13	0.00382
S22 (dB)	-15.61	-15.79	1.10E-04	0.17	0.00442	-15.91	-16.04	3.9041E-4	0.12	0.00362
Gain (dB)	17.01736	16.51736	8.44E-04	0.5	0.00249	16.71736	16.26736	3.4372E-4	0.45	0.00169
Pout (dBm)	17.43309	16.23309	0.00814	1.2	0.00597	17.13309	15.98309	0.00764	1.15	0.00517
1 dB Compression point (dBm)	24.4	23.3	0.00926	1.1	0.0067	24.1	23.05	0.00876	1.05	0.0059
ACP (dBc)	-65.8	-66.9	0.00713	0.11	0.00575	-66.1	-67.15	0.00663	0.06	0.00495
3rd Harmonics (dBc)	-78.6003	-81.1003	0.00225	2.5	0.02358	-78.90031	-81.35031	0.00175	2.45	0.02278
4th Harmonics (dBc)	-205.396	-207.896	1.22E-04	2.4	0.02158	-205.6962	-208.1462	3.7774E-4	2.35	0.02078
5th Harmonics (dBc)	-152.397	-154.897	7.04E-04	2.5	0.02458	-152.6971	-155.1471	2.03873E-4	2.45	0.02378

squared difference between the measured and simulated data. It is used to measure the variance of N residuals.

Table 1 shows the comparative summary of relative error performance for different simulated and measured parameters for 25 °C and 85 °C. The value of N for S11, S12, S21, S22, and ACP is 39. For gain, pout and 1 dB compression point, N = 201 and for 3rd harmonics, 4th harmonics, and 5th harmonics, N = 106. It can be seen that the RMSE value for ACP, i.e., 0.11, is less as compared to other parameters. The value of MAE, i.e., 0.00249, is less for gain, and the value of NMSE, i.e., 0.0000559, is less for S12 as compared to other parameters. The overall performance of NMSE is better compared to the other 2 error matrices. It is due to the existence of less value of deviation between measured and simulated results.

5. CONCLUSION

This paper focuses on designing a model by which we can incorporate the experimental results of the device inside an ADS tool to forecast its behavior when used in a transceiver system. Thus, we require measurement data to represent the behavior of the driver amplifier inside the ADS tool. The behavioral model of the driver amplifier is utilized for verifying the non-linear characteristics of a driver amplifier. The measured S-parameters and large signal parameters are imported into S2P and S2D model setups in respective file formats in order to perform small signal and large signal simulations. Then, the obtained simulated results are compared with the measured results

to verify the importance of the behavioral model in the characterization of the silicon-based driver amplifier. The error occurring between measured and simulated results for different parameters has been accurately estimated. Among 3 error matrices, NMSE shows the lower value of deviation. The calculated value of NMSE (in %) for S11, S12, S21, S22, gain, pout, 1 dB compression point, ACP, 3rd harmonics, 4th harmonics, and 5th harmonics are 0.0083, 0.0055, 0.0086, 0.011, 0.0844, 0.814, 0.926, 0.71, 0.22, 0.012 and 0.070 respectively. For future extension of this work, instead of using circuit-level simulation, a model-based setup can be utilized for the design and characterization of the driver amplifier. After implementation of the model-based setup of PA, accuracy can be greatly improved with a low value of error and performance analysis becoming fast. This work can be utilized to determine the influence of the driver amplifier properties on the driver amplifier measurements via simulation.

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India. He received a BE degree in Electronics and Communication Engineering from RGPV Bhopal, India, in 2009 and an MTech degree in Microelectronics and VLSI Design from S.G.S.I.T.S. Indore, India, in 2012. He has received a fellowship from the Government of India for pursuing MTech and PhD. He got the award of \$100 from Maury Microwave for designing a power amplifier in a student design competition. He has two journals and 3 conference publications till now. His research interest includes III-V device-based Analog circuit de-



sign. **Shubhankar Majumdar** received his Ph.D. degree from the Indian Institute of Technology Kharagpur, India. He has significantly contributed to several AI techniques to model the semiconductor devices for the device-circuit co-design application. Presently, he is an Assistant Professor at the Department of Electronics and Communication, National Institute of Technology Meghalaya. He is a Mentor of a startup incubation company, namely SOIL Agritech Private Limited. He works on developing and modelling of Internet of Things (IoT) network for wireless power transfer, disaster management, and air pollution. He received several awards, such as the enlistment in the golden reviewer list of IEEE TED, the Marie Skłodowska-Curie Actions Seal of Excellence Award from the European Commission, and two post-doctoral scholarships from the Italian Government and the Government of India. He has published over 50 peer-reviewed journals, book chapters, and conferences. He has 1 granted Australian patent and 1 granted Indian Patent. He garnered about 10 research grants, including AISTIC, Indo-Czech, Indo-Japan, and Device Development Program projects.



Farid Medjdoub is a CNRS senior scientist and leads a research team WIND focused on wide bandgap material and devices at IEMN in France. He received his Ph.D. in Electrical engineering from the University of Lille in 2004. Then, he moved to the University of Ulm in Germany as a research associate before joining IMEC as a senior scientist in 2008. Multiple state-of-the-art results have been realized in the frame of his work. Among others, world record thermal stability up to 1000°C for a field effect transistor, the best combination of cut-off frequency/breakdown voltage or highest lateral GaN-on-silicon breakdown voltage using a local substrate removal have been achieved. His research interests are the design, fabrication, characterization, and simulation of innovative wide bandgap devices. He is the author and co-author of more than 200 papers in this field. He holds several patents deriving from his research. Starting in 2019, he has been leading the Nitride power activities within the French national network called GaNexT.