Wafer-Level Calibration on Indium Phosphide

Introduction

In current research of devices for THz-applications innovations such as the resonant tunnel diode (RTD) or the heterojunction bipolar transistor (HBT) are promising technologies. Such components, especially those on InP substrate, are researched and developed at the department of Components for High Frequency Electronics (BHE). In the course of the development process, electronic components are fabricated in a clean room and then have to be electrically characterized. This includes the determination of the scattering parameters (S-parameters) of the electronic components or the networks in which they are integrated, in order to be able to make statements about the performance and thus about possible applications. A vector network analyzer (VNA) is typically used to measure S-parameters. To ensure high accuracy of the measurement results, such an instrument must be calibrated. Classically, the calibration of a VNA consists of measuring various known standards. These often include matched resistors, which are subject to high accuracy, temperature and frequency stability requirements. The focus of this work is the development of a fabrication process for such resistors. Commercially available calibration standards are deposited on substrates other than InP. Calibration with standards on the same substrate or even on the same wafer (on-wafer) as the devices can yield further improvements in accuracy. This thesis presents a process for structuring thin films of nickel-chromium. A sputter deposition machine recently acquired by the department is used for this purpose. Suitable machine parameters for the fabrication are found by appropriate series of experiments, and fabricated test structures are characterized by their electrical properties. Different manufacturing processes are carried out and compared. The use of these resistors as calibration standards is discussed and a suitable calibration procedure is selected. This includes manual implementation of the calibration algorithm using an appropriate programming language. Furthermore, a workflow is presented which allows to extract the model parameters of fabricated resistors by EM simulations and to use them in calibration algorithm.

Calibration Procedure

The thesis discusses various calibration methods for on-wafer testing, including TRL, SOLT (TOSM), and LRM (TRM). The LRM calibration, requiring three standards (Thru, Reflect, Match), is selected for implementation. The calibration algorithm is developed in Python, utilizing the scikit-rf package for network representations. The Python script follows the generalized theory proposed by Pulido-Gaytán et. Al., ensuring accurate calibration regardless of load symmetry or frequency-dependent variations. The workflow involves determining the expected S-parameters of match standards through simulation. The thesis details the modeling process using Ansys Electronics Desktop software and HFSS simulation.

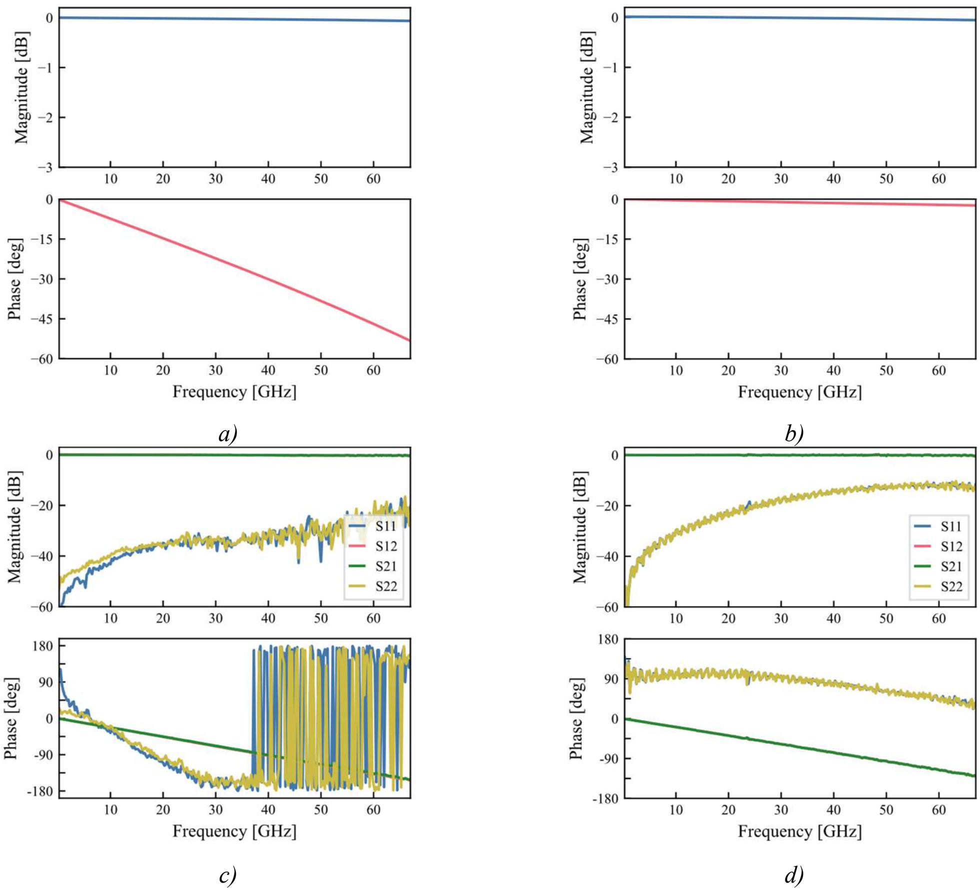


Figure 1: Bode plots of the S_{11}-Parameter of the open standard a) before andb) after applying the calibration algorithm and of the calibrated line standard 0709 of the AC2 substrateusing c) TOSM and d) LRM algorithm.

The developed Python algorithm is tested with simulated NiCr calibration standards, which demonstrates successful calibration, flattening the phase response of the open standard (Figure 1 a/b). Additionally, the thesis applies the workflow to real data from AC2 standards, which are reverse-engineered for modeling in Ansys HFSS. Material analysis using energy dispersive X-ray spectroscopy (EDX) helps determine the resistor composition. The results of calibrating raw data from AC2 line standards using both TOSM and the implemented LRM algorithm show improved measurement results(Figure 1 c/d), validating the effectiveness of the calibration approach.

Technology Process

The Leybold Univex 600 model is used for deposition in a vacuum chamber, equipped with DC/pulsed DC and RF sputtering sources. Various parameters, including sputtering power, deposition time, and working pressure, are investigated for their impact on sheet resistance. Analysis of deposition time and sputtering power indicates a nonlinear relationship with sheet resistance. Chamber pressure variation reveals not expected behavior of sheet resistance, indicating changes in the deposition rate. To develop a technology process sequence for thin film resistors, the study uses benchmark 6 parameters as its starting point. The thesis explores different structuring methods for NiCr, including wet etching, lift-off, and dry etching. Wet etching results in an unsuccessful experiment, while the lift-off technique shows promise for precise and convenient structuring. Two contact methods, top contact and sandwich contact, are investigated, with the latter involving depositing contact pads before NiCr deposition. Successful fabrication and structural analysis of samples for electrical characterization are presented. Additionally, the thesis explores lift-off techniques for patterning NiCr/Au mesas, addressing challenges related to gold sputtering pressure and enabling deposition of NiCr and Gold in the same vacuum. The final lithography and metallization steps (Figure 2) are applied to achieve the desired structures for further electrical characterization.

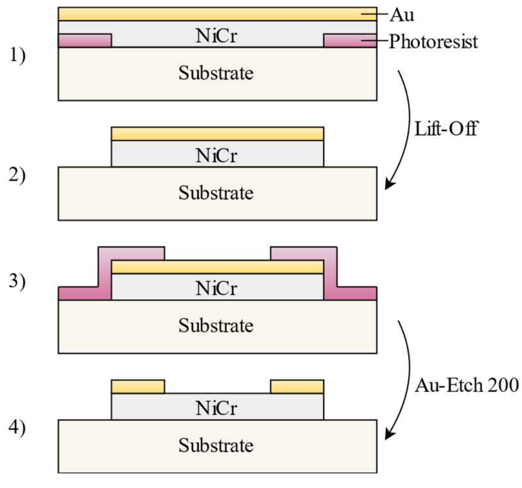


Figure 2: Schematic diagram of NiCr/Au Mesa lift-off followed by gold etching.

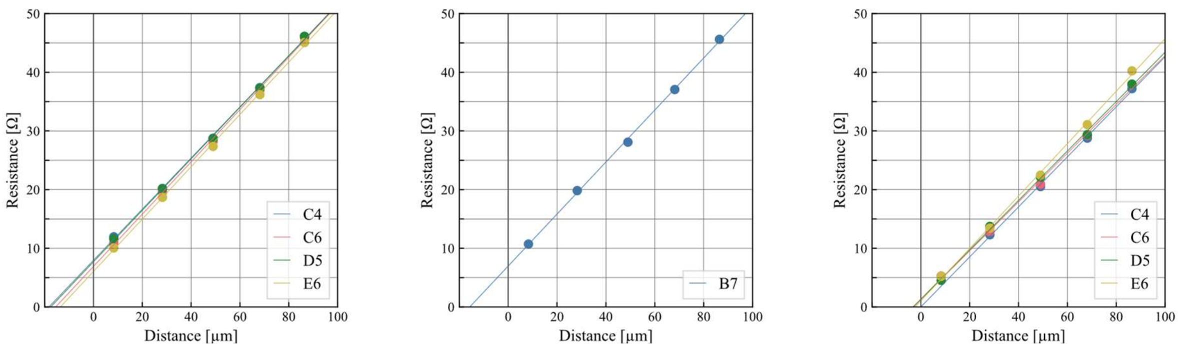
Transfer Length Method Measurements

The transfer length method (TLM) is employed, and a four-wire measurement setup is used to measure TLM structures on the samples. The resistance values for different lengths of a structure are measured, and a Python script is used for automated evaluation. The contact resistance and specific contact resistivity are determined by contextualizing measured resistance values with respect to length. A least-squares fitted linear function is applied to the measurement points to calculate contact resistance and contact resistivity. The TLM measurement results for the NiCr/Au-mesa sample are presented (Figure 3), showing improvements in contact resistance and resistivity compared to the top- and sandwich-contact sample. The results of the measurements are shown in Table 1.

Table 1: Results of the TLM measurements performed on the three samples presented

Sample	Contact resistance [Ω]	Contact resistivity [1E-8 x Ωcm²]	Sheet resistance [Ω/□]
Top contact	3.8	1782	22.10
Sandwich-Contact	3.483	1368	22.18
NiCr/Au-mesa	0.45	32.7	21.37

These results are consistent with values from similar experiments, and potential improvements are suggested by conditioning the surface of the initial gold layer before deposition of contact pads.



a) *b)* *c)*

Figure 3: TLM measurement results of a) the top-contact sample, b) the sandwich-contact sample and c) the NiCrAu lift-off sample.

Conclusion

This thesis introduces the implementation of on-wafer calibration standards into existing workflows, focusing on the fabrication of NiCr resistors. Calibration methods are presented and evaluated, with the Thru-Reflect-Match (TRM) algorithm chosen for implementation in

Python. A workflow for calibration, including parameter extraction, is described. The Python algorithm is tested through electromagnetic simulation and application to existing AC2 standards. The study explores PVD deposition equipment for NiCr thin film fabrication, conducting systematic test runs to examine the influence of various technology parameters on sputtering results. Different analysis methods, such as sheet resistance measurement, EDX, and optical lithography, are employed to evaluate thin films. Parameters like time, power, and pressure are varied, and a stable process with desired sheet resistance is selected. Wet etching and lift-off techniques are investigated, along with various approaches to contacting NiCr with gold. The prepared samples are electrically characterized using 4-point probe measurements and TLM measurements. The repeatability and consistency of the sputtering process are evaluated, predicting variations in sheet resistance across a wafer. Different contact types are measured, determining contact resistance, contact resistivity, and sheet resistance of the NiCr strip. A complete thin-film technology process is developed for reproducible NiCr resistor implementation, targeting a 25 Ω/□ design for incorporation into circuit designs.

Outlook

The developed process is ready to be used for the fabrication of NiCr thin film resistors. A mask design can be created that allows on-wafer calibration standards to be fabricated as a back-end process. The calibration algorithm should be evaluated for accuracy by comparison with benchmark methods. Procedures will be developed to passivate fabricated NiCr structures. In addition, the use of laser ablation could be applied to optimize the accuracy of the resistivity value.