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Polyimide-based Thin Film Conductors for High Frequency Data Transmission in Ultra-Conformable Implants

Abstract:

Application-specific integrated circuits (ASICs) embedded in polymers have been subject in implant manufacturing for the recent years. The increased functionality combined with good biocompatibility due to flexibility of thin implants makes them interesting for further studies. Thin-film ASICs can be used for the recording and processing of a high amount of biological signals, improving the performance of neural implants.

Fabrication and analysis of gold and platinum thin-film connections are subject of this study, especially their capability as high frequency data transmission lines. Three layers of polyimide are used as flexible substrate and insulator of the traces. Various test structures were designed and fabricated, to investigate the resistance and reactance up to GHz frequencies, crosstalk and influence of vias between metallization layers. All conducting structures have a comparable design with a length of 50 mm and a metal thickness of 300 nm, while the line widths were varied.

In this configuration gold and platinum thin-film conductors are both suitable for high-frequency data transmission up to 100 MHz. This transmission frequency limit and impedances are unaffected by a wet environment and in accelerated aging tests.

However, both metals show a high pass filter behavior, whose frequency behavior is mostly dependent by the self-inductance and resistance. A simplified ideal transmission model predicts the electrical behavior sufficiently and can be used to design the favored line impedance matching input impedances of the connected ASICs.

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1 Introduction

The improvement of neural interfaces for electrical stimulation of nerves, has become increasingly important to help patients overcome physical impairments [1].

For this purpose, a large number of implants with increasing complexity has been developed, i.e. high density electrode arrays [2]. The challenges of these implants are a rising functionality, while maintaining small sizes of the components and biostability- and compatibility. More advanced features could be realized with encapsulated ASICs, which have to be connected to the electrodes or terminals via a rising number of feedthroughs. To guarantee a high biocompatibility, chip-in-foil systems would be preferable, whereas thin film conductors protect the chips non-hermetically.

Requirements for the encapsulations of ASICs are materials with a good adhesion, stability against water and vibration, a high breakdown voltage and no pin-holes after casting [3]; all these requirements are met by polyimide (PI) [4]. Moreover, PI shows only a mild foreign body reaction in applications of the peripheral and central nervous system and a good biocompatibility; it is therefore ideal as encapsulant [5]. Using standard photolithographic processes, metal conductor tracks and structures can be integrated into PI substrates with high spatial resolution. Even, an increasing number of interconnects between components, which are not only power transmission lines, but also transmission links for high-frequency data communication could be realized [6]. These thin-film traces have to transmit even smallest electrical signals, with minor electrical losses and no, or at least low, crosstalk.

The aim of this study was the investigation of miniaturized gold and platinum thin-films embedded into PI, with regard to the possibility of being used for high-frequency data transmission in medical implants.

2 Materials and Methods

2.1 Test structure fabrication

Two metal layers (Gold: evaporated, sputtered; Platinum: sputtered; layer thickness 300 nm each) were embedded between three layers of PI (layer thickness 4 µm each, BDPA-PPD, tradename: U-Varnish-S, UBE Industries, Japan) and structured via lift-off processes, four different designs were developed and fabricated in a cleanroom: single tracks, parallel and overlapping lines and vias. All test structures had a length of 50 mm and 4 connector pads at the end, while the width was varied between 5 µm, 10 µm, 20 µm and 50 µm (theoretical resistances: R_{Au} = 72 Ω - 723 Ω, R_{Pt} = 344 Ω - 3431 Ω). These values are based on the assumed design of a microchip-based implant. The 'single track' (Figure 1, design and structure) structure was used to determine the line impedance, whereas the three further layouts were developed to study different high frequency dependent phenomena: influence of the deposition methods (evaporation vs. sputtering), of the metallic interconnects (vias) and their frequency behaviour and the crosstalk between parallel and overlapping structures. These structures are displayed in the Figure 2 with corresponding microscope images of the critical and therefore smallest fabricated structures (5 µm trace width).

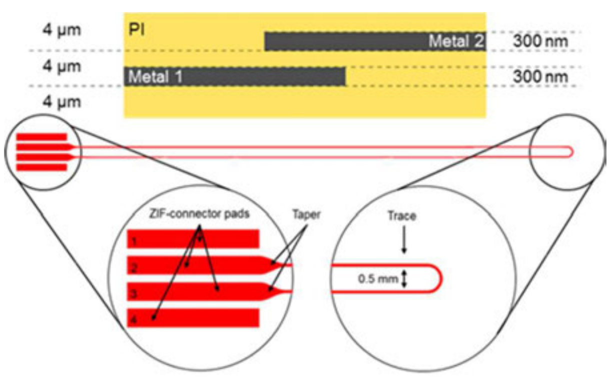

Figure 1: Structure and design of the test structures with the corresponding layer heights and important features.

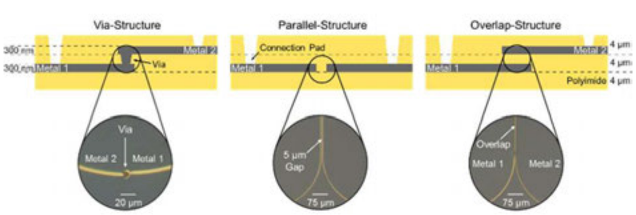

Figure 2: Design of the Via-, Parallel- and Overlap-Structure with the corresponding microscope images of the critical structures.

2.2 Electrical evaluation

All electrical properties of the structures at different frequencies were measured by a network analyser (VNA; Agilent E5071B, Keysight, USA), connected through a PCB adapter. The frequency was swept with 2000 logarithmically distributed measurement points in the frequency range of f_{Sweep} = 300 kHz – 1.1 GHz. All s-parameters for a 2-port measurement (s_{11}, s_{21}, s_{12}, s_{22}) were recorded. The VNA was calibrated before every measurement, the intermediate frequency bandwidth was set to f_{IF} = 1 kHz.

The impedance of the traces was determined, with a focus on the resistance, self-capacitance and self-inductance and their change over the sweep of frequencies or a change of the environment (dry vs. wet). For the body-like, wet environment, phosphate-buffered saline (PBS; pH 7.4, PBS P3813, Sigma-Aldrich) was chosen. Additionally, to investigate the change of the structures after several weeks or months, the structures were stored in 60 °C for six weeks, which accelerates the aging of the polymers with a factor of 4.92 according to the Arrhenius assumption [7]. After a soaking period of one week, the structures were measured weekly over the period of six weeks at room temperature.

In the further course, the crosstalk between parallel lying structures was measured in dry and wet environment with changing distances between the traces. The distance between the traces was the same as their width (e.g. 10 µm trace width = 10 µm distance). Also, the crosstalk between overlapping structures (length of the overlapping area: l_{OL} = 20.9 mm, same trace width) was recorded. At least, vias and their high frequency dependency were examined, with the focus on their deposition methods. All measurements were conducted in dry and wet environment.

As comparison to the measurements, a high frequency analysis was performed with *Ansys* (Ansys HFSS, Ansys, USA). Also, the structures were modelled and simulated with with *Capture* and *PSpice* (Cadence Design Systems, USA) to verify the measurements and HFSS-simulations.

3 Results

The previously described measurement structures were successfully fabricated, even the critical structure sizes as parallel lying traces with a spacing of 5 µm, overlapping structures with a 5 µm overlap and vias with a diameter down to 6.6 µm (also displayed in Figure 2).

3.1 Impedance Measurements

Four samples of single structures for each trace width and material were measured using the high frequency sweep analysis (Figure 3). The data in the plot can be divided into two sections: In the section below 100 MHz, the resistance is stable and equal to the DC-resistances (measured with Agilent 34410A Keysight, USA). The impedance raises above 100 MHz for all structural widths with a peak at 800 MHz, in both test samples and the simulation. No differences in impedances between dry and wet environment was found.

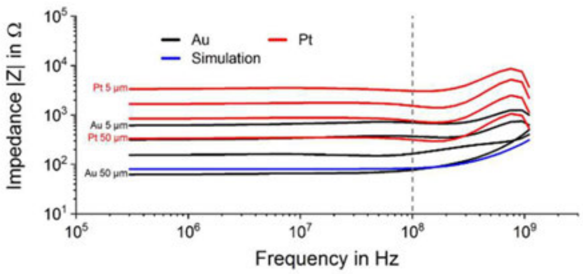

Figure 3: Measurement results of the frequency sweep with the impedances of the gold structures (black, 5 - 50 µm structural width, dry and wet state), platinum structures (red, 5 - 50 µm structural width, dry and wet state) and a simulated HFSS-test structure (blue, 50 µm structural width, dry and wet state).

3.2 Crosstalk

In high frequency applications not only the impedance of the structure itself is important, but also the transmission of energy between two conducting paths and thus possible interferences. In the dry state 8 samples, in the wet state 2 samples were measured for each width and material.

First, the capacitance of the parallel lying traces was examined in the dry and wet condition. In Figure 4 the values are plotted versus the four different distances (depending on their width) and materials. Immersing the structures in PBS alters the capacitance, but only minor changes could be

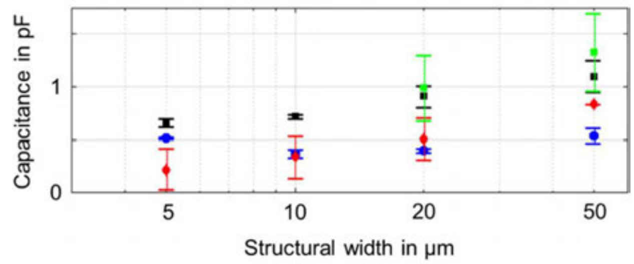

Figure 4: Coupling capacitances of parallel structures in dry environment (blue = Au, red = Pt) and wet environment (black = Au, green = Pt) with 5 - 50 µm structural width.

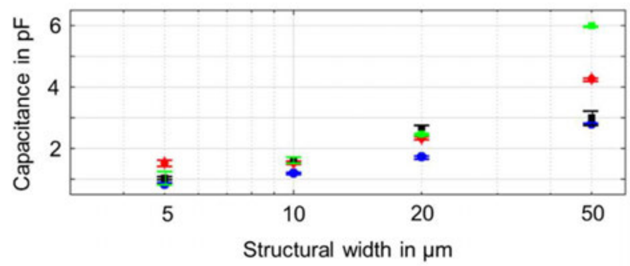

Figure 5: Coupling capacitances of overlapping structures in dry environment (blue = Au, red = Pt) and wet environment (black = Au, green = Pt) with 5 - 50 µm structural width.

observed over a subsequent period of six weeks. The structures immersed in PBS show a higher capacitive coupling, than the structures in dry conditions for both metals. Also, the platinum structures show a higher coupling then the gold structures. For all structures anw increase of the coupling capacitance was observed with rising structural width, besides the dry gold measurement. In a following investigation the capacitances of overlapping structures are studied (Figure 5). It can be seen, that the capacitance rises with increasing structural width for dry and wet. In general, the capacitances are higher in wet environments for both metals.

3.3 Vias

The structures with the metallic interconnects were examined, with 48 samples for each deposition method. No changes that could be clearly attributed to the high-frequencies were found, the emitted impedance is similar to the basic structure. Only small changes in the resistance (R_{Au} = 1.8 – 5.9 %, R_{Pt} = -0.6 – 1.0 %) were detected. However, there were differences in the functionality of the vias, depending on the deposition method. The yield is $Y_{Au,Sp}$ = 100 % (Au, sputtered), $Y_{Au,Ev}$ = 59.4 % (Au, evaporated) and $Y_{Pt,Sp}$ = 87.5 % (Pt, sputtered). Cross-sections of the gold vias (performed with a focused ion beam, examined with a SEM) showed distinctly better edge coverage for the sputtered compared to the evaporated vias.

4 Discussion

Regardless of the metal or the transmission line thickness, the impedances below 100 MHz show a linear behaviour. The deviations from the DC-resistance can be explained by deviations in the layer thicknesses of the metals. No impedance changes between dry and wet conditions have been recorded, the PBS environment does not affect the data transmission in a single transmission line. The structures exhibit similar changes in their impedance above 100 MHz. From the rise of the impedances and under consideration the simulations, the course is mainly due to the self-inductance of the traces. The assumed assembly of the equivalent circuit (Figure 6) is largely identical with the transmission line model, only the conductance G can be neglected.

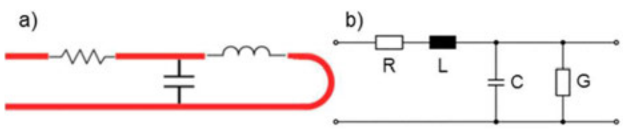

Figure 6: a) Equivalent circuit of the measurement structures with resistor, capacitor and inductor, b) ideal transmission model with resistance R, inductance L, capacitance C and conductance G.

From the measured values, the simulations and calculations, the values for the transmission line model were extracted in Table 1. These values show, that the electrical characteristics of the conductors are only depending on the trace geometry. Depending on the input impedance, inductance and capacitance of the ASIC, trace geometries can be selected that match the ASICs.

Table 1: Inductances L and Capacitances C for the single-measurement structures.

Trace width in µm	L in nH	C in fF
50 µm	56	0.5
20 µm	53	0.5
10 µm	52	0.5
5 µm	39	0.5

Also the crosstalk between adjacent traces has an impact on the signal transmission. For all measurements the capacitive coupling was higher for platinum, which can be explained by its potentially higher surface roughness. Furthermore, the measurements have shown higher capacitive coupling between traces for overlapping structures than for parallel lying traces. In all cases, the capacitance of soaked PI is higher than in dry environments due to water uptake with its high permittivity. Here, overlapping structures provide a larger area for capacitive coupling than the parallel structures. The coupling of the parallel lying structures is dominated by fringe capacitances (mostly developed through the surrounding medium, air or PBS respectively), which are built up between the large surfaces of the conductors and not between the side walls (Figure 7).

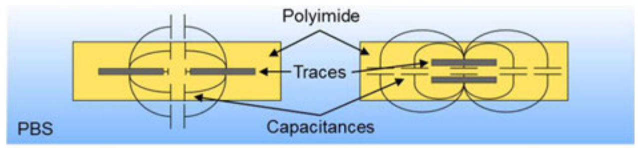

Figure 7: Visualization of the capacitances between parallel and overlapping traces immersed in PBS.

At least the metallic interconnections between two metallisation layers were investigated. The vias showed no alteration in their high-frequency behaviour, although the yield showed significant deviations. From these results it can be concluded that sputtering is the best deposition method to fabricate functioning vias, for both gold and platinum.

5 Conclusion

In this work, the frequency behaviour of gold and platinum thin-film conductors and the associated possibility of high-frequency data transmission were successfully investigated. Four different designs with four different line widths were fabricated and their electrical properties in a dry and wet environments compared. The frequency behaviour and especially the cut-off frequency is mostly dependent on the inductance and resistance. With the current design (50 µm width, 300 nm height, 50 mm length of the traces) transmission frequencies up to 100 MHz do not change the impedance for both materials. Even when used for a long time in a wet environment, no changes in resistance can be observed and only slightly stronger couplings can be observed.

Furthermore, overlapping traces should be prevented, since the surfaces react as relatively large capacitors and metallic interconnects should always be realized by sputtering for better edge coverage.

Author Statement

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References

[1] Petrini, F. M. *et al.* Sensory feedback restoration in leg amputees improves walking speed, metabolic cost and phantom pain. *Nature medicine* **25,** 1356–1363 (2019).

[2] Frank, J. A., Antonini, M.-J. & Anikeeva, P. Next-generation interfaces for studying neural function. *Nature biotechnology* **37,** 1013–1023 (2019).
[3] Gembaczka, P., Goertz, M., Goehlich, A., Mokwa, W. & Kraft, M. Encapsulation of implantable integrated MEMS pressure sensors using polyimide epoxy composite and atomic layer deposition. *Journal of Sensors and Sensor Systems* (2014).
[4] Rubehn, B. & Stieglitz, T. (eds.). Measurement of defects in spin coated polyimide films *EMBS Conference Proceedings* (IEEE, 2007)
[5] Rubehn, B. & Stieglitz, T. In vitro evaluation of the long-term stability of polyimide as a material for neural implants. *Biomaterials* **31,** 3449–3458 (2010).
[6] Kang, Y. N. *et al.* An Intrafascicular Neural Interface With Enhanced Interconnection for Recording of Peripheral Nerve Signals. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **27,** 1312–1319 (2019).
[7] Hemmerich, K. J. General aging theory and simplified protocol for accelerated aging of medical devices. *MEDICAL PLASTIC AND BIOMATERIALS*, vol5(E4),pp.16-23, 1998.