

Stability of Thin Film Neuromodulation Electrodes under Accelerated Aging Conditions

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Thin film electrodes are becoming increasingly common for interfacing with tissue. However, their long-term stability has yet to be proven in neuromodulation applications where electrical stimulation over months to years is desired. Here, the stability of pristine and PEDOT:PSS-coated Au, as well as pristine PEDOT:PSS microelectrodes are examined over a period of 3 months in an accelerated aging setup where they are exposed to current stimulation, hydrogen peroxide, mechanical agitation, and high temperature. Pristine PEDOT:PSS electrodes show the highest stability, while pristine Au electrodes show the lowest stability. Failure mode analysis reveals that delamination and Au corrosion are the key drivers of electrode degradation. The PEDOT:PSS coating slows down Au corrosion to a degree that depends on the overlap between the two films. The results demonstrate that pristine PEDOT:PSS electrodes represent a promising way forward toward thin film devices for long-term in vivo neuromodulation applications.

1. Introduction

Neuromodulation involves the delivery of electrical stimulation to specific regions of the nervous system to elicit or suppress neural activity. It has proven results in the treatment of movement disorders such as dystonia and Parkinson's disease, epilepsy, pain, and neuropsychiatric disorders such as obsessive-compulsive disorder and depression.^[1] Current neuromodulation implants use a small number of electrodes that are cut from metal foils (of the order of tens of microns thick) and are manually assembled into arrays.^[2] The technology is, however, evolving to thin (of the order of hundreds of nanometers) film electrodes made using vapor or solution deposition methods

and patterned at high resolution using photolithographic methods.^[3–5] These new implants offer dramatically improved spatial resolution, novel form factors arising from their compatibility with flexible, and stretchable polymer substrates, as well as high reproducibility and fabrication throughput.^[6,7] This surge in thin film technology addresses the growing need for high-density, highly selective microelectrode arrays, enabling precise stimulation, and recording of neuronal circuits.^[8] To translate this technology from research to clinical neuromodulation applications, the electrodes must demonstrate safety and efficacy; both properties require long-term electrode stability.^[9]

The ultimate test of implant stability requires in vivo evaluation,^[10] however, this is impractical for rapid, high-throughput

testing of new electrode technologies. In this manuscript, we develop an ISO-informed accelerated aging protocol for neuromodulation implants and use it to evaluate the stability of different thin film electrodes. These include electrodes made of Au, electrodes coated with the conducting polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), and electrodes made of PEDOT:PSS (metal free). Au is used as a model of a nominally capacitive, flat metal electrode, while PEDOT:PSS is used as a model conducting polymer. Conducting polymer coatings are known to offer mixed ionic-electronic conductivity, which improves performance in neural recording and stimulation applications.^[11–15] We show that pristine PEDOT:PSS electrodes outperform all other configurations and discuss ramifications for the design of thin film neuromodulation electrodes with improved stability.

2. Electrode Configurations and Characteristics

Four different electrode configurations were fabricated using previously published methods,^[16] as detailed in **Figure 1a**. The four electrode configurations were: 1) Au electrodes and tracks, 2) PEDOT:PSS-coated Au electrodes and tracks, 3) PEDOT:PSS electrodes and PEDOT:PSS-coated Au tracks, and 4) PEDOT:PSS electrodes and tracks. All electrodes had a diameter of 200 μm and were connected to an external pad using a track with a width of 10 μm and a length of 15 mm. They were deposited on 2 μm thick parylene C and the tracks were insulated with 2 μm thick parylene C. The electrodes were connected to the external set-up using anisotropic conducting film (ACF) and a flex cable.

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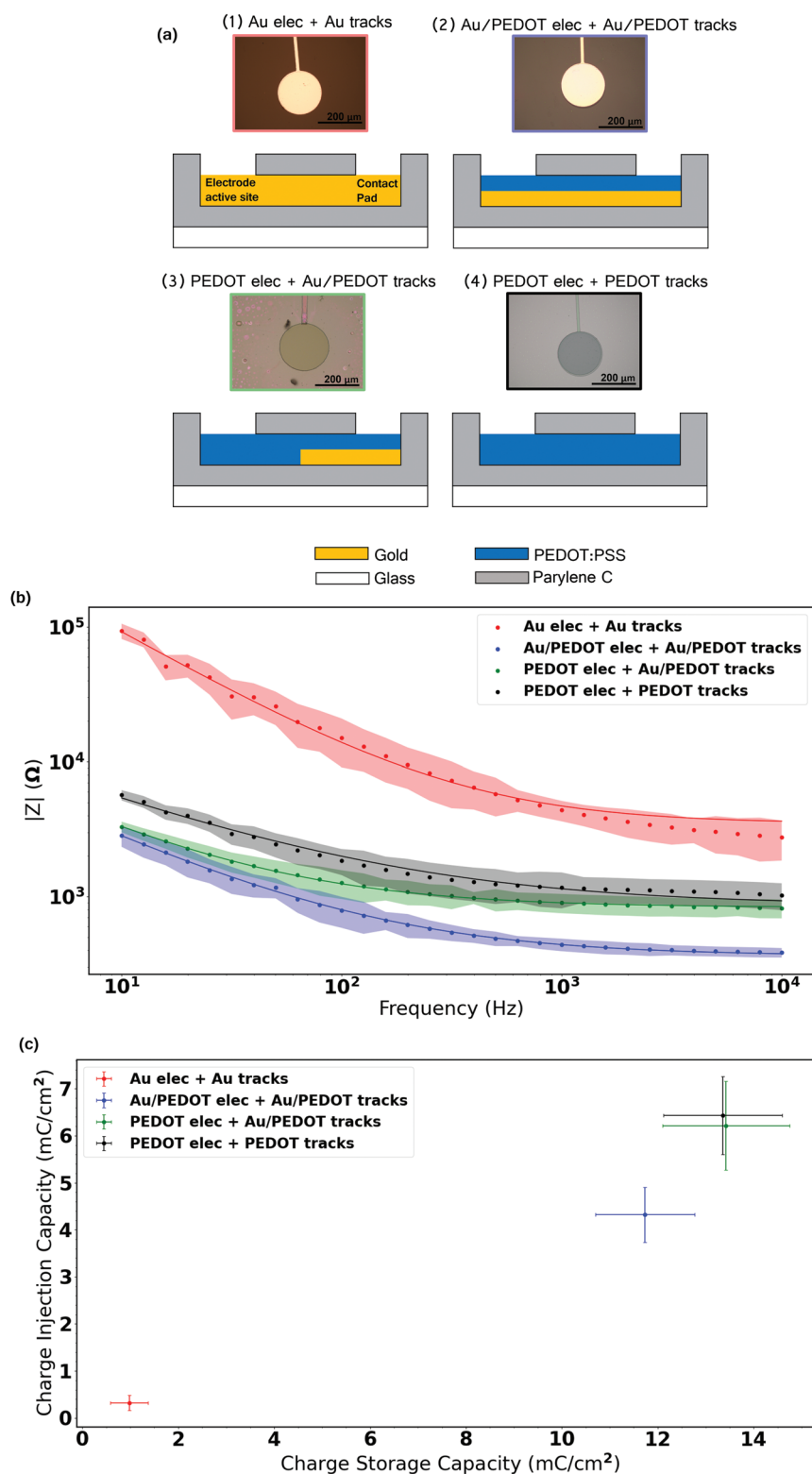


Figure 1. Fabrication and characterisation of the different electrodes. a) Cross-sectional area schematics, showing the electrode area, the insulated track and the contact pas (not to scale), and optical micrographs of the electrodes. b) Electrochemical impedance versus frequency (average of 28–31 electrodes on the same substrate). The lines are fits to a simplified Randles model. c) Charge injection capacity versus charge storage capacity. $N = 28$ –31, mean $\pm$ standard deviation.

The performance of the different electrodes was compared using electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV). The electrochemical impedance magnitude is shown in Figure 1b, and the phase in Figure S1 (Supporting Information). The Au electrodes exhibit the highest impedance, over two orders of magnitude higher than that of the PEDOT:PSS-containing electrodes at 100 Hz, a frequency that is relevant for chronic neural stimulation.^[17] The lower impedance of the latter is attributed to the volumetric capacitance of the PEDOT:PSS, which is a mixed ionic/electronic conductor.^[18] The PEDOT:PSS-coated Au electrodes have the lowest impedance ($\approx 850 \Omega$ at 100 Hz), followed by the PEDOT:PSS electrodes with Au/PEDOT:PSS tracks ($\approx 1020 \Omega$ at 100 Hz), followed by the pristine PEDOT:PSS electrodes ($\approx 1100 \Omega$ at 100 Hz). This trend is consistent in previous reports^[19] and with the fact that Au has a lower sheet resistance than PEDOT:PSS. However, the difference in impedance within the PEDOT:PSS-containing electrode group is small compared to the impedance of the pristine Au electrodes.

Fits to a simplified Randles model, where a parallel combination of a capacitor (C) and a resistor (R_p) is in series with an electrolyte resistor (R_s), allowed the extraction of electrode capacitance using the smallest number of free parameters. The fits are shown in Figure 1b; Figure S1 (Supporting Information), and detailed in Table S1 (Supporting Information). For the pristine Au electrodes, a capacitance of $C = 5.98 \text{ nF}$ is obtained. This corresponds to a capacitance per area of $18.7 \mu\text{F cm}^{-2}$, in agreement with double-layer capacitance values measured in flat metal films.^[20] Upon application of the PEDOT:PSS coating, C increases to 601 nF. Considering the PEDOT:PSS thickness of $402 \pm 18 \text{ nm}$, this yields a volumetric capacitance of 45.5 F cm^{-3} , in agreement with previous reports.^[21] The capacitance increases to 829 nF upon removal of the Au from the electrode site, and to 907 nF upon removal of the Au from the tracks. This increase in effective electrode volume indicates that a fraction of the PEDOT:PSS track is recruited as part of the electrode in these configurations. This is consistent with the fact that the high conductance Au film reduces the potential drop along with the electrode and/or track and hence reduces ion drift laterally in the PEDOT:PSS electrode and into the track.

To characterize the electrode's neurostimulation ability, we determined their charge storage capacity (CSC) from the area inside their CV curves, and their charge injection capacity (CIC) from their transient characteristics (see materials and methods). The two values are plotted in Figure 1c. The pristine Au electrodes have both the lowest CSC ($\approx 1.2 \text{ mC cm}^{-2}$), and the lowest CIC ($\approx 0.3 \text{ mC cm}^{-2}$). Both values are consistent with previously published reports.^[15] Upon coating the Au electrode with PEDOT:PSS, both the CSC and CIC increase by an order of magnitude to ≈ 11.3 and $\approx 4.2 \text{ mC cm}^{-2}$, respectively, consistent with a higher electrode capacitance. These values are higher than previously reported in the literature (≈ 2.5 and $\approx 0.2 \text{ mC cm}^{-2}$, respectively), likely due to differences in the thickness of the PEDOT:PSS layer.^[15] In electrodes where Au is confined to the tracks or not used at all, we see a further increase in the CSC and CIC, consistent with the increased electrode capacitance. The conversion rate measuring the efficiency of charge transfer from storage to injection (calculated

as the ratio of CIC/CSC) is 33% for Au. In PEDOT:PSS-coated Au electrodes the conversion rate is 36% and increases to 42% when Au is confined to the tracks, and to 46% when Au is removed altogether.

3. Impact of Aging on Electrochemical Characteristics

An accelerated aging set-up, shown in Figure S2 (Supporting Information), was developed in accordance with ISO 10993-13, which details the identification and qualification of degradation products from polymeric medical devices.^[22] The ISO bases its methodology on providing a more extreme version of the environment experienced by the implanted device within the body. To mimic oxidative degradation resulting from the foreign body response, 0.01 M PBS with 3% (v/v) hydrogen peroxide was used as the electrolyte.^[23] To mimic the dynamic movement of the electrodes with respect to the brain tissue, the electrodes were shaken at 20 rpm. To accelerate the aging process, the electrodes were tested at 70°C , which is 34°C above body temperature and yields an acceleration factor of 9.2.^[24] To test electrical stability, the electrodes were continuously stimulated with current-controlled biphasic pulses with an amplitude of $100 \mu\text{A}$, a pulse width of $100 \mu\text{s}$, an interphase gap of $33 \mu\text{s}$, and a frequency of 200 Hz. The electrodes were aged in this set-up for 84 days, corresponding to an extrapolated aging time of 800 days (> 2 years and 2 months).

Figure 2a shows the number of functional electrodes as it evolves with (extrapolated) aging time. Consistent with previously published papers, electrodes are considered "functional" if their impedance was $< 1 \text{ M}\Omega$ at 1 kHz.^[25] Electrodes with a higher impedance at the beginning of the test were taken out of this study and were not counted in the statistics. The number of functional Au electrodes is shown to decrease the fastest, exhibiting a rapid decrease, with 7 out of 30 electrodes remaining functional after the first 300 days. At the end of the run, only 4 electrodes continue to function, corresponding to 86.7% failure rate. The number of functional PEDOT:PSS-coated Au electrodes stays stable for the first ≈ 150 days, but then shows similarly rapid decrease. At the end of the run, 79.3% of the electrodes have failed. In contrast, when Au is removed under the active site, the number of functional electrodes decreases at a much slower pace and only 28.6% of the electrodes fail at the end of the run. The slowest decrease is seen in the pristine PEDOT:PSS electrodes, with 26 out of 31 electrodes remaining functional at the end of the run, corresponding to a failure rate of only 16.1%. This value represents a five-fold increase in stability compared to Au electrodes. It should be mentioned that similar degradation trends are observed in CSC and CIC, shown as figure S3 (Supporting Information).

Analysis of the impedance spectra allows the identification of two different modes of failure: A "connection failure" manifests itself as an open circuit (working electrode disconnected), with higher impedance than all electrode configurations (Figure S4, Supporting Information). Connection failures occurred when the bond between the flex cable and the contact pads of the electrode array broke. A "delamination or corrosion failure", on the other hand, manifests itself as a shift in the impedance

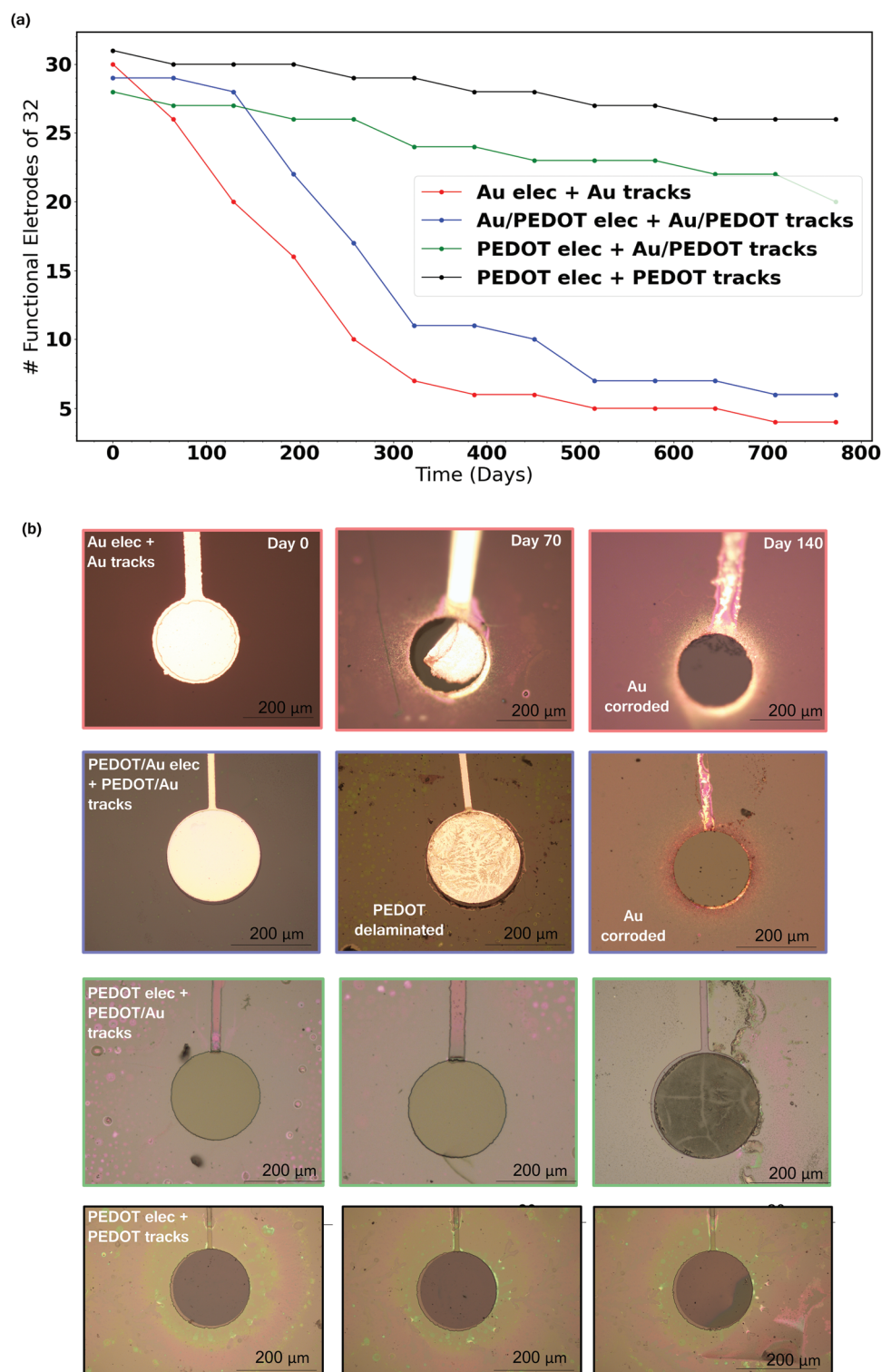


Figure 2. Impact of aging on impedance and electrode structure. a) Number of functional electrodes (impedance lower than 1 M Ω at 1 kHz) as a function of extrapolated aging time. b) Optical micrographs of the electrodes at different time points (extrapolated aging time).

spectra toward a different state. For example, when the impedance spectrum of an electrode shifts to that of a track embedded in an insulating parylene stack (Figure S4, Supporting Information), this is interpreted as loss of the electrode due to

delamination or corrosion. Similarly, when the impedance of a PEDOT:PSS-coated Au electrode shifts to that of a Au electrode, this is interpreted as delamination of the PEDOT:PSS coating from the Au electrode. The results of this failure mode analysis

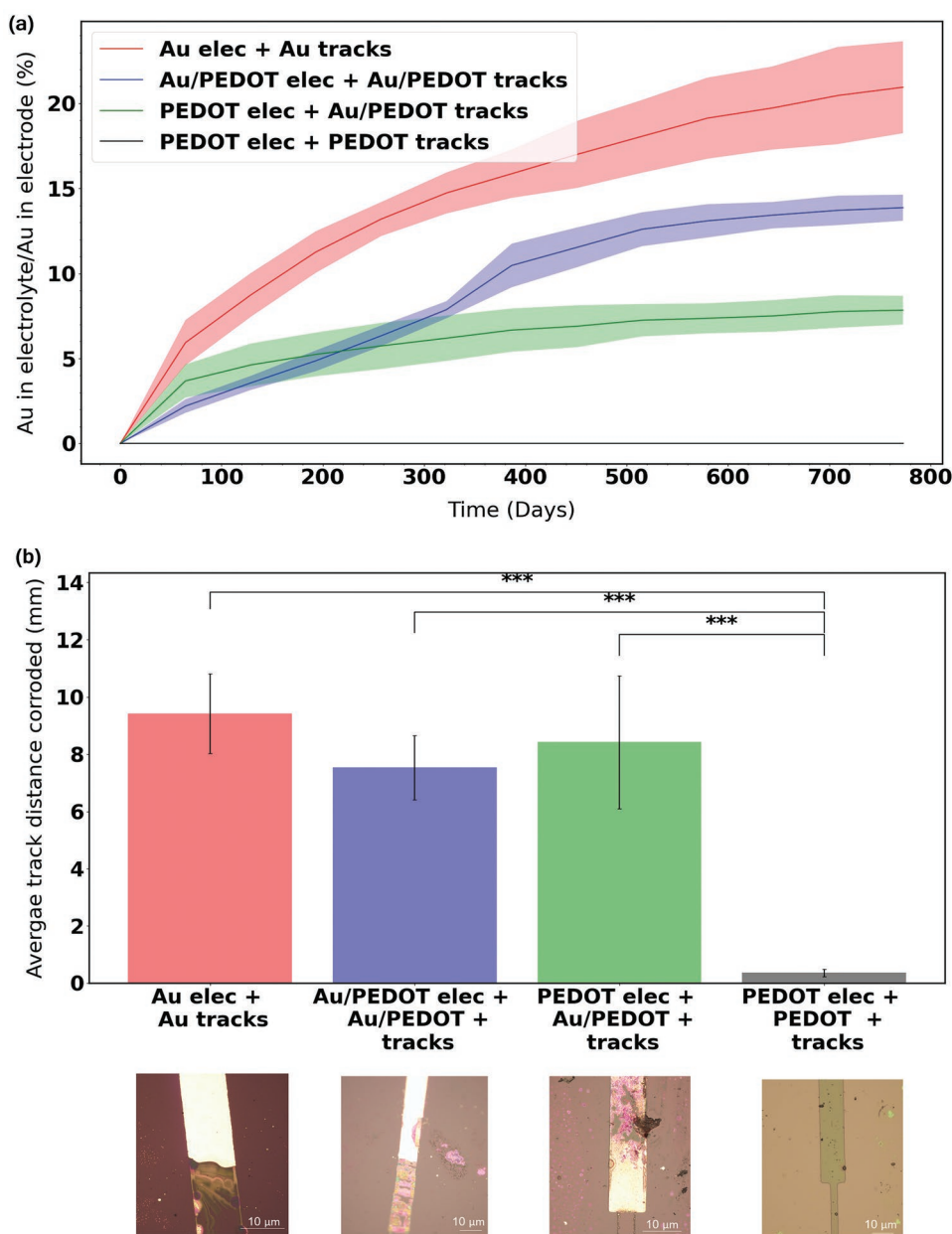


Figure 3. a) Amount of Au dissolved in the electrolyte normalized to the total mass of Au in the electrode. b) Quantification of track ingress after aging alongside optical micrographs of the tracks. $N = 28\text{--}31$, $***p < 0.001$, two-sided t -test, mean $\pm$ standard deviation.

are detailed in Table S2 (Supporting Information). The data shows that in all electrode configurations, the predominant failure mechanism was delamination or corrosion, accounting for over 75% of all failures. However, the formation of reliable connections remains a challenge, with poor connections accounting for 25% of all failures in the PEDOT:PSS electrodes.

4. Impact of Aging on Electrode Structure

To get more insight into the degradation mechanism, electrodes were periodically taken out of the aging setup, gently washed with deionized water, dried, and examined by optical

microscopy. Figure 2b shows three optical micrographs per electrode configuration, obtained at day 0, day 70, and day 140 (extrapolated aging time). The first row of micrographs shows the typical degradation mechanism observed in Au electrodes: They appear to delaminate in large fragments, and once partially delaminated, they would always go on to fully delaminate. This behavior can be attributed to the difference in Young's modulus between Au and parylene,^[26,27] and is consistent with the buckling behavior of metal films from polymer substrates that has been reported widely in the past.^[28] PEDOT:PSS-coated Au electrodes, on the other hand, often show cracking and delamination of the PEDOT:PSS layer, followed by delamination of the Au (second row of micrographs).

The final two rows in Figure 2b show PEDOT:PSS electrodes with Au/PEDOT:PSS tracks and pristine PEDOT:PSS electrodes. In this group, only three of 59 electrodes showed some evidence of cracking (shown in Figure 2b for the PEDOT:PSS electrode with the Au/PEDOT:PSS track).

Inductively coupled plasma optical emission spectroscopy (ICP-OES) measurements were performed to look for signs of Au corrosion. Samples from the electrolyte in the reaction vessel were periodically taken, filtered to remove particles from delamination, and analyzed. The results are plotted in Figure 3a. The results from the Au electrodes reveal that a large amount of material is dissolved in the electrolyte. This finding is consistent with data obtained in thin-film Pt electrodes,^[29] which also corrode under stimulation conditions. The Au electrodes suffer a loss of 21% of their original mass. As the electrode sites themselves contain only $\approx 17\%$ of the original Au mass, this finding implies that corrosion of the tracks takes place. Au dissolution is also detected in PEDOT:PSS-coated electrodes. Although the PEDOT:PSS coating somewhat slows down the process, 13.9% of the original Au mass is found in the electrolyte after aging. In electrodes where Au was confined only to the tracks, small amounts of Au (5% of original mass) were still detected in the electrolyte. Optical microscopy at the end of the aging run was used to quantify the distance over which corrosion took place into the tracks (Figure 3b). Large ingress of up to 9.2 ± 0.9 mm is observed in the Au electrodes. A PEDOT:PSS coating did not significantly reduce the ingress, and the Au tracks are shown to still corrode. Pristine PEDOT:PSS electrodes, on the other hand, do not show corrosion but some ingress is observed attributed to delamination of the parylene layers leading to subsequent PEDOT:PSS delamination (1 ± 0.2 mm of track).

5. Results and Discussion

Conducting polymer coatings are receiving a great deal of attention in neural applications as a means to overcome the double-layer capacitance limit and lower the impedance of metal electrodes. PEDOT:PSS has emerged as a model material for this applications due to its commercial availability and good performance. While PEDOT:PSS coatings have demonstrated excellent short-term stability (of the order of weeks),^[30–34] especially under recording conditions, here we show that they fail by delamination under current stimulation conditions in a harsh environment. PEDOT:PSS is available as an aqueous dispersion and a cross-linker (such as GOPS in this work), is used to prevent its dissolution and enhance adhesion to the substrate. Different cross-linkers or surface modification layers might be more successful than GOPS in slowing down delamination, and lead to improvements in the stability of the coating. The ISO-based setup reported here is easy to replicate and can form the basis for screening new electrode materials and architectures. It mimics aspects of the in vivo environment by inducing oxidative stress and mechanical micromotions, and uses elevated temperature to accelerate the aging process. It could be further developed by replacing the liquid electrolyte with a gel with similar mechanical properties as the brain, though this could introduce variability in the contact between different electrodes and the gel.

Our results point to a second direction for improving the stability of thin film electrodes. Electrodes made using PEDOT:PSS alone showed the best stability among the different configurations investigated in this work. Their impedance was slightly higher than that of electrodes with an underlying Au film, as the conductivity of PEDOT:PSS is lower than that of Au. There seems to be, therefore, scope for replacing thin film metal electrodes with PEDOT:PSS ones, as long as the dimensions of the track do not make electrode impedance prohibitively high. Indeed, the tracks used in the PEDOT:PSS electrode arrays presented here were 15 μm wide, and removing Au from the tracks led to an increase in impedance (at 1 kHz) of only $\approx 500 \Omega$. Given that in most implantable electrodes the track width is $\approx 10 \mu\text{m}$, electrodes made of PEDOT:PSS alone should still be able to give high quality recordings. Finally, it is important to note that connection failures were identified as a secondary mechanisms for electrode loss. New materials and methods for establishing reliable connections (for example, novel anisotropic conductors^[35]) represent an important area of research in neurotechnology.

6. Conclusions

In this paper, we develop an ISO-informed high-throughput accelerated aging setup to test the stability of thin-film electrodes. Using this setup, we show that PEDOT:PSS electrodes exhibit relatively little degradation over an extrapolated aging time exceeding two years. Au electrodes were found to corrode and delaminate. Coating them with PEDOT:PSS delays the point of failure somewhat, but the electrodes still fail after the coating delaminates. This work highlights the need to remove metal layers entirely from thin film neuromodulation electrodes and focus on devices made exclusively from conducting polymers.

7. Experimental Section

Electrode Array Fabrication: The fabrication of the electrode array was based on that reported by Middy et al.^[19] Briefly, 1×3 square inch glass slides were cleaned by sonication in acetone and isopropyl alcohol for 15 min. Then a 2 μm layer of parylene C was deposited using a Specialty Coating Systems PDS 2010 labcoater 2. Subsequently, negative lift-off photoresist AZnLoF 3035 was spin-coated onto the cleaned glass slides, and then soft baked. After the substrates returned to ambient temperature, they were exposed to UV (7 s , 80 mJ cm^{-2}) using a mask aligner (Karl Suss Contact Mask Aligner MA/BA6). This was followed by a second baking step. The substrates were then developed in AZ826. They were activated with oxygen (O_2) plasma under vacuum (60 s at 100 W and 0.6 mbar O_2). Using a Lesker e-Beam evaporator, Ti (5 nm) and Au (100 nm) were deposited to produce the electronic components of the device. Au lift-off was performed with acetone, the substrates were allowed to soak for 10 min. For the preparation of the PEDOT:PSS, commercially available PEDOT:PSS dispersion 1% wt. (Heraeus Clevios PH1000) was used. 5% v/v ethylene glycol (EG) (Sigma Aldrich) was added to improve the electrical conductivity, and 0.05% wt. dodecyl benzene sulfonic (DBSA) (Sigma Aldrich) to improve the homogeneity of the film upon spin coating. The mixture was then sonicated for 15 min. 1% wt. 3-Glycidyloxypropyltrimethoxysilane (GOPS) (Sigma Aldrich) was then added as the polymer cross-linker and the mixture was sonicated for 1 min. The mixture was then filtered through

a polytetrafluoroethylene (PTFE) 0.45 mm filter and spun at 500 rpm for 5 s and then 3000 rpm for 30 s. This was followed by a baking step at 120 °C for 60 s. Four layers of PEDOT:PSS were spin-coated using the aforementioned protocol with baking steps in between each layer. After all the layers were deposited, the PEDOT:PSS was hard-baked on a hotplate at 110 °C for 1 h. After hardbaking, the samples were soaked in DI water overnight to remove any excess PSS and low molecular weight compounds. AZ5214E photoresist (Microchemical GmbH, Germany) was spin-coated at 500 rpm for 5 s and then 3000 rpm for 30 s. This was followed by a baking step on a hotplate at 115 °C for 120 s. The second layer of resist was spin coated using the same parameters and also soft-baked. They were exposed to UV (5.7 mJ cm⁻²) using a mask aligner (Karl Suss Contact Mask Aligner MA/BA6). The substrates were then developed in AZ726 MIF for 20–24 s. The PEDOT: PSS layer was subsequently etched by reactive ion etching (Oxford Plasma Pro 80 RIE, 160 W, 50 sccm O₂, 5 sccm CF₄). A self-assembled monolayer (SAM) of the adhesion promoter methacryloxypropyl trimethoxysilane (A174 Silane, Sigma Aldrich, UK) was created to improve the adhesion of the 500 nm parylene C insulation layer to the glass substrate. Briefly, a 3% wt solution of A174 was produced from 600 µl A174, 20 ml ethanol + 0.1% acetic acid. The samples were immersed in the solution for 45 s before being rinsed with Et-OH. The samples were then hard baked for 1 h at 75 °C. A 2 µm parylene layer was deposited onto the substrates via CVD using a Specialty Coating Systems PDS 2010 labcoater 2 (175 °C, less than 20 mTorr pressure). To define the insulation pattern, AZ10XT photoresist (Microchemical GmbH, Germany) was spin coated at 500 rpm for 5 s and then 3000 rpm for 30 s. This was followed by a baking step on hotplate at 115 °C for 120 s. The substrates were flood exposed with UV light (30 s, 80 mJ cm⁻²), flood exposure was split into two exposures of 15 s each to limit the heating of the substrate. The substrates were developed in AZ726 MIF for 5 min. The parylene C layer was then subsequently etched for 3 min in a RIE (Oxford Plasma Pro 80 RIE, 160 W, 50 sccm O₂, 5 sccm CHF₃). The Au and PEDOT:PSS-coated Au electrodes were fabricated similarly. Finally, the device was washed in deionized water to remove excess low molecular weight compounds and to delaminate the device from the glass slide. Polyimide/copper flex cables (Printed Electronics) were used to connect the samples to the current stimulator. The flex cables were bonded to the contact pads of the thin film electrode using an anisotropic conducting film (ACF) and attached using the Finetech Bonder Pico ma.

Accelerated Aging and Stimulation Setup: The top parts of the electrode arrays were mounted onto a glass slide, to ensure they did not curl up upon aging, while the part containing the electrode sites was left free-standing. They were then inserted into a custom-built PTFE reaction vessel. This was designed to allow the glass slides to rest above the base of the vessel meaning the flexible tips of the electrodes were freestanding within the electrolyte. A large Au counter electrode (CE, 2 cm × 5 cm) was patterned onto a polyimide substrate by using a polyimide shadow mask and e-beam evaporation of titanium (5 nm) and Au (100 nm). The CE was coated with the same PEDOT:PSS formulation as the electrode arrays to minimize the CE/electrolyte voltage drop. The CE was then inserted into the vessel through the lid via a hermetic insertion rubber sheet to minimize electrolyte evaporation. A Ag/AgCl electrode was used as a reference electrode (RE), this was inserted into the vessel via a tight aperture in the lid and secured with O-rings. Finally, the electrode arrays were connected to a zero insertion force (ZIF) connector with cable. The cable was then passed through the lid of the vessel via a hermetic insertion rubber sheet. The reaction vessel was then placed inside a Corning LSE Benchtop Shaking Incubator. The electrodes were continuously stimulated with current-controlled biphasic pulses with an amplitude of 100 µA, a pulse width of 100 µs, an interphase gap of 33 µs, and a frequency of 200 Hz.

Electrochemical Impedance Spectroscopy: EIS measurements were performed in the reaction vessel with a PGSTAT128N Metrohm Autolab, where the electrodes from the array were the working electrodes and the large 1 cm × 1 cm electrode was the counter electrode. A 10 mV sinusoidal voltage was applied at a frequency range of 1 to 100 000 Hz.

Cyclic Voltammetry: Cyclic voltammetry (CV) was performed in the reaction vessel using a PGSTAT128N Metrohm Autolab. A Pt electrode was used as the counter electrode, while an Ag/AgCl electrode was used as a reference. CV measurements were carried out using a 0.1 V s⁻¹ sweep rate and 2.44 mV step within a window of -0.6 to 0.8 V, the established water window for Au. A minimum of ten cycles were performed for each measurement to allow the recording to stabilize, and only the final recorded cycle was analyzed. Typical CV curves are shown in Figure S5 (Supporting Information). The charge storage capacity was calculated from the CV by integrating the current over the scan time.

Voltage Transients: The charge injection capacity of the device was determined using a current-controlled stimulation and measuring the electrode voltage transients using an oscilloscope with the samples in the reaction vessel. An Intan RHS 128-channel stim/recording controller and an RHS2000 32-channel headstage were used to connect to the electrodes and provide a charge-balanced current stimulation pulse with a phase width of 300 µs and an interphase delay of 33.3 µs. Pt probes were used as both counter and reference electrodes. The pulse was gradually increased in amplitude while observing the voltage transient trace from a Keysight DSOX1204G oscilloscope. When the cathodic interphase transient reached -0.6 V or the anodic transient reached 0.9 V, the current amplitude was recorded. Typical voltage transients are shown in Figure S5 (Supporting Information). The CIC was then determined by multiplying the current amplitude by the pulse width and dividing by the area of the electrode active site.

Inductively Coupled Plasma Optical Emission Spectrometry: ICP-OES was performed on 10 mL of extracted electrolyte from the reaction vessel. A calibration curve was established using Au standard solutions prepared by stepwise dilution. The unknown sample concentrations were then compared against the calibration curve to obtain the concentration of Au. Using optical microscopy (see below), it was evident that delamination occurred in large segments (often the entire electrode), while corrosion manifested with smaller features. To distinguish between delamination and corrosion, the particle size distribution was determined using dynamic light scattering (Malvern Panalytical Zetasizer) and the threshold for delamination was set at 10 µm. The electrolyte was then filtered with a 10 µm filter to allow through only Au due to corrosion.

Optical Profilometry and Microscopy: Profiles of the electrode arrays were obtained using from a Bruker Contour optical profilometry. PEDOT:PSS film thickness recorded in wet films that were soaked in PBS for at least 24 h prior to measurement. Multiple measurements were taken across the insulation to either the contact pads or electrode active sites and the average thickness was found to be 402 ± 18 nm. Track ingress was observed using a calibrated optical microscope and quantified using Image J.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

neurotechnology, PEDOT:PSS, thin film electrodes

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