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BI-LAYER ENCAPSULATION OF UTAH ARRAY BASED NERUAL INTERFACES BY ATOMIC LAYER DEPOSITED Al_2O_3 AND PARYLENE C

Xianzong Xie[1], *Loren Rieth*[1], *Ryan Cardwell*[2], *Rohit Sharma*[1], *Je-Min Yoo*[1], *Mohit Diweka*[1],
Prashant Tathireddy[1], *Florian Solzbacher*[1,2]
[1]Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA
[2]Department of Bioengineering, University of Utah, Salt Lake City, UT, USA

ABSTRACT

We present a novel coating method that combines atomic layer deposited Al_2O_3 and Parylene C for encapsulation of biomedical implantable devices, focusing on its application on Utah electrode array based neural interfaces. The alumina and Parylene C bi-layer encapsulated wired Utah electrode array showed relatively stable impedance during the 320 days of soak testing at 37 °C in phosphate buffered solution. Also bi-layer coated fully integrated Utah array based wireless neural interfaces had stable power-up frequency and constant RF signal strength during the 600 days of equivalent soaking time at 37 °C. Bi-layer coated Utah arrays had constant current drawing of about 3 mA during 140 days of soak testing.

KYEWORDS

Atomic layer deposition, Al_2O_3, Parylene, Utah electrode array, encapsulation of neural interfaces

INTRODUCTION

Implantable devices are widely developed for both research and clinical applications. Lids and metal cans were used to seal biomedical implantable devices, e.g. deep brain stimulators and peacemakers [1], in order to protect them from the physiological environment. Device miniaturization raises new challenges for traditional hermetic encapsulation. Thus, thin film based encapsulation have been widely employed. Compared with metal cans and lids based hermetic encapsulation, thin film based encapsulation takes less space, can handle feedthroughs easily, and is more economic and easier for mass production.

We are developing neural interfaces for neural recording and stimulation based on Utah Electrode Arrays (UEAs) [2] that incorporate with active electronics for signal extracting and processing. Encapsulation of three dimensional neural interfaces with complex geometries and tight gaps between components is one of the greatest challenges to achieve long-term functionality and stability. Excellent encapsulation is needed in order to achieve the targeted lifetime of 70 years for neural interfaces. The insulation performance of encapsulation and its change over time are critical for achieving separation between channels and good selectivity for neural interfaces. The encapsulation has to be biocompatible, conformal, highly resistive, and have a low dielectric constant [3]. Also, the process temperature for encapsulation has to be low enough to be compatible with the existing active electronics and different polymers used in the implantable systems.

Parylene C has been widely used as coating material for biomedical implantable devices [4-7] due to its many attractive properties. It is chemically inert, has low dielectric constant, high resistivity and relative low water vapor transmission rate (WVTR). It can be deposited at room temperature through CVD process to form conformal and pin-hole free film. It is also a good ion barrier [8], which is critical for implantable devices exposed to physiological environment. Failure of Parylene C encapsulation has been reported[9] due to moisture diffusion and interface contamination. Atomic layer deposited (ALD) alumina is an excellent moisture barrier with WVTR at the order of ~ 10^{-10} g·mm/m^2·day [10-13]. But alumina alone is not suitable for encapsulation since it dissolves in water [14].

Our approach combines the highly effective moisture barrier properties of ALD alumina, and Parylene as a barrier to many ions and for preventing contact of alumina with liquid water. The alumina-Parylene C bi-layer encapsulation has been demonstrated with excellent insulation performance on interdigitated electrode test structures [15]. By applying this new bi-layer coating method, longer lifetime is expected for UEA based neural interfaces.

EXPERIMENTAL DETAILS

Array Assembly

Different configurations of UEA based neural interfaces were used to evaluate the alumina and Parylene C bi-layer encapsulation performance from three different aspects: long-term impedance stability, long-term wireless signal strength and frequency stability, and current drawing level.

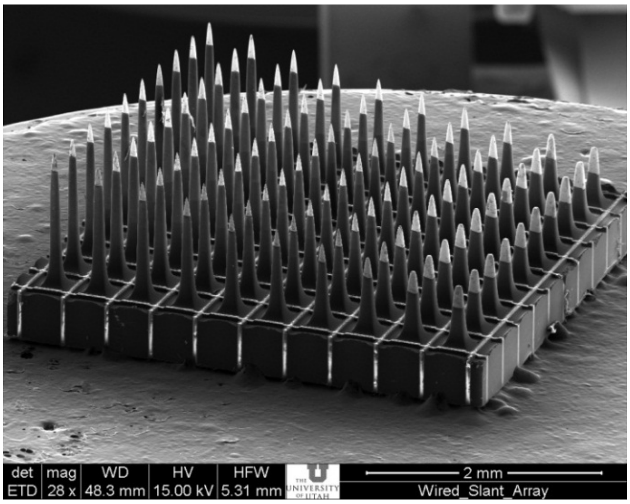


Figure 1: SEM images of a 10×10 Utah electrode array

UEAs, shown in Figure 1, were wire bonded (West Bond, Inc.) to a 96-channel adapter using 1 mil gold wire for later long-term tip impedance measurements (Figure 2). The length of wire bundle was about 10 cm in order to have enough flexibility for later experiment. Silicone (MED 4211, NuSil Technology) was applied to the backside of the array and the wire bundle to secure the bond connection and increase the strength of the wire buddle, respectively.

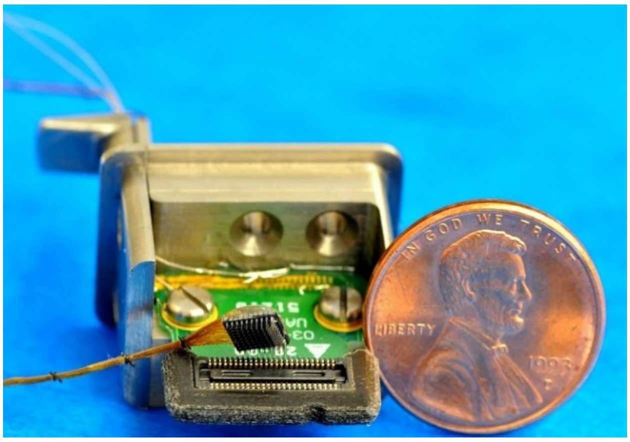


Figure 2: Fully assembled wired Utah electrode array with connector for impedance measurement

Alumina and Parylene coated wireless integrated neural interfaces (INIs) were used to assess both the long-term frequency stability and RF signal strength. An ASIC chip with capabilities of signal processing and transferring was flip-chip bonded to the backside of UEA (Figure 3). Two SMD capacitors were soldered at the edge of UEA. One was part of the resonating circuit and the other one worked as a smoothing capacitor for inductive powering. A hand-wound gold coil was wire-bonded to form the resonating circuit around 2.765 MHz for inductively powering up the device.

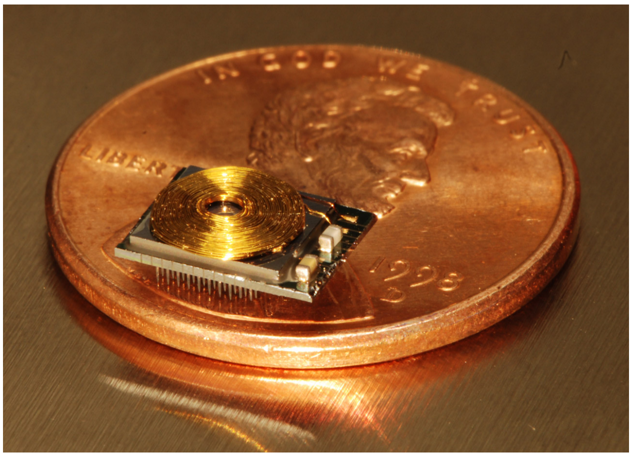


Figure 3: Utah array based fully integrated wireless neural interfaces, with flip-chip bond ASIC for signal processing and hand-wound coil for inductive powering.

Another version of neural interfaces was built to monitor the current drawing of the implantable devices over time under soak testing. It was similar to the wireless neural interfaces with a flip-chip bonded ASIC for on-site signal processing. Instead of inductive powering and wireless communication, it used 16 wire-bonded gold wires for data transferring and powering. In this way, the current drawing can be directly measured.

Alumina and Parylene C Deposition

52 nm of Al_2O_3 was deposited by plasma-assisted (PA) ALD on assembled UEAs at 120 °C. Details of the deposition process can be found at [15]. A 6-µm thick Parylene-C layer was deposited by CVD using Gorman process [16] on top of Al_2O_3 as the external layer. A-174 (Momentive Performance Materials), an organosilane, was used as adhesion promoter between the alumina and Parylene C layer. For wired neural interfaces, the connectors were covered with aluminum foil to avoid coating.

Tip Deinsulation

Fully coated neural interfaces are isolated form the physiological environment. For neural recording and stimulation, coating materials have to be removed from the tips in order to be able to interact with surrounding neurons. Traditionally oxygen plasma was used to remove the Parylene C by poking the tips through aluminum foil. The challenge was to control the exposure of the tips with an uneven backside during the poking process, especially for Utah Slant Electrode Arrays (USEAs). Therefore, hybrid method was developed to deinsulate the alumina and Parylene C bi-layer coated tips. Laser ablation and oxygen plasma etching were used to remove the Parylene and buffer oxide etch (BOE) was used to remove the thin alumina film.

Excimer laser was first used for ablation of Parylene C. 200 laser pulses with fluence of 1400 mJ/cm^2 were applied to remove 6-µm Parylene C. Laser pulse was at frequency of 100 Hz with duration of 5 ns. The alumina layer underneath Parylene acted as a shield layer, protecting the tip metal (iridium oxide) from being damaged by laser. In order to get a clean surface, carbon residual left on the surface from laser deinsulation was removed by adding 2 minutes of oxygen plasma. The alumina film has to be removed to reduce the impedance of the tips. Alumina was etched by dipping the array into BOE for 8 minutes. Parylene C acted as a mask layer for BOE etching and only alumina in the area where Parylene was removed by laser was etched away. The tip exposure was about 35 µm. The devices were then put into PBS solution for soak testing.

Testing Setup

For long-term impedance measurement, the wired array was soaked in 1× PBS solution at 57 °C for accelerated lifetime testing with an estimated aging factor of 4 [15]. The PBS solution was changed every other week to minimize the ion change effect on impedance. The impedance was measured by connecting the TDT connector with a customized automated impedance tester [17]. The impedance tester automatically switches between channels and measures impedance for all 96 channels at 1 kHz.

For wireless neural interface testing, the arrays were submerged in 1× PBS solution at 57 °C as well. The wireless neural interfaces were powered by a customized transmission board at 2.765 MHz. Power-up frequency and RF signal strength from the ASIC chip were monitored by using a Matlab-based GUI system with spectra analyzer and customized RF hand receiver.

RESULTS AND DISCUSSION

Impedance for wired array was measured at 1 kHz with 10-mV sine wave and was in the range of 30 to 100 kΩ for most electrodes as shown in Figure 4. Those impedance values are reasonable compared with typical Parylene C coated UEA impedance. The variation in impedance is mostly because of tip exposure variation and manufacturing difference during dicing and etching. The impedance of alumina and Parylene coated UEAs stayed relatively constant during equivalent soaking time of 320 days at 37 °C (80 days at 57 °C, up to date), indicating good insulation of individual electrodes. Impedance for Parylene coated samples usually dropped significantly (about 2 to 5 times) within 2 to 8 weeks, suggesting water ingress and insulation degradation of the coating. The arrays are still under soak testing and we are expecting longer impedance stability.

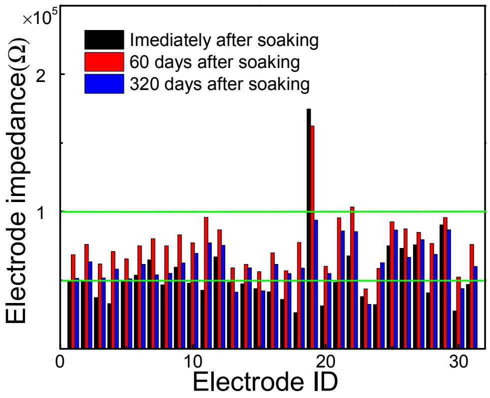
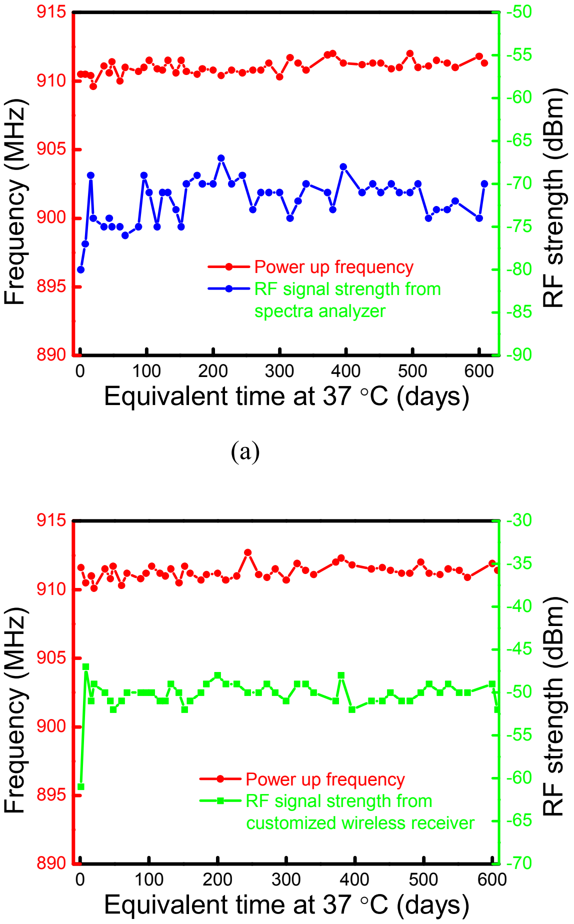


Figure 4: Electrode impedance of alumina and Parylene coated wired arrays. The impedance stayed relative constant for each electrode over equivalent soaking time of 320 days at 37 °C.

Wireless integrated neural interface (INI) devices were soaked at 57 °C for 150 days (up to date, equivalent soaking time of 600 days at 37 °C). The device was powered up only during the testing. When the device was in air, it was inductively powered up at 910.5 MHz with RF signal strength of -80 dBm measured from spectra analyzer. The RF signal strength was boosted up to -75 dBm right after the immersion of the device in PBS solution (Figure 5(a)). The power-up frequency stayed around 910.5 MHz. RF signal strength increase was confirmed by measurement from custom-developed wireless receiver (Figure 5(b)). The increase in RF signal strength is most likely due to the change of media from air to PBS solution. The power-up frequency was constantly ~ 910 MHz and the RF signal strength was stably around -73 dBm (Figure 5 (a)) during the equivalent soaking time of 600 days at 37 °C. This is a big progress compared with Sharma *et al.*'s reporting of a lifetime of 250 days at room temperature [18]. The devices are still under soak testing. The long-term stability of power-up frequency and RF signal strength of the device implied the good insulation performance of the alumina and Parylene C bi-layer encapsulation for biomedical implantable devices.

UEAs with flip-chip bonded ASIC chips on the backside were used to monitor the current drawing of the device over time under soak testing. The device was powered up through wire-bonded gold wires and was soaked at 57 °C in PBS solution. Failure of encapsulation would induce high current drawing of the device. The current drawing was stably about 3 mA for 140 days of soaking period at 37 °C (35 days at 57 °C). The device was then implanted into cat for *in-vivo* experiment.



(a)

(b)

Figure 5: Transmitted wireless RF signal monitored as a function of soak time in PBS. (a) Peak RF signal strengths and the respective frequencies as extracted from the spectra measured using the spectrum analyzer. (b) RF signal strengths and the respective frequencies as monitored on custom-developed wireless receiver board.

CONCLUSION

In summary, we have demonstrated a novel ALD alumina and Parylene C for neural interfaces. Impedance of alumina and Parylene coated wired arrays was stable over 320 equivalent days of soak testing at 37 °C. Bi-layer coated wireless neural interfaces incorporated with active electronics had lifetime of 600 days at 37 °C, showing the excellent insulation performance of alumina and Parylene C coating. Based on the coating performance on neural interfaces, it is believed that this bi-layer encapsulation can be used in many other chronic biomedical implantable devices for further extending their lifetime.

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CONTACT

*Xianzong Xie, Tel: +1(801)5870683
xianzongxie@gmail.com