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Advances in Flexible Electronics based on Shape Memory Polymers

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Abstract

Shape memory polymers (SMPs) are a class of self-adjusting smart materials that change shape and stiffness through a thermal transition such as a glass transition. In the past, the design norm for electronic devices had been to avoid these transitions in substrate materials in use temperature ranges. We demonstrate a host of new devices which embrace useful thermal transitions to overcome specific device limitations. Utilizing click copolymers made with thiol, alkene and acrylate monomers we demonstrate the ability for substrates to withstand full photolithographic processing up to 350°C with 5 micron minimum feature sizes. We describe a transfer-by-polymerization process to enhance adhesion and enable 3D devices and complex shapes manufactured in 2D top down environments with standard lithography toolsets. We describe devices that can be implanted into the body while stiff and rigid (> 1GPa) and soften after insertion towards the modulus of tissue to reduce the chronic immune response. We fabricate organic, thin-film transistors with mobility of 0.2 $cm^2V^{-1}s^{-1}$ and turn on voltage of-4.5V. Ongoing work will further examine force-touch sensors, ITO replacement layers, pH sensors, high density matrix-addressed arrays, and stimulating/recording interfaces for both the central and peripheral nervous system.

1. Introduction

Shape memory materials are a widely-investigated class of smart materials capable of changing from one predetermined shape to another in response to a stimulus. This macro-scale phenomenon has been demonstrated in ceramics, metals and a range of polymeric systems, but results from very different mechanics in each material. Shape memory polymers (SMPs) can "remember" a metastable shape and upon application of a stimulus, such as heat or light, recover a globally-stable shape. This memory phenomenon is referred to as dual-shape memory and is enabled by the presence of a switching phase and a crosslinking phase in a polymer network.

We describe smart engineered SMP substrates, which have been proposed for use in biomedical devices extensively over the past decade [1]. Specifically, the paradigm of softening electronics enables devices such as neural interfaces to be implanted while mechanically rigid and subsequently soften in physiological conditions. Others including Harris et al. have demonstrated the potential utility of softening intracortical electrodes [2].

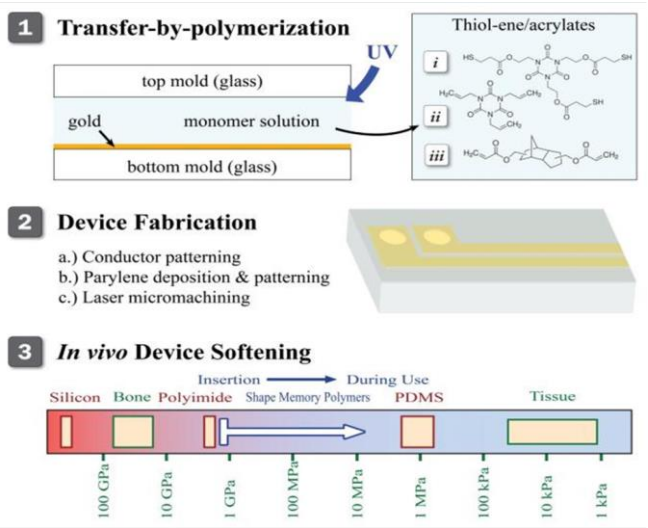

Fig. 1: 1) During the transfer-by-polymerization process, thiol, alkene and acrylate monomers are polymerized directly onto a sheet of gold. After polymerization the bottom part of the mold is removed exposing the gold film. 2) This film is then patterned and an insulating film (e.g. Parylene-C) is subsequently deposited and patterned. Devices are then micromachined from the surrounding substrate. 3) Schematic indicating the modulus of materials used in neural interfaces relative to biological tissues.

2. Results and Discussion

We have demonstrated the fabrication, characterization and demonstration of softening, intracortical electrode arrays with 5 micron minimum feature sizes patterned using full-photolithography reaching temperatures up to 350°C on softening substrates with minimal swelling [3]. Utilizing the transfer-by-polymerization process shown in **Fig. 1**, thiol-ene/acrylate copolymers are designed to position the glass transition temperature (T_g) to near 55°C, such that after plasticization in fluid, the T_g shifts 20°C triggering softening [4]. This paradigm allows surgeons adequate time for implantation, and maintains sub 3% swelling of the substrate to minimize abiotic device failure and delamination of the patterned Parylene-C barrier coating. This can be seen on the intracortical electrode shown in **Fig. 2** and in

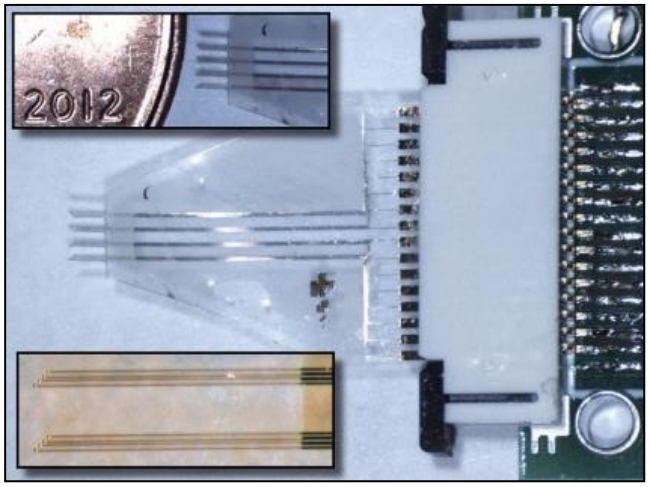

Fig. 2: SMP intracortical electrode softens from above 1GPa to less than 20 MPa and swells less than 3% in the body.

Table I: SMP Device Prototypes

Device	Channel count
Intracortical recording electrode	16
Neural microstimulators	8
Longitudinal intrafascicular electrode	16
Multi-electrode array for cell culture	64
Self-coiling vagus nerve stimulator	3
Softening cochlear implant	6
Matrix-addressed transistor-driven probes	4

devices seen in **Table I**. Other studies have shown how higher modulus materials, such as silicon, tungsten, Parylene-C and polyimides maintain sufficient stiffness to allow implantation into tissue [5, 6]. Our devices match these supra 1 GPa insertion properties, but chronically behave mechanically more similarly to polydimethylsiloxane. **Fig. 3** shows a comparison of modulus as a function of temperature for flexible electronic substrates [7]. **Fig. 4** demonstrates transistor behavior on SMPs which are optically transparent due to their amorphous structure [8].

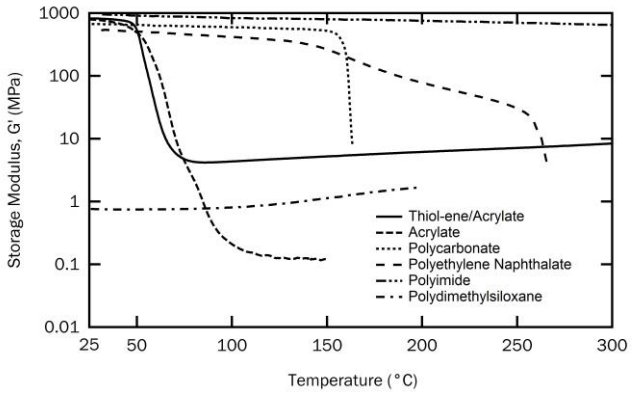

Fig. 3: Thiol-ene/Acrylate copolymers are compared to other flexible electronic substrates. The SMP can be processed below, through and above its T_g with excellent thermal stability.

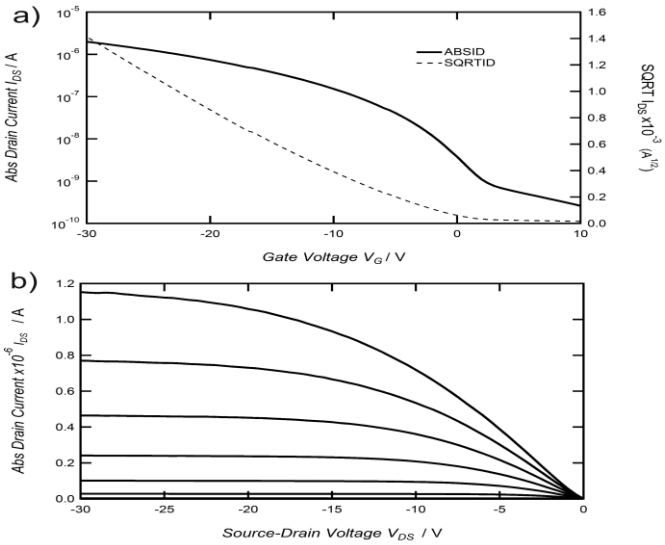

Fig. 4: The transfer curve (a) and the family curve (b) of a representative device indicate transistor behavior on SMPs. These values are used to extract the mobility and the V_{th} of the devices: 0.2 $cm^2V^{-1}s^{-1}$ and -4.5V respectively.

3. Conclusions

A ternary thiol-ene/acrylate substrate developed for softening, neural interfaces has been synthesized and characterized. Several neural interfaces were fabricated using a transfer-by-polymerization process. Excellent dimensional stability of the synthesized film enables processes that exceed the glass transition by more than 80 ºC. The limit of this temperature stability has not yet been found. The physiological response of these polymers, combined with excellent tolerance to photolithographic processes, makes this a promising system of substrates for neural interfaces that decrease the mechanical mismatch at the biotic-abiotic interface while offering increasingly advanced device and design capabilities. Future work in consumer electronics seeks to utilize these intriguing properties demonstrated in the bio-neuro prototypes developed to date.

Acknowledgements

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