Heat-Depolymerizable Tethers for Microelectromechanical System Assembly

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***Abstract*—Microelectromechanical systems (MEMS) assembly into packages that interface with the environment is critical in electronic sensor applications ranging from soft biomedical systems to telecommunications. This article presents a novel process using heat-depolymerizable polyethylene carbonate (QPAC-25) as a sacrificial tether, and demonstrates it for assembling wafer-bound MEMS onto wires. The assembly mechanism is thermal removal of the tether, allowing a strained layer to pop up from the substrate and make electrical and mechanical contact with the wire. We detail the QPAC-25 fabrication procedures, characterize the relationship between QPAC-25 thickness and spin speed and determine a route to pattern QPAC-25 without a metal hard mask or photosensitizers.**

***Index Terms*—MEMS, polymer patterning, sensor packaging, sacrificial layer, photolithography**

I. Introduction

MICRO-ELECTROMECHANICAL systems (MEMS) applications include sensors for the mechanical, electrical, and aeronautical industries [1]–[4]. The key to positioning MEMS for these applications has been packaging devices with flexible, three-dimensional, and mobile parts. Tether-based chip transfer is emerging, but most methods rely on adhesion forces to break tethers [5]. In this paper, the sacrificial polymer QPAC-25 (Empower Materials, Inc., USA) is heated to release a demonstration device, a strained cantilever that pops up from internal stress [6]–[10] to make electrical contact with a wire in packaging applications. Our previous studies with these strained layers had etching as the final step [11], limiting substrate size and composition to materials compatible with the etch chamber. Other previous work with QPAC layers used them for temporary supports or adhesives [12], rather than as tethers, and required making the QPAC photosensitive [13] or using a hard metal mask [14]. Our method makes sacrificial tethers from heat-depolymerizable QPAC-25, moving device packaging outside the etch chamber.

II. Methods

A. Sacrificial Polymer Tether Formulation

Heat depolymerizable polycarbonates are used as binders for microelectronic solder pastes because they break down into non-toxic gases at 250°C during solder reflow. Here we formulate this material as a liquid for spin-coating thin sacrificial structures. QPAC-25 poly (ethylene carbonate) with a molecular weight range of 50,000 to 200,000, was obtained from Empower Materials, USA. A 20 wt% QPAC-25 solution was prepared by dissolving as-obtained 99.99% pure QPAC-25 pellets in gamma-butyrolactone (Sigma-Aldrich, Inc., USA) and subjecting it to a 72-hour rotation on a mixing wheel at 5 RPM. Films were spun, and thicknesses were measured using profilometry (Dektak profilometer, Veeco Inc., USA).

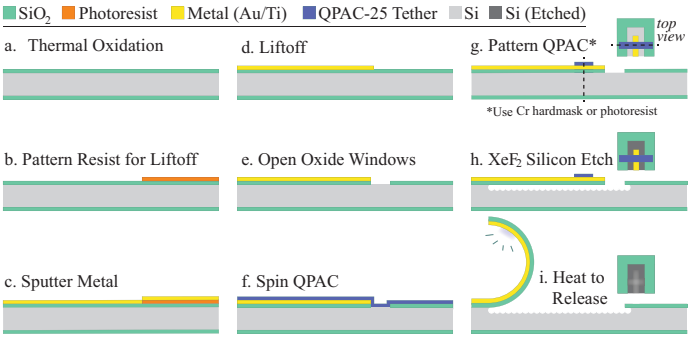

Fig. 1: Fabrication process for strained metal-oxide bilayer microcontacts with releasable QPAC-25 polymer tethers.

B. Fabricating Grippers for Tethering

Tethers made from QPAC-25 were added at the end of an existing process that creates three-dimensional metal grippers [15]. The combined process is shown in Fig. 1. Briefly, silicon wafers with a 500 nm compressively stressed thermal oxide layer were patterned with a 170 nm thick titanium (Ti) and gold (Au) metal layer using sputtering and lift-off. These metal features served as a mask for removing the surrounding thermal oxide by reactive oxide etching.

C. Patterning QPAC-25 Tethers using a Chromium Hardmask

Figure 1g shows the tether definition process. Tethers were patterned at gripper tips and across gripper beams. Following the lift-off and oxide etch process, the wafer was coated with adhesion promoter (SurPass 4000, DisChem Inc., USA) at 3000 RPM for 30 seconds, allowed to dry, then coated at 2000 RPM for 30 s with the QPAC-25 formulation described above and heated for 45 minutes on a hot plate at 95°C to remove any residual solvent.

Afterward, a chromium layer of 350 nm was sputtered for 5 minutes on the QPAC-25 polymer-coated wafer to act as a hardmask for QPAC-25 etching. We coated the metal layer with SurPass 4000 adhesion promoter, then Shipley 1813 as

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described above, doing the pre-exposure bake in an oven for 20 minutes at 115°C instead of a hotplate to protect the QPAC from thermal stress. A second photomask was aligned to define the QPAC tethers, followed by UV exposure. The developed photoresist was baked for 10 minutes post-exposure in the oven at 115°C to improve resistance to wet etching.

Next, we immersed the wafer in a bath of CEP-200 Chromium Etchant (HTA Enterprises, San Jose, CA) for 13 minutes to remove the chromium in the exposed regions. A 10-minute bake at 95°C followed this to ensure the complete removal of any water from the etchant. At this point, the wafer was optionally split into individual die by cleaving or dicing for experimentation on separate pieces. Next, a 10-minute reactive ion etch was performed to remove the QPAC-25 in areas not protected by chromium. The conditions in the March CS-1701 reactive ion etcher (RIE) were 300 mTorr oxygen at 300 Watts RF power. Finally, any remaining photoresist was removed by flood exposure and development, and the Cr layer was removed by etching in CEP-200 for 5 minutes.

This use of a metal hardmask and oxygen plasma etching is the most common way to pattern non-photosensitive polymer thin films in microfabrication. However, the hardmask adds extra steps. In a separate section, we will detail an effort to pattern the QPAC-25 using only a photoresist layer.

D. Device Release onto Wires

Following the etching process, photoresist was removed in the RIE system at 300 mTorr O_2 and 300 Watts RF power in preparation for undercutting the grippers and tethers. Undercutting was performed by silicon etching in a XeF_2 cyclic vapor etching system (Xactix, Inc., USA), with each cycle consisting of 30 seconds of 3 Torr XeF_2 followed by a 30-second, 3 Torr N_2 purge. After sufficient cycles elapsed to undercut the 10-micron-wide grippers and tethers, we performed a 40-second oxygen plasma etching step to clean up any polymer residue introduced by XeF_2 etching. Finally, the undercut devices were aligned with wires, and the assembly was heated to 250°C on a hotplate to remove the tethers and release the grippers under video observation.

III. Results and Discussion

A. QPAC-25 Spin Speed and Solvent Processing

The solution of QPAC-25 was applied to separate wafers using spin coating techniques at five rotational speeds between 500 and 3000 revolutions per minute (rpm). The thickness of the developed QPAC-25 decreases with spin speed. The typical linear dependence of thickness on inverse square root of spin speed is shown in Fig. 2.

Our investigation focused on finding solvents for photolithography and etching steps that would not interfere with previously-deposited QPAC-25 layers. Swelling, resulting from solvent absorption, can lead to the detachment of the polymer film from the wafer surface, potentially causing undercutting and damage to the device wafer by premature device release. QPAC-25 films underwent exposure to various solvents over 24 hours. Table I presents the results of solvent exposure after this extended soaking.

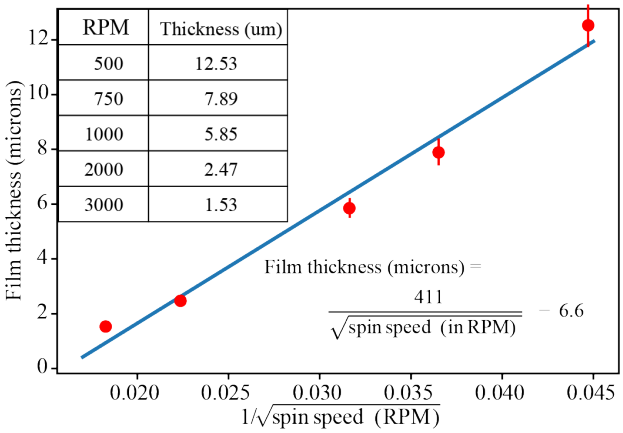

Fig. 2: Relationship between thickness and spin speed for 20 weight % solutions of QPAC-25 in gamma butyrolactone; error bars estimate variation within a single spun film.

Solvent	QPAC Results	Photoresist Results
Acetone	Swelling	Removed
MF 319 Developer	Dissolved	Partially Removed
AZ Developer	Dissolved	Removed
Toluene	Not Dissolved	Not Removed
MIBK	Not Dissolved	Removed

TABLE I: Solvent compatibility table for QPAC-25 film and Shipley 1800-series photoresists

B. Microgripper thermal release results

Figure 3 shows the progression from etching to thermal release. To prepare grippers for thermal release, it was important to fully undercut the tethers and devices, each having a typical width of 10 microns, without expensive over-etching in the XeF_2 system. 20 etch cycles was optimal. The presence of QPAC, which holds the microgrippers in place after XeF_2 etching, can be seen in the highlighted regions in Fig. 3b. The resulting features became distinctly apparent when the wafer was heated on a hot plate at 250°C, as depicted in Fig. 3d. Fig. 3e-g show the results after the heating process. Here, the wire interferes with the grippers fully curling up, and an electrical junction is produced at a contact point underneath the wire. The resistance between the wire and pad was measured using a probe station (Fig. 4), with likely contact area variation caused by facets and surface roughness of the drawn wire.

IV. Patterning of QPAC-25 without a hardmask

We then investigated whether it was possible to remove the chromium hardmask from the process, using only Shipley 1813 photoresist to protect the QPAC-25 from oxygen plasma etching. Although the photoresist developer MF 319 dissolves QPAC-25 after 24 hours (Table I) the unexposed photoresist protects it, and we were also able to limit the development time to 1 minute. Feasibility was investigated on silicon without the metal and oxide grippers, starting from the spinning step (Fig. 1f) and finishing at step g. By spinning Shipley 1813 at 4000 RPM for 30 seconds (approximately 1.3 microns thick) on a QPAC-25 layer spun at 1500 RPM for 30 s (approximately 4 microns thick) after the above photolithography step, followed

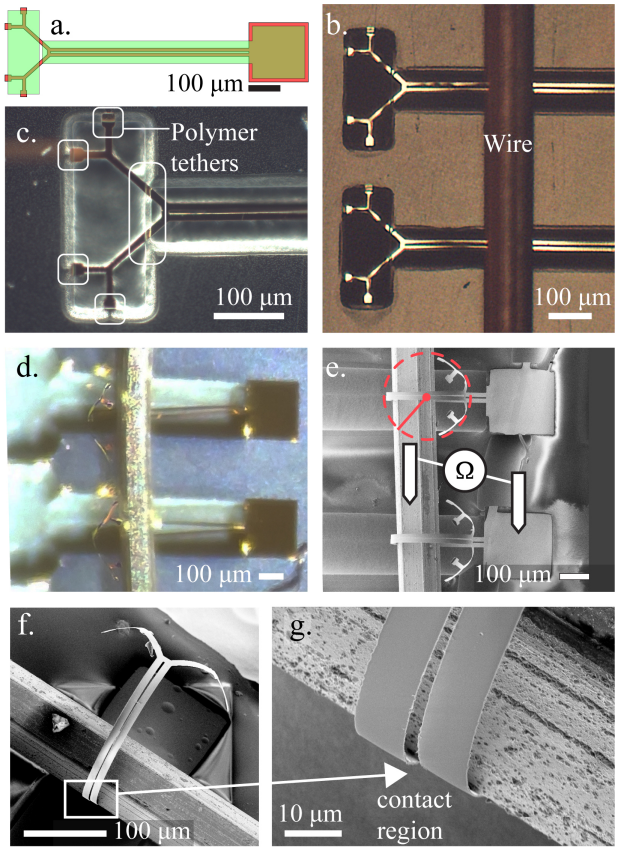

Fig. 3: Tethered gripper design and thermal release. a: layout with dark red areas representing metal/oxide bilayer and light green areas representing removed QPAC-25, b: Devices after XeF_2 etching with QPAC-25 tethers keeping grippers planar under an aligned wire, c: Close-up darkfield image showing suspended QPAC-25 tethers at the edges and across the gripper, d: Tethers disappearing during heating, e: SEM image after thermal release, showing radius (140-150 micron) and resistance measurement methods; f, g: contact region SEMs.

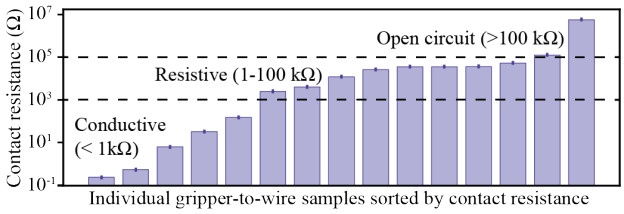

Fig. 4: Contact resistance of 16 different thermally released gripper-to-wire samples measured using method of Fig 3e.

by 10 minute oxygen plasma etching, we were able to fully pattern the sacrificial material using only photoresist.

V. Conclusion

In conclusion, our research has successfully demonstrated thermally-released microcontact grippers employing QPAC-25 as a sacrificial layer to secure the tips of the grippers until release time. The 140-150 micron radius of these grippers (Fig. 3e) and examples of sub-200 ohm resistance provide insights into their applications in sensor packaging. Redundant arrays of parallel contacts are likely to overcome the open circuits seen in our results while providing stronger mechanical anchoring. We found the required number of XeF_2 cycles for full undercutting of microgrippers ranges between 20 and 35 cycles, depending on the specific characteristics of the design. Furthermore, we have shown the feasibility of patterning QPAC-25 without using a metal hardmask.

Moving forward, our future investigations target temperature-lowering additives for QPAC-25 and their impact on the microgrippers' contact, particularly when patterned without a hardmask. This avenue of study has the potential to move microcontact grippers to lower-temperature fabric and elastomeric substrates, using their flexibility to package sensors on the irregular and highly deformable surfaces found in wearables and soft robotics.

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I. Biography Page

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