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Short Communication

A surface acoustic resonator with template-patterned interdigitated fingers

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ABSTRACT

Printed electronics techniques show promise as high-throughput, low-cost methods for fabricating micro-scale device features. In this work, we demonstrate a SAW resonator fabricated through a printing process. Silver nanoparticle ink is introduced to a vapor-permeable template that is patterned with the desired SAW resonator metallization. After the solvent in the ink evaporates, the nanoparticles within the patterned template tightly pack to form the device metallization. Interdigitated resonator electrodes with widths and spacing ranging from 500 nm to 1 μm were patterned on lithium niobate, corresponding to center frequencies of 2.1–2.4 GHz. The maximum quality factor was 13. Limitations and potential process improvements are discussed to improve resonator quality factor in future work.

1. Introduction

Nanoimprint lithography [1] and printed electronics processes [2] have recently attracted interest as potential methods for micro- and nanoscale metallization because they may reduce process complexity and cost over traditional fabrication methods. One such method, Advective Micromolding in vapor-Permeable Templates (AMPT) [3–6], deposits metal nanoparticles on a desired substrate using microfluidic channels to form a device metallization layer. Previously, the AMPT process has fabricated features as small as 350 nm in width [6].

In this work, we demonstrate the AMPT process's potential towards surface acoustic wave (SAW) resonator fabrication though additive patterning of nanoparticle ink. SAW resonators are an excellent candidate for printed electronics techniques such as AMPT because the resonant frequency is defined by the pitch of patterned electrodes and only one metal layer is required. In lithium niobate, the minimum feature size to reach the 2.4 GHz industrial, scientific, and medical radio band is 420 nm [7,8], which is within the theoretical capabilities of AMPT fabrication. Four SAW resonators with electrode width of 500 nm, 600 nm, 800 nm, and 1 μm are fabricated and the resonant behavior is characterized.

2. Design and fabrication

A critical part of the AMPT process is the vapor-permeable template: a polymer film that is patterned with the desired device features, into which the nanoparticle ink is drawn to form the metallization [3]. The template is patterned from a master fabricated through photolithography. The master contains raised features in a layout identical to that of the desired nanoparticle pattern. In this work, the resonator electrode features (width of 1 μm or less) are patterned lithographically (Fig. 1a) onto a thermally-grown SiO_2 layer and etched using deep reactive ion etching (DRIE) (Fig. 1b). The wider fill channels that lead to the electrodes are lithographically patterned on an SU-8 layer that is spun onto the smaller SiO_2 features.

The template is composed of a poly(4-methyl-2-pentyne) (PMP) film. PMP is highly rigid (1.6 GPa [6]) and extremely permeable to organic solvents, with a permeability for ethanol of 185,000 Barrer. The combination of rigidity and permeability insures that the nanoparticle ink solvent can rapidly evaporate through the film while the patterned channels retain their shape during deposition and formation of the nanoparticle features.

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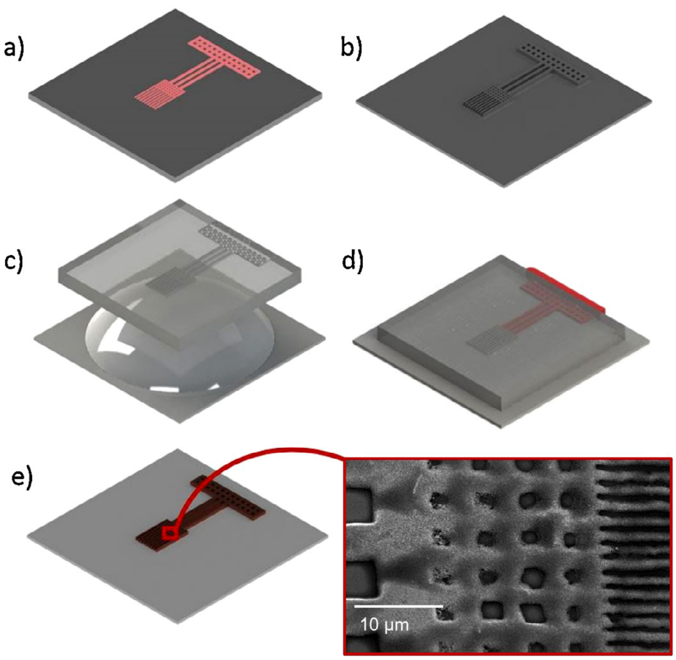

Fig. 1. A schematic of the AMPT process showing (a) lithography, (b) etching of the master wafer, (c) the template on the substrate, (d) introduction of nanoparticle ink, (e) drying and removal of the template.

The template is fabricated by casting PMP dissolved in cyclohexane onto the master. The cyclohexane is evaporated slowly through a PDMS membrane over the course of three days. The slow evaporation into a high concentration cyclohexane environment ensures proper feature formation and minimal residual stress. When fully dry, the template is removed from the master by softening it with isopropanol and peeling gently.

To pattern the desired features using the AMPT process, the template is placed channel-side-down on a substrate flooded with solvent (Fig. 1c). Nanoparticle ink is introduced to fill ports which are connected to features in the center of the template by means of fill channels (Fig. 1d). As solvent in the channels evaporates through the template, nanoparticle ink is drawn into the channels. The nanoparticles become increasingly concentrated and begin to densely pack as the ink solvent evaporates. After the features are fully packed and the excess solvent evaporates, the template is removed (Fig. 1e).

The conductive features are patterned with DGP AP ink from Advanced Nano Products Co. Ltd., (Buyong-myeon, South Korea). This ink contains nanoparticles averaging 20 nm at about 40 wt% in ethanol. The ink was diluted to about 8 wt% during the patterning process. Features were patterned by heating the substrate to 45 °C and lowering the template onto ethanol. Silver ink and ethanol were added to the fill ports over 30 min to evaporate all solvent. After solvent evaporation, the device and template were sintered in nitrogen at 250 °C for 30 min. Finally, the template was removed by soaking the patterned device in acetone to swell the template and aid in delamination from the substrate.

The resonator layout is shown in Fig. 2. The widths w and d are equal to each other and range from 500 nm to 1 μm. The lengths l_a and l_d range from 60 μm and 5 μm to 120 μm and 10 μm, respectively. The ratio of l_a to l_d's length remains constant across all fabricated resonators. Each resonators has 40 pairs of interdigitated electrodes.

A surface acoustic wave was only excited along the length marked ℓ_a in Fig. 2. The remaining electrode length from the interdigitated transducer (IDT) to the fill ports (ℓ_d in Fig. 2) was designed to dampen higher order modes. Gratings on either side of the IDT contained arrays of grounded electrodes to reflect the SAW wave at the Bragg condition interval, constraining the wave within the IDT area. The grid features that connected to the IDTs and fill ports served two purposes. The large surface area served as the contact pad to test the resonator operation using a ground-source-ground (GSG) probe. These contact pads were designed as grids with the same feature width as the IDTs, rather than open areas, because a grid of channels is less prone to collapse under the induced pressure of evaporating solvent.

To test the ability of the AMPT process to fabricate SAW resonators with various center frequencies, a template with four resonators was fabricated. The SAW resonators were patterned on a Y-Z cut lithium niobate ($LiNbO_3$) substrate, which was chosen for its high speed of sound and coupling efficiency. The model for the center frequency of a SAW was used to determine the appropriate electrode pitch [9],

$$f_c = \frac{v}{2(w+d)} \tag{1}$$

where v is the longitudinal velocity of wave propagation in the substrate, and w and d are electrode width and spacing, respectively. The target frequencies of the resonators were 860 MHz, 1.07 GHz, 1.43 GHz, and 1.72 GHz, corresponding to electrode width and spacing of 1 μm, 800 nm, 600 nm, and 500 nm, respectively.

3. Results and discussion

The 1 μm and 600 nm electrode width resonators are shown in Fig. 3. In both resonators, the fill ports are well defined, but the interdigitated electrodes are not completely patterned across the resonator. The circled areas indicate regions where the patterning is not complete. Lighter areas indicate places where silver nanoparticles have completely filled the template, whereas darker areas show uneven or incomplete patterning, or the existence of increased solvent residue. Both incomplete patterning and solvent residue increase the resistivity of the resonator features, reducing the quality factor of the resonator.

These patterning errors are caused by limitation of the AMPT process. One such limitation is the use of polymers as the template materials. During patterning, the PMP and polydimethysiloxane (PDMS) backing material absorb the solvent in the nanoparticle ink and swell. Mismatch in PMP and PDMS solvent diffusion rate and solvent absorption distorts the template [10,11].

Distortion may also occur within the template. The solvent diffusion rates vary over the template due to feature size and the presence of corners [12]. The PMP along the channel walls swells more than the PMP far from the channel walls. The localized swelling causes the PMP closest to the ink channels to expand more than the rest of the template. The concentration gradient of solvent can also lead to buckling, in which solvent in the fill channels causes the bottom of the template to disproportionately swell and fold in on itself.

Distortion is a concern for patterning fidelity and device functionality. The effects of swelling are visible in the pattern in Fig. 3a. The circled areas show where the swollen template buckled and delaminated from the template during patterning. As a result, the Bragg gratings are not completely formed. The circled area in Fig. 3b also shows incomplete nanoparticle ink patterning. In comparison to the IDT area in Fig. 3a, the interdigitated fingers are not clearly outlined.

The real and imaginary components of each resonator's reflection signal were measured using an Agilent Technologies E5071B network analyzer with a load termination of 50 Ω. Each device showed a resonance between 1.1 and 1.5 GHz (Fig. 4). As predicted by the center frequency model in (1), the measured center frequency is inversely related to electrode width. A mismatch of 5%