INTRODUCTION

Soft lithography is abundantly used as a versatile, rapid and economic patterning technique that has achieved feature dimensions smaller than 1 \( \mu \)m [1,2]. It is considered as one of the enablers of printable electronics. Previous microcontact printing (muCP) work has already demonstrated single layer printing on 4 inch substrates [3], ±1 \( \mu \)m alignment on 1 cm\(^2\) substrates [4], or 50 \( \mu \)m alignment on 12-cm-square substrates [5]. However, to date, difficulties such as single layer distortion control, multilayer alignment, contact control, and defect management [2] have hampered accurate and up-scalable soft lithography for large area printable electronic. In this first article, we discuss one mechanical reason for these difficulties, we introduce the concept of wave printing that solves most of these issues, and we demonstrate single layer printing capability with very low distortions. The second article discusses the multilayer capabilities and demonstrates thin film transistors [6].

MECHANICAL CONSIDERATIONS

It is generally claimed that the low elasticity modulus of the stamp material typically used in muCP provides good conditions for stamp-substrate contact, thereby offering prospects for easy large area printing without defects. Some mechanical aspects of muCP have been examined [2,7]. It is notably difficult to print features with both small and large dimensions using a single stamp: if the printing posts are slender (height to width ratio h/w > 2.5 [2][7]) they are liable to buckling or sticking with their neighbors. On the other hand, if the posts are shallow (h << w) the stamp recesses separating the posts will be squeezed by the printing pressure needed to obtain contact everywhere and will collapse, making unwanted contact between the posts. We define a dimensionless pressure \( \sigma^* = \frac{\sigma_\infty L}{\pi E^* h_{\text{post}}} \) with \( \sigma_\infty \) the pressure at collapse, \( E^* = \frac{E}{(1-\nu^2)} \) with \( E \) the Young’s modulus and \( \nu \) Poisson’s ratio. We furthermore define the pitch \( L \) of the features, their width \( w \) and the post height \( h_{\text{post}} \). For \( w << L \), the pressure at which the collapse of a stamp will occur has been derived [7]:

\[
\sigma^* = \frac{1}{2} \text{ArcCosh} \left( \sin \left( \frac{\pi w}{2L} \right) \right)^{-1}
\]

Assuming \( w=5 \mu m, L_{\text{pixel}} = 250 \mu m, L_{\text{TFT}} = 5 \mu m, h_{\text{post}} = 5 \mu m \) (h/w to prevent buckling), \( E = 2 \) MPa and \( \nu = 0.5 \) (Sylgard 184, PDMS, Dow Corning, USA), the critical collapse pressures for the pixel spacing will be \( \sigma_{\infty, \text{pixel}} = 0.01 \) MPa. We found experimentally that \( \sigma_{\infty, \text{TFT}} = 1 \pm 0.02 \) MPa. This means that the TFT regions can sustain a pressure 100 times higher than that allowable in the pixel regions. Let us now compare these pressures with those necessary to print over large areas. It will be difficult in practice to have stamp and substrate height variations
smaller than a few µm if sizes approach or exceed 0.5 m. In conventional printing techniques, the soft stamp is fixed to a stiff roll or plate. When the stamp material is constrained in this way, its relevant elasticity modulus is the bulk modulus \( B = E (1-\nu)/(1+\nu)(1-2\nu) \) instead of Young’s modulus \( E \). The pressure needed to obtain contact over the entire size of the substrate is thus \( \sigma = \varepsilon B \), where \( \varepsilon \) is the strain. Since silicone elastomers like PDMS are incompressible, their Poisson’s ratio is very close to 0.5. We have estimated \( B_{PDMS} > 200 \text{ MPa} \), amounting to \( \nu = 0.498 \) (note that \( B \) can frequently reach a few GPa for common polymers). Using \( \sigma = \varepsilon B \), the actual pressure needed to print every region of a 800-µm-thick stamp having thickness variations of about 5 µm is thus \( \sigma \approx 1 \text{ MPa} \). One immediately sees that while TFT regions would be printed without problem, the maximum allowable pressure to prevent collapse in pixel regions would be exceeded by a factor 100. This problem will be encountered for every printing technique that combines stiff surfaces and incompressible stamps with large ranges of feature sizes and pitches.

**WAVE PRINTING CONCEPT**

We propose wave printing as a new printing concept to solve the challenges of large area soft lithographic printing. In wave printing the 150-mm-diameter stamp (800-µm-thick PDMS) is mounted on a flexible glass backplate (200-µm-thick AF45, Schott, D) that provides rigidity and prevents stamp distortion in the plane of printing while offering flexibility perpendicular to the substrate and stamp (see figure 1). The stamp-backplate assembly (1) is maintained on a thick grooves-plate (8) by vacuum on the grooves (4). The substrate (2) is brought at a constant working gap (3) of 100 ± 10 µm from the stamp. Every groove is controlled by a valve that can switch between vacuum and a mild pressure (5) of about 2 kPa. When a few grooves (6) are fed with low pressure air, the flexible backplate stretches slightly and creates a “wave”. Under our conditions, the wave has a free height of about 150 µm. Since the working gap (3) is smaller, part of the now wavy stamp (1) makes contact with the substrate (2) at a pressure close to the working pressure of 2kPa, effecting the printing. When the next groove is opened to pressure, and the opposite groove switched back to vacuum, the wave “progresses” one groove further down the substrate. We have worked with 5-mm-wide grooves at a pitch of 10 mm. Our waves were 6-grooves-wide, with a stamp-substrate contact width of about 20 mm. The prototype printer accommodates substrate sizes up to 150-mm-diameter. It includes alignment optics and x-, y- and \( \theta_z \)- substrate manipulators designed for 1 µm alignment accuracy [6].

**Figure 1. Cross-section of the wave printing prototype:**

1: Stamp-backplate assembly.
2: Substrate. 3: Working gap (≈ 100 µm). 4: Vacuum supply.
5: Pressure supply (≈ 2 kPa).
6: Valves switched to pressure supply, thereby creating the wave.
7. 8: Grooves-plate.

**RESULTS**

We have microcontact printed SAMs of octadecanethiol on gold (25 nm Au, 5 nm Ti, on glass) using test features of TFT source drain electrodes with dimensions as small as 0.75 µm, with \( h_{post} = 2.3 \) µm. The stamp was soaked for 20 min. in a solution of octadecanethiol in ethanol.
(2 mM), then left for one hour to dry after rinsing with pure ethanol and nitrogen blowing. The printing contact time was 15 s. The gold was subsequently etched with a ferricyanide-thiosulfate bath and octanol as an additive [8]. Figure 2 shows a full picture of a 100-mm-square substrate, with a detailed view of printed features. The smallest printed features were 1-µm-wide lines with 1 µm separation. Note the presence of the very large open region (1400×700 µm²) without collapse. Considering the post height of 2.3 µm, these results confirm the great potential of wave printing for large area soft lithographic printing.

![Figure 2](image)

**Figure 2.** Printing results obtained with the wave printing prototype. Structured gold on a 100-mm-square glass substrate (left, 1 € coin for reference). Detailed optical micrograph view (right).

The average in-plane printing distortion from 155 regularly distributed positions was found to be 0.69 ± 0.045 µm, with only three values exceeding 2 µm.

**CONCLUSIONS**

Wave printing combines a flexible back plate supporting an elastomeric stamp with low air pressures to create localized and controlled contact between the stamp and a substrate. Line resolutions of 1 µm, pattern distortions of a few µm and open regions with stamp height to region widths as large as 400 have been demonstrated on 100-mm-square substrates. This holds promise for large area, high resolution printing of electronic devices, demonstrated elsewhere [6]. This work was partly supported by a Growth grant (EC), contract nr. GRD1-CT2000-25592.

**REFERENCES**