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Technical paper

A prototype printer for laser driven micro-transfer printing

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ABSTRACT

This paper demonstrates a new mode of automated micro transfer printing called laser micro transfer printing (LμTP). As a process, micro-transfer printing provides a unique and critical manufacturing route to extracting active microstructures from growth substrates and deterministically assembling them into a variety of functional substrates ranging from polymers to glasses and ceramics and to metallic foils to support applications such as flexible, large-area electronics, concentrating photovoltaics and displays. Laser transfer printing extends micro-transfer printing technology by providing a non-contact approach that is insensitive to the preparation and properties of the receiving substrate. It does so by exploiting the difference in the thermo-mechanical responses of the microstructure and transfer printing stamp materials to drive the release of the microstructure or 'ink' from the stamp and its transfer to substrate. This paper describes the process and the physical phenomena that drive it. It focuses on the use of this knowledge to design and test a print head for the process. The print head is used to demonstrate the new printing capabilities that LμTP enables.

1. Introduction

In micro-transfer printing (μTP), a patterned viscoelastic stamp is used to pick up and transfer functional microstructures made by conventional microfabrication techniques in dense arrays on typical growth/handle substrates (such as silicon, germanium, sapphire or quartz) to a broad range of receiving substrates such as transparent, flexible and stretchable polymers, glass, ceramics and metallic foils. This provides an efficient pathway to the manufacture of flexible electronics and photovoltaics, transparent displays, wearable electronics, conformal bio-compatible sensors and many more [1,2]. Fig. 1 [1,2,5–8] provides a few examples of the types of devices or systems that are realized by transfer printing.

Fig. 2 shows a schematic of the process along with photographs of the donor substrate with microstructures (also referred to as 'ink') and a receiving substrate with printed microstructures. The transfer printing stamp is typically made of molded polydimethylsiloxane (PDMS) and patterned with posts to selectively engage microstructures on the donor substrate. The ink is picked up by adhesion to the PDMS posts. Printing occurs when the 'inked' stamp is subsequently brought into contact with a receiving substrate, followed by a slow withdrawal of the stamp. Adhesiveless transfer printing exploits the viscoelastic rate-dependent adhesion at the stamp–ink interface to enable either retrieval or printing via control of the separation velocity [3,4]. This approach to printing fabricated microstructures without adhesives simplifies downstream processing and is easily automatable by integrating on to a programmable, computer controlled positioning stage. Fig. 3 shows an automated micro-transfer printing machine developed at the University of Illinois. The major components of the system include (a) an automated *XY*-stage for positioning, (b) a *Z*-stage for moving the stamp up and down and controlling the separation speed and force, (c) an orientation stage that assists in obtaining parallel alignment between stamp and the receiving and donor substrates and (d) imaging system used for alignment and monitoring the printing process. The typical size of the printed inks ranges from 10s of microns up to the millimeter scale. The microstructure donor substrate is usually densely packed and can be of centimeter scale. The receiving substrate's dimensions are, in general, several times larger, especially when the ink is sparsely distributed on it. The stamp surfaces are typically patterned with posts with the same lateral dimensions as the microstructures being printed.

While the process is simple and easy to implement, its robustness is dependent on the properties and preparation of the surface of the receiving substrate. For successful printing, the adhesion between the ink and receiving surface must be sufficient to extract

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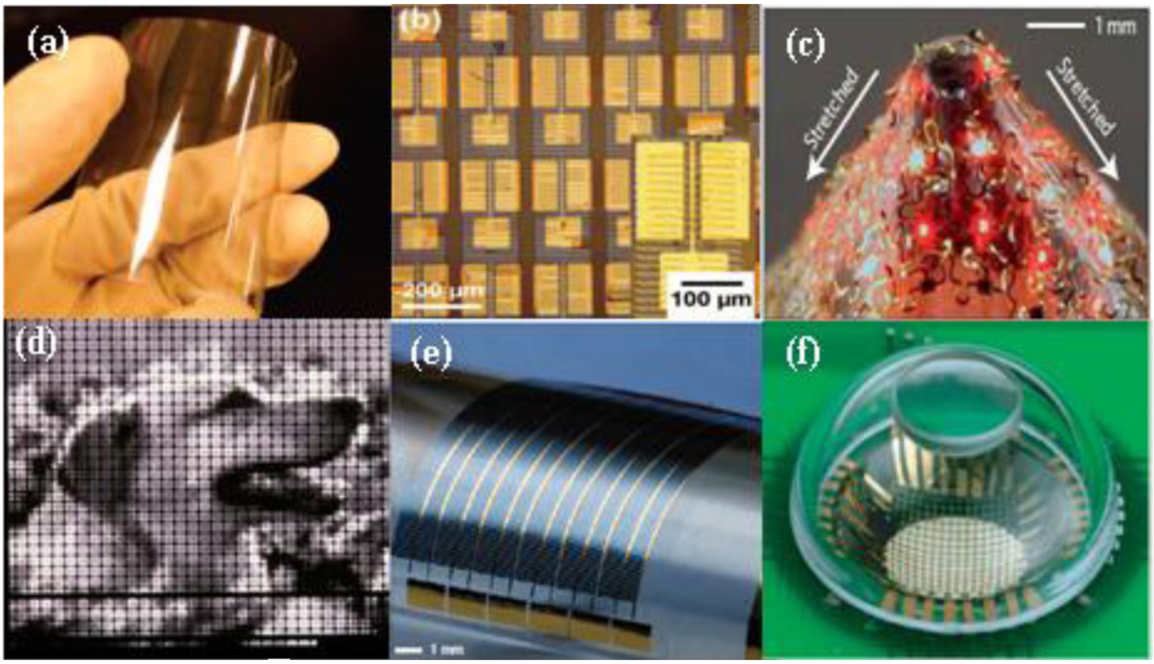

Fig. 1. Some examples of devices made using transfer printing. (a) Transparent carbon nanotube based transistors [5]. (b) GaN transistors on plastic substrate [7]. (c) LED on stretchable substrate [1]. (d) OLED display with printed electronics [6]. (e) Ultrathin silicon solar microcells [2]. (f) A hemispherical electronic eye camera [8].

the ink from the stamp and, when these conditions are satisfied, the surface much be clean and flat so that good contact is developed with the ink. Thus, printing on low-adhesion surfaces, patterned surfaces or soft gels can be challenging.

The process depicted in Fig. 2 can be scaled into a high transfer-rate, parallel printing process by increasing the number of posts on the stamp. As this parallelism increases, additional challenges accrue. Small misalignments between the substrate and the stamp get magnified as the size of the stamp increases causing substantial variations in the printing conditions at posts in different areas of the stamps leading to printing failures. Failure to print a microstructure in one cycle can result in repeated failures at that post in subsequent cycles, until the residual micro-structure is removed. When large receiving substrates are involved, waviness of the substrates gives rise to non-repeatable variability in printing conditions across the stamp. Finally, when large area expansions are involved, i.e., the printed microstructures has a high pitch or low areal density on the receiving substrates, the stamps used have posts that are spaced far apart and are therefore susceptible to stamp collapse [9,10], especially when larger printing forces are used to compensate for misalignments ('wedge' errors) between the stamp and the substrate. Such collapses result in the peeling out of microstructures by the stamp wherever contact occurs, and can damage both, the donor and receiver substrates.

In this paper, we develop a new, non-contact mode for this process that uses a laser to supply the energy required to drive the release of the ink from the stamp and its transfer to the receiving substrate. Since it does not rely on the strength of ink–substrate interface, created by mechanically pressing the ink onto the receiving substrate, to achieve its release from the stamp, the process does not depend on properties or the preparation of the receiving substrate for successful printing. Further, by using a scanned laser beam to address different inks or microstructures on the stamp, high-throughput modes of printing, not susceptible to small wedge errors between the stamp and the substrate, are possible. Thus, this new process mode that we call laser-driven micro-transfer printing (LμTP) has the potential to become a highly scalable, robust and versatile printing process.

The next section of this paper describes the laser transfer printing process and the phenomena it exploits. It also provides a detailed design of the laser print head for prototype laser transfer printing tool along with its calibration and testing. The third section demonstrates successful LμTP for situations that would be difficult to achieve with conventional transfer printing. It also explores one important parameter, separation of the stamp and receiving substrate on the accuracy of the transfer. Finally, conclusions and directions for future work are discussed.

2. Laser-driven micro-transfer printing

2.1. Process description

LμTP builds on micro-transfer printing technology [3,4]. It uses the same well-developed semiconductor processing technologies for creating donor substrates with dense arrays of printable microstructures, the same materials and techniques for fabricating the transfer stamps, and the stamps are 'inked' with microstructures using the same strategies [3,4]. The critical point of departure is the printing or transfer of the ink from the stamp to the receiving substrate. Instead of using mechanical means, LμTP uses a pulsed laser beam focused on the interface between the stamp and the microstructure to release and drive the microstructure to the receiving substrate. The wavelength of the laser is chosen so that the stamp material is transparent to the laser while the ink is absorbing. Here we choose an IR laser with wavelength 805 nm. Additionally, the stamp material is chosen so as to have a large mismatch in the coefficient of thermal expansion (CTE). For example, in the prototype reported here, single crystal silicon is used as the ink and PDMS as the stamp with CTEs of 2.6 ppm/°C and 310 ppm/°C respectively, to produce a CTE mismatch of two orders of magnitude.

Fig. 4 shows a schematic of the LμTP process. For printing step, the inked stamp is positioned so that the ink is close (about 6–10 μm) to the receiving substrate. A pulsed laser beam is then focused on the interface between the stamp and the ink to cause the transfer of the ink to the substrate. Since a PDMS stamp is