Mechanics Research Communications 43 (2012) 46–49

Contents lists available at SciVerse ScienceDirect

Mechanics Research Communications

journal homepage: www.elsevier.com/locate/mechrescom

An analytical model for shear-enhanced adhesiveless transfer printing

Huanyu Cheng[a,1], Jian Wu[b,1], Qingmin Yu[a,c], Hyun-Joon Kim-Lee[d], Andrew Carlson[e], Kevin T. Turner[f], Keh-Chih Hwang[b], Yonggang Huang[a,*], John A. Rogers[e]

[a] Department of Mechanical Engineering and Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL 60208, United States
[b] Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China
[c] School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710072, China
[d] Department of Mechanical Engineering, University of Wisconsin, Madison, WI 53706, United States
[e] Department of Materials Science and Engineering, Beckman Institute, and Frederick Seitz Materials Research Laboratory, University of Illinois, Urbana, IL 61801, United States
[f] Department of Mechanical Engineering, University of Pennsylvania, Philadelphia, PA 19104, United States

ARTICLE INFO

Article history:
Received 16 December 2011
Received in revised form 25 February 2012
Accepted 27 February 2012
Available online 8 March 2012

Keywords:
Adhesion
Shear
Transfer printing
Interfacial delamination

ABSTRACT

Transfer printing is an important technique for assembling micro/nanomaterials on unusual substrates, with promising applications in the fabrication of stretchable and flexible electronics designed for use in areas such as biomedicine. The process involves retrieval of structures (e.g., micro-devices) from their growth (donor) substrate via an elastomeric stamp (i.e., an element with posts on its surface), and then delivers them onto a different (receiver) substrate. An analytical mechanics model is developed to identify the key parameters for a shear-enhanced mode for transfer printing. The results predict that the pull-off force decreases linearly with increasing shear strain in the post, or with shear displacement across the stamp. This prediction agrees well with the experiments.

Published by Elsevier Ltd.

Transfer printing is a technique that allows micro-devices to be retrieved (i.e., picked up) from their growth (donor) substrate via an elastomeric stamp, and then allows their delivery onto a different (receiver) substrate (Carlson et al., 2011; Feng et al., 2007; Kim et al., 2009, 2010c; Meitl et al., 2006; Wu et al., 2011). Stretchable electronics represents an application example where transfer printing is critical; the process yields micro-devices printed in arrays onto elastomeric substrates (e.g., PDMS) for systems such as structural health monitoring devices (Nathan et al., 2000), flexible sensors (Lumelsky et al., 2001; Mannsfeld et al., 2010; Someya et al., 2005; Someya and Sekitani, 2009), flexible display (Crawford, 2005; Forrest, 2004; Gelinck et al., 2004), stretchable and foldable circuits (Kim et al., 2008; Sekitani et al., 2010), flexible inorganic solar cells (Yoon et al., 2008) and LEDs (Park et al., 2009; Sekitani et al., 2009). Transfer printing has also been used to develop biomimetic, curvilinear electronics (Ko et al., 2008), bio-dissolvable electronics (Kim et al., 2010a), stretchable and flexible devices for cardiac electrophysiology (Viventi et al., 2010) and ablation therapy (Kim et al., 2011b), foldable electrode array for mapping brain activity (Viventi et al., 2011), smart surgical gloves (Someya et al., 2004), waterproof optoelectronics for biomedicine (Kim et al., 2010b), and epidermal electronics (Kim et al., 2011a).

There exist several different transfer printing techniques.

(1) *Kinetically controlled transfer printing* (Feng et al., 2007; Meitl et al., 2006). The viscoelastic stamp picks up the micro-devices rapidly and prints them slowly onto the receiver substrate because it has high and low adhesion strengths at the large and small peeling rates, respectively.
(2) *Surface-relief-assisted transfer printing* (Kim et al., 2010c; Wu et al., 2011). The stamp surface consists of surface relief structures, such as microtips, to achieve large surface contact with micro-devices (and therefore large adhesion force) during pickup, and small contact area during printing.
(3) *Load-enhanced transfer printing* (Carlson et al., 2011; Kim et al., 2009). Different mechanical loading protocols are adopted to facilitate large and small adhesion forces during pickup and printing, respectively. Directional shearing at an interface is shown to control the behavior in various micro- and nano-structured dry adhesives (Aksak et al., 2008; Jeong et al., 2009; Kramer et al., 2010; Murphy et al., 2009; Varenberg and Gorb, 2007). In particular, shear-enhanced transfer printing (Carlson et al., 2011) shows that the directional shearing at an interface mechanically initiates separation at the adhesive surface and therefore can be used to facilitate the printing of micro-devices.

* Corresponding author.
E-mail address: y-huang@northwestern.edu (Y. Huang).
[1] These authors contributed equally.

0093-6413/$ – see front matter. Published by Elsevier Ltd.
doi:10.1016/j.mechrescom.2012.02.011

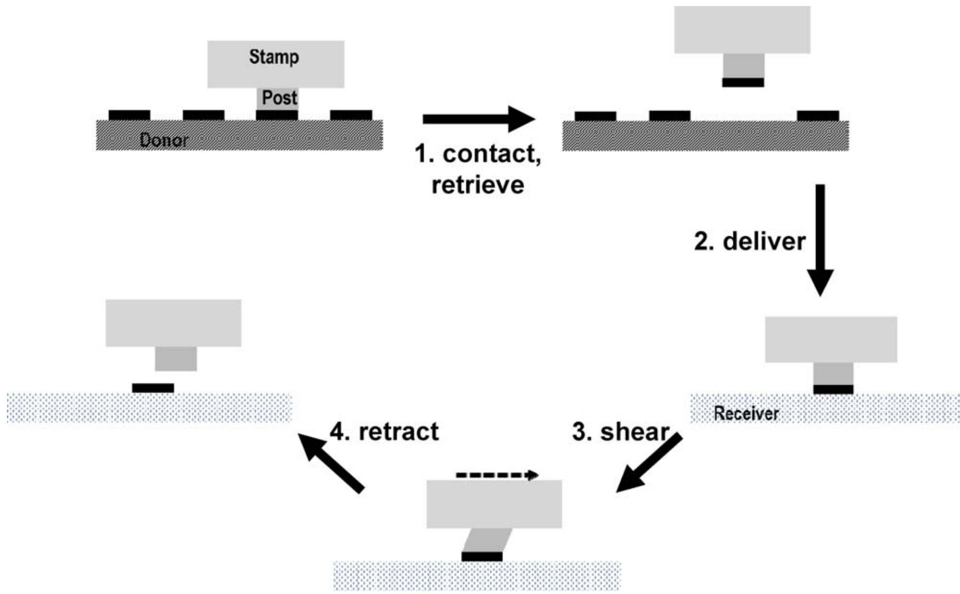

Fig. 1. Illustration of the shear-enhanced transfer printing technique. During pickup, the stamp is retracted rapidly to maximize adhesion after conformal contact to the micro-device. To print, the stamp with micro-device is placed in contact with a receiver substrate, which is displaced laterally followed by a slow retraction on the stamp.

(4) *Laser-driven transfer printing* (Saeidpourazar et al., in press). During printing a laser pulse initiates separation at the adhesive surface due to large thermal mismatch between the stamp and micro-devices.

For kinetically controlled and surface-relief-assisted transfer printing, Feng et al. (2007) and Wu et al. (2011) developed analytical mechanics models to establish the scaling laws, respectively, i.e., a single (or few) non-dimensional combination of key parameters that governs the transfer printing. For shear-enhanced transfer printing, Carlson et al. (2011) developed the numerical model (finite element analysis). A schematic illustration of shear-enhanced transfer printing is shown in Fig. 1. An elastomeric stamp is a single, rectangular post mounted to a thick backing layer. The post and the underlying micro-device to be transferred have identical lateral dimensions, and have conformal contact. The micro-device is picked up rapidly to maximize adhesion through viscoelastic effects of the stamp. The stamp with the micro-device is placed in contact with a receiver substrate. The receiver substrate is then displaced laterally to induce shear on the stamp, which reduces the pull-off force of the stamp to slowly delaminate from the micro-device. The induced shear facilitates the efficient printing of the micro-device onto the receiver substrate.

The purpose of this paper is to establish analytically the scaling law for shear-enhanced transfer printing. Specifically, the reduced pull-off force of the stamp is obtained analytically in terms of the shear strain. This relation is validated by the experiments, and is useful to the optimal design of the stamp for shear-enhanced transfer printing.

Fig. 2 shows a schematic diagram of the stamp and micro-device. On top of a thick backing layer ($H = 950\,\mu$m), the poly(dimethylsiloxane) (PDMS, 5:1 monomer:catalyst mix ratio) post ($L \times L \times h = 100\,\mu\text{m} \times 100\,\mu\text{m} \times 50\,\mu\text{m}$) was brought into intimate contact onto a monocrystalline silicon micro-device ($100\,\mu\text{m} \times 100\,\mu\text{m} \times 3\,\mu\text{m}$) illustrated as a black plate. The backing layer and post are casted and cured together to form the stamp from a prepolymer of PDMS, which ensures strong bonding between the backing layer and post. Using a custom adhesion test setup described elsewhere (Kim et al., 2010c), the shear displacement u was applied on the micro-device in the x direction followed by a vertical retraction with pull-off force F on the stamp in the z direction.

The shear strain in the post γ is determined analytically from the shear displacement u and stamp geometry. The backing layer is much wider and thicker than the post, and is modeled as a semi-infinite solid subjected to a shear stress τ in the x direction over the post area $L \times L$ at the surface of $z = 0$ as shown in Fig. 2. For a concentrated shear force $\tau dx_0 dy_0$ at (x_0,y_0) over an infinitesimal area $dx_0 dy_0$ of the bottom surface, the x-direction displacement at (x,y) on the surface is $dw = \tau dx_0 dy_0/[2\pi\mu\sqrt{(x-x_0)^2+(y-y_0)^2}][1-\nu+\nu((x-x_0)^2/[(x-x_0)^2+(y-y_0)^2)]]$ (Landau and Lifshitz, 1986), where μ and ν are the shear modulus and Poisson's ratio of the stamp, respectively. For a uniform shear stress τ applied to the post, the displacement at (x,y) is

$$w(x,y) = \int_{L\times L} dw = \frac{\gamma}{2\pi}\int_{-L/2}^{L/2} dx_0 \int_{-L/2}^{L/2} \frac{1}{\sqrt{(x-x_0)^2+(y-y_0)^2}} \times \left[1-\nu+\nu\frac{(x-x_0)^2}{(x-x_0)^2+(y-y_0)^2}\right] dy_0, \quad (1)$$

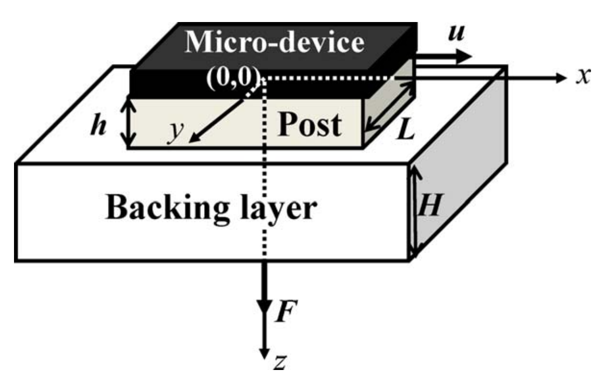

Fig. 2. The critical dimensions of the post and backing layer and loading conditions in a custom adhesion test set up.