Acta Mechanica Solida Sinica, Vol. 23, No. 6, December, 2010 ISSN 0894-9166
Published by AMSS Press, Wuhan, China

# MECHANICS ANALYSIS OF TWO-DIMENSIONALLY PRESTRAINED ELASTOMERIC THIN FILM FOR STRETCHABLE ELECTRONICS***

**Ming Li**[1,2**] **Jianliang Xiao**[3**] **Jian Wu**[2] **Rak-Hwan Kim**[3] **Zhan Kang**[1]
**Yonggang Huang**[2*] **John A. Rogers**[3]

([1] *State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian* 116024*, China*)
([2] *Departments of Civil and Environmental Engineering and Mechanical Engineering, Northwestern University, Evanston, IL* 60208*, USA*)
([3] *Department of Materials Science and Engineering, Beckman Institute for Advanced Science and Technology, and Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL* 61801*, USA*)

Received 12 November 2010, revision received 24 November 2010

**ABSTRACT** Various methods have been developed to fabricate highly stretchable electronics. Recent studies show that over 100% two dimensional stretchability can be achieved by mesh structure of brittle functioning devices interconnected with serpentine bridges. Kim et al show that pressing down an inflated elastomeric thin film during transfer printing introduces two dimensional prestrain, and therefore further improves the system stretchability. This paper gives a theoretical study of this process, through both analytical and numerical approaches. Simple analytical solutions are obtained for meridional and circumferential strains in the thin film, as well as the maximum strain in device islands, which all agree reasonably well with finite element analysis.

**KEY WORDS** stretchable electronics, shell, soft materials

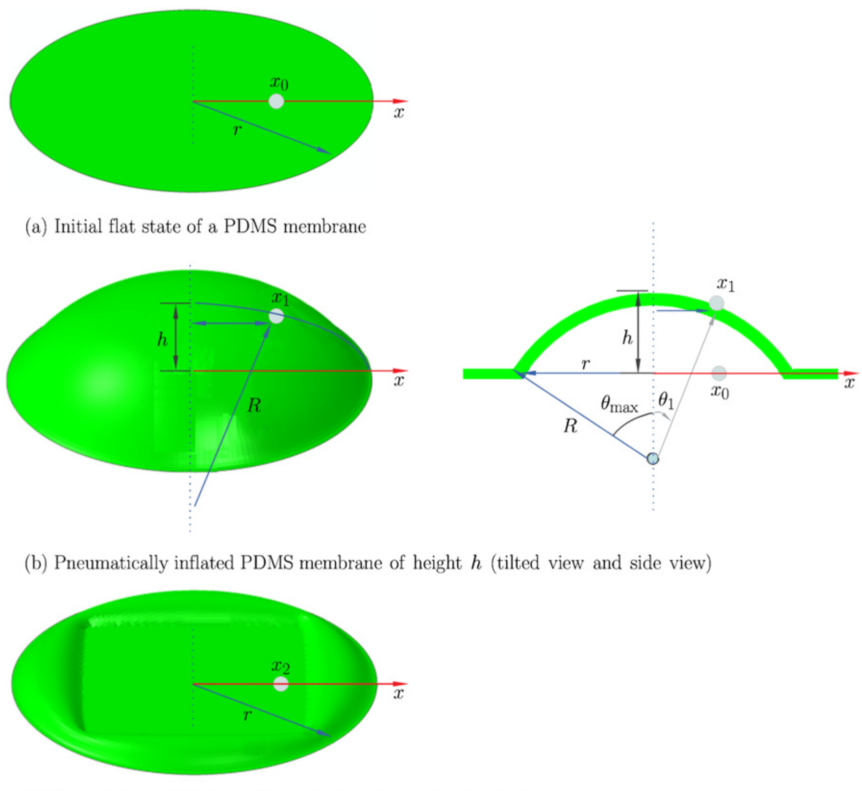
## I. INTRODUCTION

Stretchable and flexible electronics and optoelectronics[1–3] have shown potential applications in biomedicine[4,5], robotics[6–9], flexible displays[10–14], electronic eyeball cameras[15–21], and flexible solar cells[22,23] (See the review papers [24,25]). These accomplishments use systems that offer high stretchability with active materials of Si, GaAs, carbon nanotubes or silicon nanowires[26–50], transfer printed from hard, rigid growth substrates (e.g., semiconductor wafers) to soft, elastic elastomeric substrates[51–59]. An effective approach is to place functional but fragile devices on isolated islands, connected by robust, wavy bridges serving as electrical interconnection[60,61]. This strategy gives very large, two-dimensional stretchability (>100%) because mechanical deformations are mostly absorbed by the bridges, such that the strain in functional devices remain very small. Applying two-dimensional prestrain during the fabrication of systems with this type of stretchable design can further enhance the stretchability, and enable

* Corresponding author. E-mail: y-huang@northwestern.edu, jrogers@illinois.edu
** These authors contribute equally.
*** Project supported by the NSF (Nos. DMI-0328162 and ECCS-0824129). Yonggang Huang also acknowledges the support from NSFC and Ming Li acknowledges the support from China Scholarship Council.

application to extreme conditions[13,25]. Thermal manipulation of the elastomeric substrate represents one means to apply uniform two dimensional prestrain[39,62], but the magnitudes are only typically a few percent or less.

As recently reported by Kim et al.[9], transfer printing optoelectronics onto a pneumatically inflated elastomeric thin film can induce very high two dimensional prestrain, thereby greatly enhancing the stretchability. Demonstration experiments with inorganic light emitting diodes illustrated the effectiveness of this procedure. Figure 1 schematically describes the fabrication process. A thin polydimethylsiloxane (PDMS) film is mounted onto a chamber. Injecting air into the chamber inflates the PDMS film to a balloon shape (Fig.1(b)). Transfer begins by pushing a PDMS stamp with an array of prefabricated and transferred devices against the inflated film until the entire contact area of the film becomes flat (Fig.1(c)). Removing the PDMS stamp leaves the device array on the PDMS balloon. Deflating the balloon results in an array of electronic devices on a two dimensionally prestrained PDMS thin film. Such an approach gives very large prestrain (> 30%), and therefore significantly increases the system stretchability.



(a) Initial flat state of a PDMS membrane

(b) Pneumatically inflated PDMS membrane of height $h$ (tilted view and side view)

(c) Pressed down PDMS membrane to transfer electronic devices

Fig. 1. Schematic illustration of introducing two dimensional prestrain to stretchable electronics.

A simple, analytical model is established in §II to determine the distribution of prestrain induced by transfer printing of electronic or optoelectronic devices onto an inflated thin film. The analytical model is validated by finite element method (FEM) in §II, and can be used in a unit cell model to determine the maximum strain in serpentine interconnects. The maximum strain in devices is obtained analytically in §III.

## II. ANALYTIC MODEL AND NUMERICAL RESULTS

Figure 1(a) shows a circular, flat PDMS thin film of radius $r$ fixed at its outer boundary. Inflation of air deforms the thin film to a spherical cap of height $h$, as shown in Fig.1(b). For the height $h$ comparable to radius $r$ as in experiments, the thin film is mainly stretched, and bending becomes negligible except near the fixed boundary. The radius and polar angle of the spherical cap are approximately given by

$$R = \frac{h^2 + r^2}{2h}, \quad \theta_{\max} = \sin^{-1}\left(\frac{2hr}{r^2 + h^2}\right) \tag{1}$$

As to be confirmed by FEM results in §III, the strain in the meridional direction is approximately uniform away from the fixed boundary, and is obtained as

$$\varepsilon^{(1)}_{\text{meridional}} = \frac{R\theta_{\max}}{r} - 1 = \frac{h^2 + r^2}{2hr}\sin^{-1}\left(\frac{2hr}{r^2 + h^2}\right) - 1 \tag{2}$$

For a point of distance $x_0$ to the film axis at the initially flat state, it moves to the position of distance $x_1$ to the axis and of polar angle $\theta_1$ at the inflated state, as shown in Fig.1(b). The uniform meridional strain gives $\theta_1 = (x_0/r)\theta_{\max}$ and $x_1 = R\sin\theta_1$. The circumferential strain is then obtained as

$$\varepsilon^{(1)}_{\text{circumferential}} = \frac{h^2 + r^2}{2hx_0}\sin\left[\frac{x_0}{r}\sin^{-1}\left(\frac{2hr}{h^2 + r^2}\right)\right] - 1 \tag{3}$$

The PDMS thin film is pressed downward after inflation by a thick PDMS stamp to transfer electronic devices. The point $x_1$ on the inflated film moves to the position of distance $x_2$ to the axis. Due to the strong adhesion between PDMS stamp and thin film, the area on PDMS thin film having contact with the stamp moves vertically downward, which gives $x_2 = x_1$ and the circumferential strain

$$\varepsilon^{(2)}_{\text{circumferential}} = \varepsilon^{(1)}_{\text{circumferential}} = \frac{h^2 + r^2}{2hx_0}\sin\left[\frac{x_0}{r}\sin^{-1}\left(\frac{2hr}{h^2 + r^2}\right)\right] - 1 \tag{4}$$

The meridional strain equals $\mathrm{d}x_2/\mathrm{d}x_0 - 1$, and is obtained as

$$\varepsilon^{(2)}_{\text{meridional}} = \frac{h^2 + r^2}{2hr}\sin^{-1}\frac{2hr}{r^2 + h^2}\cos\left[\frac{x_0}{r}\sin^{-1}\left(\frac{2hr}{h^2 + r^2}\right)\right] - 1 \tag{5}$$

The simple analytical expressions for strains in Eqs.(4) and (5), once validated, are useful to determine the maximum strain in devices and their positions in §III after the devices are transfer printed on the inflated PDMS thin film.

The finite element method (FEM) is also used to study the deformation of PDMS thin film due to inflation via the commercial FEM software ABAQUS. PDMS thin film, of Young's modulus 2 MPa and Poisson's ratio 0.48, is modeled by shell elements S4R since its thickness (0.4 mm) is much smaller than radius (10 mm). The outer boundary of PDMS thin film is fixed, and uniform pressure is applied to the bottom surface of PDMS thin film. For an inflation height $h$=4 mm, the contours for meridional and circumferential strains in the inflated thin film are shown in Figs.2(a) and 2(b), respectively. They agree reasonably well with the simple analytical solutions in Eqs.(2) and (3), as shown in Fig.2(c). The inflated profile of the thin film obtained by FEM is shown in Fig.2(d), which agrees well with the simple, analytical solution in Eq.(1).

The meridional and circumferential strain contours in the pressed thin film are shown in Figs.3(a) and 3(b), respectively. As shown in Fig.3(c), they agree reasonably well with the simple analytical solutions in Eqs.(4) and (5), which can be used to determine buckling of interconnects between device islands. For interconnect linking two device islands, the elongation equals the product of device spacing and the strain in Eq.(4) (for two device islands along the circumferential direction) or Eq.(5) (for meridional direction). The lateral buckling pattern of serpentine interconnect can then be determined by a unit cell model of a single interconnect subject to this elongation. The strain in interconnect can also be obtained.

## III. MAXIMUM STRAIN IN DEVICES

The maximum strain in devices is critical to their reliability. After pressing the devices down against the PDMS substrate, the pressure is released, causing the PDMS to return back to the original hemi-spherical shape, with devices on top. The strain in devices results from three sources:

(i) stretching of PDMS substrate during inflation (after the stamp is removed);

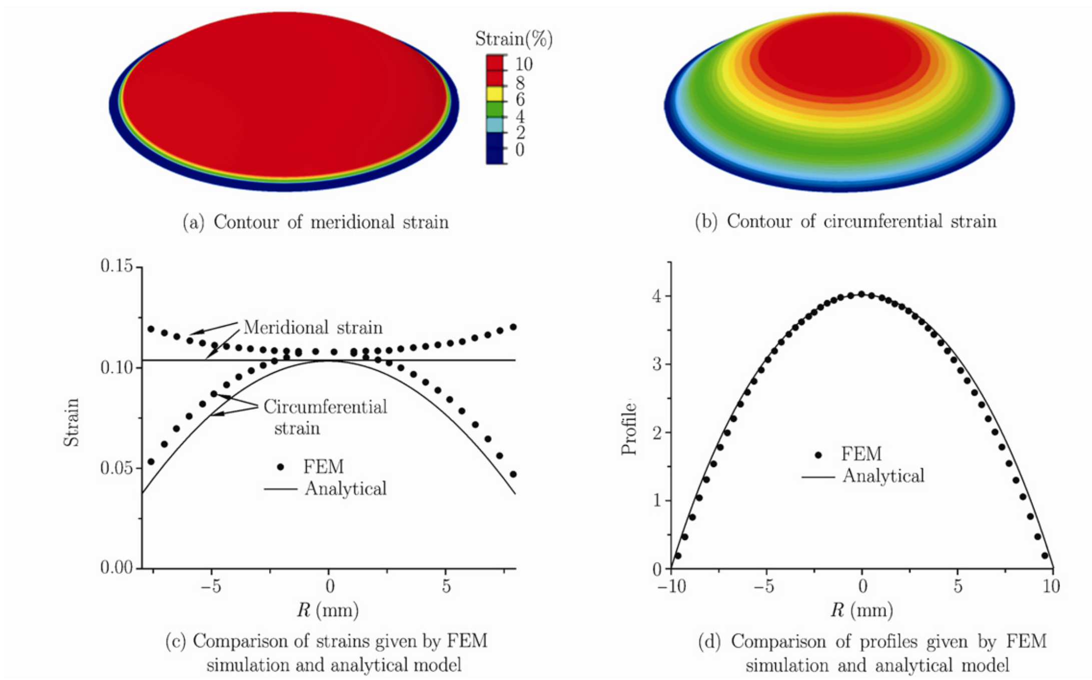



Fig. 2. Strain distribution and profile of inflated PDMS embrane.

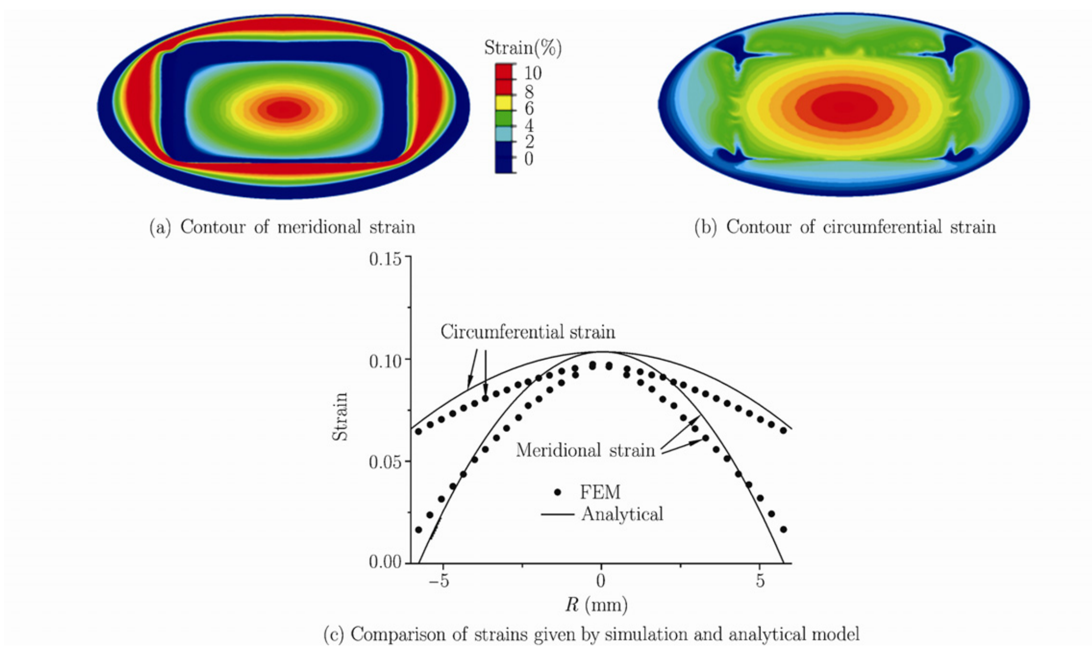



Fig. 3. Strain distribution of pressed down PDMS membrane.

(ii) bending due to lateral buckling of interconnects;

(iii) bending due to the spherical shape of inflated PDMS substrate.

The finite element analysis has shown that the strains resulting from (i) and (ii) are much smaller than that from (iii), and the latest is given analytically by

$$\varepsilon_{\text{device}} = \frac{y}{R} = \frac{2hy}{h^2 + r^2} \tag{6}$$

where $y$ is the distance from the neutral mechanical plane. For a device consisting of $n$ layers with elastic modulus $E_i$ and thickness $t_i$ of the $i^{\text{th}}$ layer ($1^{\text{st}}$ layer at the top), the distance between the neutral mechanical plane and the top surface is

$$b = \frac{\sum_{i=1}^{n} E_i t_i \left( \sum_{j=1}^{i} t_j - \frac{1}{2} t_i \right)}{\sum_{i=1}^{n} E_i t_i} \tag{7}$$

The device in experiments[9] has 6 layers, SU8/Au/SU8/GaAs/SU8/PI, which have elastic moduli $E_1 = E_3 = E_5 = 4.4\,\text{GPa}$, $E_2 = 78\,\text{GPa}$, $E_4 = 77.5\,\text{GPa}$ and $E_6 = 2.5\,\text{GPa}$, and thickness $h_1 = 2.5$ $\mu$m, $h_2 = 300$ nm, $h_3 = 1.0$ $\mu$m, $h_4 = 2.5$ $\mu$m, $h_5 = 1.2$ $\mu$m and $h_6 = 1.2$ $\mu$m.

For 0.4 mm-thick PDMS thin film and the inflation height $h$=4 mm in experiments, the finite element method gives the maximum strain 0.0172% in the Au layer, while Eq.(6) gives 0.0148%.

## IV. CONCLUSIONS

Pressing an inflated elastomeric thin film during transfer printing of electronic devices is shown to be an effective way to introduce two dimensional prestrain, in a way that increase the stretchability of the electronics. An analytical model has been developed to study the strain induced in this process. Simple analytical solutions are obtained for both meridional and circumferential strains, which show good agreement with FEM simulations. These analytical solutions can give the strain in serpentine interconnects between device islands. The maximum strain in device islands is also obtained analytically. This model can be used to guide the design of two dimensional stretchable electronics.

## References

[1] Kim,D.H., Ahn,J.H., Choi,W.M., Kim,H.S., Kim,T.H., Song,J., Huang,Y., Liu,Z., Lu,C. and Rogers,J.A., Stretchable and foldable silicon integrated circuits. *Science*, 2008, 320: 507-511.

[2] Kim,D.H., Choi,W.M., Ahn,J.H., Kim,H.S., Song,J., Huang,Y., Liu,Z., Lu,C., Koh,C.G. and Rogers,J.A., Complementary metal oxide silicon integrated circuits incorporating monolithically integrated stretchable wavy interconnects. *Applied Physics Letters*, 2008, 93: 044102.

[3] Kim,D.H., Liu,Z., Kim,Y.S., Wu,J., Song,J., Kim,H.S., Huang,Y., Hwang,K.C., Zhang,Y. and Rogers,J.A., Optimized structural designs for stretchable silicon integrated circuits. *Small*, 2009, 5: 2841-2847.

[4] Kim,D.H., Viventi,J., Amsden,J.J., Xiao,J., Vigeland,L., Kim,Y.S., Blanco,J.A., Panilaitis,B., Frechette,E.S., Contreras,D., Kaplan,D.L., Omenetto,F.G., Huang,Y., Hwang,K.C., Zakin,M.R., Litt,B. and Rogers,J.A., Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics. *Nature Materials*, 2010, 9: 511-517.

[5] Viventi,J., Kim,D.H., Moss,J.D., Kim,Y.S., Blanco,J.A., Annetta,N., Hicks,A., Xiao,J., Huang,Y., Callans,D.J., Rogers,J.A. and Litt,B., A conformal, bio-interfaced class of silicon electronics for mapping cardiac electrophysiology. *Science Translational Medicine*, 2010, 2: 24ra22.

[6] Mannsfeld,S.C.B., Tee,B.C.K., Stoltenberg,R.M., Chen,C.V.H.H., Barman,S., Muir,B.V.O., Sokolov,A.N., Reese,C. and Bao,Z., Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers. *Nature Materials*, 2010, 9: 859-864.

[7] Takei,K., Takahashi,T., Ho,J.C., Ko,H., Gillies,A.G., Leu,P.W., Fearing,R.S. and Javey,A., Nanowire active-matrix circuitry for low-voltage macroscale artificial skin. *Nature Materials*, 2010, 9: 821-826.

[8] Someya,T., Sakurai,T., Sekitani,T. and Noguchi,Y., Printed organic transistors for large-area electronics. In: 6th International Conference on Polymers and Adhesives in Microelectronics and Photonics, 2007: 6-11.

[9] Kim,R.H., Kim,D.H., Xiao,J., Kim,B.H., Park,S.I., Panilaitis,B., Ghaffari,R., Yao,J., Li,M., Liu,Z., Malyarchuk,V., Kim,D.G., Le.,A.P., Nuzzo,G., R., Kaplan.,D.L., Omenetto.,F.G., Huang,Y., Kang,Z. and Rogers,J.A., Waterproof AlInGaP optoelectronics on flexible substrates with applications in biomedicine and robotics. *Nature Materials*, 2010, 9: 929-937.

[10] Bernards,D.A., Biegala,T., Samuels,Z.A., Slinker,J.D., Malliaras,G.G., Flores-Torres,S., Abruna,H.D. and Rogers,J.A., Organic light-emitting devices with laminated top contacts. *Applied Physics Letters*, 2004, 84: 3675-3677.

[11] Park,S.I., Le,A.P., Wu,J., Huang,Y., Li,X. and Rogers,J.A., Light emission characteristics and mechanics of foldable inorganic light-emitting diodes. *Advanced Materials*, 2010, 22: 3062-3066.

[12] Lee,T.W., Zaumseil,J., Bao,Z., Hsu,J.W.P. and Rogers,J.A., Organic light-emitting diodes formed by soft contact lamination. *Proceedings of the National Academy of Sciences of the United States of America*, 2004, 101: 429-433.

[13] Park,S.I., Xiong,Y., Kim,R.H., Elvikis,P., Meitl,M., Kim,D.H., Wu,J., Yoon,J., Yu,C.J., Liu,Z., Huang,Y., Hwang,K.C., Ferreira,P., Li,X., Choquette,K. and Rogers,J.A., Printed assemblies of inorganic light-emitting diodes for deformable and semitransparent displays. *Science*, 2009, 325: 977-981.

[14] Rogers,J.A., Bao,Z., Baldwin,K., Dodabalapur,A., Crone,B., Raju,V.R., Kuck,V., Katz,H., Amundson,K., Ewing,J. and Drzaic,P., Paper-like electronic displays: Large-area rubber-stamped plastic sheets of electronics and microencapsulated electrophoretic inks. *Proceedings of the National Academy of Sciences of the United States of America*, 2001, 98: 4835-4840.

[15] Jung,I., Shin,G., Malyarchuk,V., Ha,J.S. and Rogers,J.A., Paraboloid electronic eye cameras using deformable arrays of photodetectors in hexagonal mesh layouts. *Applied Physics Letters*, 2010, 96: 021110.

[16] Wang,S., Xiao,J., Jung,I., Song,J., Ko,H.C., Stoykovich,M.P., Huang,Y., Hwang,K.C. and Rogers,J.A., Mechanics of hemispherical electronics. *Applied Physics Letters*, 2009, 95: 181912.

[17] Ko,H.C., Stoykovich,M.P., Song,J., Malyarchuk,V., Choi,W.M., Yu,C.J., Geddes,J.B., Xiao,J., Wang,S., Huang,Y. and Rogers,J.A., A hemispherical electronic eye camera based on compressible silicon optoelectronics. *Nature*, 2008, 454: 748-753.

[18] Ko,H.C., Shin,G., Wang,S., Stoykovich,M.P., Lee,J.W., Kim,D.H., Ha,J.S., Huang,Y., Hwang,K.C. and Rogers,J.A., Curvilinear electronics formed using silicon membrane circuits and elastomeric transfer elements. *Small*, 2009, 5: 2703-2709.

[19] Shin,G., Jung,I., Malyarchuk,V., Song,J., Wang,S., Ko,H.C., Huang,Y., Ha,J.S. and Rogers,J.A., Micromechanics and advanced designs for curved photodetector arrays in hemispherical electronic eye cameras. *Small*, 2010, 6: 851-856.

[20] Kim,D.H., Xiao,J., Song,J., Huang,Y. and Rogers,J.A., Stretchable, curvilinear electronics based on inorganic materials. *Advanced Materials*, 2010, 22: 2108-2124.

[21] Wang,S., Xiao,J., Song,J., Ko,H.C., Hwang,K.C., Huang,Y. and Rogers,J.A., Mechanics of curvilinear electronics. *Soft Matter*, 2010, 6: 5757-5763.

[22] Yoon,J., Baca,A.J., Park,S.I., Elvikis,P., Geddes,J.B., Li,L., Kim,R.H., Xiao,J., Wang,S., Kim,T.H,, Motala,M.J., Ahn,B.Y., Duoss,E.B., Lewis,J.A., Nuzzo,R.G., Ferreira,P.M., Huang,Y., Rockett,A. and Rogers,J.A., Ultrathin silicon solar microcells for semitransparent, mechanically flexible and microconcentrator module designs. *Nature Materials*, 2008, 7: 907-915.

[23] Baca,A.J., Yu,K.J., Xiao,J., Wang,S., Yoon,J., Ryu,J.H., Stevenson,D., Nuzzo,R.G., Rockett,A.A., Huang,Y. and Rogers,J.A., Compact monocrystalline silicon solar modules with high voltage outputs and mechanically flexible designs. *Energy Environmental Science*, 2010, 3: 208-211.

[24] Rogers,J.A. and Huang,Y., A curvy, stretchy future for electronics. *Proceedings of the National Academy of Sciences of the United States of America*, 2009, 106: 10875-10876.

[25] Rogers,J.A., Someya,T. and Huang,Y., Materials and mechanics for stretchable electronics. *Science*, 2010, 327: 1603-1607.

[26] Khang,D.Y., Jiang,H., Huang,Y. and Rogers,J.A., A stretchable form of single-crystal silicon for high-performance electronics on rubber substrates. *Science*, 2006, 311: 208-212.

[27] Jiang,H., Khang,D,Y., Song,J., Sun,Y., Huang,Y. and Rogers,J.A., Finite deformation mechanics in buckled thin films on compliant supports. *Proceedings of the National Academy of Sciences of the United States of America*, 2007, 104: 15607-15612.

[28] Khang,D.Y., Xiao,J., Kocabas,C., MacLaren,S., Banks,T., Jiang,H., Huang,Y. and Rogers,J.A., Molecular scale buckling mechanics on individual aligned single-wall carbon nanotubes on elastomeric substrates. *Nano Letters*, 2008, 8: 124-130.

[29] Xiao,J., Jiang,H., Khang,D.Y., Wu,J., Huang,Y. and Rogers,J.A., Mechanics of buckled carbon nanotubes on elastomeric substrates. *Journal of Applied Physics*, 2008, 104: 033543.

[30] Ryu,S.Y., Xiao,J., Park,W.II., Son,K.S., Huang,Y., Paik,U. and Rogers,J.A., Lateral buckling mechanics in silicon nanowires on elastomeric substrates. *Nano Letters*, 2009, 9: 3214-3219.

[31] Xiao,J., Ryu,S.Y., Huang,Y., Hwang,K.C., Paik,U. and Rogers,J.A., Mechanics of nanowire/nanotube in-surface buckling on elastomeric substrates. *Nanotechnology*, 2010, 21: 085708.

[32] Lacour,S.P., Chan,D., Wagner,S., Li,T. and Suo,Z., Mechanisms of reversible stretchability of thin metal films on elastomeric substrates. *Applied Physics Letters*, 2006, 88: 204103.

[33] Lacour,S.P., Wagner,S., Huang,Z. and Suo,Z., Stretchable gold conductors on elastomeric substrates. *Applied Physics Letters*, 2003, 82: 2404.

[34] Li,T., Suo,Z., Lacour,S.P. and Wagner,S., Compliant thin film patterns of stiff materials as platforms for stretchable electronics. *Journal of Materials Research*, 2005, 20: 3274-3277.

[35] Li,T., Huang,Z., Suo,Z., Lacour,S.P. and Wagner,S., Stretchability of thin metal films on elastomer substrates. *Applied Physics Letters*, 2004, 85: 3435-3437.

[36] Mcdonald,J.C. and Whitesides,G.M., Poly (dimethylsiloxane) as a material for fabricating microfluidic devices. *Accounts of Chemical Research*, 2002, 35: 491-499.

[37] KMaltezos,G., Nortrup,R., Jeon,S., Zaumseil,J. and Rogers,J.A., Tunable organic transistors that use microfluidic source and drain electrodes. *Applied Physics Letters*, 2003, 83: 10.

[38] Kim,H.J., Son,Ch. and Ziaie B., A multiaxial stretchable interconnect using liquid-alloy-filled elastomeric microchannels. *Applied Physics Letters*, 2008, 92: 011904.

[39] Choi,W.M., Song,J., Khang,D.Y., Jiang,H., Huang,Y. and Rogers,J.A., Biaxially stretchable 'Wavy' silicon nanomembranes. *Nano Letters*, 2007, 7: 1655-1663.

[40] So,J.H., Thelen,J., Qusba,A., Hayes,G.J., Lazzi,G. and Dickey,M.D., Reversibly deformable and mechanically tunable fluidic antennas. *Advanced Functional Materials*, 2009, 19: 3632-3637.

[41] Jiang,H., Khang,D.Y., Fei,H., Kim,H., Huang,Y., Xiao,J. and Rogers,J.A., Finite width effect of thin-films buckling on compliant substrate: experimental and theoretical studies. *Journal of the Mechanics and Physics of Solids*, 2008, 56: 2585-2598.

[42] Wang,S., Song,J., Kim,D.H., Huang,Y. and Rogers,J.A., Local versus global buckling of thin films on elastomeric substrates. *Applied Physics Letters*, 2008, 93: 023126.

[43] Song,J., Jiang,H., Liu,Z., Khang,D.Y., Huang,Y., Rogers,J.A., Lu,C. and Koh,C.G., Buckling of a stiff thin film on a compliant substrate in large deformation. *International Journal of Solids and Structures*, 2008, 45: 3107-3121.

[44] Siegel,A.C., Tang,S.K.Y., Nijhuis,C.A., Hashimoto,M., Phillips,S.T., Dickey,M.D. and Whitesides,G.M., Cofabrication: a strategy for building multicomponent Microsystems. *Accounts of Chemical Research*, 2010, 43: 518-528.

[45] Jones,J., Lacour,S.P., Wagner,S. and Suo,Z., Stretchable wavy metal interconnects. *Journal of Vacuum Science & Technology A*, 2004, 22: 1723-1725.

[46] Brosteaux,D., Axisa,F., Gonzalez,M. and Vanfleteren,J., Design and fabrication of elastic interconnections for stretchable electronic circuits. *IEEE Electron Device Letters*, 2007, 28: 552-554.

[47] Zoumpoulidisa,T., Barteka,M., de Graafb,P. and Dekkera,R., High-aspect-ratio through-wafer parylene beams for stretchable silicon electronics. *Sensors and Actuators A: Physical*, 2009, 156: 257-264.

[48] Hsu,Y.Y., Gonzalez,M., Wolf,I.D., In situ observations on deformation behavior and stretchinginduced failure of fine pitch stretchable interconnect. *Journal of Materials Research*, 2009, 24: 3573-3582.

[49] Kim,H.J., Maleki,T., Wei,P., Ziaie,B. and Member, S., A biaxial stretchable interconnect with liquid-alloy-covered joints on elastomeric substrate. *Journal of Microelectromechanical systems*, 2009, 18: 138-146.

[50] Lin,K.L. and Jain,K., Design and fabrication of stretchable multilayer self-aligned interconnects for flexible electronics and large-area sensor arrays using excimer laser photoablation. *IEEE Electron Device Letters*, 2009, 30: 14-17.

[51] Huang,Y., Zhou,W., Hsia,K.J., Menard,E., Park,J.U., Rogers,J.A. and Alleyne,A.G., Stamp collapse in soft lithography. *Langmuir*, 2005, 21: 8058-8068.

[52] Hsia,K.J., Huang,Y., Menard,E., Park,J.U., Zhou,W., Rogers,J.A. and Fulton,J.M., Collapse of stamps for soft lithography due to interfacial adhesion. *Applied Physics Letters*, 2005, 86: 154106.

[53] Zhou,W., Huang,Y., Menard,E., Aluru,N.R., Rogers,J.A. and Alleyne,A.G., Mechanism for stamp collapse in soft lithography. *Applied Physics Letters*, 2005, 87: 251925.

[54] Meitl,M.A., Zhu,Z.T., Kumar,V., Lee,K.J., Feng,X., Huang,Y., Adesida,I., Nuzzo,R.G. and Rogers,J.A., Transfer printing by kinetic control of adhesion to an elastomeric stamp. *Nature Materials*, 2006, 5: 33-38.

[55] Meitl,M.A., Feng,X., Dong,J., Menard,E., Ferreira,P., Huang,Y. and Rogers,J.A., Stress focusing for controlled fracture in microelectromechanical systems. *Applied Physics Letters*, 2007, 90: 083110.

[56] Feng,X., Meitl,M.A., Bowen,A.M., Huang,Y., Nuzzo,R.G. and Rogers,J.A., Competing fracture in kinetically controlled transfer printing. *Langmuir*, 2007, 23: 12555-12560.

[57] Kim,T.H., Carlson,A., Ahn,J.H., Won,S.M., Wang,S., Huang,Y. and Rogers,J.A., Kinetically controlled, adhesiveless transfer printing using microstructured stamps. *Applied Physics Letters*, 2009, 94: 113502.

[58] Kim,S., Wu,J., Carlson,A., Jin,S.H., Kovalsky,A., Glass,P., Liu,Z., Ahmed,N., Elgan,S.L., Chen,W., Ferreira,P.M., Sitti,M., Huang,Y. and Rogers,J.A., Microstructured elastomeric surfaces with reversible adhesion and examples of their use in deterministic assembly by transfer printing. *Proceedings of the National Academy of Sciences of the United States of America*, 2010, 107: 17095-17100.

[59] Kim,D.H., Kim,Y.S., Wu,J., Liu,Z., Song,J., Kim,H.S., Huang,Y., Hwang K.C. and Rogers,J.A., Ultrathin silicon circuits with strain-isolation layers and mesh layouts for high-performance electronics on fabric, vinyl, leather, and paper. *Advanced Materials*, 2009, 21: 3703-3707.

[60] Kim,D.H., Song,J., Choi,W.M., Kim,H.S., Kim,R.H., Liu,Z., Huang,Y., Hwang,K.C., Zhang,Y.W. and Rogers,J.A., Materials and noncoplanar mesh designs for integrated circuits with linear elastic responses to extreme mechanical deformations. *Proceedings of the National Academy of Sciences of the United States of America*, 2008, 105: 18675-18680.

[61] Song,J., Huang,Y., Xiao,J., Wang,S., Hwang,K.C., Ko,H.C., Kim,D.H., Stoykovich,M.P. and Rogers,J.A., Mechanics of non-coplanar mesh design for stretchable electronic circuits. *Journal of Applied Physics*, 2009, 105: 123516.

[62] Bowden,N., Brittain,S., Evans,A.G., Hutchinson,J.W. and Whitesides,G.M., Spontaneous formation of ordered structures in thin films of metals supported on an elastomeric polymer. *Nature*, 1998, 393: 146-149.