Laser dynamic forming of functional materials laminated composites on patterned three-dimensional surfaces with applications on flexible microelectromechanical systems

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Laser dynamic forming (LDF) is a three-dimensional (3D) forming technique, which utilizes laser to induce shock wave and shape the target thin films onto micro/nanoscale 3D surfaces. This technique has been used to form metals on 3D surfaces. This letter extends LDF to functional and brittle materials sandwiched by elastomeric polymers on patterned 3D surface. The elastomeric polymers absorb the shock energy and minimize the degradation of the functional materials. The patterned 3D surfaces control the plasticity in the structure and therefore retain the function of the structure. The performance was evaluated and mechanisms were studied. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3222863]

Laser dynamic forming (LDF) is a three-dimensional (3D) microfabrication technique.[1] LDF combines the advantages of laser shock peening[2] and high strain rate forming.[3] This process utilizes laser to induce shock wave that propagates in target thin films, resulting in conformal 3D forming of the thin films onto micro/nanoscale 3D surfaces. LDF has great potential for meso-, micro-, and nanoscale 3D forming because laser provides high precision, localized high intensity, high repeatability, and superb flexibility. Similar to other high strain rate forming processes,[3] LDF provides good formability, elimination of wrinkling and springback. The advantages of the LDF technique over current 3D forming processes[4] are several folds, ranging from fast forming (i.e., forming taking place within nanoseconds), direct and high throughput, potential capability of mass production, and superplasticity in metallic thin films induced by high strain rate deformation. Currently, LDF has been used to form metallic materials on various 3D shapes of molds made from a wide variety of materials, such as metals, silicon, polymers, and photosensitive glass.[5]

In this letter, we study a unique process to expand the application of LDF from metallic materials to functional devices and materials, such as electric resistors and semiconductor materials (e.g., silicon and ZnO), which are widely used in microelectronics and microelectromechanical systems (MEMS) due to their unique functionalities. During LDF, the shock wave propagates into the target thin film and interacts with existing dislocations in the thin film. As a result, dislocation density increases and plastic deformation is generated. The dislocation activity during laser induced shock wave interaction with metals and brittle materials has been investigated.[6,7] However, during LDF, the shock pressure is higher than the compressive strength of these functional materials, which leads to fracture; therefore the above-mentioned functional materials may not survive under shock wave during LDF. To secure the functionality during LDF, our approach is to embed these functional materials within elastomeric layers, which absorb the shock energy and minimize the deformation of the functional materials. After LDF, the functionality of the formed MEMS devices has been evaluated, and the plastic deformation and energy absorption in various layers could be estimated by cross sectioning the formed devices. Thus, this study provides a means, with the potential capability of mass production, to fabricate functional devices on 3D surfaces without significant degradation.

The setup of patterned 3D LDF of functional material embedded laminates is illustrated in Fig. 1. A beam diffuser is used to uniform laser intensity distribution. When the laser pulse transmits through the confinement layer (glass or water) and irradiates the ablator (graphite coating or aluminum), the ablator is ionized instantly. The ionized plasma is bounced by the confining media and generates a strong shock wave, which provides a sufficient momentum to shape the target materials on molds. In order to have accurate evaluation of the pressure for controlled amount of plastic deformation, a widely used the model of Fabbro *et al.*[8] is employed. The magnitude of shockwave pressure is governed by the laser intensity, shock impedance of confining media and ablation coating, absorption coefficient of laser energy in plasma generation, and plasma layer thickness. In this study, shock pressure can be controlled by laser intensity and the confining media, while the laser pulse width (10 ns) and

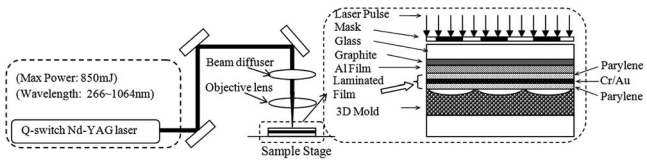

FIG. 1. Schematic setup of patterned 3D LDF of functional material embedded laminates.

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ablative coating (graphite) are fixed.[9] When water is used as confining media, the laser intensity ranges from 0.25 to 6 GW/cm^2, and the calculated shock pressure ranges from 489 to 3098 MPa; for glass confinement, the laser intensity 0.25–10 GW/cm^2, and shock pressure 1059–6703 MPa. The least last intensity to generate plasma and shock pressure is found to be 0.25 GW/cm^2 in the experiment; while the break down energy of water and glass with pulse width of 30 ns are 6 and 10 GW/cm^2, respectively.

The deformation generated by the LDF process is plastic and permanent, which is desirable for shaping the metallic components. At the same time, the plastic deformation, however, may cause degradation or even fracture in the formed materials, especially for brittle materials. To expand this approach to functional devices (e.g., MEMS) consisting of brittle materials, LDF methods must be able to produce "controlled" plastic deformation over various desired regions. Specifically, the plastic deformation at the device regions, where the functional materials are involved, must be minimized in order not to degrade the function of the device; similarly, the wiring region should remain certain flexibility for versatile connection in complex surfaces. In this work, not only the magnitude of shock pressure could be controlled, but also the location of the applied shock pressure could be specified by a mask (as shown in Fig. 1). The mask controls the transmission of laser energy in selected area, and thus controls the resulted shock pressure and plastic deformation. In particular, "phase-shift mask"[10] can be used to control light diffraction using constructive and destructive interference to selectively altering the phase of the light passing through certain areas. Using such a mask, one can control both the amplitude and the phase of the light.

In this study, we use laminated structures (functional devices and brittle materials sandwiched between flexible encapsulating layers) to be formed on patterned 3D surfaces. The encapsulating layers are made of Parylene, one of the polymers that have been used frequently as shock absorbents.[11] The first kind of laminated structure used in this work is an embedded electrical resistor structure: Parylene/Cr/Au/Parylene with thickness of 8.5/0.02/0.73/12.5 μm. The others are two MEMS devices sandwiched by Parylene layers. Specifically, the MEMS thin wire electrical resistor and film bulk acoustic resonators with brittle materials (e.g., ZnO and SiO_2) as functional components, are embedded between Parylene layers. The Parylene layers store elastic/plastic deformation energy during LDF to offer the entire system certain flexibility.

The patterned 3D surfaces allow the different regions (functional devices and wiring regions) to experience different shock loads during LDF. For example, Fig. 2 schematically shows a wavy mold with certain uneven and even regions. After LDF, the embedded metal connectors and functional devices are conformed on uneven and even regions, respectively. It is expected that the metal connectors (wirings) aligned to the wavy regions will have certain flexibility due to the flexible polymer, will be formed to wavy shapes and will have certain level of plastic deformation; while the functional devices aligned with the even regions will have minimal plastic deformation and should work properly. To verify this hypothesis, in fact two subhypotheses, namely, minor degradation over wiring regions on uneven surfaces due to the absorption of shock energy by elastomeric layers, and negligible degradation of the functional

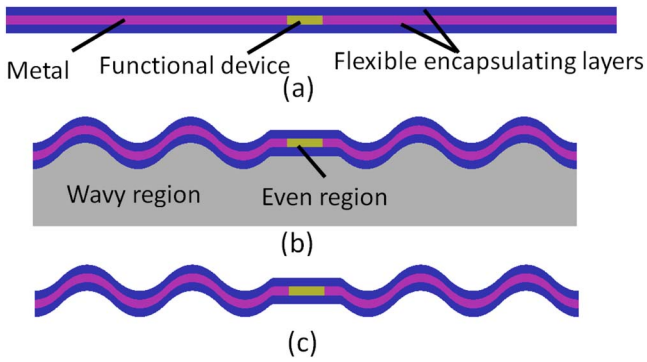

FIG. 2. (Color online) Schematic view of LDF of metal/functional devices embedded laminates formed on a 3D wavy mold with certain even and uneven regions.

devices over flat surfaces, metal wires and two MEMS devices are formed on wavy and flat surfaces, respectively, and are tested after LDF.

Figure 3(a) shows a scanning electron micrograph of the wavy mold to be employed on forming the wavy wirings. The wavy mold is made of a micrometer-thick SiO_x-like thin film on a poly(dimethylsiloxane) (PDMS) substrate.[11] The wiring, composed of composite structure Parylene/Cr/Au/Parylene (9/0.02/0.5/12 μm) thin film lines sandwiched by three Parylene lines (21 μm), was fabricated and laser formed on a 3D wavy PDMS mold [Fig. 3(b)], with laser intensity of 0.25 GW/cm^2, glass as confinement and graphite as ablator. After LDF, the electrical resistance of Cr/Au thin microelectrode line, encapsulated between Parylene layers, was measured to be at 27 Ω, which corresponded to a fair low (35%) increase over the intact micro Cr/Au line. This confirms the first hypothesis, i.e., minor degradation over wiring regions on uneven surfaces. The laser formed Polymer/metals/Polymer structures on 3D surface do not have significant degradation and, therefore, can serve as electrodes in functional devices.[12]

In order to fundamentally understand the reason why LDF process does not degrade the laminated composite structures, the structure prior to and after LDF was investigated using 3D focused ion beam (FIB) tomography.[13] Figures 4(a) and 4(b) show the cross section images of the laminate thin film prior to and after LDF. The layer thickness of Parylene/Cr-Au/Parylene 12.49/0.759/8.58 μm was changed to 7.16/0.752/6.78 μm after LDF. It is noteworthy that the strains in the top and bottom Parylene layers of the sandwich structure were −55.6% and −23%, respectively, while the strain in the midlayer (Cr/Au) was negligible. The results confirm the hypothesis that elastomeric

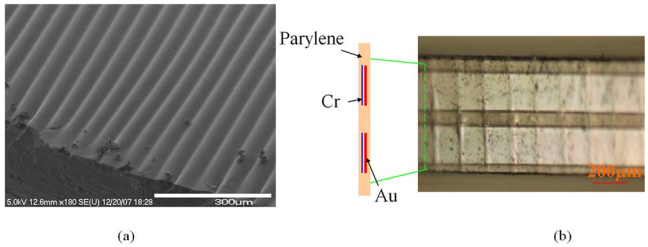

FIG. 3. (Color online) (a) SEM micrograph of a laminated structure and (b) optical microscope image of a patterned laminated structure after LDF on 3D wavy molds.

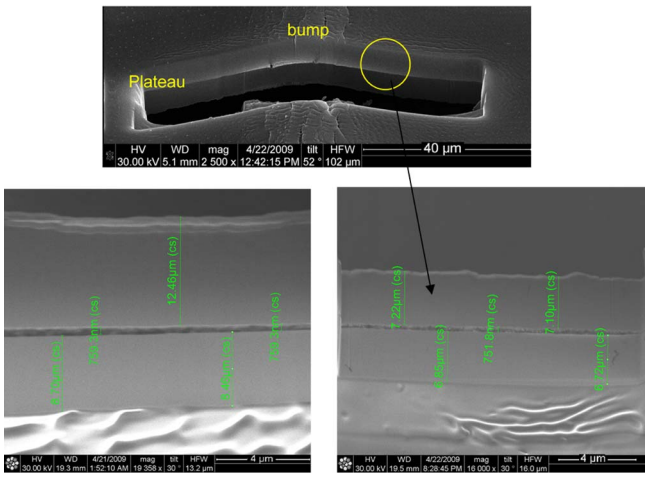

FIG. 4. (Color online) Results of 3D FIB tomography—the cross section images of the laminate thin film prior to (l) and after LDF (r).

layers (Parylene) absorb most of the shock energy during LDF, and protect the functional layers from degradation.

To verify if the LDF may damage the functional devices on even surface, two types of devices: shear stress sensors with micron scale thin electrical wire resistor and film bulk acoustic resonators (FBARs), were laser formed on an even surface. Similar laser forming conditions were used. The 2 μm wide, 240 μm long Ti/Pt (0.06/0.015 μm thick) electrical resistor was covered by a Parylene layer, whose resistances prior and after LDF process on a flat glass slide were measured to evaluate its functionality. The result indicates only 2% change of resistance from 597 Ω (prior to LDF) to 610 Ω (after LDF), which suggests that the LDF process on a flat surface does not damage the shear stress sensor. Laser forming an FBAR on a flat surface further evaluates the effect of LDF on brittle functional materials on even surface since the functionality of the FBAR is closely related to its quality factor, which is different from the electrical resistance. The FBAR used in this test works at 4.4GHz with $SiO_2/Si/SiO_2/Al/ZnO/Al$ (1.7/6.2/3.0/0.1/1.0/0.1 μm) structure, where Si is single crystal, ZnO is polycrystalline and SiO_2 is amorphous structure. After LDF, FBAR on a glass slide has quality factor of 930 at 4.4GHz, which shows negligible degradation of the function. Little performance degradation of these two devices upon LDF on even surface confirms that LDF on flat surface will have no harm to functional composite structures, even with brittle materials in it.

This work develops a means to form functional materials sandwiched by elastomeric polymers on patterned 3D surface using LDF. As shock energy absorption layers, the elastomeric polymers avoid the fracture and minimize the degradation of the functional materials. The patterned surface leads to controllable plasticity on the functional materials. The performance of the shaped laminated structures is found to have tolerant degradation and the fundamental mechanisms have been addressed. The implementation of this method will significantly extend the applications of LDF, such as flexible electronics.

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