Mechanics Design for Stretchable, High Areal Coverage GaAs Solar Module on an Ultrathin Substrate

Xiaoting Shi[1]
Shanghai Key Laboratory of Materials Laser Processing and Modification,
School of Materials Science and Engineering,
Shanghai Jiao Tong University,
Shanghai 200240, China;
Departments of Mechanical Engineering and Civil and Environmental Engineering,
Center for Engineering and Health,
and Skin Disease Research Center,
Northwestern University,
Evanston, IL 60208

Renxiao Xu[1]
Departments of Mechanical Engineering and Civil and Environmental Engineering,
Center for Engineering and Health, and Skin Disease Research Center,
Northwestern University,
Evanston, IL 60208

Yuhang Li
School of Aeronautical Science & Engineering,
Institute of Solid Mechanics,
Beihang University,
Beijing 100191, China

Yihui Zhang
Departments of Mechanical Engineering and Civil and Environmental Engineering,
Center for Engineering and Health, and Skin Disease Research Center,
Northwestern University,
Evanston, IL 60208;
Center for Mechanics and Materials,
Tsinghua University,
Beijing 100084, China

Zhigang Ren
School of Civil Engineering and Architecture,
Wuhan University of Technology,
Wuhan 430070, China

Jianfeng Gu
Shanghai Key Laboratory of Materials Laser Processing and Modification,
School of Materials Science and Engineering,
Shanghai Jiao Tong University,
Shanghai 200240, China

John A. Rogers
Department of Materials Science and Engineering,
University of Illinois,
Urbana, IL 61801

Yonggang Huang[2]
Departments of Mechanical Engineering and Civil and Environmental Engineering,
Center for Engineering and Health, and Skin Disease Research Center,
Northwestern University,
Evanston, IL 60208
e-mail: y-huang@northwestern.edu

The trench design of substrate together with curvy interconnect formed from buckling provides a solution to stretchable electronics with high areal coverage on an ultrathin substrate, which are critically important for stretchable photovoltaics. In this paper, an improved trench design is proposed and verified by finite element analysis (FEA), through use of a heterogeneous design, to facilitate strain isolation and avoid possible fracture/delamination issue. A serpentine design of interconnect is also devised to offer ∼440% interconnect level stretchability, which is >3.5 times that of previous trench design, and could transform into 20% system-level stretchability, even for areal coverage as high as ∼90%. [DOI: 10.1115/1.4028977]

Keywords: high areal coverage, ultrathin, substrate, interconnect, strain

Recent developments in mechanics, materials and manufacturing science enable the integration of advanced semiconductor devices with ultralow modulus substrates to yield performance comparable to that of conventional, rigid wafer-based technologies, but with the ability to stretch like a rubber band, twist like a rope, and bend over the tip of a pencil [1]. These capabilities enable new applications ranging from sensitive robotic skins [2,3] to eyeball-like digital cameras [4,5], to soft surgical instruments [6–8], to "epidermal" health/wellness monitors [9–11]. Figure 1(*a*) shows a representative design [12], in which the rigid, functional components reside on raised regions (i.e., mesas with height h_{mesa}, Fig. 1(*c*)) of a soft, elastomeric substrate (with height h_{base}) in order to isolate the components from strain that arise from stretching the substrate. The top view in Fig. 1(*b*) shows the square mesas (with edge length l_{mesa}) separated by trenches (with width l_{trench}). Stretchable interconnects between functional

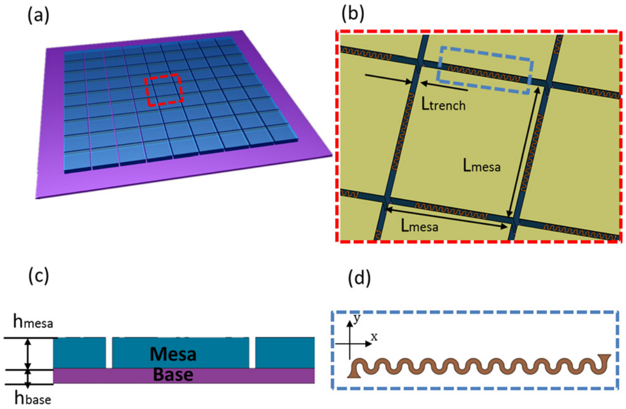

Fig. 1 Schematic illustration of the solar module, featuring (*a*), (*c*) substrate with base and mesa, (*b*) mounted solar cells, and (*d*) serpentine-shape interconnects

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[1] These authors contribute equally to this work.

[2] Corresponding author.

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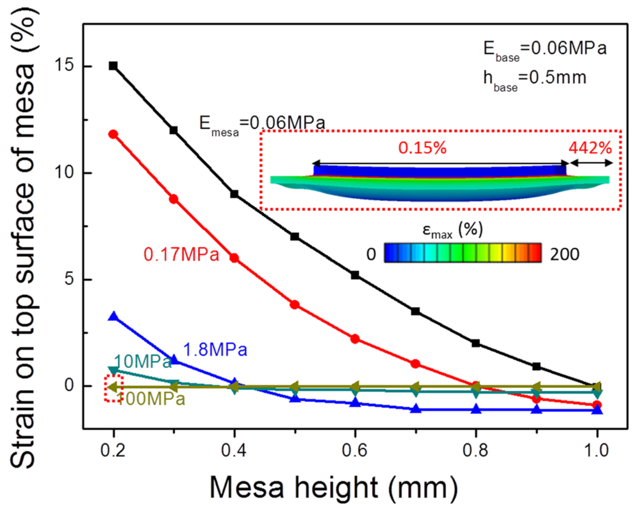

Fig. 2 The maximum principal strain on the top surface of mesa versus the mesa thickness for mesa with different Young's moduli on the base (Young's modulus 0.06 MPa and thickness 0.5 mm). The inset shows the distribution of maximum principal strain in the ultrathin substrate subject to 20% system stretching (mesa: Young's modulus 100 MPa, thickness 0.2 mm and base: Young's modulus 0.06 MPa, thickness 0.5 mm).

devices (Fig. 1(*d*)) reside in the trenches to provide system-level stretchability ($\varepsilon_{\text{system}}$), which is related to the interconnect level stretchability ($\varepsilon_{\text{interconnect}}$) via the areal coverage (η) of functional components [13]

$$\varepsilon_{\text{system}} = (1 - \sqrt{\eta})\varepsilon_{\text{interconnect}} \tag{1}$$

Stretchable photovoltaics [12] require a high areal coverage of functional components (e.g., GaAs solar cells) for efficient capture of sunlight. This requirement demands small spacing, $l_{\text{trench}} \ll l_{\text{mesa}}$, or equivalently, high areal coverage η, and therefore large $\varepsilon_{\text{interconnect}}$ for a given $\varepsilon_{\text{system}}$. Lee et al. [12] achieved interconnect stretchability $\varepsilon_{\text{interconnect}} = 123\%$, which yields a system stretchability $\varepsilon_{\text{system}} = 20\%$ for an areal coverage $\eta \sim 70\%$. For a target areal coverage $\sim 90\%$ (e.g., $l_{\text{mesa}} = 5.25$ mm and $l_{\text{trench}} = 0.25$ mm leading to $\eta = 91\%$), and similar level of system stretchability of $\sim 20\%$, the interconnect must sustain $\sim 440\%$ stretchability according to Eq. (1). This extreme interconnect stretchability cannot be achieved using prior approaches [12] for a relatively shallow trench, e.g., $h_{\text{mesa}} = 0.25$ mm. For such shallow trenches and ultrathin substrates (<1 mm), the surface strain of the mesa may reach 15% at 20% system stretchability, which does not provide sufficient isolation of the functional components from strain, leading to their fracture or delamination from the substrate.

In order to achieve high areal coverage ($\eta > 90\%$) and large stretchability ($\varepsilon_{\text{system}} > 20\%$) for an ultrathin substrate (< 1 mm), a new design is proposed to use a relatively stiff elastomer (e.g., Young's modulus 10 MPa) for the mesa to further facilitate strain isolation at mesa's top surfaces, for mounting of the photovoltaic components. In response to tensile load, the deformation in the substrate localizes to regions underneath the trenches. A commercially available soft silicone elastomer (Ecoflex, Young's modulus 60 kPa, Poisson's ratio 0.49, and failure strain $\sim 500\%$) serves as the base material to accommodate $\sim 440\%$ stretchability of the substrate. For small h_{mesa}, this combination of very compliant base and relatively stiff mesa offers high η and large stretchability. FEA provides guidance on selection of a structure optimized to minimize the surface strains at the mesa so as to avoid possible damage to functional components during stretching. Figure 2 shows the average strain on the top surface of the mesa versus h_{mesa} for the mesa Young's modulus $E_{\text{mesa}} = 0.06$ MPa (Ecoflex), 0.17 MPa (Solaris), 1.8 MPa (PDMS), 10 MPa, and 100 MPa. This average strain is approximately the same as the maximum strain since the strain distribution over the mesa top surface is quite uniform [12]. The average strain increases rapidly as the mesa height decreases. For $h_{\text{mesa}} = 0.2$ mm, it reaches 15% for Ecoflex (same as the base material), but is reduced to $<1\%$ for $E_{\text{mesa}} = 10$ MPa and $<0.2\%$ for 100 MPa, which clearly shows that the strain decreases rapidly as the mesa modulus increases. The inset in Fig. 2 gives the maximum principal strain distribution in the substrate for $E_{\text{mesa}} = 100$ MPa and 20% system stretchability; the mesa top surface remains almost undeformed, which shields the photovoltaics components from strains.

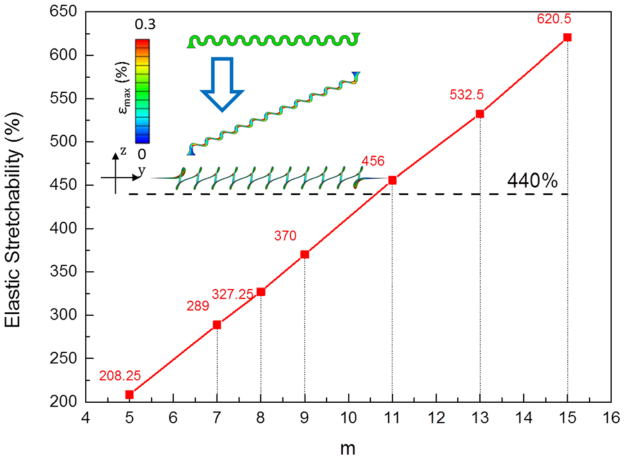

Fig. 3 The elastic stretchability of interconnect versus the number *m* of periodic units. The inset shows the deformed serpentine interconnect (for 11-Unit) stretched to elastic limit (456%), in top and side views.

The serpentine interconnect in Fig. 1(*d*) is proposed to achieve extremely high stretchability ($\varepsilon_{\text{interconnect}} = 440\%$). This design differs from previously reported layouts [14] because the serpentine structures lie perpendicular to the stretching direction, as illustrated in the top inset in Fig. 3. A copper layer for electrical conductance (Young's modulus 119 GPa, Poisson's ratio 0.34, thickness 0.5 μm, and width 50 μm), sandwiched by two layers of polyimide for insulation (Young's modulus 2.5 GPa, Poisson's ratio 0.34, and thickness of each layer 2.4 μm) is used for the interconnect. The interconnect has m periodic units, and each unit consists of two interchained semicircular arcs with the diameter 125 μm. Under stretching the interconnect buckles laterally, as illustrated in the bottom inset in Fig. 3. Figure 3 shows that the elastic stretchability of the interconnect, defined by the yield strain 0.3% of copper, is approximately linear with respect to the number of period units, m. For $m \geq 11$, the interconnect gives the required elastic stretchability 440%.

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