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Review

Recent advances on thermal analysis of stretchable electronics

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HIGHLIGHTS

- Recent advances on thermal analysis of stretchable electronics are overviewed.
- Scaling laws for the temperature increase in a constant and pulsed mode are established.
- Design guidelines for thermal management of stretchable electronics are provided.

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ABSTRACT

Stretchable electronics, which offers the performance of conventional wafer-based devices and mechanical properties of a rubber band, enables many novel applications that are not possible through conventional electronics due to its brittle nature. One effective strategy to realize stretchable electronics is to design the inorganic semiconductor material in a stretchable format on a compliant elastomeric substrate. Engineering thermal management is essential for the development of stretchable electronics to avoid adverse thermal effects on its performance as well as in applications involving human body and biological tissues where even 1–2 °C temperature increase is not allowed. This article reviews the recent advances in thermal management of stretchable inorganic electronics with focuses on the thermal models and their comparisons to experiments and finite element simulations.

Contents

1. Introduction

Fast developments and substantial achievements have been made on various aspects of stretchable electronics [1–7], which has superior mechanical properties that are inaccessible to conventional wafer-based electronics such as stretched like a rubber band and twisted like a rope without any significant reduction in electronic performance. Two complementary approaches have been demonstrated to develop stretchable electronics. One approach involves the use of the intrinsically compliant semiconductor materials to replace the intrinsically brittle inorganic semiconductor materials [8–11] that are widely used in conventional electronics. The other approach designs conventional high-performance inorganic semiconductor materials (e.g., Silicon) in a novel stretchable structure on a compliant substrate [12–15]. One such design is the bridge-island design with functional components residing on the island interconnected by the bridges to keep the islands almost un-

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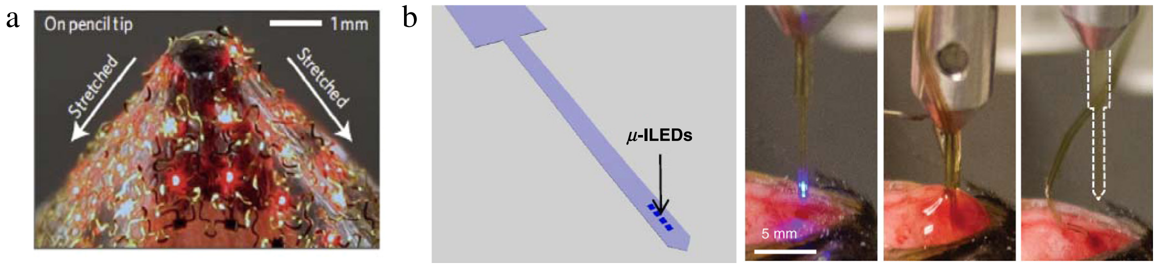

Fig. 1. (a) Stretchable inorganic light-emitting diodes with serpentine bridges, tightly stretched onto the sharp tip of a pencil. Reproduced with permission from Ref. [15]. Copyright 2010 Nature Publishing Group. (b) Scanning electron microscope (SEM) image of an injectable array of μ-ILEDs and the process of injection and release of the μ-ILEDs into the mouse brain for in vivo optogenetics. Reproduced with permission from Ref. [16]. Copyright 2013 AAAS.

deformed under stretching as shown in Fig. 1(a) of inorganic light-emitting diodes stretched onto the sharp tip of a pencil.

Thermal management of stretchable electronics is critically important because excessive heating may induce adverse responses such as the reduction of device performance and tissue lesioning (even 1–2 °C temperature increase) in applications (e.g., optogenetics, see Fig. 1(b)) involving biological tissues. The low conductivity ($\sim$0.1 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$) of elastomeric substrate for stretchable electronics, which is about 3 orders lower than that of typical substrate for conventional electronics, imposes more challenges on the thermal management. This review paper will focus on the latter approach based on inorganic semiconductor materials and take microscale, inorganic light-emitting diodes (μ-ILEDs), which serve as heat sources and the active device islands in the bridge-island design for stretchable electronics, as an example to overview the recent advances in heat management of stretchable electronics through discussions of analytic, finite element simulations and experimental results.

2. Thermal analysis of μ-ILEDs under a constant power

Conventional design with individual packaged components interconnected by bulk wire bonding and mounted on a millimeter-scale heat sink for thermal management is not suitable for stretchable electronics, especially for applications of μ-ILEDs biology. Kim et al. [17] reported strategies using advanced methods in epitaxial liftoff and deterministic assembly and successfully fabricated μ-ILEDs on different substrates. Figure 2(a) shows the schematic diagram of the μ-ILED structure with the μ-ILED, encapsulated by benzocyclobutene (BCB) and metal layers, on the top of a glass substrate. Lu et al. [18] developed an analytic model by ignoring the structure details (e.g., p and n contacts) as shown in Fig. 2(b) to study the thermal properties of μ-ILEDs and establish a scaling law for the device temperature under a constant power. For simplicity, an axisymmetric model is adopted. The μ-ILED ($L \times L$) is modeled as a circular planar heat source with radius $r_0 = L/\sqrt{\pi}$ and the input power of Q at the BCB–glass interface. The comparison of surface temperature distributions in Fig. 2(c) from the analytical model, 3D finite element analysis (FEA) and experiments validates the analytical model. The μ-ILED temperature increase $\Delta T_{\mu\text{-ILED}} = T_{\mu\text{-ILED}} - T_0$ from the ambient temperature T_0 is given by

$$\Delta T_{\mu\text{-ILED}} = \frac{2Q}{\pi k_B r_0^2}\int_0^\infty \beta(\xi) J_1^2(\xi r_0)\frac{\mathrm{d}\xi}{\xi^2} \approx 0.451\frac{Q}{k_g L}\left\{1-0.842\left(\frac{k_g L}{k_m H_m}\right)^{-1} \times\left[1-\exp\left(-1.07\frac{k_g L}{k_m H_m}\right)\right]\right\}, \tag{1}$$

where k and H are the thermal conductivity and thickness with subscripts m, B and g for metal, BCB and the glass substrate, respectively, J_1 is the 1st-order Bessel function of the first kind and $\beta(\xi)$ is an analytic expression depending on material and geometry parameters [18]. The approximation in Eq. (1) holds for the facts that the glass thickness is much larger than other thickness ($H_g \gg H_m, H_B, r_0$), the thermal conductivity of metal is much larger than that of BCB ($k_m \gg k_B$), and the μ-ILED size is much larger than the metal and BCB layer thicknesses ($r_0 \gg H_m, H_B$). A simple scaling law could be easily established from Eq. (1): the normalized μ-ILED temperature $k_m H_m \left(T_{\mu\text{-ILED}} - T_0\right)/Q$ depends on only one non-dimensional parameter $k_g L/(k_m H_m)$. The scaling law (i.e., the approximate solution) agrees well with the accurate solution, 3D FEA and experiments in Fig. 2(d). It suggests that thick metal layer or large metal thermal conductivity help to reduce the μ-ILED temperature.

The temperature increase in Eq. (1) is for the single μ-ILED on a glass substrate and it can be easily extended to study other μ-ILED system with similar layouts and materials. Figure 3(a) shows the μ-ILED temperature as a function of μ-ILED size on a polyethylene terephthalate (PET) substrate at 160 $\mathrm{mW \cdot mm^2}$. The analytical prediction agrees very well with experiments. The temperature decreases with decreasing the μ-ILED size, which clearly indicates an effective route for thermal management: to divide a large LED to an array of μ-ILEDs. To find the temperature increase for μ-ILED array, the method of superposition can be used, i.e., $T_{\text{array}}(r,z) = T_0 + \sum_i \Delta T_i(r,z)$, where $\Delta T_i(r,z)$ is the temperature increase due to ith μ-ILED. The temperature increases for a conventional, macro-size LED (i.e., $0.5 \times 0.5\ \mathrm{mm^2}$), an array of 25 μ-ILEDs (i.e., $100 \times 100\ \mu\mathrm{m}^2$) at different spacings are shown in Fig. 3(b). The temperature of μ-ILED array decreases with increasing spacing and becomes independent of spacing for the spacing larger than $\sim$200 μm, which suggests a critical spacing to maximally reduce the temperature.

3. Thermal analysis of μ-ILEDs in a pulsed operation

In order to further decrease the device temperature, Kim et al. [19] applied a pulsed power and successfully fabricated μ-ILEDs on hydrogel substrate to simulate biological tissue. Figure 4(a) shows the layouts of a single μ-ILED on a polyimide (PI) layer attaching to a hydrogel substrate encapsulated by an epoxy (SU8) layer. Li et al. [20] developed an analytic model, validated by experiments and 3D FEA, to study the thermal properties of μ-ILED in a pulsed operation and derived a scaling law for the μ-ILED temperature increase. The PI layer and hydrogel substrate are taken as a single hydrogel layer (see Fig. 4(b)) since the PI layer has similar thermal properties as hydrogel. The pulsed power applied to the μ-ILED is defined by $Q(t) = Q_0 U(t)$ with Q_0 as the peak power and $U(t)$ as a unit pulsed power in Fig. 4(c). Let τ denote the pulse duration and t_0 the period of the pulse, the duty cycle D is defined by $D = \tau/t_0$. It is noted that under a pulsed power, the μ-ILED temperature first increases in a fluctuation way and then reached saturation